MATERIALS and PROCESS SELECTION for ENGINEERING DESIGN

Third Edition

Mahmoud M. Farag

CRC Press
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To

Penelope, Serif, Sophie, Eamon, Hisham, Nadia, and Nadine

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Preface to the Third Edition

Since the publication of the second edition in 2009, changes have occurred in the fields of materials and manufacturing. Nanostructured and smart materials now appear more frequently in products. Composites are now used in manufacturing essential parts of civilian airliners and even the whole aircraft, as in the Boeing 787 Dreamliner. Biodegradable materials are increasingly used instead of traditional plastics, as emphasis is placed nowadays on environment friendly products. Companies manufacture more of their products in-house rather than outsourcing them to ensure quality and reduce cost. These changes have been reflected in the curricula and courses of materials and manufacturing in a variety of engineering programs and schools.

Experience in using the second edition as a textbook for junior and senior engineering students has shown that although they have completed a first course in materials, they still need practical information on the treatment, behavior, and use of engineering materials in various applications. The appendices in Part IV have been revised and expanded to provide such information.

Twenty-two new cases studies and design examples have also been added throughout the book, as experience has shown that case studies are helpful in explaining engineering concepts in addition to increasing student interest in the subject and encouraging active learning. A list of expected outcomes has also been added at the beginning of each part of the book to enhance the use of the third edition as a textbook.

Several new sections have been added and the content of many others has changed to reflect the recent developments in engineering materials and manufacturing. The main new features in the third edition include the following:

- Using House of Quality (HOQ) as a tool for identifying customer needs and relating them with the technical characteristics of the product (Chapters 1, 5, and 9)
- Taking environmental issues into consideration, including environmental impact of products, environmentally responsible designs, environmental impact assessment of materials and processes, and recyclability issues (Chapters 1, 5, and 8)
- Taking product safety and reliability issues into consideration, including failure mode and effects analysis, design for Six Sigma, product reliability and safety, and product liability legislation (Chapters 2 and 5)
- Using nontraditional and advanced materials in engineering products, including the use of layered structures as a replacement for steel sheets and polymers in mechanical design, and presenting the technical and economic feasibility of using carbon nanotubes (Chapters 6, 9, 10, and 11)

- Manufacturing considerations, including product manufacture in industry, manufacturing processes selection, automation of manufacturing processes, and computer-integrated manufacturing (Chapter 7)
- Selecting engineering products on the basis of benefit/cost ratio and cost-effectiveness analysis (Chapter 8)
- Using MATLAB® in materials selection and materials substitution (Chapters 9 and 10)

Preface to the Second Edition

Introducing a new engineering product or changing an existing model involves making designs, reaching economic decisions, selecting materials, choosing manufacturing processes, and assessing its environmental impact. These activities are interdependent and should not be performed in isolation from each other. This is because the materials and processes used in making the product can have a large influence on its design, cost, and performance in service. For example, making a part from injection-molded plastics instead of pressed sheet metal is expected to involve large changes in design, new production facilities, and widely different economic and environmental impact analysis.

Experience has shown that in most industries it is easier to meet the increasing challenge of producing more economic and yet reliable, aesthetically pleasing, and environmentally friendly products if a holistic decision-making approach of concurrent engineering is adopted in product development. With concurrent engineering, materials and manufacturing processes are considered in the early stages of design and are more precisely defined as the design progresses from the concept to the embodiment and finally the detail stage.

The objective of this book is to illustrate how the activities of design, materials and process selection, and economic and environmental analysis fit together and what sort of trade-offs can be made in order to arrive at the optimum solution when developing a new product or changing an existing model.

The book starts with an introductory chapter that briefly reviews the stages of product development in industry, recycling of materials, and life-cycle costing. The subject matter is then grouped into three parts. Part I consists of three chapters, which discuss the performance of materials in service. After a review of different types of mechanical failures and environmental degradation, the materials that are normally selected to resist a given type of failure are discussed. Part II consists of three chapters, which deal with the effect of materials and manufacturing processes on design. The elements of industrial and engineering design are first explained, followed by a discussion of the effect of material properties and manufacturing processes on the design of components. Part III consists of four chapters, which are devoted to the selection and substitution of materials in industry. After a brief review, the economics and environmental aspects of materials and manufacturing processes as well as several quantitative and computer-assisted methods of screening are presented; comparing and ranking of alternative solutions and selecting the optimum solution are also discussed. The final chapter presents five different detailed case studies in materials selection and substitution.

The book is written for junior and senior engineering students who have completed a first course in engineering materials; however, first year graduate students and practicing engineers will also find the subject matter interesting and useful. In order to enhance the value of the text as a teaching device, a variety of examples and open-ended case studies are given to explain the subject matter and to illustrate its practical application in engineering. Each chapter starts with an introduction, which includes its goals and objectives, and ends with a summary, review questions, suggestions for student projects, and selected references for further reading. SI units are used throughout the text, but imperial units are also given whenever possible. Tables of composition and properties of a wide variety of materials, conversion of units, and a glossary of technical terms are included in the appendices. PowerPoint presentations and a solution manual are also made available to instructors.

Author

Dr. Mahmoud M. Farag received his BSc in mechanical engineering from Cairo University and his MMet and PhD from Sheffield University, United Kingdom. He currently serves as a professor of engineering at the American University in Cairo (AUC).

Dr. Farag's academic interests include engineering materials and manufacturing. He has published three engineering textbooks, edited one book, and written several engineering book chapters. He has also authored and coauthored about 100 papers in academic journals and conference proceedings on issues related to the effect of microstructure on the behavior of engineering materials. His current research interests include studying the behavior of nanostructured materials, with an emphasis on NiTi alloys, natural fiber–reinforced plastics, and biodegradable composite materials and using quantitative methods in selecting materials and processes for engineering applications. In addition to his academic work, he has extensive industrial and consulting experience.

Dr. Farag has more than 30 years of teaching experience and has taught a variety of materials courses at different levels, ranging from introductory overview to sophomore/junior students to advanced topics to students pursuing their master's degree. He has also taught manufacturing courses, focusing on how processing affects the properties of materials. One of Dr. Farag's favorite courses, which he created at AUC and has written textbooks for, is materials selection. This is a capstone course for mechanical/materials engineering senior students, which integrates economic analysis with the process of product design and material and process selection.

Dr. Farag was a visiting scientist/scholar at the University of Sheffield (United Kingdom), MIT, the University of Kentucky–Lexington (United States), Aachen Technical University (Germany), and Joint Research Center, Commission of the European Communities (Ispra, Italy). He is a member of the American Society of Mechanical Engineers; the Materials Information Society; the American Society for Metals (ASM) International; the Institute of Materials, Minerals and Mining (United Kingdom); and the Egyptian Society for Engineers. He is listed in *Marquis Who's Who in the World*, *Who's Who in Science and Engineering*, and *Who's Who in Finance and Industry*. Dr. Farag is a recipient of the Egyptian State Award for the promotion of science and the First Order of Merit in Arts and Sciences.

1 Product Design and Development in the Industrial Enterprise

1.1 INTRODUCTION

Product design and development involve interdisciplinary activities with contributions from different segments of an industrial enterprise including design, materials and manufacturing, finance, legal, sales, and marketing. This is because in addition to satisfying the technical requirements, a successful product should also be esthetically pleasing, safe to use, economically competitive, and compliant with legal and environmental constraints.

The total development effort depends on the complexity of the product, and project teams can consist of a few people working for a few days or weeks on a simple product like a hand tool to several hundred people working for several months or even years on a complex product like a motorcar or an airplane. The cost of development can range from a few hundred dollars for a simple product to millions of dollars for a complex product.

A product usually starts as a concept that, if feasible, develops into a design and then a finished product. While each engineering product has its own individual character and its own sequence of development events, the following seven phases can be identified in a variety of product design and development projects:

1. Identification of needs, feasibility study, and concept selection
2. System-level design, detail design, and selection of materials and processes
3. Testing and refinement
4. Manufacturing the product
5. Launching the product
6. Selling the product
7. Planning for its retirement

The overall goal of this chapter is to introduce the spectrum of activities that are normally involved in different product development phases. The main objectives are to

1. Review the main activities of identification of needs, performing a feasibility study and selecting an optimum concept
2. Discuss the main stages of designing and manufacturing a product

3. Discuss the main activities involved in testing and refining a new product and then launching and selling it
4. Analyze the environmental issues that are involved in making a product and in retiring it
5. Explain the concepts of life cycle costing and the product life cycle

Several of these activities will be discussed in more detail later in this book.

1.2 FEASIBILITY STUDY, IDENTIFICATION OF NEEDS, AND CONCEPT SELECTION

A statement describing the function, main features, general shape, and essential features of the product is normally followed by a feasibility study that addresses market environment, customer views, technical specifications, economic analysis, as well as social, environmental, safety, and legal issues.

1.2.1 Market Research

Market research involves a survey to evaluate competing products and their main characteristics in addition to identifying the customer needs. Elements of the market research include the following:

1. The range of features and technical advantages and disadvantages of the existing products, the mechanism of their operation, and the materials and processes used in making them.
2. Past and anticipated market growth rate and expected market share by value and volume.
3. The number of companies entering and leaving the market over the past few years and reasons for those movements.
4. The reasons for any modifications that have been carried out recently and the effect of new technology on the product.
5. Patent or license coverage and what improvements can be introduced over the existing products.
6. Profile of prospective customers (income, age, sex, etc.) and their needs in the area covered by the product under consideration.
7. Ranking of customer needs in the order of their importance.
8. Product price that will secure the intended volume of sales.
9. How long will it take for the competition to produce a competitive product?
10. What is the optimum packaging, distribution, and marketing method?

The preceding information is essential for determining the rate of production, plant capacity, and financial and economic evaluation of the proposed product.

1.2.2 Customer Needs and Product Specifications

Identification of needs and customer views is an important first step in the development and design of a new product. The house of quality (HOQ) is a structured process for translating customer requirements and market research into quantifiable product characteristics and specifications to be met by the product design. HOQ is a diagram, resembling a house, and consists of six sections, as follows:

1. Voice of the customer is a list of customer requirements from the product. These are usually gathered through conversations, opinion surveys, and market research. Examples of such requirements are shown in Table 1.1 for a cordless power drill for domestic use.
2. Prioritized customer requirements and the degree of customer satisfaction with various competing products relative to the different requirements are included in this section. This information is also based on opinion surveys and market research.
3. Voice of the company can be a list of the technical parameters, product characteristics, from the point of view of the manufacturer in terms of engineering specifications. These include measurable quantities such as weight, dimensions, level of noise, power consumption, and cost. For example, a specification of "the total weight of the product must be less than 5 kg" can be based on the customer need of a "lightweight product" and the observation that the lightest competing product is 5 kg. Similarly, a specification of "average time to unpack and assemble the product is less than 22 min" can be based on a customer need of "the product is easy to assemble" and the observation that the competing product needs 24 min to unpack and assemble.

   The voice of the company can also include nontechnical parameters such as look and feel of the product, fashion, the type of prospective customer, and the culture of society in which the product will be sold. An example of the voice of the company is shown in Table 1.1 for a cordless power drill for domestic use.
4. Interrelation matrix correlates the customer requirements with a technical parameter based on inputs from sections 1, 2, and 3. The correlation between one of the customer requirements and one of the engineering specifications can be high (9 points), medium (3 points), low (1 point), or none (zero points). For example, the padding thickness of a seat can have high correlation to comfort (9 points), medium or low correlation to esthetic quality (3 or 1 point), and no correlation to robustness of the seat (zero points). Table 1.1 shows an example of the interrelation matrix for a cordless power drill for domestic use.
5. Correlation matrix, roof of the house, shows how the technical parameters support or impede one another. When an improvement in one parameter leads to an improvement in another, a (+) sign is given to indicate support. On the other hand, when the improvement leads to deterioration in another parameter, a (–) sign is given to indicate trade-off. The roof shows where a design improvement could lead to a range of benefits and also focuses attention on the areas where compromises have to be made.
6. Design targets give the conclusions drawn from the data in the other sections of the HOQ. This section gives the relative importance of the technical parameters in meeting customer needs, compares the product with the competition, and indicates the levels of performance to be achieved in the new product. Table 1.1 shows an example of the design targets for a cordless power drill for domestic use.

TABLE 1.1
Using HOQ to Translate the Voice of the Customer into Product Specifications for a Cordless Power Drill for Domestic Use

Technical Parameters → / Customer Requirements ↓	Importance to Customer	Keyless Chuck	Variable Speed, Reverse, Hammer	Variable Torque Settings	Ergonomic Design	Soft Grip	Maximum Weight	Overload Function	Light Powerful Battery	Tough Construction Material	Maximum Price
Safe to use	5	3	3	3	3	1	3	9	1	1	
Lightweight	4				1		9			3	
Rugged and long life	5							3		9	
Long life for battery charge	3								9		
Can drill holes in different materials and screw bolts	5	3	9	9			1	3	1		
Ergonomic	3	1			9	3	3				
Easy to use	4	9	3	3	3	9	3	3			
Inexpensive	3										9
Importance		69	72	72	58	50	77	87	37	62	27
Relative importance (%)		11	12	12	10	8	13	14	6	10	4
Target design parameters/specifications		Keyless design of chuck	0–450/0–1500 rpm at no load. Drill 24 mm holes in wood and 10 mm holes in concrete and steel	Use 18 V battery and 24 torque settings. Drill 24 mm holes in wood and 10 mm holes in concrete and steel	Ergonomic design for good grip and maximum thrust of hand	Soft rubbery material on the grip	3 kg	Include overload function to avoid overheating of motor	Lithium ion technology	High toughness materials for construction of body	$120

TABLE 1.2
Concept-Screening Matrix

Selection Criteria	Reference Concept	Concept A	Concept B	Concept C	Concept D
Criterion 1	0	–	+	+	0
Criterion 2	0	+	+	0	0
Criterion 3	0	+	+	+	–
Criterion 4	0	0	0	+	–
Criterion 5	0	0	–	–	+
Total (+)	0	2	3	3	1
Total (–)	0	1	1	1	2
Total (0)	5	2	1	1	2
Net score	0	1	2	2	–1
Decision	No	Consider	Consider	Consider	No

1.2.3 Concept Generation, Screening, and Selection

Product specifications are then used to develop different product concepts that satisfy customer needs. Some of the concepts may be generated by the development team as novel solutions, but others may be based on existing solutions or patents. The different concepts are then compared to select the most promising option. The Pugh method is useful as an initial concept-screening tool. In this method, a decision matrix is constructed as shown in Table 1.2. Each of the characteristics of a given concept is compared against a base/reference concept, and the result is recorded in the decision matrix as (+) if more favorable, (–) if less favorable, and (0) if the same. Concepts with more (+) than (–) are identified as serious candidates for further consideration.

1.2.4 Economic Analysis

The economic analysis section of the feasibility study normally provides an economic model that estimates the development costs, initial investment that will be needed, manufacturing costs, and income that will probably result for each of the selected concepts. The economic analysis also estimates sources and cost of financing based on the rate of interest and schedule of payment. The model should allow for a "what if" analysis to allow the product development team to assess the sensitivity of the product cost to changes in different elements of cost.

1.2.5 Selecting an Optimum Solution

The final stage of the feasibility study identifies an optimum solution. Selection is usually based on economics as well as technical specifications, since the product is expected to satisfy the customer needs at an acceptable price. This process involves trade-offs between a variety of diverse factors, such as

TABLE 1.3
Concept Selection

Product Specifications/ Selection Criteria	Weight	Concept A		Concept B		Concept C	
		Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Criterion 1	0.1	2	0.2	4	0.4	4	0.4
Criterion 2	0.2	4	0.8	4	0.8	3	0.6
Criterion 3	0.2	4	0.8	4	0.8	4	0.8
Criterion 4	0.3	3	0.9	3	0.9	5	1.5
Criterion 5	0.2	3	0.6	1	0.2	2	0.4
Total score			3.3		3.1		3.7
Rank		Second		Last		First (optimum)	

Note: Rating: 5, excellent; 4, very good; 3, good; 2, fair; 1, poor.

- Customer needs
- Physical characteristics of size and weight
- Expected life and reliability under service conditions
- Energy needs
- Maintenance requirements and operating costs
- Availability and cost of materials and manufacturing processes
- Environmental impact
- Quantity of production
- Expected delivery date

A quantitative method that can be used in concept selection gives weight to product specifications according to their importance to the function of the product and preference of the customer. The total score of each concept is determined by the weighted sum of the ratings of its characteristics, as shown in Table 1.3.

The optimum solution should be acceptable not only to the consumer of the product but also to the society in general. If other members of the community object to the product, whether for legal or safety reasons, causing harm to the environment, or merely because of social customs or habit, then it may not be successful. This part of the study requires an understanding of the structure and the needs of the society and any changes that may occur during the intended lifetime of the product. The following case study uses a hypothetical product—the Greenobile—to illustrate how the issues discussed in concept development and feasibility studies may apply in practice.

Case Study 1.1: Developing the Greenobile

A motorcar company is considering the introduction of an inexpensive, environment-friendly, two-passenger (two-seater) model. The idea behind this product is based on the statistics that in about 80% of all trips, American cars carry no more than two people, and in a little more than 50% of all trips, the driver is alone. Such cars will be predominantly driven in city traffic, where the average vehicle speed is about 55 km/h (30 mph).

Market Research

Market research is carried out through interviews and discussions with focus groups of 8–12 prospective customers. The questions discussed include the following:

1. Frequency of driving the car, how far is each journey on an average, expected distance traveled per year, and expected life of the car
2. Esthetic qualities: main preferences for body styling and look, number of doors, number of wheels, etc.
3. Level of comfort on a bumpy road
4. Ease of handling and parking
5. Safety issues including stability on the road, especially when turning around sharp corners
6. Expected cost

Based on the market research, the following customer needs were identified: safe to drive, economical to run, reaches city speed limit quickly, easy to park, nice to look at, comfortable to drive, easy to get in and out of the car, spacious trunk, seats two adults, long life, and inexpensive. The importance of each need to the customers was also identified and allocated as weights, with five as most important and one as least important. These needs and their weights are placed on the left-hand side of the HOQ, voice of the customer, in Table 1.4.

The technical parameters, product characteristics, from the point of view of the car manufacturer, voice of the company, are listed in the upper part of HOQ, in Table 1.4 as engineering specifications. The main characteristics of the car are correlated to the customer needs in the interrelation matrix in the middle section of Table 1.4. Nine points are allocated to a strong correlation between a customer requirement and a product characteristic, three points for medium correlation, and one point for low correlation. The importance of each product characteristic is then calculated as the sum of the multiplications of correlation factors times the weight of the corresponding customer need. Targets for improvement to be achieved by the car design team are also included in Table 1.4. The information gained from the HOQ will now be used to compare design concepts and select an optimum concept.

The Greenobile development team came up with three concepts that satisfy the product specifications listed in the HOQ:

Concept A is a sedan with a hard roof, four wheels, two seats side by side, hybrid drive (internal combustion engine and batteries), expected life 5 years, expected weight 850 kg, acceleration from 0 to 90 km/h 15 s, higher level of comfort, and expected cost $18,000.

TABLE 1.4
Using the HOQ to Correlate Customer Requirements with Technical Characteristics for the Greenobile

Voice of the Company → / Voice of the Customer ↓	Weight/Importance to Customer	1. Maximum Weight 850 kg	2. Maximum Length 3 m	3. Maximum Speed 90 km/h	4. Acceleration: Reaches Maximum Speed in 20 s	5. Maintains Speed of 60 km/h on 5% Gradient	6. Expected Life 4 Years	7. Spacious Trunk	8. Maximum Price $18,000	9. Passes Safety Tests for Vehicles	10. Styling and Body Design	11. Suspension and Steering Mechanism
Safe to drive	5				1	3				9		1
Economical to run	4	9		3	3	3			3			
Reaches city speed limit quickly	3				9					3		
Easy to park	4		9					1				3
Nice to look at	3							1			9	
Comfortable to drive	2	1										9
Easy to get in and out of the car	3		3							1	9	
Spacious trunk	2		3					9			1	
Long life	4			1	1	1	9		3			3
Inexpensive	3	3	1	3	3	3			9		1	
Importance of car characteristics		47	54	25	57	40	36	25	51	57	59	47
Relative importance %		9	11	5	12	8	7	5	10	12	12	9
Targets/direction of improvement		Achieve 750 kg	Achieve 2.5 m	Maintain this value	Maintain this value	Maintain this value	Achieve 5 years	Achieve 8,000 cm^3	Achieve $12,000	Meet this requirement	Achieve nice looks while maintaining space requirements	As comfortable as possible

Concept B is a sedan with a hard roof, three wheels (one in front and two in the back), two seats side by side, rechargeable battery-operated engine, expected life 4 years, expected weight 800 kg, acceleration from 0 to 90 km/h 25 s, medium level of comfort, and expected cost $15,000.

Concept C is a sedan with a movable roof, three wheels (one in front and two in the back), two seats one behind the other, rechargeable battery-operated engine, expected life 4 years, expected weight 750 kg, acceleration from 0 to 90 km/h 20 s, lower level of comfort, and expected cost $12,000.

Concept Selection

Table 1.5 gives the technical requirements, targets, and their relative importance as given in the HOQ. The table also gives the ratings relative to the target values and the weighted ratings for concepts A, B, and C. The weighted ratings are obtained by multiplying the relative importance times the ratings relative to targets. The total score for each concept is the added values of the individual weighted ratings.

Conclusion

The results of Table 1.5 indicate that concept A is the optimum solution by a small margin with concepts B and C of equal score. The points in favor of concept A are the styling, larger trunk space, longer life, the flexibility of hybrid drive, and greater comfort. With these advantages, the higher price and longer length are justified. Figure 1.1 shows the model of the car developed using the selected concept.

1.3 SYSTEM-LEVEL DESIGN

The product specifications of the selected concept are translated to system-level design, which gives a broad description of the product's appearance and architecture in addition to technical specifications and functions. Appearance and architecture are in the realm of industrial design, which is concerned with the esthetic qualities (visual and tactile) in addition to product–human interface, ease of use and maintenance, and safety features. Technical specifications and function are in the realm of engineering design, which is concerned with the level and type of technology on which it is based, performance under service conditions, efficiency, energy consumption, and environmental issues.

A simple product that consists of a few parts can usually be easily drawn schematically to illustrate its appearance and function. More complex products, however, need to be divided into subsystems or subassemblies, each of which performs part of the total function of the product. The product architecture in this case can be schematically represented by blocks representing the different subassemblies and how they interact together to perform the total function of the product. At this stage, it may be appropriate to perform a make-or-buy decision to determine whether a subassembly is to be manufactured specially for the product or if there is a ready-made

TABLE 1.5
Concept Selection for the Greenobile

Technical Requirements	Targets	Relative Importance	Concept A		Concept B		Concept C	
			Rating Relative to Target	Weighted Rating	Rating Relative to Target	Weighted Rating	Rating Relative to Target	Weighted Rating
1. Maximum weight 850 kg	Achieve 750 kg	0.09	750/850	0.079	750/800	0.084	750/750	0.09
2. Maximum length 3.0 m	Achieve 2.5 m	0.11	2.5/3.0	0.092	2.5/2.5	0.11	2.5/2.8	0.98
3. Maximum speed 90 km/h	Maintain this value	0.05	1	0.05	1	0.05	1	0.05
4. Acceleration: reaches maximum speed in 20 s	Maintain this value	0.12	1	0.12	1	0.12	1	0.12
5. Maintains speed of 60 km/h on 5% gradient	Maintain this value	0.08	1	0.08	1	0.08	1	0.08
6. Expected life 4 years	Achieve 5 years	0.07	5/5	0.07	4/5	0.056	4/5	0.056
7. Spacious trunk	Achieve 8,000 cm^3	0.05	8/8	0.05	7/8	0.044	7/8	0.044
8. Maximum price $18,000	Achieve $12,000	0.10	12/18	0.067	12/15	0.08	12/12	0.1
9. Passes safety tests for vehicles	Meet this requirement	0.12	1	0.12	1	0.12	1	0.12
10. Styling and body design	Achieve nice looks while maintaining space requirements	0.12	1	0.12	0.9	0.11	0.8	0.096
11. Suspension and steering mechanism	As comfortable as possible	0.09	1	0.09	0.9	0.08	0.9	0.08
Total score				0.938		0.934		0.934

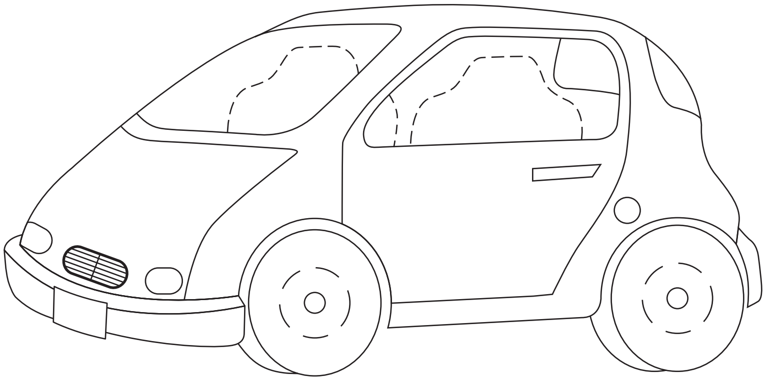

FIGURE 1.1 The Greenobile.

standard alternative. Examples of functional subassemblies in a motorcar include the engine, steering and brake system, and electric system.

Each of the subassemblies that need to be manufactured is then divided into components that can be fitted together to perform the function of that subassembly. The function of each of the components is then identified and its critical performance requirements determined. These requirements are then used to define the material performance requirements. The following example illustrates these concepts.

Case Study 1.2: Planning for a New Model of a Household Refrigerator

Based on market survey, a medium-sized manufacturer of household refrigerators is considering the production of a new model based on the established concepts of other models already in production by the company. To plan for the manufacture of the new model, decisions need to be made on which components are to be made in-house and which to be bought from outside vendors.

Figure 1.2 gives a breakdown of the refrigerator into major subassemblies, subassemblies, etc. Some of the subassemblies or parts are obviously bought from specialized outside manufacturers, including the motor–pump unit and the electric system. Some of the subassemblies that will be manufactured in-house include the refrigerator body and door, as well as the cooler and condenser subassemblies. Some parts of the control system, however, may present an option. The company policy to specialize and concentrate its efforts and skills in one basic line rather than diversify may favor buying the control system from a specialized supplier. However, factors such as quality and reliability of supply may rule in favor of manufacturing some parts in-house.

For the subassemblies that will be manufactured in-house, a list of components, detail designs, bill of materials, sequence of manufacturing processes, and estimates of processing and assembly times are normally needed. A master production and purchasing schedule is then prepared to ensure that materials, parts, and subassemblies are available when needed.

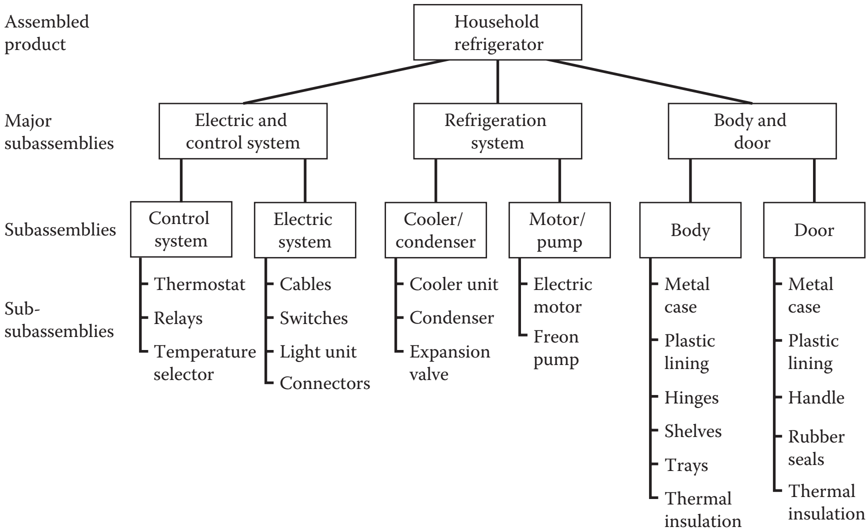

FIGURE 1.2 Breakdown of a household refrigerator into major subassemblies, subassemblies, and sub-subassemblies.

1.4 DETAIL DESIGN AND SELECTION OF MATERIALS AND PROCESSES

As progress is made from product specifications to system-level design and then to detail design, the tasks to be accomplished become more narrowly defined. In the detail design stage, the focus is on static and dynamic forces and their effect on the performance of the component under the expected service conditions. This latter task requires thorough knowledge of how materials behave in service and what processes are needed to achieve the final shape of the component. Behavior of materials in service is discussed in Part I, and the effect of materials and processes on design is discussed in Part II. A two-step process may be used in developing the final detail design and deciding on the materials and processes: configuration and final detail design.

1.4.1 Configuration (Embodiment) Design

In the configuration, or embodiment, design stage, a qualitative sketch of each part is first developed giving only the order of magnitude of the main dimensions and the main features: wall, bosses, ribs, holes, grooves, etc. The material performance requirements are used to narrow down the field of possible materials and processes to a few promising candidates. In many cases, the different performance requirements that have to be met by a given part present conflicting limitations on the material properties. For example, the material that meets the strength requirements may be difficult to manufacture using the available facilities, or the material that resists the corrosive environment may be too expensive. To resolve such problems, compromises or trade-offs have to be made. Quantitative methods of selection can be helpful in ranking the candidate combinations of materials and processes, as discussed in Part III.

At this stage, make-or-buy decisions are made on whether to manufacture the component specially for this product or to use a standard part that is purchased from an external supplier.

1.4.2 Final Detail Design

If more than one combination of material and process prove to be viable, then each of the candidate combinations is used to make a detail design. Each of the detail designs should give complete specification of geometry, tolerance, material treatment, weight, material and manufacturing cost, etc. A final detail design is then selected based on technical performance and economic value.

The design and material selection for a subassembly that contains several components can be complicated by the fact that a well-matched combination of components needs to be found. It is not sufficient that each individual part is well designed, but the assembled components should function together to achieve the design goals. The issue of successfully matching a group of components should also be addressed when redesigning a component in an existing subassembly. If the material of the new component is too different from the surrounding materials, problems resulting from load redistribution or galvanic corrosion could arise, for example. A detailed account of material selection and substitution is given in Part III.

1.4.3 Design Reviews

Design reviews represent an important part of each phase of the design process. They provide an opportunity to identify and correct problems before they can seriously affect the successful completion of the design. The design review teams normally have representatives from the materials and manufacturing, quality control, safety, financial, and marketing areas. This ensures that the design is satisfactory not only from the performance point of view but also from the manufacturing, economic, reliability, and marketing points of view.

1.5 TESTING AND REFINEMENT

The testing and refinement phase is normally carried out as part of the R&D function of the company. A first prototype (alpha) is usually built from parts with the same geometry and material as the final product but not necessarily using the same manufacturing processes. Alpha prototypes are tested to ensure that the product works as intended and that it satisfies its main requirements. After modifications, a second prototype (beta) may be built to ensure reliability of the product and to measure its level of performance. Potential customers may also be involved at this stage to incorporate their feedback in making the final product.

1.6 LAUNCHING THE PRODUCT

Launching the product covers the activities of planning and scheduling, manufacturing the product, marketing, and arranging for after-sales services. This stage is best organized on the basis of planning and scheduling schemes, which are drawn to meet the product delivery times, as discussed in this section.

1.6.1 Project Planning and Scheduling

Engineering projects and activities normally have a series of deadlines that are set to meet a final completion or delivery date as part of a contract with penalties for not finishing on time. To avoid delays and in view of the complexity of many of the engineering projects, planning and scheduling should play an important role in project development. The first step in planning is to identify the activities that need to be controlled. The usual way to do that is to start with the entire system and identify the major tasks. These major tasks are then divided into sections, and these in turn are subdivided until all the activities are covered. The following simple example illustrates this process.

Case Study 1.3: Planning for Installation of an Injection Molding Machine

Task

Establish and plan the activities involved in installing and commissioning an injection molding machine for plastics.

Analysis

The activities involved in installing and commissioning the machine can be divided into three major sections:

1. Site preparation
2. Installation
3. Preparation of the machine for production

The foregoing major activities can be divided into the simple activities shown in Table 1.6. The sequence in which the activities should be performed and the time required to complete each activity are also included. Figure 1.3 shows the sequence of the activities on a bar chart or Gantt chart.

The bar, or Gantt, chart shown in Figure 1.3 is one of the many analytical techniques that have been developed to facilitate the planning and scheduling of a large number of activities that are usually involved in industrial projects. Using network planning models makes it possible to locate the activities that are critical and must be done on time and the activities that have schedule slack. The critical path method (CPM) and the program evaluation and review technique (PERT) are widely used network planning models. Some references that give detailed accounts of project planning and scheduling techniques are provided in the bibliography.

TABLE 1.6
Installing and Preparing an Injection Molding Machine for Operation

Major Task	Activity	Description	Immediate Predecessor	Time (h)
I	a	Excavate foundation	—	5
	b	Pour concrete in foundation	a	2
	c	Unpack parts	—	3
II	d	Place machine body on foundation	b, c	2
	e	Level machine body	d	1
	f	Assemble rest of the machine parts	c, e	3
	g	Connect electric wiring	f	1
	h	Connect cooling water and drainage	f	2
III	i	Install injection molding die	g, h	3
	j	Calibrate temperature controller	i	2
	k	Place plastic pellets in hopper	f	1
	l	Adjust plastic metering device	k	1
	m	Perform experimental runs	j, l	2

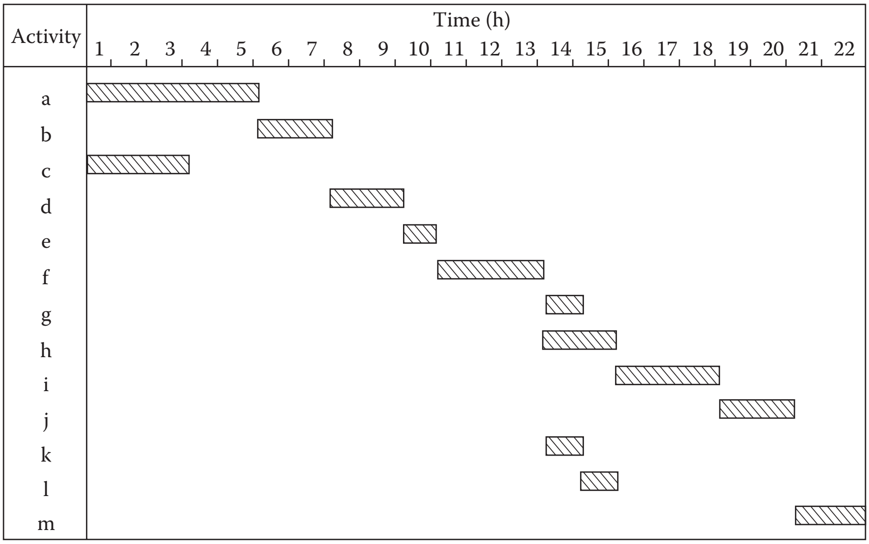

FIGURE 1.3 Bar chart describing the activities of installing and preparing an injection molding machine for operation. See Table 1.6 for a description of the activities.

1.6.2 Manufacturing

The sequence of manufacturing processes is first established for each part of the product and recorded on a process sheet. The form and condition of the material, as well as the tooling and production machines that will be used, are also

<table>
<tr><td colspan="3">Process sheet</td><td colspan="2">Page 1 of 3 pages</td></tr>
<tr><td colspan="2">Written by M.M.F.
Date 1/3/88</td><td colspan="2">Order no. 1844
Date 1/1/88 Pcs req'd 30</td><td>Dwg no. 12
Patt. no. 5</td></tr>
<tr><td colspan="2">Enters assembly at stage x-23 loader 6</td><td colspan="3">Part name 250 mm pulley</td></tr>
<tr><td colspan="2">Material condition
Gray CI, ASTM A48-74 35, 245 BHN</td><td colspan="2">Rough weight
15 kg</td><td>Finish weight
12 kg</td></tr>
<tr><td>Oper. no.</td><td>Description</td><td>Set-up time (h)</td><td>Cycle time (h)</td><td>Mach. no.</td></tr>
<tr><td>10</td><td>Turn O.D. of body and flanges, face hub
speed 200 rpm, feed 0.25 mm per rev
tool no. TT-25</td><td>0.5</td><td>0.5</td><td>L-2</td></tr>
<tr><td>20</td><td>Turn bore and face other side of hub
speed 200 rpm, feed 0.25 mm per rev
tool no. TT-25</td><td>0.6</td><td>0.3</td><td>L-2</td></tr>
<tr><td>30</td><td>Drill and tap 2 holes, 10 and 12 mm diameter
standard metric thread M10 and M12</td><td>0.3</td><td>0.2</td><td>D-1</td></tr>
</table>

FIGURE 1.4 Example of a simple process sheet.

recorded on the process sheet. An example of a simple process sheet is shown in Figure 1.4. Allocating established standard times and labor costs for each operation, the information in the process sheets is used to estimate the processing time and cost for each part. Further discussion of cost estimation in manufacturing is given in Chapter 8. The information in the process sheets is also used to estimate and order the necessary stock materials; design special tools, jigs, and fixtures; specify the production machines and assembly lines; and plan work schedules and inventory controls.

Before starting large-scale production, a pilot batch is usually made to test the tooling and familiarize the production personnel with the new product and also to identify outstanding problems that could affect the efficiency of production.

1.6.3 Quality Control

Quality control represents an important activity in manufacturing. It could vary from 100% inspection of produced parts to statistical sample inspection, depending on the application and the number of parts produced. In some applications, it may be necessary to test subassemblies and assemblies to ensure that the product performs its function according to specifications.

1.6.4 Packaging

Packaging is meant to protect the finished product during its shipping to the consumer. Secondary functions of packaging include advertising and sales appeal, which are important aspects of marketing the product, especially in the case of consumer goods.

1.6.5 Marketing

The marketing personnel should be involved in the various stages of product development to allow them to develop the publicity material that will help in selling the product. In addition to publicity material, installation and maintenance instructions need to be prepared and distributed with the product. Clear installation, operation, and maintenance instructions will make it easier for the user to achieve the optimum performance of the product.

1.6.6 After-Sales Service

Most products require either regular or emergency service during their useful life. The accuracy and speed of delivering the needed service and the availability of spare parts could affect the company's reputation and the sales volume of the product. Feedback from the user is an important factor to be considered in making an improved version of a product and in developing a new product.

1.7 SELLING THE PRODUCT

In a free enterprise, the price of goods and services is ultimately determined by supply and demand. Typical supply and demand curves are illustrated in Figure 1.5. The demand curve shows the relationship between the quantity of a product that customers are willing to buy and the price of the product. The supply curve shows the relationship between the quantity of a product that vendors will offer for sale and the price of the product. The intersection of the two curves determines both the quantity "n" and the price "p" of the product in the free market. The concept of supply and demand is important in engineering economy studies, since proposed ventures frequently involve action that will increase the supply of a product or influence its demand. The effect of such action upon the price at which the product can be sold is an important factor to be considered in evaluating the desirability of the venture.

In some cases, a product is meant to compete directly with the existing products. In such cases, the selling price is already established, and the problem is to work backward from it to determine the cost of each of the product elements. This procedure is sometimes called design to cost. An understanding of the elements that make up the cost of a product is, therefore, essential in ensuring that the product will be competitive economically as well as technically. There are numerous examples of

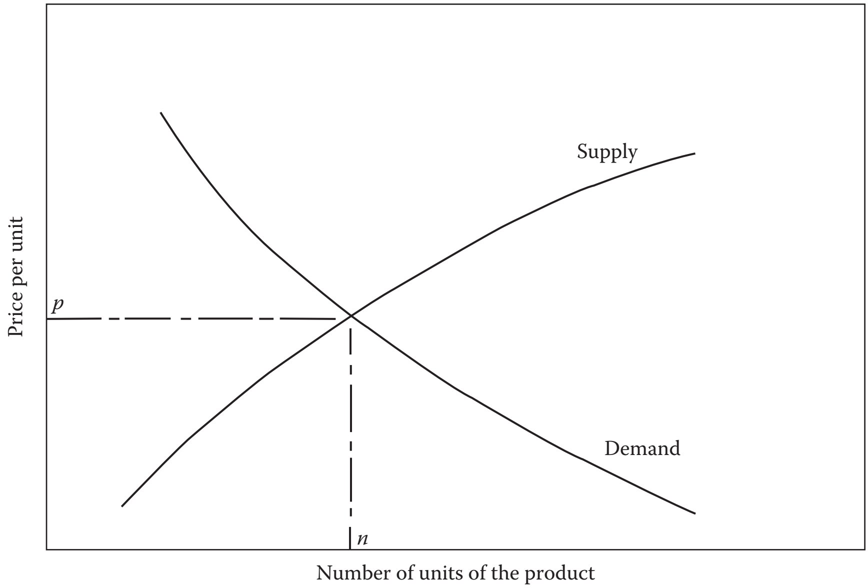

FIGURE 1.5 Schematic representation of typical supply and demand curves.

products that exhibit excellent performance but possess little economic merit and consequently have not been adopted commercially. In almost all cases, the value of engineering products lies in their utility measured in economic terms. This means that the selling price has to be low enough to be competitive but sufficiently high for the company to make a profit, as illustrated in Figure 1.6.

1.7.1 Cost of Product Engineering

Figure 1.6 shows the elements of the cost of product engineering, which covers the direct cost of labor and materials required to prepare the design and drawings, to perform development work and experiments, and to make tools or dies for the different parts of the product. The cost of product engineering is usually charged to the number of products to be sold within a given period. Each department has direct labor and overhead rates per hour for each class of work charged to the product.

1.7.2 Actual Manufacturing Cost

As shown in Figure 1.6, the actual manufacturing cost covers direct materials that form part of the product in measurable quantities. The quantities of direct materials required as well as sizes are normally recorded on bill of materials or on process sheets. The quantities should be gross, which include necessary allowance for waste and scrap. For example, the quantity of bar stock required for a part should be indicated in units of length to cover the length of the part plus the length of the cutoff.

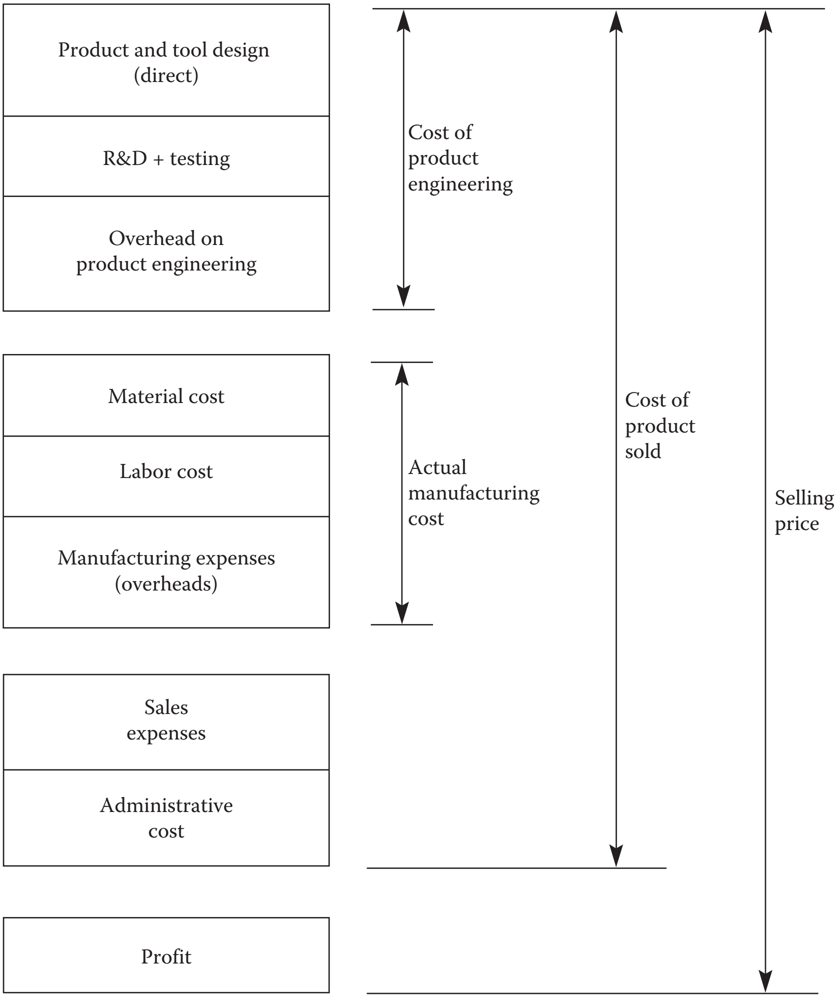

FIGURE 1.6 Factors involved in determining the selling price of a product.

Indirect materials include materials used in quantities too small to be readily identified with units of product. Examples include cutting oils, solders, and adhesives. Such items are considered as shop supplies. A credit should be included to account for recycled scrap or by-products that are sold elsewhere. Labor may be defined as the employment costs, wages, and other associated payments of the employees whose effort is involved in the fabrication of the product.

Manufacturing expense, or overhead cost, covers all the other costs associated with running a manufacturing company. Examples of manufacturing expense include salaries and fringe benefits of company executives, accounting personnel, purchasing department, and R&D. Other overhead expenses include depreciation, taxes, insurance, heating, light, power, and maintenance. Chapter 8 discusses the cost of materials and processes in more detail.

1.7.3 Sales Expense and Administrative Cost

The sales expense covers the cost of distribution as well as the cost of advertising and marketing the product. Administrative expenses can be treated in a similar manner to manufacturing overheads.

1.7.4 Selling Price

The cost of product sold, as shown in Figure 1.6, is the total cost of product engineering, manufacturing, selling, and administration. An amount of profit is then added to this total cost to arrive at the selling price. The net profit to the company that results from selling a certain number of units of the product per year can be calculated as

$$\text{Net profit} = (\text{number of units} \times \text{profit per unit}) - \text{income taxes}$$

Income taxes are usually calculated as a certain percent of the total profits.

1.8 PLANNING FOR RETIREMENT OF THE PRODUCT AND ENVIRONMENTAL CONSIDERATIONS

The final step in the product development cycle is disposal of the product when it has reached the end of its useful life. In the past, little attention was paid to this stage, and the retired product was just abandoned or used for landfill. However, increasing environmental awareness, increasing cost of energy and raw materials, and tighter legislation have made it necessary for product development teams to consider reuse, ease of scrap recovery, recycling, and disposal costs when designing new products. The sustainable product development approach attempts to minimize the impact of a product on the environment during its life cycle. To inform the public whether a certain product is environmentally friendly, different kinds of environmental labeling have been developed by various agencies, including the blue Energy Star that is awarded to appliances that meet the strict energy efficiency criteria set by the Environmental Protection Agency (EPA) in the United States and the EU Ecolabel of flower with 12 stars that is awarded by the European Union according to environmental criteria agreed on by experts, industry, consumer organizations, and environmental NGOs at European level.

The life cycle assessment (LCA) method can be used to evaluate the environmental impacts associated with the various stages starting with the mining and extraction of materials, manufacturing of components and assembling them into products, using or operating to products during its service life, and finally the end of life and disposal phases, as shown in Figure 1.7. LCA will be discussed in more detail in Chapter 8.

1.8.1 Recycling of Materials

Table 1.7 compares the unit energy for production of some metals from the ore (primary metal) and from scrap (secondary metal). The table shows the energy savings that result from recycling, especially in the case of nonferrous metals. Figure 1.7 shows how recycling fits in the total material cycle.

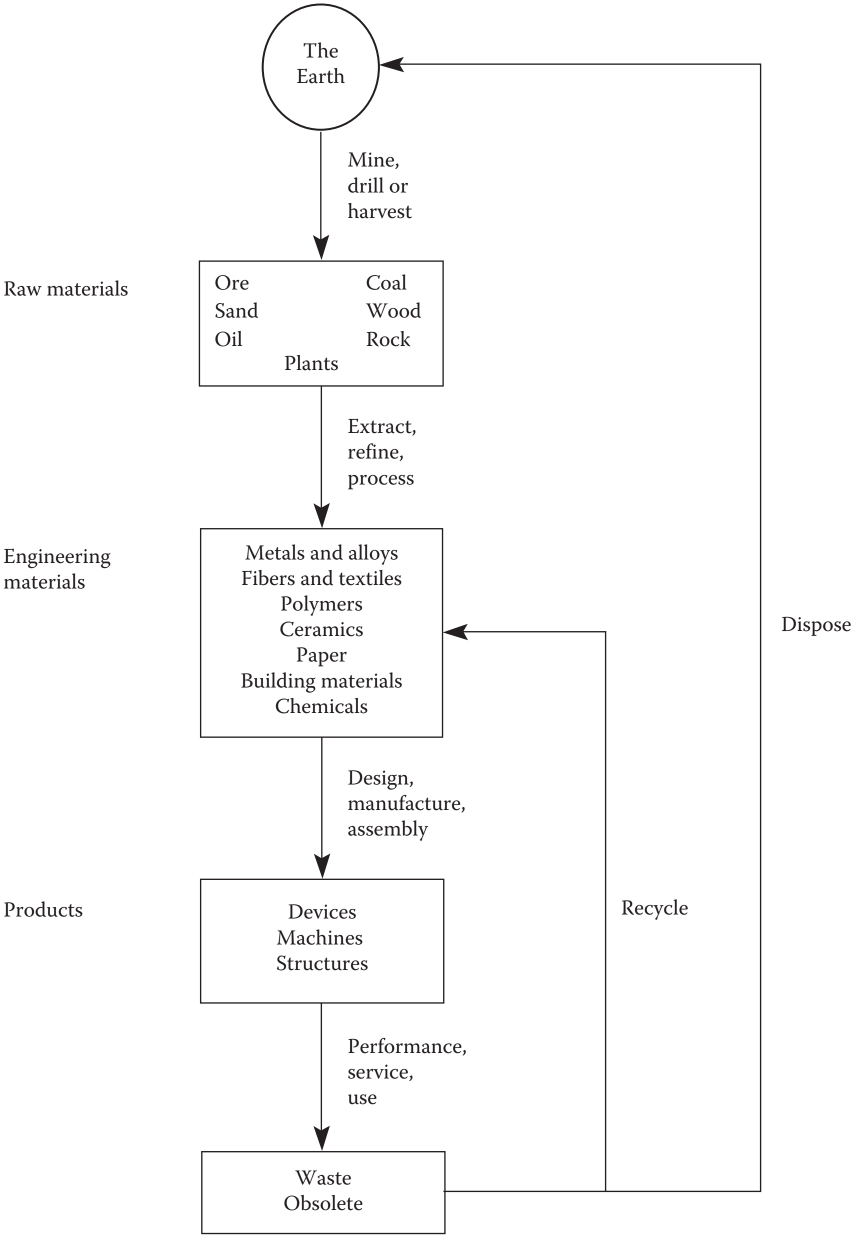

FIGURE 1.7 The place of recycling in the total material cycle.

1.8.2 Sources of Materials for Recycling

The processes involved in recycling materials depend on their type and source. For example, in the manufacturing industries, the sources of metallic scrap are mainly turnings and borings from the machine shop, punchings and skeletons from the

TABLE 1.7
Energy Used for the Production of Some Engineering Materials

	Primary Metal		Secondary Metal	
Metal	**GJ/t**	**%**	**GJ/t**	**% of Primary Metal**
Mg	370	100	10	2.7
Al	350	100	15	4.3
Ni	150	100	15	10
Cu	120	100	20	17
Zn	70	100	20	29
Pb	30	100	10	33
Steel	35	100	15	43

Source: Data based on Boyer, H.E. and Gall, T.L., *ASM Metals Handbook—Desk Edition*, ASM International, Materials Park, OH, 1985, p. 31.5.

press shop, trimmings from the forging shop, and sprues and gates from the foundry. Another source for recycling is materials recovered from used products, such as worn-out machinery or discarded packages. Salvaging materials from the latter source is more complex. This is because the different materials have to be collected from various sources and sorted to separate the different materials, which are sent to the appropriate secondary manufacturer.

1.8.3 Infrastructure for Recycling Packaging Materials

Recycling of materials involves a series of interrelated activities. This is called recycling infrastructure, starting with the individual consumer and ending with material producer mill. For recycling to work effectively, the various activities involved must be coordinated. Collection can be an expensive step, especially in the case of plastic containers that occupy a large volume but a small fraction of the total weight of recycled materials. The method of collection depends on the community and includes curbside programs, voluntary drop-off or buyback centers, and resource recovery facilities.

Curbside collection follows the traditional form of refuse pickup, while voluntary drop-off centers involve consumers bringing the recyclable items. Resource recovery facilities are repositories for all postconsumer solid waste in which recyclables are sorted and the waste is used to create either fuel (refuse-derived fuel) or energy by burning directly at the facility (waste to energy).

1.8.4 Sorting

Identification and sorting of the various materials for recycling are not always easy, and the lack of proper identification is often a source of contamination and loss of

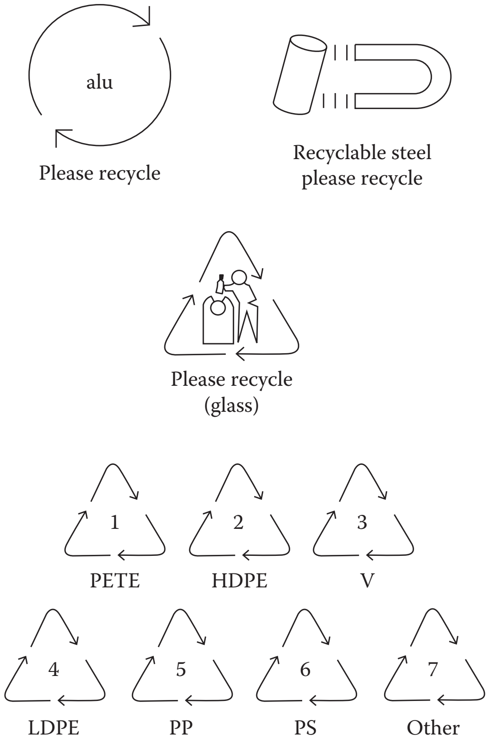

FIGURE 1.8 Examples of the symbols used to help in sorting materials for recycling.

quality in recycled materials. Identification of materials in the recycling industry is usually based on the following:

- Color: For example, copper is reddish, brasses are light yellow, and zinc alloys are bluish or dark gray.
- Weight: For example, the specific gravity of aluminum and its alloys is about 2.7, steels about 7.8, copper about 8.7, and lead about 11.3.
- Magnetic properties for separating steels from other materials.
- Spark testing: For example, when subjected to high-speed grinding wheel, carbon steels produce heavy dense sparks that are white in color with bursts that depend on the carbon content, but nickel-based alloys emit thin short sparks that are dark red in color.

To help consumers in identifying the various packaging materials so that they may participate in sorting, the symbols shown in Figure 1.8 are printed or embossed into the containers.

1.8.5 Scrap Processing

After sorting, recyclable materials are sold to secondary material producers or intermediate processors for remelting and processing into finished products. The processes and equipment used for processing scrap vary widely depending on its nature, which can range from aluminum cans and plastic bottles to large machinery and motorcars.

1.8.6 Recyclability of Materials

Recyclability of a material is defined as the ease with which it can be collected, separated, reprocessed, and reused for manufacturing a new product. Generally, metals and alloys have high recyclability since they can be remelted and reused with little or no loss of quality. Glass also has high recyclability as cullet, or broken glass, and easily substitutes for primary materials. However, rubber has lower recyclability since vulcanizing is an irreversible process that precludes reprocessing in the original form. Composites and laminated products also have lower recyclability as it is difficult to separate the different materials used in making them. Economic issues related to recycling are discussed in Chapter 8.

1.9 PRODUCT MARKET CYCLE

The product market cycle is defined as the length of time between its appearance on the market for the first time and the time when the company decides to stop its production. The market cycle of a product may vary from a few months to several years depending on its nature, competition, economic and social climates, as well as political decisions. Examples of products that normally have a relatively short market cycle are found in the clothing and toy industries where the main determining parameters are fashion and consumer desires. Other examples are found in the electronic and computer industries where technological development is relatively fast and competition pressures are high. In contrast, machines for power generation and production as well as similar heavy equipment have a relatively long market cycle, which is determined mostly by the relatively slow advances in their well-established technology.

The market cycle of a successful product can generally be represented by a curve similar to that shown in Figure 1.9. The sales are low in the introduction stage and gradually increase as the product gradually gains the acceptance of an increasing number of consumers. As the product reaches maturity, the production rates and sales volume reach the design values. While the initiation and growth stages should be as short as possible, the maturity stage should be prolonged. That is because during this stage production rates are most efficient, the investment used in the product development is recovered, and most profits are made.

As shown in Figure 1.9, there is a time lag between sales and profit. Heavier investments in product development will take longer to recover, which means a longer time lag. To prolong the maturity stage, efforts should be made to develop new markets by adopting new marketing strategies. Introducing an improved version of the product can also prolong its life cycle. This can be achieved by introducing design modifications or employing new materials or manufacturing processes. This could improve efficiency or extend the use of the product to new applications and environments.

Eventually, social change, appearance of other competitive products, or technological advances make the product less competitive causing the sales to decrease

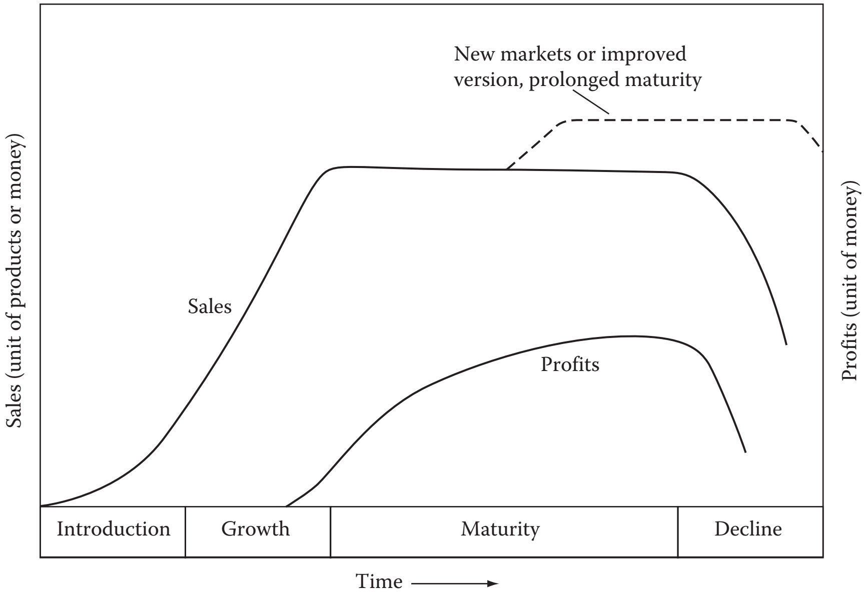

FIGURE 1.9 Market cycle of a product.

and the product to reach the decline stage. When the sales volume causes the production to reach uneconomical rates, the product is normally discontinued, thus ending its market cycle.

1.10 SUMMARY

1. Ideally, product development is performed by an interdisciplinary team with representatives from different segments of an industrial enterprise including engineering design, materials and manufacturing, finance, legal, sales, and marketing. This is because in addition to satisfying the technical requirements, a successful product should also be esthetically pleasing, safe to use, economically competitive, and compliant with legal and environmental constraints.
2. The activities involved in product development include seeking consumer views and translating them into technical requirements, developing concepts and performing feasibility study, performing system-level design, developing detail design and selecting materials and processes, testing and refining a prototype, launching the product, and selling the product. The HOQ approach makes it easier to correlate customer needs with product technical characteristics.
3. The selling price of a product is determined by the cost of product engineering (design, R&D, testing, and refinement), manufacturing cost (material and labor costs), sales expense and administrative cost, income taxes, and net profit.

4. Because material industry consumes a considerable amount of energy in making its products, it is no longer acceptable that engineering materials are used and then discarded in landfills. Better alternatives include waste reduction and recycling. Efficient recycling needs an infrastructure for sorting and scrap processing.
5. The market cycle of a product consists of an introduction stage, a growth stage, a maturity stage in which the production rates and sales volume reach the design value, and decline where sales decrease, leading to the end of the market cycle of the product. Because most profits are made during the maturity stage, it should be prolonged by developing new markets and introducing design modifications.

REVIEW QUESTIONS

1.1 Select one of the following items and, using HOQ approach, list five or more customer requirements and at least five technical characteristics. Construct a correlation matrix between customer requirements and technical characteristics and calculate the relative weights of the different technical characteristics:

a. Racing bicycle
b. Stepladder for domestic use
c. Cordless drill for domestic use
d. Computer mouse
e. Refrigerator for household use
f. Wheel chair for the disabled

1.2 Select a product that you would like to produce if you had your own company. Follow a procedure similar to that outlined for the Greenobile car in Case Study 1.1 in deciding on the selection criteria, setting the specifications, developing the concepts, arriving at the relative importance of the selection criteria, and finally selecting an optimum concept.

1.3 Survey the market and identify two different concepts for devices to open corked bottles. Compare the concepts on the basis of (a) the force needed to remove the cork, (b) whether the cork can be reused to reseal the bottle, (c) appearance and esthetic qualities of the device, and (d) cost of the device. Which concept would you select and why? Suggest ways to improve the concept that you did not choose to make it more competitive.

1.4 Carry out the analysis in Question 1.3 but for devices that help in removing jar lids.

1.5 A dairy producer near a large city is considering different expansion schemes for their fresh milk department. Among the various alternatives are (a) doorstep delivery and (b) delivery to supermarkets in the city. Compare the feasibility of each alternative scheme.

1.6 The previously mentioned dairy producer is also considering different materials for packaging their product. Among the alternative materials are reusable glass bottles, plastic containers, and multilayer carton packages. Compare the advantages and limitations of each material. Which material will be most suitable for (a) doorstep delivery and (b) supermarket delivery?

1.7 A group of new engineering graduates are thinking of starting a small business in manufacturing educational toys. What are the steps that they need to take before they can start production? Assume a reasonable development time for the project and draw a Gantt chart to show the time relations between the different activities.

1.8 What is the sequence of events involved in building, decorating, and furnishing a house with a small garden? If the total time for building, decorating, and furnishing the house is 18 months, draw a Gantt chart to show the time relations between the different events.

1.9 Explain what is meant by sustainable development and show how it is influenced by recycling of materials.

1.10 Compare the use and recyclability of teacups made of china, glass, melamine, and Styrofoam.

1.11 Compare the use of porcelain and plastics in making soup dishes.

1.12 Discuss the use of composite laminates in fruit juice packaging.

1.13 Collect 10 simple items that are in daily use:

- Draw a neat sketch of the item showing its main dimensions.
- Identify/guess the material out of which they are made.
- What is the expected life of each item?
- Are there any other uses for any of the items after its useful life?
- Determine the amount of energy that may be saved by recycling.
- Classify the items according to the ease with which they can be recycled as excellent, very good, good, fair, or poor.
- Suggest changes that may improve the recyclability of the items.

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Part I

Performance of Materials in Service

CLASSES OF ENGINEERING MATERIALS

Modern engineers have a great and diverse range of materials at their disposal. These materials can be conveniently classified into ferrous and nonferrous metals and alloys, nonmetallic organic and inorganic materials, composite materials, and semiconductors. Part IV discusses the different classes of engineering materials, and Figure P.1 gives a graphic representation of the classification. Part IV also gives some properties of widely used engineering materials. Examples of materials within each of the classes include the following:

Ferrous metals and alloys: carbon steels, high-strength low-alloy steels, high-alloy steels, stainless steels, gray cast irons, nodular cast irons, etc.

Nonferrous metals and alloys: light metals and alloys (Al, Mg, and Ti), copper and zinc and their alloys (brasses, bronzes, and zamak), low melting point metals and alloys (Pb, Sn, Bi, Sb, Cd, and In), precious metals (Au, Pt, and Ag), refractory metals (W, Mo, Ta, and Nb), nickel and alloys, superalloys (Fe–Ni based, Ni based, and Co based), etc.

Organic nonmetallic: thermoplastics (polyethylene, polystyrene, vinyls, polypropylene, acrylonitrile–butadiene–styrene [ABS], acrylic, nylon, acetals, polycarbonate, fluoroplastics, polyesters, polyurethane, cellulosics, polyester ether ether ketone [PEEK], polyethylene terephthalate [PETE], and polymethylmethacrylate [PMMA]), thermosetting plastics (phenolics, epoxy, polyester, silicone, urea, and melamine), elastomers (natural rubber, neoprene, butyl rubber, styrene butadiene rubber, and silicone elastomers), natural materials (wood, cork, and bamboo), etc.

Inorganic nonmetallic materials: refractory ceramics (oxides, carbides, and nitrides), whitewares, clay products, glasses (fused silica, soda-lime, lead glasses, borosilicates, and glass ceramics), bricks, stone, concrete, etc.

Composite materials: polymer–matrix composites (CFRP, GFRP, KFRP, CNTRP, NFRP, laminated composites, and sandwich materials), metal–matrix composites (SAP, aluminum–graphite composites, Al–SiC composites, and TD nickel), etc.

Semiconductors: Semiconductors have electric properties that are intermediate between the conducting metallic materials and the insulating nonmetallic materials. Small concentrations of impurity atoms in semiconductors are known to have substantial effect on their characteristics. Members of this group include single-crystal silicon, germanium, and gallium arsenide. Organic semiconductors are recent important additions to this group.

High-performance materials have been developed to meet the more challenging demands of modern technology applications, such as space travel, biomedical applications, and electronic products. Nanostructured materials exhibit unusual mechanical, electric, magnetic, or optical properties and can be metals, ceramics, polymers, or composites whose structures contain features smaller than 100 nm. Carbon nanotubes (CNTs) consist of one-atom thick graphite sheet rolled into a tube. Section 11.5 gives an example of the use of CNTs in sports equipment.

Smart materials are able to sense changes in their surroundings and then respond in a predetermined manner. Shape-memory materials, such as nickel–titanium (NiTi) alloys, change their shape when their temperature changes. Piezoelectric materials, such as quartz and lead zirconate ($PbZrO_3$), expand and contract in response to an applied electric field or voltage or conversely generate an electric field when their dimensions change. An application of smart materials is in building microelectromechanical systems (MEMS), which integrate miniature mechanical devices with electronic circuits. The size of MEMS devices ranges from 20 μm to 1 mm, and their applications range from sensors that are used in airbag deployment systems in motorcars to gyroscopes and microphones that are used for military and aerospace applications.

TYPES OF FAILURE OF COMPONENTS

The level of performance of a component in service is governed not only by the inherent properties of the material used in making it but also by the stress system acting on it and the environment in which it is operating. An unacceptably low level of performance can be taken as an indication of failure. Part I of this book discusses the different types of failure and how to prevent, or at least delay, such failures by selecting appropriate materials. Failure of engineering components occurs by several mechanisms, which can be arranged in order of importance as follows:

1. Corrosion, which can be defined as the unintended destructive chemical or electrochemical reaction of a material with its environment, represents about 30% of the causes of component failures in engineering applications.
2. Fatigue, which occurs in materials when they are subjected to fluctuating loads, represents about 25% of the causes of component failures in engineering applications.

3. Brittle fractures are accompanied by a small amount of plastic deformation and usually start at stress raisers, such as large inclusions, manufacturing defects, and sharp corners or notches. They represent about 15%–20% of the causes of failure of engineering components.
4. Ductile fractures are accompanied by larger amount of plastic deformation and normally occur as a result of overload. They represent about 10%–15% of the causes of failure of engineering components.
5. Creep and stress rupture, thermal fatigue, high-temperature corrosion, and corrosion fatigue occur as a result of a combination of causes including high temperature, stress, and chemical attack. They represent about 10%–15% of the causes of failure of engineering components.
6. Other minor causes of failure include wear, abrasion, erosion, and radiation damage.

Failure under mechanical loading is discussed in Chapter 2 and failure as a result of environmental attack in Chapter 3.

CAUSES OF FAILURE OF COMPONENTS

The aforementioned types of failure can occur as a result of a variety of causes, which can be arranged in order of importance as follows:

1. Poor selection of materials represents about 40% of the causes of failure of engineering components. Failure to identify clearly the functional requirements of a component could lead to the selection of a material that only partially satisfies these requirements. As an example, a material can have adequate strength to support the mechanical loads, but its corrosion resistance is insufficient for the application.
2. Manufacturing defects, as a result of fabrication imperfections and faulty heat treatment, represent about 30% of the causes of failure of engineering components. Incorrect manufacturing could lead to the degradation of an otherwise satisfactory material. Examples include decarburization and internal stresses in a heat-treated component. Poor surface finish, burrs, identification marks, and deep scratches due to mishandling could lead to failure under fatigue loading.
3. Design deficiencies constitute about 20% of the causes of failure of engineering components. Failure to evaluate working conditions correctly due to the lack of reliable information on loads and service conditions is a major cause of inadequate design. Incorrect stress analysis, especially near notches, and complex changes in shape could also be a contributing factor.
4. Exceeding design limits, overloading, and inadequate maintenance and repair represent about 10% of the causes of failure of engineering components. If the load, temperature, speed, voltage, etc. are increased beyond the limits allowed by the factor of safety in design, the component is likely to fail. As an example, if an electric cable carries a higher current than the

design value, it overheats, and this could lead to melting of the insulating polymer and then short circuit. Subjecting the equipment to environmental conditions for which it was not designed also falls under this category. An example is using a freshwater pump for pumping seawater. In addition, when maintenance schedules are ignored and repairs are poorly carried out, service life is expected to be shorter than anticipated in the design.

In spite of the efforts to avoid failure, components do fail in service, and it is the responsibility of the manufacturer to find out why and how to avoid similar failures in the future. Failure analysis is best carried out by interdisciplinary teams consisting of designers, materials and manufacturing engineers, as well as service personnel. Failure analysis techniques are described in Chapter 2, selection of materials to resist failure is discussed in Chapter 4, material-related design deficiencies are discussed in Chapter 6, and manufacturing defects are discussed in Chapter 7.

PART I OUTCOMES

After completing Part I, the reader will be able to

1. Understand the behavior of engineering materials, including similarities and differences between the different types
2. Assess the effect of mechanical loading and service environment on the performance of engineering materials
3. Recognize the different types of failure of components as a result of mechanical loading and environmental attack
4. Perform experimental and analytical failure analysis on failed components and products and determine the probable causes of failure
5. Select the appropriate materials and processes that can resist a given type of loading or a source of failure

2 Failure under Mechanical Loading

2.1 INTRODUCTION

With an increasing pressure for higher performance, cheaper products, and lighter components, manufacturers are using materials closer to their limits of performance, with subsequent higher probability of failure. For example, using a stronger material allows the designer to reduce the cross-sectional area and possibly the weight of a component, but will also increase the tendency for buckling as the slenderness of the component increases. Stronger materials are also likely to exhibit lower toughness and ductility with an increasing tendency for catastrophic brittle fracture.

This chapter begins by defining the different types of failures under mechanical loading and then gives a brief description of each type and how it takes place under service conditions. The chapter ends with a brief review of some experimental methods and analytical techniques of failure analysis. The objectives of the chapter are to

1. Examine the relationships between material properties and failure under static loading
2. Discuss the different types of fatigue loading and factors affecting the fatigue strength of materials
3. Review the categories of elevated-temperature failures
4. Describe some experimental and analytical techniques of failure analysis

2.2 TYPES OF MECHANICAL FAILURES

Failure under mechanical loading can take place either as a result of permanent change in the dimensions of a component, which results in an unacceptably low level of performance, or as a result of actual fracture. The general types of mechanical failures encountered in practice are as follows:

1. Yielding of the component material under static loading. Yielding causes permanent deformation, which could result in misalignment or hindrance to mechanical movement.
2. Buckling takes place in slender columns when they are subjected to compressive loading or in thin-walled tubes when subjected to torsional loading.
3. Creep failure takes place when the creep strain exceeds allowable tolerances and causes interference of parts. In extreme cases, failure can take

place through rupture of the component subjected to creep. In bolted joints and similar applications, failure can take place when the initial stressing has relaxed below allowable limits, so that the joints become loose or leakage occurs.

4. Failure due to excessive wear takes place in components where relative motion is involved. Excessive wear can result in unacceptable play in bearings and loss of accuracy of movement. Other types of wear failure are galling and seizure of parts.
5. Failure by fracture due to static overload. This type of failure can be considered as an advanced stage of failure by yielding. Fracture can be either ductile or brittle.
6. Failure by fatigue fracture due to overstressing, material defects, or stress raisers. Fatigue fractures usually take place suddenly without apparent visual signs.
7. Failure due to the combined effect of stresses and corrosion usually takes place by fracture due to cracks starting at stress concentration points, for example, caustic cracking around rivet holes in boilers.
8. Fracture due to impact loading usually takes place by cleavage in brittle materials, for example, in steels below brittle–ductile transition temperature and plastics below glass transition temperature.

Of the types of mechanical failures mentioned, the first four do not usually involve actual fracture, and the component is considered to have failed when its performance is below acceptable levels. However, the latter four types involve actual fracture of the component, and this could lead to unplanned load transfer to other components and perhaps other failures. The following sections discuss the types of failures mentioned in the foregoing list, with the exception of wear failures, which are discussed in Section 3.8, and the combined effect of stress and corrosion, which is discussed in Section 3.4.

2.3 FRACTURE TOUGHNESS AND FRACTURE MECHANICS

It is now recognized that all engineering materials contain potential sites for cracks in the form of discontinuities, heterogeneities, flaws, inclusions, or microstructural defects that can be classified as follows:

- Microstructural features such as oxide or sulfide inclusions, large carbide and intermetallic precipitates, and inhomogeneous distribution of alloying elements leading to hard or soft spots
- Processing defects such as shrinkage and gas pores in castings, slag inclusions and similar welding defects, laps and stringers in forgings, contaminants in powder metallurgy parts, and decarburization in heat treatment
- Damage during service such as surface pits due to corrosion, cracks at discontinuities due to fatigue loading, surface damage due to wear and fretting, and internal voids and cracks due to creep

Such cracks cause high local stresses at their tips, and these stresses depend on the geometry and size of the flaw and the geometry of the component. The ability of a particular flaw or stress concentrator to cause fracture depends on the fracture toughness of the material, which can be qualitatively defined as the resistance of that material to the propagation of an existing flaw or crack. Therefore, to predict the fracture strength of a component, both the severity of the stress concentration and the fracture toughness of the material must be known.

2.3.1 Flaw Detection

To ensure that the severity of stress concentration remains within safe limits, quality control techniques of flaw detection are used to determine the flaw size, orientation, and distribution in components. Table 2.1 gives a sample of the commonly used nondestructive methods of flaw detection.

- Visual inspection is normally carried out to detect macroscopic surface flaws in the form of cracks, gouges, porosity, laps, and seams. It may be followed by liquid penetrant tests for better definition of surface flaws. External flaws on the order of 0.2 mm, or even smaller, can be detected by visual inspection with the aid of magnifying glasses.

TABLE 2.1
Nondestructive Methods of Crack Detection

Method	Applications and Standard Covering the Practice
Visual examination. The naked eye or a magnifying glass is used to locate and measure cracks.	Surface cracks
Penetrant test. Liquids that enter surface discontinuities by capillary action are first applied to the surface and then wiped off. A developer is then applied to help delineate the areas where the liquid has penetrated.	Defects open to the surface of metallic and nonmetallic materials (ASTM E 165)
Radiographic examination. X-rays and γ-rays are used to penetrate materials and are then caught on a sensitized film. Cavities or inclusions absorb the rays differently from the rest of the material and are delineated on the developed film.	Radiographs show the size and shape of discontinuities (ASTM E 94)
Magnetic particle method. A liquid containing iron powder is first brushed on the surface, and the part is then placed in a strong magnetic field. The particles pile up at discontinuities.	Detects surface cracks in magnetic materials (ASTM E 109 and E 138)
Ultrasonic tests. Ultrasonic vibrations that are transmitted through the material are reflected back at an internal discontinuity earlier than when reaching the opposite surface. The difference between the reflected waves is used to locate the position of the discontinuity.	Internal defects in ferrous and nonferrous metals and alloys (ASTM E 127)
Eddy current inspection. A coil is excited to induce eddy currents in the component to be inspected. In turn, this excitation induces a current in the coil. The presence of defects affects the induction of the component, which affects the current in the coil.	Used for the inspection of surface and subsurface defects in electrically conducting materials

- Dye penetrant can detect surface flaws and cracks that are too small to detect by visual examinations. Such flaws can be as small as 0.25 mm or even smaller.
- Radiographic examination is carried out to detect and provide a permanent record of internal flaws in components and assemblies. Radiographic equipment can be expensive and precautions should be taken to avoid health hazards to operators. Subsurface flaws greater than 2% of the section thickness can be detected by radiographic examination.
- Magnetic particle tests can detect surface and subsurface cracks, laps, voids, porosity, and inclusions in steels and cast irons. The equipment is relatively simple and inexpensive but requires experienced operators to avoid irrelevant indications. Flaw size on the order of 0.1 mm, or even smaller, can be detected by this method.
- Ultrasonic can detect and provide a permanent record of a variety of internal flaws including cracks, voids, inclusions, delaminations, and debonding between dissimilar materials. This method requires acoustic coupling between equipment and component and careful interpretation of results. Flaw size on the order of 0.1 mm, or even smaller, can be detected by ultrasonic testing.
- Eddy current inspection can detect cracks, changes in alloy composition or heat treatment, or wall thickness in tubing, sheet metal, and coatings.

2.3.2 Fracture Toughness of Materials

Quantitative prediction of the fracture strength can be made using fracture mechanics techniques, and in the simple case of glass, Griffith showed that

$$\sigma_f = \left(\frac{2Ev_s}{\pi a} \right)^{1/2} \tag{2.1}$$

where

σ_f is the fracture stress in MPa (or psi)
a is the crack length for edge cracks and 1/2 crack length for center cracks (this is measured in meters or inches)
E is Young's modulus in MPa (or psi)
v_s is the energy required to extend the crack by a unit area in J/m^2 (or in lb/in.^{2})

For glass, v_s is simply equal to the surface energy. However, this is not the case with metals due to the plastic deformation that occurs at the tip of the propagating crack. In the latter case, the fracture toughness is proportional to the energy consumed in the plastic deformation. Because it is difficult to accurately measure this energy, the parameter called the stress intensity factor, K_I, is used to determine the fracture toughness of most materials. The stress intensity factor, as the name suggests, is a measure of the concentration of stresses at the tip of the crack under consideration.

For a given flawed material, catastrophic fracture occurs when the stress intensity factor reaches a critical value, K_C. The relationship between stress intensity factor, K_I, and the critical intensity factor, K_C, is similar to the relationship between stress and tensile strength. The value of K_I is the level of stress at the crack tip and is material independent. However, K_C is the highest value for K_I that the material can withstand without fracturing; it is material and thickness dependent.

The reason why K_C is thickness dependent is that lateral constraint imposed on the material ahead of a sharp crack in a thick plate gives rise to a triaxial state of stress, which reduces the apparent ductility of the material. Thus, the fracture strength is less for thick plates compared with thinner plates, although the inherent properties of the material have not changed. As the thickness increases, K_C decreases and reaches a minimum constant value, K_{IC}, when the constraint is sufficient to give rise to plane-strain conditions, as shown in Figure 2.1.

The thickness, t, at which plane-strain conditions occur is related to the fracture toughness, K_{IC}, and yield strength of the material, YS, according to the relationship

$$t = 2.5\left(\frac{K_{IC}}{\mathrm{YS}}\right)^2 \tag{2.2}$$

The critical stress intensity factor for plane-strain conditions, K_{IC}, is found to be a material property that is independent of the geometry. In an expression similar

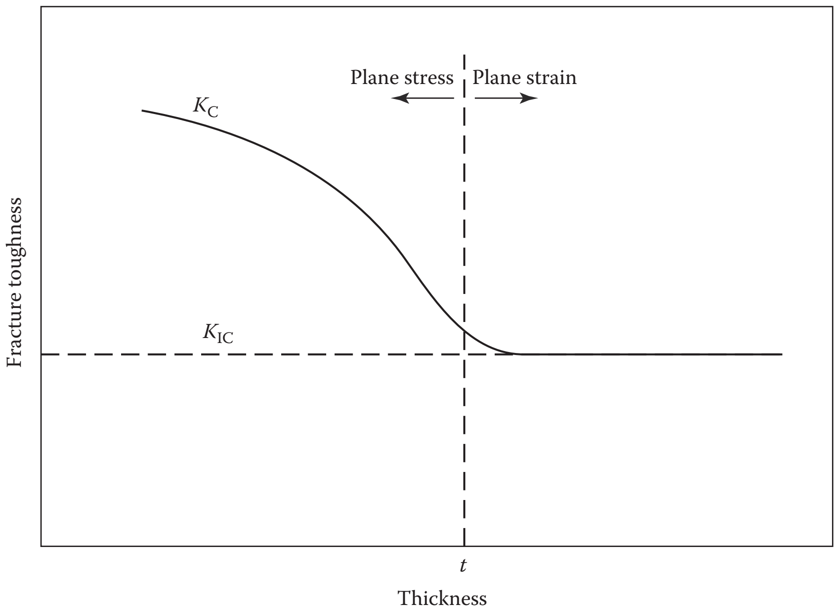


FIGURE 2.1 Effect of thickness on fracture toughness behavior.

to Griffith's, the fracture stress σ_f can be related to the fracture toughness, K_{IC}, and the flaw size, $2a$:

$$\sigma_f = \frac{K_{IC}}{Y(\pi a)^{1/2}} \tag{2.3}$$

where Y is a correction factor that depends on the geometry of the part, that is, thickness, width W, and the flaw size $2a$ for center crack and a for edge crack. For the case of thick plates, as a/W decreases to 0, that is, plane strain, Y decreases to 1. From Equation 2.3, it can be shown that the units of K_{IC} are MPa $(m)^{1/2}$ or psi $(in.)^{1/2}$.

As K_{IC} is a material property, the designer can use it to determine the flaw size that can be tolerated in a component for a given applied stress level. Conversely, the designer can determine the stress level that can be safely used for a flaw size that may be present in a component. Examples 2.1 and 2.2 illustrate the use of fracture toughness in design.

Design Example 2.1: Critical Crack Length

Consider a wide plate containing a crack of length $2a$ extending through the thickness. If the fracture toughness of the material is 27.5 MPa $(m)^{1/2}$ and the YS is 400 MPa, calculate the fracture stress σ_f and compare it to the YS σ_y for different values of crack lengths.

Assume $Y=1$.

Solution

Using Equation 2.3, σ_f can be calculated for different crack lengths. The results are given in Table 2.2.

With the smallest crack, the YS is reached before catastrophic failure occurs. However, longer cracks cause fracture before yielding.

Design Example 2.2: Using Fracture Toughness in a Material Selection

Problem

Ti-6Al-4V ($K_{IC}=60$ MPa $(m)^{1/2}$) and aluminum AA7075 alloy ($K_{IC}=24$ MPa $(m)^{1/2}$) are widely used in making lightweight structures. If the available nondestructive testing (NDT) equipment can only detect flaws larger than 4 mm in

TABLE 2.2
Variation of Fracture Stress with Crack Length

***a* (mm)**	**1**	**2**	**4**	**6**	**8**	**10**
σ_f (MPa)	490.6	346.9	245.3	200.3	173.5	155.2
σ_f/σ_y	1.23	0.87	0.61	0.50	0.43	0.39

length, can we safely use either of these alloys for designing a component that will be subjected to a stress of 400 MPa?

Solution

From Equation 2.3 and taking $Y = 1$,

$$\text{For Ti-6Al-4V, } \sigma_f = 400 = 60/(\pi a)^{1/2} \quad 2a = 14 \text{ mm}$$

$$\text{For AA7075, } \sigma_f = 400 = 24/(\pi a)^{1/2} \quad 2a = 2.3 \text{ mm}$$

The preceding figures show that the critical crack can be detected in the titanium alloy but not in the aluminum alloy. Titanium alloy can be used safely but not the aluminum alloy.

Fracture toughness data are available for a wide range of materials and some examples are given in Section 4.5. Fracture toughness data can also be easily established for new materials using standardized testing methods, for example, American Society for Testing and Materials (ASTM) Standard E399. Because of possible anisotropy of microstructure, it is important to orient the test specimen to correspond to the actual loading conditions of the part in service.

Fracture toughness, like other material properties, is influenced by several factors including strain rate or loading rate, temperature, and microstructure, as discussed in more detail in Section 4.5. Also, increasing the yield and tensile strengths of the material usually causes a decrease in K_{IC}. The use of fracture mechanics in design is discussed in Section 6.4.

Fracture toughness is widely accepted as a design criterion for high-strength materials where ductility is limited. In such cases, the relationship between K_{IC}, applied stress, and crack length governs the conditions for fracture in a part or a structure. This relationship is shown schematically in Figure 2.2. If a particular combination of stress and flaw size in a structure reaches the K_{IC} level, fracture can occur. Thus, there are many combinations of stress and flaw size that may cause fracture in a structure made of a material having a particular value of K_{IC}. The figure shows that materials with higher K_{IC} values tolerate larger flaws at a given stress level or higher stress levels for a given flaw size.

Figure 2.2 also shows that if a material of known K_{IC} is selected for a given application, the size of the flaw that will cause fracture can be predicted for the anticipated applied stress. If the design stress of a part is taken as 0.5 YS, the critical flaw length would be (a_1). Therefore, provided that no defect of size greater than (a_1) is present, failure should not occur on loading. If in a proof test the part is loaded to a stress above the expected service stress and the test was successful, then a flaw of size greater than a_2 could not have existed. During service life, crack growth of the order of ($a_1 - a_2$) could be tolerated before failure.

From Equation 2.3 and Figure 2.2, it can be shown that the maximum allowable flaw size is proportional to $(K_{IC}/\text{YS})^2$, where K_{IC} and YS are measured at the expected service temperature and loading rate. Thus, the ratio (K_{IC}/YS) can be taken as an index for comparing the relative toughness of structural materials. Higher

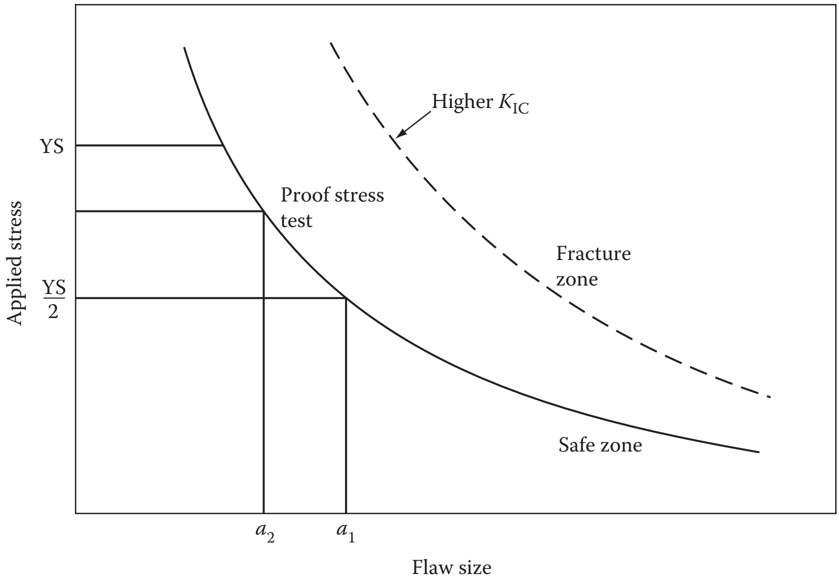


FIGURE 2.2 Schematic relationship between stress, flaw size, and fracture toughness.

values of (K_{IC}/YS) are more desirable as they indicate tolerance to larger flaws without fracture, as discussed in Section 4.5. The sensitivity of the NDT techniques used to detect manufacturing defects that approach the critical size in the part or structure is determined by the value of the allowed flaw size.

2.4 DUCTILE AND BRITTLE FRACTURES

Machine and structural elements often fail in service as a result of either ductile or brittle fracture. The terms ductile and brittle are usually used to indicate the extent of macroscopic or microscopic plastic deformation that precedes fracture. For example, materials with plastic strains of less than 2% at fracture are considered brittle. The terms ductile and brittle are also related to fracture toughness, and materials with K_{IC} less than 15 MPa $(m)^{1/2}$ are considered brittle. Impact toughness, which is a measure of the energy needed for fracture, can also be used as an indication, and materials that absorb less than 15 ft lb (20.3 J) are considered brittle.

2.4.1 Ductile Fractures

Service failures that occur solely by ductile fracture are relatively infrequent and may be a result of errors in design, incorrect selection of materials, improper fabrication techniques, or abuse, which arises when a part is subjected to load and environmental conditions that exceed those of the intended use.

The following case study illustrates an approach to failure analysis and the type of solution that may be available to the engineer who tries to solve the problem.

Case Study 2.3: Ductile Fracture of a Ladder

Problem

An aluminum ladder, which is 3 m long and made of four T-sections and hollow cylindrical rungs, is shown in Figure 2.3. The ladder failed when a man weighing 100 kg climbed halfway up when it was leaning against a wall at an angle of 15°. Although this was the first time the man used the ladder, his wife, who weighed 60 kg, had used it many times earlier. As a result of failure, T-sections S2 and S3 suffered severe plastic deformation and buckling caused by bending, while T-sections S1 and S4 cracked just under the rung where the man was standing (Figure 2.3).

Analysis

Investigation showed that a large reduction in area accompanied the fracture, and chemical analysis showed that the T-sections were made of AA 6061 alloy. The hardness of the alloy was in the range 25–30 RB in most areas but was about 20 RB in section S2. These hardness values correspond to T4 temper condition of the AA 6061 alloy.

It is expected that the weakest section S2, which was on the tension side during loading, has yielded causing the load to be redistributed and section S3 to yield. This, in turn, caused sections S1 and S4 to be overloaded in tension.

Solution

As failure is caused by overload during normal use, it is recommended that a stronger material be used. It would be sufficient to change the temper condition from T4 to T6. The AA 6061 T6 has a hardness of 45–55 RB and YS about twice that of the AA 6061 T4.

2.4.2 Brittle Fractures

Brittle fractures are usually initiated at stress raisers, such as large inclusions, cracks or surface defects, and sharp corners or notches. The single most frequent initiator of brittle fracture is the fatigue crack, which accounts for more than 50% of all brittle fractures in the manufactured products. Brittle fractures are insidious in character because they may occur under static loading at stresses below the YS and without warning.

Once started, the brittle fracture will run at high speed, reaching 1200 m/s in steel, until total failure occurs or until it runs into conditions favorable for its arrest. The risk of occurrence of brittle fracture depends on the notch toughness of the material under a given set of service conditions. A characteristic feature of brittle fracture surfaces is the chevron pattern, which consists of a system of ridges curving outward from the center line of the plate, as shown in Figure 2.4. These ridges, or chevrons, may be regarded as arrows with their points on the center line and invariably pointing toward the origin of the fracture, thus providing an indication of its propagation pattern. This feature is useful in the analysis of service failures.

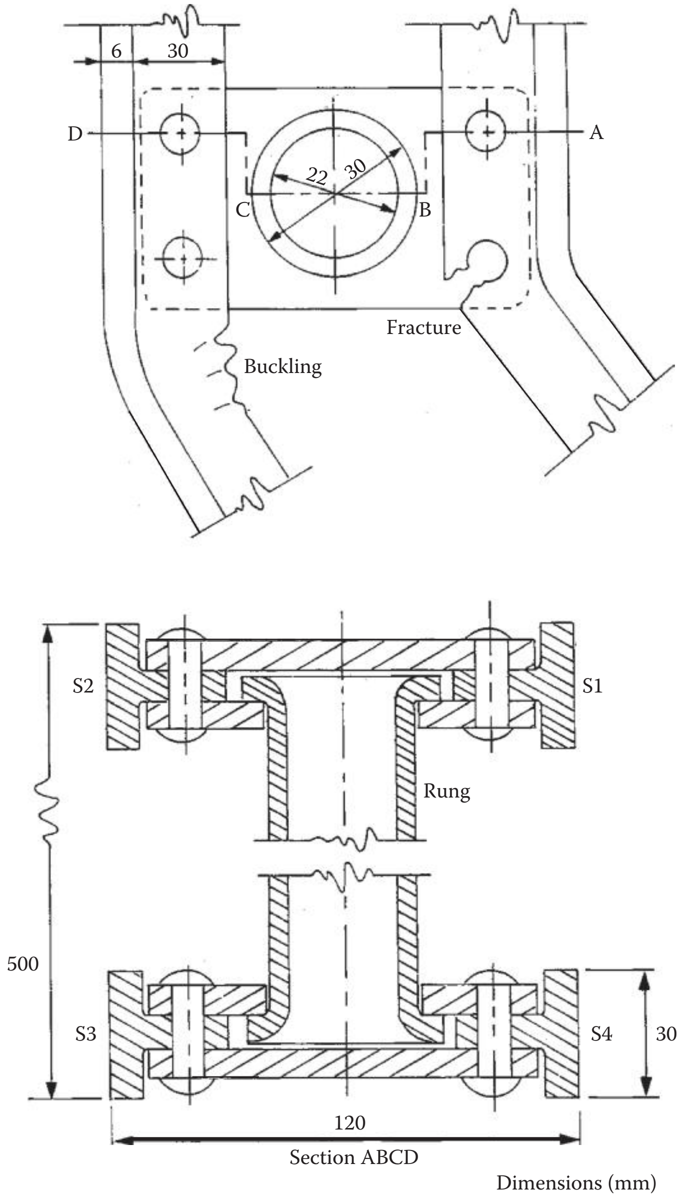
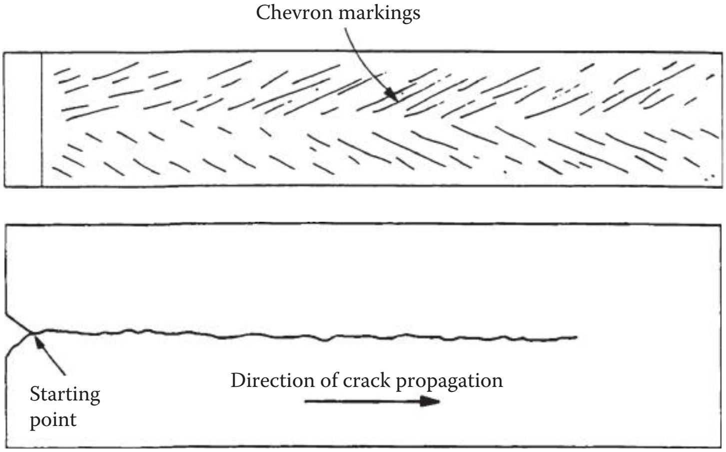


FIGURE 2.3 Failure of an aluminum ladder.

(a)



(b)

FIGURE 2.4 Chevron patterns in brittle fracture. (a) Chevron markings in steel. (From Rollason, E.C., *Metallurgy for Engineers*, 4th edn., Edward Arnold, London, U.K., 1977.) (b) Schematic representation.

2.4.3 Ductile–Brittle Transition

The temperature at which the component is working is one of the most important factors that influence the nature of fracture. Brittle fractures are usually associated with low temperature, and in some steels, conditions may exist where a difference of a few degrees, even within the range of atmospheric temperatures, may determine the difference between ductile and brittle behavior. This sharp ductile–brittle transition is only observed in body-centered cubic (bcc) and hexagonal close-packed (hcp) metallic materials and not in face-centered cubic (fcc) materials, as illustrated schematically in Figure 2.5.

The most widely used tests for characterizing the ductile-to-brittle transition are the Charpy, ASTM Standards A23 and A370, and Izod. The temperature at which the material behavior changes from ductile to brittle is called the ductile–brittle transition temperature (T_c) and may be taken as the temperature at which the fractured surfaces exhibit 50% brittle fracture appearance. In Charpy V-notch (CVN)

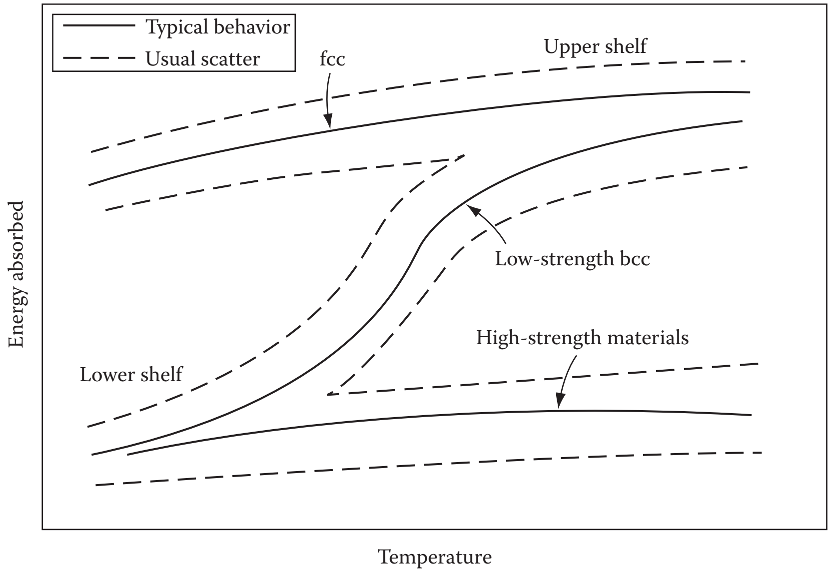


FIGURE 2.5 Schematic representation of the effect of temperature on the energy absorbed in fracture.

experiments, the transition temperature can be set at a level of 20.3 J (15 ft lb) or at 1% lateral contraction at the notch. The transition temperature based on fracture appearance always occurs at a higher value than if based on a ductility or energy criterion. Therefore, the fracture appearance criterion is more conservative.

The rate of change from ductile-to-brittle behavior depends on the strength, chemical composition, structure, and method of fabrication of the material. The state of stress and the speed of loading also influence the nature of fracture. A state of triaxial tensile stresses, such as those produced by a notch, can be the cause of brittle fracture. The notches in a component can be due to shape changes, processing defects, or corrosion attack. Materials that behave normally under slowly applied loads may behave in a brittle manner when subjected to sudden applications of load, such as shock or impact. The ductile-to-brittle transition also shifts to higher temperatures as the rate of loading increases.

In the case of steels, the shift in transition temperature depends on the strength and can be as high as 68°C (155°F) in steels of YS of 280 MPa (about 40 ksi). The shift in transition temperature between static and impact loading decreases with increasing strength and becomes negligible at YSs of about 900 MPa (about 130 ksi).

In applying the CVN results to industrial situations, it should be borne in mind that the shock conditions encountered in the test may be too drastic. Many industrial components operate successfully in extreme cold without special consideration for notch toughness values or transition temperature. However, where stress concentration and rate of strain are high and service temperatures are low, special design and fabrication precautions should be taken and materials with low transition temperatures should be selected.

2.4.4 Design and Manufacturing Considerations

The design and fabrication precautions that should be taken to avoid brittle fracture include the following:

1. Abrupt changes in section should be avoided to avoid stress concentrations, and thickness should be kept to a minimum to reduce triaxial stresses.
2. Welds should be located clear of stress concentrations and of one another, and they should be easily accessible for inspection.
3. Whenever possible, welded components should be designed on a fail-safe basis. This concept is discussed in Section 5.2.

A useful relation between plane-strain fracture toughness (K_{IC}) and the upper-shelf CVN impact energy was suggested for steels of YSs higher than about 770 MPa (ca. 110 ksi) by Rolfe and Barson (1977) as

$$\left(\frac{K_{IC}}{YS}\right)^2 = \left(\frac{5}{YS}\right)\left(CVN - \frac{YS}{20}\right) \tag{2.4}$$

where

K_{IC} is in ksi (in.)$^{1/2}$
YS is in ksi
CVN is in ft lb

2.5 FATIGUE FAILURES

Generally, fatigue fractures occur as a result of cracks, which usually start at some discontinuity in the material or at other stress concentration locations, and then gradually grow under repeated application of load. As the crack grows, the stress on the load-bearing cross section increases until it reaches a high level enough to cause catastrophic fracture of the part. This sequence is reflected in the fracture surfaces that usually exhibit smooth areas that correspond to the gradual crack growth stage and rough areas that correspond to the catastrophic fracture stage, as shown in Figure 2.6. The smooth parts of the fracture surface usually exhibit beach marks, which occur as a result of changes in the magnitude of the fluctuating fatigue load. Another feature of fatigue fractures is that they lack macroscopic plastic deformation and, in this respect, they resemble brittle fractures. The following case studies are used to illustrate some of the frequent causes of fatigue fracture and to show some of the solutions that may be used to solve the problem.

Case Study 2.4: Fatigue Failure of a Pressure Line

Problem

The steel pressure line of a hydraulic pump in a power-generation unit started leaking at the exit line flange assembly shown in Figure 2.7. The source of leakage was found to be a crack in the fillet weld.

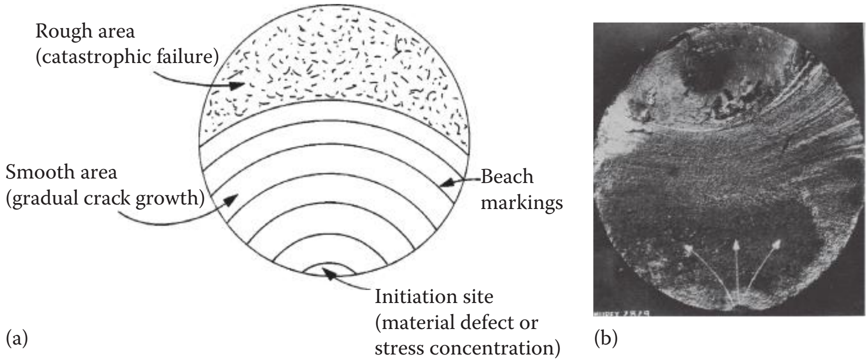


FIGURE 2.6 General appearance of a fatigue fracture surface. (a) Schematic representation; (b) fatigue fracture of automobile axle shaft. (From Rollason, E.C., *Metallurgy for Engineers*, 4th edn., Edward Arnold, London, U.K., 1977.)

Analysis

Investigation of the working conditions showed that although the pressure in the line was within the design limits, excessive vibrations existed in the 2 m long tube, which was not sufficiently supported by the flexible hose at its end. This caused the line to act as a cantilever beam with maximum forces at the flange.

It is concluded that the crack in the fillet weld took place as a result of fatigue loading caused by the vibrations in the line.

Solution

The corrective action taken was to change the design to move the weld from the area of high stress concentration, as shown in Figure 2.7. The line was also adequately supported at the point where it joined the flexible hose to minimize vibrations.

Case Study 2.5: Comet Aircraft Failures

Background

The de Havilland DH 106 Comet was the first commercial airliner to be powered by jet engines. This allowed it to fly at higher altitudes in order to take advantage of the lower air resistance, which also meant pressurizing the fuselage to maintain atmospheric pressure inside the cabin.

Problem

The first flight of the Comet with passengers was in May 1952. During the period March 1953 and January 1954, three planes crashed, killing all those on board. As a result, the Comet fleet was grounded and several design modifications introduced and flights resumed. However, another crash occurred in April 1954 and the fleet was grounded again.

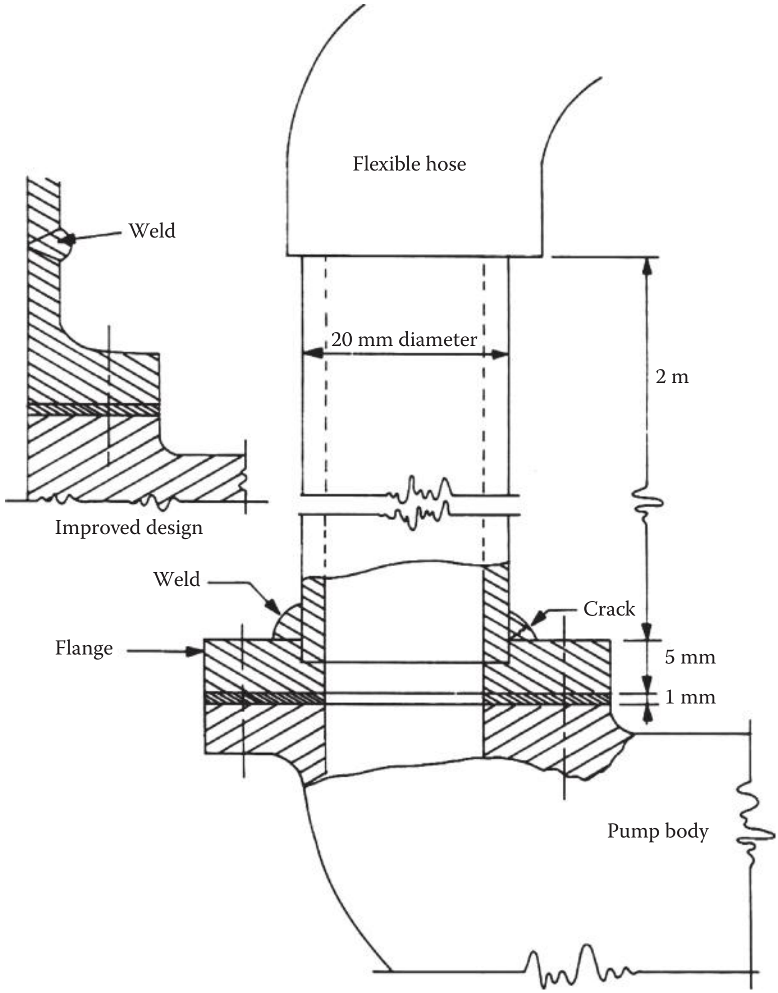


FIGURE 2.7 Failure of pressure line of a hydraulic pump.

Analysis

Inspection parts of the fuselage that were recovered from crash sites showed beach marks on the fracture surfaces, which indicated possible fatigue failure. This was confirmed by testing a full length fuselage in a specially constructed water tank to simulate the compression and decompression during flight and landing. After about 3000 cycles, the fuselage burst open at a sharp corner of the forward port-side escape hatch cutout. Several fatigue cracks were also found at rivet holes, which were produced by punching.

Solutions

All the remaining Comets were withdrawn from service, and new versions were built with rounded corners for all openings and windows in order to reduce stress concentration. The skin sheeting was also made thicker. Rivet holes were drilled instead of punching to produce smoother surfaces. A periodic inspection procedure was also introduced. With these changes, commercial flights of the new Comet resumed in 1958 and successfully continued for nearly 30 years.

2.5.1 Types of Fatigue Loading

The simplest type of fatigue loading is the alternating tension–compression without a static direct stress (Figure 2.8a). In this case, the stress ratio, defined as $R = \sigma_{min}/\sigma_{max}$, is −1. If a static mean stress σ_m is superimposed on the alternating stress, then the stress varies between the limits of

$$\sigma_{max} = \sigma_m + \sigma_a \quad \text{and} \quad \sigma_{min} = \sigma_m - \sigma_a$$

as shown in Figure 2.8b. A special case is the pulsating stress with $R = 0$.

Under actual service conditions, parts may be subjected to more than one form of load, for example, alternating torsion with static tension. Many other combinations are known to be met in different applications. However, most of the available fatigue test results are for the simple alternating stresses, that is, $R = -1$. Such results are usually

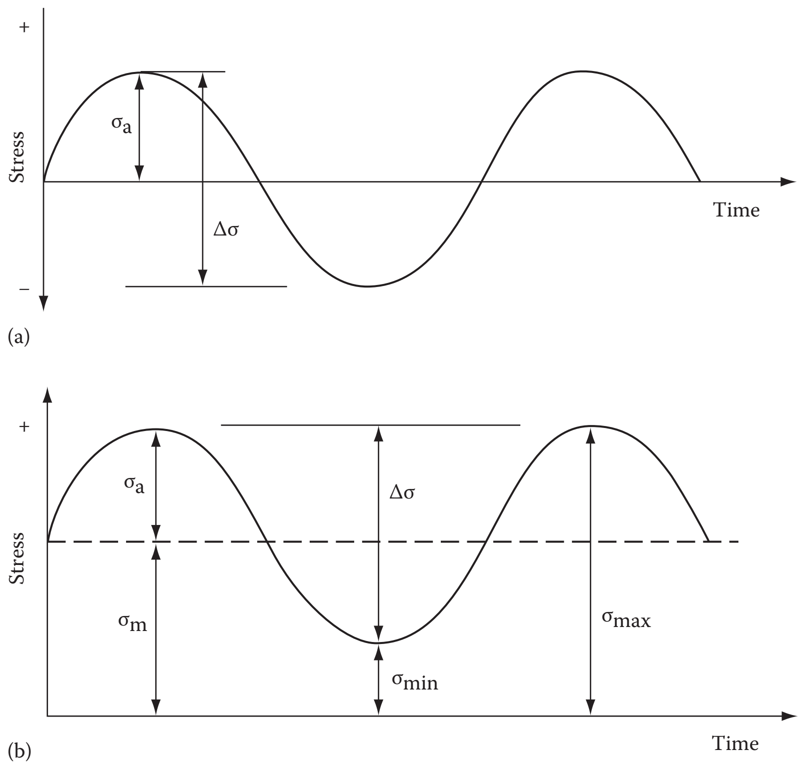


FIGURE 2.8 Types of fatigue loading. (a) Alternating stress, $R = -1$; (b) fluctuating stress.

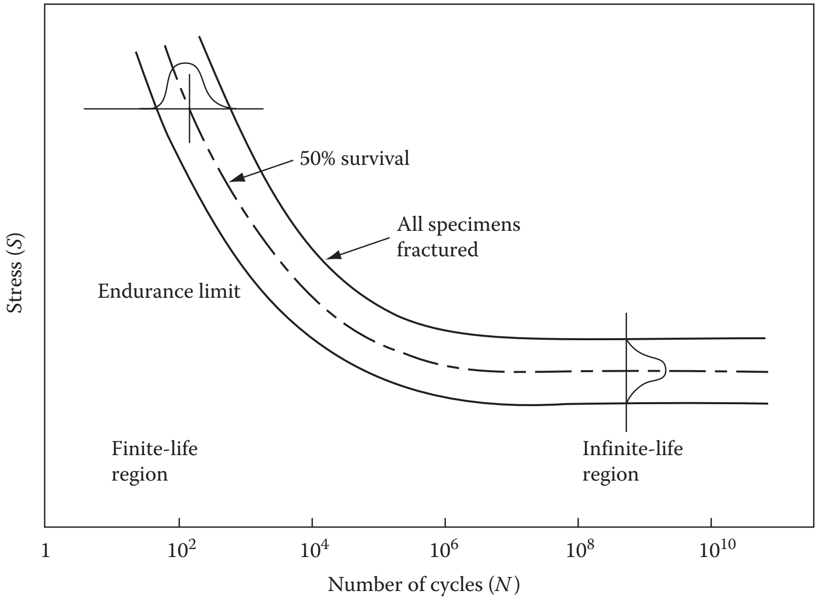


FIGURE 2.9 Representation of fatigue test results on the *S–N* curve.

presented as *S–N* curves, as shown in Figure 2.9. In this case, *S* is the alternating stress and *N* is the number of cycles to failure. Although most available *S–N* curves and endurance limit values are based on laboratory experiments and controlled test conditions, fatigue results always show larger scatter than other mechanical properties. The standard deviation for endurance limit results is usually in the range of 4%–10%, but in the absence of statistical values, an 8% standard deviation can be assumed. The reported endurance results can be taken to correspond to 50% survival reliability. Statistical variation of material properties is discussed in Section 5.9.

2.5.2 Fatigue Strength

Some materials, such as steels and titanium, exhibit a well-defined fatigue or endurance limit below which no fatigue fracture occurs (Figure 2.10). The figure also shows that other materials, such as aluminum alloys, do not have such a limit, and their *S–N* curves continue to decrease at high number of cycles. For these materials, fatigue strength is reported for a specified number of cycles. As this number of cycles is not standardized, the reported fatigue strength values are subject to large variations depending on whether the strength is taken at $N = 10^6$, 10^7, or 10^8 cycles. Therefore, it is necessary to specify the number of cycles for which the strength is reported. When the material does not exhibit a well-defined fatigue or endurance limit, it is only possible to design for a limited life.

The endurance limit, or fatigue strength, of a given material can usually be related to its tensile strength, as shown in Table 4.7. The endurance ratio, defined as endurance limit/tensile strength, can be used to predict fatigue behavior in the absence

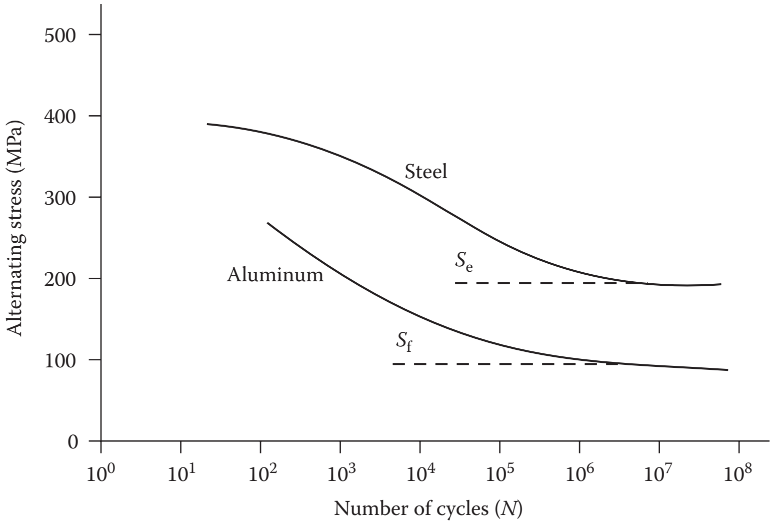


FIGURE 2.10 Fatigue results as represented by the *S–N* curves. Steel exhibits an endurance limit and its curve levels off at S_e. Aluminum does not exhibit an endurance limit, and its curve continues to decline for all values of *N*.

of endurance limit results. As the table shows, the endurance ratio of most ferrous alloys varies between 0.4 and 0.6.

An important limitation of *S–N* curves and the endurance limit results is that they are usually determined for relatively small specimens under controlled conditions and simple loading systems. In addition, these results do not distinguish between crack initiation life and crack propagation life. These disadvantages limit their use in designing large structural components where crack-like defects can exist in the material or as a result of manufacturing. Under such conditions, it is the rate of fatigue-crack propagation that determines the fatigue life of the part.

2.5.3 Crack Initiation

Even if the nominal stresses acting on the part are below the elastic limit, local stresses may exceed the yield stress as a result of stress concentration or material discontinuity. As a result, cyclic plastic deformation takes place on favorably oriented slip planes, leading to local strain hardening and eventual crack nucleation.

It can be shown that the local stress range at the site of crack nucleation, $\Delta\sigma_{max}$, can be related to the range of the stress intensity factor, ΔK_I, by the following relationship:

$$\Delta\sigma_{max} = \Delta\sigma K_t = \left(\frac{2}{\pi^{1/2}}\right)\left(\frac{\Delta K_I}{r^{1/2}}\right) \qquad (2.5)$$

where

r is the notch-tip radius
$\Delta\sigma$ is the range of applied nominal stress
K_t is the stress concentration factor

Experience shows that $\Delta K_I/(r)^{1/2}$ is the main parameter that governs fatigue-crack initiation in a benign environment. In the case of steels, there is a fatigue-crack initiation threshold, $[\Delta K_I/(r)^{1/2}]$, below which fatigue cracks do not initiate. The value of this threshold increases with increasing strength and with decreasing strain hardening exponent.

2.5.4 Crack Propagation

The performance of most parts and structures under fatigue loading is more dependent on their resistance to crack propagation than to crack nucleation. This is because microcracks are known to nucleate very early in the lives of parts, and notched high-strength materials may have propagating cracks effectively throughout their service lives. Initially, the crack propagates along the slip plane along which it nucleated, stage I, and then turns on to a plane perpendicular to the direction of the maximum tensile stress, stage II. Stage I may account for more than 90% of the life of a smooth ductile part under light loads or may be totally absent in a sharply notched, highly stressed part.

Experience based on experimental data shows that the fatigue-crack propagation behavior is controlled primarily by the stress intensity factor range, ΔK_I, and can be divided into three regions, as shown in Figure 2.11. In region 1, fatigue cracks grow extremely slowly or not at all, and in region 3, an increase in growth rate leads to rapid unstable growth as K_C or K_{IC} is approached.

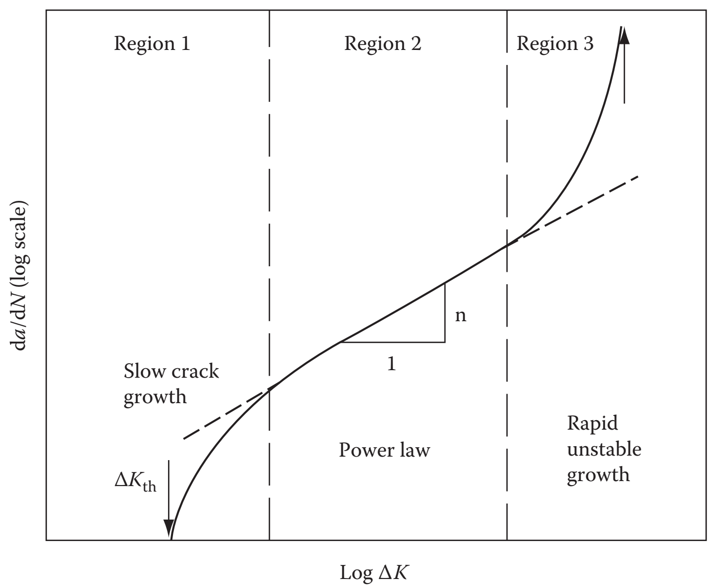


FIGURE 2.11 Schematic illustration of the effect of the range of the stress intensity factor (ΔK_I) on fatigue-crack growth rate (da/dN).

The crack growth in region 2 represents most of the crack propagation duration and can be represented by a power law, which is usually called the Paris relationship:

$$\frac{da}{dN} = C(\Delta K_I)^n \tag{2.6}$$

where

a is the crack length

N is the number of cycles

da/dN is the crack growth per cycle

C and n are the experimentally determined constants that depend on material properties and environment (the value of n normally ranges between 1 and 6)

ΔK is the stress intensity factor range at the crack tip and equals $K_{max} - K_{min}$ (in alternating stress regimes where the minimum stress is compressive, K_{min} can be taken as zero and K_{max} as K_{IC})

Equation 2.6 can be used to give a rough estimation of the fatigue life of components, as illustrated in the following design example.

Design Example 2.6: Prediction of the Fatigue Life of a Component

Problem

A rotating shaft in a power-generation system has been inspected by nondestructive tests that can only reveal surface cracks larger than 2 mm. The shaft is made of AISI 4340(T260°C) steel of $K_{IC} = 50$ MPa m$^{1/2}$. The loading conditions of the shaft cause an alternating stress of 200 MPa. Estimate the fatigue life of the shaft.

Solution

As the maximum stress is expected to be at the surface of the shaft, surface cracks should not be allowed to grow large enough to cause fracture at the maximum stress of 200 MPa. The critical surface crack size as estimated using Equation 2.3 is 19.9 mm.

The approximate fatigue life of the shaft can be measured in terms of the number of cycles needed to extend the crack from 2 to 19.9 mm. This can be estimated from Equation 2.6 using the information from Callister, $C = 1.0 \times 10^{-12}$ and $n = 3$:

$$da = 1.0 \times 10^{-12} \times (50)^3 \times dN$$

$$= (19.9 - 2) \times 10^{-3}$$

Approximate fatigue life of the shaft $= N = 1.4 \times 10^5$ cycles.

2.6 ELEVATED-TEMPERATURE FAILURES

The effect of service environment on material performance at elevated temperature can be divided into the following three main categories:

1. Mechanical effects such as creep and stress rupture
2. Chemical effects such as oxidation
3. Microstructural effects such as grain growth and overaging

Although oxidation and creep can directly lead to the failure of a part in service, the microstructural changes can lead to weakening of the material and, therefore, can indirectly lead to failure. Many of the strengthening mechanisms that are effective at room temperature become ineffective at elevated temperatures. Generally, nonequilibrium structures change during long-term high-temperature service and this leads to lower creep strength. Thus, materials that depend on their fine grains for strengthening may lose this advantage by grain growth, and materials that have been strain hardened by cold working may recover or anneal. Structures that have been precipitation hardened to peak values may overage, and steels that have been hardened and tempered may overtemper.

2.6.1 Creep

A major factor that limits the life of components in service at elevated temperatures is creep. Creep is defined as the time-dependent deformation, which occurs under the combined effect of stress and elevated temperature, normally in the range of 35%–70% of the melting point of the material expressed in absolute temperature. Creep occurs as a result of the motion of dislocations within the grains, grain boundary rotation, and grain boundary sliding. It is sensitive to grain size, alloying additions, microstructure of the material, and service conditions.

When creep reaches a certain value, fracture occurs. Creep fracture (also called stress rupture) usually takes place at strains much less than the fracture strains in tension tests at room temperature.

In most practical cases, the strain that is suffered by a component under creep conditions can be divided into the stages shown schematically in Figure 2.12. Following an initial instantaneous deformation, creep takes place at a decreasing strain rate, which is the slope of the curves in Figure 2.12, during the primary or transient stage. This is followed by the secondary creep or steady-state stage where the strain rate is constant under constant stress conditions.

At the end of the steady-state stage, tertiary creep starts and the strain rate increases rapidly with increasing strain and fracture finally occurs. Tertiary creep can be caused by

1. Reduction of the cross-sectional area of the component due to cracking or necking
2. Oxidation and other environmental effects, which reduce the cross-sectional area
3. Microstructural changes that weaken the material such as coarsening of precipitates

Under certain conditions, some materials may not exhibit all the mentioned stages of creep. For example, at high stresses or high temperatures, the primary stage may

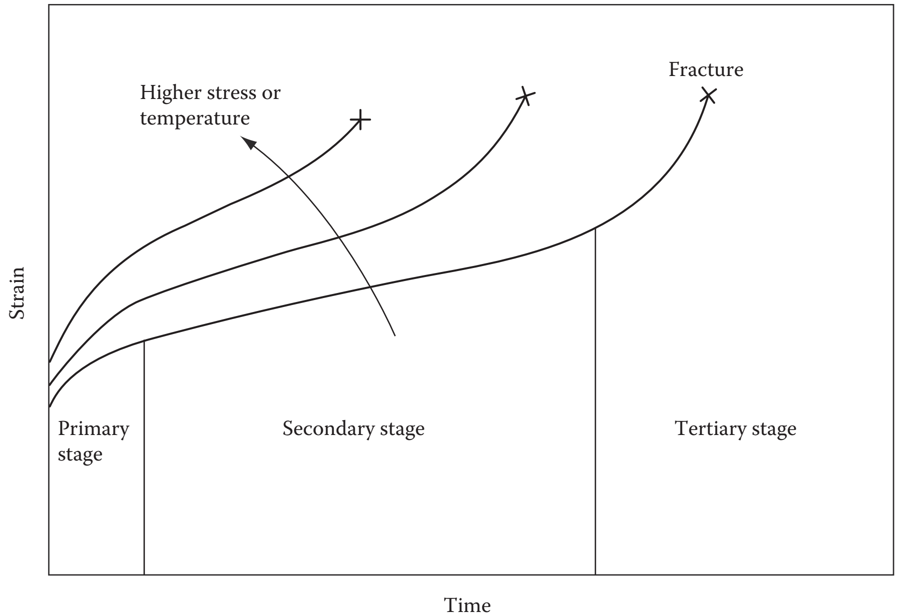


FIGURE 2.12 Schematic creep curve under tensile loading.

not be present, with secondary creep or even tertiary creep starting soon after load application. Another example is the case where fracture occurs before the tertiary stage is reached, as in the case of some low-ductility cast alloys. Creep ductility is an important factor in material selection. Although the permissible creep strain in practice is usually of the order of 1%, selecting materials with higher creep ductility means a higher safety margin.

The steady-state creep rate is often a high-temperature design parameter and may be required to be lower than a specified value to ensure a minimum life of a component in service. At a given temperature, the steady-state creep rate ($\dot{\varepsilon}$) can be expressed as a function of the applied stress (σ) as follows:

$$\dot{\varepsilon} = B\sigma^m \tag{2.7}$$

where B and m are experimental constants and depend on the material and operating temperature. Equation 2.7 is often called Norton's equation and m is Norton Index. At low stresses and high temperatures, creep takes place as a result of atomic diffusion either through the grains or along the grain boundaries of metals. In such cases, m in Equation 2.7 can be taken as unity. At higher stresses, creep takes place as a result of dislocation movement and m can take values ranging from 2 to 9, depending on the material and temperature values. The following design example illustrates the use of Equation 2.7 in designing of components for high-temperature service.

Design Example 2.7: Designing for Steady-State Creep Using Norton's Equation

Problem

A cylindrical pressure vessel has an internal diameter of 45 cm and a wall thickness of 20 mm and operates at 800°C. When operating at the design pressure, the vessel diameter is expected to reach its maximum allowable increase in diameter of 5 mm in 4 years. As a result of increasing demand, it was decided to increase the operating pressure by 25%. Calculate the expected decrease in life of the vessel as a result of this action.

Solution

Given the stress level and operating temperature for the vessel material, a Norton Index m can be assumed as 4. The creep strain rate under the original design conditions ($\dot{\varepsilon}$) is

$$\dot{\varepsilon} = (5)/450 \times 4 \times 360 \times 24 = 2.5 \times 10^{-7}$$

$$= B\sigma^4$$

From Equation 2.7, the creep strain rate under conditions of increased pressure is

$$\dot{\varepsilon}_n = B(1.25\,\sigma)^4 = 2.5 \times 10^{-7} \times (1.25)^4$$

Expected life of the vessel under increased operating pressure $= (5)/450 \times 360 \times 24 \times 2.5 \times 10^{-7} = 2.1$ years.

Remark: Please notice how an increase of 25% in stress has resulted in about 50% reduction in expected life.

2.6.2 Combined Creep and Fatigue

In many high-temperature applications in practice, the applied loads are cyclic and could lead to a combined creep–fatigue failure. Under these conditions, the life of a component is determined by the initiation and growth of a creep or a fatigue crack. At high load frequencies and relatively lower temperatures, crack growth is independent of the frequency or temperature. This is because the material just ahead of the crack does not suffer any time-dependent processes, such as oxidation or creep relaxation. Under these conditions, the mechanism of crack growth is essentially the same as room temperature fatigue.

At low frequencies and relatively high temperatures, crack growth is affected by time-dependent processes. A mixture of the two extreme cases of behavior is expected at intermediate temperatures and load frequencies.

2.6.3 Thermal Fatigue

Another form of elevated-temperature failures is thermal fatigue. Stresses and strains induced in a component due to thermal gradients can cause failure if repeated a sufficient number of times. Faster changes in temperature, lower thermal conductivity of the material, higher elastic constant, higher thermal expansion coefficient, lower ductility, and thicker component sections often account for shorter service life. Ceramic materials are particularly prone to thermal fatigue in view of their limited thermal conductivity and brittleness.

In high-temperature applications, the environment plays an important role in determining the performance of components. Selecting the material that will resist the environment, controlling the environment, or protecting the surface is essential for prolonged service. Examples of aggressive environments are those that contain vanadium compounds, sulfur compounds, or salt. A vacuum environment may be more harmful than air if some of the alloy constituents evaporate at high temperatures.

2.7 FAILURE ANALYSIS: EXPERIMENTAL METHODS

When a component fails in service, it is important that the source of failure is located to identify the responsible party and to avoid similar failures in future designs. Owing to the complexity of most failure cases, it is useful to follow a systematic approach to the analysis such as the following:

1. Gathering background information about the function, source, fabrication, materials used, and service history of the failed component is an important step.
2. Site visits involve locating all the broken pieces, making visual examination, taking photographs, and selecting the parts to be removed for further laboratory investigation. Macroscopic, microscopic, chemical analysis, nondestructive, and destructive tests are normally used to locate possible material and manufacturing defects. Presence of oxidation and corrosion products, temper colors, surface markings, etc., can also provide valuable clues toward failure mode identification.
3. Based on the gathered information, it should be possible to identify the origin of failure, direction of crack propagation, and sequence of failure. Presence of secondary damage not related to the main failure should also be identified.
4. The final step in failure analysis usually involves writing a report to document the findings and to give the conclusions. This report usually includes the background information and service history of the failed part, description of the specimens examined and procedure of examination, information about materials and comparison with specifications, manufacturing methods, causes of failure, and how to avoid such failure in the future.

The following case study illustrates the use of the experimental method in failure analysis of a welded component.

Case Study 2.8: Failure of Welded Alloy Steel Component

Problem

A component made of alloy steel, which was manufactured by welding, failed next to the fusion zone. What factors could have contributed to this failure?

Analysis

The first step is to ensure that the failure zone does not have obvious cavities or cracks and that the load did not exceed the design limit and that the weld was not placed in a stress concentration zone. Assuming that there are no obvious weld defects and that the design parameters are correct, the next step is to look for the less obvious materials and manufacturing defects. The following are questions that need to be answered:

1. What was the grade of the welding electrodes? Could it have introduced hydrogen in the weldment? (Look for the electrode number and specifications and whether it is a low-hydrogen grade.)
2. What is the composition of the alloy steel and what is its hardenability? Was there martensitic structure in the fracture zone? (Find out the designation number, look for chemical analysis, estimate hardenability, and perform hardness tests.)
3. What was the welding procedure? Was appropriate preheating and postwelding heating applied? (Look for the records and process sheets of the weld.)
4. Was there severe grain growth in the heat-affected zone where fracture occurred? (Perform microscopic examination.)
5. Did the parent metal have inclusions that could have caused stress concentration? (Perform microscopic examination.)

Answers to these questions would be helpful in identifying the cause of failure.

2.8 FAILURE ANALYSIS: ANALYTICAL TECHNIQUES

Several analytical techniques and computer-based methods have been developed to help the engineer in solving failure problems. Identification of failure mode is not only important for determining the cause of failure, but also a powerful tool for reviewing the design. The following discussion gives a brief review of some of the analytical techniques that have been developed for systematic identification of failure modes. Reference should be made to the original publications for more details.

2.8.1 Root Cause Analysis

Having identified the main cause of failure using the experimental techniques described in Section 2.7, the next step is to identify all the possible root causes for that main cause. A root cause is sufficiently basic to be treated independently of other causes. The analysis starts by identifying the subordinate causes (primary causes) that could have led to the main cause. Each of the subordinate causes is then analyzed to identify its subordinate causes (secondary causes). Possible subordinates of each secondary cause are identified as tertiary causes, which may be followed by quaternary causes if needed. A useful organization tool for complex root cause analysis cases is the failure tree analysis (FTA), which will be described in Section 2.8.2.

Having identified the root causes of failure, the next step is to evaluate the probability that each of the root causes was responsible for the failure. The causes are then analyzed starting with the most likely, highest probability and then the less likely or lower probability. Physical evidence for the presence of each of the root causes is then documented. Tests and analysis can then be performed on the failed component to look for the physical evidence of their presence. Corrective action plan to eliminate the present root causes is then proposed together with a preventive action plan to reveal their presence if they happen to occur in spite of the corrective action. The following case study illustrates the use of root cause analysis to the failure of a crankshaft of an auxiliary power-generation diesel engine.

Case Study 2.9: Failure of a Crankshaft of an Auxiliary Power-Generation Diesel Engine

Problem

The crankshaft of an auxiliary power-generation diesel engine failed after 2 years of service.

Analysis

The failed crankshaft is made of forged steel. Failure analysis attributed the failure to fatigue loading with the fatigue crack initiating at a surface defect in the crankshaft. The major causes that could have caused a surface defect in the forged crankshaft are judged to be casting defect in the steel ingot before forging, a defect that developed during the forging process, or a surface defect that developed during the heat treatment process that followed forging. Table 2.3 gives a simplified root cause analysis for the failure.

Conclusion

Table 2.3 shows that four root causes are identified as likely to occur. The recommended tests to verify the most likely cause include chemical analysis and optical microscopy. The recommended preventive action will be based on the test results and can include better control of impurities in the steel, better filtering process of the liquid steel, better design of the forging dies, and better control of the reheating furnace temperature. Recommended preventive actions include nondestructive inspection for surface defects; these include visual inspection, liquid penetrant test, and magnetic particle tests, as described in Section 2.3.1.

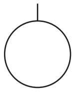
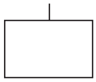
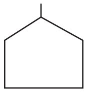
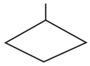
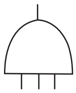
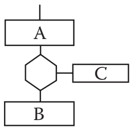
2.8.2 Fault Tree Analysis

Fault tree analysis (FTA) is an analysis technique that is widely used in organizing the logic in studying reliability, critical failure modes, safety, availability, or

TABLE 2.3
Root Cause Analysis of a Forged Steel Crankshaft

Surface Defect of Forged Crankshaft							
Casting Defect in Ingot					Forging Defect		Heat Treatment Defect
Nonmetallic inclusion		Shrinkage cavity		Gas porosity	Surface lap	Hot shortness	Quenching crack
Chemical analysis	Filtering process	Casting temperature	Metal flow rate	Gas content	Metal flow in the die	Forging temperature	Quenching medium
Likely to occur	Likely to occur	Unlikely	Unlikely	Unlikely	Likely to occur	Likely to occur	Unlikely
Check with chemical analysis	Check with optical microscopy	No further action is needed	No further action is needed	No further action is needed	Check with optical microscopy for the low of grains	Check with optical microscopy for grain size	No further action is needed
Ensure that impurities are within permissible limits	Improve filtering process and use new filters				Better die design and less surface oxidation on reheating	Better control of reheating furnace temperature	

TABLE 2.4
Some Standard Symbols Used in FTA

Symbol	Event
	Basic event that requires no further development and does not depend on other parts of the system for its occurrence.
	An event that results from a combination of basic events and needs further analysis to determine how it can occur. It is the only symbol on the fault tree that can have a logic gate and input events below it.
	Switch. Used to include or exclude parts of the tree that may or may not apply to certain situations.
	An event that depends upon lower events but has not been developed further.
	A connection to another part of the tree. A line from the apex indicates a transfer-in whereas a line from the side indicates a transfer-out.
	AND gate. Failure of next higher part will occur only if all inputs fail (parallel redundancy).
	OR gate. Failure of next higher part will occur if any input fails (series reliability).
	Inhibit gate. Combines AND and IF logic. Event A will occur if B occurs and C's value lies in some predetermined range.

advantages of design redundancy. When any of these issues is selected for analysis, it is considered to be the "top event" that forms the main trunk from which logic branches develop. The analysis proceeds by determining how the top event can be caused by individual or combined lower-level events. As the fault tree grows, its logic is separated into successively smaller events until each element is sufficiently basic to be treated independently of other events. This separation is recorded using AND and OR gates in addition to other standard symbols, as shown in Table 2.4.

Normally, an engineering system's failure tree would have a large number of branches, gates, and elements that need a computer routine to keep track of the analysis. Many FTA programs are commercially available and can be used for generating and evaluating large failure trees.

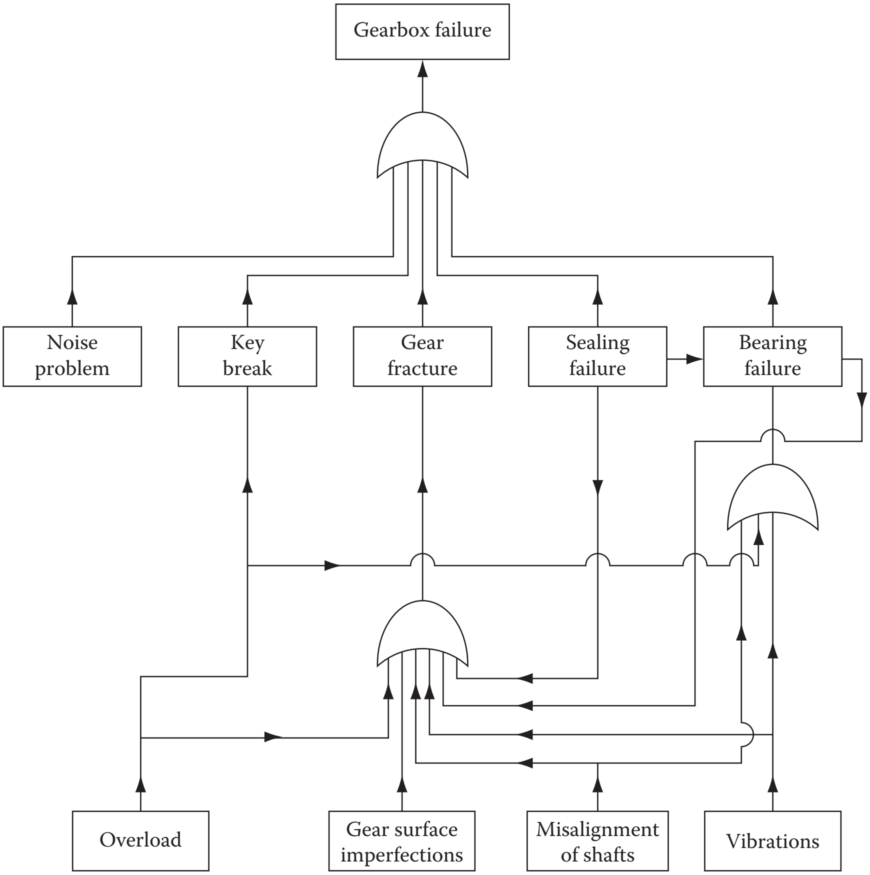


FIGURE 2.13 Simple analysis of a gearbox failure.

Case Study 2.10: Application of FTA

Problem

Use FTA to analyze the possible causes of failure in a gearbox.

Solution

Figure 2.13 gives a simple analysis of the common causes of failure that are encountered in a mechanical gearbox.

In addition to providing a qualitative view of the impact of each element on the system, FTA can be used to quantify the top event probabilities from reliability predictions of different events. In these calculations, an AND gate multiplies probabilities of failure and an OR gate acts additively. Two events that are connected by an OR

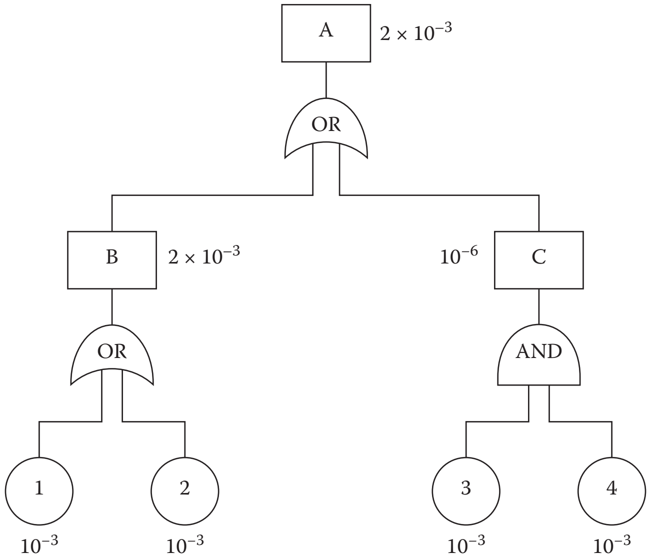


FIGURE 2.14 Sensitivity of system reliability to probabilities of failure of various components. Numbers beside each event represent probabilities.

gate will have larger contribution to the failure of the system than similar two events that are connected by an AND gate, as shown in Figure 2.14. Comparing events 1 and 2 with events 3 and 4 shows that the former events have much larger contribution to the higher event and need more accurate assessment and more care in design.

In performing an FTA, care should also be taken to identify common mode, or common cause, failures. These can lead to the failure of all paths in a redundant configuration, which practically eliminates its advantage. Examples of sources of common mode failures include

1. Failure of a power or fuel supply that is common to the main and backup units
2. Failure of a changeover system to activate redundant units
3. Failure of an item causing an overload and failure of the next item in series or the redundant unit

An indirect source of failure that should be identified in performing FTA is the enabling event. This event may not necessarily be a failure in itself but could cause a higher level failure event when accompanied by a failure. Examples of enabling events include

1. Redundant system being out of action due to maintenance
2. Warning system disabled for maintenance
3. Setting the controls incorrectly or not following standard procedures

Besides its use in design and reliability assessment, FTA can also be used as a tool in troubleshooting, failure analysis, and accident investigations.

2.8.3 Failure Logic Model

The materials failure logic model (MFLM) proposed by Marriott and Miller (1982) is based on the assumptions that

1. Material failure can be modeled as a logic sequence of elementary go/no-go events.
2. Each material failure mechanism can be characterized by a logic expression, which serves to identify that mechanism regardless of context.

The following case study is given as an example to illustrate the use of MFLM.

Case Study 2.11: Use of MFLM in Failure Analysis

Problem

Consider a welded low-carbon steel pressure vessel that failed during commissioning at less than operating load.

Solution

The failure event can be described as

$$F = A \cdot B \cdot (C1 + C2) \cdot D \cdot E \cdot G \cdot H \tag{2.8}$$

where
- A is the low-alloy steel
- B is the heat treatment defect resulting in brittle structure
- $C1$ is the welding defect
- $C2$ is the residual stress from welding
- D is the presence of corrosive environment
- E is the high residual stresses as a result of inappropriate postweld heat treatment
- G is the failure of nondestructive tests to detect initial defect
- H is the failure to detect incorrect heat treatment of material
- $(\,) \cdot (\,)$ is the Boolean AND operator
- $(\,) + (\,)$ is the Boolean OR operator

In this case, either of the following logic events could have been sufficient to cause failure:

$$F1 = A \cdot B \cdot C1 \cdot G \cdot H \tag{2.9}$$

This means that the initial defect, combined with the brittle structure, constituted a major risk:

$$F2 = A \cdot B \cdot C2 \cdot D \cdot E \cdot H \tag{2.10}$$

This means that stress corrosion cracking is likely to lead to crack growth even in the absence of initial defect.

2.8.4 Failure Experience Matrix

Collins and Daniewicz (2006) introduced the failure experience matrix as a means of storing failure information for mechanical systems. The matrix is 3D, as shown in Figure 2.15, with the axes defined as follows:

1. *Failure modes*. This axis covers the different types of failure, for example, fatigue, corrosion, and wear.
2. *Elemental mechanical functions*. This axis covers all the different functions that are normally performed by mechanical elements. Examples include supporting, force transmitting, shielding, sliding, fastening, liquid storing, pumping, and damping.
3. *Corrective actions*. This axis gives any measure or combination of steps taken to return a failed component or system to satisfactory performance. Examples of corrective actions include design change, change of material, improved quality control, change of lubricant, revised procurement specifications, and change of vendor.

This system can be computerized and could be of help to engineers in designing critical components. If the function of the component is entered, the system will give the most likely modes of failure and the corrective actions needed to avert them.

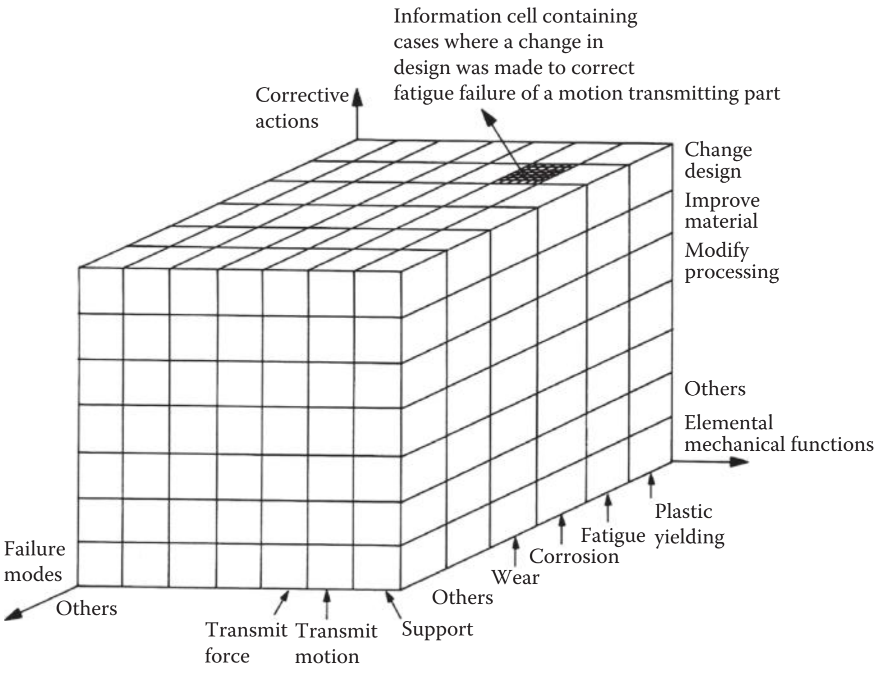


FIGURE 2.15 Part of failure experience matrix, which can be used to store failure information.

2.8.5 Expert Systems

Another technique that was proposed by Weiss (1986) uses expert systems for failure analysis. A logic program is written using LOGLISP language, which is a combination of logic, that is, predicate calculus and resolution, and LISP, which is the language usually used for artificial intelligence.

The principal ingredients for failure analysis are symptom–cause relationships and facts and rules about the system under consideration. For example, the presence of a neck is a symptom of a failure due to tensile overload. Symptoms can be related to loading, for example, tension, torsion, bending, and fatigue, and failure mode, for example, neck, dimples, shear lips, beach marks, or cleavage.

Based on the observed symptoms, the expert system program gives the possible causes of failure. Introducing more than one symptom for a given failure reduces the number of possible causes of failure. For a realistic failure analysis case, the expert system needs to interface with a material database and probably a finite element stress analysis program. More information about expert systems is given in Section 9.7.

2.9 FAILURE PREVENTION AT THE DESIGN STAGE

Anticipating the different ways by which a product could fail while still at the design stage is an important factor that should be considered when selecting a material or a manufacturing process for a given application. The possibility of failure of a component can be analyzed by studying on-the-job material characteristics, the stresses and other environmental parameters that will be acting on the component, and the possible manufacturing defects that can lead to failure. The various sections of the analysis include the following:

1. *Environmental profile*. This provides a description of the expected service conditions that include operating temperature and atmosphere, radiation, presence of contaminants and corrosive media, other materials in contact with the component and the possibility of galvanic corrosion, and lubrication.
2. *Fabrication and process flow diagram*. Such flow diagrams provide an account of the effect of the various stages of production on the material properties and of the possibility of quality control. Certain processes can lead to undesirable directional properties, internal stresses, cracking, or structural damage, which can lead to unsatisfactory component performance and premature failure in service.
3. *Failure logic models*. These models describe all possible types of failure and the conditions that can lead to those failures. In addition to its use in failure analysis, the MFLM described earlier can be interfaced with a computer-aided design system to aid the designer in the identification of potential failures.
4. The failure mode effect analysis (FMEA) provides a logical way of identifying all possible scenarios of failures of a product during the design stage and how to modify the design to avoid them. The FMEA is described in the following section.

2.10 FAILURE MODE EFFECT ANALYSIS

FMEA is a step-by-step process for identifying all possible scenarios of failures during the design of a product. The process can also be used during fabrication, assembly, shipment, or service. The process identifies the different types of possible failures and the consequences of each of them. Failures are prioritized according to how serious their consequences are, how frequently they occur, and how easily they can be detected. Actions can then be taken to eliminate or reduce such failures, starting with the highest-priority ones. FMEA can be used in conjunction with FTA, which was described in Section 2.8.2.

The FMEA process starts with identifying the different functions of the product and the expected level of performance. The product subsystems and their function and expected level of performance are then identified. For each function, the possible modes of failure and possible consequences are identified. Failure can be a result of upstream operation or can cause a downstream operation to fail. The severity of each consequence (S) is then rated on a scale of 1 to 10, with 1 being insignificant and 10 catastrophic. The possible cause of each failure is then identified and rated according to the likelihood of occurrence (O) on a scale of 1 to 10, with 1 being extremely unlikely and 10 being inevitable. The ease with which the failure can be detected (D) is then evaluated and rated on a scale from 1 to 10, with 1 being the failure can certainly be detected in time and 10 being the failure cannot possibly be detected with the available methods. The risk priority number (RPN) is then calculated as ($S \times O \times D$). Criticality is also calculated by multiplying severity by occurrence ($S \times O$). These numbers can be used to rank potential failures in the order they should be addressed. Actions to resolve the problem are then recommended. Such actions may include design or process changes or the introduction of controls to improve detection. The FMEA process is then repeated to ensure that the actions taken have resulted in reduced PRN and criticality to within acceptable limits. The following design example illustrates the application of FMEA in improving the performance of a water storage tank.

Design Example 2.12: FMEA of a Water Storage Tank

Construct a FMEA for a water storage tank. The tank consists of a welded steel shell, an inlet valve system, and an exit filter system. Table 2.5 gives an analysis of the failure modes, consequences of such failures, possible causes, and likelihood of detection. The scales described in Section 2.10 are used to evaluate RPN and criticality.

The analysis shows that clogged filter and stuck inlet valve have the highest RPN and criticality followed by cracked welds and cracked filter. Table 2.5 gives recommended actions to reduce risk of failure in various parts of the storage tank.

TABLE 2.5
Using FMEA in Designing Water Storage Tank

Product: Water storage tank
Subsystems/parts: Tank shell, inlet valve system, outlet filter system

System/Subsystem/Part	Function	Possible Failure Mode	Consequence of Failure	Severity (S)	Possible Cause of Failure	Likelihood of Occurrence (O)	Ease of Detecting Failure (D)	RPN ($S \times O \times D$)	Criticality ($S \times O$)	Action to Reduce Risk
Tank shell	Contains water	Water leak	Loss of water	7	a. Cracks in welds	a. 5	a. 7	a. 245	a. 35	a. Inspect welds
					b. General corrosion	b. 4	b. 5	b. 140	b. 28	b. Weld filler same as tank material c. Galvanic protection
Inlet valve system	Controls water entering the tank	a. Valve is not shut when tank is full.	a. Water floods surroundings.	8	a. Valve stuck open	a. 5	a. 7	a. 280	a. 40	a. Use corrosion-resistant material for valve
		b. Valve is shut when tank is empty.	b. No water supply from tank		b. Valve stuck shut	b. 5	b. 7	b. 280	b. 40	b. Better tolerance for moving valve parts
Outlet filter system	Ensures no debris in water out of tank	a. Filter does not let water through.	a. No water supply from tank	8	a. Filter clogged	a. 6	a. 6	a. 288	a. 48	a. Improve filter design
		b. Filter lets debris through.	b. Debris in water from tank		b. Filter broken	b. 4	b. 7	b. 224	b. 32	b. Use better filter material

2.11 SUMMARY

1. Causes of failure of engineering components can usually be attributed to design deficiencies, poor selection of materials, manufacturing defects, exceeding design limits and overloading, or inadequate maintenance.
2. The general types of mechanical failure include yielding, buckling, creep, wear, fracture, stress corrosion, and failure under impact loading.
3. Fracture toughness is defined as the resistance of materials to the propagation of an existing crack and is a function of the critical stress intensity factor K_{IC}. Fracture toughness is widely used as a design criterion for high-strength materials where ductility is limited. Higher values of K_{IC}/YS, where YS is the yield strength, are more desirable as they indicate tolerance to larger flaws without fracture.
4. Brittle fractures of metals are usually associated with low temperatures and usually take place at stress raisers such as sharp corners, surface defects, inclusions, or cracks. Steels and other materials that have bcc lattice are prone to brittle fracture at temperatures below the ductile–brittle transition.
5. Fatigue failures account for the largest number of mechanical failures in practice and occur in components that are subjected to fluctuating loads. The fatigue strength of most steels is usually about 0.4–0.6 times the tensile strength.
6. Creep is a major factor at high temperatures and can cause fracture at strains much less than the fracture strains in tensile tests. When the applied creep load is fluctuating, failure takes place by a combination of creep and fatigue.
7. Thermal fatigue takes place as a result of repeated changes in temperature. Faster changes in temperature, lower thermal conductivity, higher elastic constant, higher thermal expansion coefficient, lower ductility, and thicker sections encourage thermal fatigue. Ceramics are particularly prone to this type of failure.
8. Several experimental and analytical techniques are available for the analysis of failure and for predicting its occurrence at the design stage. FMEA is a step-by-step process for identifying all possible scenarios of failures and the consequences of each of them. Failures are prioritized and actions are then taken to eliminate or reduce such failures, starting with the highest-priority ones.

REVIEW QUESTIONS

2.1 K_{IC} for the aluminum alloy used in making a structure is 45 MPa $(m)^{1/2}$. If the structure contains a crack 2.5 mm long, what is the applied stress that will cause fracture? Assume $Y=1$.

2.2 If the available NDT equipment can detect internal cracks 1 mm in length or longer, determine whether or not alloy AA 7475-T651 with YS = 462 MPa and $K_{IC}=47$ MPa $(m)^{1/2}$ can be safely used to make a component that will be subjected to a tensile stress of 390 MPa. Assume $Y=2$.

2.3 Explain the difference between alternating stress and fluctuating stress cycles. Which one of these loading modes is encountered in the motorcar rear axle and the connecting rod of an internal combustion engine?

2.4 Why is fatigue failure a potentially serious problem in many welded steel structures? What are the best ways of avoiding such failure?

2.5 A manufacturer of sports equipment is considering the possibility of using fiber-reinforced plastics (FRPs) in making racing bicycle frames. It is expected that fatigue failures of the joints could be a problem in this case. Describe a design and testing program that can solve this problem.

2.6 Use FTA to analyze the possible causes of failure of a motorcar to start.

2.7 Maraging 300 and AISI 4340 ($T=260°C$) steels are being considered for making a structure. If the available NDT equipment can only detect flaws greater than 3 mm in length, can we safely use either of these alloys for designing a component that will be subjected to a stress of 600 MPa? Use the information in Table 4.7 and take $Y=1$.

2.8 Construct an FMEA table for a flashlight.

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3 Corrosion, Wear, and Degradation of Materials

3.1 INTRODUCTION

Engineering materials, to varying degrees, are susceptible to degradation as a result of interaction with the environment in which they serve. Such degradation can be classified into three main categories:

1. Corrosion and oxidation
2. Wear
3. Radiation damage

Corrosion may be defined as the unintended destructive chemical or electrochemical reaction of a material with its environment. Metallic, polymeric, and ceramic materials are susceptible to attack from different environments, and although the corrosion of metals is electrochemical in nature, the corrosion of other materials usually involves chemical reaction.

Oxidation represents a direct chemical reaction between the material and oxygen. There are various mechanisms for building up an oxide layer on the material surface. For some metals, such as pure aluminum, the oxide layer is strong and impervious and provides protection against further oxidation. For others, such as plain-carbon steels, the oxide layer is weak and porous and is not protective.

The nature, composition, and uniformity of the environment and the attacked surface can greatly influence the type, rate, and extent of attack. In addition, externally imposed changes and changes that occur as a result of corrosion and oxidation processes themselves are known to influence the type and rate of attack. Corrosion and oxidation frequently lead to failure of engineering components or render them susceptible to failure by some other mechanisms. The rate and extent of corrosive attack that can be tolerated in a certain component depend on the application. For example, in many structural applications, some uniform corrosion or oxidation can be allowed, while in food-processing equipment, for instance, even a minute amount of metal dissolution is not tolerated.

Wear is another form of material degradation that is usually mechanical, rather than chemical, in nature. The material is removed from the surface by the mechanical action of another solid or liquid. The rate of wear is usually accelerated in the presence of corrosion.

Radiation can cause damage to all types of materials. The nature of damage varies with the nature of radiation. Damage by ultraviolet (UV) radiation is principally encountered in polymers. In nuclear reactors, damage to the construction materials occurs by the bombardment of neutrons. Although damage takes place on the atomic scale, it generally leads to large-scale changes in strength and ductility.

The goal of this chapter is to illustrate how engineering materials degrade as a result of environmental attack and the measures that can be taken to prevent or delay the harmful effects of degradation. The main objectives are to

1. Review the electrochemical principles of corrosion and to use them to describe the different types of corrosion in metallic materials
2. Examine the combined effect of stress and corrosion on the behavior of materials in service
3. Discuss the corrosion of polymers and ceramics
4. Examine how metallic materials oxidize in service
5. Describe widely used methods of corrosion control
6. Discuss the different types of wear and radiation damages

3.2 ELECTROCHEMICAL PRINCIPLES OF METALLIC CORROSION

In the case of metallic materials, where corrosion takes place by electrochemical attack, the corroding metal is the anode in a galvanic cell, and the cathode can be another metal, a conducting nonmetal, or an oxide, as shown in Figure 3.1. The reaction can be written as

$$M \rightarrow M^{n+} + ne^- \tag{3.1}$$

where M stands for the metal atom which emits n electrons and becomes a positive ion.

In oxygen-free liquids, such as stagnant water or HCl, the cathode-reduction reaction results in the evolution of hydrogen, usually called the hydrogen electrode:

$$2H^+ + 2e^- \rightarrow H_2 \tag{3.2}$$

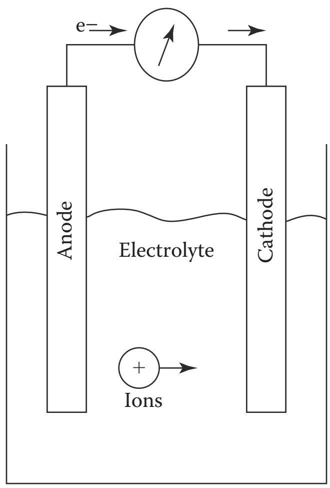

FIGURE 3.1 Electrochemical cell.

In aerated water, oxygen is available and an oxygen electrode is formed:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (3.3)$$

This reaction enriches the electrolyte in OH^- ions that react with the metal ions, M^{n+}, to form a solid product. For example, Fe^{2+} combines with two OH^- ions to form $Fe(OH)_2$ or rust.

When two metals are placed in a galvanic cell, one of them assumes the role of the anode, and the other assumes the role of the cathode based on their relative tendency to ionize. For example, iron becomes the anode when placed with copper in a galvanic cell because of its stronger tendency to ionize. However, iron becomes the cathode when placed with zinc in the galvanic cell because of the stronger tendency of zinc to ionize. Table 3.1 ranks some common metals and alloys in order of their tendency to ionize in seawater. This galvanic series is a useful guide to design engineers in predicting the relative behavior of electrically connected metals and alloys in marine applications. Figure 3.2 shows examples of galvanic corrosion, in which dissimilar metals are unwisely placed in contact in the presence of an electrolyte.

Corrosion by galvanic action can also take place in a single electrode as a result of local variations in metal composition or ion concentration in the electrolyte. For example, if a piece of iron is immersed in oxygenated water, ferric hydroxide, $Fe(OH)_3$, will form at microscopic local anodes as shown in Figure 3.3. In this case, the anodic reaction is

$$Fe \rightarrow Fe^{2+} + 2e^- \quad (3.4)$$

The reaction at the local cathode is

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (3.5)$$

The overall reaction is obtained by adding the two reactions 3.4 and 3.5 to give

$$2Fe + 2H_2O + O_2 \rightarrow 2Fe^{2+} + 4OH^- \rightarrow 2Fe(OH)_2 \quad (3.6)$$

The ferrous hydroxide is further oxidized to ferric hydroxide to give the red color of iron rust:

$$2Fe(OH)_2 + H_2O + \frac{1}{2}O_2 \rightarrow 2Fe(OH)_3 \quad (3.7)$$

3.3 TYPES OF METALLIC CORROSION

Corrosion of metallic materials may occur in a number of forms, which differ in appearance.

TABLE 3.1
Position of Some Metallic Materials in the Galvanic Series Based on Seawater

Protected, noble, or cathodic end
Platinum
Gold
Graphite
Titanium
Silver
Chlorimet 3 (61 Ni, 18 Cr, 18 Mo)
Hastelloy C (62 Ni, 17 Cr, 15 Mo)
Inconel 625 (61 Ni, 21.5 Cr, 9 Mo, 3.6 Nb)
Incoloy 825 (21.5 Cr, 42 Ni, 3 Mo, 30 Fe)
Type 316 stainless steel (passive)
Type 304 stainless steel (passive)
Type 410 stainless steel (passive)
Monel alloy 400 (66.5 Ni, 31.5 Cu)
Inconel alloy 600 (passive) (76 Ni, 15.5 Cr, 8 Fe)
Nickel 200 (passive) (99.5 Ni)
Leaded tin bronze G, 923, cast (87 Cu, 8 Sn, 4 Zn)
Silicon bronze C65500 (97 Cu, 5 Al)
Admiralty brass C44300, C44400, C44500 (71 Cu, 28 Zn, 1 Sn)
Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
Inconel 600 (active)
Nickel 200 (active)
Naval brass C46400 to C46700 (60 Cu, 39.25 Zn, 0.75 Sn)
Muntz metal C28000 (60 Cu, 40 Zn)
Tin
Lead
Type 316 stainless steel (active)
Type 304 stainless steel (active)
Lead–tin solder (50 Sn, 50 Pb)
Cast irons
Low-carbon steels
Aluminum alloy 2117 (2.6 Cu, 0.35 Mg)
Aluminum alloy 2024 (4.5 Cu, 1.5 Mg, 0.6 Mn)
Aluminum alloy 5052 (2.5 Mg, 0.25 Cr)
Aluminum alloy 3004 (1.2 Mn, 1 Mg)
Aluminum 1100, commercial-purity aluminum (99 Al min, 0.12 Cu)
Galvanized steel
Zinc
Magnesium alloys
Magnesium
Corroded, anodic, least noble end

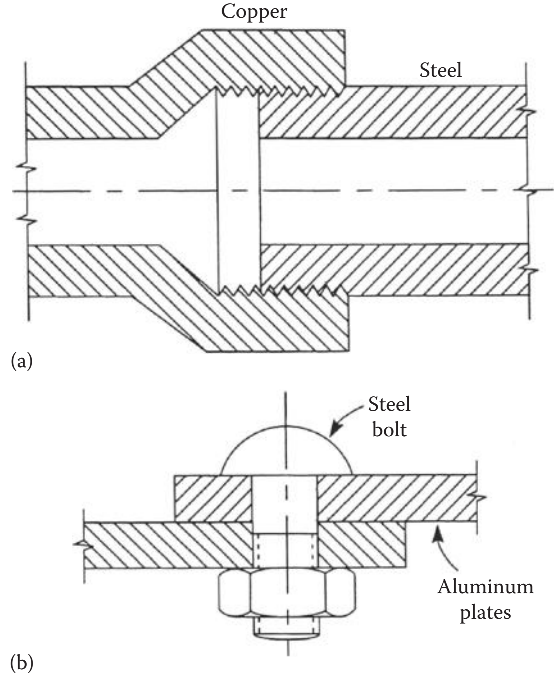

FIGURE 3.2 Examples of galvanic corrosion between dissimilar metals in contact with one another in the presence of an electrolyte. (a) Copper and iron with the fluid inside the tubes as the electrolyte. (b) Aluminum and steel with water from rain, splash or condensation as the electrolyte.

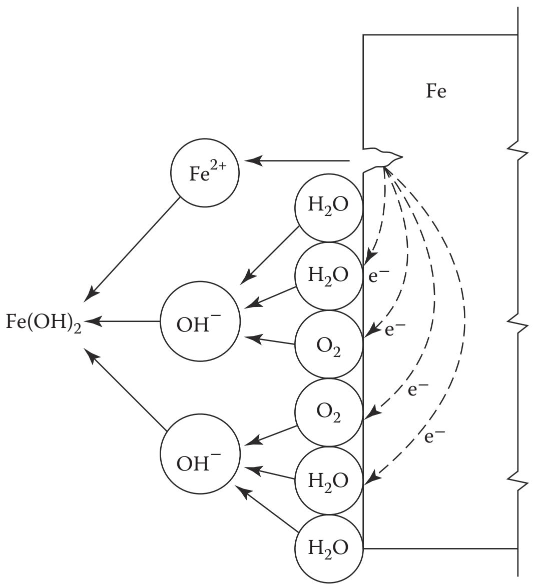

FIGURE 3.3 Corrosion of iron in water containing oxygen.

3.3.1 General Corrosion

General or atmospheric corrosion of metals is probably the most commonly encountered and the most significant, in terms of economic losses, form of corrosion. When a metal is exposed to the atmosphere, its surface is covered with a thin layer of condensed or adsorbed water, even at relative humidity <100%, and this layer can act as the electrolyte. The presence of industrial contaminants in the atmosphere increases the corrosion rate. Examples are dust, sulfur dioxide, and ammonium sulfate. Sodium chloride is also an impurity, which is present in marine atmospheres, and it increases the corrosion rate.

General corrosion does not usually lead to sudden or unexpected failure, but gradual reduction in thickness needs to be taken into account during the design stage, as illustrated in Example 3.1.

Design Example 3.1: Effect of General Corrosion on Service Life

Problem

The rate of corrosion of a steel tank is measured regularly and is approximately constant, 50 $mg/dm^2/day$. What is the useful life of the tank if the initial thickness is 10 mm and the minimum safe thickness is 6 mm?

Solution

Taking the density of steel as 7.8 g/cc, the weight loss = 0.050 g = $10 \times 10 \times 7.8 \times t$, and t = the thickness loss per day = 6.41×10^{-5} cm = 6.41×10^{-4} mm,

$$\text{Useful life} = \frac{10-6}{t} = 6.24 \times 10^3 \text{ days} = 17 \text{ years}$$

3.3.2 Galvanic Corrosion

When dissimilar metals are in electric contact in an electrolyte, the less noble metal becomes the anode in the galvanic cell and is attacked to a greater extent than if it were exposed alone. The more noble metal becomes the cathode and is attacked to a lesser extent than if it were exposed alone. The severity of galvanic corrosion depends on the separation of the two metals in the galvanic series (Table 3.1). In most cases, metals from one group can be coupled with one another without causing a substantial increase in the corrosion rate.

Another factor that affects the severity of galvanic corrosion is the relative areas of the anodic metal to the cathodic metal. Because the density of current is higher with small anode, a steel rivet in a copper plate will be more severely corroded than a steel plate containing a copper rivet.

Galvanic corrosion can also take place between two different areas of a structure, which is made of the same metal and immersed in the same electrolyte, if the contact areas are at different temperatures. For a steel structure in contact with dilute aerated chloride solution, the warmer area is anodic to the colder area, whereas for copper in aqueous salt solution, the warmer area is cathodic to the colder area.

If a structure, which is made of the same material, is in contact with two different concentrations of an electrolyte, concentration–cell corrosion will take place. This type of attack is known to take place in buried metals as a result of their being in contact with soils that have different chemical compositions, especially with respect to the concentration of sodium chloride, sodium sulfate, and organic acids. Differences in water contents or degrees of aeration can also be detrimental. Corrective action in such cases usually involves coating of the buried metal in asphalt, enclosing in a concrete trough, or adopting cathodic protection.

Design Example 3.2: Avoiding Galvanic Corrosion

Problem

Plain-carbon steel bolts, which were used to fasten an aluminum roof truss, exhibited severe corrosive attack:

1. How would you explain this problem?
2. What action would you recommend to avoid this problem?

Analysis

According to the galvanic series in Table 3.1, steel should be protected since it is higher than aluminum. However, with the tendency of aluminum to form strong nonporous oxide film, the galvanic couple is actually between Al_2O_3 and steel, with steel being the anode. The corrosion rate of the steel bolts is increased as a result of their small area compared with the cathode.

Solution

It is recommended to use high-strength aluminum alloy fasteners. Although aluminum fasteners are more expensive than steel bolts, they are expected to give a longer trouble-free service.

3.3.3 Crevice Corrosion

Crevice corrosion occurs within confined spaces or crevices formed when components are in close contact. A crevice at a joint between two metallic surfaces or between a metallic and nonmetallic surface provides conditions for concentration–cell corrosion, as shown in Figure 3.4. The area of the metallic surface just inside the crevice becomes anodic and suffers faster attack than other surfaces as a result of the oxygen concentration difference in the two locations. For crevice corrosion to occur, the crevice must be wide enough to allow liquid to enter but sufficiently narrow to keep the liquid stagnant.

Crevice corrosion occurs under gaskets, rivets, and bolts and under porous deposits. This type of corrosion is called poultice corrosion when it occurs beneath the shielded areas caused by mud splashes and road debris thrown by motorcar tires on

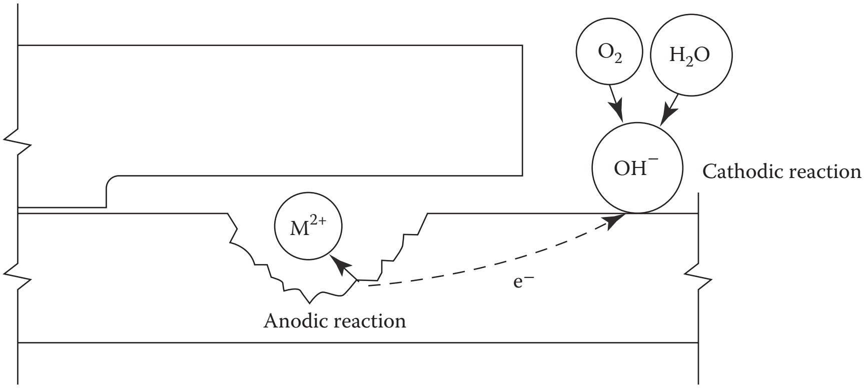

FIGURE 3.4 Crevice corrosion as a result of differences in concentration.

the underside of the fenders and other parts of the car body. Crevice corrosion occurs in many metallic materials including carbon and stainless steels and titanium, aluminum, and copper alloys.

Crevice corrosion can be minimized by taking appropriate precautions in design and manufacture of components and assemblies. These include using weldments instead of rivets, application of passivation compounds such as chromates and nitrates to surfaces, using nonabsorbent gaskets, and provision of complete drainage in vessels where stagnant solutions may accumulate. Cathodic protection and addition of corrosion inhibitors to bulk solutions could also be effective in preventing crevice corrosion.

3.3.4 Pitting Corrosion

Pitting is a form of localized attack that produces pits or holes in a metal. Pitting corrosion occurs when one area of the surface becomes anodic with respect to the rest of the surface due to segregation of alloying elements or inclusions in the microstructure. Surface deposits that set up local concentration cells, dissolved halides that produce local anodes by rupture of the protective oxide film, or mechanical ruptures in protective organic coatings are also common sources of pitting corrosion. Differences in ion and oxygen concentrations create concentration cells, which can also initiate pits.

Failure due to pitting can occur unexpectedly because of its localized nature. Pits may also contribute to the initiation of fatigue cracks in components subjected to fatigue by acting as notches.

Selection of materials with adequate pitting resistance is among the measures that can be taken to avoid failures. For example, titanium and type 316 stainless steel have better pitting corrosion resistance than type 304 stainless steel.

3.3.5 Intergranular Corrosion

Intergranular attack is another type of localized corrosion, which takes place at grain boundaries when they become more susceptible to corrosion than the bulk of the grains.

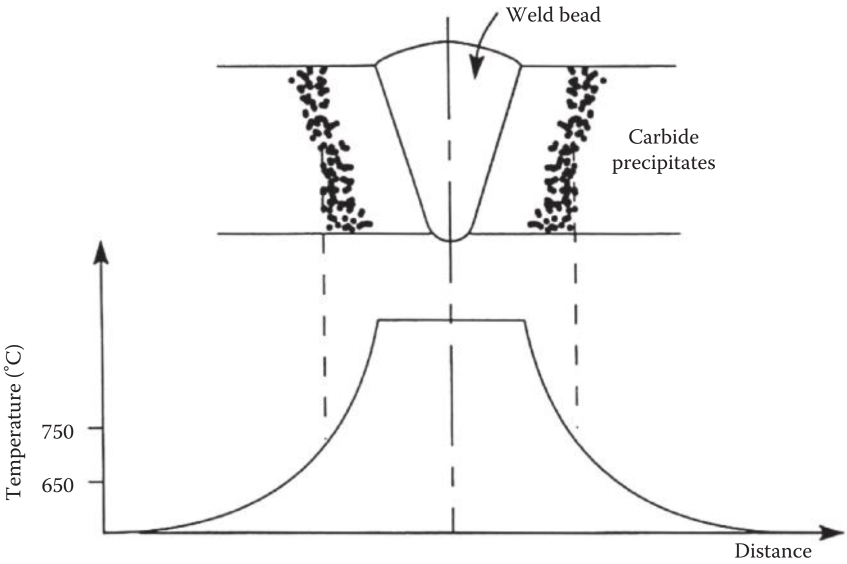

FIGURE 3.5 Corrosion of a sensitized stainless steel near the weld area.

Intergranular attack is often strongly dependent on the mechanical and thermal treatment given to the alloy. For example, unstabilized stainless steels are susceptible to intergranular corrosion when heated in the temperature range of 550°C–850°C (1000°F–1550°F). In this sensitizing temperature range, chromium combines with carbon to form chromium carbides, which precipitate at the grain boundaries, and this depletes the neighboring areas of chromium. In many corrosive environments, the chromium-depleted areas are attacked. Intergranular attack may take place in welded joints in the areas that were heated to the sensitizing temperature range, as shown in Figure 3.5. Dissolving chromium carbides by solution heat treatment at 1060°C–1120°C (about 1950°F–2050°F) followed by water quenching eliminates sensitization. Susceptibility of stainless steels to sensitization can also be reduced by reducing the carbon content to <0.03% as in the case of extra-low-carbon grades, for example, 304L, or by adding sufficient titanium and niobium to combine with all the carbon in the steel, for example, 347 or 321 stainless steels. The following case study illustrates how intergranular corrosion occurs in practice and how to avoid it.

Design Example 3.3: Failure of an Exhaust Pipe Assembly

Failure Analysis

An exhaust pipe assembly of a racing motorcar was found to be cracked at the toe of a weld between a pipe and flange after one season of racing. Examination of the cracked surface with a magnifying lens showed signs of brittle fracture, and no measurable deformation and microscopic examination of polished and etched samples of the fractured pipe revealed relatively large precipitates, some of which were connected by cracks at the grain boundaries in the heat-affected zone. Chemical analysis gave the following results: C = 0.15%, Cr = 18%, and Ni = 9%, which are close to AISI 302 stainless steel.

Conclusion

Failure took place as a result of intergranular corrosion as a result of Cr depletion near chromium carbide precipitates.

Recommended Action

After welding of the exhaust pipe assembly, heat to a temperature of 1100°C to dissolve chromium carbides and cool rapidly by quenching in water.

3.3.6 Selective Leaching

Some alloys are susceptible to selective leaching, or dissolution, where the less corrosion-resistant element is removed by corrosion. Common examples include dezincification, where zinc is removed from brasses, and graphitic corrosion or graphitization, where iron is removed from gray cast irons. The severest attack occurs when the dissolved material is present as a continuous phase. There may be a little change in the geometry of the component, but the mechanical properties are severely reduced and unexpected fracture could occur. Dezincification can be minimized by changing to a brass with lower zinc content (85% Cu, 15% Zn) or to cupronickel (70%–90% Cu, 10%–30% Ni).

3.4 COMBINED ACTION OF STRESS AND CORROSION

During their service life, components may be subjected to corrosion in addition to the normal stresses they are designed to bear. Experience has shown that the corrosion rate of some materials is accelerated as a result of stress. In some cases, chemical attack does not take place in the absence of stresses.

3.4.1 Stress Corrosion Cracking

Stress corrosion cracking (SCC) occurs in some alloys as a result of the combined effect of tensile stresses and chemical attack. The stresses involved in SCC can be either due to normal service loads or due to residual stresses resulting from manufacturing and assembly processes. Examples of manufacturing processes, which could lead to residual stresses, include casting, welding, cold forming, and heat treatment.

Normally, a threshold stress is required for SCC to occur, and shorter lives are expected with higher stresses. This threshold stress may be as low as 10% of the yield stress and is not usually a practical design stress. The susceptibility of an alloy to SCC is often a function of the content of major alloying elements, such as nickel and chromium in stainless steels and zinc in brasses. Increasing the strength is also known to increase the susceptibility to SCC.

Another important factor that affects the occurrence of SCC is the environment. The presence of certain ions, even in small concentrations, can be detrimental to some alloys but not to others. For example, stainless steels crack in chloride environments but not in ammonia-containing environments, whereas brasses crack in ammonia-containing environments but not in chlorides.

In the presence of certain chemicals and under the influence of stress, some plastics can fail by gradual cracking. This is known as environmental stress cracking. For example, polyethylenes suffer environmental stress cracking in detergents and oils.

SSC may be reduced or prevented by using one or more of the following methods:

1. Lowering the stress below the threshold value by eliminating residual stresses and reducing externally applied stresses.
2. Eliminating the critical environmental species, such as ammonia with copper alloys, seawater with austenitic stainless steels, and caustic with carbon steels.
3. Selecting the appropriate alloy. For example, carbon steels, rather than stainless steels, are often used in the construction of heat exchangers used in contact with seawater. This is because carbon steels are more resistant to SCC although they are less resistant to general corrosion than stainless steels.
4. Applying cathodic protection, as discussed in Section 3.7.
5. Adding inhibitors to the system, as discussed in Section 3.7.
6. Applying protective coatings, as discussed in Section 4.9.
7. Introducing residual compressive stresses in the surface by processes such as shot peening to avoid residual tensile stresses, which increase SCC.

3.4.2 Corrosion Fatigue

Corrosion fatigue is caused by the combined effects of fluctuating stresses and corrosive environment. Unfavorable environments cause fatigue cracks to be initiated within fewer cycles and increase the crack growth rate, thus reducing the fatigue life. For example, the fatigue strength of smooth samples of high-strength steel in saltwater can be as little as 12% of that in dry air as shown in Table 6.4. Under saltwater conditions, the smooth surface is attacked, creating local stress raisers that make the initiation of fatigue cracks much easier. Saltwater also increases crack growth rate in steels. However, austenitic stainless steels and aluminum bronzes retain about 75% of their normal fatigue strength when tested in seawater.

Under corrosion fatigue conditions, the frequency of the stress cycle, the shape of the stress wave, the stress ratio, as well as the magnitude of the cyclic stress and the number of cycles affect the fatigue life. Generally, corrosion fatigue strength decreases as the stress frequency decreases, because this allows more time for interaction between the material and environment. This effect is most important at frequencies of <10 Hz. The temperature, pH, and aeration of the environment affect the corrosion fatigue life.

Many of the methods used to reduce or eliminate SCC can also be used to combat corrosion fatigue. Among the possible methods are the following:

1. Reducing the applied stress by changing the design and eliminating tensile residual stresses
2. Introducing residual compressive stresses in the surface, to avoid tensile stresses, which increase corrosion fatigue
3. Selecting the appropriate materials
4. Using corrosion inhibitors
5. Applying protective coatings

3.4.3 Erosion Corrosion

Erosion corrosion can be defined as the acceleration of the rate of corrosion in a metallic material under wear and abrasion conditions. Metallic surfaces that have been subjected to erosion corrosion are characterized by the appearance of grooves, valleys, pits, and other means of surface damage, which usually occur in the direction of motion.

The increased corrosion rate in carbon steel pipes conveying sand slurries and similar sludge is believed to be due to the removal of the surface rust by the abrasive action of the hard suspended particles, thus allowing easy access of dissolved oxygen to the corroding surface.

3.4.4 Cavitation Damage

Cavitation damage occurs in a metallic surface where high-velocity liquid flow and pressure changes exist, as in the case of pump impellers and ship propellers. The damage is caused as a result of the formation and collapse of air bubbles or vapor-filled bubbles in the liquid near the surface. It has been shown that localized pressures as high as 400 MPa (60,000 psi) can be generated as a result of collapsing vapor bubbles. Such pressures are capable of removing surface films or even tearing metal particles away from the surface. Cavitation damage increases the corrosion and wear rates.

3.4.5 Fretting Corrosion

Fretting corrosion takes place between mating surfaces that are subjected to sliding and vibrations, as in the case of shafts and bearings. The damage appears as grooves or pits surrounded by corrosion products, which have been torn loose by the wearing action. Damage is accelerated as more debris accumulate and act as an abrasive between the two surfaces.

3.5 CORROSION OF PLASTICS AND CERAMICS

Plastics and ceramics do not corrode in the same way as metals since they are electric insulators. They do not suffer any of the damage caused by corrosion in metals. In many cases, plastic parts can be used to insulate metal parts from corrosive interaction. However, plastics and ceramics can suffer chemical reaction, dissolution, or absorption, depending on the type of material and the nature of solution.

3.5.1 Corrosion of Plastics

Plastics are only slightly affected by the atmosphere but can be affected by sunlight. Plastic coatings degrade and crack as they lose their plasticizers and cross-link by oxygen. UV radiation from sunlight accelerates this degradation.

Plastics are generally resistant to water, but there is a small percentage of water absorption except for Teflon. Polyethylene, acrylics, and polyester are less absorbent than others (Table 3.2).

Plastics show a wide variation in their resistance to chemicals, but most of them are resistant to weak acids and alkalis. Strong acids, strong alkalis, and organic solvents attack certain plastics, as shown in Table 3.2. An important rule in predicting the performance of plastics in organic solvents is that "like dissolves like." For example, straight-chain polymers tend to dissolve in straight-chain solvents such as ethyl alcohol, whereas those with benzene rings tend to dissolve in benzene and other aromatic solvents. Table 3.3 gives the effect of some chemicals on the strength of selected plastics. Increasing the molecular weight and crystallinity decreases the attack by organic solvents. The most resistant plastics are Teflon, polyethylene, and vinyl.

TABLE 3.2
Relative Chemical Stability of Selected Polymeric Materials

Material	Water Absorption[a]	Weak Acids	Strong Acids	Weak Alkalis	Strong Alkalis	Organic Solvents
Thermoplastics						
Fluoroplastics	0	5	5	5	5	5
Polyethylene	0.01–0.02	5	2	5	5	5
Polyvinylidene chloride	0.04–0.10	5	3	5	5	3
Vinyl chloride	0.45	5	3	5	3	2
Polycarbonate	—	5	3	5	3	2
Acrylics	0.03	3	3	5	3	1
Polyamides (nylon)	1.5	3	1	5	3	3
Acetals	—	2	1	2	1	5
Polystyrene	0.04	3	1	3	1	1
Cellulose acetate	3.80	3	1	3	1	2
Thermosets						
Epoxy	0.10	5	3	5	5	3
Melamine	0.30	5	1	5	1	5
Silicones	0.15	5	3	3	2	3
Polyesters	0.01	3	1	2	1	2
Ureas	0.60	3	1	2	1	2
Phenolics	0.07–1.00	2	1	2	1	3

Note: 1, poor: rapid attack; 2, fair: temporary use; 3, good: reasonable service; 4, very good: reliable service; 5, excellent: unlimited service.

[a] After 24 h of immersion (wt.%).

TABLE 3.3
Relative Tensile Strength in Polymers after 24 h Exposure to Chemicals at 93°C

	Polyphenylene Sulfide	Nylon 6/6	Polycarbonate	Polysulfone
Hydrochloric acid (37%)	100	0	0	100
Sulfuric acid (30%)	100	0	100	100
Sodium hydroxide (30%)	100	89	7	100
Gasoline	100	80	99	100
Chloroform	87	57	0	0
Ethylene chloride	72	65	0	0
Phenol	100	0	0	0
Ethyl acetate	100	89	0	0

Source: Data based on Kuhn, H. and Medlin, D., *Advanced Materials and Processes, Guide to Engineering Materials,* Vol. 138, ASM International, Materials Park, OH, 1988.

3.5.2 Corrosion of Ceramics

Ceramics are only slightly affected by the atmosphere. The main danger is the effect of water as it enters the cracks or joints and expands on freezing. Salt in water aggravates this problem. Acids associated with air pollution could also cause damage. Nonporous ceramics are widely used for water containment, as in the case of glass-lined and enameled steel tanks, water pipes, etc.

There are wide differences in the resistance of ceramics to chemicals. Fused silica and borosilicate glasses are very resistant, but soda-lime silica glasses are slowly attacked by alkalis. Glasses are attacked by hydrofluoric acid (HF). Organic solvents have no effect on ceramics.

3.6 OXIDATION OF MATERIALS

Many materials, metallic and nonmetallic, combine with oxygen during service, especially at elevated temperatures. In the case of metals, the high-temperature oxidation is particularly important in the design of gas turbines, rocket engines, and high-temperature petrochemical equipment. Unlike electrochemical corrosion, oxidation does not require an electrolyte as part of the process.

3.6.1 Oxidation of Metals

In metals, oxidation often starts rapidly and continues until an oxide film or scale is formed on the surface. After this stage, the rate of further oxidation depends on the soundness of the oxide film. The degree of protection provided by the oxide film to the metal surface depends on several factors including the following:

1. The ratio of volume of the oxide layer to the volume of the metal used in forming it should be close to unity to avoid excessive internal stresses in the oxide layer.
2. The film should strongly adhere to the metal surface to avoid peeling off.
3. The coefficient of expansion of the oxide should be close to that of the metal to avoid excessive internal stresses in the oxide layer on cooling from the oxidation temperature.
4. The film should have low conductivity and low diffusion coefficients for metal ions and oxygen to prevent or reduce further oxidation of the metal.
5. The film should have good, high-temperature plasticity, high melting point, and low vapor pressure to avoid cracking and ensure high-temperature stability.

If the oxide film is porous and allows continuous access of oxygen to the metal surface, oxidation will continue until all the material is oxidized. Examples of such metals include sodium and potassium. The rate at which oxidation occurs, as represented by the oxide film thickness, *T*, in such cases, can be given by a linear relationship:

$$T = Kt \tag{3.8}$$

where
- K is a constant
- t is the exposure time

A parabolic relationship is observed when diffusion of ions or electrons through a nonporous oxide film is the controlling factor, as in the case of iron, copper, and nickel:

$$T = (Kt)^{1/2} \tag{3.9}$$

A logarithmic relationship is observed when the oxide film is dense, impervious, and exceptionally protective against further oxidation, as in the case of aluminum and chromium. The degree of protection provided by the oxide film increases as its thickness increases, and oxidation practically stops after a critical thickness is reached:

$$T = K \log\,(ct + 1) \tag{3.10}$$

where c is a constant.

The ratio of the volume of the oxide film to the volume of the metal used in making it is called the Pilling–Bedworth (P–B) ratio. It may be calculated from the relationship

$$\text{P} - \text{B ratio} = \frac{\text{volume of oxide produced by oxidation}}{\text{volume of metal consumed by oxidation}} = \frac{Wd}{Dw} \tag{3.11}$$

where
- W and w are the molecular weights of the oxide molecules and metal atoms, respectively
- D and d are the densities of the oxide and metal, respectively

When the P–B ratio is much less than unity, the oxide is nonprotective because it will be porous and cracked. However, if it is much greater than unity, the oxide may crack off because of the volume difference. The following example illustrates how the P–B ratio is calculated.

Design Example 3.4: Calculation of the P–B Ratio

Problem

Compare the P–B ratios of the oxidation of Al, Mg, and W and use the results to explain the behavior of their oxide layers.

Solution

The oxidation reactions can be represented by

$$4Al + 3O_2 \rightarrow 2Al_2O_3$$

$$2Mg + O_2 \rightarrow 2MgO$$

$$2W + 3O_2 \rightarrow 2WO_3$$

The molecular weights of Al, Mg, and W are 26.98, 24.32, and 183.85, and those of their oxides are 101.96, 40.32, and 231.85, respectively. The densities of Al, Mg, and W are 2.7, 1.74, and 19.25, and those of their oxides are 3.7, 3.58, and 7.3, respectively:

$$\text{P} - \text{B ratio for Al} = \frac{(101.96 \times 2.7)}{(2 \times 26.98 \times 3.7)} = 1.379$$

$$\text{P} - \text{B ratio for Mg} = \frac{(40.32 \times 1.74)}{(24.32 \times 3.58)} = 0.806$$

$$\text{P} - \text{B ratio for W} = \frac{(231.85 \times 19.25)}{(183.85 \times 7.3)} = 3.325$$

The P–B ratio for Al is close to unity and is, therefore, expected to provide better protection than that for either Mg, which is less than unity, or W, which is higher than unity. Experience substantiates these observations.

In many cases, the compositions and characteristics of oxide films can be changed by adding alloying elements to the base metal. For example, chromium, aluminum, and silicon are added to iron to modify its normally porous oxide layer and make it more protective. Materials for elevated-temperature service can also be protected against oxidation by applying protective coatings.

3.6.2 Oxidation of Plastics

Most plastics and rubbers oxidize in the presence of oxygen. Rubbers are especially susceptible to oxidation, and the process is called aging. The reaction of oxygen with rubber initially reduces elasticity and increases hardness. This is because oxygen diffuses into the structure and provides additional cross-linking. As aging proceeds, the rubber degrades and eventually loses most of its strength. The rate of aging depends on the temperature, type of atmosphere, material composition, and method of manufacture.

Oxygen may also cause depolymerization or chain scission, permitting small molecules to escape as a gas, or cause charring or even burning of the polymer at high temperatures. Polymers based on silicon rather than carbon are more resistant to oxidation and can be used at higher temperatures.

3.6.3 Oxidation of Ceramics

Most oxide ceramics are not significantly affected by oxygen, even at high temperatures. Carbides and nitrides can oxidize, which limits their use at high temperatures.

3.7 CORROSION CONTROL

Corrosion can be prevented or at least controlled by several methods. The selection of the method of control is usually influenced by the cost. For example, it may be more economical to make a certain component out of a less-expensive but less-resistant material and periodically replace it than to make it from a more-resistant material, which is also more expensive. The deleterious effects of the different types of corrosion can be eliminated or at least reduced by adopting one or more of the following preventive measures:

1. Using galvanic protection, as discussed in this section
2. Using corrosion inhibitors, as discussed in this section
3. Selecting the appropriate material, as discussed in Section 4.8
4. Using protective coatings, as discussed in Section 4.9
5. Observing certain design rules, as discussed in Section 6.7

3.7.1 Galvanic Protection

Galvanic protection methods are used to protect metallic structures and can be divided into cathodic protection and anodic protection. Cathodic protection is achieved by supplying electrons to the component to be protected. For example, the corrosion of a steel structure in an acidic environment involves the following reactions:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^- \tag{3.12}$$

$$2\mathrm{H}^+ + 2\mathrm{e}^- \rightarrow \mathrm{H}_2 \tag{3.13}$$

Supplying electrons to the steel from another source will suppress the corrosion reaction in Equation 3.12 and increase the hydrogen evolution in Equation 3.13.

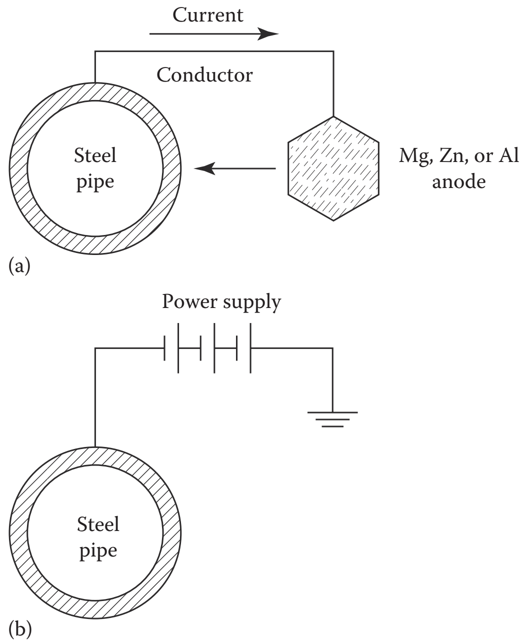

FIGURE 3.6 Cathodic protection. (a) Protection using sacrificial anode and (b) protection using impressed voltage to oppose the electrochemical potential difference.

Electrons for cathodic protection can be supplied by

1. Connecting the steel structure to a more anodic metal, sacrificial anode, such as Zn, Mg, or Al, as shown in Figure 3.6a. The sacrificial anode will corrode instead of the steel and is replaced periodically. This method is commonly used in protecting pipelines, ship hulls, and marine structures.
2. Using an external power supply to provide a voltage, which will oppose the one caused by electrochemical reaction, as shown in Figure 3.6b. This voltage stops the flow of electrons needed for the corrosion reaction to proceed.

Anodic protection can only be used for metallic materials that passivate and is based on the formation of a protective passive film on the surface to be protected by externally impressed anodic current. A potentiostat is used to control the anodic current, which is normally very small. The high installation cost is a disadvantage of this method. The following example illustrates the use of sacrificial anode in corrosion protection.

Design Example 3.5: Calculating the Life of a Sacrificial Anode

Problem

A steel ship hull is protected by a magnesium sacrificial anode weighing 3 kg. The current produced by the anode was found to be 2 A. Estimate the expected life of the Mg anode.

Solution

The weight of metal *w* lost in uniform corrosion can be estimated from Faraday's equation:

$$w = \frac{ItM}{nF} \tag{3.14}$$

where

w is the weight of metal corroded in g
I is the corrosion current in A
t is the time in s
n is the number of electrons/atoms involved in the process
M is the atomic mass of the corroding metal in g/mol
F is the Faraday's constant = 96,500 As/mol

The corrosion reaction of Mg is

$$\mathrm{Mg} \rightarrow \mathrm{Mg}^{2+} + 2\mathrm{e}^{-2}$$

From Equation 3.14,

$$\text{The expected life of the anode} = t = \frac{wnF}{IM} = \frac{3{,}000 \times 2 \times 96{,}500}{2 \times 24.31}$$

$$= 11.9 \times 10^{6}\ \mathrm{s} = 4.6\ \text{months}$$

3.7.2 Inhibitors

Adding inhibitors to a system can decrease corrosion by inhibiting the corrosion reaction at either the anode or the cathode. In many cases, the role of the inhibitor is to form an impervious, insulating film of a compound either on the anode or the cathode. Most inhibitors have been developed by empirical methods and are of proprietary nature. Adsorption inhibitors are adsorbed on the surface and form a protective film. The scavenger inhibitors react to remove corrosion agents such as oxygen from solution.

A common example of inhibitors is chromate salts in motorcar radiators. The iron ions liberated at the anode surface combine with the chromate to form an insoluble film. Many oils, greases, and waxes are adsorbed on metallic surfaces and provide temporary protection.

3.8 WEAR FAILURES

Wear can be defined as the removal of surface material and reduction of dimensions and loss of weight as a result of plastic deformation and detachment of material. This phenomenon normally occurs in components whose function involves sliding or rolling contact with other surfaces. Examples of such components include sliding and rolling bearings, gears and splines, piston rings, and breaks and clutches. Wear can also take place as a result of contact with moving liquids or gases, especially when they contain hard particles. Wear in any material can occur by a variety of mechanisms, depending on the relative motion (rolling, sliding, or a combination), service environment (dry or wet and whether abrasive particles are present), and type of motion (impact, unidirectional, or oscillating). Therefore, life under wear conditions is a function of both the wear resistance of the material and the wear system variables.

The following sections describe the different types of wear, which include adhesive wear, abrasive and erosive wear, surface fatigue, corrosive wear, erosion corrosion, and fretting. Erosion corrosion and fretting are discussed in Section 3.4. Table 3.4 shows the predominant type of wear as a function of the type of motion and service environment.

3.8.1 Adhesive Wear

Adhesive wear, also known as scoring, galling, or seizing, occurs when two surfaces slide against each other under pressure. The process involves plastic deformation

TABLE 3.4
Predominant Type of Wear as a Function of the Type of Motion and Service Environment

		Predominant Mechanism		
Type of Motion	**Environment**	**Surface Fatigue**	**Adhesive**	**Abrasive**
Pure rolling	All environments	x		
Rolling with slip	Without abrasive particles	x	x	
	With abrasive particles	x	x	x
Sliding in one direction	Dry	x	x	
	Fluid	x	x	
	With abrasive particles	x	x	x
Sliding cyclic	Dry	x	x	
	Fluid	x	x	
	With abrasive particles	x	x	x
Impact with another moving body	Dry or wet without particles	x	x	
	Dry or wet with particles	x	x	x
Impingement with fluid	Without abrasive particles	x		
	With abrasive particles	x	x	
	Streamline without particles			
	Streamline with particles		x	
	Turbulent without particles		x	
	Turbulent with particles	x	x	

Source: Bayer, R.G., Design for wear resistance, in *Materials Selection and Design, ASM Handbook*, Vol. 20, Dieter, G.E., Ed., ASM International, Materials Park, OH, 1997, pp. 603–614.

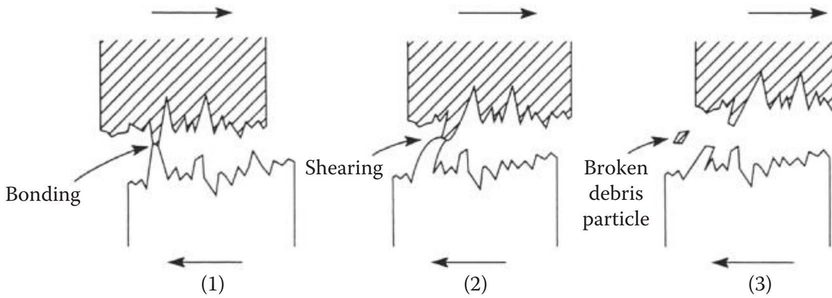

FIGURE 3.7 Schematic representation of the processes involved in adhesive wear.

followed by adhesion and then fracture of surface asperities, as shown in Figure 3.7. The fractured asperities frequently form tiny abrasive particles, which contribute to further wear of the surfaces.

The volume of material (V) removed from a surface of hardness (H) under a load (P) and a sliding distance (D) can be estimated from the relationship

$$V = \frac{kPD}{3H} \tag{3.15}$$

where k is a dimensionless quantity referred to as the wear coefficient. Representative values of k are

0.045, for low-carbon steel on low-carbon steel
0.0015, for copper on low-carbon steel
0.021, for stainless steel on stainless steel
0.00002, for phenol formaldehyde on phenol formaldehyde

Relationship 3.15 shows that the adhesive wear is reduced when the load is reduced or the hardness increased. It is also generally better to avoid contact between similar metals, since adhesion takes place more readily. Smoother surfaces will also wear at a slower rate.

Design Example 3.6: Designing for Adhesive Wear

Problem

A rotating steel shaft is supported by a sleeve bearing. Compare the rate of wear when the sleeve is (a) made of the same steel and (b) made of copper.

Analysis

Assuming that the hardness of steel is 54 R_c and the hardness of copper is 36 R_c, from Equation 3.15, the relative volume loss due to wear in (a) and (b) is given by

$$\frac{V_a}{V_b} = \frac{0.045/54}{0.0015/36} \approx 20$$

If the volume loss is taken as an indication of the expected life of the bearing, the mentioned figures indicate that using a copper sleeve will allow the bearing to last about 20 times longer than if a steel sleeve is used. Introducing a lubricant with the copper sleeve will allow the bearing life to be even longer.

3.8.2 Abrasive, Erosive, and Cavitation Wear

Abrasive wear results from contact with hard projections on a mating surface or with loose hard particles that are trapped between two surfaces. Unlike adhesive wear, no bonding occurs. This type of wear is common in earth-moving equipment, scraper blades, and crushers. Materials with high hardness exhibit better resistance to abrasive wear.

Erosion usually takes place as a result of contact with a moving fluid that contains hard particles. Erosion can also be caused by liquid impingement caused by droplets carried in a fast-moving gas.

Cavitation is a related type of wear, which occurs when a liquid containing dissolved gas enters a low-pressure region. Gas bubbles precipitate from the liquid and then subsequently collapse when the pressure increases again. The collapse of the gas bubbles sends high-pressure waves that exert high pressures against the surrounding surface. Cavitation is frequently encountered in hydraulic pumps, propellers, and dams.

3.8.3 Surface Fatigue

Surface fatigue is a special type of surface damage where parts of the surface are detached under externally applied cyclic stresses. Surface or subsurface crack formation causes particles to separate from the surface causing pitting or spalling. This is an important source of failure in rolling-contact systems such as ball bearings and railway lines.

3.8.4 Lubrication

In practice, determining the cause of wear may be difficult because failure may have resulted from the combined effect of different types of wear modes. In addition, as wear progresses, there may be a change in the predominant wear mode.

An important method of combating wear is lubrication. Many kinds of surface films can act as lubricants, preventing cold welding of asperities, and thus reducing friction and wear. Lubricants may be solid, liquid, or gas. Liquid lubricants have the advantage of combining cooling with lubricating action. In systems, which depend on lubricants to combat wear, failure of the lubricant can lead to scuffing, galling, or even seizure. Most lubricant failures occur due to chemical decomposition, contamination, or change in properties due to excessive heat. In many cases in practice, more than one of the discussed causes can be involved in lubricant failures.

Case Study 3.7: Designing for Combined Effect of Mechanical Loading, Environmental Attack, and Wear at High Temperatures

Problem

Gas turbine blades are subjected to the combined effect of mechanical loading at high temperatures, environmental attack, and erosion and wear. As a result, more than 40% of gas turbine engine failures can be attributed to blade problems. Blades need to be replaced after 25,000–30,000 h of operation at a cost of about $3 million per raw of blades.

Analysis

Failure modes in gas turbine blades operating in the hot section can be classified as follows:

a. Creep damage that can accelerate as a result of unplanned increase in operating temperature.
b. Thermal fatigue as a result of thermal stresses such as differential expansion of hot section components during start-up and shutdown operations.
c. Oxidation as a result of high-temperature exposure. Such oxide layers tend to crack and spall when the blades are subjected to vibration during engine operation and thermal cycling during start-up and shutdown.
d. Sulfidation and hot corrosion as a result of the sulfur contained in the fuel.
e. Standby corrosion during the engine shutdown as a result of the corrosive action of residuals on the blades. This surface damage can reduce fatigue life of the blades.
f. Erosion resulting from suspended particles in the hot gases.
g. Thermal overaging, especially in Ni-based superalloys, which derive their strength from gamma prime precipitates formed within the grains during manufacturing. This causes a decrease in strength and induces brittle behavior.

The aforementioned failure mechanisms can combine and cause accelerated failure of the turbine blades. For example, surface attack as a result of oxidation, sulfidation, corrosion, and erosion reduces the effective load-bearing area, which increases the effective stress and accelerates creep. In addition, overaging causes a reduction in creep resistance, which also accelerates creep.

Solution

Changes in the design of gas turbine blades can allow them to resist failure. These include the introduction of cooling channels in the blades to prolong their creep life and coating them to prevent environmental attack.

Blade cooling involves creating longitudinal channels inside the blades and ducting cooler air through them. This allowed an increase of about 100°C in the operating with the same alloy composition. Film cooling is another technique in which air is passed over the surface through small holes to give a cool boundary layer between blade and gases. The drawback of blade cooling is that it can reduce the thermal efficiency by taking too much of the heat away from the combustion chamber.

Thermal barrier coatings (TBCs) are used extensively in aircraft turbines and allow another 100°C increase in operating temperatures. Currently, the peak metal temperatures of over 1,100°C are experienced in some turbines with service lives around 10,000 h. TBCs that are based on yttria-stabilized zirconia (YSZ) can be penetrated by surface deposits such as glassy dust and sulfate salts, thus resulting in premature chipping or flaking. Using electron beam physical vapor deposition (EB-PVD) in making TBC results in less porous and longer-lasting coatings.

3.9 RADIATION DAMAGE

In many applications, materials are subjected to radiation fields as part of their service function. Examples of such applications include nuclear power generation, radiation therapy, and communication satellites. Radiation can be either electromagnetic waves or particles, as described in Table 3.5.

3.9.1 Radiation Damage by Electromagnetic Radiation

In the case of electromagnetic radiation, the radiation energy E increases with decreasing wavelength, λ, according to the relation

$$E = \frac{hc}{\lambda} \tag{3.16}$$

where

h is Planck's constant = 0.6626×10^{-33} J/s
c is the speed of light = 0.2998×10^{9} m/s

TABLE 3.5
Types and Characteristics of Radiations

Category of Radiation	Characteristics
Electromagnetic	
UV	Wavelength 1–400 nm
X-ray	Wavelength 0.001–10 nm
Γ-ray	Wavelength < 0.1 nm
Particles	
α particles	Helium nucleus (two protons + two neutrons)
β particles	Positive or negative particles with a mass of an electron

The amount of radiation damage depends on the energy of radiation, the radiation density, time of exposure, and the bond strength of the material receiving the radiation.

Electromagnetic radiation may be absorbed by the material, thus becoming a potential source of damage, or transmitted through it, thus causing no damage.

Polymers are especially susceptible to UV radiation damage. A single UV photon has sufficient energy to break the C–C bond in many linear-chain polymers. Breaking in C–C bond reduces the molecular weight and strength, encourages cross-linking, and also provides sites for oxidation. Adding carbon black or TiO_2 to polymers or applying an appropriate coating material reduces the damage caused by UV radiation.

3.9.2 Radiation Damage by Particles

In the case of metals, radiation damage caused by particles such as neutrons involves knocking atoms out of their normal lattice sites and creating interstitials and vacancies, which can collect to form dislocations. These point and line defects reduce electric conductivity and ductility and increase hardness. Annealing reduces the number of vacancies and dislocation lines and thus reduces or eliminates radiation damage.

Ceramics are also affected by particle radiation. Thermal conductivity and optical properties may be impaired. In the case of ionic bonds, the damage is similar to that in metals and can be eliminated by annealing. In the case of covalent bonds, however, the damage causes irreversible breaking of the bonds and results in modification of the structure.

3.10 SUMMARY

1. Corrosion may be defined as the unintended destructive chemical or electrochemical reaction of a material with its environment.
2. Corrosion of metallic materials may occur in a number of forms that differ in appearance. These include general corrosion, galvanic corrosion, crevice corrosion, pitting, intergranular corrosion, selective leaching, stress corrosion, corrosion fatigue, erosion corrosion, cavitation damage, and fretting corrosion.
3. Corrosion of plastics and ceramics takes place by chemical reaction. Most plastics resist a variety of chemicals but are usually attacked by organic solvents. Glasses resist most chemicals but are attacked by HF acid.
4. Corrosion can be controlled by using galvanic protection, corrosion inhibitors, material selection, and protective coatings or observing certain design rules.
5. Oxidation is the reaction between the material and oxygen. Oxidation usually starts rapidly and then slows down depending on the degree of protection provided by the oxide film. The P–B ratio, which is the ratio of volume of oxide to the volume of metal consumed by oxidation, gives a good indication of the degree of protection. Metals with P–B ratios close to unity are expected to have protective oxides.
6. Wear can be defined as the removal of surface material as a result of mechanical action. Adhesive wear, also known as scoring, galling, or seizing, occurs when two surfaces slide against each other under pressure. Abrasive and

erosive wear results from contact with hard particles. Most types of wear can be reduced by selecting a hard surface and using a lubricant.

7. Radiation damage can be the result of electromagnetic waves such as UV radiation, x-rays, γ-rays, or particles such as neutrons and α or β particles. The amount of damage depends on the energy of radiation, radiation density, time of exposure, and the bond strength of the material receiving radiation.

REVIEW QUESTIONS

3.1 What are the differences in the mechanism of corrosion protection by galvanizing and chrome plating when used for plain-carbon steels?

3.2 Discuss the mechanisms by which plastics are attacked by the environment and explain why they do not corrode in the same way as metallic materials.

3.3 The following methods are used to protect steel sheets against corrosion: galvanizing, tinning, and coating by polymeric paints. Explain the mechanism by which steel is protected.

3.4 Compare the merits of using galvanizing and tinning in protecting steel for (a) food cans and (b) outdoor fencing.

3.5 Discuss two of the methods that can be used in practice to eliminate or reduce corrosion attack. Give examples of where each method is used.

3.6 The wall thickness of a steel tank is measured monthly, and the loss in thickness is approximately the same each month, 50 mg/dm^2/day. What is the useful life of the tank, if the initial thickness is 10 mm and the minimum safe thickness is 6 mm? (Answer: 17 years)

3.7 A steel tank of 1 m diameter is made of welded AISI 1030 steel sheets of 350 MPa yield strength. The loss in thickness due to corrosion is constant and equals 50 mg/dm^2/month. If the pressure in the tank is 3.5 MPa and expected life is 10 years, what is the starting thickness of the steel sheet? Take a weld efficiency of 0.7 and a factor of safety of 2. You may treat the tank as a thin-walled container and calculate the stress in walls (σ) according to the formula $\sigma = (pr)/t$, where p is the pressure, r the radius of the tank, and t the wall thickness. What are the possible measures that can be taken to reduce the corrosion rate?

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4 Selection of Materials to Resist Failure

4.1 INTRODUCTION

In addition to design deficiencies, manufacturing defects, overloading, and inadequate maintenance, a poor selection of materials is known to be a major source of failure of engineering components in service. Generally, most widely used engineering materials have established ranges of applications and service conditions that match their capabilities. Exceeding such capabilities could lead to a failure in service. However, erring on the conservative side by underutilizing the material capabilities will usually result in uneconomic products.

The discussion in this chapter identifies the material properties that are required for a given type of loading or service environment. The different types of materials that are most suited for a given application are then examined. The objectives of the chapter are to

1. Provide an overview of how materials are grouped and identified in industry
2. Identify the material properties that are required to resist failure under mechanical loading—including static, dynamic, fatigue, and creep
3. Review the different types of materials that are most suited for resisting failure under mechanical loading
4. Identify the material properties that are required to resist failure in hostile service environments including corrosion and wear
5. Review the different types of materials that are most suited for resisting failure under corrosion and wear conditions

4.2 GROUPING AND IDENTIFYING ENGINEERING MATERIALS

4.2.1 Classification and Designation of Engineering Materials

Classification is the systematic arrangement or division of materials into groups on the basis of some common characteristics. A common way of classifying engineering materials is on the basis of their major constituent materials or internal structure. For example, ferrous materials are based on iron, aluminum alloys have a majority of aluminum in their composition, glasses are noncrystalline, and composites are mixtures of different materials. The introduction to Part I and Appendix A describes the different classes of engineering materials.

Designation is the identification of each class by a number, letter, symbol, name, or a combination thereof. Designations are developed by professional societies and organizations and are normally based on either the chemical composition or the mechanical properties. Appendix A gives some examples. The unified numbering system (UNS) has been developed by the American Society for Testing and Materials (ASTM), the Society of Automotive Engineers (SAE), and several other technical societies, trade associations, and the U.S. government agencies. The UNS number is a designation of chemical composition and consists of a letter and five numerals. The letter indicates the broad class of alloys, and the numerals define specific alloys within that class. A sample of the UNS numbering system is included in Appendix A.

It should be noted that the designation systems are not specifications but are often incorporated into specifications describing products that are made of the designated materials. A standard specification is a published document that describes the characteristics a product must have to be suitable for a certain application, as discussed in Section 5.4.

4.2.2 Considerations in Material Selection

In most engineering applications, selection of materials is usually based on one or more of the following considerations:

1. Product shape: (a) sheet, strip, or plate; (b) bar, rod, or wire; (c) tubes; (d) forgings; and (e) castings or moldings
2. Mechanical properties, as ordinarily revealed by the tensile, fatigue, hardness, creep, or impact tests
3. Physical and chemical properties such as specific gravity, thermal and electric conductivities, thermal expansion coefficient, and corrosion resistance
4. Microstructural considerations such as anisotropy of properties, hardenability of steels, grain size, and consistency of properties, that is, the absence of segregations and inclusions
5. Processing considerations such as castability, formability, machinability, weldability, and moldability
6. Esthetic qualities and environmental impact
7. Cost and availability

In the following discussion, the main types of materials are evaluated and compared on the basis of their mechanical, physical, and chemical properties. Processing considerations will be discussed in Chapter 7; economic, esthetic, and environmental considerations will be discussed in Chapter 8.

4.3 SELECTION OF MATERIALS FOR STATIC STRENGTH

4.3.1 Aspects of Static Strength

Static strength can be defined as the ability to resist a short-term steady load at moderate temperatures. This resistance is usually measured in terms of yield strength, ultimate tensile strength, compressive strength, and hardness. When the material does not exhibit a well-defined yield point, the stress required to cause 0.1% or 0.2% plastic strain, that is, the proof stress, is used instead. Most ductile wrought metallic materials are equally strong in tension and compression; brittle materials, however, are generally much stronger in compression than in tension.

Although many engineering materials are almost isotropic, there are important cases where significant anisotropy exists. In the latter cases, the strength depends on the direction in which it is measured. The degree of anisotropy depends on the nature of the material and its manufacturing history. Anisotropy in wrought metallic materials is more pronounced when they contain elongated inclusions and when processing consists of repeated deformation in the same direction. Composites reinforced with unidirectional fibers also exhibit pronounced anisotropy, which can be useful if the principal external stress acts along the direction of highest strength.

4.3.2 Level of Strength

The level of strength in engineering materials may be viewed either in absolute terms or relative to similar materials. For example, it is generally understood that high-strength steels have tensile strength values in excess of 1400 MPa (ca. 200 ksi), which is also high strength in absolute terms. Relative to light alloys, however, an aluminum alloy with a strength of 500 MPa (ca. 72 ksi) would also be designated as high-strength alloy even though this level of strength is low for steels.

From the design point of view, it is more convenient to consider the strength of materials in absolute terms. From the manufacturing point of view, however, it is important to consider the strength as an indication of the degree of development of the material concerned, that is, relative to similar materials. This is because highly developed materials are often complex, more difficult to process, and relatively more expensive compared to other materials in their class. Figure 4.1 gives the strength of some materials, both in absolute terms and relative to similar materials. In a given class of materials, the medium-strength members are usually more widely used because they generally combine optimum strength, ease of manufacture, and economy. The most developed members in a given class of materials are usually highly specialized, and, as a result, they are produced in much lower quantities. The low-strength members of a given class are usually used to meet requirements other than strength. Requirements such as electric and thermal conductivities, formability, corrosion resistance, or cost may be more important than high strength in some applications.

Frequently, higher-strength members of a given class of materials are also more expensive. Using a stronger but more expensive material could result in a reduction of the total cost of the finished component. This is because the amount of material used would be less as a result of smaller cross section, as discussed in Section 8.5.

4.3.3 Load-Carrying Capacity

The load-carrying capacity of a given component is a function of both the strength of the material used in making it and its dimensions. This means that a lower-strength material can be used in making a component to bear a certain load, provided that

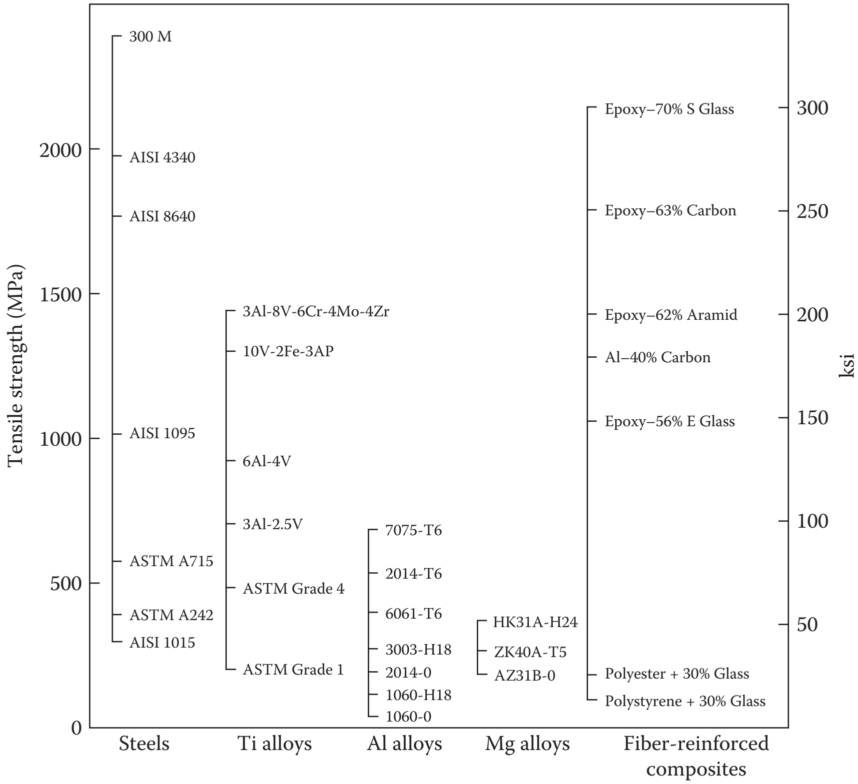


FIGURE 4.1 Comparison of some engineering materials on the basis of tensile strength.

its cross-sectional area is increased proportionally. However, the designer is not usually completely free in choosing the strength level of the material selected for a given part. Other factors like space and weight limitations could limit the choice. Space limitations can usually be solved by using stronger material, which will allow smaller cross-sectional area and smaller total volume of the component.

Weight limitations are encountered with many applications including aerospace, transport, construction, and portable appliances. The weight of a component is a function of both its volume and density. For example, the weight w of a tie-rod of cross-sectional area A and length l is given by

$$w = Al\rho = \left(\frac{L}{S}\right) l\rho \tag{4.1}$$

where

- ρ is the density of the material
- L is the applied tensile load
- S is the working strength of the material, which is equal to the yield strength of the material divided by a factor of safety, typically in the range 1.5–3

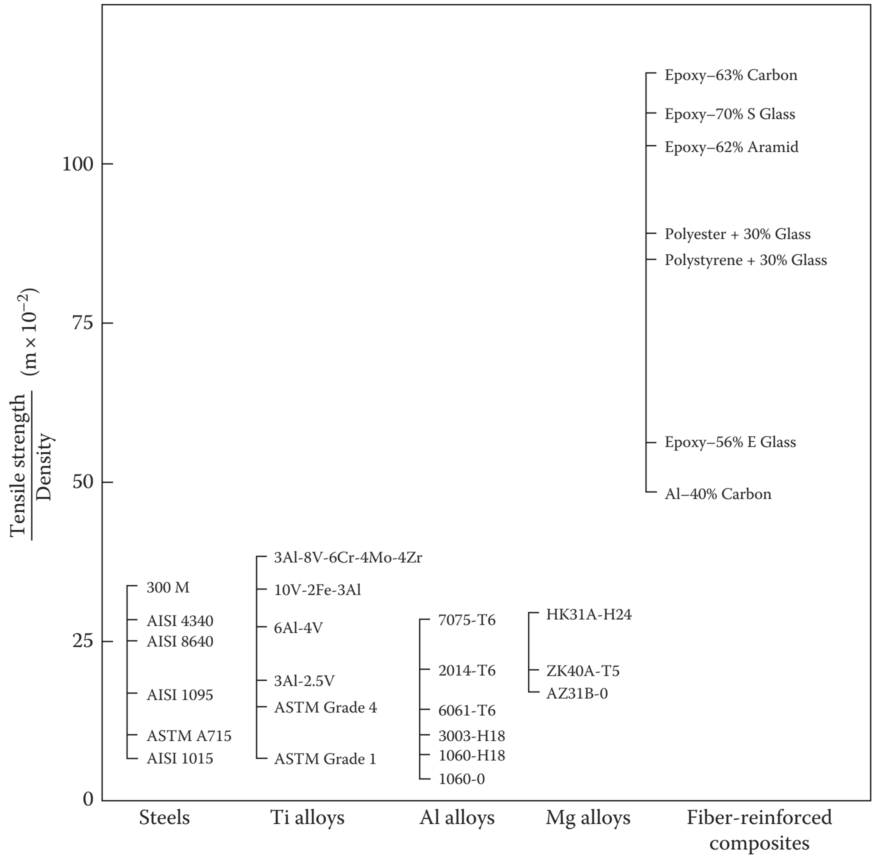


FIGURE 4.2 Comparison of some engineering materials on the basis of specific tensile strength.

Equation 4.1 shows that the weight of the tie-rod can be minimized by maximizing the ratio S/ρ, which is the specific strength of the material. In selecting a material for a tie-rod from a list of candidates, S/ρ can be used as the main performance index for comparison. The optimum material in this case is the one that has the highest S/ρ. Figure 4.2 compares the materials of Figure 4.1 on the basis of specific strength. The figure shows that the light alloys—Ti, Al, and Mg—have similar specific strengths to steel, whereas fiber-reinforced composites have a clear advantage over other materials.

Following a procedure similar to Equation 4.1, performance indices of components subjected to different types of loading can be calculated, and the results are shown in Table 4.1. The table shows that although strength and density have equal influence on the performance index in cylinders under tension, compression, or internal pressure, density has more influence in the case of flat plates, rectangular sections, and cylinders under torsion or bending since S has a power less than unity.

TABLE 4.1
Performance Indices in Selection for Static Strength

Cross Section and Loading Condition	Performance Index
Solid cylinder in tension or compression	S/ρ
Solid cylinder in torsion	$S^{2/3}/\rho$
Solid cylinder in bending	$S^{2/3}/\rho$
Solid rectangle in bending	$S^{1/2}/\rho$
Flat plate in bending	$S^{1/2}/\rho$
Flat plate under in-plane compression	$S^{1/2}/\rho$
Thin-walled cylindrical pressure vessel	S/ρ

In cases where a component carries a compressive load, reducing the cross-sectional area by choosing a strong material could cause failure by buckling due to increased slenderness of the part. Example 4.1 illustrates this point.

Design Example 4.1: Material Selection for a Compression Element

Problem

A load of 50 kN is to be supported on a cylindrical compression element of 200 mm length. As the compression element has to fit with other parts of the structure, its diameter should not exceed 20 mm. Weight limitations are such that the mass of the element should not exceed 0.25 kg. Which of the materials given in Table 4.2 is most suited for making the compression element?

Solution

Table 4.2 shows the calculated diameter of the compression element when made of different materials. The diameter is calculated on the basis of strength and buckling. The larger value for a given material is used to calculate the mass of the element. The results in Table 4.2 show that only epoxy–62% Kevlar satisfies both the diameter and weight limits.

4.4 SELECTION OF MATERIALS FOR STIFFNESS

4.4.1 Effect of Material Stiffness on Deflection under Load

Stiffness of a component can be defined as its resistance to deflection under load. In many cases, such resistance is a function of both material stiffness and geometry of the component. For example, when a load is placed on a beam, the beam is bent and every portion of it is moved in a direction parallel to the direction of the load. The distance that a point on the beam moves, deflection, depends on its position in the beam, the type of beam, and the type of supports. A beam that is simply supported at

TABLE 4.2
Comparison of Compression Element Materials

Material	Strength (MPa)	Elastic Modulus (GPa)	Specific Gravity	Diameter Based on Strength (mm)	Diameter Based on Buckling[a] (mm)	Mass Based on Larger Diameter (kg)	Remarks
Steels							
ASTM A675 grade 45	155	211	7.8	20.3	15.75	—	Reject (1)
ASTM A675 grade 80	275	211	7.8	15.2	15.75	0.3	Reject (2)
ASTM 717 grade 80	550	211	7.8	10.8	15.75	0.3	Reject (2)
Aluminum							
AA 2014-T6	420	70.8	2.7	12.3	20.7	—	Reject (1)
Plastics and Composites							
Nylon 6/6	84	3.3	1.14	27.5	44.6	—	Reject (1)
Epoxy–70% glass	2100	62.3	2.11	5.5	21.4	—	Reject (1)
Epoxy–62% Kevlar	1311	82.8	1.38	7.0	19.9	0.086	Accepted

Note: Reject (1) = material is rejected because it violates the limits on diameter; Reject (2) = material is rejected because it violates the limits on weight.

[a] Assuming that the ends of the compression element are not constrained, the Euler formula can be used to calculate the minimum diameter that will allow safe use of the compression member without buckling.

both ends suffers maximum deflection (y) in its middle when subjected to a concentrated central load (L). In this case, the maximum deflection, y, is given by

$$y = \frac{Ll^3}{48EI} \tag{4.2}$$

where

- l is the length of the beam
- E is Young's modulus of the beam material
- I is the second moment of the area of the beam cross section, with respect to the neutral axis

Equation 4.2 shows that the stiffness of a beam may be increased by increasing its second moment of area, which is computed from the cross-sectional dimensions, and by selecting a high-modulus material for its manufacture.

An important characteristic of metallic materials is that their elastic moduli are very difficult to change by changing the composition or heat treatment. However, the elastic moduli of composite materials can be changed over a wide range by changing

TABLE 4.3
Comparison of Stiffness of Selected Engineering Materials

Material	Modulus of Elasticity E (GPa)	Density ρ (mg/m³)	$(E/\rho) \times 10^{-5}$	$(E^{1/2}/\rho) \times 10^{-2}$	$(E^{1/3}/\rho)$
Steel (carbon and low alloy)	207	7.825	26.5	5.8	35.1
Aluminum alloys (average)	71	2.7	26.3	9.9	71.2
Magnesium alloys (average)	40	1.8	22.2	11.1	88.2
Titanium alloys (average)	120	4.5	26.7	7.7	50.9
Epoxy–73% E glass fibers	55.9	2.17	25.8	10.9	81.8
Epoxy–70% S glass fibers	62.3	2.11	29.5	11.8	87.2
Epoxy–63% carbon fibers	158.7	1.61	98.6	24.7	156.1
Epoxy–62% aramid fibers	82.8	1.38	60	20.6	146.6

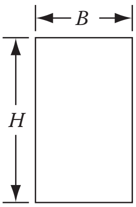
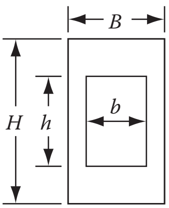
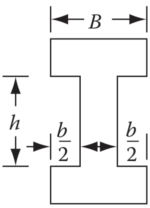
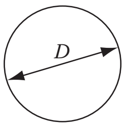
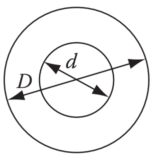
the volume fraction and orientation of the constituents. Table 4.3 gives representative values of the modulus of elasticity of some engineering materials. When a metallic component is loaded in tension, compression, or bending, Young's modulus, E, is used in computing its stiffness. When the loading is in shear or torsion, the modulus of rigidity, G, is used in computing stiffness. The relationship between these two elastic constants is given by

$$G = \frac{E}{2(1+\nu)} \tag{4.3}$$

where ν is Poisson's ratio.

The importance of stiffness arises in complex assemblies where differences in stiffness could lead to incompatibilities and misalignment between various components, thus hindering their efficiency or even causing failure. Using high-strength materials in attempts to reduce weight usually comes at the expense of reduced cross-sectional area and reduced second moment of area. This could adversely affect stiffness of the component if the elastic constant of the new strong material does not compensate for the reduced second moment of area. Another solution to the problem of reduced stiffness is to change the shape of the component cross section to achieve higher second moment of area, I. This can be achieved by placing as much as possible of the material as far as possible from the axis of bending. Table 4.4 gives the formulas for calculating I for some commonly used shapes and the values of I for constant cross-sectional area.

TABLE 4.4
Effect of Shape on the Value of Second Moment of Area (I) of a Beam in Bending

Section Shape	Formula for I	Value of I for Different Geometries		
	$\frac{BH^3}{12}$	$H/B=1$		$I=833$
		$H/B=2$		$I=1650$
		$H/B=3$		$I=2511$
		$H/B=4$		$I=3333$
 	$\frac{BH^3-bh^3}{12}$	$H=19$	$B=10$	$I=4028$
		$h=15$	$b=6$	$I=4536$
		$H=21$	$B=8$	
		$h=17$	$b=4$	
	$\frac{\pi D^4}{64}$	$D=11.29$		$I=796$
	$\frac{\pi\left(D^4-d^4\right)}{64}$	$D=20$	$d=16.5$	$I=4300$

Note: Cross-sectional area is the same in all cases and equals 100 units of area.

4.4.2 Specific Stiffness

In applications where both the stiffness and weight of a structure are important, it becomes necessary to consider the stiffness/weight, specific stiffness, of the structure. In the simple case of a structural member under tensile or compressive load, the specific stiffness is given by E/ρ, where ρ is density of the material. In such cases, the weight of a beam of a given stiffness can be easily shown to be proportional to ρ/E. The performance index in this case is E/ρ. This shows that the weight of the component can be reduced equally by selecting a material with lower density or higher elastic modulus. When the component is subjected to bending, however, the dependence of the weight on ρ and E is not as simple. From Equation 4.2 and Table 4.4, it can be shown that the deflection of a simply supported beam of square cross-sectional area is given by

$$y = \frac{Ll^3}{4Eb^4} \tag{4.4}$$

where b is the breadth or width of the beam.

The weight of the beam, w, can be shown to be

$$w = lb^2\rho = \frac{l^{5/2}}{2}\left(\frac{L}{y}\right)^{1/2}\frac{\rho}{E^{1/2}} \tag{4.5}$$

This shows that for a given deflection y under load L, the weight of the beam is proportional to $\rho/E^{1/2}$. The performance index in this case is $E^{1/2}/\rho$. As E in this case is present as the square root, it is not as effective as ρ in controlling the weight of the beam. It can be similarly shown that the weight of the beam in the case of a rectangular cross section is proportional to $\rho/E^{1/3}$ and the performance index is $E^{1/3}/\rho$, which is even less sensitive to variations in E, as shown in Table 4.3.

4.4.3 Effect of Material Stiffness on Buckling Strength

Another selection criterion, which is also related to the elastic modulus of the material and cross-sectional dimensions, is the elastic instability, or buckling, of slender components, struts, subjected to compressive loading. The compressive load, L_b, that can cause buckling of a strut is given by Euler formula as

$$L_b = \frac{\pi^2 EI}{l^2} \tag{4.6}$$

where l is the length of the strut.

Equation 4.6 shows that increasing E and I will increase the load-carrying capacity of the strut. As buckling can take place in any lateral direction, an axially symmetric cross section can be considered. For a solid round bar of diameter, D, the second moment of area, I, is given as

$$I = \frac{\pi D^4}{64} \tag{4.7}$$

The use of the resistance to buckling as a selection criterion is illustrated in Example 4.1.

The weight of a strut, w, is given by

$$w = l\frac{\pi D^2}{4}\rho = \left(\frac{2l^2 L_b^{1/2}}{\pi^{1/2}}\right)\left(\frac{\rho}{E^{1/2}}\right) \tag{4.8}$$

Equation 4.8 shows that the weight of an axisymmetric strut can be reduced by reducing ρ or by increasing E of the material, or both, with the performance index in this case being $E^{1/2}/\rho$. However, reducing ρ is more effective, as E is present as the square root. In the case of a flat panel subjected to buckling, it can be shown that the weight is proportional to $\rho/E^{1/3}$ and the performance index is $E^{1/3}/\rho$.

TABLE 4.5
Performance Indices in Selection for Stiffness

Cross Section and Loading Condition	Performance Index
Solid cylinder in tension or compression away from the buckling limit	E/ρ
Column in compression, with failure by buckling	$E^{1/2}/\rho$
Solid cylinder in torsion	$G^{1/2}/\rho$
Simply supported beam of square cross section in bending	$E^{1/2}/\rho$
Simply supported beam of rectangular cross section in bending	$E^{1/3}/\rho$
Flat plate in bending	$E^{1/3}/\rho$
Flat plate under in-plane compression	$E^{1/3}/\rho$
Thin-walled cylindrical pressure vessel	E/ρ

Following a procedure similar to the one just mentioned, the performance indices of components subjected to different types of loading can be calculated, and the results are shown in Table 4.5. The use of performance indices in making material substitution decisions is illustrated in Example 4.2.

Design Example 4.2: Material Substitution for an Interior Door Panel

Problem

A motorcar manufacturer is considering material substitution of the interior door panels of one of their models as part of a weight reduction effort. The panel is 100 cm long and 50 cm wide and is currently made of polyvinyl chloride (PVC) of 3.7 mm thickness. The candidate materials under consideration include PP + 40% glass fibers and PP + 40% flax fibers. If PVC is substituted, the new panels should have at least the same stiffness and buckling resistance.

Solution

The performance index for equal stiffness and buckling resistance of the panel is $E^{1/3}/\rho$.

The thickness of the new (t_n) and the original (t_o) panels for equal performance indices is related as

$$t_n = t_o\left(\frac{E_o}{E_n}\right)^{1/3},$$

where E_o and E_n are the moduli of elasticity of the original and new materials, respectively. Table 4.6 compares the thickness and corresponding weight of the different material considerations.

Conclusion

Panels made of PP + 40% flax fibers are lighter than the current PVC panels and can be used as a substitute.

TABLE 4.6
Comparison of Thickness and Weights of Interior Door Panels for Motorcar

Material	*E* (GPa)	ρ (g/cc)	*t* (mm)	Weight (kg)
PVC	2	1.3	3.7	1.85
PP + 40% glass fibers	7.75	1.67	2.37	3.33
PP + 40% flax fibers	4.65	1.19	2.8	1.67

Note

It is interesting to note that several car manufacturers are now using polymer-based composite materials for this application and similar components in modern cars.

4.5 SELECTION OF MATERIALS FOR HIGHER TOUGHNESS

It is now recognized that small cracks or discontinuities can exist in materials during their manufacture, processing, or service life and can lead to catastrophic failure if they exceed a critical size, as discussed in Section 2.3. It was also shown that the maximum allowable flaw size is proportional to $(K_{IC}/YS)^2$, where YS is the yield strength of the material and K_{IC} fracture toughness, which is the property of a material that allows it to withstand fracture in the presence of cracks. The ratio K_{IC}/YS can be taken as performance index when comparing the relative toughness of materials. Higher values of K_{IC}/YS are more desirable as they indicate tolerance to larger flaws without fracture.

4.5.1 Metallic Materials

There is a close relationship between toughness and other mechanical properties. Within a given class of materials, there is an inverse relationship between strength and toughness, as shown in Figure 4.3 and Table 4.7.

Generally, the toughness of a material is influenced by its chemical composition and microstructure. For example, steels become less tough with increasing carbon content, larger grain size, and more brittle inclusions. The grain size of steels is affected by the elements present, especially those used for deoxidizing. Small additions of aluminum to steel are known to promote fine grain size, which improves the toughness. Fully killed fine-grained steels also have lower ductile–brittle transition temperatures and are normally selected for applications where brittle fracture may occur. Fine grains can also be obtained in steels by using alloying elements, by controlling the rolling practice, or by normalizing treatment. A thoroughly deoxidized steel grade has fewer nonmetallic inclusions and gives better toughness. When brittle inclusions are elongated, their influence on ductility is more pronounced in the transverse and through-thickness directions.

The method of fabrication can also have a pronounced effect on toughness, and experience has shown that a large proportion of brittle fractures originate from welds

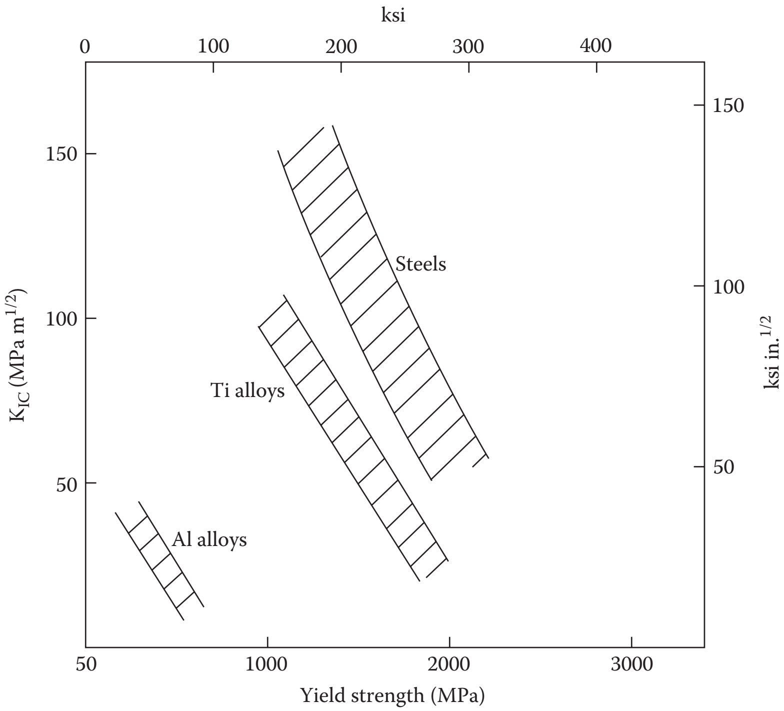


FIGURE 4.3 Variation of fracture toughness with yield strength for some alloy systems.

or their vicinity. This can be caused by the residual stresses generated by the welding process, by reduction of toughness of the heat-affected zone (HAZ), or by defects in the weld area.

The rate of load application also influences the toughness. Materials that are tough under slowly applied load may behave in a brittle manner when subjected to shock or impact loading.

Decreasing the operating temperature generally causes a decrease in toughness of most engineering materials. This is particularly important in the case of body-centered cubic (bcc) materials, as they tend to go through a ductile–brittle transition as the temperature decreases. All carbon and most alloy steels are of the bcc group, and their behavior is illustrated in Figure 4.4. Figure 4.5 shows the catastrophic failure of a welded steel ship as a result of brittle fracture under reduced service temperature. As most bcc materials become too brittle to use under cryogenic temperatures, austenitic steels and nonferrous materials of face-centered cubic (fcc) structures become the only possible materials, as they do not suffer ductile–brittle transition. Several aluminum-, titanium-, copper-, and nickel-based alloys are available for cryogenic applications.

An important aspect of selecting materials for toughness is the likelihood of detection of a crack before it reaches a critical size. As larger cracks can be more easily discovered, it follows that materials tolerating larger critical cracks are more advantageous. The materials listed in Table 4.7 are compared on the basis of

TABLE 4.7
Comparison of Toughness and Strength of Some Engineering Materials

	Yield Strength		K_{IC}		K_{IC}/YS	
	MPa	ksi	MPa m$^{1/2}$	ksi in.$^{1/2}$	m$^{1/2}$	in.$^{1/2}$
Steels						
Medium-carbon steel	260	37.7	54	49	0.208	1.30
ASTM A533B Q&T	500	72.5	200	182	0.400	2.51
AISI 4340 (T260°C)	1640	238	50	45.8	0.030	0.19
AISI 4340 (T425°C)	1420	206	87.4	80	0.062	0.388
Maraging 300	1730	250	90	82	0.052	0.328
Aluminum Alloys						
AA 2024-T651	455	66	24	22	0.053	0.333
AA 2024-T3	345	50	44	40	0.128	0.80
AA 7075-T651	495	72	24	22	0.048	0.306
AA 7475-T651	462	67	47	43	0.102	0.642
Titanium Alloys						
Ti-6Al-4V	830	120	55	50	0.066	0.417
Ti-6Al-4V-2Sn	1085	155	44	40	0.04	0.258
Ti-6Al-4Mo-2Sn-0.05Si	960	139	45	40	0.047	0.288
Plastics						
PMMA	30	4	1	0.9	0.033	0.225
Polycarbonate	63	8.4	3.3	3	0.052	0.357
Ceramics						
Reaction-bonded Si_3N_4	450	63.3	5	4.6	0.011	0.07
Al_2O_3	262	36.9	4.5	4.1	0.017	0.11
SiC (self-bonded)	140	19.7	3.7	3.4	0.026	0.173

the performance index K_{IC}/YS. The values in the table show that a material may exhibit a good crack tolerance even though its fracture toughness is modest. In general, therefore, the material selected for a given application must have such combination of K_{IC} and YS that the critical crack length is appropriate for that application and the available nondestructive testing (NDT) techniques, as illustrated in Example 4.3.

Design Example 4.3: Selecting a Material for a Light Tie-Rod

Problem

Aluminum AA7075-T651 and titanium Ti–6Al–4V are being considered for making a 1 m long tie-rod that will carry a tensile load of 50 kN. If the available NDT equipment can only detect flaws larger than 3 mm in length, which of these

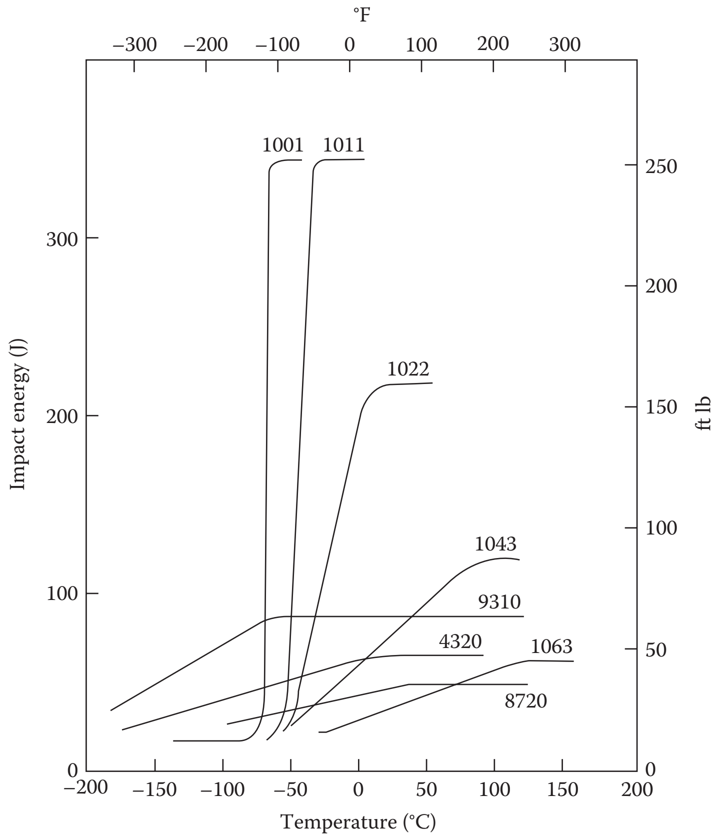


FIGURE 4.4 Effect of temperature on the notch toughness of some AISI-SAE steels.

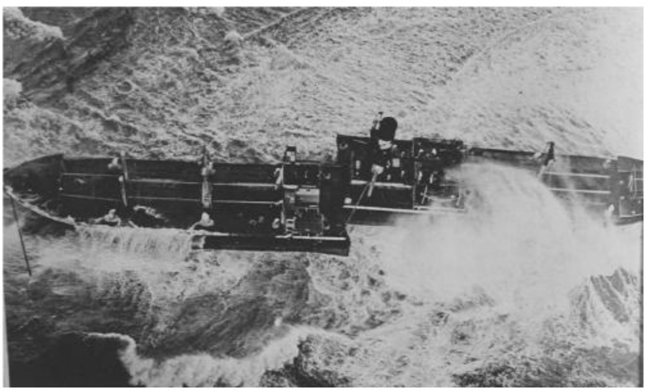


FIGURE 4.5 Catastrophic brittle fracture of a steel liberty ship at relatively low temperatures. (From Flinn, R.A. and Trojan, P.K., *Engineering Materials and Their Applications*, 4th edn., Houghton Mifflin, Boston, MA, 1990.)

two materials can be used to make a lighter member? Ignore the factor of safety in this example and assume the following:

AA7075: yield strength $\sigma_y = 495$ MPa, $K_{IC} = 24$ MPa $m^{1/2}$, specific gravity = 2.7
Ti–6Al–4V: yield strength $\sigma_y = 830$ MPa, $K_{IC} = 60$ MPa $m^{1/2}$, specific gravity = 4.5

Answer

From Equation 2.3,

$$\sigma_f = \frac{K_{IC}}{\left[Y(\pi a)^{1/2}\right]}$$

where
a is half the crack length
σ_f is the fracture stress
Y is 1
σ_f for AA7075 = 338 MPa; this is lower than σ_y. For this case, σ_f should be used for calculating the cross section
σ_f for Ti–6Al–4V = 845 MPa; this is higher than σ_y. For this case, σ_y is used for calculating the cross section
Cross section of the member when made from AA7075 = 148 mm^2, weight = 400 g
Cross section of the member when made from Ti–6Al–4V = 60 mm^2, weight = 270 g

Conclusion

Ti–6Al–4V can be used to make a lighter member.

4.5.2 Plastics and Composites

Although unreinforced plastics generally have lower impact strength than most metallic materials, as shown in Table 4.7, numerous techniques have been developed to improve their toughness. Examples of such techniques include the following:

1. Alloying the plastic with a rubber phase or with another higher-impact plastic. Examples of this method include toughened nylons, which are alloyed with polyolefin or other polymeric modifier. An alloy of nylon and ABS combines the characteristics of both crystalline and amorphous polymers, which result in a combination of high-flow rate, high-temperature warp resistance, good-surface appearance, chemical resistance, and toughness.
2. Copolymerization to create a tougher chemical structure. This approach is used to produce less notch-sensitive polycarbonates that retain their ductility at lower temperatures.

3. Incorporating high-impact-resistance fibers. For example, PETE, nylon, and polyethylene fibers have been used to replace a portion of the glass fibers in injection-molded polyesters for automotive components.

In general, thermoplastic–matrix composites are tougher than those with thermoset matrix, which is one of the reasons why the former are being developed to replace current epoxies.

4.5.3 Ceramics

The fracture of ceramics is dependent on critical flaw size, which is a function of fracture toughness (K_{IC}). With careful processing, the average flaw size can be reduced to about 30 μm, but this may still be larger than the critical flaw size. In addition, a single flaw in the material that is larger than the critical flaw size is sufficient to cause fracture. This is why toughness data for ceramic materials are often inconsistent, and strength and toughness do not always respond in the same manner to changes in microstructure or interfacial properties. Table 4.7 lists typical toughness values of some ceramic materials.

An important technique to improve the toughness of ceramics like ZrO_2, $A1_2O_3$, and Si_3N_4 is to induce a phase transformation in the region of applied stress within the material. This absorbs energy at the tip of the advancing crack, arresting its propagation and significantly increasing both strength and toughness. Another technique is to introduce fibers to increase the toughness as a result of fiber debonding, crack deflection, or fiber pullout. Internal stresses due to the differences in thermal expansion between matrix and fibers in a composite can also provide a toughening effect.

Because ceramics are sensitive to surface damage, surface modification techniques are also being developed as a means of improving their toughness.

4.6 SELECTION OF MATERIALS FOR FATIGUE RESISTANCE

In many engineering applications, the behavior of a component in service is influenced by several other factors besides the properties of the material used in its manufacture. This is particularly true for the cases where the component or structure is subjected to fatigue loading. Under such conditions, the fatigue resistance can be greatly influenced by the service environment, surface condition of the part, method of fabrication, and design details. In some cases, the role of the material in achieving satisfactory fatigue life is secondary to the mentioned parameters, as long as the material is sound and free from major flaws. For example, if the component has welded, bolted, or riveted joints, the contribution of crack initiation stage (see Section 2.5) is expected to be small, and most of the fatigue life is determined by the crack propagation stage. Experience shows that crack propagation rate is more sensitive to continuum mechanics considerations than to material properties.

Fatigue strength of metallic materials generally increases with increasing tensile strength, as shown in Table 4.8. However, the higher the strength, the higher the notch sensitivity of the material and the greater the need to eliminate coarse

TABLE 4.8
Comparison of Static and Fatigue Strengths of Some Engineering Materials

Material	Tensile Strength		Endurance Limit		Endurance Ratio
	MPa	ksi	MPa	ksi	
Ferrous Alloys					
AISI 1010, normalized	364	52.8	186	27	0.46
1025, normalized	441	64	182	26.4	0.41
1035, normalized	539	78.2	238	34.5	0.44
1045, normalized	630	91.4	273	39.6	0.43
1060, normalized	735	106.6	315	45.7	0.43
1060, oil Q, tempered	1295	187.8	574	83.3	0.44
3325, oil Q, tempered	854	123.9	469	68	0.55
4340, oil Q, tempered	952	138.1	532	77.2	0.56
8640, oil Q, tempered	875	126.9	476	69	0.54
9314, oil Q, tempered	812	177.8	476	69	0.59
302, annealed	560	81.2	238	34.5	0.43
316, annealed	560	81.2	245	35.5	0.44
431, quenched, tempered	798	115.7	336	48.7	0.42
ASTM 20 GCI	140	20.3	70	10.2	0.50
30 GCI	210	30.5	102	14.8	0.49
60 GCI	420	61	168	24.4	0.40
Nonferrous Alloys					
AA 2011-T8	413	59.9	245	35.5	0.59
2024, annealed	189	27.4	91	13.2	0.48
6061-T6	315	45.7	98	14.2	0.31
6063-T6	245	35.5	70	10.2	0.29
7075-T6	581	84.3	161	23.4	0.28
214 as-cast	175	25.4	49	7.1	0.28
380 die-cast	336	48.7	140	20.3	0.42
Phosphor bronze, annealed	315	45.7	189	27.4	0.60
Phosphor bronze, hard drawn	602	87.3	217	31.5	0.36
Aluminum bronze, quarter hard	581	84.3	206	29.9	0.35
Incoloy 901, at 650°C (1202°F)	980	142.1	364	52.8	0.37
Udimet 700, at 800°C (1472°F)	910	132	343	49.7	0.38
Reinforced Plastics					
Polyester–30% glass	123	17.8	84	12.2	0.68
Nylon 66–40% glass	200	29	62.7	9.1	0.31
Polycarbonate–20% glass	107	15.5	34.5	5	0.32
Polycarbonate–40% glass	131	19	41.4	6	0.32

second-phase particles and to produce a more refined, homogeneous structure. Meeting these needs could require expensive metallurgical processes or the addition of expensive alloying elements. A measure of the degree of notch sensitivity of the material is usually given by the parameter q:

$$q = \frac{K_f - 1}{K_t - 1} \tag{4.9}$$

where

K_t is the stress concentration factor, which represents the severity of the notch and is given by the ratio of maximum local stress at the notch to average stress. K_t is mainly related to the geometry of the component, as discussed in Section 5.5, and is material independent

K_f is the ratio of the fatigue strength in the absence of stress concentrations to the fatigue strength with stress concentration. Unlike K_t, K_f is material dependent

The value of q is a measure of the degree of agreement between K_f and K_t and can be taken as a fatigue notch sensitivity index. Thus, as q increases from 0 to 1, the material becomes more sensitive to the presence of stress concentrations. Generally, increasing the tensile strength of the material makes it more notch sensitive and increases q. The value of q is also dependent on component size, and it increases as size increases. Therefore, stress raisers are more dangerous in larger components made from stronger materials.

4.6.1 Steels and Cast Irons

Steels are the most widely used structural materials for fatigue applications as they offer high fatigue strength and good processability at a relatively low cost. Steels have the unique characteristic of exhibiting an endurance limit, which enables them to perform indefinitely, without failure, if the applied stresses do not exceed this limit. Table 4.8 shows that the endurance ratio of most steels ranges between 0.4 and 0.6.

The optimum steel structure for fatigue resistance is tempered martensite, since it provides maximum homogeneity. Steels with high hardenability provide high strength with relatively mild quenching and, hence, low residual stresses, which is desirable in fatigue applications. Normalized structures, with their finer structure, give better fatigue resistance than the coarser pearlitic structures obtained by annealing.

Inclusions in steel are harmful as they represent discontinuities in the structure that could act as initiation sites for fatigue cracking. Therefore, free-machining steels should not be used for fatigue applications. However, if machinability considerations make it essential to select a free-machining grade, leaded steels are preferable to those containing sulfur or phosphorus. This is because the rounded lead particles give rise to less structural stress concentrations than the other angular and elongated inclusions. By the same token, cast steels and cast irons are not recommended for critical fatigue applications. In rolled steels, the fatigue strength is subject to the same directionality as the static properties.

4.6.2 Nonferrous Alloys

Unlike ferrous alloys, the nonferrous alloys, with the exception of titanium, do not normally have an endurance limit. Aluminum alloys usually combine corrosion resistance, lightweight, and reasonable fatigue resistance. The endurance ratio of aluminum alloys is more variable than that of steels (Table 4.8), but an average value can be taken as 0.35.

Generally, the endurance ratio is lower for as-cast structures and precipitation-hardened alloys. Fine-grained inclusion-free alloys are most suited for fatigue applications.

4.6.3 Plastics

The viscoelasticity of plastics makes their fatigue behavior more complex than that of metals. In addition to the set of parameters that affect the fatigue behavior of metals, the fatigue behavior of plastics is also affected by the type of loading, small changes in temperature and environment, and method of sample fabrication. Because of their low thermal conductivity, hysteretic heating can build up in plastics causing them to fail in thermal fatigue or to function at reduced stress and stiffness levels. The amount of heat generated increases with increasing stress and test frequency. This means that failure of plastics in fatigue may not necessarily mean fracture. In flexural fatigue testing by constant amplitude of force, ASTM D671 sets an arbitrary level of stiffness—70% of the original modulus—as failure.

Some unreinforced plastics such as polytetrafluoroethylene (PTFE), polymethylmethacrylate (PMMA), and polyesterether ether ketone (PEEK) have fatigue endurance limits. At stresses below this level, failure does not occur. Other plastics, usually amorphous materials, show no endurance limit. In many unreinforced plastics, the endurance ratio can be taken as 0.2.

4.6.4 Composite Materials

The failure modes of reinforced materials in fatigue are complex and can be affected by the fabrication process when differences in shrinkage between fibers and matrix induce internal stresses. There is a growing body of practical experience, however, and some FRP are known to perform better in fatigue than some metals, as shown in Table 4.8. The advantage of FRP is even more apparent when compared on per weight basis. For example, because of its superior fatigue properties, glass-fiber-reinforced epoxy has replaced steel leaf springs in several motorcar models.

Generally, fiber-reinforced crystalline thermoplastics exhibit well-defined endurance limits, whereas amorphous-based composites do not. The higher strengths, higher thermal conductivity, and lower damping account for the superior fatigue behavior of crystalline polymers.

As with static strength, fiber orientation affects the fatigue strength of fiber-reinforced composites. In unidirectional composites, the fatigue strength is significantly lower in directions other than the fiber orientation. Reinforcing with continuous unidirectional fibers is more effective than reinforcing with short random fibers. Example 4.4 illustrates the use of fatigue strength in design.

Design Example 4.4: Selecting a Material for a Connecting Rod

Problem

Aluminum alloy AA 6061-T6, steel AISI 4340 oil Q and tempered, and polyester–30% glass fibers are being considered as a replacement for steel AISI 1025 normalized, in manufacturing a connecting rod to save weight. The connecting rod has a circular cross section and a length of 300 mm and is subjected to an alternating tensile load of 60 kN. Given the following information and assuming a derating factor of 0.4 on the fatigue strength for all alternatives, select the most suitable material:

AISI 1025: Tensile strength = 440 MPa, endurance ratio = 0.41, specific gravity = 7.8
AA 6061-T6: Tensile strength = 314 MPa, endurance ratio = 0.31, specific gravity = 2.7
AISI 4340: Tensile strength = 952 MPa, endurance ratio = 0.56, specific gravity = 7.8
Polyester–30% glass: Tensile strength = 123 MPa, endurance ratio = 0.68, specific gravity = 1.45

Answer

AISI 1025: Cross section = 832 mm^2, weight = 1.947 kg
AA 6061-T6: Cross section = 1541 mm^2, weight = 1.248 kg
AISI 4340: Cross section = 281 mm^2, weight = 0.658 kg
Polyester–30% glass: Cross section = 1793 mm^2, weight = 0.780 kg

Using steel AISI 4340 gives the lightest connecting rod, with polyester–30% glass as a close second.

4.7 SELECTION OF MATERIALS FOR HIGH-TEMPERATURE RESISTANCE

4.7.1 Creep Resistance of Metals

It is shown in Section 2.6 that creep is a major factor that limits the service life of parts and structures at elevated temperatures. Experience shows that many of the methods used to improve low-temperature strength of metallic materials become ineffective as the operating temperature approaches 0.5 T_m (T_m is the absolute melting temperature expressed in degrees Kelvin or Rankine). This is because atomic mobility is sufficient to cause softening of cold-worked structures and coarsening of unstable precipitates. At these high temperatures, the differences in creep resistance from one material to another depend on the stability of the structure and on the hardening mechanism.

The most important method of improving creep strength is to incorporate a fine dispersion of stable second-phase particles within the grains. These particles can be introduced by dispersion, as in the case of thoria particles in nickel (TD nickel), or by precipitation, as in the case of precipitation-hardened nickel alloys. To minimize particle coarsening, it is the practice to make the chemical composition of the precipitates as complex as possible and to reduce the thermodynamic driving force for coarsening by reducing the interfacial energy between the precipitates and the matrix. Precipitates at the grain boundaries are important in controlling creep rupture ductility as they control grain boundary sliding, which causes premature failure.

4.7.2 Performance of Plastics at High Temperatures

The mechanical strength of plastics at high temperatures is usually compared on the basis of deflection temperature under load (DTUL), also known as heat deflection temperature. According to ASTM D-648 specification, DTUL is defined as the temperature at which a specimen deflects 0.25 mm (0.010 in.) under a load of 455 or 1820 kPa (66 or 264 psi), when heated at the rate of 2°C/min. Generally, thermosets have higher temperature resistance than thermoplastics. However, adding glass and carbon fibers, as well as mineral and ceramic reinforcements, can significantly improve DTUL of crystalline thermoplastics such as nylon, thermoplastic polyesters, polyphenylenesulfone (PPS), and fluoroplastics. For example, at 30% glass–fiber, the DTUL of nylon 6/6 at 264 psi increases from about 71°C to 249°C (160°F–480°F).

Although several plastics can withstand short excursions to high temperatures, up to 500°C (930°F), continuous exposure can result in a dramatic drop in mechanical properties and extreme thermal degradation.

4.7.3 Widely Used Materials for High-Temperature Applications

Because operating temperature is the single most important factor that affects the selection of materials for elevated-temperature service, it is normal practice to classify temperature-resistant materials according to the temperature range in which they are expected to be used. Table 4.9 provides a summary of the widely used materials at the different temperature ranges, and the following description provides additional information.

4.7.3.1 Room Temperature to 150°C (300°F)

Most engineering metals and alloys, with the exception of lead, can be used in this temperature range. Several unreinforced thermoplastics are suitable for continuous service at temperatures above 100°C (212°F). In addition, fluoroplastics, polycarbonates, polyamides, polysulfones, polyphenylene sulfides, and the newly developed materials like PEEK and PPS can be used at temperatures up to 200°C. Several FRPs, for example, nylon 6/6–glass fiber, can also serve in this temperature range.

TABLE 4.9
Widely Used Materials for Different Temperature Ranges

Temperature Range	Widely Used Materials
Room temperature—150°C	≤100°C thermoplastics
	≤150°C most engineering metals and alloys, FRP
150°C–400°C	≤200°C high-temperature plastics (polysulfones, polyphenylene sulfides, polyethersulfone, and fluoroplastics)
	≤250°C aluminum alloys, thermosetting plastics
	≤400°C plain-carbon steels (short exposures), low-alloy steels (long exposures)
400°C–600°C	≤450°C alpha–beta titanium alloys, low-alloy steels
	≤600°C 5%–12% (Cr + Mo) steels
600°C–1000°C	≤650°C ferritic stainless steels
	≤750°C austenitic stainless steels
	≤800°C Fe–Ni-based superalloys
	≤850°C Ni-based superalloys
	≤980°C Co-based superalloys
1000°C and above	Refractory metals (Mo, Nb, Ta, W) and ceramics

4.7.3.2 150°C–400°C (300°F–750°F)

Plain-carbon or manganese–carbon steels provide adequate properties in this temperature range, although it may be necessary to use low-alloy steels if very long service, more than 20 years, is required. High-grade cast irons can be used at temperatures up to 250°C for engine casings. Aluminum alloys can be used at temperatures up to about 250°C (480°F), although some P/M alloys have been used for short intervals at about 480°C (900°F).

High-temperature plastics can be used at temperatures up to 200°C (400°F) and will withstand temperatures up to about 300°C (500°F) for short periods. These include polysulfones, polyphenylene sulfides, polyethersulfones, and fluoroplastics. Thermoset polyamides–graphite composites can serve in the range of 260°C–290°C (500°F–550°F). New experimental plastics, like polyparaphenylene benzobisthiazole, are expected to withstand temperatures up to about 370°C (700°F) for long periods.

4.7.3.3 400°C–600°C (750°F–1100°F)

Low-alloy steels and titanium alloys are the main materials used in this temperature range. Low-alloy steels are relatively inexpensive and are used if there are no restrictions on weight. The main alloying elements that are usually added to these steels include molybdenum, chromium, and vanadium. An example of such steels is the 0.2C–1Cr–1Mo–0.25V steel, which is used for intermediate- and high-pressure steam turbine rotors.

In applications at temperatures approaching 600°C (1100°F), oxidation resistance becomes an important factor in determining the performance of materials. In such cases, at least 8% chromium needs to be added to steels. Several steels are available with chromium contents in the range of 5%–12%. These steels usually also contain molybdenum to improve their creep resistance.

Titanium alloys of alpha-phase structure exhibit better creep resistance than those of beta-phase structure. The alpha–beta 6Al–4V alloy is most widely used for general purposes and is limited to a maximum operating temperature of about 450°C (840°F). The near-alpha alloy 5.5Al–3.5Sn–3Zr–1Nb–0.25Mo–0.25Si can be used at temperatures up to about 600°C (1110°F).

4.7.3.4 600°C–1000°C (1100°F–1830°F)

The most widely used materials for this temperature range can be divided into the following groups:

- Stainless steels
- Fe–Ni-based superalloys
- Ni-based superalloys
- Co-based superalloys

Oxidation and hot corrosion resistance of the mentioned alloys becomes increasingly important with increasing operating temperature. The level of oxidation resistance in this temperature range is a function of chromium content. Aluminum can also contribute to oxidation resistance, especially at higher temperatures. Chromium is also important for hot corrosion resistance. Chromium content in excess of 20% appears to be required for maximum resistance.

When the oxidation and hot corrosion resistance of a given alloy is not adequate, protective coatings may be applied. Diffusion coatings, CoAl or NiAl, are commonly used for protection. FeCrAl, FeCrAlY, CoNiAl, or CoNiAlY overlay coatings can also be used, and they do not require diffusion for their formation.

4.7.3.4.1 Stainless Steels

The ferritic stainless steels of the 400 series are less expensive than the austenitic grades of the 200 and 300 series (see Table A.7). The ferritic grades are usually used at temperatures up to 650°C (1200°F) in applications involving low stresses. Austenitic stainless steels of the 300 series can be used at temperatures up to 750°C (1380°F). Type 316 stainless steel with 2.5% Mo is widely used and has the highest stress-rupture strength of all the 300 series alloys. The more highly alloyed compositions 19-9 DL and 19-9 DX contain 1.25–1.5 Mo, 0.3–0.55 Ti, and 1.2–1.25 W. They have superior stress-rupture strengths than the 300 series alloys. These alloys can be used at temperatures up to 815°C (1500°F). Also, the 202 and 216 Cr–Ni–Mn alloys have higher stress-rupture capabilities than the 300 series alloys.

4.7.3.4.2 Fe–Ni-Based Superalloys

Fe–Ni-based superalloys consist mainly of fcc solid-solution matrix, γ phase, strengthened by intermetallic compounds and carbide precipitates. A common precipitate is gamma prime, γ', which is $Ni_3(Al,Ti)$. Other precipitates include carbides, nitrides, and carbonitrides. Table A.16 gives the composition of a representative sample of these alloys.

4.7.3.4.3 Ni-Based Superalloys

Ni-based superalloys (see Table A.16) also consist of fcc matrix strengthened by intermetallic compound precipitates. Gamma prime, γ', is used to strengthen alloys like Waspaloy and Udimet 700. Oxide dispersions are also used for strengthening, as in the case of IN MA-754 and IN MA-6000E. Other Ni-based superalloys are essentially solid-solution strengthened in addition to some carbide precipitation, as in the case of Hastelloy X. Table A.17 gives the rupture strength of selected Ni-based superalloys.

4.7.3.4.4 Co-Based Superalloys

Co-based superalloys (Table A.16) are strengthened mainly by a combination of carbides and solid-solution hardeners. In terms of strength, Co-based alloys can only compete with Ni-based superalloys at temperatures above 980°C (1800°F). Co-based superalloys are used in the wrought form, for example, Haynes 25, and in the cast form, for example, X-40. Table A.17 gives the rupture strength of selected Co-based superalloys.

4.7.3.5 1000°C (1830°F) and Above

The refractory metals Mo, Nb, Ta, and W as well as their alloys can be used for stressed applications at temperatures above 1000°C (1830°F). Table A.18 lists the composition of some commercial refractory metals and alloys. Mo-30W alloy has a melting point of 2830°C (5125°F) and excellent resistance to liquid-metal attack.

4.7.4 Niobium, Tantalum, and Tungsten

Niobium (Table A.18) can be used in contact with liquid lithium and sodium–potassium alloys at high temperatures, even above 800°C (1470°F). An addition of 1% Zr to niobium increases its resistance to embrittlement due to oxygen absorption.

Tantalum (Table A.18) can be used for structural applications at temperatures in the range of 1370°C–1980°C (2500°F–3600°F), but it requires protection against oxidation. Tantalum is also used for heat shields and heating elements in vacuum furnaces.

Tungsten (Table A.18) has the highest melting point of all materials, which makes it the obvious candidate for structural applications at very high temperatures. Molybdenum is added to tungsten to improve its machinability, and rhenium is added to improve resistance to cold fracture in lamp filaments. Surface protection is an important obstacle to the widespread use of refractory metals in high-temperature oxidizing environments. Various aluminide and silicide coatings are available commercially, but they all have a maximum temperature limit of about 1650°C (3000°F).

4.7.5 Ceramics

Ceramics (Table C.1) can withstand extremely high temperatures and are being increasingly used for structural applications. Creep resistance, thermal conductivity, thermal expansion, and thermal-shock resistance are the major factors that determine the suitability of a ceramic material for high-temperature applications. Creep resistance of many ceramics is affected by intergranular phases. Because crystalline phases are generally more creep resistant than amorphous ones, it is the usual practice to reduce the amorphous intergranular phases as a means of improving creep resistance. Doping can also be used to improve the strength of grain boundary phases, as in the case of doping Si_3N_4 with Y_2O_3 and ZrO_2. Silicon-based ceramics have lower thermal expansion coefficient, which helps in improving their thermal-shock resistance. However, this may not be an advantage if the ceramic is used as a coating on metals where a large difference in expansion may present difficulties.

Thermal-shock resistance is a function of thermal conductivity, coefficient of thermal expansion, tensile strength, and modulus of elasticity. For structural ceramics, thermal-shock resistance is dependent on both material type and processing method. For example, silicon nitride (Si3N4) has a better thermal-shock resistance when hot-pressed than when reaction sintered. Generally, silicon carbide (SiC) and tungsten carbide have better thermal-shock resistance than zirconium oxide and aluminum oxide. Si3N4 has good thermal-shock resistance and good oxidation resistance, which make it a feasible candidate for service temperatures of about 1200°C (2192°F) in gas turbines.

Case Study 4.5: Developing Materials and Processes to Resist Failure of Gas Turbine Blades

Problem

Analysis in Case Study 3.7 has shown that blades in the hot section of gas turbines are subject to the combined effects of mechanical loading at high temperature, which results in creep damage and thermal fatigue, and environmental attack, which causes oxidation, sulfidation, corrosion, and erosion.

Analysis

The combined effect of high-temperature exposure and stress causes thermal overaging, which causes a decrease in strength and induces brittle behavior with a resulting accelerated creep rate and rupture. In addition, surface attack as a result of oxidation, sulfidation, corrosion, and erosion decreases the effective load-bearing area, which increases the effective stress and causes further acceleration of creep. Case Study 3.7 discussed blade cooling and thermal barrier coating that are used to extend the life of gas turbine blades. This case study illustrates how materials and processes can be improved to achieve the same objective.

Solutions

Attempts have been made to overcome the aforementioned material problems and have resulted in the development of several new material systems and manufacturing techniques. Some of these solutions are more developed and are being used on an industrial scale, while others are still in the development stage. Examples include the following:

Directionally solidified materials: As the presence of grain boundaries makes the blade alloys susceptible to creep and cracking under the high temperatures and stresses acting on the blades, directional solidification (DS), and single crystal (SX) techniques were developed to reduce or eliminate the amount of grain boundaries. In DS, grains are aligned longitudinally with no transverse grain boundaries, which makes the blades stronger in the direction of the applied stress. DS and SX are obtained by controlling the solidification process during the casting of the blades. Using DS blades allows about 25°C increase in the turbine operating temperatures. SX blades improved the creep and thermal-shock resistance even further and allowed an additional 25°C increase in operating temperature. DS of eutectic alloys is another development in which second-phase compounds of a eutectic system are aligned in the maximum stress direction along the blade length.

Monolithic ceramic and intermetallic blades: SiC and Si3N4 families of ceramics are considered for turbine blades because of their better thermal-shock resistance due to their low thermal coefficient of expansion, high strength, and moderate thermal conductivity. Si3N4 material is capable of retaining room-temperature strength of 140 MPa up to operating temperatures of 1400°C. These materials can be fabricated to near-net shape either by reaction-bonding or hot-pressing techniques at costs competitive with the forged, DS or SX, blades. A major drawback of SiC and nitride components is their sensitivity to macroscopic flaws that are bigger than 150 μm. This problem can be solved by improving the densification of the sintered part by hot isostatic pressing (HIP). Ceramics are strong competitors to conventional turbine blades as they allow operating temperatures up to about 1370°C with uncooled configurations. Intermetallic materials such as TiAl or Ti3Al have relatively low density and high operating temperature. Their specific strength is superior to Ni-based superalloys.

Metal–matrix composites (MMCs): High-strength Ti-based MMCs are suitable candidates for turbine blades, and they have the potential for weight reduction of up to 50% relative to conventional Ti alloys. High-modulus continuous fibers of SiC about 0.1 mm in diameter are used for the reinforcement of the Ti matrix. The SiC fibers are coated with a carbon layer, to prevent extensive reaction between the fiber and the matrix, and then coated with the Ti matrix using plasma or PVD. The coated fibers are consolidated using HIP.

Ceramic–matrix composites (CMCs): The relatively low fracture toughness of the monolithic ceramic materials can be improved by incorporating SiC or Al_2O_3 fibers in a matrix of SiC, Al_2O_3, or a mixture of both. A drawback of non-oxide fibers is their potential for chemical reaction with the ceramic–matrix at operating temperatures >1000°C for several hundred hours.

Conclusion

The solutions given in Case Study 3.7 and the aforementioned solutions can be combined to produce improved gas turbine blades for industrial applications. Case Study 9.4 compares the materials discussed here and selects the optimum candidates for use in aerospace and auxiliary power generation applications.

4.8 SELECTION OF MATERIALS FOR CORROSION RESISTANCE

Although corrosion resistance is usually the main factor in selecting corrosion-resistant materials, it is often difficult to assess this property for a specific application. This is because the behavior of a material in a corrosive environment can be dramatically changed by seemingly minor changes in the medium or the material itself. The main factors that can affect the behavior of the material can be classified as follows:

- Corrosive medium parameters
- Design parameters
- Material parameters

4.8.1 Corrosive Medium Parameters

Corrosive medium parameters include

1. Chemical composition and presence of impurities
2. Physical state whether solid, liquid, gas, or combinations
3. Aeration, oxygen content, and ionization
4. Bacteria content

In the case of metallic materials, the most significant factor controlling the probability of atmospheric corrosion is whether or not an aqueous electrolyte is provided by condensation of moisture under prevailing climatic conditions. Hot and dry as well as cold and icy conditions give less attack than wet conditions. Clean atmosphere is less aggressive than industrial or marine atmospheres containing sulfur dioxide and salt, respectively. Direction of exposure to the sun, wind, and sources of pollution can also affect the rate of atmospheric corrosion.

In buried structures, increasing the porosity of the soil and the presence of water raises the rate of corrosion. In addition to allowing continuing access of oxygen to the corroding surface, porosity also encourages the activity of aerobic bacteria, which can lead to local variation in aeration, consumption of organic protection systems, and production of corrosive H_2S. In general, dry, sandy, or chalky soils of high electric resistance are the least corrosive, whereas heavy clays and saline soils are the most corrosive.

The rate of corrosion of underwater structures is affected by the amount of dissolved oxygen as well as the amount of dissolved salts and suspended matter. Since oxygen enters the water by dissolution from the air, its concentration can vary with depth and flow rate. Soft freshwater is generally more corrosive than hard water, which precipitates a protective carbonate on the corroding surface. In seawater, the presence of chloride ions increases the electric conductivity and, therefore, the rate of corrosion. The presence of organic matter, such as bacteria or algae, in water can decrease the rate of corrosion in the covered areas but produce regions of local deaeration where accelerated attack occurs. Increasing the water temperature generally increases the rate of attack. In chemical plants, the rate of attack depends on several factors including the temperature, concentration of chemicals, fluid velocity, degree of aeration, purity of the metal, and applied stresses. In general, the attack is severest where protective or oxide films are disrupted or become locally unstable.

4.8.2 Design Parameters

The design parameters that affect the rate of corrosive attack include the following:

1. Stresses acting on the material in service
2. Operating temperature
3. Relative motion of medium with respect to the material
4. Continuity of exposure of the material to the medium
5. Contact between the material and other materials
6. Possibility of stray currents
7. Geometry of the component

Combating corrosion by design is discussed in Section 6.7.

4.8.3 Material Parameters

The main parameters that affect the corrosion resistance of materials include chemical composition and the presence of impurities, nature and distribution of microstructural constituents, surface condition and deposits, and processing history. Generally, the corrosion resistance improves in pure metals as their purity increases. An example is the localized attack in commercially pure aluminum due to the presence of iron impurities. Table 4.10 shows the relative corrosion resistance of some commonly used metallic materials under different service conditions.

4.8.4 Carbon Steels and Cast Irons

Carbon steels and cast irons are used in large quantities because of their useful mechanical properties and low cost. These materials, however, are not highly corrosion resistant, with the exception of resistance to alkalis and concentrated sulfuric acid, as shown in Table 4.10. Low-carbon steels have adequate resistance to scaling in air up to about 500°C (ca. 930°F), but this temperature is reduced in the presence of sulfur in flue gases. The addition of chromium in amounts of about 3% increases the resistance to both oxidation and sulfide scaling. Chromium additions also improve resistance to atmospheric corrosion. Nickel is also added to improve the resistance to sodium hydroxide.

4.8.5 Stainless Steel

Stainless steels represent a class of highly corrosion-resistant materials and have widespread applications in engineering. It should be remembered, however, that stainless steels do not resist all corrosive environments, as shown in Table 4.10. For example, when subjected to stresses in chloride-containing environments, stainless

TABLE 4.10
Relative Corrosion Resistance of Some Uncoated Metallic Materials

Material	Industrial Atmosphere	Fresh Water	Seawater	Acids H_2SO_4 5%–15% Concentration	Alkalis 8%
Low-carbon steel	1	1	1	1	5
Galvanized steel	4	2	4	1	1
GCI	4	1	1	1	4
4%–6% Cr steels	3	3	3	1	4
18–8 stainless steel	5	5	4	2	5
18–35 stainless steel	5	5	4	4	4
Monel (70% Ni–30% Cu)	4	5	5	4	5
Nickel	4	5	5	4	5
Copper	4	4	4	3	3
Red brass (85% Cu–15% Zn)	4	3	4	3	1
Aluminum bronze	4	4	4	3	3
Nickel silver (65% Cu–18% Ni–17% Zn)	4	4	4	4	4
Aluminum	4	2	1	3	1
Duralumin	3	1	1	2	1

Note: 1, poor: rapid attack; 2, fair: temporary use; 3, good: reasonable service; 4, very good: reliable service; 5, excellent: unlimited service.

steels are less resistant than ordinary structural steels. Stainless steels, unless correctly fabricated and heat treated, can also be more susceptible to localized corrosion such as intergranular corrosion, SCC, crevice corrosion, and pitting than ordinary structural steels.

Increasing chromium content in stainless steels increases their resistance. This is because corrosion resistance of stainless steels can be attributed to the presence of a thin film of hydrous oxide on the surface of the metal. The condition of the film depends on the composition of the stainless steel and the treatment it receives. To give the necessary protection, the film must be continuous, nonporous, self-healing, and insoluble in the corrosive medium. In the presence of such an oxide film, the stainless steels are passive and have solution potentials approaching those of noble metals. When passivity is destroyed, the potential is similar to that of iron, as shown in Table 3.1. Exposing stainless steels to mildly oxidizing corrosive agents causes them to become active, and increasing the oxygen concentration causes them to regain passivity. When the passive film is destroyed locally, stainless steels can fail catastrophically by localized mechanisms such as pitting, crevice corrosion, intergranular corrosion, or SCC, as shown in Example 3.3 and Case Study 4.6.

Chromium plays an important role in forming the passive film on the stainless steel surface. The presence of nickel in high-chromium steels greatly improves their resistance to some nonoxygenating media. It is also an austenite stabilizer. Manganese can be used as a substitute for part of the nickel as an austenite stabilizer, although it does not significantly alter the corrosion resistance of high-chromium steels. Molybdenum strengthens the passive film and improves resistance to pitting in seawater. Other elements such as copper, aluminum, and silicon also increase corrosion resistance of stainless steels.

Case Study 4.6: Corrosion of Welded 304 Stainless Steel Tank

Problem

A food processing welded 304 stainless steel tank exhibited considerable pitting corrosion near the welded joints after 6 months of service.

Analysis

Microscopic examination showed extensive precipitates in the affected areas. It is assumed that the precipitates are chromium carbides, which precipitated in the areas that were heated to the sensitizing temperature range (650°C–750°C). Precipitation of the carbides depleted the neighboring areas from chromium.

Solution

It is recommended that 304L stainless steel be used. With its carbon content of $<0.03\%$, there is less opportunity for chromium carbides to form during welding. Other possible solutions include using stabilized stainless steels, for example, 347 or 321.

4.8.6 Nickel

Nickel has a relatively high corrosion resistance and is particularly useful for handling caustic alkalis. Nickel resists SCC in chloride environments but may be susceptible in caustic environments if highly stressed and if it contains impurities in solution.

Inconel, 78/16/6 Ni–Cr–Fe, is resistant to many acids and has outstanding resistance to nitriding at high temperatures. Nimonic alloys, based on the 80/20 Ni–Cr basic composition, have particularly good combination of high strength and oxidation resistance at high temperatures. As shown in Table 4.10, Monel alloys, which are based on the 70/30 Ni–Cu composition, have similar resistance to pure nickel with the additional advantage of being less expensive and being able to handle seawater and brackish waters at high fluid velocities. Monel alloys present an economic means of handling hydrofluoric acid and are also resistant to other nonoxidizing acids. Monel alloys are not, however, resistant to oxidizing media such as nitric acid, ferric chloride, sulfur dioxide, and ammonia.

4.8.7 Copper

Pure copper is a noble metal and is, therefore, highly corrosion resistant. It is especially compatible with most industrial, marine, and urban atmospheres, in addition to water and seawater, as shown in Table 4.10. When copper is alloyed with zinc in concentrations more than 15%, dezincification may occur in some environments. An addition of about 1% tin can reduce this problem. Tin bronzes are resistant to a variety of atmospheres, waters, and soils. Phosphorus is added to impart oxidation resistance. Aluminum bronzes, containing about 10% Al, are resistant to corrosion from chloride–potash solutions, nonoxidizing mineral acids, and many organic acids. Cupronickels are widely used in saltwater; they have excellent resistance to biofouling and SCC.

4.8.8 Tin

Over half of the tin production is used as protective coatings of steels and other metals. In addition to its corrosion resistance, tin is nontoxic and it provides a good base for organic coatings. This explains its wide use in coating the steel cans, tin cans, used for the storage of food products and beverages. Tin is normally cathodic to iron, but the potential reverses in most sealed cans containing food products and the tin acts as a sacrificial coating, thus protecting steel. Tin is also resistant to relatively pure water and dilute mineral acids in the absence of air. This makes it suitable for coating copper pipes and sheets in contact with distilled water and medicaments. Tin is attacked by strong mineral acids and alkalis.

4.8.9 Lead

A large proportion of lead production goes into applications where corrosion resistance is important, especially those involving sulfuric acid. The corrosion resistance of lead is due to the protective sulfates, oxides, and phosphates that form on its surface as a result of reaction with corrosive environments. Lead containing about 0.06% copper is usually specified for process equipment in contact with sulfuric, chromic, hydrofluoric, and phosphoric acids. It is also used for neutral solutions, seawater, and soils. Lead is attacked by acetic, nitric, hydrochloric, and organic acids.

4.8.10 Aluminum

Aluminum is a reactive metal, but it develops an aluminum oxide film that protects it from corrosion in many environments. The film is quite stable in neutral and many acid solutions but is attacked by alkalis. The aluminum oxide film is also resistant to a variety of organic compounds, including fatty acids. This oxide film forms in many environments, but it can be artificially produced by anodization.

Pure aluminum and nonheat-treatable aluminum alloys exhibit high resistance to general corrosion but, because of their dependence on the surface oxide film, are liable to suffer local attack under deposits and in crevices. Heat-treatable alloys in the 2000 series and those in the 7000 series contain copper and exhibit lower resistance to general corrosion, as shown in Table 4.10. Such alloys are used in applications where corrosion resistance is secondary to strength. The following case study illustrates the role played by crevice corrosion in causing failure of an aircraft.

Case Study 4.7: Aloha Airlines Boeing 737-200 Failure

Problem

A Boeing 737-200 operated by Aloha Airlines lost about 6 m of the upper skin and structure of its cabin at an altitude of about 8000 m. Although the pilot managed to land the plane safely, one life was lost, and several of the 90 passengers on board suffered injuries.

Analysis

The plane was manufactured in 1969, and the accident took place in 1988 after about 36,000 flight hours and nearly 90,000 flight cycles. The fuselage was made of 0.9 mm aluminum sheets that were assembled using lap joints with three rows of rivets in addition to cold bonding with epoxy. Inspection of the joints showed that there were areas in the lap joints where bonding was not complete or where the sheets became unbounded during service. Such areas allowed most of the operating stress to transfer through the rivets, thus initiating causing fatigue cracks. In addition, moisture penetration in the unbounded areas caused crevice corrosion, which aggravated the situation further. It can be concluded that failure was the result of fatigue damage at various rived holes linking up through the areas that were weakened by crevice corrosion.

Solution

The process of cold bonding was discontinued, and periodic nondestructive inspection using eddy current to detect unbounded areas was mandated.

4.8.11 Titanium

Titanium exhibits excellent corrosion resistance because of its stable, protective, strongly adherent surface oxide film. Titanium is immune to all forms of corrosive attack in seawater and chloride salt solutions at ambient temperatures and to hot, strong oxidizing solutions. It also has very high resistance to erosion corrosion in seawater. Titanium also resists attack by moist chlorine gas, but if moisture concentration in the gas falls below 0.5%, rapid attack can result. Hydrofluoric acid is also among the substances that attack titanium by destroying the protective oxide film. An addition of alloying elements can affect corrosion resistance if they alter the properties of the oxide film.

4.8.12 Tantalum and Zirconium

Tantalum is inert to practically all organic compounds at temperatures below 150°C (300°F). Exceptions are hydrofluoric acid and fuming sulfuric acid. Zirconium is resistant to mineral acids, molten alkalis, alkaline solutions, and most organic and salt solutions. It has excellent oxidation resistance in air, steam, CO_2, SO_2, and O_2 at temperatures up to 400°C (750°F). Zirconium is attacked by corrosion in hydrofluoric acid, wet chlorine, aqua regia, ferric chloride, and cupric chloride solutions. Tantalum and zirconium will seldom be economic, but they are the only available resistant materials for a few applications.

4.8.13 Metallic Glasses

Metallic glasses, amorphous alloys, are produced by quenching from the liquid state; they have undercooled liquid structures similar to those of ceramic glasses. The compositions of these materials are adjusted to be close to low melting, stable eutectics that yield noncrystalline structures on rapid solidification. Some of the iron-based metallic glasses have corrosion resistances approaching those of tantalum or the noble metals. Typical compositions include

- 8%–20% Cr, 13% P, 7% C, remainder Fe
- 10% Cr, 5%–20% Ni, 13% P, 7% C, remainder Fe

These materials passivate very easily, and at 8% Cr, they are superior to conventional stainless steels. Their pitting resistance is equal to or greater than that of the high-nickel alloys, Hastelloy C, and titanium.

4.8.14 Plastics and Fiber-Reinforced Plastics

Because of their corrosion resistance, plastics and composites have replaced metals in many applications. Examples from the automotive industry include fenders, hoods, and other body components. However, there are several environmental effects that should be considered when selecting plastics and FRP.

Several plastics absorb moisture, which causes swelling and distortion in addition to degrading their strength and electric resistance. Polymers can also be attacked by organic solvents, as discussed in Section 3.5 and as shown in Table 3.2. Generally, crystalline thermoplastics, such as fluorocarbons, Teflon, and nylon, have superior chemical stability than amorphous types like polycarbonate. Fluorocarbons, for example, PTFE, are among the most chemically inert materials available to the engineer. They are inert to all industrial chemicals, and they resist the attack of boiling aqua regia, fuming nitric acids, hydrofluoric acid, and most organic solvents. Other thermoplastics like polyketones and polyphenylene sulfide provide excellent chemical resistance, even at relatively elevated temperatures. Among thermosetting plastics, epoxies represent the best combination of corrosion resistance and mechanical properties.

There are several standard tests for measuring the chemical resistance of polymers and FRP. The immersion test, ASTM D 543, is used extensively as it measures the changes in weight, dimensions, and mechanical properties that result from immersion in standard reagents. Table 3.3 gives the relative chemical resistance, expressed in terms of percent retention of tensile strength, of some plastics.

4.8.15 Ceramic Materials

Most ceramic materials exhibit good resistance to chemicals, with the main exception of hydrofluoric acid. Glasses are among the most chemically stable materials, and they have exceptionally good resistance to attack by water, aqueous solutions of most acids, alkalis, and salts. However, their relative performance in various environments may vary considerably between different grades. For example, borosilicate and silica glasses show much higher resistance to boiling water and hot dilute acid solution than do soda-lime and lead-alkali glasses.

Enamels, which are made of silicate and borosilicate glass with the addition of fluxes to promote adhesion, are highly resistant to corrosion and are widely used to protect steels and cast irons.

4.8.16 Other Means of Resisting Corrosion

Occasionally, no material may offer an economical combination of corrosion resistance and other performance requirements. In such cases, a low-cost base material that satisfies the mechanical and physical requirements can be selected provided that it is adequately protected against corrosion. Protection can take the form of sacrificial coatings, passivation, corrosion inhibitors, barrier coatings, or cathodic protection, as discussed in Section 3.7. Barrier coatings are also commonly used for protection against corrosion, and their selection is discussed in Section 4.9.

4.9 COATINGS FOR PROTECTION AGAINST CORROSION

Coatings are usually applied for one or more of the following purposes:

1. To modify the surface quality of color, brightness, reflectivity, or opacity
2. To provide protection against corrosion or oxidation
3. To provide protection against abrasion and wear
4. To provide electric and thermal conductivity or insulation

The following discussion is mainly concerned with the use of coatings for protection against corrosion. In such cases, protection against corrosion can be achieved in two ways:

1. Isolation of the surface from the environment
2. Electrochemical action

Isolation of the surface is usually performed by nonmetallic coatings, and in such cases, the thickness, soundness, and strength of the coating will control its effectiveness as an isolator. Nonmetallic coatings can be either inorganic, as in the case of vitreous enamels, or organic, as in the case of varnishes and lacquers. Electrochemical action is achieved with metallic coatings.

4.9.1 Metallic Coatings

The coating metal can be nobler than the base metal and thus protects it, as in the case of tin coatings on steel. However, if pores or cracks are present in the coating, more severe attack could result than if the base metal had no coating. When the coating is anodic with respect to the base metal, the coating dissolves anodically, although the base metal, which is the cathode in the galvanic cell, will not be attacked. Examples of such coatings include aluminum, cadmium, and zinc that are anodic with respect to iron. The two ways of isolation and electrochemical action can be combined by first applying an anodic coating to the base metal followed by a nonmetallic finish.

4.9.2 Organic Coatings

Organic coatings depend mainly on their chemical inertness and impermeability in providing protection against corrosion. An organic coating is made up of two principal components: a vehicle and a pigment. The vehicle contains the film-forming ingredients that dry to form the solid film. It also acts as a carrier for the pigment. Vehicles can be either oil or resin, but oils have limited industrial uses. Nearly all polymers can be used as film formers, and frequently two or more kinds are combined to give the required properties. The properties of polymers as coatings are usually similar to those of the bulk polymers.

Pigments, which may or may not be present, give the required color, opacity, and flow characteristics. They can also contribute to the protection against corrosion of the base metal and against the destructive action of UV light on the polymeric vehicle. Table 4.11 gives the relative properties of some commonly used organic coatings.

4.9.3 Vitreous Enamels

Vitreous, or porcelain, enamels are inorganic coatings applied primarily to protect metal surfaces against corrosion. The composition should be adjusted so that the coefficient of thermal expansion closely matches with that of the base metal. Two coats are usually needed. Ground coats contain oxides that promote adhesion to the metal base, cobalt or nickel oxides for steel base and lead oxide for cast iron base, and cover coats improve the appearance and properties of the coating. The composition of porcelain enamels varies widely depending on the metal base and the application. Table 4.12 gives typical compositions of some porcelain enamels for steel and cast iron.

TABLE 4.11
Rating of Organic Coatings

	Cost	Abrasion Resistance	Flexibility	Adhesion	Resistance to Atmosphere (Salt Spray)	Exterior Durability	Color Retention	Resistance to Chemicals (General)	Maximum Service (Temperature Rating)
Alkyd	3	2	3	3	1	3	1	1	1
Amine-alkyd	3	3	2	3	1	3	1	1	2
Acrylic	2	2	3	2	3	3	3	1	1
Cellulose (butyrate)	1	2	3	2	3	2	3	1	1
Epoxy	1	3	3	3	3	1	1	3	2
Epoxy ester	2	3	1	3	3	2	1	1	2
Fluorocarbon	0.5	1	1	2	3	3	1	3	2
Phenolic	2	3	1	3	3	3	0	2	2
Polyamide	2	3	1	2	1	0	2	1	2
Plastisol	3	3	3	2	3	2	1	3	1
Polyester (oil-free)	2	2	2	3	3	2	2	1	1
Polyvinyl fluoride (PVF)	0.5	3	3	2	3	3	2	3	1
Polyvinylidene fluoride (PVF2)	0.5	3	3	2	3	3	2	3	1
Silicone	1	2	1	1	3	3	3	1	3
Silicone alkyd	1	2	1	2	2	3	2	2	3
Silicone polyester	1	2	2	2	3	3	2	2	3
Silicone acrylic	1	2	1	2	2	3	3	2	3
Vinyl	2	2	3	1	3	3	2	1	1
Vinyl alkyd	2	2	2	2	2	1	2	1	1
PVC	1	3	3	3	3	2	1	3	1
Neoprene (rubber)	3	3	3	2	3	3	1	1	1
Urethane	0.5	3	3	3	3	3	1	1	2

Notes: Properties: 3, excellent; 2, very good; 1, fair; 0, poor.
Cost: 3, cheapest; 2, moderate price; 1, expensive; 0.5, very expensive.

TABLE 4.12
Acid-Resistant Porcelain Enamels for Steel and Cast Iron

	Enamel for Steel (wt.%)		Enamel for Cast Iron (wt.%)	
Constituent	**Ground Coat**	**Cover Coat**	**Ground Coat**	**Cover Coat**
SiO_2	56.44	41.55	77.7	37.0
B_2O_3	14.90	12.85	6.8	4.9
Na_2O	16.59	7.18	4.3	16.8
K_2O	0.51	7.96	—	1.7
Li_2O	0.72	0.59	—	—
CaO	3.06	—	—	2.0
ZnO	—	1.13	—	5.9
Al_2O_3	0.27	—	7.2	1.9
TiO_2	3.10	21.30	—	7.9
CuO	0.39	—	—	—
MnO_2	1.12	—	—	—
NiO	0.03	—	—	—
CO_3O_4	1.24	—	—	—
P_2O_5	—	3.03	—	—
F_2	1.63	4.41	—	—
PbO	—	—	4.0	8.8
Sb_2O_3	—	—	—	13.1

4.10 SELECTION OF MATERIALS FOR WEAR RESISTANCE

The main factors that influence the wear behavior of a material can be grouped as

1. Metallurgical variables, including hardness, toughness, chemical composition, and microstructure
2. Service variables, including contacting materials, contact pressure, sliding speed, operating temperature, surface finish, lubrication, and corrosion

Although the performance of a material under wear conditions is generally affected by its mechanical properties, wear resistance cannot always be related to one property. In general, wear resistance does not increase directly with tensile strength or hardness although if other factors are relatively constant; hardness values provide an approximate guide to relative wear behavior among different materials. This is particularly true for applications involving metal-to-metal sliding. In such cases, increasing the hardness increases wear resistance as a result of decreasing penetration, scratching, and deformation. Increasing toughness also increases wear resistance by making it more difficult to tear off small particles of deformed metal.

Because wear is a surface phenomenon, surface coatings and treatments play an important role in combating it. Surface coatings consist of wear-resistant materials that are applied to the surface, as discussed in Section 4.11. Surface treatment avoids

TABLE 4.13
Surface Hardening Treatments for Steels

Process	Treatment	Applications
Flame hardening	Heat the surface using torch, then quench	Hardened depth is 0.5–6 mm. Used for gear teeth, crankshafts, and axles
Induction hardening	Heat the surface using high-frequency induction current, then quench	
Carburizing: increasing carbon content of the surface	Heat component at 850°C–950°C in a carbon-rich gas or solid, then quench	Hardened depth is 0.5–1.5 mm. Used for gear teeth, cams, shafts, bolts, and nuts
Cyaniding: increasing carbon and nitrogen content of the surface	Heat component at 700°C–850°C in a cyanide-rich salt bath, for example, sodium cyanide, then quench	Hardened depth is 0.02–0.3 mm. Used for small gears, bolts, and nuts
Nitriding: increasing nitrogen content of the surface	Heat component at 500°C–650°C in ammonia gas	Hardened depth is 0.05–0.6 mm. Used for gears, shafts, and tools
Carbonitriding: increasing carbon and nitrogen content of the surface	Heat component at 700°C–850°C in a mixture of carbon-rich and ammonia gases, then quench	Hardened depth is 0.05–0.6 mm. Used for gears, tools, and nuts

having to make the entire part of a wear-resistant material, which may not provide all the other functional requirements or may be more expensive. Surface treatments include the following:

- Surface heat treatment, as in the case of flame and induction heating, allows hardening of the surface without affecting the bulk of the material (Table 4.13).
- Surface alloying, as in the case of carburizing, cyaniding, nitriding, and carbonitriding, increases the hardness of the surface by increasing its carbon and nitrogen content (Table 4.13).

In spite of the widespread use of surface treatments and surface coatings to combat wear, these solutions are not without problems. Not all materials or parts can be surface treated, and surface coatings can fail by spalling. In many applications, wear problems are solved, wholly or in part, by the proper selection of materials, as discussed in the following sections.

4.10.1 Wear Resistance of Steels

Mild steels, although among the cheapest and most widely used materials, have poor wear resistance and can suffer severe surface damage during dry sliding. This can be avoided by selecting compatible mating materials, such as babbitt alloys or white metals, and providing adequate lubrication. Increasing the carbon content of the steel improves the wear resistance but increases the cost.

Surface-hardenable carbon or low-alloy steels are another step higher in wear resistance. Components made from these steels can be surface hardened by carburizing, cyaniding, or carbonitriding (Table 4.13) to achieve better wear resistance at a still higher cost. An even higher wear resistance can be achieved either by nitriding medium-carbon–chromium or chromium–aluminum steels or by surface hardening high-carbon–high-chromium steels. Precipitation-hardened stainless steels can be used in applications involving wear, elevated temperature, and corrosion.

Austenitic manganese steels are selected for a wide variety of applications where good abrasion resistance is important. The original austenitic manganese steel, Hadfield steel, contains 1.2% C and 12% Mn; however, several compositions are now available as covered by ASTM A128. These steels have carbon contents between 0.7% and 1.45% and manganese contents between 11% and 14%, with or without other elements such as chromium, molybdenum, nickel, vanadium, and titanium. Compared with other abrasion-resistant ferrous alloys, austenitic manganese steels have superior toughness at moderate cost. They have excellent resistance to metal-to-metal wear, as in sheave wheels, rails, and castings for railway track work. Manganese steels are also valuable in conveyors and chains subjected to abrasion and used for carrying heavy loads.

4.10.2 Wear Resistance of Cast Irons

As-cast gray cast iron (GCI) has adequate wear resistance for applications such as slideways of machine tools and similar sliding members. Better wear resistance is achieved with white pearlitic and martensitic irons, which are used in chilled iron rolls and grinding balls. Alloyed white irons have even better wear resistance but are more expensive.

4.10.3 Nonferrous Alloys for Wear Applications

Aluminum bronzes (Table A.14) range from the soft and ductile alpha alloys, which are used for press guides and wear plates, to the very hard and brittle proprietary die alloys, which are used for tube bending dies and drawing die inserts. The softest alloys contain about 7% Al with some additions of Fe and Sn. Increasing the aluminum content increases the hardness. Aluminum bronzes are not self-lubricating and should only be used where adequate lubrication can be maintained. These alloys are recommended for applications involving high loads and moderate to low speeds. Increasing the hardness increases abrasion resistance but lowers conformability and embeddability of these alloys when used as sleeves for sliding bearings. This subject is discussed in more detail in Chapter 11, case study on material selection for lubricated journal bearing.

Beryllium–copper alloys are among the hardest and strongest of all copper alloys. Properly lubricated, they have better wear resistance than other copper alloys and many ferrous alloys. An alloy containing 1.9% Be, 0.2% Co, and rest Cu is usually specified for wear applications, and it has better load-carrying capacity than all other copper-based alloys. In addition, beryllium coppers exhibit excellent corrosion resistance in industrial and marine atmospheres. Wear properties of beryllium–copper can be increased by oxidizing the surface of the alloy, by placing graphite in the surface, and by using cast parts rather than machining them from wrought alloys.

Wrought cobalt-based wear-resistant alloys have excellent resistance to most types of wear in addition to good resistance to impact and thermal shock, heat and oxidation, corrosion, and high hot hardness. The primary Co-based alloys for severe wear applications are the following:

1. *Stellite* 6*B*. It contains 0.9%–1.4% C, 28%–32% Cr, 3% Ni, 1.5% Mo, 3.5%–5.5% W, 3% Fe, 2% Mn, 2% Si, and rest Co.
2. *Stellite* 6*K*. It contains 1.4%–2.2% C, 28%–32% Cr, 3% Ni, 1.5% Mo, 3.5%–5.5% W, 3% Fe, 2% Mn, 2% Si, and rest Co.
3. *Haynes* 25. It contains 0.05%–0.10% C, 19%–21% Cr, 9%–11% Ni, 14%–16% W, 3% Fe, 1%–2% Mn, 1% Si, and rest Co.

Stellite has better resistance to abrasive wear, while Haynes 25 has better resistance to adhesive wear. Wrought Co-based alloys are nearly identical in chemical composition to their hard-facing alloy counterparts (Section 4.11) but with small differences in boron, silicon, or manganese levels. Another difference is the microstructure, which depends on the method of fabrication.

4.10.4 Wear Resistance of Plastics

Wear-resistant, self-lubricating plastics are favorably competing with metals in many applications including bearings, cams, and gears. In addition to ease of manufacture, these plastics have better lubricating properties and need less maintenance. Wear-resistant plastics are formulated with internal lubricating agents and are available in both unreinforced and reinforced versions. A combination of lubricating additives is usually employed to achieve optimum wear resistance. For example, silicone and PTFE are usually added to thermoplastics to improve their performance at high speeds and pressures. Carbon and aramid fibers, which are usually added for mechanical reinforcement, are also known to improve wear resistance. Table 4.14 lists some commonly used wear-resistant plastics in the order of decreasing resistance to wear when sliding against steel.

In spite of the advantages of plastics as wear-resistant materials, the following limitations should be kept in mind when selecting them for some applications:

1. *Plastics rubbing against plastics*. In such cases, wear is much more severe than in plastic–metal systems. The severity of wear can be reduced by adding PTFE or other internal lubricants and by similarly reinforcing the mating surfaces.
2. *Sensitivity of wear resistance to seemingly small variations in temperature*. For example, the wear rate of 15% PTFE and 30% glass-fiber nylon 6/6 at 200°C (ca. 400°F) is about 40 times its wear rate at room temperature.

TABLE 4.14
Wear Properties of Some Lubricated Plastics on Steel

Plastic Material	Reinforcing Fibers	Wear Factor[a]	Coefficient of Friction[b]
Nylon 6/6–18% PTFE, 2% silicone	—	6	0.08
Nylon 6/6–13% PTFE, 2% silicone	30% carbon	6	0.11
Polyester–13% PTFE, 2% silicone	30% glass	12	0.12
Acetal–20% PTFE	—	13	0.13
Acetal–2% silicone	—	27	0.12
Polyimide–10% PTFE	15% carbon	28	0.12
Polypropylene–20% PTFE	—	33	0.11
Polyurethane–15% PTFE	30% glass	35	0.25
Polystyrene–2% silicone	—	37	0.08

[a] 10^{10} in. 3 min/ft lb h.
[b] Dynamic at 40 lb/in.^{2}, 50 ft/min.

3. *Sensitivity of plastics to the surface roughness of the mating metallic surface*. Finishes that are too rough or too smooth can result in excessive wear. Minimum wear of lubricated plastics is usually obtained with metallic surface roughness in the range of 12–16 μm.
4. *Type of metal can strongly affect the results*. For example, using an aluminum alloy instead of steel can dramatically increase the wear rate of plastics.

4.10.5 Wear Resistance of Ceramics

Ceramics can be used in a variety of applications where wear resistance is required. The wear behavior of ceramics is determined by the nature of the mating surfaces and the presence of surface films. In general, as the grain size and porosity of the ceramic material increases, wear increases. The presence of surface films, such as water and oils, can affect adhesion and wear. For example, wear of partially stabilized zirconia increases in aqueous environments but decreases in fatty acids such as stearic acid. For engines and similar applications, SiC against lubricated steel has lower friction and less scuffing than chilled cast iron, which makes it suitable for engine valves, train components, and bearings.

4.11 WEAR-RESISTANT COATINGS

Hard-facing coatings are normally used for protection against wear. These coats may be applied to new parts made of soft materials to improve their resistance to wear or to worn parts to restore them to serviceable condition. The selection of hard-facing alloys for a given application is guided primarily by wear and cost considerations. However, other factors, such as impact resistance, corrosion and oxidation resistance, and thermal requirements, should also be considered. In general, the impact resistance of hard-facing alloys decreases as the carbide content increases. As a result, a compromise has to be made in applications where a combination of impact and abrasion resistance is required.

Most hard-facing alloys are marketed as proprietary materials and are classified as follows:

- Low-alloy steels (group 1)
- High-alloy ferrous materials (groups 2 and 3)
- Nickel-based and cobalt-based alloys (group 4)
- Carbides (group 5)

Generally, both wear resistance and cost increase as the group number increases.

The alloys in group 1 contain up to 12% Cr + Mo + Mn and have the greatest shock resistance of all hard-facing alloys, except austenitic manganese steels. They are less expensive than other hard-facing alloys and are extensively used where machinability is necessary and only moderate improvement over the wear properties of the base metal is required.

Alloys in group 2A and 2B contain up to 25% Cr + Mo and are more wear resistant but less shock resistant than group 1 alloys. Alloys 2C and 2D contain up to 37% Mn + Ni + Cr and are highly shock resistant but have limited wear resistance unless subjected to work hardening.

Group 3 alloys contain up to 50% Cr + Mo + Co + Ni. Their structure contains massive hypereutectic alloy carbides that improve wear resistance and give them some degree of corrosion and heat resistance.

The nonferrous Ni- and Co-based alloys of group 4A contain 50%–100% Co + Cr + W and are the most versatile hard-facing alloys. They resist heat, abrasion, corrosion, impact, galling, oxidation, thermal shock, erosion, and metal-to-metal wear. Some of these alloys retain useful hardness up to 825°C (1500°F) and resist oxidation up to 1100°C (200°F). Alloys of group 4B and 4C contain 50%–100% Ni + Cr + Co + B and are the most effective for service involving both corrosion and wear. They retain useful hardness up to about 650°C (1200°F) and resist oxidation up to 875°C (1600°F).

Group 5 materials provide maximum abrasion resistance under service conditions involving low or moderate impact. They are made of 75%–96% carbides cemented by a metal–matrix. Either WC or WC + TiC + TaC is used as the carbide phase, whereas Fe-, Ni-, or Co-based alloys are used as the matrix material.

4.12 SUMMARY

1. Most ductile wrought metallic materials are equally strong in tension and compression; brittle materials, however, are generally much stronger in compression than in tension.
2. The elastic modulus of a given class of materials is almost independent of chemical composition and heat treatment. The stiffness of a component may be increased by increasing the second moment of area of its cross section or by selecting a higher modulus class of materials for its manufacture.

3. When weight is an important consideration, the specific strength (strength/density) and specific stiffness (modulus of elasticity/density) may be used as the selection criteria.
4. Within a given class of materials, there is an inverse relationship between strength and toughness. Decreasing the operating temperature generally causes a decrease in toughness, particularly for bcc materials, such as carbon and low-alloy steels.
5. The fatigue strength of metallic materials generally increases with increasing tensile strength. However, the higher the strength, the higher the notch sensitivity and the greater is the need to eliminate coarse second-phase particles and to produce a more refined, homogeneous structure. Some fiber-reinforced composites perform better in fatigue than some metals, especially when compared on per weight basis.
6. Many of the methods used to increase the strength at normal temperatures become ineffective at high temperatures. Fine dispersion of stable second-phase particles may be used to improve the creep strength.
7. The main parameters that affect the corrosion resistance of a metallic material are its composition and the presence of impurities, nature and distribution of microstructural constituents, surface condition and deposits, and processing history. Plastics and glasses exhibit good resistance to most chemicals with the exception of organic solvents in the case of plastics and HF acid in the case of glasses.
8. Coatings for protection against corrosion either isolate the surface from the environment, as in the case of nonmetallic coatings, or by electrochemical action, as in the case of metallic coatings.
9. Increasing the hardness and toughness increases wear resistance. Hard-surface coatings and surface hardening treatments may be used to improve wear resistance.

REVIEW QUESTIONS

4.1 a. What are the main performance requirements of the wing structure of a two-passenger training aircraft, and what are the corresponding material properties?

b. Compare the use of the following materials in making the wing structure for the two-passenger training aircraft:

	Specific Gravity	Elastic Modulus (GPa)	Tensile Strength (MPa)
Aluminum alloy	2.7	70	580
Magnesium alloy	1.7	45	280
Epoxy + 56% E glass fibers	1.97	42.8	1028

4.2 Would you use AISI 1050 steel for manufacturing a component that will serve at −50°C (−58°F)? If not, suggest substitute materials.

4.3 If the available NDT equipment can detect internal cracks longer than 1 mm in length, determine the diameter of a bar that can bear a load of 150 kN without failure if it is made of AISI 4340 steel with yield strength of 1480 MPa and $K_{IC} = 87.4$ MPa $m^{1/2}$.

4.4 Ti–6Al–4V and aluminum 7075 T6 alloys are widely used in making lightweight structures. If the available NDT equipment can only detect flaws larger than 1 mm in length, can you safely use either of the mentioned alloys for designing a component that will be subjected to 400 MPa? Use the information in Table 4.7.

4.5 Explain why the crankshaft in a motorcar engine is only hardened on the surface and not throughout the whole cross section.

4.6 What are the material requirements for the blades of a household scissor? Suggest possible materials.

4.7 What are the material requirements for the radiator of a motorcar? Suggest possible materials.

4.8 An aluminum alloy is being considered as a replacement for steel in manufacturing a tensile member to save weight. The member has a circular cross section and a length of 1 m and is subjected to alternating tensile load of 6000 kg. Given the following information,

a. Determine if aluminum is a viable material for saving weight in this case.
b. Compare the relative cost of the two solutions.

Characteristic	Steel	Aluminum Alloy
Ultimate tensile strength	735 MPa	315 MPa
Endurance ratio	0.43	0.31
Surface finish derating factor	0.68	0.64
Size derating factor	0.80	0.77
Reliability derating factor	0.75	0.70
Specific gravity	7.8	2.7
Relative cost	1	3.2

4.9 Why are stainless steels corrosion resistant? Explain the phenomena of passivation and sensitization.

4.10 What are the material requirements for the electric heating wires in a heat treatment furnace that is expected to operate at temperatures up to 1000°C?

4.11 What are the differences between galvanizing and tinning of steel parts? Compare the merits of using each of these methods for (a) food cans and (b) outdoor fencing.

4.12 What are the differences between organic coatings and vitreous enamels? Give examples of the uses of each type of coating in household applications.

4.13 Why is aluminum more resistant to atmospheric corrosion than plain-carbon steel even though it is lower in the galvanic series?

4.14 What are the main material requirements for a kitchen knife blade? What is the type of material that you would recommend for such blades? Can ceramics be used for such an application?

4.15 What are the main material requirements for a gas turbine blade that is expected to operate at 900°C? Suggest possible materials.

4.16 What are the reasons that mechanical engineers do not always specify the strongest available material?

4.17 What are the advantages and disadvantages of low-carbon steels? How are the limitations overcome in practice?

4.18 What are the main material requirements for the following components: motorcar exhaust manifold, coil for electric resistance heater, and railway line?

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Part II

Relationships between Design, Materials, and Manufacturing Processes

The Successful Designer!

The designer bent across his board,
Wonderful things in his head were stored,
And he said as he rubbed his throbbing bean,
'How can I make this hard to machine?'

'If this part here were only straight,
I'm sure the thing would work first rate,
But't would be so easy to turn and bore,
It would never make the machinists sore.

'I'd better put in a right angle there,
Then watch those babies tear their hair,
Now I'll put the holes that hold the cap
'Way down here where they're hard to tap.

'Now this piece won't work, I'll bet a buck,
For it can't be held in a shoe or chuck;
It can't be drilled or it can't be ground,
In fact the design is exceedingly sound.'

He looked again and cried, 'At last-
Success is mine, it can't even be cast!'

Anon

Unlike the design made by the designer in the previously presented poem, a successful design should result in the creation of a product that satisfies a certain need and performs its function efficiently and economically within the prevailing legal, social, safety, environmental, and reliability requirements. In order to satisfy such requirements, the design engineer has to take into consideration a large number of diverse factors that can be grouped into three categories, as shown in Figure 5.1 and summarized as follows:

Factors related to product function and consumer requirements. These are related to human factors, ease of operation, ease of repair, esthetics and styling, noise level, pollution, intended service environment, and possibility of reuse and recycling after retirement, design codes, capacity, size, weight, safety, expected service life, reliability, maintenance, frequency of failure, initial cost, and operating cost.

Material-related factors such as static strength and ductility, stiffness, toughness, fatigue resistance, creep resistance, and corrosion resistance.

Manufacturing-related factors such as available fabrication processes, accuracy, surface finish, shape, size, required quantity, delivery time, cost, and required quality.

Although not all of the previously mentioned factors are applicable or are of equal importance for all design situations, the list illustrates the multifaceted nature of design. Figure 5.1 also shows that there are other secondary relationships between material properties and manufacturing processes, between function and materials properties, and between manufacturing processes and function.

Quality function deployment (QFD) is a structured process for translating customer needs and requirements into specific product characteristics and specifications and for specifying the processes and systems to produce that product with high quality. QFD consists of four phases:

1. *Performance requirements*, where the customer needs and requirements are prioritized and translated into product characteristics and performance requirements. Information from competitors' products is also used. A matrix is used to show the correlation between the customer needs and product characteristics. This matrix is part of an HOQ matrix, as will be discussed in the following section.
2. *Product design*, where the product characteristics and performance requirements are translated into product specifications and design using a matrix similar to HOQ. Parts and components that will be critical for the product are identified and then the part properties are set.
3. *Process design*, where the product design is translated into manufacturing process specifications and design using a matrix similar to HOQ. Methods for process control and process improvement are decided upon.
4. *Production design/process control* translates process design into control specifications and process control using a matrix similar to HOQ. Production instructions are designed. Critical product characteristics that have to be observed are identified. Prototype prepared and production launched.

This part of the book discusses the relationships between engineering design, materials, and manufacturing processes. Chapter 5 discusses the factors related to function and consumer requirements, Chapter 6 discusses the effect of material properties on design, and Chapter 7 discusses the effect of manufacturing processes on design.

PART II OUTCOMES

After completing Part II, the reader will be able to

1. Understand the nature and major phases of engineering design
2. Identify the material properties needed for design under different loading conditions and environments
3. Recommend ways of improving product safety and reliability
4. Consider environmental issues when designing and manufacturing components
5. Suggest ways of modifying the design of a component to make it more suitable for the material out of which it is made
6. Introduce design features to improve the manufacturability of a product
7. Select the optimum manufacturing process for a given product

5 Nature of Engineering Design

5.1 INTRODUCTION

Engineering design is an interdisciplinary process that transforms marketing ideas and consumer wishes into specific information and instructions that will allow successful manufacture of the product. Figure 5.1 shows the diverse factors that have to be considered when designing a component. In industry, design work is normally carried out by the design engineer in collaboration with other departments including customer service, marketing, and sales; legal and patents; safety, codes, and regulations; R&D; and materials and manufacturing. The design team is often required to make compromises to satisfy the conflicting requirements of the different constituencies. Engineering design work is usually performed on three different levels:

1. Development of existing products or designs, redesign, by introducing minor modifications in size, shape, or materials to improve performance or to overcome difficulties in production. This type of work represents a large proportion of the design effort in industry and may be accompanied by failure analysis to reduce the likelihood of further failures.
2. Adaptation of an existing product or design to operate in a new environment or to perform a different function. In some cases, the new design may be widely different from the starting one.
3. Creation of a totally new design that has no precedent. This type of work is most demanding in experience and creativity of the design team and is not performed as often as the other types of design work. It often requires the solution of problems that may not have been encountered before and could require a considerable effort in R&D.

The goal of this chapter is to give an overview of the parameters that influence the engineering design process in industry. The main objectives are the following:

1. To discuss the various issues that have to be considered in design
2. To review the major phases of the design process and how the views of customer are taken into account using the HOQ methodology
3. To explain the use of codes and standards in design
4. To discuss the effect of component geometry on design
5. To rationalize the use of the factor of safety in design
6. To calculate the probability of failure of a component at the design stage
7. To discuss the various parameters involved in making products more safe and reliable and the related liability issues

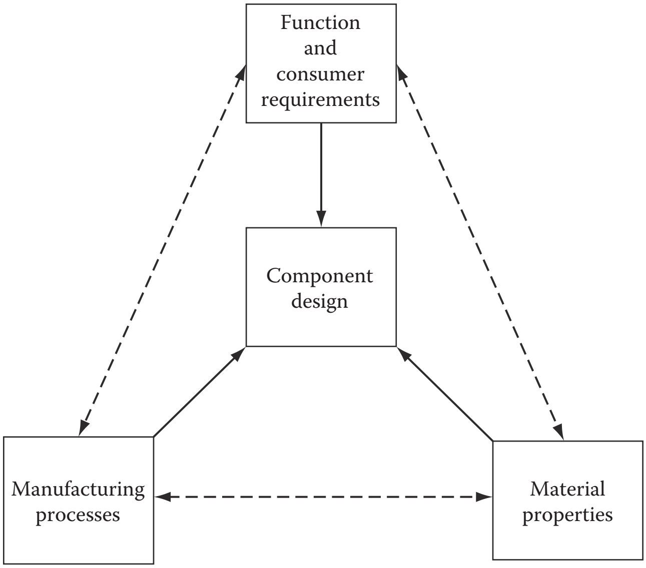


FIGURE 5.1 Factors that should be considered in component design.

5.2 GENERAL CONSIDERATIONS IN ENGINEERING DESIGN

Because of its interdisciplinary nature, an optimum engineering design involves trade-offs among the many, and often conflicting, conditions that it has to satisfy. Such conditions include human factors, marketing and esthetic considerations, functional requirements, manufacturing considerations, economic factors, as well as safety and environmental requirements.

5.2.1 Human Factors

Adaptation of the product to make it convenient for human use is an important aspect of a successful design. The design should also account for variations among human beings in terms of height, weight, physical strength, visual and hearing acuity, conceptual capacity, etc. Using the product efficiently must not require the use of excessive physical force or the performance of too many functions simultaneously. Controls must also follow natural expectations of the user. For example, moving a lever forward or the clockwise rotation of a rotary control is normally expected to increase output.

The designer must also anticipate that the product may be used in unintended ways or functions. Protective measures should also safeguard against the possibility of injuries as a result of errors in use or poor maintenance. For example, the driver cannot press the accelerator and the brake of a motor vehicle at the same time, and the blade of a shear press would not move unless the operator's hands have been completely withdrawn from the work area.

5.2.2 Industrial Design, Esthetic, and Marketing Considerations

Styling of the product to reflect its function with emphasis on esthetic and visual features is the realm of industrial design. Esthetic attributes are the qualities that appeal to the senses, such as vision, touch, hearing, smell, and taste. Visual attributes include whether the surface is colorful or subdued, transparent or opaque, and glossy or matte. Tactile attributes include whether the surface feels soft or hard to the touch, flexible or stiff, and warm or cold. Sounds can be resonant or dull, muffled or sharp, low or high pitch, etc.

It is generally accepted that the success of a product is influenced by both engineering and industrial designs, both of which are emphasized when marketing the product. In more technically mature products, where differences in technical performance are slight and the prices are nearly the same, distinction from competing products can be achieved through industrial design. In such cases, a product can be distinguished by its styling, configuration, proportion, color, texture, ease of use, and character, which are all in the realm of industrial design. For example, in marketing a wristwatch, which is a mature product, the accuracy is taken for granted and more emphasis is placed on its character, for example, rugged and relatively large for a sportsperson but stylish and elegant to go with evening wear. However, the relatively new and still developing mobile (cellular) phone is marketed with more emphasis on its technological capabilities and less on styling and looks.

5.2.3 Environmental Considerations

With the increasing concern for the negative impact of many of the products that are associated with human development, environmental constraints are becoming tighter and more forcefully imposed by the many agencies concerned. Several of these agencies issue guidelines for environmentally responsible design or design for environment (DFE). The U.S. EPA and the International Organization for Standardization (ISO) are examples of agencies that issue such guidelines. The EPA provides design strategies to extend the life of products and materials, reduce material utilization, and improve process management. ISO 14000 provides the international standard for environmental management systems within a company. The ISO publications are available on the organization's website and Block (1996) describes the implementation of ISO 14001.

The following are representative examples of the guidelines for DFE:

- Design the components to be reusable or recyclable.
- Minimize the number of parts for ease of disassembly.
- Reduce the number of fasteners to reduce the disassembly time.
- Use modular design and standardize components as much as possible.
- Select materials that have lower impact on the environment.
- Reduce the number of materials in the product and choose materials that are compatible and can be recycled together.
- Avoid the use of materials or production aids that are toxic or harmful to the environment.

- If possible, avoid the use of materials that are difficult to recycle. These include FRP, laminated materials, galvanized steels, thermosetting plastics, and ceramics.
- Riveted or permanently joined assemblies that are made of different materials are difficult to recycle.

Life cycle engineering, cradle to grave, is another approach in assessing the environmental impact of a product during its entire life cycle. This approach recognizes the fact that products have different environmental impact during the different stages of their life cycle. This approach is discussed in more detail in Section 8.11.

5.2.4 Functional Requirements

Functional requirements represent the minimum level of performance that any acceptable design must have. With increasing competition among different manufacturers and with more emphasis on product liability, designs are required to meet the additional requirements of reliability, safety, marketability, and cost. Manufacturing considerations affect the feasibility of making the product at a competitive price and are discussed in Chapter 7, while economic considerations are discussed in Chapter 8.

Service life represents an important design parameter as it affects both reliability and economics of the product. Service life of a component can be estimated according to safe-life or fail-safe criteria. The safe-life criterion can be applied to a component in which undetected crack or other defects could lead to catastrophic structural failure, and a life limitation must therefore be imposed on their use. The fail-safe criterion can be applied to structures in which there is sufficient tolerance of a failure to permit continuous service until discovered by routine inspection procedure or by obvious functional deficiencies. The majority of engineering components can be designed according to the fail-safe criterion. Even a critical component can be designed according to the fail-safe criterion if failure is detectable by the maintenance program, which must define both the timing and the methods of inspection to be applied. Redistribution of the load into sufficiently robust adjacent components if failure occurs is an added safety precaution. If the use of a safe-life component is unavoidable, its safe service life must be estimated by testing and its replacement life calculated by applying an appropriate factor of safety.

5.3 DESIGN FOR SIX SIGMA

Six Sigma originated as a set of practices aimed at eliminating defects in manufactured products but was subsequently used in other types of business processes. A defect in this case is defined as any process output that does not meet customer specifications or needs. Sigma in this methodology is the standard deviation, which indicates how much variation or dispersion exists from the average of a population of measurements or data. A low standard deviation indicates that the data points tend to be close to the average, and a high standard deviation indicates that the data points are spread out over a large range of values. The capability of a manufacturing process can be measured by the number of standard deviations between the mean and the specified acceptable limit of the product. As the standard deviation of a process goes up, or the mean moves away from the center of the tolerance, fewer standard deviations will fit between the mean and the specified acceptable limit, thus decreasing the sigma number and increasing the likelihood of items outside specification, which means larger number of rejections or rework. In a Six Sigma process, the difference between the process mean and the specified acceptable limit is six standard deviations and corresponds to a rejection or rework rate of less than four items per million.

Six Sigma methodology starts by defining the problem, measuring the current level of performance and analysis to determine the root cause of defects. Improvement is then achieved by eliminating the causes of defects. The process is then monitored to ensure continuity of the improved performance. These phases of the methodology are known by the acronym DMIAC, which stands for define customer requirements, measure the process and its performance, analyze to determine the causes of defects, improve by removing causes of defects, and control to maintain quality.

Design for Six Sigma (DFSS) implements the Six Sigma methodology as early as possible in the product life cycle in order to ensure that the product satisfies the customer expectations with fewer rejections and little waste of materials and time in manufacture. Introducing changes in the design stage is much cheaper than solving problems during manufacture or after releasing the product. In this case, the acronym DMIAC is adjusted to DMADV, which stands for define, measure, analyze, design, and verify. In this context, the phases of the methodology can be defined as follows:

- Define design goals that are consistent with customer needs. This can be done using tools such as QFD, as described in Chapter 1.
- Measure and identify product characteristics that are critical to the quality of its performance (CTQ).
- Analyze to develop and design alternatives and select the best design.
- Design details and plan for design verification and optimization. This can be done using tools such as FMEA, as described in Chapter 2, and design for manufacture and assembly, as described in Chapter 7.
- Verify/validate the design and set up pilot runs if necessary.

5.4 MAJOR PHASES OF DESIGN

Engineering design is usually an iterative process that involves a series of decision-making steps, where each decision establishes the framework for the next one. There is no single universally recognized sequence of steps that leads to a workable design as these depend on the nature of the problem being solved as well as on the size and structure of the organization. Generally, however, a design usually passes through most of the phases that are shown in Figure 5.2 and grouped into the following three categories.

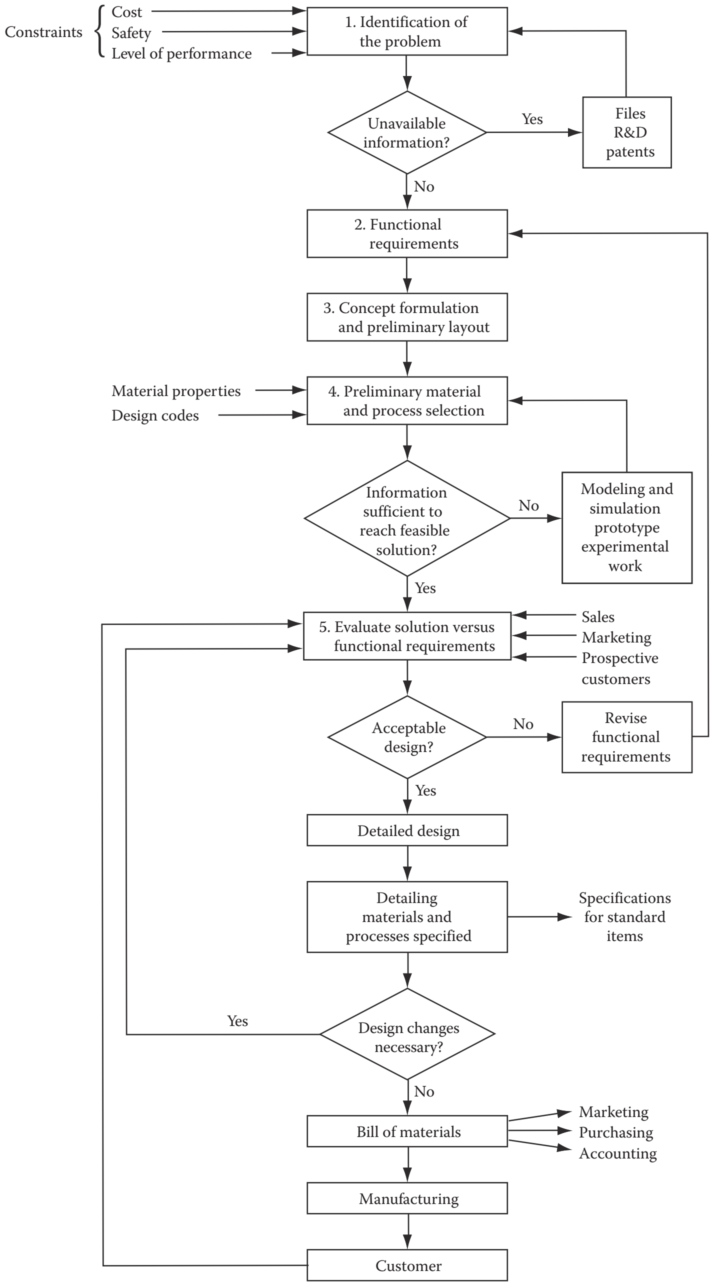


FIGURE 5.2 Major phases of a design.

5.4.1 Preliminary and Conceptual Design

1. Identifying the need, evaluating the product feasibility, selecting the most promising concept, and defining the objective of the design represent the first phase of product development in most cases. The major constraints such as cost, safety, and level of performance and the overall specifications are also defined at this stage. Effective communication with prospective customers and other departments in the organization, such as marketing, legal, R&D, and manufacturing, is essential at this stage. Unavailable information is identified at this stage and the strategy for obtaining it is outlined. The HOQ, as described in Chapter 1, provides a structured process for translating customer requirements and market research into quantifiable product characteristics and specifications to be met by the product design.
2. Functional requirements and operational limitations are directly related to the required characteristics of the product and are specified as a result of the activities of phase 1. Although it is not always possible to assign quantitative values to these product characteristics, they must be related to measurable quantities that will allow future evaluation of the product performance. This is sometimes called the conceptual design stage.
3. System definition, concept formulation, and preliminary layout are usually completed, in this order, before evaluating the operating loads and determining the form of the different components or structural members. Allowances must be made for uncertainties of loading and approximations in calculations. The consequences of component failure must also be considered at this stage. Whether the component can be easily and cheaply replaced or whether large costs will be incurred will significantly influence the design.

   Preliminary design review (PDR) may be carried out to verify that the preliminary design meets all system requirements and is within the cost and schedule constraints. PDR should show that the correct design options have been selected and that verification methods have been described. The review should also ensure that all system requirements have been considered, the proposed design will meet the functional and performance requirements, all risks have been identified and considered in the design, and the design complies with the product goals and user needs. A successful PDR establishes the basis for proceeding with detailed design.

5.4.2 Configuration (Embodiment) Design

4. Consulting design codes and collecting information on material properties will allow the designer to perform preliminary materials selection, preliminary design calculations, and rough estimation of manufacturing requirements. Preliminary design begins by expanding the conceptual design into a detailed structure of subsystems and sub-subsystems. In many cases, several solutions to the design problem can be proposed at this stage.
5. The evaluation phase involves a comparison of the expected performance of the design with the performance requirements established in phase 2.

Evaluation of the different solutions and selection of the optimum alternative can be performed using decision-making techniques, modeling techniques, experimental work, and prototypes. A common strategy is to test, evaluate, and then modify the design based on analysis and tests of the model or prototype. Usually the first prototype is assigned the letter (α) and subsequent iterations are assigned the letters β, γ, etc.

Having arrived at an optimum solution, it is often necessary to revise the design and to make more precise design calculations as well as to specify materials and manufacturing processes in more detail. A design review at this stage ensures that issues related to efficiency, compliance to environmental regulations, safety, cost, etc., have been successfully resolved. The review may also address questions related to design for manufacture and assembly as well as various other manufacturing considerations. The design review may include physical tests and engineering simulations.

In some cases, it is not possible to arrive at a design that fulfills all the requirements and complies with all the limitations established in phase 2. This means that these requirements and limitations have to be reconsidered and phases 3–5 have to be repeated until an acceptable design is arrived at.

5.4.3 Detail (Parametric) Design

6. Having arrived at a final design, the project then enters the detailed design stage where it is converted into a detailed and finished form suitable for use in manufacturing. The preliminary design layout, any available detail drawings, models and prototypes, and access to the developer of the preliminary design usually form the basis of the detailed design.
7. The next step in the detailed design phase is detailing, which involves the creation of detailed drawings for every part. All the information that is necessary to unambiguously define the part should be recorded in the detail drawing. The material of the part should also be selected and specified by reference to standard codes. The temper condition of the stock material, the necessary heat treatment, and the expected hardness may also be specified for quality control purposes. In the course of detailing, it may become clear that the manufacture, assembly, or disassembly of some parts of the layout could be improved if they are changed. In this case, communication should take place between the detail designer and the preliminary designer to agree on the proposed changes.
8. An important part of the detail design phase is the preparation of the bill of materials, sometimes called parts list. The bill of materials is a hierarchical listing of everything that goes into the final product including fasteners and purchased parts. The bill of materials is used by a variety of departments including purchasing, marketing, and accounting. When the detailed design is released for manufacturing, a working bill of materials should go with it. The manufacturing plan, production planning, and assembly will all be based on the bill of materials. An appropriate version of the bill of materials is also shipped along with the finished product for guidance in

operating and maintenance. Close interaction between design, manufacturing, and materials engineers is important at this stage.

9. The relationship between the designer and the product does not usually end at the manufacturing or even delivery stages. The manufacturing engineer may ask the detail designer for a change in some parts to make fabrication easier or cheaper. Finally, when the product gets into use, the reaction of the consumer and the performance of the product in service are of concern to the designer as the feedback represents an important source of information for future design modifications.

5.5 ENVIRONMENTALLY RESPONSIBLE DESIGN

Environmentally responsible design, also called sustainable design or eco-design, aims at designing and producing products that have no, or minimum, negative impact on the environment. An environmentally responsible design considers the environmental aspects during the life cycle of the product starting with the materials and processes used in manufacturing it, the energy and emissions it produces during its useful life, and how it is disposed of when it is no longer needed. The general principles of environmentally responsible design include the following:

- Select materials that come from renewable resources, require less energy to process, can be recycled, and are nontoxic to the environment.
- Employ manufacturing processes that require less energy, minimize waste of materials, and do not produce toxic waste products.
- Ensure maximum thermal efficiency to reduce energy consumption when using the product and, whenever possible, use energy from renewable resources.
- Consider ease of repair and replacement of parts in order to prolong the useful life of the product.
- Improve recyclability by minimizing the number of different materials used in making the product and ensuring ease of disassembly of components at the end of their useful life.

The environmental impact of products, recycling, and life cycle considerations are discussed in Chapter 8.

5.6 DESIGN CODES AND STANDARDS

A design code is a set of standards or specifications for the analysis, design, manufacture, and construction of a structure or a component. Codes of practice are set by professional groups and government bodies to achieve a specified degree of safety, efficiency, performance or quality, as well as a common standard of good design practice. Codes serve to disseminate proved data and research results to the average designer who is not expected to have the expertise to appreciate and critically examine all the specialized information associated with the part being designed. Codes are often legal requirements that are adopted and enforced by a government.

A standard specification is a published document that describes the characteristics of a part, material, or process, which is acceptable by an authority or by general consent as a basis of comparison or for approval. Standards can vary from those developed by a company for use in-house to those that represent industry consensus such as those published by the American National Standards Institute (ANSI) and ISO. Standards can also be issued by governments to regulate their own purchases and operations. When cited by the purchaser and accepted by a supplier, a standard becomes part of the purchase agreement. The widespread use of standards has benefited companies by reducing the number of products, materials, or components that need to be manufactured or held in stock. Specification of dimensions, shapes, and sizes also helps in achieving interchangeability of components.

As a standard is a document that can be used to control procurement, it should contain both technical and commercial requirements. Specifications normally cover the following information:

1. Product classification, scope of application, size range, condition, and processing details that could help either the supplier or the user.
2. Allowable ranges of chemical composition.
3. All physical and mechanical properties necessary to characterize the product are given in addition to the test methods used to determine these properties.
4. If applicable, other requirements such as special tolerances, surface preparation, loading instructions, and packaging are included.

As shown in Figure 5.2, the designer should consult the relevant design codes soon after formulating the design concept to make certain that the design meets the users' expectations, which normally include the intended function and safety requirements.

5.7 EFFECT OF COMPONENT GEOMETRY

In almost all cases, engineering components and machine elements have to incorporate design features that introduce changes in their cross section. For example, shafts must have shoulders to take thrust loads at the bearings and must have keyways or splines to transmit torques to or from pulleys and gears mounted on them. Other features that introduce changes in cross section include oil holes, fillets, undercuts, bolt heads, screw threads, and gear teeth. These changes cause localized stress concentrations that are higher than those based upon the nominal cross section of the part.

5.7.1 Stress-Concentration Factor

The severity of the stress concentration depends on the geometry of discontinuity and nature of the material. A geometric, or theoretical, stress-concentration factor, K_t, is usually used to relate the maximum stress, S_{max}, at the discontinuity to the nominal stress, S_{av}, according to the relationship:

$$K_t = \frac{S_{max}}{S_{av}} \tag{5.1}$$

The value of K_t depends only on the geometry of the part, and for the simple case of an elliptical hole in an infinitely large plate, it is given by

$$K_t = 1 + \frac{2b}{a} \tag{5.2}$$

where
   $2b$ is the dimension of the hole perpendicular to the stress direction
   $2a$ is the dimension of the hole parallel to the stress direction

In the case of a circular hole in an infinite plate, a is equal to b and $K_t = 3$. The value of K_t for other geometries can be determined from stress-concentration charts, such as those given by Peterson (1974) and Shigley and Mitchell (1983). Other methods of estimating K_t for a certain geometry include photoelasticity, brittle coatings, and finite element techniques. Table 5.1 gives some typical values of K_t.

Experience shows that, under static loading, K_t gives an upper limit to the stress-concentration value and applies only to brittle and notch-sensitive materials. With more ductile materials, local yielding in the very small area of maximum stress causes considerable relief in the stress concentration. Consequently, for ductile materials under static loading, it is not usually necessary to consider the stress-concentration factor. However, due consideration should be given to the stress concentration when designing with high-strength, low-ductility, case-hardened, or heavily cold-worked materials.

5.7.2 Stress Concentration in Fatigue

Stress concentration should also be considered in designing components that are subject to fatigue loading. Under such conditions, a fatigue stress-concentration factor, or fatigue-strength reduction factor, K_f, is usually defined as

$$K_f = \frac{\text{endurance limit of notch-free part}}{\text{endurance limit of notched part}} \tag{5.3}$$

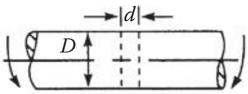
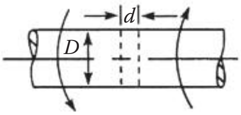
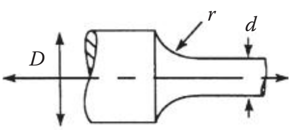
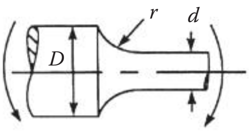
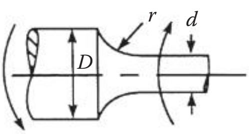
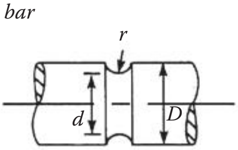
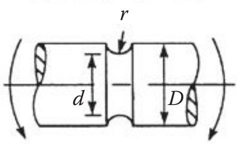
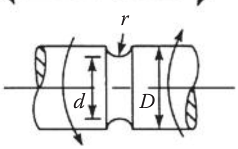
The relationship between K_f and K_t is discussed in Section 4.6 and a notch sensitivity factor, q, was defined in Equation 4.9. The value of q was shown to vary between 1 and 0. When $K_f = K_t$, the value of q is 1 and the material is fully sensitive to notches. However, when the material is not at all sensitive to notches, $K_f = 1$ and $q = 0$.

In making a design, K_t is usually determined from the geometry of the part. Then, when the material is selected, q can be specified, and Equation 4.9 is solved for K_f. Generally, the value of q approaches unity as the material strength increases, for example, UTS is more than 1400 MPa (200 ksi) for steels. Whenever in doubt, the designer can take $K_f = K_t$ and err on the safe side.

5.7.3 Guidelines for Design

Stress concentration can be a source of failure in many cases, especially when designing with high-strength materials and under fatigue loading. In such cases, the

TABLE 5.1
Approximate Values of Stress-Concentration Factor (K_t)

Component Shape		Value of Critical Parameter	K_t
Round shaft with transverse hole			
Bending		$d/D = 0.025$	2.65
		$= 0.05$	2.50
		$= 0.10$	2.25
		$= 0.20$	2.00
Torsion		$d/D = 0.025$	3.7
		$= 0.05$	0.36
		$= 0.10$	3.3
		$= 0.20$	3.0
Round shaft with shoulder			
Tension		$d/D = 1.5$, $r/d = 0.05$	2.4
		$r/d = 0.10$	1.9
		$r/d = 0.20$	1.55
		$d/D = 1.1$, $r/d = 0.05$	1.9
		$= 0.10$	1.6
		$= 0.20$	1.35
Bending		$d/D = 1.5$, $r/d = 0.05$	2.05
		$r/d = 0.10$	1.7
		$r/d = 0.20$	1.4
		$d/D = 1.1$, $r/d = 0.05$	1.9
		$r/d = 0.10$	1.6
		$r/d = 0.20$	1.35
Torsion		$d/D = 1.5$, $r/d = 0.05$	1.7
		$r/d = 0.10$	1.45
		$r/d = 0.20$	1.25
		$d/D = 1.1$, $r/d = 0.05$	1.25
		$r/d = 0.10$	1.15
		$r/d = 0.20$	1.1
Grooved round bar			
Tension		$d/D = 1.1$, $r/d = 0.05$	2.35
		$r/d = 0.10$	2.0
		$r/d = 0.20$	1.6
Bending		$d/D = 1.1$, $r/d = 0.05$	2.35
		$r/d = 0.10$	1.9
		$r/d = 0.20$	1.5
Torsion		$d/D = 1.1$, $r/d = 0.05$	1.65
		$r/d = 0.10$	1.4
		$r/d = 0.20$	1.25

following design guidelines should be observed if the deleterious effects of stress concentration are to be kept to a minimum:

1. Abrupt changes in cross section should be avoided. If they are necessary, generous fillet radii or stress-relieving grooves should be provided (Figure 5.3a).
2. Slots and grooves should be provided with generous runout radii and with fillet radii in all corners (Figure 5.3b).

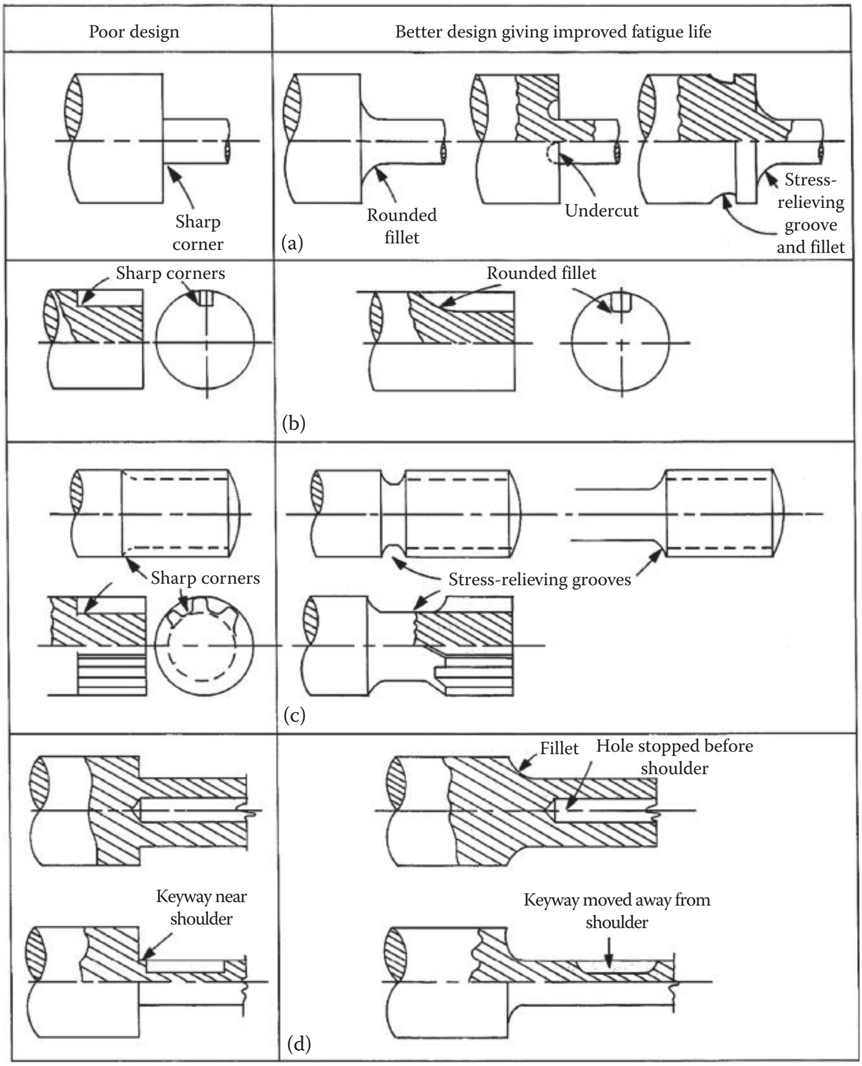


FIGURE 5.3 Design guidelines for shafts subjected to fatigue loading. (a) Changes in cross section. (b) Slots and grooves. (c) Threads and splines. (d) Combined weakening features.

3. Stress-relieving grooves or undercuts should be provided at the end of threads and splines (Figure 5.3c).
4. Sharp internal corners and external edges should be avoided.
5. Oil holes and similar features should be chamfered and the bore should be smooth.
6. Weakening features like bolt and oil holes, identification marks, and part numbers should not be located in highly stressed areas.
7. Weakening features should be staggered to avoid the addition of their stress-concentration effects (Figure 5.3d).

5.8 FACTOR OF SAFETY

The term factor of safety is applied to the factor used in designing a component to ensure that it will satisfactorily perform its intended function. The main parameters that affect the value of the factor of safety, which is always greater than unity, can be grouped into

1. Uncertainties associated with material properties due to variations in composition, heat treatment, and processing conditions as well as environmental variables such as temperature, time, humidity, and ambient chemicals.
2. Parameters related to manufacturing processes also contribute to the uncertainties of component performance. These include variations in surface roughness, internal stresses, sharp corners, identifying marks, and other stress raisers.
3. Uncertainties in loading and service conditions.

Generally, ductile materials that are produced in large quantities generally show fewer property variations than less ductile and advanced materials that are produced by small batch processes. In composite materials, small variations in fiber orientation or volume fraction can have considerable effect on properties. Manufacturing processes can also add to the variations in component behavior. For example, parts manufactured by processes such as casting, forging, and cold forming are known to have variations in properties from point to point. Dimensional and geometrical variations resulting from manufacturing process tolerances can also affect the load-carrying capacity of components. Improved quality control techniques should result in more uniform material properties and more consistent component behavior in service and therefore lower values for the factor of safety. To account for these uncertainties, the factor of safety is used to divide into the nominal strength (S) of the material to obtain the working or allowable stress (S_a) as follows:

$$n_s = \frac{S}{S_a} \tag{5.4}$$

where n_s is the material factor of safety.

In simple components, S_a in Equation 5.4 can be viewed as the minimum allowable strength of the material. However, there is some danger involved in this use especially in the cases where the load-carrying capacity of a component is not directly related to the strength of the material used in making it. Examples include long compression members, which could fail as a result of buckling, and components of complex shapes, which could fail as a result of stress concentration. Under such conditions, it is better to consider S_a as the load-carrying capacity, which is a function of both material properties and geometry of the component.

In assessing the uncertainties in loading, two types of service conditions have to be considered:

1. Normal working conditions, which the component has to endure during its intended service life
2. Limit working conditions, such as overloading, which the component is only intended to endure on exceptional occasions and which, if repeated frequently, could cause premature failure of the component

In a mechanically loaded component, the stress levels corresponding to both normal and limit working conditions can be determined from a duty cycle. The normal duty cycle for an airframe, for example, includes towing and ground handling, engine run, takeoff, climb, normal gust loadings at different altitudes, kinetic and solar heating, descent, and normal landing. Limit conditions can be encountered in abnormally high gust loadings or emergency landings. Analyses of the different loading conditions in the duty cycle lead to determination of the maximum load that will act on the component. This maximum load can be used to determine the maximum stress, or damaging stress, which if exceeded would render the component unfit for service before the end of its normal expected life. The load factor of safety (n_l) in this case can be taken as

$$n_l = \frac{L}{L_a} \tag{5.5}$$

where
L is the maximum load
L_a is the normal load

The total or overall factor of safety (n), which combines the uncertainties in material properties and manufacturing processes as well as the uncertainties in external loading conditions, can be calculated as

$$n = n_s n_l \tag{5.6}$$

Factors of safety ranging from 1.1 to 20 are known, but common values range from 1.5 to 10.

In some applications, a designer is required to follow established codes when designing certain components, such as pressure vessels and piping systems. Under these conditions, the factors of safety used by the writers of the codes may not be specifically stated but an allowable working stress is given instead.

Derating factors are numbers less than unity and are used to reduce material strength values to take into account manufacturing imperfections and the expected severity of service conditions. When a component is subjected to fatigue loading, for example, several derating factors can be used to account for imperfections in surface finish, size of the component, stress concentration, etc., as discussed in Section 6.5.

5.9 RELIABILITY OF COMPONENTS

As discussed earlier, the actual behavior of the material in a component could vary from one point to another and from one component to another. In addition, it is usually difficult to precisely predict the external loads acting on the component under actual service conditions. To account for these variations and uncertainties, both the load-carrying capacity S and the externally applied load L can be expressed in statistical terms. As both S and L depend upon many independent factors, it would be reasonable to assume that they can be described by normal distribution curves. Consider that the load-carrying capacity of the population of components has an average of $\bar{S}$ and a standard deviation σ_S, whereas the externally applied load has an average of $\bar{L}$ and a standard deviation σ_L. The relationship between the two distribution curves is important in determining the factor of safety and reliability of a given design. Figure 5.4 shows that failure takes place in all the components that fall in the area of overlap of the two curves, that is, when the load-carrying capacity is less than the external load. This is described by the negative part of the $(\bar{S} - \bar{L})$ curve of Figure 5.4. Transforming the distribution $(\bar{S} - \bar{L})$ to the standard normal deviate z, the following equation is obtained:

$$z = \frac{[(S-L)-(\bar{S}-\bar{L})]}{[(\sigma_S)^2+(\sigma_L)^2]^{1/2}} \tag{5.7}$$

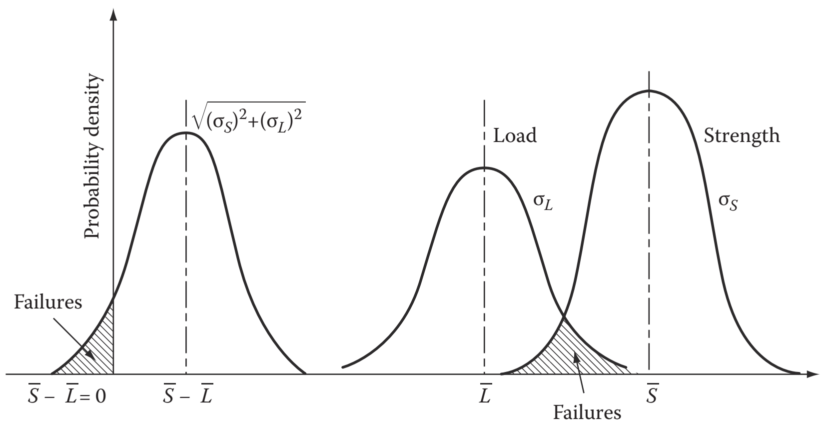


FIGURE 5.4 Effect of variation in load and strength on the failure of components.

TABLE 5.2
Values of *z* and Corresponding Levels of Reliability and Probability of Failure

z	Reliability	Probability of Failure
−1.00	0.8413	0.1587
−1.28	0.9000	0.1000
−2.33	0.9900	0.0100
−3.09	0.9990	0.0010
−3.72	0.9999	0.0001
−4.26	0.99999	0.00001
−4.75	0.999999	0.000001

From Figure 5.4, the value of z at which failure occurs is

$$z = \frac{[0-(\bar{S}-\bar{L})]}{[(\sigma_S)^2+(\sigma_L)^2]^{1/2}} = \frac{-(\bar{S}-\bar{L})}{[(\sigma_S)^2+(\sigma_L)^2]^{1/2}} \tag{5.8}$$

For a given reliability, or allowable probability of failure, the value of z can be determined from the cumulative distribution function for the standard normal distribution. Table 5.2 gives some selected values of z that will result in different values of probabilities of failure.

Knowing σ_S, σ_L, and the expected $\bar{L}$, the value of $\bar{S}$ can be determined for a given reliability level. As defined earlier, the factor of safety in the present case is simply $\bar{L}/\bar{S}$. Example 5.1 illustrates the use of the previously mentioned concepts in design.

Design Example 5.1: Estimating the Probability of Failure of a Structural Member

Problem

A structural element is made of a material with an average tensile strength of 2100 MPa. The element is subjected to a static tensile stress of an average value of 1600 MPa. If the variations in material quality and load cause the strength and stress to vary according to normal distributions with standard deviations of $\sigma_S = 400$ and $\sigma_L = 300$, respectively, what is the probability of failure of the structural element?

Solution

From Figure 5.4,

$$\bar{S} - \bar{L} = 2100 - 1600 = 500 \text{ MPa}$$

Standard deviation of the curve

$$(S - L) = [(\sigma_S)^2 + (\sigma_L)^2]^{1/2} = [(400)^2 + (300)^2]^{1/2} = 500$$

From Equation 5.8,

$$z = \frac{-500}{500} = -1$$

From Table 5.2, the probability of failure of the structural element is 0.1587, that is, 15.87%, which is too high for many practical applications.

One solution to reduce the probability of failure is to impose better quality measures on the production of the material and, thus, reduce the standard deviation of the strength. Another solution is to increase the cross-sectional area of the element to reduce the stress. For example, if the standard deviation of the strength is reduced to $\sigma_S = 200$, the standard deviation of the curve $(\bar{L} - \bar{S})$ will be $[(200)^2 + (300)^2]^{1/2} = 360$:

$$z = \frac{-500}{360} = -1.4$$

which according to Table 5.2 gives a more acceptable probability of failure value of 0.08, that is, 8%.

Alternatively, if the average stress is reduced to 1400 MPa,

$$(\bar{S} - \bar{L}) = 700 \text{ MPa}$$

$$z = \frac{-700}{500} = -1.4$$

with a similar probability of failure as the first solution.

As the discussion shows, statistical analysis allows the generation of data on the probability of failure and reliability, which is not possible when a deterministic safety factor is used. One of the difficulties with this statistical approach, however, is that material properties are not usually available as statistical quantities. In such cases, the following approximate method can be used.

In the case where the experimental data are obtained from a reasonably large number of samples, more than 100, it is possible to estimate statistical data from non-statistical sources that only give ranges or tolerance limits. In this case, the standard deviation σ_S is approximately given by

$$\sigma_S = \frac{\text{maximum value of property} - \text{minimum value}}{6} \tag{5.9}$$

This procedure is based on the assumption that the given limits are bounded between plus and minus three standard deviations. Example 5.2 illustrates this point.

Design Example 5.2: Estimating the Coefficient of Variation in Material Strength

Problem

If the range of strength of an alloy is given as 800–1200 MPa, what is the mean strength, the standard deviation, and coefficient of variation?

Solution

The mean strength can be taken as 1000 MPa.

The standard deviation σ can be estimated as

$$\sigma = \frac{1200 - 800}{6} = 66.67 \text{ MPa}$$

The coefficient of variation ν' is then

$$\nu' = \frac{66.67}{1000} = 0.0667$$

If the results are obtained from a sample of about 25 tests, it may be better to divide by 4 in Equation 5.9 instead of 6. With a sample of about 5, it is better to divide by 2.

In the cases where only the average value of strength is given, the following values of coefficient of variation, which is defined as $\nu' = \sigma_S/S$, can be taken as typical for metallic materials:

$\nu' = 0.05$ for UTS
$\nu' = 0.07$ for yield strength
$\nu' = 0.08$ for endurance limit for steel
$\nu' = 0.07$ for fracture toughness

5.10 PRODUCT RELIABILITY AND SAFETY

Reliability engineering and safety engineering are closely related, in that they use common methods for their analysis and may require input from each other. Reliability engineering focuses on costs of failure caused by system downtime, cost of spares, repair equipment, personnel, and cost of warranty claims. On the other hand, safety engineering focuses on preserving life and nature and therefore deals only with particular dangerous system failure modes. In the early stages of a product development, the design is analyzed to identify the faults that can occur, and then changes are proposed to make it safer. Similarly, an existing product may be analyzed to improve its safety. Both reliability and safety engineering use tools and techniques such as failure analysis and prevention, reliability hazard analysis, FMEA, and FTA. Such tools are discussed briefly in Part II of this book.

Product reliability can be defined as the probability that it will continue to perform its intended function without failure for a specified period of time under stated conditions. Reliability is an important aspect of product quality as it affects the reputation of the manufacturer, customer satisfaction, warranty costs, and recall expenses. The goal of reliability engineering is to evaluate the reliability of a product and identify actions to alleviate the effects of those failures. This is an ongoing process starting at the conceptual phase of a product design and continuing throughout all phases of a product life cycle. The objective is to identify potential reliability problems as early as possible in the product life cycle since changes in the early stages of design are much less expensive than those carried out during manufacture or after the product is released for use.

Risk is the combination of the severity of failure and the probability of occurring. Severity of failure includes the cost of damage, repair, and production loss as a result of downtime. Acceptable level of risk is determined by the manufacturer and/or customers. Assessment of product reliability begins at the system design stage. FTA provides a graphical means of evaluating the relationships between different parts of the system and can be used to compare the reliability parameters of the different design alternatives. The most common reliability parameter is the mean time to failure (MTTF) or the number of failures during a given period. Reliability increases as the MTTF increases. The MTTF is usually specified in hours, but can also be used with other units of measurement, such as miles or cycles.

Creating redundancy in the design is an important means of increasing reliability. Redundancy provides an alternate success path if one part of the system fails. Design redundancy can be used to increase the safety of a system. For example, two redundant systems with independent failure modes, each having a failure rate of 10^{-5} per hour, could achieve a failure rate on the order of 10^{-10} per hour because of the multiplication rule for independent events. When adding redundant equipment is impractical, a fail-safe design may be adopted so that the failure modes of the system are not catastrophic. For example, the cable carrying the elevator cabin keeps spring-loaded brakes open. If the cable breaks, the brakes grab the guide rails, and the cabin does not fall. Combining redundancy with a high level of failure monitoring and the avoidance of common causes of failure, as discussed in part II of this book, can improve the system reliability even if some parts have relatively lower reliability. Additionally, reliability-centered maintenance (RCM) can be used to analyze potential failures within a system and determine maintenance actions that can reduce the risk of failure. RCM is used in aircraft to predict future failures and take maintenance actions. Such actions can be based on readings of gauges or simply time of operation.

Testing programs for reliability and safety can also be designed to discover potential problems with the design as early as possible and, ultimately, provide confidence that the system meets its reliability and safety requirements. Testing may be performed at several levels including component, subassembly, and system. Accelerated tests may be performed on components or products that are expected to last long times under normal operating conditions. Increasing the number of items tested and the test time increases the confidence in the test results but also increases to the cost of the test program. The voice of the customer should be helpful to the manufacturer in deciding the strategy for reliability and safety testing.

Safety can also be improved by planning for containment and isolation. For example, isolating valves can be used to isolate pumps and tanks that may fail or need routine maintenance. In addition, tanks containing oil or other hazardous chemicals are required to have containment barriers around them to contain 100% of the volume of the tank in the event of a catastrophic tank failure.

5.11 PRODUCT LIABILITY

Product liability is the area of law in which manufacturers are held responsible for the injuries caused by their products. Such injuries can be caused as a result of manufacturing defects, design defects, or failure to warn. Manufacturing defects can be caused by poor-quality materials or unsatisfactory manufacturing. Design defects occur where the product design is inherently dangerous regardless of how carefully manufactured. Failure to warn defects arise in products that have inherent dangers that could be avoided if the user is adequately warned. For example, toy manufacturers are often mandated to display age limits of the children who are intended to play with the toy, especially for toys that contain loose parts that can be swallowed by or cause chocking in young children.

Strict liability claims focus on the product itself. Under strict liability, the manufacturer is liable if the product is defective, even if the manufacturer was not negligent in making that product defective.

In addition to liability, the law provides the consumer with protection against product defects that merely render the product unusable and hence cause economic injury, even if they do not cause physical injury or damage to property. Consumer protection laws and regulations are designed to safeguard the rights of consumers and to ensure availability of truthful information about products in the marketplace. Consumer protection laws deal with fraud and unfair practices and cover a wide range of issues including product safety, contracts, after-sales service and repair, as well as pricing. For example, manufacturers may be required to disclose detailed information about products—particularly in areas where safety or public health is an issue, such as food.

Product recall is a request to return to the maker a batch or an entire production run of a product, usually due to the discovery of safety issues. The recall is an effort to limit liability for manufacturers' negligence. Recalls can result in reduced trust in the manufacturer in addition to the cost of replacing the recalled product or paying for damage caused by its use. Many of the product recalls in the food industries occur as a result of contamination or presence of foreign objects in food or beverage containers. In the motorcar industry, some recalls that received wide publicity include the unsafe design of the gas tank used in the Ford Pinto, the unintended acceleration in the Audi 5000, the faulty accelerator pedals in several million Toyota cars, and the improperly placed spring in 700,000 Honda engines. One of the product recall incidents in the toy industry was in the 1990s and involved "Snack Time Kids," which was a "Cabbage Patch Kids" line of dolls. The dolls were designed to "eat" plastic snacks. The mechanism consisted of a pair of metal rollers behind a plastic slot representing the mouth. After 700,000 dolls were distributed in the market and as a result of several incidents in which a child's hair or finger was caught in the mouths, the manufacturer, Mattel, announced that they would place warning labels on all unsold dolls, but soon after that the dolls were removed from the market.

5.12 SUMMARY

1. Engineering design is an interdisciplinary process that transforms consumer needs into instructions that allow successful manufacture of the product.
2. A good design should result in an attractive and user-friendly product that performs its function efficiently and economically within the prevailing legal, social, safety, and reliability requirements.
3. Major phases of design can be grouped into three categories: preliminary and conceptual design, configuration (embodiment) design, and detail (parametric) design. Materials and manufacturing processes are better defined as the design progresses.
4. A design code is a set of specifications for the analysis, design, manufacture, and construction of a structure or a product. A standard specification is a published document that describes the characteristics of a part, material, or process and should contain both technical and commercial requirements.
5. The factor of safety is used in design to ensure satisfactory performance. This factor is normally in the range of 1.5–10 and is used to divide into the strength of the material to obtain the allowable stress or the load to obtain the allowable load.
6. The lack of homogeneity of a material property or variations in the externally applied load can be statistically described by a mean value, a standard deviation, and a coefficient of variation. These parameters can be used to estimate a factor of safety and to calculate the probability of failure of a component and its reliability in service. When the available material properties are not available in a statistical form, approximate methods may be used.
7. Reliability engineering focuses on costs of failure caused by system downtime, cost of spares, repair equipment, personnel, and cost of warranty claims. On the other hand, safety engineering focuses on preserving life and nature and therefore deals only with particular dangerous system failure modes.
8. Product liability is the area of law in which manufacturers are held responsible for the injuries caused by their products. Such injuries can be caused as a result of manufacturing defects, design defects, or failure to warn. Strict liability claims focus on the product itself. Under strict liability, the manufacturer is liable if the product is defective, even if the manufacturer was not negligent in making that product defective.

REVIEW QUESTIONS

5.1 An aluminum 2014 T6 tube of 75 mm (3 in.) outer diameter and 1 mm (0.04 in.) thickness is subjected to internal pressure of 8.4 MPa (1200 lb/in.^{2}). What is the factor of safety that was taken against failure by yielding when the pipe was designed? (Answer: 1.35)

5.2 Distinguish between the factor of safety and the derating factor. What are the main factors that affect the value of the factor of safety?

5.3 A structural member is made of steel of mean yield strength of 200 MPa (28.6 ksi) and a standard deviation on strength of 30 MPa (4.3 ksi). The applied stress has a mean value of 150 MPa (14.3 ksi) and a standard deviation of 5 MPa (700 lb/in.^{2}). (a) What is the probability of failure? (Answer: 6.9%) (b) What factor of safety is required if the allowable failure rate is 1%? (Answer: 1.55)

5.4 What are the steps required for a manufacturer of domestic water heaters to convert gas into solar energy heating?

5.5 A structural element is made of FRP with an average tensile strength of 2400 MPa. The element is subjected to a static tensile stress of an average value of 1800 MPa. If the variations in material quality and load cause the strength and stress to vary according to normal distributions with standard deviations of $\sigma_S = 380$ and $\sigma_L = 330$, respectively, what is the probability of failure of the structural element?

5.6 Select an everyday product such as a bicycle, child toy, or can opener. List the different areas in the product in order of importance to the function and safety. Assign factors of safety that you would use in designing each area.

5.7 For the product selected in Question 5.6, which features would you emphasize when you plan the marketing campaign?

5.8 A manufacturer of sports equipment is considering the possibility of using FRP in making racing bicycle frames. It was suggested that fatigue failures of the joints could be a problem in this case. Describe a testing program that can address this problem.

5.9 Two batches of steel components were heat-treated in two different shops. The RC hardness results were as follows:

Shop 1: 48, 51, 52, 49, 50, 50, 47, 50, 51, and 47

Shop 2: 50, 49, 47, 48, 50, 48, 49, 52, 51, and 48

Did treating the steel in the different shops make a significant difference? (Answer: no)

5.10 Study a car jack. Suggest changes in the design to make it easier to be used by a handicapped driver.

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6 Effect of Material Properties on Design

6.1 INTRODUCTION

Figure 5.1 illustrates the direct relation between material properties and component design. This relation, however, is complex because the behavior of the material in the finished product can be quite different from that of the stock material used in making it. This point is illustrated in Figure 6.1, which shows the direct influence of stock material properties, production method, component geometry, and external forces on the behavior of materials in the finished component. The figure also shows that secondary relationships exist between geometry and production method, between stock material and production method, and between stock material and component geometry. The effect of stock material properties, component geometry, and applied forces on the behavior of materials is discussed in this chapter, and the effect of production method on the design and component geometry is discussed in Chapter 7.

The goal of this chapter is to illustrate how the material-related factors affect the design. The main objectives are to get a better understanding of the material properties that need to be considered when designing for the following:

1. Static strength, stiffness, and toughness
2. Fatigue resistance
3. High-temperature conditions
4. Hostile environments
5. Wear resistance

6.2 DESIGNING FOR STATIC STRENGTH

Designs based on the static strength usually aim at avoiding yielding of the component in the case of soft, ductile materials and at avoiding fracture in the case of strong, low-toughness materials. Designs based on soft, ductile materials are discussed in this section, whereas those based on strong, low-toughness materials are discussed in Section 6.4.

6.2.1 Designing for Simple Axial Loading

Components and structures made from ductile materials are usually designed so that no yield will take place under the expected static loading conditions. When the component is subjected to uniaxial stress, yielding will take place when the local stress reaches the yield strength of the material. The critical cross-sectional area, A, of such a component can be estimated as

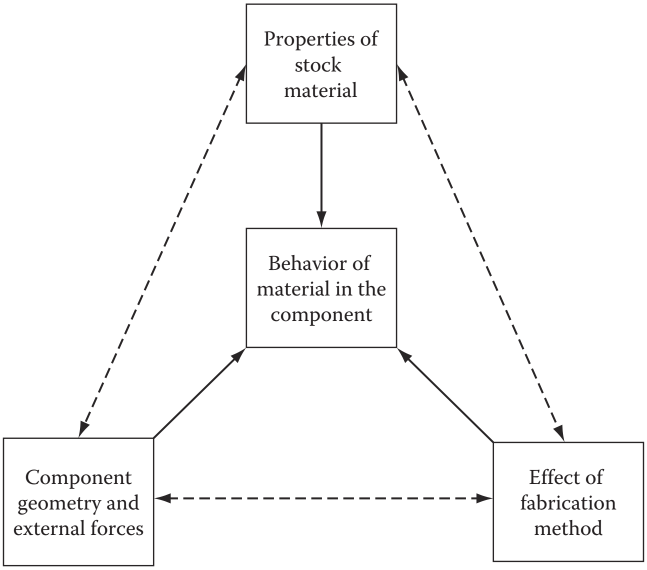

FIGURE 6.1 Factors that should be considered in anticipating the behavior of a material in the component.

$$A = \frac{K_t n L}{\mathrm{YS}} \tag{6.1}$$

where
- K_t is the stress concentration factor
- L is the applied load
- n is the factor of safety
- YS is the yield strength of the material

6.2.2 Designing for Torsional Loading

The critical cross-sectional area of a circular shaft subjected to torsional loading can be determined from the relationship

$$\frac{2I_p}{d} = \frac{K_t n T}{\tau_{max}} \tag{6.2}$$

where
- d is the shaft diameter at the critical cross section
- τ_{max} is the shear strength of the material
- T is the transmitted torque
- I_p is the polar moment of inertia of the cross section

$I_p = \pi d^4/32$ for a solid circular shaft

$I_P = \pi(d_o^4 - d_i^4)/32$ for a hollow circular shaft of inner diameter d_i and outer diameter d_o

Although Equation 6.2 gives a single value for the diameter of a solid shaft, a large combination of inner and outer diameters can satisfy the relationship in the case of a hollow shaft. Under such conditions, either one of the diameters or the required thickness has to be specified to calculate the other dimensions.

The ASTM code of recommended practice for transmission shafting gives an allowable value of shear stress of 0.3 of the yield or 0.18 of the UTS, whichever is smaller. With shafts containing keyways, ASTM recommends a reduction of 25% of the allowable shear strength to compensate for stress concentration and reduction in cross-sectional area.

6.2.3 Designing for Bending

When a relatively long beam is subjected to bending, the bending moment, the maximum allowable stress, and dimensions of the cross section are related by the equation

$$Z = \frac{nM}{\mathrm{YS}} \tag{6.3}$$

where

M is the bending moment

Z is the section modulus $= I/c$

I is the moment of inertia of the cross section with respect to the neutral axis normal to the direction of the load (Figure 4.2 gives the formulas for calculating the value of I for some commonly used cross sections)

c is the distance from the center of gravity of the cross section to the outermost fiber

Example 6.1 illustrates the use of Equation 6.3 in design.

Design Example 6.1: Designing a Cantilever Beam

Problem

Determine the dimensions of a cantilever beam of length 1 m and rectangular cross section of depth-to-width ratio 2:1. The cantilever is expected not to deflect more than 50 mm for every 1000 N increment of load at its tip. The material used in making the beam is steel AISI 4340 with a yield strength of 1420 MPa and UTS 1800 MPa. What is the maximum permissible load? Assume a suitable factor of safety.

Answer

Deflection (y) of a cantilever beam under a load (L) acting on its tip is given by the relationship

$$y = \frac{Ll^3}{3EI}$$

where

l is the length of the cantilever
E is the elastic modulus of the cantilever material = 210 GPa
I is the second moment of area of the cross section

From Table 4.4,

$$I = \frac{b(2b)^3}{12} = \frac{Ll^3}{3yE} = \frac{1000 \times (1000)^3}{3 \times 50 \times 210 \times 10^3}$$

The preceding equation gives the width of the beam, $b = 14.77$ mm.

Taking a factor of safety $n = 1.5$ and using Equation 6.3,

$$Z = \frac{14.77(2 \times 14.77)^3}{12 \times 14.77} = 2148 \text{ mm}^3 = \frac{nM}{\text{YS}} = \frac{1.5 \times L \times 1000}{1420}$$

The safe value of $L = 2033$ N.

6.3 DESIGNING FOR STIFFNESS

In addition to being strong enough to resist the expected service loads without yielding, there may also be the added requirement of stiffness to ensure that deflections do not exceed certain limits. Stiffness is important in applications such as machine elements to avoid misalignment and to maintain dimensional accuracy of machine parts. In such cases, the dimensions of a component are calculated once for resistance to yielding and another for resistance to deflection, and the larger dimensions are selected. This point is illustrated in Example 6.2.

Design Example 6.2: Selection of a Material for a Tie-Rod

Problem

It is required to select a structural material for the manufacture of the tie-rods of a suspension bridge. A representative rod is 10 m long and should carry a tensile load of 50 kN without yielding. The maximum extension should not exceed 18 mm. Which one of the steels listed in Table 6.1 will give the lightest tie-rod?

Solution

For the present case, calculations of the area will be carried out twice:

1. Area based on yield strength = load/YS
2. Area based on deflection = (load × length)/(E × deflection)

TABLE 6.1
Candidate Materials for Suspension Bridge Tie-Rods

Material	YS (MPa)	*E* (GPa)	Specific Gravity	Area Based on Yield Strength (mm^2)	Area Based on Deflection (mm^2)	Mass (kg)
ASTM A675 grade 60	205	212	7.8	244	131	19
ASTM A572 grade 50	345	211	7.8	145	131	11.3
ASTM A717 grade 70	485	211	7.8	103	131	10.2
Maraging steel grade 200	1400	211	7.8	36	131	10.2
Al 5052-H38	259	70.8	2.7	193	392	10.6
Cartridge brass 70% hard temper	441	100.6	8.0	113	276	22.1

The larger of the two areas will be taken as the design area and will be used to calculate the mass.

The results of the calculations, given in Table 6.1, show that steel A717 grade 70 and maraging steel grade 200 give the least mass. As the former steel is more ductile and less expensive, it will be selected.

6.3.1 Design of Beams

When an initially straight beam is loaded, it becomes curved as a result of its deflection. As the deflection at a given point increases, the radius of curvature at this point decreases. The radius of curvature, r, at any point on the curve is given by the relationship

$$r = \frac{EI}{M} \tag{6.4}$$

Equation 6.4 shows that the stiffness of a beam under bending is proportional to the elastic constant of the material, E, and the moment of inertia of the cross section, I. Selecting materials with higher elastic constant and efficient disposition of material in the cross section are essential in designing of beams for stiffness. Placing the material as far as possible from the neutral axis of bending is generally an effective means of increasing I for a given area of cross section.

When designing with plastics, whose elastic modulus is 10–100 times less than that of metals, stiffness must be given special consideration. This drawback can usually be overcome by making some design adjustments. Figure 6.2 shows examples of how the low stiffness of plastics is overcome by increasing the second moment of area of the critical cross section. Example 6.3 illustrates this point.

(a)

(b)

(c)

FIGURE 6.2 Examples of how the low stiffness of plastics is overcome by increasing the second moment of area of the critical cross section: (a) spoons, (b) forks, and (c) knives.

Design Example 6.3: Substitution of HDPE for Stainless Steel

Problem

What design changes are required when substituting high-density polyethylene (HDPE) for stainless steel in making a fork for a picnic set while maintaining similar stiffness?

Solution

E for stainless steel = 210 GPa
E for HDPE = 1.1 GPa

The narrowest cross section of the original stainless steel fork is rectangular, of 0.6 × 5 mm:

$$I \text{ for the stainless steel section} = \frac{5\times(0.6)^3}{12} = 0.09 \text{ mm}^4$$

From Equation 6.4, *EI* should be kept constant for equal deflection under load.
EI for stainless steel = 210 × 0.09 = 18.9
EI for HDPE design = 1.1 × *I*
I for HDPE design = 17.2 mm^4
Taking a channel section of thickness 0.5 mm, web height 4 mm, and width 8 mm, from Table 4.4,

$$I = \frac{[8 \times (4)^3 - 7 \times (3.5)^3]}{12} = 17.7 \text{ mm}^4$$

which meets the required value.

Area of the stainless steel section = 3 mm^2

Area of the HDPE section = 7.5 mm^2

The specific gravity of stainless steel is 7.8 and that of HDPE is 0.96:

$$\frac{\text{Relative weight of HDPE}}{\text{Stainless steel}} = \frac{7.5 \times 0.96}{3 \times 7.8} = 0.3$$

6.3.2 Design of Shafts

The torsional rigidity of a component is usually measured by the angle of twist, θ, per unit length.

For a circular shaft, θ is given in radians by

$$\theta = \frac{T}{GI_p} \tag{6.5}$$

where

T is the torque

I_p is the polar moment of area

G is the modulus of elasticity in shear

$$G = \frac{E}{2(1+v)} \tag{6.6}$$

where

v is Poisson's ratio

E is the elastic modulus

The usual practice is to limit the angular deflection in shafts to about 1°, that is, π/180 radians, at a length of 20 times the diameter.

6.3.3 Design of Columns

Elastic instability becomes an important design criterion in the case of columns, struts, and thin-wall cylinders subjected to compressive axial loading where failure can take place by buckling. Buckling takes place if the applied axial compressive load exceeds a certain critical value, P_{cr}. The Euler column formula is usually used to calculate the value of P_{cr}, which is a function of the elastic modulus of the material, geometry of the column, and restraint at the ends. For the fundamental case of a pin-ended column, that is, ends are free to rotate around frictionless pins, P_{cr} is given as

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{6.7}$$

where

I is the least moment of inertia of the cross-sectional area of the column
L is the length of the column

Equation 6.7 can be modified to allow for end conditions other than the pinned ends. The value of P_{cr} for a column with both ends fixed, that is, built in as part of the structure, is four times the value given by Equation 6.7. However, the critical load for a free-standing column, that is, one end is fixed and the other free as in a cantilever, is only one quarter of the value given by Equation 6.7.

The Euler column formula shows that the critical load for a given column is only a function of E and I and is independent of the compressive strength of the material. This means that the resistance to buckling of a column of a given material and a given cross-sectional area can be increased by distributing the material as far as possible from the principal axes of the cross section. Hence, tubular sections are preferable to solid sections in carrying loads. Reducing the wall thickness of such sections and increasing the transverse dimensions increase the stability of the column. However, there is a lower limit for the wall thickness below which the wall itself becomes unstable and causes local buckling.

Experience shows that the values of P_{cr} calculated according to Equation 6.7 are higher than the buckling loads observed in practice. The discrepancy is usually attributed to manufacturing imperfections, such as lack of straightness of the column and lack of alignment between the direction of the compressive load and the axis of the column. This discrepancy can be accounted for by using an appropriate imperfection parameter or a factor of safety. For normal structural work, a factor of safety of 2.5 is usually used. As the extent of the imperfections mentioned is expected to increase with increasing slenderness of the column, it is suggested that the factor of safety be increased accordingly. A factor of safety of 3.5 is recommended for columns with $[L(A/I)^{1/2}] > 100$, where A is the cross-sectional area.

Equation 6.7 shows that the value of P_{cr} increases rapidly as the length of the column, L, decreases. For a short enough column, P_{cr} becomes equal to the load required for yielding or crushing of the material in simple compression. Such a case represents the limit of applicability of the Euler formula as failure takes place by yielding or fracture rather than elastic instability. Such short columns are designed according to the procedure described for simple axial loading. This design procedure is illustrated in Example 4.1.

6.4 DESIGNING WITH HIGH-STRENGTH, LOW-TOUGHNESS MATERIALS

High-strength materials are being increasingly used in designing critical components to save weight or to meet difficult service conditions. Unfortunately, these materials tend to be less tolerant of defects than the traditional lower-strength, tougher materials. Although a crack-like defect can safely exist in a component made of low-strength ductile material, it can cause catastrophic failure if the same part is made of a high-strength low-toughness material. This has led to more demand for accurate calculation of acceptable defect levels and to an increased use of NDT in manufacture. These defects can be the result of

1. Initial flaws in the material, for example, inclusions and cavities
2. Production deficiencies, for example, welding defects
3. Service conditions, for example, fatigue cracks or stress corrosion cracks

6.4.1 Fail-Safe Design

Fail safety requires a structure to be sufficiently damage tolerant to allow defects to be detected before they develop to a dangerous size. This means that inspection has to be conducted before the structure is put into service to ensure that none of the existing defects exceed the critical size. In addition, the structure has to be inspected periodically during its service life to ensure that none of the subcritical defects grow to a dangerous size, as illustrated in Figure 6.3. The figure shows that it is not strictly necessary to select a material with a low crack propagation rate. In principle, the structure can be made fail safe when cracks propagate fast if the inspection interval is short enough. However, short inspection periods are not always possible or cost-effective. A better alternative is to use a more sensitive inspection method to reduce the minimum detectable defect size.

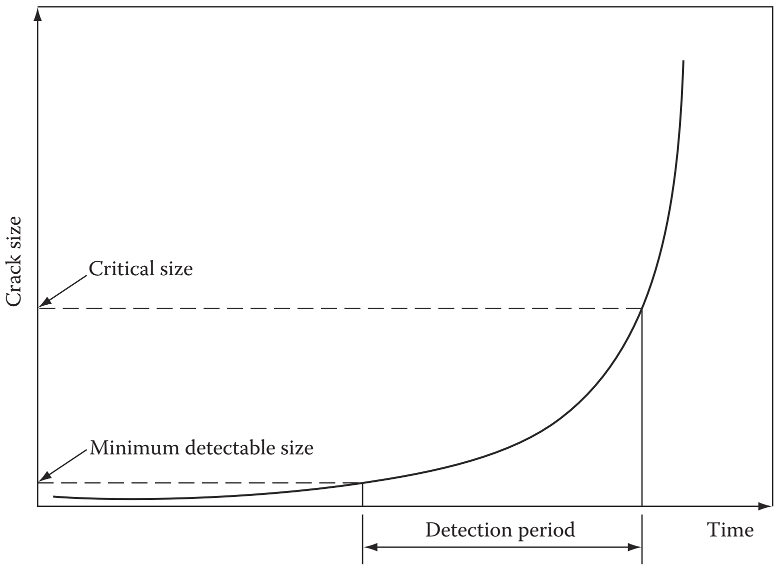

FIGURE 6.3 Principles involved in fail-safe designs.

6.4.2 Guidelines for Design

In designing with high-strength low-toughness materials, the interaction between fracture toughness of the material, the allowable crack size, and the design stress should be considered. An analogy can be drawn between these parameters and the yield strength and the nominal stress, which are considered in designing with ductile unflawed part. In the latter case, as the load increases, the nominal stress increases until it reaches the yield stress and plastic deformation occurs. In the case of high-strength low-toughness material, as the design stress increases (or as the size of the flaw increases), the stress concentration at the edge of the crack, stress intensity K_I, increases until it reaches K_{IC} and fracture occurs. Thus, the value of K_I in a structure should always be kept below the K_{IC} value in the same manner that the nominal design stress is kept below the yield strength. It was shown in Section 2.3 that the condition for failure under plane strain conditions, where a crack of length $2a$ exists in a thick infinitely large plate, is given by

$$K_I = K_{IC} = Y\sigma_f (\pi a)^{1/2} \tag{6.8}$$

where

- σ_f is the fracture stress and is controlled by the applied load and shape of the part
- a is a quality control parameter, which is controlled by the manufacturing method and NDT technique used
- Y is a dimensionless shape factor, which is a function of crack geometry

The value of Y can be estimated experimentally, analytically, or numerically. For simplicity, Y is taken as 1 for infinite plate with center through thickness crack or surface crack and as 1.12 for edge cracks. More accurate estimations of Y can be found in ASTM STP 380 and 410 standards.

Equation 6.8 may be used in several ways to design against failure. For example, selecting a material to resist other service requirements automatically fixes K_{IC}. In addition, if the minimum crack size that can be detected by the available NDT methods is known, Equation 6.8 is used to calculate the allowable design stress, which must be less than $K_{IC}/Y(\pi a)^{1/2}$. Alternatively, if the space and weight limitations necessitate a given material and operating stress, the maximum allowable crack size can be calculated to check whether it can be detected using routine inspection methods. Example 6.4 illustrates the use of K_{IC} in design.

Design Example 6.4: Designing with K_{IC}

Problem

If the minimum detectable crack in the beam described in Example 6.1 is 3 mm, what is the maximum permissible load? K_{IC} of the beam material is 87.4 MPa $(m)^{1/2}$.

Answer

From Equation 6.8,

$$K_{IC} = 87.4 = Y\sigma_f\,(\pi a)^{1/2}$$

Taking $Y = 1$ and $a = 1.5$ mm, we have $\sigma_f = 1273.2$ MPa

From Equation 6.3,

$$L = \frac{\sigma_f \times Z}{n \times l} = \frac{1273.2 \times 2148}{1.5 \times 1000} = 1824 \text{ N}$$

Conclusion

This load is less than the "safe load" calculated in Example 6.1, which means that, had the presence of cracks been ignored, failure would have taken place.

6.4.3 Leak-before-Burst

Another design approach that utilizes the fracture mechanics approach is the leak-before-burst concept, which can be used in designing pressure vessels and similar structures. This approach is based on the concept that if a vessel containing pressurized gas or liquid contains a growing crack, the toughness should be sufficiently high to tolerate a defect size that will allow the contents to leak out before it grows catastrophically. For leakage to occur, the crack must grow through the vessel wall thickness, t. This means that the crack length $2a$ is about $2t$. From Equation 6.8, it can be seen that this condition is satisfied when $(K_{IC}/Y\sigma)^2$ is larger than πt. Example 6.5 illustrates the use of the leak-before-burst approach in design.

Design Example 6.5: Designing a Pressure Vessel for Leak-before-Burst Conditions

Problem

Design a pressure vessel of the following specifications:

Internal pressure, $p = 16$ MN/m^2 (2320 psi)

Internal diameter, $D = 400$ mm (15.75 in.)

The pressure vessel will be manufactured by welding of sheets, and the welded joints will then be inspected using an NDT technique, which is capable of detecting surface cracks of sizes greater than 3 mm (ca. 0.118 in.).

Solution

As a preliminary step, consider the use of AISI 4340 in the manufacture of the pressure vessel (see Table 4.7). When tempered at 260°C (500°F), this steel has a yield strength of 1640 MPa (238 ksi) and $K_{IC} = 50.0$ MPa (m)$^{1/2}$ (45.8 ksi (in.)$^{1/2}$).

Treating the pressure vessel as a thin-wall cylinder, the wall thickness, t, can be calculated as

$$t = \frac{pD}{2S_w} \tag{6.9}$$

where S_w is the working stress.

Taking a factor of safety of 2, the working stress is 820 MPa (119 ksi) and the wall thickness is 3.9 mm (0.15 in.).

The critical surface crack size can then be calculated from Equation 6.8 as

$$K_{IC} = 50 = Y\sigma_f\,(\pi a)^{1/2} = Y \times 820(\pi a)^{1/2}$$

Taking Y as 1, for σ_f/YS = 0.5, the critical crack length is found to be 2.37 mm (0.093 in.). This length is too small to be detected by the available NDT technique and does not satisfy the condition for leak before burst, which makes the selected steel unsuitable.

Taking the same steel, AISI 4340, but tempering at 425°C (800°F) gives a yield strength of 1420 MPa (206 ksi) and K_{IC} of 87.4 MPa (m)$^{1/2}$ (80 ksi in.$^{1/2}$).

Following the same procedure as before, $t = 4.5$ mm (0.177 in.) and the critical crack length is 9.66 mm (0.38 in.), which can be detected by the available NDT technique and also satisfies the condition for leak before burst. This means that the steel in this tempered condition is acceptable for making the pressure vessel from the fracture mechanics point of view. Other factors such as availability of material, weldability, weight of vessel, and cost have to be taken into consideration before this steel is finally selected.

6.5 DESIGNING AGAINST FATIGUE

The fatigue behavior of materials is usually described by means of the S–N diagram that gives the number of cycles to failure, N, as a function of the maximum applied alternating stress, S_a, as shown in Figure 2.9.

6.5.1 Factors Affecting Fatigue Behavior

In the majority of cases, the reported fatigue strengths or endurance limits of materials are based on tests of carefully prepared small samples under laboratory conditions. Such values cannot be directly used for design purposes because the behavior of a component or structure under fatigue loading depends not only on the fatigue or endurance limit of the material used in making it but also on several other factors including

- Size and shape of the component or structure
- Type of loading and state of stress
- Stress concentration
- Surface finish
- Operating temperature
- Service environment
- Method of fabrication

The effect of some of these parameters on the fatigue strength of some steels is shown in Table 6.2. The influence of the previously mentioned factors on fatigue behavior of a component can be accounted for by modifying the endurance limit of the material using a number of factors, as discussed in the following paragraphs.

TABLE 6.2
Effect of Surface Condition and Environment on the Fatigue Strength of Steels

	Fatigue Strength as Percentage of Maximum Endurance Limit						
UTS (MPa) (ksi)	Mirror Polish	Polished	Machined	0.1 mm Notch	Hot-Worked Surface	Under Freshwater	Under Saltwater
280 (40)	100	95	93	87	82	72	52
560 (80)	100	92	88	77	63	53	36
840 (122)	100	90	84	66	47	37	25
1120 (162)	100	88	78	55	37	25	17
1400 (203)	100	88	72	44	30	19	14
1540 (223)	100	88	69	39	30	19	12

6.5.1.1 Endurance-Limit-Modifying Factors

A variety of modifying factors, or derating factors, are usually used to account for the main parameters that affect the behavior of components or structures in service. The numerical value of each of the modifying factors is less than unity and each one is intended to account for a single effect. This approach is expressed as follows:

$$S_e = k_a k_b k_c k_d k_e k_f k_g k_h S_e' \tag{6.10}$$

where

- S_e is the endurance limit of the material in the component
- S_e' is the endurance limit of the material as determined by laboratory fatigue test
- k_a is the surface finish factor
- k_b is the size factor
- k_c is the reliability factor
- k_d is the operating temperature factor
- k_e is the loading factor
- k_f is the stress concentration factor
- k_g is the service environment factor
- k_h is the manufacturing processes factor

Equation 6.10 can be used to predict the behavior of a component or a structure under fatigue conditions, provided that the values of the different modifying factors are known. The effect of some of the previously mentioned factors on fatigue behavior is known and can be estimated accurately; others are more difficult to quantify, as the following discussion shows.

6.5.1.1.1 Surface Finish Factor

Surface finish factor, k_a, is introduced to account for the fact that most machine elements and structures are not manufactured with the same high-quality finish that

TABLE 6.3
Effect of Surface Finish and UTS on Surface Finish Factor (k_a) for Steels

UTS (MPa) (ksi)	Forged $R_a = 500–125$	Hot Rolled $R_a = 250–63$	Machined or Cold Drawn $R_a = 125–32$	Ground $R_a = 63–4$	Polished $R_a < 16$
420 (60)	0.54	0.70	0.84	0.90	1.00
700 (100)	0.40	0.55	0.74	0.90	1.00
1000 (143)	0.32	0.45	0.68	0.90	1.00
1400 (200)	0.25	0.36	0.64	0.90	1.00
1700 (243)	0.20	0.30	0.60	0.90	1.00

is normally given to laboratory fatigue test specimens. The value of k_a can vary between unity and 0.2 depending on the surface finish and the strength of the material. As shown in Tables 6.2 and 6.3, stronger materials are more sensitive to surface roughness variations.

6.5.1.1.2 Size Factor

Size factor, k_b, accounts for the fact that large engineering parts have lower fatigue strengths than smaller test specimens. In general, the larger the volume of the material under stress, the greater is the probability of finding metallurgical flaws that could cause fatigue crack initiation. Although there is no quantitative agreement on the precise effect of size, the following values can be taken as rough guidelines:

$k_b = 1.0$ for component diameters less than 10 mm (0.4 in.)
$k_b = 0.9$ for diameters in the range of 10–50 mm (0.4–2.0 in.)
$k_b = 1 - [(D - 0.03)]/15$

where D is the diameter expressed in inches, for sizes 50–225 mm (2–9 in.).

6.5.1.1.3 Reliability Factor

Reliability factor, k_c, accounts for the random variations in fatigue strength. The published data on endurance limit usually represent average values representing 50% survival in fatigue tests. Since most designs require higher reliability, the published values of endurance limit must be reduced by the reliability factor, k_c. The following values can be taken as guidelines:

$k_c = 0.900$ for 90% reliability
$k_c = 0.814$ for 99% reliability
$k_c = 0.752$ for 99.9% reliability

6.5.1.1.4 Operating Temperature Factor

Operating temperature factor, k_d, accounts for the difference between the test temperature, which is normally room temperature, and the operating temperature of the component or structure. For carbon and alloy steels, the fatigue strength is not greatly affected by operating temperature in the range from 45°C to 450°C (–50°F to 840°F) and, therefore, k_d can be taken as 1.0 in this temperature range. At higher operating temperatures, k_d can be calculated according to the following relationships:

$$k_d = 1 - 5800(T - 450) \text{ for } T \text{ between } 450°\text{C and } 550°\text{C}$$

or

$$k_d = 1 - 3200(T - 840) \text{ for } T \text{ between } 840°\text{F and } 1020°\text{F}$$

6.5.1.1.5 Loading Factor

Loading factor, k_e, can be used to account for the differences in loading between laboratory tests and service. Transient overloads, vibrations, shocks, and changes in load spectrum that may be encountered during service can greatly affect the fatigue life of a component or structure. Experience shows that repeated overstressing, that is, stressing above the fatigue limit, can reduce the fatigue life. Under such conditions, k_e should be given a value less than unity. The type of loading also affects the fatigue life. Most published fatigue data are based on reversed bending test. Other types of loading, for example, axial or torsional, generate different stress distributions in the material, which could affect the fatigue results. The factor k_e can be used as a correction factor to allow the use of reversed bending data in a different loading mode. Thus,

$k_e = 1$ for applications involving bending
$k_e = 0.9$ for axial loading
$k_e = 0.58$ for torsional loading

6.5.1.1.6 Stress Concentration Factor

Stress concentration factor, k_f, accounts for the stress concentrations that may arise due to changes in cross section or similar design features, as discussed in Section 5.5. Experience shows that low-strength, ductile steels are less sensitive to notches than high-strength steels.

6.5.1.1.7 Service Environment Factor

Service environment factor, k_g, accounts for the reduced fatigue strength due to the action of hostile environment. The sensitivity of the fatigue strength of steels to corrosive environments is also affected by their strength, as shown in Table 6.4.

TABLE 6.4
Effect of Environment and UTS on the Service Environment Factor (k_g) for Steels

UTS (MPa) (ksi)	k_g under Freshwater	k_g under Saltwater
280 (40)	0.72	0.52
560 (80)	0.52	0.36
840 (122)	0.37	0.25
1120 (162)	0.25	0.17
1400 (203)	0.19	0.14
1540 (223)	0.19	0.12

6.5.1.1.8 Manufacturing Process Factor

Manufacturing process factor, k_h, accounts for the influence of fabrication parameters such as heat treatment, cold working, residual stresses, and protective coatings on the fatigue strength of the material. Although the factor, k_h, is difficult to quantify, it is included here as a reminder that the previously mentioned parameters should be taken into account.

Example 6.6 illustrates the use of the mentioned parameters in design.

Design Example 6.6: Design of an Axle for Fatigue Resistance

Problem

Calculate the diameter of the two rear axle shafts for a truck of gross mass of 6000 kg when fully loaded. Assume that two-thirds of the mass of the truck is supported by the rear axles, and the construction is such that the axles can be treated as cantilever beams each of 1 m length with the load acting on its end. The shaft material is heat-treated 4340 steel of tensile strength 952 MPa. The shaft construction requires a change in diameter to allow the fitting of bearings.

Solution

From Table 4.8, the endurance ratio of the steel is 0.56 and the endurance limit is 532 MPa. Assuming that the shaft will be finished by machining, the surface finish factor, k_a, can be taken as 0.68 (Table 6.3). As the shaft diameter is expected to be in the range of 50–225 mm, the size factor, k_b, can be taken as 0.8, assuming a 3 in. diameter. The reliability of the shaft should be high and the reliability factor is taken as $k_c = 0.752$. The loading factor can be taken as $k_e = 1$, as the shaft is loaded in bending. Stress concentration due to change in diameter can be reduced by taking a relatively large fillet radius at the change in diameter, and in this case $k_f = 0.7$. From Equation 6.10, the endurance limit of the shaft material S_e is

$$S_e = 532 \times 0.68 \times 0.8 \times 0.752 \times 1.0 \times 0.7 = 152.3 \text{ MPa}$$

$$\text{The load acting on each shaft} = 6000 \times \frac{2}{3} \times \frac{1}{2} \times 9.8 = 19{,}600 \text{ N}$$

Bending moment $M = 19{,}600 \times 1 = 19{,}600$ Nm
Stress acting on the surface of the shaft $= S = M/Z = 32\ M/\pi D^3$

$$D^3 = \frac{32 \times 19{,}600 \times 1000}{\pi \times 152.3} = 1{,}310{,}860 \text{ mm}^3$$

$$D = 109.5 \text{ mm}$$

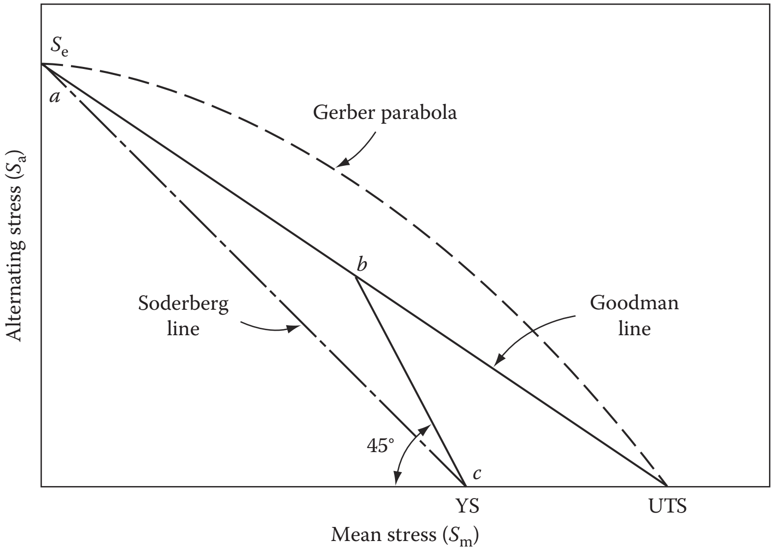

FIGURE 6.4 Fatigue behavior under combined static and alternating stresses.

6.5.2 Effect of Mean Stress

In the majority of cases, the fatigue behavior is determined using the rotating bending test, which applies alternating tension–compression and a stress ratio $R = -1$, as shown in Figure 2.8. In practice, however, conditions are often met where a static mean stress, S_m, is also present, as shown in Figure 2.8. Several methods are available for describing the fatigue behavior of materials under such conditions, as shown in Figure 6.4. The point S_e represents the fatigue or endurance limit under a stress ratio $R = -1$, whereas the points UTS and YS represent the UTS and yield strength under static loading, that is, $S_a = 0$. In general, experimental results for ductile materials fall between the Goodman line and the Gerber parabola, but because of scatter in the results, the Goodman line is usually preferred for design. The Goodman line can be represented by the relationship

$$\left(\frac{S_m}{\mathrm{UTS}}\right) + \left(\frac{S_a}{S_e}\right) \tag{6.11}$$

The Soderberg line is more conservative and uses the yield strength as the limiting mean stress instead of the UTS, as shown in Figure 6.4. The Soderberg line can be represented by Equation 6.11 by substituting YS for UTS.

A criterion that follows the line *abc* of Figure 6.4 is not as conservative as the Soderberg criterion but avoids gross yielding at high mean stresses. Along the line *bc*, which is drawn from the yield stress at 45°, the sum of the mean and alternating stresses equals the yield stress. Operating below this line avoids gross yielding of smooth components under combined alternating and static stresses.

A factor of safety is usually applied when using Equation 6.11 for design. It is generally preferable to employ separate factors of safety for the static and alternating strengths of the material, n_m and n_a, respectively. When the component contains a stress concentration, the maximum allowable static stress is reduced by an amount proportional to the stress concentration factor, K_t, and the fatigue strength is reduced by an amount proportional to the fatigue stress concentration factor, K_f. The factors of safety and stress concentration factors can be incorporated in Equation 6.11, which will allow it to be used for design. Thus,

$$\left(\frac{n_m K_t S_m}{\text{UTS}}\right)+\left(\frac{n_a K_f S_a}{S_e}\right)=1 \tag{6.12}$$

The use of the previously mentioned parameters in design is illustrated in Example 6.7.

Design Example 6.7: Design of a Cantilever Beam for Fatigue Resistance

Problem

If the load acting on the cantilever beam described in Example 6.1 is fluctuating around a mean value of 1000 N, what is the maximum alternating load that can be applied without causing fatigue failure? The endurance ratio of the AISI 4340 steel is 0.56. Use suitable factors of safety.

Answer

From Example 6.1, $Z = 2148\ \text{mm}^3$,

$$\text{Mean stress} = S_m = \frac{M}{Z} = \frac{1000 \times 1000}{2148} = 465.3\ \text{MPa}$$

$$\text{Endurance limit} = S_e = 1800 \times 0.56 = 1008\ \text{MPa}$$

Taking a factor of safety of 1.5 for the static load and 3 for the dynamic load, from Equation 6.12,

$$\left(\frac{1.5 \times 465.3}{1800}\right)+\left(\frac{3 \times S_a}{1008}\right)=1$$

$$S_a = 205.7\ \text{MPa}$$

$$\text{Alternating load} = \frac{(205.7 \times 2148)}{1000} = 440\ \text{N}$$

6.5.3 Cumulative Fatigue Damage

Engineering components and structures are often subjected to different fatigue stresses in service. Estimation of the fatigue life under variable loading conditions is normally based on the concept of cumulative fatigue damage, which assumes that successive stress cycles cause a progressive deterioration in the component.

The Palmgren–Miner rule, also called Miner's rule, proposes that if cyclic stressing occurs at a series of stress levels, S_1, S_2, S_3, … , S_i, each of which would correspond to a failure life of N_1, N_2, N_3, … , N_i, if applied singly, then the fraction of total life used at each stress level is the actual number of cycles applied at this level, n_1, n_2, n_3, … , n_i, divided by the corresponding life. The part is expected to fail when the cumulative damage satisfies the relationship

$$\frac{n_1}{N_1}+\frac{n_2}{N_2}+\frac{n_3}{N_3}+\cdots+\frac{n_i}{N_i}=C \tag{6.13}$$

The constant C can be determined experimentally and is usually found to be in the range 0.7–2.2. When such experimental information is lacking, C can be taken as unity.

The Palmgren–Miner rule takes into account neither the sequence of loading nor the effect of mean stress, and it should only be taken as a rough guide to design.

6.5.4 Other Fatigue Design Criteria

Components made of steel or other materials that have well-defined endurance limits can be designed for an indefinite fatigue life, provided that working stresses do not exceed this critical value. According to the discussion in Section 6.5.1, the endurance limit has to be reduced to account for adverse service environment as well as material, manufacturing, and design inaccuracies. In some cases, components and structures whose design is based on the resulting working fatigue strength would be too heavy or too bulky for the intended application. In such cases, other design criteria such as safe-life, fail-safe, or damage tolerance may be employed.

Safe-life, or finite-life, design is based on the assumption that the component or structure is free from flaws but the stress level in certain areas is higher than the endurance limit of the material. This means that fatigue-crack initiation is inevitable and the life of the component is estimated on the basis of the number of stress cycles that is necessary to initiate such a crack. Fail-safe design is based on the philosophy that cracks that form in service will be detected and repaired before they can lead to failure. Materials with high fracture toughness, crack-stopping features, and a reliable NDT program should be employed when the fail-safe criterion is adopted. Damage-tolerant design is an extension of the fail-safe criterion; it assumes that flaws exist in engineering components and structures before they are put in service. Fracture mechanics techniques as discussed in Section 2.3 and this section are used to determine whether such cracks will grow large enough to cause failure before they are detected during a periodic inspection.

6.6 DESIGNING UNDER HIGH-TEMPERATURE CONDITIONS

From the discussions in Sections 2.6 and 4.7, it becomes clear that the service temperature has a considerable influence on the strength of materials and, consequently, on the working stress used in the design. Depending on the temperature range, the design can be based on the following:

1. Short-time properties of the material, as described by the yield strength and UTS, for moderate temperatures
2. Both short-time and creep properties for intermediate temperature range
3. Creep properties of the materials for high temperatures

For example, in the case of carbon steels, 300°C (575°F) and 400°C (750°F) can be taken as the upper and lower temperature limits of ranges 1 and 3, respectively. Adding alloying elements to the steel generally increases the limiting temperatures of the three ranges. For example, short-time properties of 18–8 stainless steel can be used at temperatures up to 425°C (800°F).

In addition to creep, the other factors that must be taken into consideration when designing for elevated temperatures include

1. Metallurgical and microstructural changes that occur in the material due to long-time exposure to elevated temperature
2. Influence of method of fabrication, especially welding, on creep behavior
3. Oxidation and hot corrosion that may take place during service and shut-down periods

6.6.1 Design Guidelines

For design purposes, creep properties are usually presented on plots that yield reasonable straight lines. Common methods of presentation include log–log plots of stress versus steady-state creep rate and stress versus time to produce different amounts of total strain (instantaneous strain on load application plus creep strain), as shown schematically in Figure 6.5. A change in the microstructure of the material is usually accompanied by a change in creep properties and consequently a change in the slope of the line.

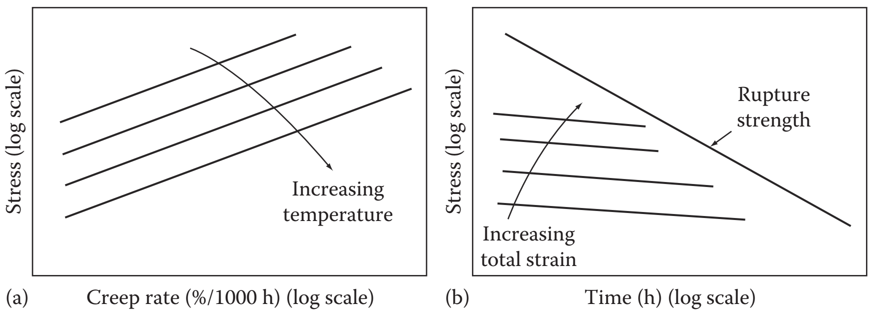

FIGURE 6.5 Presentation of creep data for design purposes. (a) Variation of stress with steady-state creep rate at various temperatures; (b) variation of stress with time to produce different amounts of total strain at a given temperature. The uppermost curve is the stress rupture, which occurs at different total strains to failure.

Generally, designing under high-temperature conditions is carried out according to well-established codes. Most countries have one or more design codes that cover plants and structures operating at high temperatures. Examples of such codes include ASME Boiler and Pressure Vessel Code: section I (power boilers) and section VIII (pressure vessels), BS 806:1975 (piping for land boilers), and BS 5500:1976 (unfired fusion-welded pressure vessels). The common feature of such codes is that calculations and stress analysis are kept to a minimum. Design of local areas, such as branch connections and supports, is provided by simple formulas and by reference to charts.

For moderate temperatures, range 1, both the ASTM Pressure Vessel Code and Boiler Code specify the allowable stresses as the lowest obtained from

1. 25% of the tensile strength at room temperature
2. 25% of the tensile strength at service temperature
3. 62.5% of the yield strength (or 0.2% offset) at service temperature

For high temperatures, range 3, the Boiler Code specifies that the stress values are based on 60% of the stress to produce a creep rate of 1/100%/1000 h. In addition, the stress values are also limited to 80% of the stress to produce rupture at the end of 100,000 h. Generally, service temperatures and pressures are lower than design values, wall thicknesses are often increased by a corrosion allowance, and material properties are usually higher than those specified. All these factors result in an increased factor of safety.

At intermediate temperatures, range 2, the code limits the stress to values obtained from a smooth curve joining the values for the low- and high-temperature ranges.

Example 6.8 illustrates the use of the concepts in design.

Design Example 6.8: Designing a Cantilever Beam to Resist Creep

Problem

If the cantilever described in Example 6.1 is made of 5% Cr–0.5% Mo steel and is to serve at 300°C, what is the maximum allowable load that can be endured at least 100,000 h?

Analysis

The allowable design stress for 5% Cr–0.5% Mo steel according to the ASME Boiler Code is shown in Figure 6.6, which is based on the data given by Clark.

From the figure, the allowable stress at 300°C is about 90 MPa:

$$\text{Maximum allowable load} = \frac{(90 \times 2148)}{1000} = 193.3\ \text{N}$$

Conclusion

Comparing the preceding result with Example 6.1 shows that the maximum allowable load at 300°C is less than 10% of the safe load at room temperature.

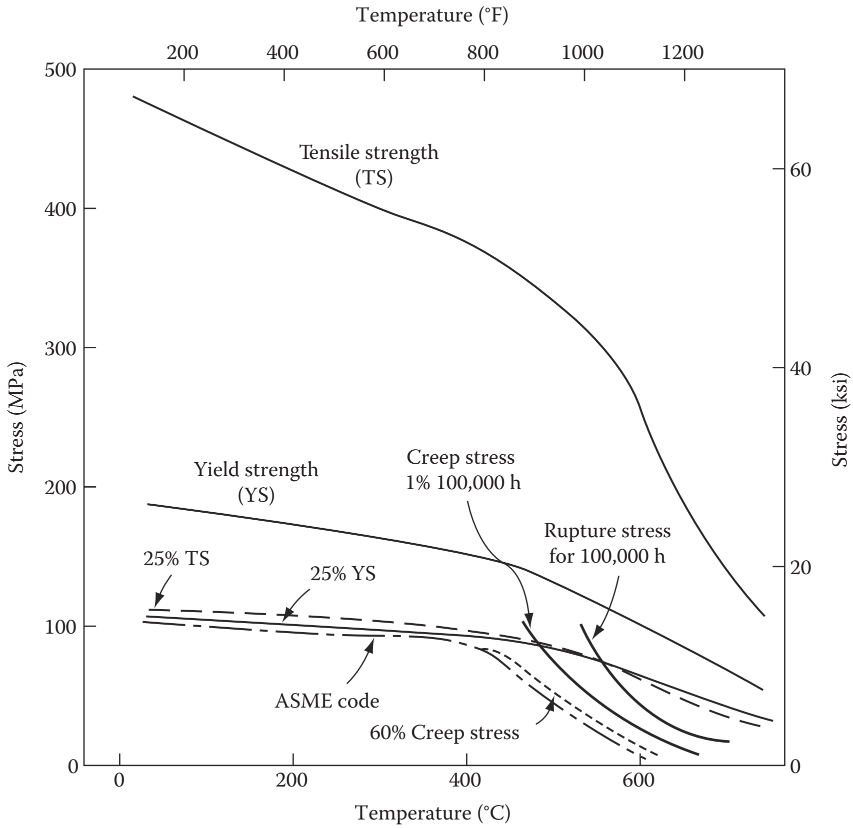

FIGURE 6.6 Determination of the design stress for 5% Cr–0.5% Mo steel according to the ASTM Boiler Code.

6.6.2 Larson–Miller Parameter

In many cases, creep data are incomplete and have to be supplemented or extended by interpolation or, more hazardously, extrapolation. This is particularly true of long-time creep- and stress-rupture data where the 100,000 h (11.4 years) creep resistance of newly developed materials is required. Reliable extrapolation of creep- and stress-rupture curves to longer times can be made only when no structural changes occur in the region of extrapolation. Such changes can affect the creep resistance, which would result in considerable errors in the extrapolated values.

As an aid in extrapolation creep data, several time–temperature parameters have been developed for trading off temperature for time. The basic idea of these parameters is that they permit the prediction of long-time creep behavior from the results of shorter time tests at higher temperatures at the same stress. A widely used parameter for correlating the stress-rupture data is the Larson–Miller parameter (LMP), which is described in Figure 6.7. LMP is described by the relationship

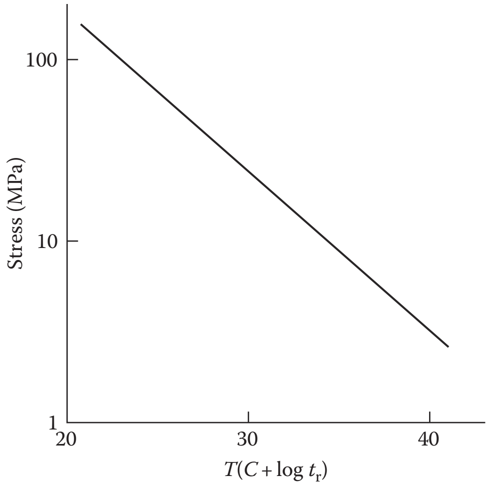

FIGURE 6.7 The Larson–Miller plot.

$$\text{LMP} = T(C + \log t_r) \tag{6.14}$$

where

T is the test temperature in degrees Kelvin (°C + 273) or degrees Rankin (°F + 460)
t_r is the time to rupture in hours, the log is to the base 10
C is the Larson–Miller constant, generally falls between 17 and 23, but is often taken to be 20

Example 6.9 illustrates the use of the LMP in design.

Design Example 6.9: Designing a Turbine Blade to Resist Creep Using LMP

Problem

Assuming that a turbine blade made of Nimonic 105 alloy had a life of 10,000 h at 150 MPa with a service temperature of 810°C, what is the expected life at the same stress but with a service temperature of 750°C?

Solution

From Equation 6.14,

$$\text{LMP} = (810 + 273)\ (20 + 4) = (750 + 273)\ (20 + \log t_r)$$

The expected life at the new service temperature is about 255,637 h.

The LMP can also be expressed in terms of time to give a specified strain, t_s; thus,

$$\text{LMP} = T\ (C + \log t_s)$$

6.6.3 Life under Variable Loading

The stress-rupture life of a component or a structure that is subjected to variable loading can be roughly estimated if the expected life at each stress level is known. Under such conditions, the life fraction rule assumes that rupture occurs when

$$\frac{t_1}{t_{r1}} + \frac{t_2}{t_{r2}} + \frac{t_3}{t_{r3}} + \cdots = 1 \tag{6.15}$$

where

$t_1, t_2, t_3, \ldots$ are the time spent by the part under stress levels 1, 2, 3, … , respectively
$t_{r1}, t_{r2}, t_{r3}, \ldots$ are the rupture lives of the part under stress levels 1, 2, 3, … , respectively

6.6.4 Life under Combined Fatigue and Creep Loading

Similar reasoning can also be applied to predict the life of a component or a structure when subjected to combined creep and fatigue loading. Cumulative fatigue damage laws, for example, Palmgren–Miner law, can be combined with the life fraction rule, given in Equation 6.15, to give a rough estimate of expected life under combined creep–fatigue loading. Thus,

$$\frac{t_1}{t_{r1}} + \frac{t_2}{t_{r2}} + \frac{t_3}{t_{r3}} + \cdots \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots = 1 \tag{6.16}$$

where

$n_1, n_2, n_3, \ldots$ are the number of cycles at stress levels 1, 2, 3, … , respectively
$N_1, N_2, N_3, \ldots$ are the fatigue lives at stress levels 1, 2, 3, … , respectively

6.7 DESIGNING FOR HOSTILE ENVIRONMENTS

Service in a hostile environment is a major source of failure in many areas of engineering. Such failures can be prevented or at least reduced by selecting the appropriate material and by observing certain design rules, as will be discussed in this section.

6.7.1 Design Guidelines

Galvanic corrosion usually takes place as a result of design errors where dissimilar metals are placed in electrical contact. Under such conditions, corrosion occurs in the anodic material, whereas the cathodic material is protected. The rate of corrosion and damage caused depends on the difference between the two materials in the galvanic series (Table 3.1) and on the relative areas of the exposed parts. A small anode and a large cathode will result in intensive corrosion of the anode, whereas a large anode and a small cathode are not as serious.

The safest way of avoiding galvanic corrosion is to ensure that dissimilar metals are not in electrical contact, by using insulating washers, sleeves, or gaskets. When protective paints are used, both metals or only the cathodic metal should be painted. Painting only the anode will concentrate the attack at the breaks or defects in the coating.

Severe corrosion can take place in crevices formed by the geometry of the structure. Common sites for crevice corrosion include riveted, adhesive bonded, and welded joints, areas of contact between metals and nonmetals, and areas of metal under deposits or dirt, as discussed in Section 3.3. Crevices can also be created between flanged pipes as a result of incorrect usage of gaskets, as shown in Figure 6.8a. Fibrous materials that can draw the corrosive medium into the crevice by capillary action should not be used as gaskets, washers, or similar applications. If crevices cannot be avoided in design, they should be sealed by welding, soldering, or brazing with a more noble alloy, adhesives, or caulking compounds.

Design features that retain undrained liquids in reservoirs or that collect rainwater should be avoided as they cause accelerated corrosion rates. Figure 6.8b shows examples of such features and how to avoid them. A similar problem is faced in closed tanks and sections where inadequate ventilation can cause condensation, or sweating, and accelerated corrosion rate. Closed sections are also difficult to paint and maintain. Avoiding closed sections and providing adequate ventilation can overcome this problem.

Sharp corners and convex surfaces that tend to have thinner coatings or are subject to coating cracks should be avoided. Similarly, coated surfaces that are exposed to direct impingement of airborne abrasive particles should be reduced. Where practicable, rounded contours and corners are preferable to angles, as illustrated in Figure 6.8c.

Design features that cause turbulence and rotary motion in moving liquids or gases should be avoided as this can cause impingement attack and other forms of accelerated corrosion near the obstruction. Figure 6.8d shows an example of such a design feature.

Fretting corrosion can take place at the interface of two closely fitting surfaces when they are subject to slight oscillatory motion. Assemblies like shrink-and-press fits, bolted joints, splined couplings, and keyed wheels are vulnerable to such attacks. Fretting corrosion can be prevented by preventing slippage or relative motion between surfaces that are not meant to move. This can be done by roughening the surface to increase friction or by eliminating the source of vibrations. Other solutions include using a soft metal surface in contact with a hard one, using low-viscosity lubricants, and phosphating.

6.8 DESIGNING WITH SPECIFIC MATERIALS (MATERIAL-SPECIFIC DESIGN FEATURES)

6.8.1 Designing with Metallic Materials

Metallic materials and the properties of commonly used alloys are described briefly in Appendix A. The load-carrying capacity of a metallic component can be related to the yield strength, fatigue strength, or creep strength of the material, depending on loading and service conditions. These properties are structure sensitive and can

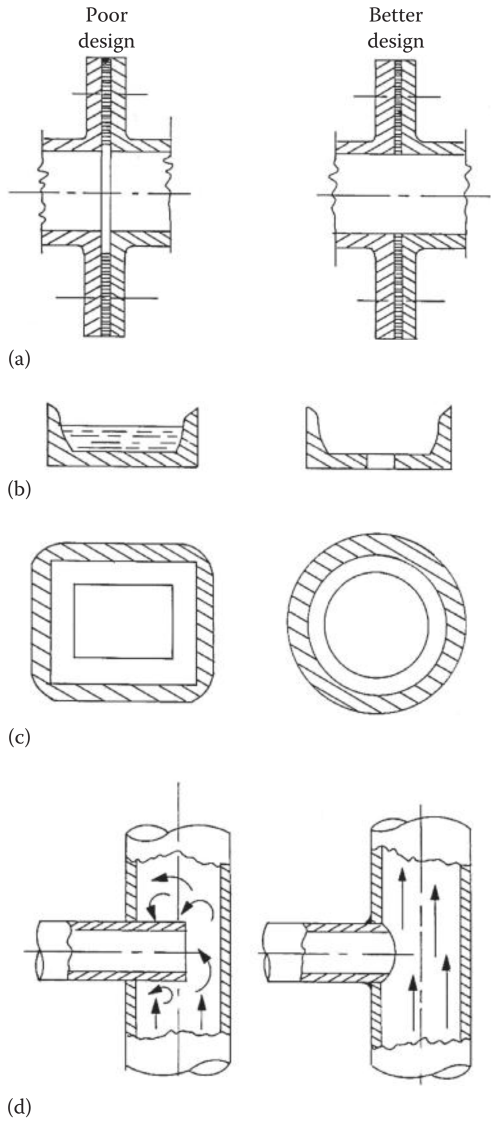

FIGURE 6.8 Examples of design features that should be considered in designing for a corrosive environment. (a) Incorrect gasket size can cause crevice corrosion. (b) Undrained liquids result in accelerated corrosion. (c) Thinner coatings offer less protection near sharp contours. (d) Obstructions to moving fluids can cause turbulence and accelerated corrosion.

be considerably changed by changing the chemical composition of the alloy, method, and conditions of manufacture as well as heat treatment. It should be noted, however, that increasing the strength of most metallic materials causes their ductility and toughness to decrease, which could adversely affect the performance of the component in service. This subject is discussed in more detail in Section 4.5.

Electrical and thermal conductivities of metallic materials can greatly affect the design and impose severe limitations on material selection in many applications. For example, electrical quality copper and aluminum may represent the only possible materials for the manufacture of a component where electrical conductivity is a primary requirement. Corrosion resistance and specific gravity requirements could impose similar limitations. However, judicious design and careful selection can, in many cases, overcome these limitations.

The design and material selection for a given component are also influenced by manufacturing considerations. The majority of metallic components have either cast or wrought microstructures. Wrought microstructures are usually stronger and more ductile than cast microstructures, and this is one of the reasons why about 80% of metallic materials are produced in the wrought form.

6.8.2 Designing with Polymers

The structure of polymers and the properties of some commonly used plastics are given in Appendix B. From the performance point of view, there are many applications where plastics outperform other materials. Their lightweight, corrosion resistance, low coefficient of friction, low thermal and electrical conductivities, optical properties, and decorative appeal are among the factors that explain the increasing use of plastics. Specific examples where plastics successfully replaced metals in the motorcar include bumpers, front and rear ends, radiator end tanks, and door handles. In most cases, plastics are not direct substitution for metals. This is because plastics have widely different properties and employ widely different processing techniques. The design should be changed to make use of the advantages of plastics and to avoid their limitations.

When the part is to carry loads, that is, a structural part, it should be remembered that the strength and stiffness of plastics vary significantly with temperature. Room temperature data cannot be used in design calculations if the part is going to be used at any other temperature. Long-term properties, that is, creep behavior, cannot be predicted from short-term properties. When a polymer is subjected to a continuously applied load, it undergoes both elastic deformation, which occurs instantaneously on application of load, and viscous deformation, which increases with time. The latter component of deformation is usually not fully recoverable upon unloading. The recovery of dimensions after load removal is dependent on the loading time and is generally more rapid after short periods of time at low strains, than after long periods of time at high strains. The recovery time is an important parameter in applications involving intermittent loading. Generally, increasing the molecular weight of the polymer, by increasing the average chain length and cross-linking, causes the viscous deformation to decrease.

Since the mechanical properties of plastics are time dependent, creep properties and stress relaxation should be considered when designing plastic parts that are expected to bear the applied stresses for considerable periods of time. A number of polymers show an exponential stress relaxation according to the relationship

$$\sigma = \sigma_0 \exp\left(\frac{-t}{\lambda}\right) \tag{6.17}$$

where
- σ_0 is the stress at time 0
- σ is the stress at time t
- λ is the relaxation time that is defined as the time necessary to reduce the stress to $(1/e)$ of its original value

Design Example 6.10 illustrates the use of Equation 6.17 in design.

Design Example 6.10: Designing a Polymer Fastener

Problem

A fastener is made of a given polymer with a relaxation time of one year at 20°C. What is the time needed to reduce the original stress exerted by the fastener by 25%?

Solution

From Equation 6.17, taking σ as the stress after relaxation,

$$\sigma = 0.75\ \sigma_0 = \sigma_0 \exp\ (-t/12)$$

$$t = 3.45 \text{ months}$$

Many of the commonly used engineering plastics have a notched impact strength <5.4 J/cm (10 ft lb/in.). From the design point of view, this means that they are brittle and the effect of stress raisers must be considered. For example, one type of acetal has an unnotched Izod impact strength of greater than 54 J/cm (100 ft lb/in.) and a notched Izod impact of only about 1 J/cm (ca. 2 ft lb/in.). A complicating factor is that many plastics achieve their impact resistance through the addition of plasticizers. With time, these additives may vaporize, leaving the aged plastic relatively brittle.

6.8.3 Designing with Ceramics

Ceramic materials and the properties of some commonly used ceramics and glasses are given in Appendix C. Designing ceramic products needs special considerations in view of their brittleness and relatively low mechanical and thermal shock resistance. If the same configuration is used when a ceramic material is substituted for a metallic alloy, the ceramic part could fail in service or even during assembly. Special designs should be developed to make use of the advantages of ceramics and to avoid their limitations. As the ratios between tensile strength, modulus of rupture, and compressive strength are usually in the range 1:2:10, every effort should be made to load ceramic parts in compression and to avoid tensile loading.

As ceramics are brittle, they are sensitive to stress concentration. Features such as sharp corners, notches, and unstrengthened holes should, therefore, be avoided. Press fits and shrink fits permit successful attachment of ceramics to steel and allow prestressing the ceramic part in compression, which increases its load-carrying capacity. Variability of properties in addition to lower toughness and thermal shock resistance results in lower reliability of ceramic components in comparison with metallic ones.

6.8.4 Designing with Composites

Composite materials are described briefly in Appendix D together with the properties of some commonly used composites and fibers. The characteristics of composite materials are different in many respects from those of common metallic materials. This means that major design and manufacturing changes have to be made when replacing a metallic material by a composite material. Efficient use of composite materials can be achieved by tailoring the material for the application. For example, to achieve maximum strength in one direction in a fibrous composite material, the fibers should be well aligned in that direction.

The desirable feature of tailorability is illustrated by the use of carbon fibers, which exhibit a negative coefficient of thermal expansion, in building dimensionally stable structures. The negative coefficient of thermal expansion of carbon fibers is balanced by the positive coefficient of thermal expansion of the epoxy matrix and the resulting composite has a zero coefficient of thermal expansion. Space structures and finely tuned optical equipment are typical applications for such composites.

An important factor that should be borne in mind when designing with composite materials is that their high strengths are obtained only as a result of large elastic strains in the fibers. In some structures, these strains can cause unacceptable deflections. An example is the case of an aircraft wing where a strain of about 1.7% could cause the wing tips to become vertical. This indicates that composite materials should not simply be substituted for other materials without making the necessary modifications in design and construction.

Differences between the fatigue behavior of metals and composite materials should also be taken into account when designing with composites. Unlike steels, which show an endurance limit or a stress below which fatigue failure does not occur, composite materials suffer fatigue damage even at relatively low stress levels. Although fatigue-crack propagation in metals is usually limited to a single crack, which progressively grows with each cycle, fibrous composites may have many cracks, which can be growing simultaneously. Cracks may propagate through the matrix, be arrested by a fiber, or move along a fiber–matrix interface. This makes fatigue failure of fibrous composites a more gradual, noncatastrophic event than for metals. Fatigue loading of fibrous composites is also accompanied by a progressive reduction in modulus with increasing number of cycles. In addition, cyclic creep, which is the increase in strain at the minimum fatigue stress, can also occur in chopped FRPs. This latter weakness can be overcome by using continuous fibers that are oriented in the principal stress direction.

In spite of their high strength, fibrous composites can exhibit low fracture toughness. This is because the conditions required for high strength, for example, short critical aspect ratio and strong interfacial bond between fibers and matrix, are in conflict with the conditions required for high fracture toughness, for example, long critical aspect ratio and weak interfaces parallel to the fibers. In general, a compromise between strength and toughness will be required for a given application. Several hybrid composites have been developed to achieve such compromise. For example, Kevlar fibers, which have good impact resistance but relatively low compressive strength, complement graphite fibers, which have roughly four times the compressive strength but are less tough. Because each fiber retains its own identity, hybrid technology is becoming increasingly important as a way of selectively utilizing the dominant properties of each fiber and reducing the overall cost of the composite, for example, mixing carbon and glass fibers in a composite and placing the carbon fibers at critical locations, high-performance lightweight structures with minimal amount.

Laminated or sandwich composites usually consist of a thin facing material and a low-density core. Sandwich materials combine high section modulus with low density; for example, an aluminum-faced, honeycomb sandwich structure beam is about one-fifth the weight of a solid aluminum beam of equivalent rigidity. The facing material in a sandwich structure carries the major applied load and therefore determines the stiffness, stability, and strength of the composite. Examples of possible facing materials are aluminum, stainless steel, magnesium, titanium, plastics, and fiber-reinforced materials. The core forms the bulk of a sandwich structure. Therefore, it is usually of lightweight but must also be strong enough to withstand normal shear and compressive loads. The core can be in the form of foam or cells. Foam cores are usually made from plastics, especially polystyrene, urethane, cellulose acetate, phenolic, epoxy, and silicone. Foamed inorganic materials like glass, ceramics, and concrete can also be used. Cellular cores can have corrugated or honeycomb metallic structures. Other core materials are glass-reinforced plastics (GRPs), ceramics, or paper. Plastic-cored sandwiches faced with steel or aluminum have been shown to be weight-saving, cost-effective substitutes for automotive sheet steel. Thermal and sonic insulation characteristics of these sandwiches provide secondary benefits, along with possibilities of using lower-capacity forming presses. However, sandwich materials suffer from lower in-plane strength, lower dent resistance, limited joining capability, and more difficulties in recycling.

An important use of sandwich materials is in stiffness-limited applications, where they provide weight reduction and cost savings. In applications where a structural member is replaced by a sandwich material, the flexural rigidity of the sandwich should be at least equal to that of the original member. The flexural rigidity in bending, D_1, of the symmetrical laminated composite, sandwich beam, can be calculated as

$$D_1 = E_{f\dagger}\frac{bt^3}{6} + E_{f\dagger\dagger}\frac{btd^2}{2} + E_c\frac{bc^3}{12} \tag{6.18}$$

where

E_f and E_c are the moduli of elasticity of the face and core materials, respectively
b, t, and c are beam width, face thickness, and core thickness, respectively
$(d+t)$ = laminate thickness = $c+2t$; that is, $d=c+t$

When t is thin compared with the laminate thickness and E_c is small compared with E_f, the second factor of Equation 6.18 becomes dominant.

If the composite laminate is used to replace a sheet material, the equivalent flexural stiffness of the laminate, D_l, should be equal to the flexural rigidity of the sheet, D_s, if it is to behave in a similar manner in bending. In such case,

$$D_l = D_s = \frac{bt_s^3 E_s}{12} \tag{6.19}$$

where
- t_s is sheet thickness
- E_s is elastic modulus of sheet material

Equations 6.18 and 6.19 can be used to calculate the required thicknesses in preparation for comparing weight and cost of different sandwich and sheet materials. Design Example 6.11 illustrates the use of laminated composite to replace a steel sheet in order to save weight.

Design Example 6.11: Substitution of a Steel Sheet by a Lighter Laminated Composite

Problem

In order to save weight, a steel plate of thickness $t_s = 10$ mm is to be replaced by a steel–polyethylene sandwich panel of the same width and stiffness. If the thickness of the steel facing is 0.5 mm, calculate the total thickness of the laminate and the mass ratio.

Solution

From Equations 6.18 and 6.19,

$$D_l = D_s = \frac{b10^3 E}{12} = \frac{b0.5td^2 E}{2}$$

$d = 18.26$ mm
Laminate thickness $= d + 0.5 = 18.76$ mm
Core thickness $c = d - t = 18.26 - 0.5 = 17.76$ mm
Mass of steel plate/(m^2) $= 78$ kg
Mass of laminate/(m^2) $= 7.8 + 3.55 = 11.35$ kg
Mass ratio of steel plate to laminate $= 6.87$

6.9 SUMMARY

1. A successful design should take into account the function, material properties, and manufacturing processes. The relationship between material properties and design is complex because the behavior of the material in the finished product can be quite different from that of the stock material.
2. The stiffness of components under bending is proportional to the elastic constant of the material (E) and the moment of inertia of the cross section (I).

Selecting materials with higher E and efficient disposition of material in the cross section are essential in designing such components for stiffness. Placing material as far as possible from the neutral axis of bending is generally an effective means of increasing I for a given area of cross section.

3. Fail-safe design requires a structure to be sufficiently damage tolerant to allow defects to be detected before they develop to a dangerous size. In the case of high-strength materials, the interaction between fracture toughness, crack size, and the design stress should be considered.
4. Leak before burst is a useful design criterion in the case of pressure vessels and similar products. The toughness of the material used in such applications should be sufficiently high to tolerate a defect size that will allow the contents to leak out before it grows catastrophically.
5. In designing for fatigue resistance, the designer should consider the fatigue strength of the material as well as size and shape of the component or structure, type of loading and state of stress, stress concentration, surface finish, operating temperature, service environment, and method of fabrication.
6. Safe-life, or finite-life, design is based on the assumption that the component or structure is free from flaws but the stress level in certain areas is higher than the endurance limit of the material. This means that fatigue-crack initiation is inevitable and the life of the component is estimated on the basis of the number of stress cycles that are necessary to initiate such a crack.
7. The LMP can be used when creep data are incomplete and have to be supplemented or extended by interpolation or extrapolation.
8. Many of the causes of failure in hostile environment can be avoided by observing appropriate design rules such as avoiding electrical contact between dissimilar metals, sealing crevices, providing appropriate ventilation and drainage of liquids in closed containers, avoiding sharp corners in coated components, preventing turbulence in moving liquids, and preventing slippage between surfaces that are not meant to move.
9. A successful design with a specific material must use its points of strength and avoid its points of weakness. With metallic materials, the ductility and toughness generally decrease as the strength increases. Polymers are light but their stiffness and impact strength are much lower than metals. Ceramics are corrosion resistant and strong in compression but are very brittle and sensitive to mechanical and thermal shocks. Composite materials generally have high strength/weight ratio and their properties can be tailored to suit the type of loading.

REVIEW QUESTIONS

6.1 Determine the dimensions of a cantilever beam of length 2 m (80 in.) and rectangular section of depth-to-width ratio 3:1. The cantilever is expected not to deflect more than 25.4 mm (1 in.) for every 1000 N (220 lb) increment of load at its tip. The material used in making the beam is steel AISI 4340 with a yield strength of 1420 MPa (206 ksi) and UTS 1800 MPa (257 ksi). What is the maximum permissible load? Assume a suitable factor of safety.

6.2 For the cantilever beam in Question 6.1, if the minimum detectable crack is 3 mm (0.118 in.), what is the maximum permissible load? K_{IC} of the beam material is 87.4 MPa $(m)^{1/2}$ (80 ksi $(in.)^{1/2}$).

6.3 If the load of the cantilever beam in Question 6.1 is fluctuating around a mean value of 1000 N (220 lb), what is the maximum alternating load that can be applied without causing fatigue failure? The endurance ratio for this steel is 0.56. Use a suitable factor of safety and modifying factors for the endurance limit.

6.4 A component made of steel with a static tensile strength of 600 MPa and endurance ratio of 0.4 is to be subjected to a combination of static and alternating stresses. If the average static stress is 150 MPa, what is the maximum alternating stress that can be safely applied to the component?

6.5 Distinguish between the stiffness of a component and the modulus of elasticity of the material used in making that component.

6.6 Low elastic modulus is one of the main limitations in using plastics for load-bearing components. Using actual products, select three design features that were used to overcome this limitation.

6.7 Compare the uses of titanium and aluminum alloys as supersonic aircraft wing tip materials.

6.8 What are the main material requirements for the following components: motorcar exhaust manifold, coil for electrical resistance heater, kitchen knife blade, and railway line? Suggest suitable materials for these components.

6.9 What are the main requirements for materials used for gas turbine blades? Suggest suitable materials for the turbine blades.

6.10 What are the main requirements for materials used for the sleeves of lubricated journal bearings? Suggest suitable materials for the sleeves.

6.11 What are the main requirements for materials used for making motorcar bodies? Suggest suitable materials for such bodies.

6.12 What would be the advantages and disadvantages of substituting FRPs for steel in making motorcar bumpers?

6.13 (a) What are the main material requirements for the paper clip? (b) What is the type of material that you would recommend for such application? (c) Can plastics be used for such application? If so, what are the design changes that would be necessary?

6.14 What are the main material requirements for the wing of a small aircraft wing structure? Compare the uses of the following materials in making the wing structure:

	Specific Gravity	Elastic Modulus (GPa)	Tensile Strength (MPa)
Aluminum alloy	2.7	70	580
Magnesium alloy	1.7	45	280
Polyester + 65% glass fibers	1.8	19.6	340

6.15 Calculate the diameter of a steel shaft that is subjected to a cyclic tensile load of 5000 kg. The shaft material has a tensile strength of 950 MPa and its endurance ratio is 0.5. Assume that the surface finish factor $k_a = 0.68$, the reliability factor $k_c = 0.75$, the size factor $k_b = 0.8$, and the stress concentration factor $k_f = 0.7$. Take a factor of safety of 2 to account for possible overloads and material defects.

6.16 The deflection (y) of a simply supported beam of length (l) under a concentrated load (L) is given by the formula

$$y = \frac{(Ll^3)}{(48EI)}$$

where
E is the elastic constant of the material
I is the second moment of area

a. Discuss the possible alternatives that are open to the design engineer in maximizing the stiffness of the beam.
b. Compare the use of steels and CFRPs for such applications (Esteel = 210 GPa, Ecfrp = 200 GPa).

6.17 You have used the tensile-testing machine in the materials testing laboratory to test the mechanical properties of different materials: (a) What are the main material properties that are usually measured in a tensile test? (b) How can you compute the toughness of materials from the tensile test? (c) What are the main design requirements for the structural members used in making tensile-testing machines? (d) What are the important properties of materials used in making the structural members of tensile-testing machines?

6.18 What are the main material requirements for airplanes? Compare the uses of aluminum alloys, titanium alloys, magnesium alloys, and FRPs in the various parts of a civilian aircraft.

6.19 It is known that, compared with metals, plastics have a very low static modulus.

a. In some applications, the low modulus of plastics can be a limitation if the product is required to be stiff. Identify two of such products and draw some of the design features that were used to overcome this limitation.
b. In other applications, the low modulus of plastics can be an advantage. Identify two of such products and draw some of the design features that were used to take advantage of the very low static modulus of plastics.

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7 Effect of Manufacturing Processes on Design

7.1 INTRODUCTION

Manufacturing can be defined as the act of transforming materials into usable and saleable end products. This means that the products must function satisfactorily and provide value for money. The cost, rate of production, availability, and quality of product are important criteria that should be considered when selecting a manufacturing process. With the increasing sophistication of many products and the increasing range of available materials, new manufacturing technologies have been developed to produce more sound and accurate components economically.

The introduction of automation, computers, and robots in manufacturing processes has been of great help to industry in producing better products more economically as they improve productivity, increase product quality and uniformity, and reduce labor cost. The integration of these elements in computer-integrated manufacturing (CIM) allows manufacturers to respond rapidly to market demand and product modification and to exercise better control of production operations, as well as better utilization of materials, machines, and human resources.

The goal of this chapter is to illustrate how the manufacturing processes influence the design of components, with emphasis on the following topics:

1. Types of available manufacturing processes and their selection
2. Design for manufacture and assembly
3. Design considerations for cast components
4. Design considerations for molded plastic components
5. Design considerations for forged components
6. Design considerations for P/M parts
7. Designs involving welding processes
8. Designs involving machining processes
9. Automation of manufacturing processes and CIM

7.2 PRODUCT MANUFACTURE IN THE INDUSTRIAL ENTERPRISE

Manufacturing is generally a complex function that encompasses process planning, scheduling, production cost, machinery and tooling, materials, and quality control and assurance. As the backbone of many industries, manufacturing interfaces with a variety of activities including product design, purchasing, environmental control, marketing and sales, shipping, and customer services.

Traditionally, a product was first designed and detail drawings were then sent for manufacturing. This approach, although logical, can slow down the product development process in addition to being expensive and wasteful of resources. In many cases, a design may need to be changed to account for availability of materials or to accommodate manufacturing process requirements. It is now widely recognized that design, material selection, and manufacturing are intimately related activities that cannot be performed in isolation of one another. It is uneconomical to make the design first and then modify it later to accommodate manufacturing requirements. This is because the later the design changes are made in the product development cycle, the more expensive they are. It is also recognized that over 70% of the final product costs are determined during the design phase, which means that it is more effective to consider materials and manufacturing costs while developing the design. The recognition of the capabilities and limitations of the available processes would make it possible to specify the correct manufacturing instructions and to select the processing route that will yield the required product quality at the optimum cost.

7.3 CLASSIFICATION OF MANUFACTURING PROCESSES

7.3.1 Processing of Metallic Materials

The relationship between the different manufacturing processes that are normally used in processing metallic materials can generally be presented as shown in Figure 7.1. Most metallic materials are found in nature in the form of ores, which have to be reduced or refined and then cast as ingots of convenient size and shape for further processing. Casting processes involve pouring the liquid metal, or alloy, into a mold cavity and allowing it to solidify. Powdered materials can be shaped by pressing in suitably shaped dies and then sintering, heating, to achieve the required properties. An important advantage of casting and P/M processes is that parts of complex shapes can be obtained in one step.

Bulk forming processes are generally used to change the shape of metallic materials by plastic deformation. The deformation can be carried out at relatively high temperatures, as in the case of hot working processes, or at relatively low temperatures, as in the case of cold working processes. The basic bulk deformation processes are forging; rolling; extrusion; swaging; and drawing of rod, wire, and tube. These processes are called primary working when applied to ingots to break down their cast structure into wrought structure and to change their shape to slabs, plates, or billets. Secondary working involves further processing of the products from primary working into final or semifinal shapes.

Sheet metal working processes are normally carried out at room temperature and usually involve the change of sheet form without greatly affecting its thickness. The basic sheet metal working processes include shearing, bending, stretch forming, bulging, deep drawing, spinning, and press forming. Other sheet metal forming operations have been developed for the manufacture of certain components and special materials.

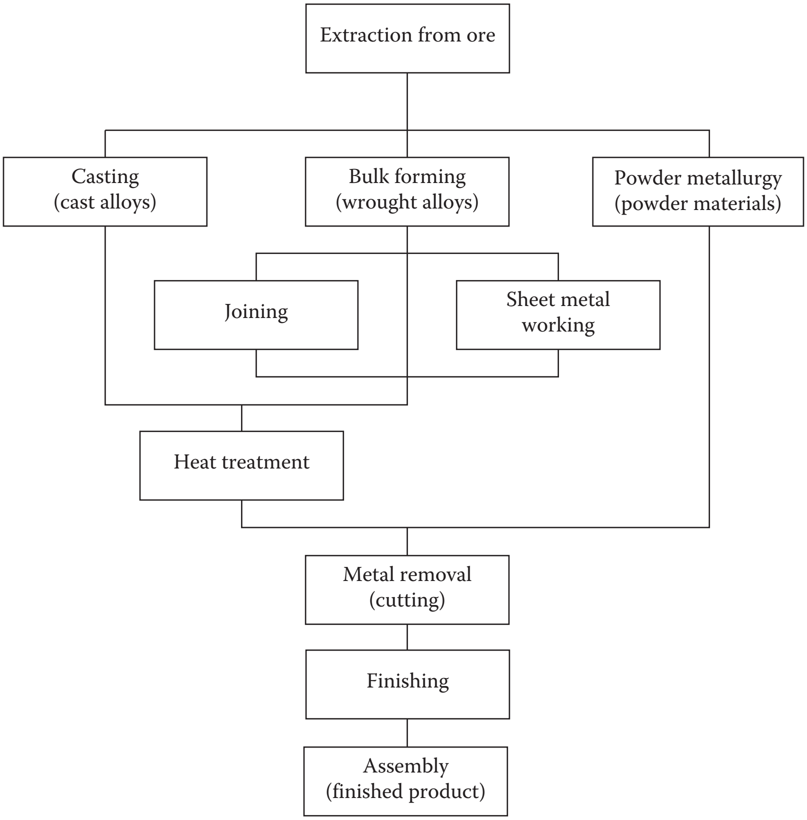

FIGURE 7.1 Types and usual sequence of manufacturing processes that are normally used in processing metallic materials.

Heat treatment is normally carried out to control the structure and properties of the material. By proper control of temperature and cooling rate, the material can be softened to permit further processing or hardened to increase its mechanical strength. Heat treatment can also be used to remove internal stresses, control grain size, or produce a hard surface on a ductile interior. With the proper heat treatment, a less expensive material could replace a more expensive material or a less costly processing could be employed.

Material removal or cutting processes are normally used to remove unwanted material in the form of chips by using cutting tools, which are mounted in machine tools. The traditional, basic machine tools are lathes, boring machines, shapers and planers, milling machines, drill presses, saws, broaches, and grinding machines. The productivity in cutting processes can be improved by using machining centers, which are single machines that can perform the functions of several basic machine tools. When cutting very hard metals or when machining intricate shapes and delicate parts, nontraditional or chipless processes can be used. These cutting methods include ultrasonic, electric discharge, electrochemical, chemical milling, abrasive jet, electro arc, plasma arc, electron beam, and laser cutting.

In many cases, products are manufactured as separate units and then assembled either by fastening, as in the case of temporary or semipermanent joints, or by joining, as in the case of permanent joints. Examples of fastening methods include screws, bolts, and rivets, whereas joining methods include welding, brazing, soldering, and adhesive bonding. Assembling by press and shrink fitting is also used in some applications. Finishing processes are normally used to control the quality of the surface and to make it ready for service. Cleaning, deburring and polishing, anodizing, tinning, galvanizing, plating, and painting are among the frequently used finishing processes. In addition to controlling the appearance of the surface, many of the finishing processes provide some protection against corrosion.

7.3.2 Processing of Plastic Parts

There are many methods of manufacturing plastic parts, which can be considered as molding processes. These processes usually employ the following sequence of steps:

1. Plastics in the form of powder, pellets, or granules are usually heated above the softening point.
2. The molten plastic is forced or placed into a mold that determines the dimensions of the molded part.
3. The material is then allowed to harden, by curing or freezing, and is then ejected from the mold.
4. In some molding processes, the ejected part is ready for use. With others, trimming and other finishing processes are necessary to make it ready for use.

Pressure-molding processes cover compression molding, transfer molding, and injection molding. These processes are similar in some ways to die-casting processes used for metals. It should be noted, however, that molten plastics are more viscous and much less conducting to heat than metals. These differences are reflected in the design and operation of the plastic-molding machines.

7.3.3 Processing of Ceramic Products

The raw materials used for making ceramic parts are usually in the form of particles or powder. After mixing and blending the appropriate ingredients, processing is carried out either in a dry, semidry, or liquid state and either cold or hot condition. Forming processes include slip casting, molding, jiggering, extrusion, and pressing. After forming the plastic ceramic mass into the required shape, it is dried to remove the water and then fired to sinter the ceramic powder into a final product.

7.3.4 Manufacture of Reinforced Plastic Components

Thermoplastics that are reinforced with short-chopped, randomly oriented fibers are easily fabricated using conventional techniques of injection molding and extrusion.

Composites based on thermosetting plastics are processed using specially developed methods like

1. Contact molding, which employs single-surface molds as in the case of hand layup, spray-up, and filament winding
2. Compression-type molding, as in the case of sheet molding, bulk molding, preform molding, and cold molding
3. Resin-injection molding, which is similar to the process used for nonreinforced materials and reinforced thermoplastics
4. Pultrusion, which is a modification of the extrusion process

7.3.5 Manufacture of Reinforced Metal Components

MMCs can be prepared in a variety of ways, which can be broadly classified into the following:

1. Processes based on solid-state diffusion
2. Liquid-phase infiltration
3. *In situ* processes

Selection of the appropriate process is a function not only of the required shape and properties of the composite but also of the fiber–matrix combination.

7.4 SELECTION OF MANUFACTURING PROCESSES

Figure 5.1 shows that in addition to having a direct influence on the design of components, manufacturing processes are also closely related to the material out of which the component is made and to its function and shape. The importance of manufacturing processes is further emphasized in Figure 6.1, where it is shown that the behavior of the material in the component is not only a function of the stock material properties but is also strongly influenced by the fabrication method. Such intimate relations between manufacturing processes, material properties, and design have led to widely used practice of concurrent, or simultaneous, engineering in product development. As the design progresses from concept to configuration and the material choices get narrower, manufacturing processes, which have initially been broadly defined, also need to be better identified. Successful product development requires a good match between the capabilities and limitation of the manufacturing process and the component attributes, which include its size, geometrical features, number required, and the type of material used.

As most components require a sequence of processes for their manufacture, there will be hundreds of possible process combinations, which can be used to make a given part. The choices can be narrowed down based on the following:

1. Screening based on component material group because not all processes are suitable for all materials. For example, cast iron cannot be forged and P/M is uneconomical for a limited production run. Table 7.1 outlines the

TABLE 7.1
Compatibility between Some Widely Used Metallic Materials and Processes

	Carbon Steel	Stainless Steel	Cast Iron	Aluminum Alloys	Copper and Alloys	Magnesium and Alloys	Zinc and Alloys	Titanium and Alloys	Superalloys
Sand casting	XX	XX	XX	XX	XX	XX	X	Nr	XX
Investment casting	XX	XX	Nr	XX	XX	X	Nr	X	XX
Die casting	Nr	Nr	Nr	XX	X	XX	XX	Nr	Nr
P/M	XX	XX	Nr	XX	XX	Nr	Nr	X	XX
Forging	XX	XX	Nr	XX	XX	XX	Nr	X	X
Rolling	XX	XX	Nr	XX	XX	XX	X	X	XX
Extrusion	X	X	Nr	XX	XX	XX	X	X	X
Sheet metal work	XX	XX	Nr	XX	XX	X	X	X	X
Cold heading	XX	XX	Nr	XX	XX	Nr	Nr	Nr	X
Metal cutting	XX	XX	XX	XX	XX	XX	XX	X	X
Fusion welding	XX	XX	X	XX	XX	XX	Nr	XX	XX

Note: XX = common practice, X = less common or performed with difficulty, and Nr = not recommended.

compatibility between some widely used metallic materials and processes; further details appear throughout this chapter.

2. Screening based on component shape because manufacturing processes also have limitations on the shapes they can produce. For example, wires and sheets cannot be produced by casting and 3D shapes cannot be produced by rolling or extrusion. Table 7.2 shows the compatibility between shapes and manufacturing processes.
3. Screening based on the required number of components because the most economical batch size varies from one manufacturing process to another. For example, the number of components produced by P/M or die casting has to be large enough to justify the high cost of dies. Table 7.2 gives the economic batch sizes for some manufacturing processes.
4. Many processes form a natural sequence for shape generation, surface finish or dimensional accuracy. For example, casting and forging are normally followed by machining and then surface finishing, if needed, as shown in Figure 7.1. From this point of view, processes can be grouped as follows:
   a. Primary processes, including casting (sand casting, investment casting and die casting, etc.), bulk forming (forging, rolling, extrusion, etc.)
   b. Primary/secondary processes, including joining and welding, sheet metal work, heat treatment, and metal cutting
   c. Tertiary processes or finishing processes, including surface treatment, grinding, and coating

Case study 7.1 illustrates the use of the previous steps in selecting processes for a connecting rod for an internal combustion engine.

Case Study 7.1: Process Selection for a Connecting Rod

Problem

It is required to select the optimum sequence of manufacturing processes for a connecting rod for an internal combustion engine for use in a motorcar, as shown in Figure 7.2. The distance between centers of the big end and small end normally ranges between 140 and 180 mm and the weight can range from 600 to 900 g for steel connecting rods. The numbers produced in connecting rod batches are normally in the tens of thousands.

Analysis

The most important mechanical property for the connecting rod material is fatigue resistance. Experience has shown that wrought components have better fatigue properties than cast components. Normally steels, such as AISI 4340 and C-70, are used for making motorcar connecting rods. Cast irons, such as ductile irons, were used in the past, but steels give better fatigue resistance and are lighter. Aluminum alloys, titanium and magnesium alloys are used in high

TABLE 7.2
Economic Batch Size and Compatibility between Product Shape and Manufacturing Processes

		3D (Similar Dimensions in All Directions)		Prismatic (1D Much Longer than the Other 2Ds)		Sheet (1D Much Shorter than the Other 2Ds)	
	Economic Batch Size	**Solid**	**Hollow**	**Circular Cross Section**	**Noncircular Cross Section**	**Flat**	**Cupped**
Sand casting	1–1,000	XX	XX	XX	XX	Nr	Nr
Investment casting	50–1,000	XX	XX	XX	XX	Nr	Nr
Die casting	>10,000	XX	XX	XX	XX	Nr	Nr
P/M	>5,000	XX	XX	XX	XX	Nr	Nr
Forging	1–10,000	XX	Nr	XX	XX	Nr	Nr
Rolling	N/A	Nr	Nr	XX	XX	XX	Nr
Extrusion	N/A	Nr	Nr	XX	XX	Nr	Nr
Sheet metal work	>50,000	Nr	Nr	XX	XX	XX	XX
Cold heading	1–10,000	XX	Nr	XX	XX	X	X
Metal cutting	N/A	XX	XX	XX	XX	XX	XX
Fusion welding	N/A	XX	XX	XX	XX	XX	XX
Injection molding	>10,000	XX	XX	Nr	Nr	Nr	Nr
Blow molding	>100,000	Nr	XX	Nr	Nr		
Compression molding	>5,000						

Note: N/A = does not apply, XX = common practice, X = less common or performed with difficulty, Nr = not recommended.

FIGURE 7.2 Connecting rod of an internal combustion engine of a motorcar.

performance and racing cars where weight reduction is at a premium. The current practice for splitting the big end to allow insertion around the crank pin is to make a groove and fracture the rod. The halves are then easily assembled and the hole of the big end remains circular. Using a cutting process to split the big end results in a noncircular hole due to loss of material at the cut surfaces. Also the parting surfaces have to be finished to a high degree to allow accurate assembly.

Primary Process Selection

From Tables 7.1 and 7.2, the most suited primary processes for making 3D solid components, such as the connecting rod, are casting, P/M, and forging. Since cast irons are no longer used in making connecting rods, casting processes will be eliminated. Both P/M and forging processes are suitable for steel connecting rods and are used in practice. The powder process is competitive in spite of the higher cost of material, as it has less waste, requires less machining, and consumes less energy in manufacture.

Finishing Processes and Assembly

After obtaining the rough shape by either powder forging or traditional die forging, a series of processes are then performed to obtain the finished connecting rod. These processes include the following:

- Machining and grinding the side faces
- Drilling and broaching the small end and the big end
- Drilling and tapping the bolt holes of the big end and machining the bolt head seats.
- Machining the fracture splitting groove and fracture splitting the big end
- Assembly of the connecting rod parts
- Finish grinding of the side faces

- Milling of bearing positioning grooves, inserting big end shells, and small end bush
- Honing the internal surfaces of the big end shell and the small end bush
- Inspection and packaging

7.5 DESIGN FOR MANUFACTURE AND ASSEMBLY

The intimate relation between design and manufacturing has resulted in a variety of methods to improve the design of components and products with respect to specific manufacturing processes and activities. Examples include design for manufacture, design for assembly, design for disassembly, design for casting, design for injection molding, and design for machining. Designing for "X" (DFX) is the collective name of this methodology, which seeks to lower costs and cycle times by ensuring that components are designed to be compatible with the activity of the process concerned.

Design for manufacture and assembly seeks to minimize the cost of a product by designing components that are easier to manufacture design for manufacture (DFM) and designing components that are easier to assemble design for assembly (DFA). Although DFM and DFA are separate design activities, they are often interrelated and are best addressed at the configuration stage of the design, as discussed in Section 5.3. Changes during the detail design stage can also be introduced to further improve ease of manufacture and assembly. Design for manufacture and assembly (DFMA) provides a structured procedure for analyzing a design from the point of view of manufacture and assembly. Such a procedure normally results in simpler designs with fewer components in an assembly. In addition to reduction in assembly time and cost, having fewer components means fewer detail drawings, smaller number of materials and specifications, less inventory, and lower overheads. Boothroyd et al. (1994) developed a DFA software to provide guidance in reducing the number of parts in an assembly. The software asks the following questions: (a) Is the part or subassembly used only for fastening or securing other items? (b) Is the part or subassembly used only for connecting other items? If the answer to either of these questions is "yes," then the part or subassembly is considered theoretically unnecessary. If the answer to both questions is "no," the following questions are then asked: Does the part move relative to all other parts? Must the part be made of different materials or isolated from other parts? If the answer is "no," the part is considered theoretically unnecessary. The design team attempts to integrate the parts that are considered theoretically unnecessary with other parts, thus reducing the total part count and assembly time of the product.

One of the methods reported by Boothroyd (1997) for DFM uses the processability evaluation method. Processability is defined as being proportional to cost of the component, which is determined by its shape, material, and the processing method. Various designs, processing methods, and materials are considered, and the cost is determined for the different combinations. For example, the cost of an injection-molded plastic component is compared with an equivalent die casting or sheet metal stamping.

Example 7.2 is based on that given by Boothroyd and the figures are reprinted with permission of ASM International.

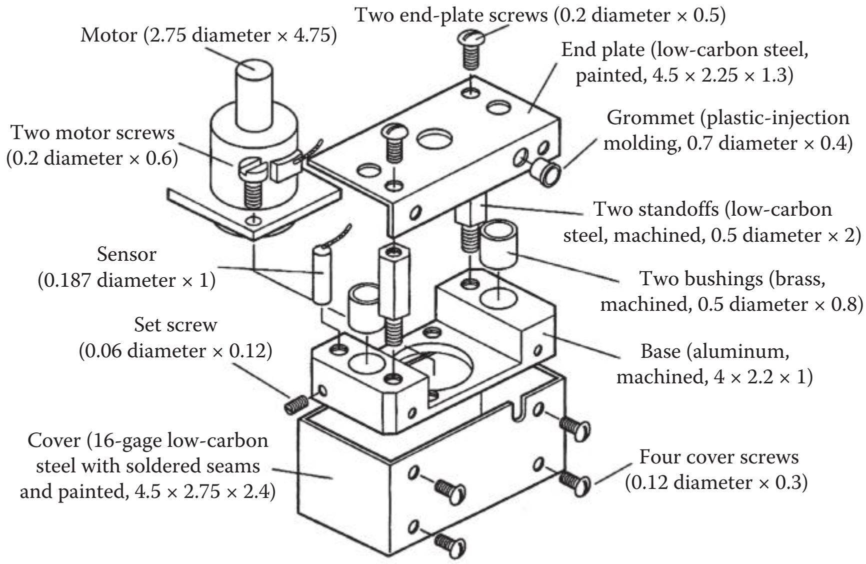

FIGURE 7.3 Initial design of motor–drive assembly. Dimensions in inches. (Reprinted from Dieter, G.E., in *Materials Selection and Design*, Vol. 20, *ASM Handbook*, *Design for Manufacture and Assembly*, ASM International, Materials Park, OH, 1997, pp. 676–686. With permission.)

Design Example 7.2: Application of DFMA Principles to the Design of a Motor–Drive Assembly

Problem

It is required to design a motor–drive assembly that senses and controls its position on two guide rails. The main requirements are that the motor must have a removable cover and a rigid base that supports both the motor and the sensor, in addition to sliding up and down the guide rails. Figure 7.3 shows a proposed design, which requires 2 subassemblies for the motor and sensor in addition to 8 additional parts and 9 screws, making a total of 19 items to be assembled.

Analysis

Using the DFMA software and asking the kind of questions mentioned earlier, it is possible to eliminate the parts that do not meet the minimum part-count criteria, and Figure 7.4 shows the resulting design. The number of items to be assembled has been reduced to six, and the assembly time has been reduced from 160 to 46 s, thus reducing the assembly cost from $1.33 to $0.38.

Although the shape of the base remains essentially the same, it is machined out of nylon in the new design instead of aluminum to eliminate the bushings and reduce the cost of material (aluminum, $2.34, and nylon, $0.49). The new base also has less drilled and tapped holes, with further reduction of cost of

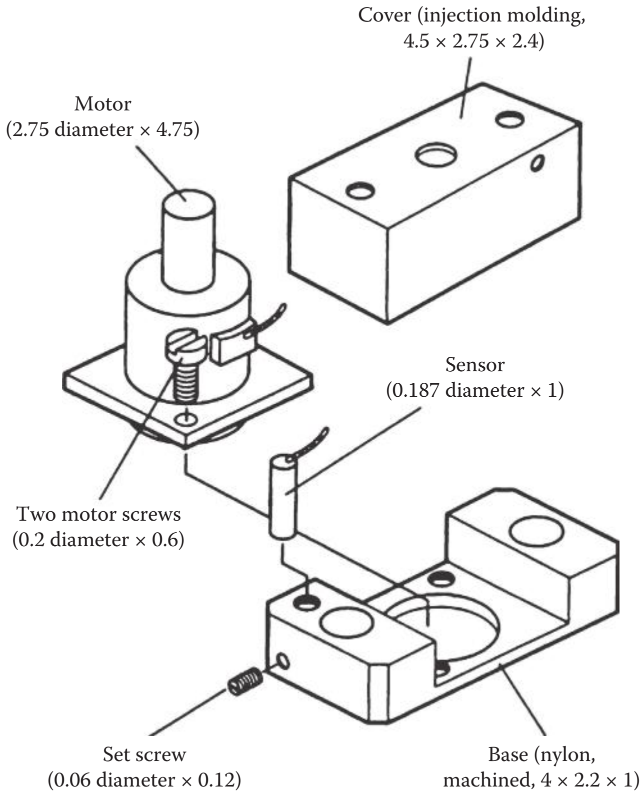

FIGURE 7.4 Redesign of motor–drive assembly following DFA analysis. Dimensions in inches. (Reprinted from Dieter, G.E., in *Materials Selection and Design,* Vol. 20, *ASM Handbook*, *Design for Manufacture and Assembly*, ASM International, Materials Park, OH, 1997, pp. 676–686. With permission.)

manufacturing. The total cost of components in the motor–drive assembly has been reduced from $35.08 for the original design to $22.00 for the new design.

These costs show that the saving in the cost of components was much more than the saving in assembly cost in this case.

Source: Based on Boothroyd, G., Design for manufacture and assembly, in *ASM Handbook*, Vol. 20, *Materials Selection and Design*, Dieter, G.E., Ed. ASM International, Materials Park, OH, 1997, pp. 676–686.

7.6 DESIGN CONSIDERATIONS FOR CAST COMPONENTS

Casting covers a wide range of processes that can be used to shape almost any metallic material and some plastics in a variety of shapes, sizes, accuracy, and surface finishes. The tolerances and surface finishes that can be achieved by standard commercial foundry practice are given in Tables 7.3 and 7.4. The number of castings can vary from very few to several thousands. In some cases, casting represents the obvious and only way of manufacturing, as in the case of components made of different types of cast iron or cast alloys. In many other applications, however, decision has to be made whether it is advantageous to cast a product or to use another method of manufacture. In such cases, the following factors should be considered:

1. Casting is particularly suited for parts that contain internal cavities that are inaccessible, too complex, or too large to be easily produced by machining.
2. It is advantageous to cast complex parts when required in large numbers, especially if they are to be made of aluminum or zinc alloys.

TABLE 7.3
Approximate Values of Surface Roughness and Tolerance That Are Normally Obtained with Different Manufacturing Processes

	Typical Tolerance (±)		Typical Surface Roughness (R_a)	
Process	**(mm)**	**(in. × 10³)**	**(μm)**	**(μin.)**
Sand casting	0.5–2.0	20–80	12.5–2.5	500–1000
Investment casting	0.2–0.8	8–30	1.6–3.2	63–125
Die casting	0.1–0.5	4–20	0.4–1.6	16–63
P/M	0.2–0.4	8–16	0.8–3.2	32–125
Forging	0.2–1.0	8–40	3.2–12.5	125–500
Hot rolling	0.2–0.8	8–30	6.3–25	250–1000
Hot extrusion	0.2–0.8	8–30	6.3–25	250–1000
Cold rolling	0.05–0.2	2–8	0.4–1.6	16–32
Cold drawing	0.05–0.2	2–8	0.4–1.6	16–32
Cold extrusion	0.05–0.2	2–8	0.8–3.2	32–125
Flame cutting	1.0–5.0	40–200	12.5–25	500–1000
Sawing	0.4–0.8	15–30	3.2–25	125–1000
Turning and boring	0.025–0.05	1–2	0.4–6.3	16–250
Drilling	0.05–0.25	2–10	1.6–6.3	63–250
Shaping and planning	0.025–0.125	1–5	1.6–12.5	63–500
Milling	0.01–0.02	0.5–1	0.8–6.3	32–250
Chemical machining	0.02–0.10	0.8–4	1.6–6.3	63–250
EDM and electrochemical machining (ECM)	0.02–0.10	0.8–4	1.6–6.3	63–250
Reaming	0.02–0.05	0.4–2	0.8–3.2	32–125
Broaching	0.01–0.05	0.4–2	0.8–3.2	32–125
Grinding	0.01–0.02	0.4–0.8	0.1–1.6	4–63
Honing	0.005–0.01	0.2–0.4	0.1–0.8	4–32
Polishing	0.005–0.01	0.2–0.4	0.1–0.4	4–16
Lapping and surface finishing	0.004–0.01	0.16–0.4	0.05–0.4	2–16

TABLE 7.4
Characteristics of Different Casting Processes and P/M

Process	Alloy	Weight kg (lb)	Surface Finish µm (µin.)	Tolerance (m/m [in./in.])	Minimum Section Thickness (mm [in.])	Porosity Rating	Least Economy Quantity	Relative Production Rate
Sand casting	Most	0.2 and up (0.4 and up)	12.5–25 (500–100)	0.03–0.2	3–5 (0.12–0.20)	Fair	1	1
Shell molding	Most	0.2–10 (0.44–22)	1.6–12.5 (63–500)	0.01–0.03	2–5 (0.08–0.20)	Good	500	4
Gravity die casting	Nonferrous	0.2–10 (0.44–22)	1.6–12.5 (63–500)	0.02–0.05	3–5 (0.12–0.2)	Very good	500	4–5
Pressure die casting	Al, Zn, Mg, Cu alloys	0.2–10 (0.44–22)	0.4–1.6 (16–63)	0.001–0.05	1–2 (0.04–0.08)	Excellent	10,000	10
Investment casting	Most	0.1–10 (0.22–22)	1.6–3.2 (63–125)	0.002–0.005	0.5–1 (0.02–0.04)	Very good	50	6
P/M	Most	0.01–5 (0.022–11)	0.8–3.2 (32–125)	0.002–0.005	0.8 (0.03)	Variable	5,000	8

3. Casting techniques can be used to produce a part, which is one of a kind in a variety of materials, especially when it is not feasible to make it by machining.
4. Precious metals are usually shaped by casting since there is little or no loss of material.
5. Parts produced by casting have isotropic properties, which could be an important requirement in some applications.
6. Casting is not competitive when the parts can be produced by punching from sheet or by deep drawing.
7. Extrusion can be preferable to casting in some cases, especially in the case of lower melting nonferrous alloys.
8. Casting is not usually a viable solution when the material is not easily melted, as in the case of metals with very high melting points such as tungsten.

7.6.1 Guidelines for Design

When casting is selected as the manufacturing process, it is important for the designer to observe the general rules that are related to solidification, material of the casting, position of the casting in the mold, and required accuracy of the part. Designs that violate the rules of sound casting can make production impossible or possible only at higher expense and large rejection rates.

A general rule of solidification is that the shape of the casting should allow the solidification front to move uniformly from one end toward the feeding end, that is, directional solidification. This can most easily be achieved when the casting has virtually uniform thickness in all sections. In most cases this is not possible. However, when section thickness must change, such change should be gradual, to avoid feeding and shrinkage problems. Sudden changes in section thickness give rise to stress concentration and possible hot tears in the casting. Figure 7.5 gives some guidelines to avoid these defects.

Another problem that arises in solidification is caused by sharp corners; these also give rise to stress concentration and should be replaced by larger radii. When two sections cross or join, the solidification process is interrupted and a hot spot results. Hot spots retard solidification and usually cause porosity and shrinkage cavities. Some solutions to this problem are given in Figure 7.5. Large unsupported flat areas should also be avoided, as they tend to warp during cooling.

7.6.2 Effect of Material Properties

The type and composition of the material play an important part in determining the shape, minimum section thickness, and strength of the casting. Materials that have large solidification shrinkage and contain low-melting phases are susceptible to hot tears. Collapsible mold materials and a casting shape that allows shrinkage with least stresses in the casting are required in such cases.

Another material variable is castability, which can be related to the minimum section thickness that can be easily achieved. Table 7.4 provides some guidelines to minimum section thickness, which can be economically obtained for different casting processes. It should be noted that the shape and size of the casting as well as the casting process and foundry practice can affect the minimum section thickness.

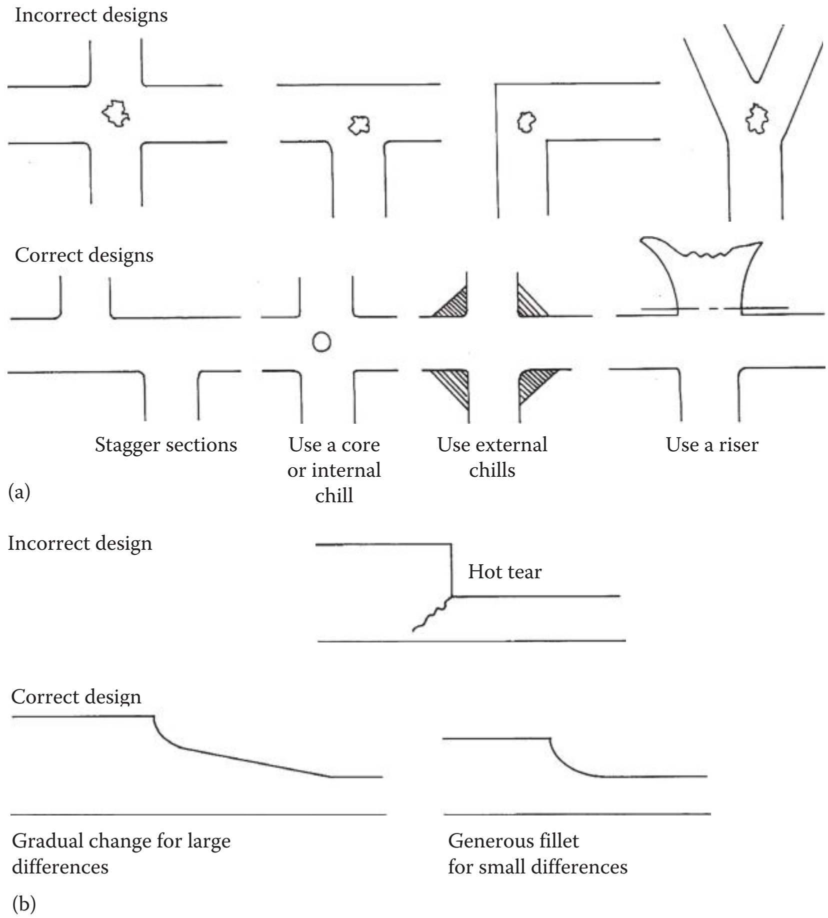

FIGURE 7.5 Design considerations for case components. (a) Solidification of intersecting sections results in hot spots and shrinkage cavities, and (b) large changes in section thickness cause hot tears.

As cooling rates are directly related to section thickness, sections of different thicknesses can develop different structures and mechanical properties. In cast iron, the grain size as well as the graphite size and the amount of combined carbon are affected. Thinner sections result in faster cooling rates and higher strength and hardness in the different classes of gray cast iron.

7.7 DESIGN CONSIDERATIONS FOR MOLDED PLASTIC COMPONENTS

Compression, transfer, and injection molding processes are the commonly used methods of molding plastic components. These processes involve the introduction of a fluid or a semifluid material into a mold cavity, permitting it to solidify into a desired shape. Although section thickness, dimensional accuracy, or the incorporation of inserts would make it desirable to use one molding technique in preference to another, there are general design rules that should be observed to ensure the quality of the product.

7.7.1 Guidelines for Design

Experience shows that the mechanical, electric, and chemical properties of molded components are influenced by the flow of molten plastic as it fills the mold cavity. Streamlined flow will avoid gas pockets in heavy-sectioned areas.

An important common feature in molding processes is draft, which is required for easy ejection of molded parts from the mold cavity. A taper of 1°–4° is usually used for polymers, but tapers of <1° can be used for deep articles. Another common feature is the uniformity of wall thickness. In general, molded parts should be designed to have uniform wall thickness. Nonuniformity of thickness in a molded piece tends to produce nonuniform cooling and unbalanced shrinkage—leading to internal stresses and warpage.

If thickness variations are necessary, generous fillets should be used to allow gradual change in thickness. The effect of junctions and corners can also be reduced by using a radius instead, as shown in Figure 7.6a. The nominal wall thickness must obviously be such that the part is sufficiently strong to carry the expected service loads. However, it is better to adjust the shape of the part to cope with the applied load than to increase the wall thickness. This is because thick sections retard the molding cycle and require more material. Ribs, beads, bosses, edge stiffeners, and flanges should be used instead. However, shrinkage dimples, sink marks, may appear opposite to ribbed surfaces if they are not proportioned correctly. Adopting the proportions shown in Figure 7.6b may eliminate sink marks.

Large, plain, flat surfaces should be avoided, as they are prone to warping and lack rigidity. Such surfaces should be strengthened by ribbing or doming. The presence of holes disturbs the flow of the material during molding and a weld line occurs on the side of the hole away from the direction of flow. This results in a potentially weak point, and some form of strengthening, such as bosses, may be necessary, as shown in Figure 7.6c. Through holes are preferred to blind holes from a manufacturing standpoint. This is because core prints can often be supported in both halves of the mold in the case of through holes but can only be supported from one end in the case of blind holes.

Undercuts are undesirable features in molded parts as they cause difficulties in ejection from the mold. Examples of external and internal undercuts are shown in Figure 7.6d. Some parts with minor undercuts may be flexible enough to be stripped from the mold without damage. Many thermoplastics can tolerate about 10% strain during ejection from the mold.

Parts with external or internal threads can be made by molding and are usually removed from the mold by unscrewing. The mold is usually costly, since unscrewing devices may need to be incorporated. External threads may be produced without special devices if they are located on the parting plane of the mold. The thread

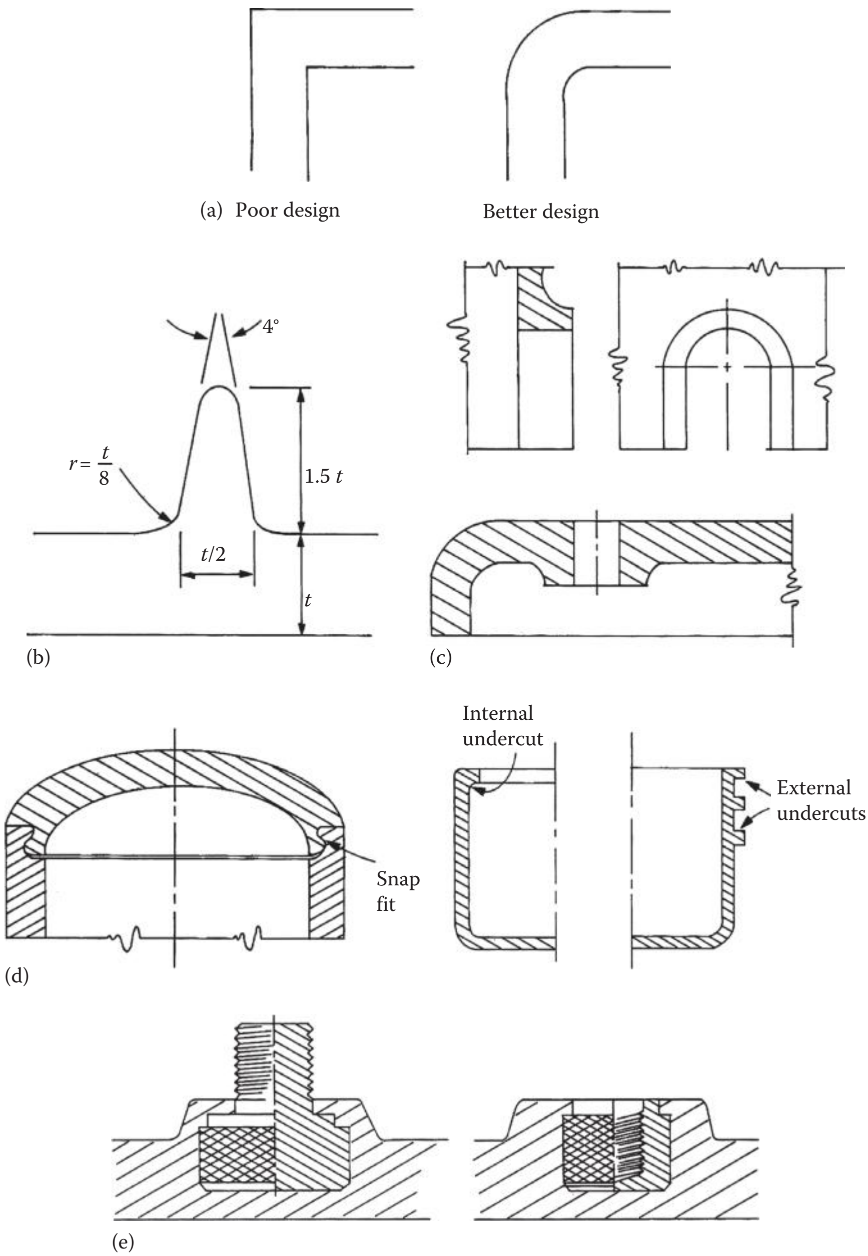

FIGURE 7.6 Some design features of plastic parts. (a) Using radii instead of sharp corners, (b) recommended rib proportions to avoid sink marks, (c) use of bosses to strengthen areas around holes and slots, (d) examples of undercuts, and (e) accommodating metal inserts.

may need secondary finishing in this case. Threads can also be formed by tapping, especially in the case of diameters <8 mm (5/16 in.). When more durable threads are needed, threaded metal inserts may be incorporated in the molded component, as shown in Figure 7.6e.

Plastic parts can be given a wide variety of surface finishes including mirrorlike finish, dull satin, wood grain, leather grain, and other decorative textures. A highly smooth surface is usually required for surfaces that are to be painted or vacuum metallized. Decorative textures are often helpful in hiding any possible surface imperfections, such as flow lines or sink marks. Raised letters on a molded part are easier and cheaper to produce than depressed letters because the lettering is machined into the mold cavity. The position of the parting plane of the mold should be carefully considered as it is normally accompanied by an unsightly flash line.

7.7.2 Accuracy of Molded Parts

Dimensional tolerances in molded plastic parts are affected by the type and constitution of the material, shrinkage of the material, heat and pressure variables in the molding process, and the toolmaker's tolerances on the mold manufacture. Generally, shrinkage has two components:

- Mold shrinkage, which occurs upon solidification
- After-shrinkage, which occurs in some materials after 24 h

For example, a thermosetting plastic like melamine has a mold shrinkage of about 0.7%–0.9% and an after-shrinkage of 0.6%–0.8%. Thus, a total shrinkage of about 1.3%–1.7% should be considered. However, a thermoplastic like polyethylene may shrink as much as 5% and nylon as much as 4%. In addition, the value of the tolerance depends on the size of the part. Larger dimensions are normally accompanied by larger tolerances. For example, dimensions <25 mm (1 in.) can be held within ±50 μm (±0.002 in.). Larger dimensions are usually given tolerances of ±10–20 μm/cm (±0.001–0.002 in./in.). The value of tolerance also depends on the direction in relation to the parting plane. Generally, dimensions at right angles to the parting plane should be given higher tolerance than dimensions parallel to it. As a rough guide, if a tolerance of ±50 μm is allowed in the direction parallel to the parting plane of the mold, a tolerance of ±200 μm should be allowed at right angles. Generous dimensional tolerances make economical production possible.

7.8 DESIGN CONSIDERATIONS FOR FORGED COMPONENTS

Forging processes represent an important means of producing relatively complex parts for high-performance applications. In many cases, forging represents a serious competitor to casting, especially for solid parts that have no internal cavities. Forged parts have wrought structures that are usually stronger, are more ductile, contain less segregation, and are likely to have less internal defects than cast parts. This is because the extensive hot working, which is usually involved in forging, closes

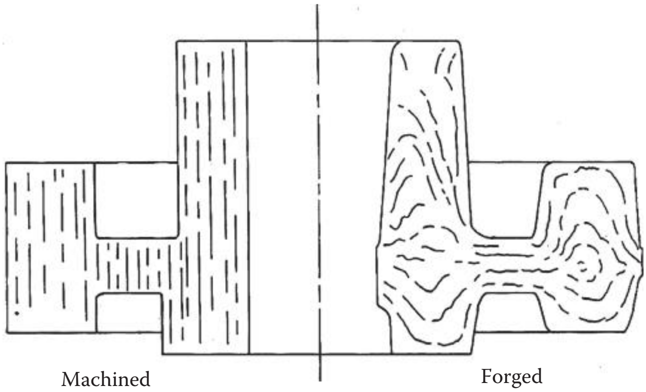

FIGURE 7.7 Schematic comparison of the grain flow in forged and machined parts.

existing porosity, refines the grains, and homogenizes the structure. However, cast parts are more isotropic than forged parts, which usually have directional properties. This directionality is due to the fiber structure that results from grain flow and elongation of second phases in the direction of deformation. Forged components are generally stronger and more ductile in the direction of fibers than across the fibers. This directionality can be exploited in some cases to enhance the mechanical performance of the forged part, as shown in Figure 7.7.

7.8.1 Guidelines for Design

When forging is selected as the manufacturing process, it is important for the designer to observe the general rules that are related to the flow of material in the die cavity. As with casting, it is better to maintain uniform thickness in all sections. Rapid changes in thickness should be avoided because these could result in laps and cracks in the forged metal as it flows in the die cavity. To prevent these defects, generous radii must be provided at the locations of large changes in thickness. Another similarity with casting is that vertical surfaces of a forging must be tapered to permit removal from the die cavity. A draft of 5°–10° is usually provided.

It is better to locate the parting line near the middle of the part. This avoids deep impressions in either of the two halves of the die and allows easier filling of the die cavity. Inaccuracies in die forging result from mismatch between the die halves, due to the lateral forces that occur during forging, and from incomplete die closure, which is usually introduced to avoid die-to-die contact. A design would be more economically produced by forging if dimensions across the parting line are given appropriate mismatch allowance, and parallel dimensions are given a reasonable die closure allowance. Specifying close tolerances to these dimensions could require extensive machining, which would be expensive. Allowance must also be made for surface scale and warpage in hot forged parts. The dimensional tolerances and surface roughness that are commercially achieved in forging processes are shown in Table 7.3.

7.9 DESIGN CONSIDERATIONS FOR POWDER METALLURGY PARTS

P/M techniques can be used to produce a large number of small parts to the final shape in few steps, with little or no machining, and at high rates. Many metallic alloys, ceramic materials, and particulate-reinforced composites can be processed by P/M techniques. Generally, parts prepared by the traditional P/M techniques, which involve mechanical pressing followed by sintering, contain from 4 to 10 vol% porosity. The amount of porosity depends on part shape, type and size of powder, lubricant used, pressing pressure, sintering temperature and time, and finishing treatments.

The distribution and volume fraction of porosity greatly affect the mechanical, chemical, and physical properties of parts prepared by P/M techniques. Using higher compaction pressures or employing techniques like P/M forging and HIP can greatly decrease porosity and provide strength properties close to those of wrought materials. The HIP process is particularly suited for producing parts from high-temperature alloys that are difficult to forge and machine.

An added advantage of P/M is versatility. Materials that can be combined in no other way can be produced by P/M. Examples include aluminum–graphite bearings, copper–graphite electric brushes, cobalt–tungsten carbide cutting tools (cermets), and porous bearings and filters. P/M is also the only practical way of processing tungsten and other materials with very high melting points.

The final tolerances in mechanically pressed and sintered components are comparable to those achievable by machining on production machine tools (Tables 7.3 and 7.4). Tolerances in the axial direction, die-fill direction, are usually about ±2% of the dimension. Closer tolerances in the diameter of circular sections are usually possible and can be less than ±0.5% of the diameter.

On a unit weight basis, powdered metals are considerably more expensive than bulk wrought or cast materials. However, the absence of scrap, elimination of machining, the fewer production steps, and the higher rates of production often offset the higher material cost. Dies needed for mechanical pressing are also an expensive item in P/M techniques. Production volumes of less than 10,000 parts are usually not practical for mechanically pressed parts. When HIP is utilized to produce relatively large parts using materials that are difficult to form by other techniques, production runs as low as 20 parts could be economical.

7.9.1 Guidelines for Design

Unlike forging or casting processes, mechanical compaction of powders is restricted to two dimensions. It is impractical to apply pressure to the sides of mechanical dies; thus, the flow of powders during compaction is almost entirely axial. It is also necessary to be able to eject the compact. These limitations give rise to certain design rules, which have been established by the Powder Metallurgy Parts Association and Metal Powder Industries Federation. These rules can be summarized as follows:

1. The shape of the part must permit ejection from the die (Figure 7.8a).
2. Parts with straight walls are preferred. No draft is required for ejection from lubricated dies.

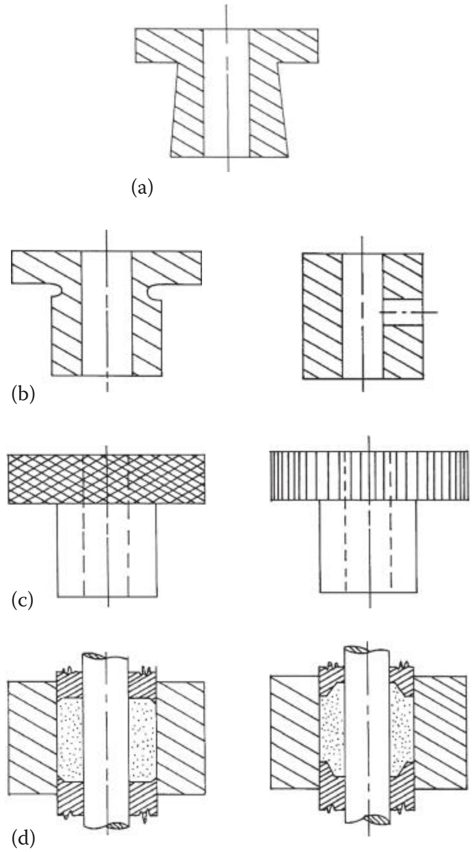

FIGURE 7.8 Design considerations for P/M components. (a) Reverse taper should be avoided, use parallel sides, and machine the required taper after sintering; (b) undercuts and holes at right angles to pressing direction should be avoided; if necessary, such features are introduced by machining and sintering; (c) diamond knurls should be replaced by straight serrations; (d) part shapes that require featheredges on punches and similar weakening features should be avoided.

3. Parts with undercuts or holes at right angles to the direction of pressing cannot be made (Figure 7.8b).
4. Straight serrations can be made easily, but diamond knurls cannot (Figure 7.8c).
5. The shape of the part should be such that the powder is not required to flow into thin walls, narrow splines, or sharp corners. Sidewalls should be thicker than 0.75 mm (0.030 in.).
6. The shape of the part should permit the construction of strong tooling, and punches should have no sharp or feather edges (Figure 7.8d).
7. The part should be designed with as few changes in diameter and section thickness as possible.

8. Since pressure is not transmitted uniformly through a deep bed of powder, the length/diameter ratio of a mechanically pressed part should not exceed about 2.5:1.
9. Take advantage of the fact that certain materials, such as cermets and porous components, which are impossible, impractical, or uneconomical to obtain by any other method, can be produced by P/M.
10. P/M parts may be bonded by assembling in the green condition and then sintering together to form a bonded assembly. Other joining methods are also possible and can be used to join P/M parts to castings or forgings.

7.10 DESIGN OF SHEET METAL PARTS

Parts made from sheet metal cover a wide variety of shapes, sizes, and materials. Many examples are found in automotive, aircraft, and consumer industries. Generally, sheet metal parts are produced by shearing, bending, or drawing. The quality of the sheet material plays an important role in determining the quality of the finished product, as well as the life of tools and the economics of the process. Grain size of the sheet material is important and should be closely controlled. Steel of 0.035–0.040 mm (0.001–0.0016 in.) grain size is generally acceptable for deep drawing applications. When formability is the main requirement in a sheet material, drawing-quality low-carbon steels represent the most economic alternative. However, with the increasing demand for lighter energy-conserving products, other steel grades are increasingly used to make thinner and stronger components. Examples include control-rolled HSLA steels and dual-phase steels.

7.10.1 Guidelines for Design

Metal sheets are usually anisotropic, which means that their strength and ductility vary when measured at different angles with respect to the rolling direction. This anisotropy is caused by the elongated inclusions, that is, stringers, and by preferred orientation in the grains, that is, texture.

The most important factor that should be considered when designing parts that are to be made by bending is bendability. This is related to the ductility of the material and is expressed in terms of the smallest bend radius that does not crack the material. Bendability of a sheet is usually expressed in multiples of sheet thickness, such as $2T$, $3T$, and $4T$. A $2T$ material has greater bendability than a $3T$ material. Because of anisotropy, bendability of a sheet is usually greater when tested such that the line of bend is at right angles to the rolling direction of the sheet.

Another factor that should be considered when designing for bending is springback, which is caused by the elastic recovery of the material when the bending forces are removed. One way of compensating for springback is to overbend the sheet. Another method is bottoming, which eliminates the elastic recovery by subjecting the bend area to high localized stresses. A tolerance of ±0.8 mm (±1/32 in.) or more should be allowed in bent parts.

7.11 DESIGNS INVOLVING JOINING PROCESSES

Joining can be considered as a method of assembly, where parts made by other processes are joined to make more complex shapes or larger structures. In this respect, joining extends the capabilities of processes like casting, forging, and sheet metal working; it allows the manufacture of products like machine frames, steel structures, motorcar bodies, beverage and food cans, storage tanks, and piping systems. Some joints are temporary and can be dismantled easily, as in the case of bolted joints, whereas others provide permanent assembly of joined parts, as in the case of rivets and weldments.

Normally, the major function of a joint is to transmit stresses from one part to another, and in such cases, the strength of the joint should be sufficient to carry the expected service loads. In some applications, tightness of the joint is also necessary to prevent leakage. Because joints represent areas of discontinuities in the assembly, they should be located in low-stress regions—especially in dynamically loaded structures. Other design considerations that are applicable to the main joining processes are discussed in the following paragraphs.

7.11.1 Welding

Welding is defined by the American Welding Society (AWS) as a "localized coalescence of metals or nonmetals produced by either heating of the materials to a suitable temperature, with or without the application of pressure, or by the application of pressure alone, and with or without the use of filler metal." The various welding processes have been classified by the AWS as shown in Table 7.5. The different processes have been assigned letter symbols to facilitate their designation. The main factors that distinguish the different processes are (a) the source of the energy used for welding and (b) the means of protection or cleaning of the welded metal. The processes given in Table 7.5 cover a wide range, which makes it possible to find an efficient and economic means of welding of almost all industrial metallic systems.

Welding has replaced riveting in many applications including steel structures, boilers, tanks, and motorcar chassis. This is because riveting is less versatile and always requires lap joints. Also, the holes and rivets subtract from strength, and a riveted joint can only be about 85% as strong, whereas a welded joint can be as strong as the parent metal. Welded joints are easier to inspect and can be made gas- and liquid-tight without the caulking, which has to be done in riveted joints. On the negative side, however, is that structures produced by welding are monolithic and behave as one piece. This could adversely affect the fracture behavior of the structure. For example, a crack in one piece of a multipiece riveted structure may not be serious, as it will seldom progress beyond that piece without detection. However, in the case of a welded structure, a crack that starts in a single plate or weld may progress for a large distance and cause complete failure. This is illustrated in Figure 4.5, which shows the catastrophic failure of the welded hull of a steel ship.

TABLE 7.5
Common Welding Processes and Their Recommended Use

Process	AWS Designation	Recommended Use: Carbon Steels	Low-Alloy Steels	Stainless Steels	Ni and Alloys	Al and Alloys
Fusion welding						
Arc welding	*W*					
Shielded metal arc welding	SMAW	a	a	a	a	—
Gas metal arc welding	GMAW	b	b	b	a	e
Pulsed arc	GMAW-P	a	a	a	a	d
Short-circuit arc	GMAW-S	d	d	d	d	—
Gas tungsten arc welding	GTAW	d	d	d	d	e
Flux-cored arc welding	FCAW	b	b	b	e	—
Submerged arc welding	SAW	a	a	a	c	—
Plasma arc welding	PAW	—	—	E	e	g
Stud welding	SW	a	a	a	—	g
Oxyacetylene welding	OAW	e	g	g	g	g
Plastic welding						
Solid-state welding	*SSW*					
Forge welding	FOW	a	—	—	—	—
Cold welding	CW	c	—	—	—	—
Friction welding	FRW	b	b	b	b	b
Ultrasonic welding	USW	g	g	g	g	f
Explosion welding	EXW	e	e	e	e	e
Resistance welding	*RW*					
Resistance spot welding	RSW	f	f	f	f	f
Resistance seam welding	RSW	f	f	f	f	f
Projection welding	RPW	f	f	f	f	f
Other welding processes						
Laser beam welding	LBW	e	e	e	e	f
Electroslag welding	ESW	i	i	i	i	—
Flash welding	FW	a	a	a	a	a
Induction welding	IW	g	—	—	—	—
Electron beam welding	EBW	A	a	a	a	a
Brazing and soldering (B&S)						
Dip brazing	DB	f	g	g	g	e
Furnace brazing	FB	a	a	e	a	e
Torch brazing	TB	e	e	e	e	e
Induction brazing	IB	e	e	e	f	g
Dip soldering	DS	g	g	g	g	g
Furnace soldering	FS	g	g	g	g	g
Torch soldering	TS	g	g	g	g	G

Note: a = all thicknesses, b = 3 mm (1/8 in.) and up, c = 6 mm (¼ in.) and up, d = up to 6 mm (¼ in.), e = up to 18 mm (¾ in.), f = up to 6 mm (¼ in.), g = up to 3 mm (1/8 in.), and i = 18 mm (¾ in.) and up.

Another factor that should be considered when designing a welded structure is the effect of size on the energy-absorption ability of steels. A Charpy impact specimen could show a much lower brittle–ductile transition temperature than a large welded structure made of the same material. The liberty ships that were made during the Second World War are examples of monolithic structures that were made out of unsuitable steel. Many of these ships failed, some while in harbor, as a result of one crack propagating across the whole structure. Thus, the notch–ductility of the steel that is to be used in large welded structures should be carefully assessed.

7.11.1.1 Weldability of Materials

In fusion welding processes, the molten filler metal solidifies quite rapidly by heat conduction into the metal adjacent to the weld. Columnar grains are usually present in the weld bead, while the base metal closest to it undergoes a considerable overheating and grain growth. This latter area, the HAZ, is usually a source of failure in welded components. Thermal contraction of welded metals may cause residual stresses and distortions. Preheating of joints is an effective method of reducing the cooling rate of the weld, which reduces distortion and residual stresses. Postwelding heat treatment can be used to relieve internal stresses and to control the microstructure of the weld area. The need for preheating and postwelding heat treatment depends primarily on the weldability of the welded metal. Weldability can be considered to have two components:

1. Fabrication weldability, which is related to the ease with which a material can be welded
2. Service weldability, which is related to the ability of the process–material combination to form a weld that will perform the intended job successfully

In general, weldability of steel decreases as hardenability increases, because higher hardenability promotes the formation of microstructures that are more sensitive to cracking. Higher hardenability means more possibility of forming brittle martensite, which cannot withstand the shrinkage strains in the weld zone. Hydrogen-induced cracking is also more prevalent in welding of hardenable steels than in welding of low-carbon steels. Proper preheat, high-heat input, and maintenance of adequate interpass temperatures reduce the rate of cooling in the HAZ, and this results in a softer, less-sensitive microstructure. The HAZ may also be softened by postweld heat treatment in the range of 480°C–670°C (895°F–1240°F). The carbon equivalent (CE) is often used to estimate the weldability of hardenable carbon and alloy steels. In this approach, the significant composition variables are reduced to a single number, CE, using one of several similar formulas as follows:

$$\mathrm{CE} = \%\mathrm{C} + \frac{\%\mathrm{Mn}}{6} + \frac{(\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V})}{5} + \frac{(\%\mathrm{Si} + \%\mathrm{Ni} + \%\mathrm{Cu})}{15} \tag{7.1}$$

Steels with CE <0.35% usually require no preheating or postheating. Steels with CE between 0.35% and 0.55% usually require preheating, and steels with CE >0.55% may require both preheating and postheating. In addition to CE, other factors such as hydrogen level, restraint, and thickness must be considered simultaneously in relation to a specific application.

7.11.1.2 Tolerances in Welded Joints

Welding jigs and fixtures are frequently used in production to reduce distortion, warping, and buckling of the welded parts. The use of jigs also increases productivity, reduces costs, and results in higher accuracy. Typical dimensional tolerances that may be held on average weldments are

- 3 mm for small parts with little welding
- 6 mm for moderate-sized parts with a small amount of welding
- 9 mm for large parts with a moderate amount of welding
- 9–12 mm for large parts with a large amount of welding

7.11.1.3 Guidelines for the Design of Weldments

In addition to cracking and residual stresses, defects like porosity, slag inclusions, incomplete fusion, and incorrect weld profile can also exist in the welded joint. Such defects can be eliminated by following the correct welding procedure and selecting the appropriate technique. Generally, strict quality control and nondestructive testing are essential if welding defects are to be eliminated and high reliability of welded joints is to be maintained. Other rules that should be considered when designing a welded structure include the following:

1. Welded structures and joints should be designed to have sufficient flexibility. Structures that are too rigid do not allow shrinkage of the weld metal, restrict the ability to redistribute stresses, and are subject to distortions and failure.
2. Accessibility of the joint for welding, welding position, and component matchup are the important elements of design.
3. Thin sections are easier to weld than thick ones.
4. Welded sections should be about the same thickness to avoid excessive heat distortion.
5. It is better to locate welded joints symmetrically around the axis of an assembly to reduce distortion.
6. If possible, welded joints should be placed away from the surfaces to be machined. Hard spots in the weld can damage the cutting tools.
7. An inaccessible enclosure in a weldment, or the mating surfaces of a lap joint, should be completely sealed to avoid corrosion.
8. Where strength requirements are not critical, short intermittent welds are preferable to long continuous ones as distortion is reduced.
9. Help shrinkage forces to work in the desired direction by presetting the welded parts out of position before welding so that shrinkage forces will bring them into alignment.
10. Use weld fixtures and clamps to reduce distortion.
11. Whenever possible, meeting of several welds should be avoided.
12. Balance shrinkage forces in a butt joint by welding alternately on each side.
13. Remove shrinkage forces by heat treatment or by shot peening.

14. Tolerances of ±1.5 mm (ca. ±1/16 in.) are possible in welded joints. Surfaces that need closer tolerances should be finished by machining after welding and postwelding heat treatment.
15. Parts that have been designed for casting or forging should be redesigned if they are to be made by welding. The new design should take advantage of the benefits of welding and avoid its limitations.

7.11.1.4 Types of Welded Joints

Metal plates can be joined by welding in five main types of joints, as shown in Figure 7.9. Lap, tee, and corner joints use fillet-type welds, as shown in Figure 7.10. Welding of thick plates requires edge preparation to ensure complete penetration. In such cases, one or both of the edges to be welded are chamfered in such a way as to minimize the amount of weld metal deposited. This is because the cost per unit weight of deposited weld metal is about 25–50 times as much as structural steel. In addition, the amount of shrinkage and distortion increases as the amount of deposited metal increases.

7.11.1.5 Strength of Welded Joints

Full-penetration butt welds are generally considered to have the same strength as the base metal. Hence, there is no need to calculate the strength of the weld if the deposited metal is the same as the base metal. The strength of a fillet weld is inherently lower than a full-penetration butt weld. When the applied load is parallel to the weld line, the plane of rupture is at 45°, weld throat. The AWS code gives the allowable force per unit length of the weld as 30% of the tensile strength, S, of the welding electrode. Thus, the load-carrying capacity, P, of the two fillet welds shown in Figure 7.11 is

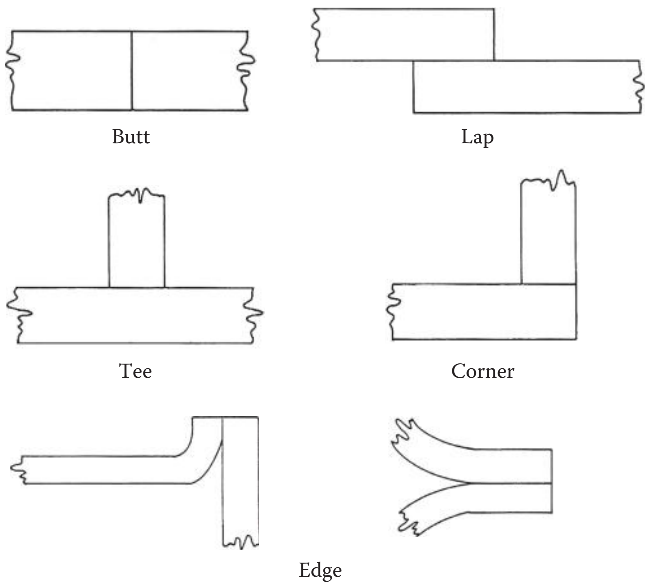

FIGURE 7.9 Types of welded joints.

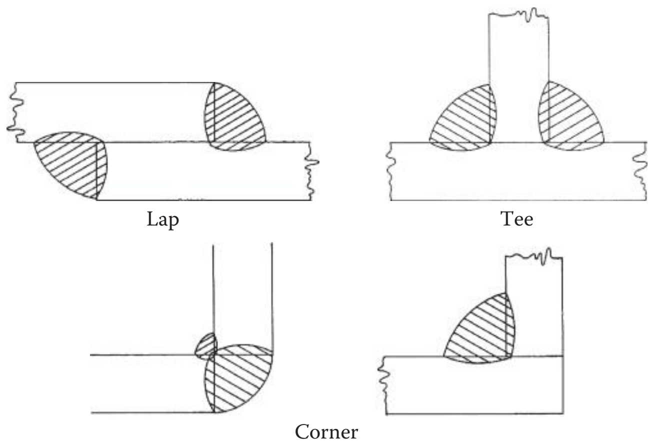

FIGURE 7.10 Use of fillet-type welds in lap, tee, and corner joints.

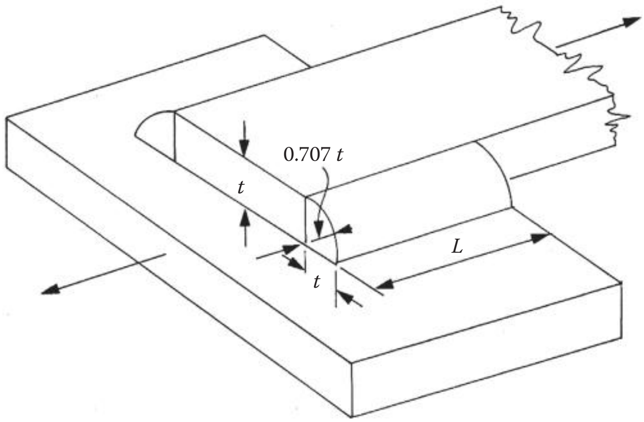

FIGURE 7.11 Parameters involved in calculating the load-carrying capacity of lap joints.

$$P = 2 \times 0.30S \times 0.707t \times L \tag{7.2}$$

where
  L is the length of weld
  t is the leg of weld—in this case, the same as plate thickness

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Design Example 7.3: Design of a Welded Joint

Problem

An AISI 1020 steel angle of dimensions 150 mm × 150 mm × 12 mm (6 in. × 4 in. × 1/2 in.) is to be welded to a steel plate by fillet welds along the edges of the 150 mm leg. The angle should support a load of 270 kN (60,000 lb) acting along its length. Determine the lengths of the welds to be specified. The welding electrode used is AWS–AISI E6012 with a tensile strength of 414 MPa (60 ksi).

Solution

From Equation 7.2,

$$270{,}000 = 2 \times 0.3 \times 414 \times 0.707 \times 12 \times L$$

where L is 128 mm on either side parallel to the axis of the angle.

7.11.2 Adhesive Bonding

Adhesives represent an attractive method of joining and their use is increasing in many applications. Some of the main advantages in using adhesives are the following:

1. Thin sheets and parts of dissimilar thicknesses can be easily bonded.
2. Adhesive bonding is the most logical method of joining polymer–matrix composites.
3. Dissimilar or incompatible materials can be bonded.
4. Adhesives are electric insulators and can prevent galvanic action in joints between dissimilar metals.
5. Flexible adhesives spread bonding stresses over wide areas and accommodate differential thermal expansion.
6. Flexible adhesives can absorb shocks and vibrations, which increases fatigue life.
7. Preparation of bonded joints requires no fastener holes, which gives better structural integrity and allows thinner-gauge materials to be used.
8. Adhesives provide sealing action in addition to bonding.
9. The absence of screw heads, rivet heads, or weld beads in adhesive-bonded joints is advantageous in applications where interruption of fluid flow cannot be tolerated or where appearance is important.
10. Adhesive bonding can also be used in conjunction with other mechanical fastening methods to improve the strength of the joint. Case study 4.6 illustrates how adhesive bonding is combined with rivets in manufacturing aircraft fuselage.

The main limitations of adhesives are the following:

1. Bonded joints are weaker under cleavage and peel loading than under tension or shear.
2. Most adhesives cannot be used at service temperatures above 300°C (ca. 600°F).
3. Solvents can attack adhesive-bonded joints.
4. Some adhesives are attacked by UV light, water, and ozone.
5. The designer should also be aware of the adhesive's impact resistance and creep, or cold flow, strength.

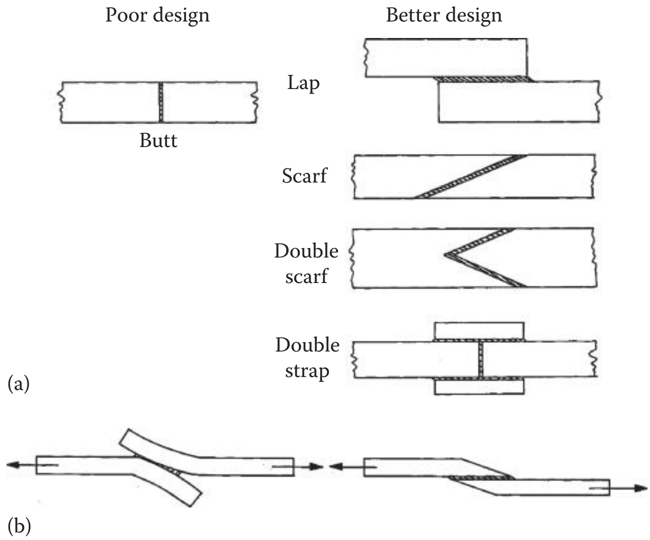

FIGURE 7.12 Adhesive joint design. Butt joint is weak, and the bond area should be increased by using lap, scarf, double-scarf, or double-strap joints. (a) The strength of an adhesive joint is limited by the bonded area, lap, scarf, double-scarf, or double-strap joints are generally stronger than butt joints. (b) Lap joints in thin sections can cause stress concentration at the ends as a result of deflection; tapering the ends gives more uniform loading throughout the joint.

7.11.2.1 Design of Adhesive Joints

The strength of the adhesive joint depends on the joint geometry, the direction of loading in relation to the joint, the adhesive material, the surface preparation, and the application and curing technique. As the strength of an adhesive joint is limited by the bonded area, lap and double-strap joints are generally preferred to butt joints. If the geometry constraints do not allow for such joints, scarf or double-scarf joints should be made, as shown in Figure 7.12a.

When a lap joint is used to bond thin sections, tensile shear causes deflection, and this results in stress concentration at the end of the lap. Tapering the ends of the joint, as shown in Figure 7.12b, gives more uniform loading throughout the joint. Since adhesive joints are weaker under pealing forces, joint design should avoid this type of loading.

7.12 DESIGNS INVOLVING HEAT TREATMENT

Heat treatment represents an important step in the sequence of processes that are usually performed in the manufacture of metallic parts. Almost all ferrous and many nonferrous alloys can be heat-treated to achieve certain desired properties. Heat treatment can be used to make the material hard and brittle, as in the case of quench-hardening of steels, or it can be used to make it soft and ductile, as in the case of annealing.

Generally, hardening of steels involves heating to the austenitic temperature range, usually 750°C–900°C (ca. 1400°F–1650°F), and then quenching to form the hard martensitic phase. The nonuniform temperature distribution that occurs during quenching and the volume change that accompanies the martensitic transformation can combine to cause distortions, internal stresses, and even cracks in the heat-treated part. Internal stresses can cause warping or dimensional changes when the quenched part is subsequently machined or can combine with externally applied stresses to cause failure. Corrosion problems can also be aggravated due to the presence of internal stresses. These difficulties can be reduced or eliminated by selecting steels with high hardenability as they require a less severe cooling rate to achieve a given hardness value. Manganese, chromium, and molybdenum are commonly added to steels to increase their hardenability.

7.13 DESIGNS INVOLVING MACHINING PROCESSES

Machining operations are the most versatile and the most common manufacturing processes. Machining could be the only operation involved in the manufacture of a component, as in the case of shafts and bolts that are machined from bar stock, or it could be used as a finishing process, as in the case of cast and forged components. In all cases, it is important for the designer to ensure that the component will be machined conveniently and economically.

7.13.1 Machinability Index

As machining is relatively expensive, it should not be performed unless necessary, and tolerances that are closer than necessary should not be specified. The economics of metal cutting can be improved by using high cutting speeds and tools with long lives. If the material to be cut gives discontinuous chips and needs less power for cutting, the economics are further improved. The ease with which one or more of the discussed factors can be realized for a given material is taken as a measure of its machinability. Thus, a material with good machinability is one that requires less power consumption, causes less tool wear, and easily acquires a good surface finish. One of the methods for comparing machinability of materials is to determine the relative power required to cut them using single-point tools. Another method is to use the machinability index, which is defined as follows:

$$\text{Machinability index \%} = \frac{\text{Cutting speed of material for 20-min tool life} \times 100}{\text{Cutting speed of SALE 1112 steel for 20-min tool life}} \tag{7.3}$$

In this definition, the free-machining steels SAE 1112 and AISI B 1112 are taken as the standard, and its machinability index is arbitrarily fixed at 100%. The higher the machinability index, the easier and the more economical it is to finish the material by metal cutting. The machinability index of some common metallic materials is given in Table 7.6.

TABLE 7.6
Machinability Index of Some Common Metallic Materials

Material	Hardness (BHN)	Machinability Index
Steels		
AISI		
1015	121	50
1020	131	65
1030	149	65
1040	170	60
1050	217	50
1112	120	100
1118	143	80
1340	248	65
3140	262	55
4130	197	65
4340	363	45
18–8 stainless steel	150–160	25
Cast irons		
Gray cast iron		
Soft	160–193	80
Medium	193–220	65
Hard	220–240	50
Malleable iron	110–145	120
Nonferrous alloys		
Aluminum alloys	35–150	300–2000
Bronze	55–210	150–500
Magnesium alloys	50–75	500–2000
Zinc alloys	80–90	200

7.13.2 Guidelines for Design

The following discussion illustrates some component shapes and features that can cause difficulties in machining, take undue length of time to machine, and call for precision and skill that may not be available or that may even be impossible to machine by standard machining and cutting tools:

1. The workpiece must have a reference surface that is suitable for holding it on the machine tool or in a fixture. This could be a flat base or a cylindrical surface. If the final shape does not have such a surface, a supporting foot or tab could be added to the rough casting or forging for support purposes and removed from the part after machining.

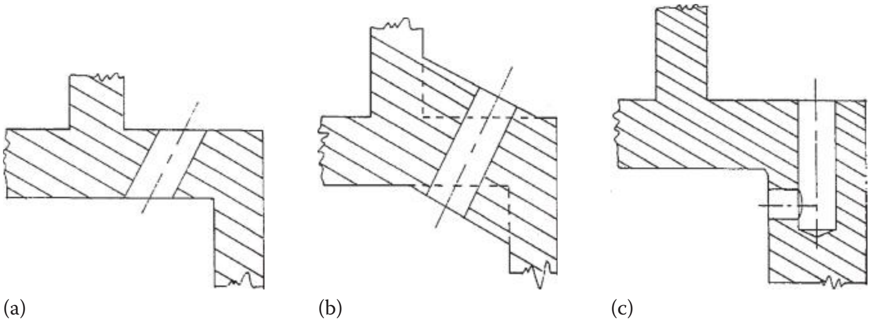

FIGURE 7.13 Design of drilled part: (a) Poor design as drill enters and exits at an angle to the surface; (b) better design, but drilling the hole needs a special attachment; (c) best design.

2. Whenever possible, the design should allow all the machining operations to be completed without resetting or reclamping.
3. Whenever possible, the radii between the different machined surfaces should be equal to the nose radius of the cutting tool.
4. If the part is to be machined by traditional cutting methods, deflection under cutting forces should be taken into account. For the same cutting force, the deflection is higher for thinner parts and for lower elastic moduli. Under these conditions, some means of support is necessary to ensure the accuracy of the machined part.
5. Twist drills should enter and exit at right angles to the drilled surface (Figure 7.13). Drilling at an angle to the surface causes deflection of the drill and could break it.
6. Features at an angle to the main machining direction should be avoided as they may require special attachments or tooling (Figure 7.13).
7. Flat-bottom drilled holes should be avoided as they involve additional operations and the use of bottoming tool.
8. To reduce the cost of machining, machined areas should be kept to a minimum. Two examples of methods of reducing the machined area are shown in Figure 7.14.
9. Cutting tools often require runout space as they cannot be retracted immediately. This is particularly important in the case of grinding, where the edges of the grinding wheel wear out faster than the center. Figure 7.15 gives some examples to illustrate this point.
10. Thread-cutting tools normally have a chamfer on their leading edge. This chamfer means that the first two pitches do not cut a full thread. If an external diameter ends at a shoulder, the mating screwed part cannot reach the shoulder unless an undercut or a countersink is provided, as shown in Figure 7.16. The length of the needed undercut or countersink is usually three pitches of the thread. Similar features are needed for internal screw threads, as shown in Figure 7.17.

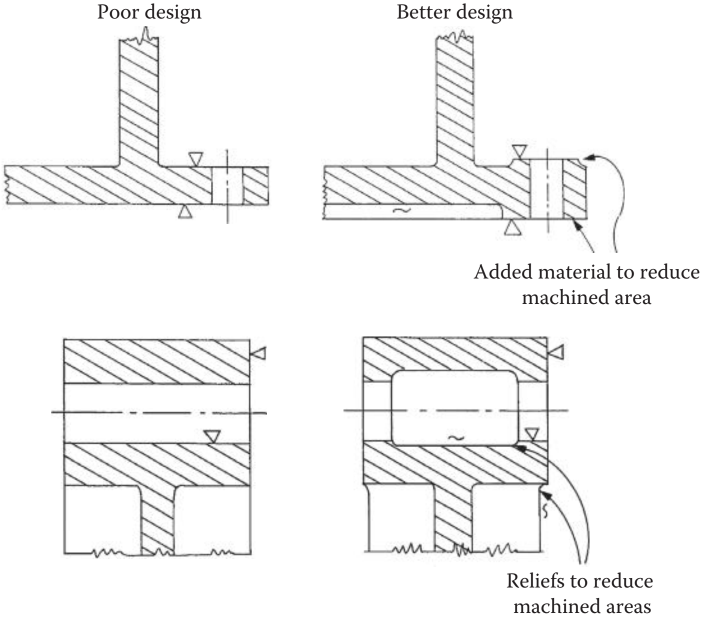

FIGURE 7.14 Some design details that can be introduced to reduce machining cost.

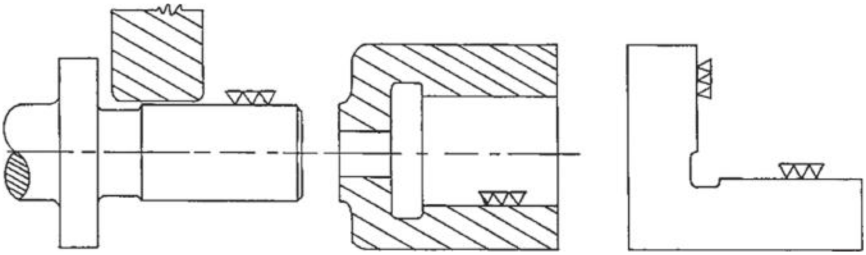

FIGURE 7.15 Some design details that can be introduced to give runout space for grinding wheels.

Example 7.4 illustrates how a part can be redesigned to facilitate machining.

Design Example 7.4: Redesign of a Shaft Support Bracket

Problem

Figure 7.18 shows the initial design of the shaft support bracket that is intended to be bolted to a housing wall to provide support and lubrication to a rotating shaft. Accurate machining is needed for the bore, and high tolerance is expected in the location of bore relative to the dowel holes. The support bracket is made of nodular cast iron, and large numbers will be machined on a horizontal spindle computer numerical control (CNC) machining center.

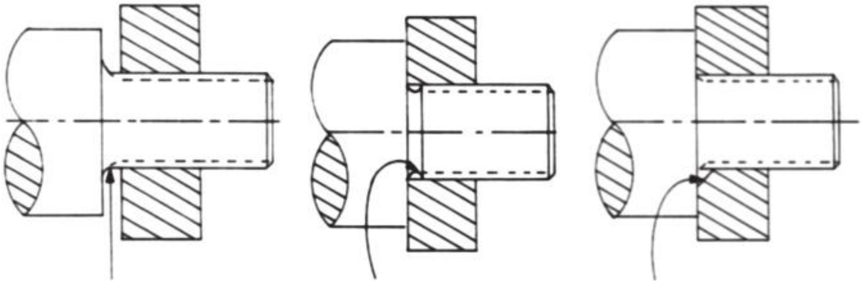

FIGURE 7.16 Some design details to account for the incomplete threads at the end of external screws.

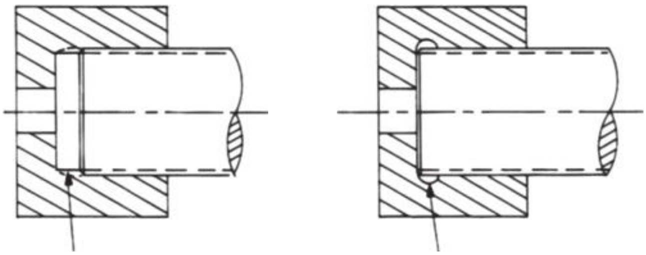

FIGURE 7.17 Some design details to account for the incomplete threads at the end of internal screws.

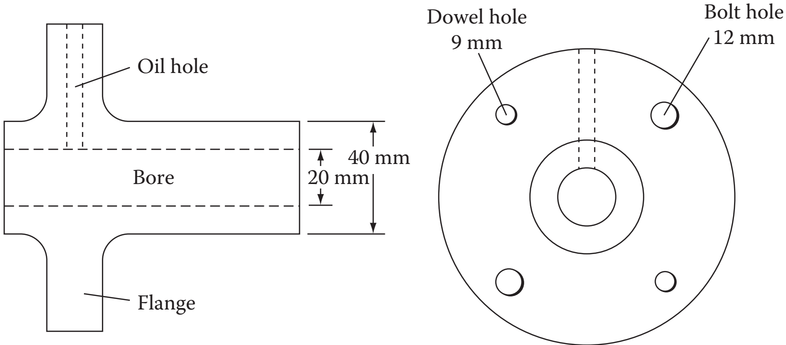

FIGURE 7.18 Side (a) and end (b) views of the initial design for a shaft support bracket. (Reprinted from Dieter, G.E., in *Materials Selection and Design,* Vol. 20, *ASM Handbook*, *Design for Manufacture and Assembly*, ASM International, Materials Park, OH, 1997, pp. 676–686. With permission.)

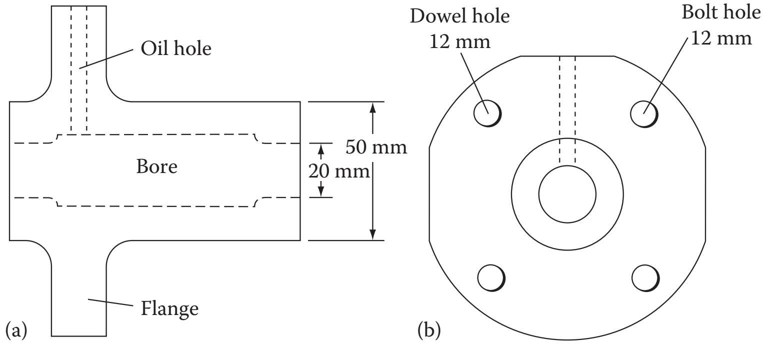

FIGURE 7.19 Side (a) and end (b) views of a shaft support bracket redesigned to simplify machining. (Reprinted from Dieter, G.E., in *Materials Selection and Design,* Vol. 20, *ASM Handbook*, *Design for Manufacture and Assembly*, ASM International, Materials Park, OH, 1997, pp. 676–686. With permission.)

Analysis

The initial design had the following features that made it difficult to machine:

- Different diameters for the dowels and bolt holes, which require tool change and loss of time.
- The bore- and oilholes are long relative to their diameter, which require long processing steps.
- There are no obvious features on the outer surface to fix the part and prevent rotation during machining.

Solution

To avoid the drawbacks of the initial design, the part was redesigned as shown in Figure 7.19. The following features were changed:

- The dowels and bolt holes have the same diameter.
- The center of the bore has a larger diameter than the ends to reduce the length to be machined. This will also eliminate the necessity to the exit burr at the end of the oilhole.
- The length of the oilhole is reduced.
- Flat surfaces were cast on outer surfaces, making it possible to locate the part and to use less fixing force while machining.

Conclusion

According to Stephenson, these changes made it possible to reduce the machining time from 173 to 119 s, which is about 33%. The changes are also expected to improve the quality by making it possible to achieve the required tolerances.

Source: Based on Stephenson, D.A., Design for machining, in *Materials Selection and Design, ASM Handbook*, Vol. 20, Dieter, G.E., (ed.), ASM International, Materials Park, OH, 1997, pp. 754–761. Figures reprinted with permission of ASM International.

7.14 AUTOMATION OF MANUFACTURING PROCESSES

Automation, which relies on machines that follow a predetermined sequence of operations with minimal human intervention, was introduced in the manufacturing industry in the middle of the twentieth century with the objective of reducing labor cost in addition to improving productivity, accuracy, and reproducibility of products. In hard automation, machines are designed to perform a specific set of operations on a specific product. Such specialized machines, generally called transfer machines, have high productivity but lack flexibility. For example, in the automotive industry, the processes of milling, drilling, tapping, boring, reaming, honing, washing, and gauging are performed by a series of 15 transfer machines arranged in a transfer line capable of processing more than a 100 cylinder heads per hour for the motorcar engine.

In flexible or programmable automation, more flexibility is achieved through the use of computers to control the machines. A flexible manufacturing system can include a number of cells, each consisting of a number of numerically controlled machines and robots and controlled by a central computer. Instructions for manufacturing of a given part are given by the central computer to the appropriate machines or robots. This flexibility allows different parts to be manufactured in any number according to the desired sequence using the same cell, which allows quick response to changing market demand.

In numerical control (NC), coded instructions are converted to signals that control the movements of machine parts. CNC uses computer programs to issue the instructions in order to increase accuracy and flexibility and reduce cost. In adaptive control, the operation parameters are automatically changed to account for situations where the workpiece parameters, such as dimensions or harness, are not uniform.

Industrial robots, which can be defined as a programmable multifunctional manipulators, can be designed to perform a variety of repetitive tasks including moving materials and parts and manipulating tools and inspection devices. Simpler robots have Cartesian, cylindrical, or polar movements and can be programmed to perform a specific sequence of operations (pick-and-place and playback robots). More advanced robots can have several degrees of freedom and often have arms ending with a wrist and sensors for increased dexterity of movement. They may also be able to observe and evaluate their environment and make appropriate decisions (intelligent robots).

7.15 COMPUTER-INTEGRATED MANUFACTURING

Ideally, CIM encompasses all aspects of operation of a company, including business planning, product design, process planning and control, shop floor automation, and quality control. An efficient database is essential for a successful CIM system as it allows smooth communication of data between the various activities of CAD, computer-aided manufacturing (CAM), and computer-aided process planning (CAPP).

CAD uses computers in creating design drawings and product models. Using CAD allows the designer to easily create alternative designs in order to select an optimum solution or modify existing designs to meet new product requirements.

The CAD system also allows the designer to test the product by subjecting it to a variety of loading and service conditions and to avoid interference between various components in order to avoid difficulties during assembly. The outputs of the CAD system include working drawings with tolerances and surface finish, specifications and properties of materials, and instructions for manufacturing.

CAM uses computers to assist in the different phases on manufacturing, which can include process planning and scheduling, NC of machines and robots, material handling, assembly, and quality control. CAM systems can also be used for die design for casting, forging and metalwork processes, design of jigs and fixtures, and cutting tools and electrodischarge machining (EDM) electrodes. Combining CAD and CAM systems allows the transfer of information from the design to the planning and manufacturing without having to reenter the data, which is expected to reduce costs and improve productivity. Kalpakjian and Schmid reported that the Boeing 777 twin-engine airliner was completely designed and directly manufactured using a CAD/CAM system consisting of 2000 workstations linked to eight computers. No prototypes or mock-ups were needed, as was the case in previous models.

CAPP uses computers to coordinate the selection of manufacturing processes and machines, processes performed by the various machines, tools and fixtures, and sequence of assembly. The CAPP system also determines optimum feeds, speeds, and the standard times for operations in order to avoid manufacturing bottlenecks and smooth flow of products in the system. CAPP is particularly effective in coordinating the forming, machining, assembly, and inspection processes for high-variety, small-volume production systems.

7.16 SUMMARY

1. As the design progresses from concept to configuration and the material choices get narrower, manufacturing processes, which have initially been broadly defined, also need to be better identified. The compatibility between the candidate materials and the manufacturing processes is used to narrow down the available alternatives.
2. DFMA seeks to minimize the cost of a product through DFM and DFA.
3. Casting is particularly suited for parts that contain internal cavities that are inaccessible, too complex, or too large to be easily produced by machining. Cast parts are isotropic but could contain shrinkage cavities if not designed well.
4. Compression, transfer, and injection molding processes are commonly used for molding plastic parts. Incorrect design could lead to internal stresses and warpage in the finished product.
5. Forged parts have wrought structures that are usually stronger and more ductile than cast products. However, cast products are more isotropic. Rapid changes in thickness of forged components could result in cracks and surface laps.
6. P/M techniques can be used to produce a large number of small parts to the final shape in few steps, with little or no machining, and at high rates. Many metallic alloys, ceramic materials, and particulate-reinforced composites

can be processed by P/M techniques. Porosity is normally undesirable and can be reduced by hot isostatic pressing.

7. Welding has replaced riveting in many applications including steel structures, boilers, and motorcar chassis. However, welded structures are monolithic and can suffer catastrophic failure. Because they represent areas of discontinuities, welded joints should be located away from highly stressed regions, especially in dynamically loaded structures.
8. Adhesives represent an attractive method of joining and are increasingly used for thin sheets, polymer–matrix composites, and dissimilar or incompatible materials. In addition, adhesives are electrically insulating, which can prevent galvanic corrosion in joints between dissimilar metals. However, they are relatively weaker and can be attacked by organic solvents.
9. Almost all ferrous and many nonferrous alloys can be heat-treated to achieve certain desired properties. Heat treatment can be used to make the material hard and brittle, as in the case of quench-hardening of steels, or it can be used to make it soft and ductile, as in the case of annealing.
10. Machining operations are the most versatile and the most common manufacturing processes. Machining could be the only operation involved in the manufacture of a component, as in the case of shafts and bolts that are machined from bar stock, or it could be used as a finishing process, as in the case of cast and forged components.
11. Automation reduces labor cost and improves productivity as it relies on machines that follow a predetermined sequence of operations with minimal human intervention. In hard automation, transfer machines perform a specific set of operations on a specific product. Such systems have high productivity but lack flexibility. In flexible automation, machines are grouped in cells each consisting of a number of numerically controlled machines and robots and controlled by a central computer. This flexibility allows different parts to be manufactured in any number according to the desired sequence using the same cell.
12. CIM encompasses all aspects of operation of a company, including business planning, product design, process planning and control, shop floor automation, and quality control. A central database communicates the data between the various activities of CAD, CAM, and CAPP.

REVIEW QUESTIONS

7.1 Recommend materials and manufacturing processes, illustrated by sketches, for the following products: (a) plastic bottle for mineral water, (b) fiberglass bathtub, (c) inner lining of a refrigerator door, and (d) steel bars for reinforcing concrete structures.

7.2 Indicate how the treatment or the composition of the following pairs of materials is expected to influence their mechanical behavior. Use (H) for higher and (L) for lower. For example, YS of AA 2014 O is lower than AA 2014 T6.

Material	YS	UTS	Elastic Modulus	Ductility	Hardness	Toughness
AA 2014 O	L	—	—	—	—	—
AA 2014 T6	H	—	—	—	—	—
AISI 1015	—	—	—	—	—	—
AISI 1040	—	—	—	—	—	—
AISI 1060 as quenched	—	—	—	—	—	—
AISI 1060 quenched and tempered	—	—	—	—	—	—
Low-density polyethylene (LDPE)	—	—	—	—	—	—
HDPE	—	—	—	—	—	—

7.3 Suggest the sequence of primary, secondary, and finishing manufacturing processes for the crankshaft. Draw details of the crankshaft end that will ensure prolonged fatigue life.

7.4 What are the main material requirements and manufacturing processes for the following products: (a) railway line, (b) electric resistance heater, and (c) small passenger airplane wing structure?

7.5 Suggest possible manufacturing processes for the following items in an internal combustion engine: (a) piston, (b) connecting rod, (c) cylinder head, and (d) camshaft.

7.6 From the manufacturing point of view, what are the main attractive features of plastics in comparison with metals?

7.7 Recommend suitable plastics and manufacturing processes for the following products: (a) telephone, (b) 2 L (0.5 gal) lubricating oil container, (c) safety shield for a mechanical press, and (d) hard hat for construction workers.

7.8 In making a milling machine frame, gray cast iron and steel AISI 1015 were considered as candidate materials. Compare the use of the two materials indicating the advantages and disadvantages of using each of them in this application. What are the most suitable manufacturing processes in each case?

7.9 It is required to select a material and manufacturing processes for tie-rods of a suspension bridge. The rods are 10 m long and should carry a tensile load of 50 kN without yielding. The maximum extension should not exceed 18 mm. Which one of the materials listed in the following table will give (a) the lightest rod and (b) the least expensive rod? Recommend the manufacturing processes for the materials selected in (a) and (b).

Material	Yield Strength (MPa)	Elastic Modulus (GPa)	Specific Gravity	Relative Cost/kg
ASTM A675 grade 60	205	212	7.8	1.00
High-strength steel	485	212	7.8	1.50
Aluminum 5052 H38	259	70.8	2.7	5.00
Polyester–65% glass fibers	340	19.6	1.8	10.00

7.10 What are the problems that are likely to arise when heat treating a steel part of nonuniform sections? How are these problems overcome?

7.11 What are the advantages of casting in comparison with welding in terms of flexibility of shape design?

7.12 What are the advantages of P/M in comparison with casting when manufacturing small gears?

7.13 An AISI 1020 steel angle of dimensions 150 mm × 100 mm × 12 mm (6 in. × 4 in. × 1/2 in.) is to be welded to a steel plate by fillet welds along the edges of the 150 mm leg. The angle should support a load of 270 kN (60,000 lb) acting along its length. Determine the lengths of the welds to be specified. The welding electrode used is AWS–AISI E6012 with a tensile strength of 414 MPa (60 ksi). (Answer: 128 mm on each side parallel to the axis of the angle.)

7.14 Compare welding and casting as methods of fabrication of 500 mm (20 in.) diameter gears. The total number required is 10 units.

7.15 Compare the use of spot welding and adhesive bonding in the assembly of the steel metal components of motorcar bodies.

7.16 Brazing alloys and adhesives are known to be relatively weak. Suggest methods of strengthening joints made by these techniques.

7.17 It is required to produce a folding chair for use at the seashore. Draw neat sketches of the folding chair showing the different elements. Suggest candidate materials and manufacturing processes for each of the elements, as well as method of assembly. It is estimated that 10,000 chairs will be produced per year.

7.18 It is required to produce water storage tanks that are to be placed on top of buildings to supply water for household use. The capacity of the tank is 1 m^3. It is estimated that 1000 tanks will be produced per year. (a) What are the main material requirements for the tank? (b) Suggest some candidate materials for the water storage tank. (c) Draw neat sketches showing the main dimensions to illustrate how the material and manufacturing processes affect the design. (d) Suggest suitable sequence of manufacturing processes for each of the candidate materials.

7.19 Pipes carrying steam at high pressure in a power station are being designed and joined by welding. What are the most important material properties that need to be considered and the quality control measure that needs to be taken to ensure that the pipes will not fail in service?

7.20 Suggest suitable manufacturing processes and indicate the main distinguishing characteristics of the materials used in manufacturing the following components: (a) nodular cast iron crankshaft for an internal combustion engine, (b) gas turbine blade made of superalloys, (c) 2 L water bottle made of polyethylene, and (d) cutting tool made of cemented carbides.

7.21 Draw a block diagram of a flexible manufacturing cell for a small machine shop. The cell consists of two machining centers, a vision-based part inspection machine and one robot with its control unit.

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Part III

Selection and Substitution of Materials and Processes in Industry

Discussion in earlier parts of this book illustrates the interdependence of the various activities involved in developing a concept into a finished product. It is shown in Part II that the materials and processes used in making a component have great influence on its design and performance in service.

In addition to designing and manufacturing products at the required level of quality, manufacturers must also be able to sell their products at competitive prices and to make profits. To achieve these objectives, it is important that the different materials and processes involved in the design and manufacture should be evaluated in terms of their economic as well as their technical merits. With the frequent introduction of new and improved materials and manufacturing processes, manufacturers are always on the lookout for opportunities to improve the competitiveness of their products.

The many changes in materials and manufacturing in recent years are clearly reflected in the automotive industry, where the tighter environmental legislation and higher safety standards in addition to increased competition on a global scale drive the change. The wheels, which are normally made of pressed steel, are meeting strong competition from aluminum and magnesium castings as they provide lighter alternatives. Bumpers are now incorporated in the styling of the car body, and plastics and composites have been developed to provide the necessary toughness and resistance to service conditions. The dashboard is now made as a single molded plastic part with enhanced styling and cost saving in manufacturing and assembly compared to the traditional panel, which is made of many separate metal components. The traditional PVC interior door panels can now be replaced with natural FRPs, which provide better sound insulation, lighter weight, and reduced cost. High-strength alloy steel sheets with transformation-induced plasticity are now competing with aluminum sheets and PMCs in making exterior body panels. Most recently, layered composites with exterior metal cladding and foam plastic interiors have provided another alternative material for body panel. With the increasing reliance on plastics and composites, the use of adhesives has increased at the expense of fasteners and welding. New adhesives provide more even distribution of load, possess high strength, and resist service environment.

Unlike the exact sciences, where there is normally only one single correct solution to a problem, materials and process selection and substitution decisions require the consideration of conflicting advantages and limitations, necessitating compromises and trade-offs; as a consequence, different satisfactory solutions are possible. This is illustrated by the fact that similar components performing similar functions, but produced by different manufacturers, are often made from different materials and even by different manufacturing processes.

This part of the book integrates both the technical and economic aspects in materials selection and substitution. Chapter 8 gives an introduction to the economics and environmental aspects of materials and processes, and Chapters 9 and 10 explore a variety of procedures that can be followed when selecting or substituting materials and processes for a given product. Chapter 11 gives several detailed case studies drawn from widely different areas in order to illustrate the use of design calculations together with materials selection and substitution procedures in arriving at the optimum choice of materials and processes.

PART III OUTCOMES

After completing Part III, the reader will be able to

1. Understand the economic issues involved in manufacturing a product in industry
2. Identify the various cost elements involved in selecting a material and manufacturing process for a given product or a component
3. Assess the environmental impact of materials and processes involved in making a product
4. Perform cost-benefit analysis as a means of selection among projects, materials, or manufacturing processes
5. Select the optimum material and manufacturing process for a given component under a set of given working conditions and financial constraints
6. Recommend a substitute material and/or a process for making a component in order to improve its performance, cost, or other attributes under a given set of service conditions

8 Economics and Environmental Impact of Materials and Processes

8.1 INTRODUCTION

The success of the product in terms of its marketability and competitiveness depends to a large extent on its selling price and acceptance by the society. In a wide range of engineering industries, the cost of materials and manufacturing represents about 30%–70% of the product cost and needs to be minimized if the product is to be economically viable.

The cost of materials and processing consists of (a) cost of standard components that are purchased from a supplier, (b) cost of components that are custom designed and made for the product, (c) cost of assembly, and (d) overheads. The cost of standard components can be estimated from previous company experience or from price quotes from suppliers. The cost of custom-made components is determined by the cost of design, materials, processing, and overheads. According to Kalpakjian and Schmid (2001), approximate breakdown of costs in manufacturing of a wide variety of components is 5% for design, 50% for materials, 15% for labor, and 30% for overheads. The factors that affect the cost of materials and processing, which account for 65% of the total cost, are discussed in the following sections of this chapter. The cost of assembly is discussed in Chapter 7. The overheads are usually assigned to a product on the basis of cost elements in (a), (b), and (c).

In addition to selling the product at a competitive price, manufacturers are now attempting to gain social acceptance by reducing the environmental impact of their products and complying with the increasingly tighter environmental legislation. These issues are also discussed in this chapter.

The goal of this chapter is to review ways of optimizing the economic and environmental parameters associated with the production of custom-made components in industry. The main objectives are to get a better understanding about

1. Elements of the cost of materials and factors affecting their prices
2. Taking cost into account when comparing materials
3. Economics of manufacturing processes
4. Environmental impact of materials and processes
5. LCC and recycling economics

8.2 ELEMENTS OF THE COST OF MATERIALS

From the economic point of view, engineering materials can generally be classified into two main categories, depending on their cost. The first category contains the commonly used materials, like plain-carbon steels and polyethylene, which are manufactured by cost-effective large-scale processes. The second category contains the special or high-performance materials, like the superalloys and silicones, which are manufactured to meet special needs. The materials in the second category are more expensive than the materials in the first and are only used to meet special requirements that cannot be met by the less-expensive, commonly used materials. This division must not be too rigid because a material developed for a particular application may prove to have properties that eventually lead to its widespread use. For example, aluminum and titanium moved in a few decades from being special and expensive materials to being moderately priced items of everyday industrial use.

Regardless of whether the material used in making a product is common and inexpensive or special and expensive, it is expected to have a considerable influence on the final cost of the product. This is because the cost of materials usually represents a high proportion of the total product cost and also because material processability affects manufacturing costs. It is, therefore, necessary to analyze the various elements of the cost of materials to find possible means of minimizing it. This can be done by considering the sequence of operations in which raw materials are progressively converted into final products. As an example, Figure 8.1 shows the buildup of the cost of steel and aluminum with the progress of processing operations from ore to finished product. The main elements of the cost of materials can be grouped as follows.

8.2.1 Cost of Ore Preparation

The main elements of the cost of ore preparation are the cost of ore at the mine and the cost of beneficiation. The cost of ore depends on its location and the method of mining it, whereas the cost of beneficiation depends on the concentration of the required material in the ore, the degree of complexity in mineralogical association, and the type of gangue materials. For example, the cost of iron ore preparation is relatively low because commercial ores are usually mined in open-pit mines and contain 50%–65% Fe. However, the preparation of copper and gold ores is much more expensive as the concentration of the metal is about 1%–1.5% and 0.0001%–0.001%, respectively.

The cost of transporting the ore from the mine to the extraction site can be considerable and can be reduced by performing the beneficiation process at the mine. Regardless, ores are known to be transported across countries and continents and the cost can be considerable.

8.2.2 Cost of Extraction from the Ore

The main elements of the cost of extraction include the cost of power and the cost of auxiliary materials. In metals, the more stable the compound in which the element is found, the greater is the amount of energy and the cost needed for reduction. For example, the large amount of electric power and the high cost of

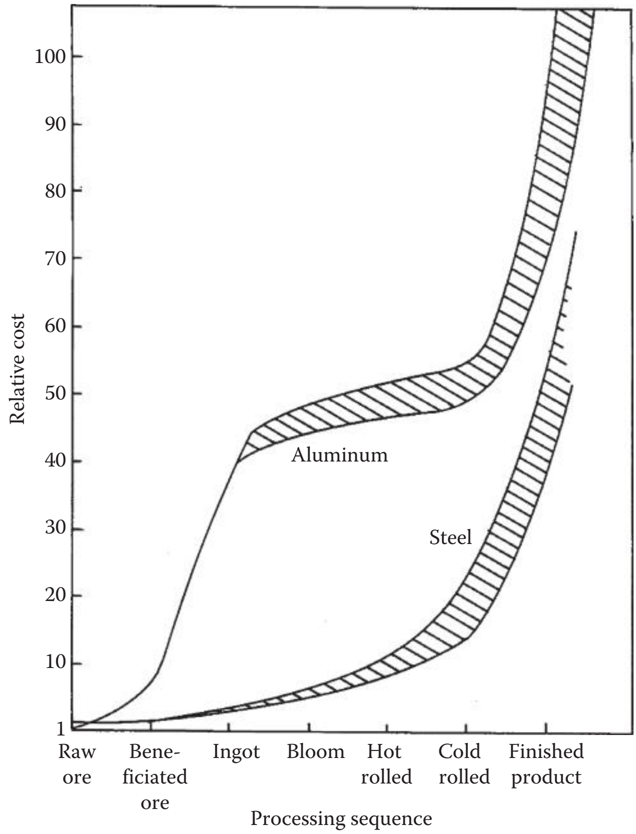

FIGURE 8.1 Buildup of material cost with the progress of manufacturing processes from ore to finished product.

auxiliary materials needed for extraction of aluminum are the main reasons for its high cost, as can be seen in Figure 8.1.

8.2.3 Cost of Purity and Alloying

Impurity level is known to have an important influence on the cost of materials, and in general, the higher the permissible impurity level, the lower is the cost. For example, the relative cost of aluminum ingots nearly doubles as the purity increases from 99.5% to 99.99%. The cost of an alloy is affected not only by the purity of the elements used but also by their nature and by the degree of complexity of alloy structure. The cost of an alloy is not simply the cost of its constituents, because in the majority of cases, more sophisticated techniques of production have to be employed to make full use of the alloying elements. For example, the less-demanding specifications of SAE 326 (LM4) aluminum alloy permit the use of lower-purity aluminum as the base metal, which makes its cost about 50% less than the cost of SAE 324 (LM10) alloy that specifies at least 99.7% purity for its base aluminum.

8.2.4 Cost of Conversion to Semifinished Products

The cost of converting ingots to semifinished products ready for delivery to the manufacturer of end products includes the costs of casting, forging, and rolling. The main cost elements in this case are labor, energy, overheads, and the cost of material losses. This last element can be considerable in metal industries where material losses can range from 25% to more than 50%. Table 8.1 gives an example of the costs in a cast iron foundry. Although this is a hypothetical case, the figures can be considered as representatives of those items found in industry.

8.2.5 Cost of Conversion to Finished Products

The final stage in production is to convert the semifinished material into a finished product ready for delivery to the end user. Manufacturing processes that are usually involved in this stage are pressing, machining, surface finishing, assembly, and packaging. Many of these processes are expensive and wasteful of materials. Material losses of 200%–300% are not uncommon at this stage. With mass production, the costs of direct labor and overheads are usually small in comparison with the material cost. In such cases, it becomes even more important to reduce the material costs and to optimize material utilization.

8.3 FACTORS AFFECTING MATERIAL PRICES

As with most other commodities, the price of engineering materials is affected by a variety of factors. Inflation, economic recessions, supply and demand, amount of

TABLE 8.1
Cost Analysis in a Cast Iron Foundry

Item	Cost ($/Casting)	Percentage of Total Cost
Metal (weight of casting 15 kg [33 lb], 55% yield, 12% scrap, sprue)	4.40	35.9
Mold and core	1.80	14.7
Clean and sort	0.53	4.3
Heat treat	0.56	4.5
Hand tool finish and grind	1.30	10.6
Inspect	0.12	1.0
Ship	0.05	0.4
Total direct cost	8.76	71.4
Overheads and administration	3.50	28.6
Total cost	12.26	100.0

material purchased, inventory costs, and quality of material are among the major factors that can influence the price, and they are discussed in this section.

8.3.1 General Inflation and Price Fluctuations

Generally, the prices of most established engineering materials show a steady increase when considered over a relatively long period of time. The main reasons for such price increases are rising costs of raw materials, energy, and labor. Governmental antipollution policies and similar legislation have also contributed to the increase in prices in recent years. Over the last two decades, most metallic and polymeric materials showed an average price inflation rate of about 5%–15% per year. In addition, material prices are also known to suffer short-term price fluctuations. Political factors, local wars, industrial strikes, and world recessions are mostly responsible for such price fluctuations that occur as a result of changes in supply and demand.

8.3.2 Supply and Demand

In a free-market economy, the price of a commodity is fixed by the equilibrium between supply and demand. When the supply increases, prices should decrease as competing producers pare their profit margins to maintain their market share.

8.3.3 Order Size

The cost of materials is usually affected by the size of order. The larger the size of an order for a given material, the smaller will be the unit cost. This is because administrative expenses and delivery charges remain almost unchanged and tend to represent a higher proportion of the total cost of a smaller order. For example, the unit prices of most popular plain-carbon steels can nearly double as the amount of material purchased decreases from 5 ton lots to about 1/2 ton. The unit price can be even higher for smaller-order sizes.

8.3.4 Standardization of Grades and Sizes

If selection of the material were based entirely on using the most suitable grade and size for each part, almost as many materials, grades, and sizes as parts would be chosen. If all the parts were produced in equal and large quantities, it might be practical to make each part from a different material. However, production is seldom in equal and large quantities, and selecting a different material for each part can lead to serious problems in material cost, storage, inventory, and equipment required by each material. The other extreme is to make all parts from material with same grade and size. This is obviously not practical, except in rare instances. A compromise is to standardize on the smallest number of material grades and sizes that will satisfy plant-wide needs at the lowest cost. Fabrication requirements must be checked to ensure that cost savings in eliminating grades and sizes are not more than offset by added manufacturing costs. Minor design changes can often be made to permit standardization.

8.3.5 Inventory Costs

It has been shown that significant savings may be realized by ordering in large quantities. Inventory costs, however, can quickly offset the initial saving in large-quantity purchases. For example, the cost of storing steel for 1 year can range from 10% to 25% of the initial cost. Inventory costs include interest on investment, storage, taxes, insurance, obsolescence, deterioration, inventory taking, record keeping, rehandling, and reinspection.

8.3.6 Cost Extras for Special Quality

In the case of most steels, a base price that represents the lowest cost is usually given to the most often used quality, for example, merchant quality for hot-rolled bars and commercial quality for sheets. Cost extras are then added to account for the customer's special requirements. Some of the special requirements that usually increase the base price, cost extras, are the following:

1. *Grade*. Standard AISI quality is supplied as the base material. Semikilled or killed grades are extra.
2. *Restrictions*. Standard quality usually allows for wider chemistry limits. Extra cost is usually charged for specifying a narrower range of carbon, a minimum manganese content, etc. Resulfurized or free machining steel is supplied at an extra cost. Specifying the grain size or hardenability is also an extra.
3. *Size and form*. Special sections or closer dimensional tolerances than specified in standards are cost extras.
4. *Treatment*. Specifying treatments like annealing, normalizing, quenching and tempering, stress relieving, or pickling is usually considered as a cost extra.
5. *Length*. Specifying a certain length of the stock is usually considered as a cost extra.
6. *Cutting*. Hot cut and cold shear are standard. Machine cutting is an extra.
7. *Packaging*. Wrapping, burlap, and boxing are extras.

The price after adding the extras can be more than twice the base price in some cases.

8.3.7 Geographic Location

Material prices are usually given free on board (FOB) of the supplier. The customer pays the cost of transportation. This cost item can be considerable for longer distances and smaller quantities.

8.4 COMPARISON OF MATERIALS ON COST BASIS

Most engineering materials are sold on the basis of cost per unit weight, although some semifinished and finished products are sold on other bases. For example, the prices of pipe and tubing are usually given per unit length basis, whereas the prices of paint are

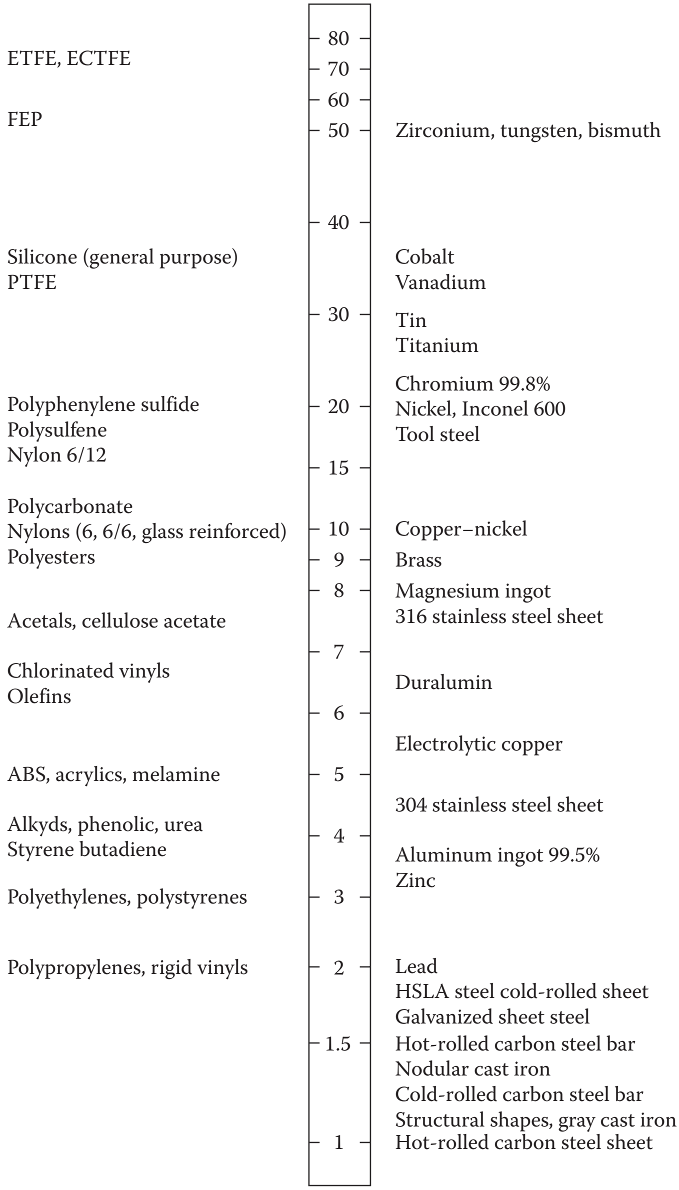

FIGURE 8.2 Comparison of some engineering materials on the basis of cost per unit mass. Comparison is made relative to the cost of hot-rolled low-carbon steel sheet.

given on the basis of cost of unit liquid volume. Figure 8.2 compares some metallic and plastic materials on the basis of relative cost per unit weight. The cost of hot-rolled plain-carbon steel is taken as unity and all other costs are given relative to it. All forms of plain-carbon steels, cast irons, and low-alloy steels are less expensive than other materials, which explains their widespread use. The figure shows the wide difference between the prices of the different materials. For example, nickel and Inconel 600 are about 20 times as expensive as plain-carbon steel, and tin and titanium 30 times as expensive, whereas zirconium and tungsten are 50 times as expensive.

In many applications, engineering materials are not highly stressed, mainly because the amount of material used is determined by the size and shape, method of production, or rigidity of the part. Examples include machine frames, motor bodies, household appliances, and fittings. In such cases, it may be more appropriate to compare materials on the basis of their cost per unit volume, as shown in Figure 8.3. As in Figure 8.2, the different materials are related to hot-rolled plain-carbon steel whose cost per unit volume is taken as unity. Some plastics now appear to be cheaper than steel because of their low density. The cost of aluminum also gets close to steel.

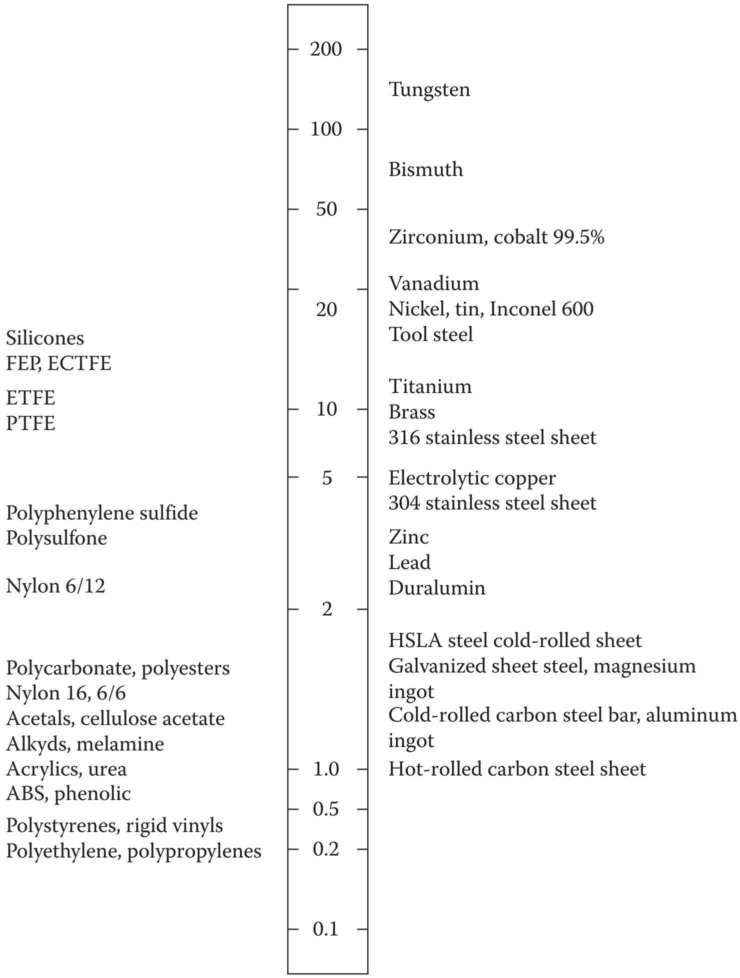

FIGURE 8.3 Comparison of some engineering materials on the basis of cost per unit volume. Comparison is made relative to the cost of hot-rolled low-carbon steel sheet.

8.5 VALUE ANALYSIS OF MATERIAL PROPERTIES

One of the important applications of value analysis is to assess the value of any product by reference to the cheapest available or conceivable product that will perform the same function. This technique can be adapted to material selection and substitution. In the case of steel, for example, plain-carbon steels should be considered as a reference point for estimating the value. Additional steel prices above those of plain-carbon steel should be critically analyzed. The value of each item of cost extras needs to be examined in relation to the function that the part has to perform in service.

When comparing materials to select the one that will perform the required function at the least cost, the engineer has two basic alternatives:

- To select the least-expensive material
- To select a more expensive material that will simplify processing or eliminate steps in manufacturing

Examples of cheaper materials that perform the job of more expensive alternatives are the manganese-containing grades of stainless steels like 201, 202, 203, and 216, which are less expensive than their type 300 counterparts because they contain less nickel. Cladding, galvanizing, and tinning offer cheaper alternatives to using stainless steels if the corrosion conditions are not severe.

An example of a higher-cost material resulting in a lower-cost component, because of savings in processing, is precoated sheet steel that enables fabricators to omit the finishing step. The coating can be alkyd, polyester, acrylic, vinyl, epoxy, or phenolic paint, or it can be a plastic, such as vinyl, fluorocarbon, or polyethylene. The coatings can be applied to most metals, for example, steel, tin, zinc, and aluminum, and each type of coating provides a different set of properties. Aluminized and chromized coatings on carbon steel resist moderate heat and do not need expensive finishing by enameling.

As the cost of materials is so important, efforts should be made to optimize their use to achieve an overall reduction of the product cost. However, selecting a cheaper material may not always be the answer to a less-expensive product. For example, as materials are usually priced on the basis of cost per unit weight, it may be more economical to pay the extra cost of higher strength since less material will be needed to carry the load. This is illustrated in Example 8.1.

Design Example 8.1: Selecting the Least-Expensive Alternative Material for a Cable Car Suspension Member

Problem

Select the least-expensive alternative out of the candidate materials in Table 8.2 for making a suspension member in the cable car system. The member is 1 m long and is expected to carry a tensile load of 50 kN without yielding.

Solution

The cross-sectional area is obtained by dividing the load by the strength of the material. The volume and then the weight are calculated. The cost of the member using different materials is calculated relative to AISI 1015.

TABLE 8.2
Candidate Materials for Suspension Member

Material	YS (MPa)	Specific Gravity	Relative Cost	Cross-Sectional Area (mm^2)	Relative Cost of Member
AISI 1015	329	7.8	1	152	1
AISI 1040	380	7.8	1.1	132	0.95
AISI 4820	492	7.8	1.8	102	1.2
Brass	532	8.5	7	94	4.7

Conclusion

Table 8.2 shows that although the cost of AISI 1040 is slightly higher than that of AISI 1015, its higher strength and the resulting smaller cross-sectional area result in a lower total cost. The higher prices of AISI 4820 and brass are not compensated by their higher strengths.

Another example is the case where manufacturing of a product involves a large amount of machining. In such cases, it may be more economical to select a more expensive material with better machinability than to select a cheaper material that is difficult to machine. This is illustrated in Example 8.2.

Design Example 8.2: Selection of the Most Economical Material for a Bolt

Problem

A large number of bolts are to be machined on a high-speed turret lathe. Compare the economics of manufacturing the bolts from AISI 1112 steel, cartridge brass, and 2014 aluminum. The dimensions of the bolt are such that it will need 10 cc of the stock material for its manufacture, and the differences in material utilization due to differences in stock sizes are being ignored. Table 8.3 gives the characteristics of the different materials and the estimated cost of manufacture.

Solution

The calculations show that the superior machinability of aluminum more than offsets the savings in material cost of steel, which makes the aluminum bolt less expensive than the steel bolt.

8.6 ECONOMICS OF MATERIAL UTILIZATION

Manufacturing a part or a product at a competitive cost can only be accomplished when materials and processes are used as effectively as possible. Ideally, the manufacturer should use the cheapest material and not pay for properties that

TABLE 8.3
Characteristics and Estimated Cost of Manufacturing of Some Materials

	AISI 1112 Steel	Cartridge Brass	2014 Aluminum
Cost of stock material ($/kg)	0.6	4.2	3.6
Machinability index	100	200	400
Density of material (g/cc)	7.8	8.5	2.8
Weight of material required (g)	78	85	28
Cost of material required ($)	0.047	0.36	0.10
Number of machined bolts per hour	52	85	90
Labor and overhead rate ($/h)	15	15	15
Labor cost per bolt ($)	0.29	0.18	0.17
Cost of material and labor ($)	0.337	0.54	0.27

are not needed for successful performance of the part. As discussed earlier, this could lead to cost and inventory problems as a result of stocking a very large number of materials, grades, and sizes. Standardization of material grades and sizes and judicious design are answers to this problem. Where production involves more than one size, it may become necessary to buy base quantities of large-size stock and use it for a variety of smaller-size parts. However, this can increase the amount of resulting scrap and, consequently, the final cost of the products since the selling price of scrap is usually only 10%–40% of the stock material price. Table 8.4 gives approximate amounts of scrap generated in some manufacturing processes.

TABLE 8.4
Approximate Amount of Scrap Generated in Some Manufacturing Processes

Process	Scrap (%)
Powder metallurgy	5
Permanent mold casting	10
Closed-die forging	20–25
Extrusion (hot or cold)	15
Sheet metal forming	10–25
Machining	10–60

Source: Based on Kalpakjian, S. and Schmid, R., *Manufacturing Engineering and Technology*, 4th edn., Prentice-Hall, Upper Saddle River, NJ, 2001.

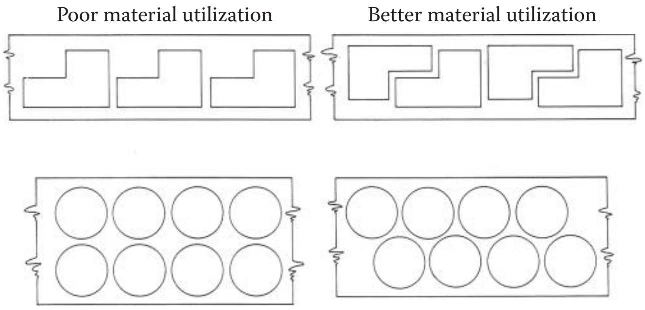

FIGURE 8.4 Effect of blanking die design on material utilization.

Another form of inefficiency in material utilization is encountered in metal casting. The yield in casting is expressed as the percentage of the weight of good castings obtained from the charged metal weight. With high yield there is less return metal to remelt, which in turn reduces the net cost of conversion, melting loss, and molten metal treatments. The metal cost of castings with a high yield is therefore less than that of low-yield castings. Typical yields in cast iron foundries range from 40% to 70%.

The efficiency of utilizing materials can be measured by a material utilization factor, m, which can be defined as

$$m = \frac{\text{weight of the finished part}}{\text{weight of material used to make the part}} \tag{8.1}$$

The nearer the value of m to unity, the less waste will be incurred and hence the lower will be the direct material cost. The cost of scrap material, C_s, that results from manufacturing N components is given by

$$C_s = (1 - m)WC_wN \tag{8.2}$$

where

W is the weight of the component

C_w is the cost of stock material per unit weight

Figure 8.4 shows an example of how the value of m can be increased by a change in the blanking die design and Example 8.3 explains the economic factors involved.

Design Example 8.3: Minimizing the Cost of a Punched Component

Problem

It is required to produce 150,000 L-shaped brass parts similar to those shown in Figure 8.4 by punching from a strip of 100 mm width and 1 mm thickness. The dimensions of the outer sides of the L shape are 60 mm each, and the dimensions of the inner sides of the L shape are 30 mm each, which means that the width of the L shape is 30 mm. In placing the L shapes within the strip, a minimum distance of 10 mm is needed all round the shape. Figure 8.4 shows two possible layouts for the L shape within the strip; choose the more economical one. The cost of the brass strip is \$4.2/kg and the scrap material can be sold at \$0.8/kg. The density of brass can be taken as 8.4 g/cc.

Analysis

With the layout on the L shape on left-hand side of Figure 8.4, a relatively simple punch and die costing \$12,000 can be used to cut a single L shape in each stroke. However, it leads to more waste of material than the layout on the right-hand side of the figure, which uses a more complicated punch and die costing \$18,000 to cut two shapes at a time.

$$\text{Weight of one L shape} = [(6\times 6) - (3\times 3)]\ 0.1\times 8.4 = 22.68\text{ g}$$

Weight of the strip for one L shape for the simple layout

$$= 10\times(6+0.5+0.5)\times 0.1\times 8.4 = 58.8\text{ g}$$

Weight of the strip for two L shapes for the complex layout

$$= 10\times(6+1+3+0.5+0.5)\times 0.1\times 8.4 = 92.4\text{ g}$$

$$m_{\text{simple}} = \frac{22.68}{58.8} = 0.386$$

$$m_{\text{complex}} = \frac{22.68\times 2}{92.4} = 0.49$$

Cost of material for simple layout

$$= 58.8\times 4.2\times 10^{-3} - 58.8\ (1-0.386)\ 0.8\times 10^{-3} = \$0.218$$

Cost of material for complex layout

$$= 46.2\times 4.2\times 10^{-3} - 46.2\ (1-0.49)\ 0.8\times 10^{-3} = \$0.175$$

$$\text{Cost saving in the complex layout} = (0.218 - 0.175)\ 150{,}000 = \$6{,}450$$

$$\text{Extra cost for complex punch and die} = 18{,}000 - 12{,}000 = \$6{,}000$$

Conclusion

Cost saving due to better utilization of material is higher than the additional cost of making a complex die and punch:

$$\text{Break-even point} = \frac{6{,}000}{(0.218-0.175)} = 139{,}535\text{ L shapes}$$

Note

If the material of the L shapes was cheaper than brass, plain-carbon steel for example, the cost saving due to better material utilization would have been less and the break-even point would have occurred at a higher number of L shapes.

8.7 ECONOMIC COMPETITION IN THE MATERIALS FIELD

Although the average world consumption of engineering materials is increasing with time, the consumption of some materials is increasing at a much faster rate than others. Generally, the consumption of the older materials like steel, copper, concrete, and timber is growing at a slower rate than aluminum and plastics. The slow growth of the older materials reflects the increasing efficiency in their utilization, as well as competitive inroads made by aluminum and plastics. The more efficient utilization of materials is illustrated by the fact that the use of copper in electrical generators has been reduced from about 100 kg (220 lb)/MW to 25 kg (55 lb)/MW during the last decade. The more efficient design and better alloys used in present-day aircraft have reduced the use of metals from 3.5 kg (7.7 lb) per passenger mile in the Boeing Stratocruiser to about 1.4 kg (3 lb) in the Boeing 707.

The substitution of a new material for an established one usually involves overcoming the inertia that tends to preserve the existing structure of the industry, that is, the investment in capital plant and labor skills. A good example of this is the difficulty some car companies might find in introducing all-plastic injection-molded or blow-molded car seats in place of the current labor-intensive tubular metal frame construction. The main forces that can overcome the inertia against change are

- Legislation
- Cost saving
- Superior performance

8.7.1 Legislation

Legislation can be a major driving force for change, as in the case of motorcar industry. For example, legislation on crash padding in car interiors led to a sudden increase in the amount of plastics employed in European cars. Similarly, the introduction of legislation in the United States requiring that new cars should average 29 miles to the gallon resulted in the initiation of development programs to reduce the weight of the car. This caused the average amount of plastics in the motorcar to increase from about 55 kg (120 lb) in 1980 to more than 100 kg (220 lb) in 1990. Legislation, however, can also oppose change, as in the case of side-impact-resistance legislation that restricted the design and the introduction of all-plastic car doors and other structural members.

8.7.2 Cost Saving

Cost saving is a major driving force for materials substitution. For example, aluminum has taken a sizable fraction of the beverage cans and oil containers market from steel, but the steel industry has now reduced the thickness of steel in a can to two-thirds in the hope of holding the market. Plastics have started competing with metals in this application and the body of some beverage cans is now made of either plastic, aluminum, or steel, as shown in Figure 8.5.

FIGURE 8.5 An example of the competition between materials. The beverage can body can be made of aluminum (*right*), steel (*middle*), and plastic (*left*).

8.7.3 Superior Performance

The superior performance of new materials is also a major cause of change. The sports-equipment industry offers many examples, like tennis rackets, rowing oars, and vaulting poles, where fiber-reinforced composites have replaced traditionally used materials. The subject of materials substitution is discussed in more detail in Chapter 10 and some detailed case studies are presented in Chapter 11.

8.8 PROCESSING TIME

The processing time represents an important parameter in most of the major elements of manufacturing costs. For example, the direct labor cost for a given process is usually calculated by multiplying the time required for the process by a labor rate. Overhead costs are also commonly calculated by multiplying operation time by an overhead rate.

8.8.1 Elements of Processing Time

The total time required to perform an operation may be divided into four parts as follows:

1. *Setup time*. This is the time required to prepare for operation and may include the time to get tools from the crib and arrange them on the machine. Setup time is performed once for each lot of parts and should, therefore, be listed separately from the other elements of the operation time. If 45 min is required for a setup and only 10 parts are made, an average of 4.5 min must be charged against each part. However,

if 90 parts are made from the same setup, only 0.5 min is charged per part. Setup time is usually estimated from previous performance of similar operations.

2. *Man or handling time*. This is the time the operator spends loading and unloading the part, manipulating the machine and tools, and making measurements during each cycle of operation. Personal and fatigue allowances as well as time to change tools are also included in this part.
3. *Machine time*. This is the time during each cycle of the operation that the machine is working or the tools are cutting. Many organizations have developed standard data for various machine classes based on accumulated time studies. In some cases, the machine time can be calculated from the process parameters.
4. *Down or lost time*. This is the unavoidable time lost by the operator because of breakdowns, waiting for tools and materials, etc.

Floor-to-floor time (FFT) is the time that elapses between picking up a part to load on the machine and depositing it after unloading from the machine. FFT includes the time for loading, manipulation, machining or processing, and unloading the part. Allowances for tool setup and changes, fatigue, and delays are added to FFT to give the basic production time for the operation.

8.9 PROCESSING COST

There are several accounting methods for estimating the cost of manufacturing, and selecting the most appropriate method depends on the organization of the company and type of products they manufacture. Some examples of cost estimation methods are discussed in the following sections.

8.9.1 Rules of Thumb

Rules of thumb employ simple conversions of a material parameter into total cost of component. For example, the cost of a sand-cast part can be given as a function of its weight, and the cost of an injection-molded component can be related to the cost of plastic used in making it. This method is based on past experience and is useful for routinely produced components. However, it has limited predictive capabilities in the case of new products.

8.9.2 Standard Costs

Standard-cost systems are based on the assumption that there is a certain amount of material and a given amount of labor that go into the manufacture of a component. Implementation of this system involves advance preparation of standard rates for materials, labor, and expenses. Standard time is defined as the total time in which a job should be completed at standard performance of a qualified worker. Information on standard times and costs can be collected by the company for their particular processes or found in the literature where a large amount of data for special or general work has been published.

Comparing the actual materials, labor, and times against the corresponding standard values makes it possible to isolate the reason for any deviation from the overall standard cost. The variance is expressed as the difference between the actual performance and the standard base. The variance can be related to materials, labor, or cost. For example, performance variance of labor may be calculated by comparing actual time worked with standard time. The ratio of actual performance to standard is sometimes called labor-effectiveness ratio or labor-efficiency ratio. Case study 8.4 illustrates the use of variance in analyzing performance.

Case Study 8.4: Using Standard Costs Method to Evaluate Manufacturing Effectiveness

Problem

A foundry has the following standard costs for a cast product for a rate of production of 2000 castings per month:

Labor = \$1.00
Materials = \$0.50
Overheads = \$2.00
Total cost = \$3.50

A scheme for increasing labor efficiency caused the production to increase to 2200 castings per month. The actual costs during this month are shown in Table 8.5.

Result

The results show that the increased labor effectiveness caused a favorable variance of \$200. However, the decreased efficiency of using materials caused an unfavorable variance of \$700, which is more than the gain due to increased labor effectiveness. The net result is unfavorable variance of \$500.

TABLE 8.5
Comparison of Standard and Actual Costs for the Cast Product

Cost Element	Actual Costs (\$)	Calculated According to Standard Costs (\$)	Variance (\$)
Labor	2000	2200	−200
Materials	1800	1100	+700
Overheads	4400	4400	—
Total cost	8200	7700	+500

8.9.3 Technical Cost Modeling

In the technical cost modeling method, elements of cost involved in the manufacturing of the component are calculated separately. For example, processing cost of a component can be divided into the following components:

1. Direct labor cost, which is usually calculated by multiplying the labor hourly rate times the FFT.
2. Direct cost of using the equipment, which can be calculated by multiplying the hourly rate of using the processing machines times the FFT. This cost accounts for the depreciation, maintenance, and utilities cost of equipment.
3. Cost of tooling and production aids, which includes the share of the component in the total cost of designing and fabricating dies, molds, cutters, jigs, and fixtures that are needed to process it. For example, if the tooling cost is $20,000 and the number of components that will be processed is 50,000, then the tooling cost per component is $0.4.
4. Overheads are usually charged as a fraction of items (1) and (2).

In some cases, and for ease of accounting, a company may develop composite hourly rate for a process, which includes the cost of labor, cost of using equipment, and overheads. According to Ulrich and Eppinger (1995), the composite hourly rates can be about $25 for a simple stamping press, $30 for a small injection-molding machine, $44 for sand casting, $50 for investment casting, and $75 for medium-sized computer-controlled milling machine. Case study 8.5 illustrates the use of the technical cost modeling in selecting the optimum processing route.

Case Study 8.5: Selection of the Least-Expensive Route for Manufacturing a Shaft

Problem

A small shaft can be machined on either a turret lathe or a single-spindle automatic lathe. Select the least-expensive route for a 100-piece order and a 1000-piece order.

Analysis

Table 8.6 compares the different times and costs for machining a small shaft on a turret lathe and a single-spindle automatic lathe. In addition to illustrating how the different costs are calculated, the table shows that the cost of processing decreases as the number of pieces per order increases. The table also shows that the turret lathe is more economical for smaller orders, whereas the automatic lathe is more economical for larger orders.

8.10 ECONOMICS OF TIME-SAVING DEVICES

Jigs and fixtures are special production tools that are specially designed for quick and accurate location of the workpiece during manufacture. A fixture is a special

TABLE 8.6
Comparison of Times and Costs for a Small Shaft

Parameter	Turret Lathe	Single-Spindle Automatic Lathe
Cost of machine and standard tools ($)	19,318	45,000
Annual depreciation on 15-year basis of machine and standard tools ($)	1,287.93	3,000
Over 2000 h/year, cost of depreciation/h ($) (a)	0.644	1.5
Overhead rate/h not including depreciation ($) (b)	9.00	9.00
Setup time (h)	2.5	3.5
Labor rate/h for setup time ($/h)	7.50	7.50
Setup cost per order ($)	18.75	26.25
Operation time per piece (min)	4.0	3.0
Production per 50-min h (pieces/h) (c)	12.5	16.67
Labor rate/h for operating lathe ($/h) (d)	7.50	3.75 (Attends to two lathes simultaneously)
Composite rate/h ($) (a + b + d)	17.14	14.25
Cost per piece without setup and special tools ($) (a + b + d)/c = (e)	1.37	0.86
Setup cost for 100-piece order ($) (f)	1.88	2.63
Cost per piece for 100-piece order ($) (e + f)	3.25	3.49
Setup cost for 1000-piece order ($) (g)	0.19	0.26
Cost per piece for 1000-piece order ($) (e + g)	1.56	1.12

Source: Based on Doyle, L.E. et al., *Manufacturing Processes and Materials for Engineers*, 3rd edn., Prentice-Hall, Englewood Cliffs, NJ, 1985.

work-holding device that holds the workpiece during machining, welding, assembly, etc. It is usually designed to facilitate setup or holding of a particular part or shape. A jig, however, not only holds the workpiece but also guides the tools, as in drill jigs, or accurately locates the parts of the work relative to each other, as in welding jigs. Such production tools are expensive and their cost adds to the total production cost. It is, therefore, important to make sure that they can be justified economically by the saving in production time that will result from their use. The following factors must be considered when considering the economics of special tooling:

1. The cost of the special tooling
2. Interest rate on the cost of the tooling
3. Savings in labor cost as a result of using the tooling
4. Savings in machine cost as a result of increased productivity
5. The number of units that will be produced using the tooling

From the economic point of view, the use of special tooling can only be justified if the savings in production costs per piece is greater than, or at least equal to, the tooling cost per piece. The savings per piece, S_p, can be calculated from the following relationship:

$$S_p = (Rt + R_o t) - (R't' + R_o t') \tag{8.3}$$

where
- R is the labor rate/h without tooling (\$/h)
- R' is the labor rate/h using tooling (\$/h)
- t is the production time per piece without tooling (h)
- t' is the production time per piece with tooling (h)
- R_o is the machine cost/h, including overheads (\$/h)

The total tooling cost, C_T, is the sum of the initial tooling cost, C_t, plus the interest on the tooling cost. Taking the number of years over which the tooling will be used as (n) and the rate of interest as (i) and assuming straight-line depreciation,

$$C_T = C_t + \frac{(C_t n i)}{2} \tag{8.4}$$

This relationship is only approximate, but it is sufficiently accurate for our purpose because the tooling life is usually relatively short. When the time over which the tooling will be used is less than 1 year, the interest on the tooling may be ignored.

The tooling cost per piece, C_p, is calculated as

$$C_p = \frac{C_T}{N} \tag{8.5}$$

where N is the number of pieces that will be produced with the tooling.

For the tooling to be economically justified, $S_p > C_p$.

Example 8.6 illustrates the use of the mentioned procedure.

Design Example 8.6: Economic Justification for Using a Drill Jig

Problem

Using a drill jig is expected to reduce the drilling time from 30 to 12 min. If a jig is not used, a skilled worker will be needed with an hourly rate of \$12. Using the jig makes it possible for a less-skilled worker to do the job at an hourly rate of \$10. The hourly rate for using the drilling machine is \$8. The cost of designing and manufacturing the jig is estimated as \$1200. The interest rate is 12%, and the expected life of the jig is 2 years. It is estimated that the jig will be used for the production of 400 parts during its useful life. Is the use of the jig economically justifiable? How many parts need to be produced for the jig to break even?

Solution

The saving per piece, S_p, as a result of using the jig is calculated from Equation 8.3 as

$$S_p = \left[12 \times \left(\frac{30}{60}\right) + 8 \times \left(\frac{30}{60}\right)\right] - \left[10 \times \left(\frac{12}{60}\right) + 8 \times \left(\frac{12}{60}\right)\right] = 10 - 3.60 = \$6.40$$

The total jig cost, C_T, is calculated from Equation 8.4 as

$$C_T = 1200 + \frac{(1200 \times 2 \times 0.12)}{2} = \$1344$$

The jig cost per part is calculated from Equation 8.5 as

$$C_p = \frac{1344}{400} = \$3.36$$

As the cost of jig per part is less than the savings per part, the jig is economically justifiable.

The break-even number of parts, N', is calculated as

$$6.40 = \frac{1344}{N'}$$

Thus,

$N' = 210$ parts

This means that at least 211 parts need to be manufactured to justify the use of the jig.

8.11 COST–BENEFIT AND COST-EFFECTIVENESS ANALYSES

Cost–benefit and cost-effectiveness analyses are methods that are used to evaluate projects or products taking into account both economic value and service provided by the project or product. Cost–benefit analysis is used when the service can be measured in monetary terms, while cost-effectiveness analysis is more convenient when the service is not measurable monetarily and can only be measured in other units appropriate to the project or product.

In cost–benefit analysis, the benefit/cost ratio (BCR) is expressed as

$$\text{BCR} = \frac{\text{benefits} - \text{disbenefits}}{\text{cost}} \tag{8.6}$$

where benefits include the monetary value of the service provided by the project or product and the disbenefits include annual expenses of maintaining the project or product. The cost includes materials, fabrication, and construction. The project or product is viable when the BCR is greater than unity. Case study 8.7 illustrates the use of cost-benefit analysis in decision making.

Case Study 8.7: Selecting the Project with Better Benefit/Cost Ratio

Problem

Two proposed alternative solutions, A and B, are proposed to replace an existing road. The road is expected to serve for 25 years (n) and interest rate on borrowed capital (i) is 10%.

Solution

The annual installments (I) to pay for the construction of the road can be estimated from Equation 8.7 using the capital recovery factor (CRF):

$$I = P(\text{CRF}) = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{8.7}$$

where P is the capital used for construction.

Table 8.7 gives the cost-benefit analysis and compares the two alternative solutions, A and B. The BCRs are calculated as follows:

Benefit/cost of solution A compared with existing road

$$= \frac{(200{,}000 - 180{,}000) - (240{,}000 - 250{,}000)}{11{,}020} = 2.722$$

Benefit/cost of solution B compared with existing road

$$= \frac{(200{,}000 - 160{,}000) - (230{,}000 - 250{,}000)}{15{,}428} = 3.89$$

The results show that solution B has better BCR in spite of its higher cost of construction.

TABLE 8.7
Selecting the Project with Better Benefit/Cost Ratio

	Existing Road	Solution A	Solution B
Construction cost P ($)	—	100,000	140,000
User's cost ($)	200,000	180,000	160,000
Owner's maintenance cost ($)	250,000	240,000	230,000
CRF		0.1102	0.1102
I ($)		11,020	15,428
Benefit/cost ratio compared to existing road		2.722	3.89

In the cost-effectiveness analysis, cost (C) consists of elements such as production, operation maintenance, and salvage, while characteristics such as utility, merit, reliability, maintainability, availability, and mobility can be taken as measures of effectiveness (E). A product with a higher E/C provides better effectiveness rating points per dollar expended. Case study 8.8 illustrates the use of cost-effectiveness analysis in decision making.

Case Study 8.8: Selecting a Hard Hat Using Cost-Effectiveness Analyses

Problem

Four hard hats for use in construction sites are available on the market, as shown in Table 8.8. Select the optimum model.

Solution

Safety, comfort, weight, and appearance are considered as the main factors that affect the utility of the hard hat. Table 8.8 gives the price and characteristics of the four models. Effectiveness of a given model is taken as the weighted sum of these characteristics. The results show that brand C has the highest E/C ratio and is, therefore, a better buy in terms of effectiveness rating points per dollar. However, brand A has the highest effectiveness rating. An incremental E/C analysis shows that

$$\frac{EA-EC}{CA-CC}=\frac{8.08-6.65}{50-40\dagger}=0.14$$

This result means that the extra effectiveness points of brand A are purchased at a rate of 0.14 effectiveness points per dollar, which is more expensive than the 0.166 points/dollar paid for brand C. Brand C is, therefore, a better choice.

8.12 ENVIRONMENTAL IMPACT ASSESSMENT OF MATERIALS AND PROCESSES

8.12.1 Environmental Considerations

From an environmental perspective, an ideal material should be extracted from vast or renewable resources, used in making products without consuming too much energy or hazardous emissions, and recycled or safely disposed of at the end of its life. These considerations are becoming increasingly important with the increasing awareness of the negative impact on environment as societies develop and populations increase. Manufacturers are under increasing pressure to reduce the environmental burden associated with their products. We now know that the production of engineering materials and their processing into products can have a considerable impact on this burden. However, assessing this impact is not always easy as there are a large number of emissions and waste products associated with these activities. For example, emissions to air can include CO_2, CO, SO_2, and NO_2, and emissions

TABLE 8.8
Selecting a Hard Hat Using Cost-Effectiveness Analysis

		Brand A		Brand B		Brand C		Brand D	
	Relative Importance	Property	Weighted Property	Property	Weighted Property	Property	Weighted Property	Property	Weighted Property
Cost (C) $		50		45		40		35	
Safety	0.55	9	4.95	7	3.85	7	3.85	6	3.3
Comfort	0.20	7	1.4	5	1.0	6	1.2	4	0.8
Weight	0.15	8	1.2	8	1.2	6	0.9	5	0.75
Appearance	0.10	5	0.5	4	0.4	7	0.7	7	0.7
Effectiveness (E)			8.05		6.45		6.65		5.55
E/C			0.161		0.143		0.166		0.159

to water can include organics, metals, nitrates, and phosphates. Several aggregation systems have been proposed to make it easy for designers to incorporate the environmental impact in their design, and the following method is an example.

8.12.2 Energy Content of Materials

Ashby uses energy associated with the production of 1 kg of a material, H_p, as an indication of its environmental impact. Table 8.9 gives the value of H_p for some materials. Example 8.9 compares the energy contents in a drink container and 8.10 illustrates the use of the energy content information in design.

Case Study 8.9: Comparing the Energy Content in Drink Containers

Problem

Compare the energy contents of carbonated—fizzy—soft drink containers.

Solution

Soft drinks are usually sold in plastic or metal containers. The energy contents of plastic (PET) bottles of 375 mL capacity and metal (aluminum and steel) cans of 330 mL capacity are compared in Table 8.9. The energy content of the material is based on the values in Table 8.10. The energy required to form the plastic bottle by blow molding and the metal can by deep drawing is based on data reported by Ashby (2005). The energy content of the formed container is

TABLE 8.9
Energy Content of Some Engineering Materials

Material Group	Material	Energy Content H_p (MJ/kg)
Ferrous metals	Cast iron	16.4–18.2
	Carbon steels	23.4–25.8
	Stainless steels	77.2–85.3
Nonferrous alloys	Aluminum alloys	184–203
	Titanium alloys	885–945
Ceramics and glasses	Soda-lime glass	13.0–14.4
	Alumina	49.5–54.7
	Silicon carbide	70.2–77.6
Polymers	Polypropylene and polyethylene	76.2–84.2
	PVC	63.5–70.2
	Epoxy	90–100
	Polyester	84–90
Composites	CFRP	258–286
	GFRP	107–118

Source: Based on Ashby, M.F., *Materials Selection in Mechanical Design*, 3rd edn., Elsevier, Amsterdam, the Netherlands, 2005.

TABLE 8.10
Comparison of the Energy Content in Drink Containers

Material and Container	PET Bottle	Al Can	Steel Can
Energy content of material	80 MJ/kg	194 MJ/kg	25 MJ/kg
Energy to form material	3.1 MJ/kg	0.13 MJ/kg	0.15 MJ/kg
Weight of container	23 g	15 g	25 g
Energy content of container	1.9 MJ	2.9 MJ	0.63

obtained by multiplying its weight times the sum of the material energy content and the energy to form the material.

Conclusion

The results in Table 8.10 show that the steel can has least energy content followed by PET bottle with the aluminum can containing the highest amount of energy. The three materials are recyclable but the aluminum can requires less energy for transportation as it is lighter. The steel can is more complicated to recycle as its top section and tab are made from aluminum. It is interesting to note that the three materials require much less energy to form them into products than to make them from the raw materials.

Design Example 8.10: Accounting for Weight and Environmental Impact in Selecting a Material for a Tie Bolt

Problem

Aluminum alloy 7075T6 (YS = 511 MPa, $\rho = 2.7$ g/cc) and titanium 6Al4V (YS = 939 MPa, $\rho = 4.5$ g/cc) are being considered for making a tensile member (tie bolt) of length 200 mm that will carry a load of 50 kN. Which of the two materials will give a lighter member and which will have less impact on environment?

Analysis

Taking a factor of safety of 1.5,

$$\text{Weight of the aluminum member} = \frac{50{,}000 \times 1.5 \times 200 \times 2.7}{511 \times 1{,}000} = 79.3 \text{ g}$$

$$\text{Weight of the titanium member} = \frac{50{,}000 \times 1.5 \times 200 \times 4.5}{939 \times 1{,}000} = 71.9 \text{ g}$$

From Table 8.9, an average energy content for aluminum and titanium alloys can be taken as 193.5 and 915 MJ/kg, respectively.

The energy content of the aluminum member = 0.0793 × 193.5 = 15.4 MJ.

The energy content of the titanium member = 0.0719 × 915 = 65.7 MJ.

Conclusion

The titanium alloy member is lighter but has higher energy content. From the foregoing analysis, it is seen that the weight of a tensile member is proportional to ρ/YS, where ρ is the density and YS the yield strength. The environmental impact of the material in the tensile member is proportional to the parameter (H_pρ/YS), which needs to be minimized for an environmental conscious design.

8.12.3 Life Cycle Assessment

Another method of aggregating the environmental impact is the use of the Eco-Indicator 99 (EI 99). According to ISO 14001, LCA, the environmental impact of a given product over its entire life cycle can be divided into three main phases:

1. Production phase, including energy requirements for primary and secondary materials used and all the processes involved in manufacturing them into a finished product ($EI_{prod} = EI_{mat} + EI_{mfct}$)
2. Use or operation phase, including the energy, fuel, and emissions over the entire lifetime of the product (EI_{use})
3. End-of-life phase, including the energy used in disposal of the discarded product and whatever energy is gained from its recycling (EI_{eol})

In this case, the total environmental impact of the product over its entire life cycle (EI_{LC}) is given by

$$EI_{LC} = EI_{mat} + EI_{mfct} + EI_{use} + EI_{eol} \tag{8.8}$$

According to Giudice et al. (2005), the environmental impact of the production phase can be expressed as follows:

$$EI_{prod} = EI_{mat} + EI_{mfct} = EI_{mat} W + EI_{prss} \mu \tag{8.9}$$

where
EI_{mat} is the eco-indicator per unit weight of material as estimated by the EI 99 method
W is the weight of the material
EI_{prss} is the eco-indicator of the process as estimated by the EI 99 method
μ is the characteristic parameter of the process or quantity of the material processed

$$EI_{eol} = EI_{dsp}(1 - \xi)W + EI_{rcl}\xi W \tag{8.10}$$

where
EI_{dsp} and EI_{rcl} are the environmental impacts of disposal and recycling processes per unit weight of material, respectively
ξ is the recyclable fraction

The relative environmental impact of the earlier three phases—production, use, and end of life—depends on the type of product under consideration. For example, the use phase is responsible for most of environmental impact in the case of aircraft and motorcars, but it is the production phase that gives most of the impact in the case of bicycles and furniture. The end-of-life phase normally contributes a small fraction of the environmental impact in most products.

Case study 8.11 illustrates the use of the previously mentioned parameters in LCA. A more detailed case study in materials substitution is discussed in Section 11.5.

Case Study 8.11: LCA for Motorcar Brake Disk

Problem

Currently, a disk brake is made of GCI, and aluminum matrix composite (AlMC) is being considered as a substitute material. Use LCA to analyze this decision.

Analysis

The following analysis is based on the case study by Giudice et al. (2005). The main performance requirements of a disk brake include resistance to the thermal and mechanical loading resulting from the braking action, lightweight, and compliance to geometric and volume constraints. The disk of the brake is currently made from GCI processed by sand casting. The substitute material under consideration is AlMC processed by squeeze casting. According to Giudice et al. (2005), for equivalent performance, the geometry and weight of disks made of the two materials are given in Table 8.11. The table also gives the different environmental impact components according to Equations 8.8 through 8.10.

The data in Table 8.11 show that the production of AlMC has greater environmental impact than GCI and recovers less points at the end of its life because of its poor recyclability. Giudice et al. (2005) calculated the EI_{use} component assuming the weight of a motorcar with GCI disks to be 1000 kg, mean fuel consumption to be 0.085 L/km, reduction in fuel consumption to be 4.5% for a 10% reduction in weight, and expected traveling distance to be 150,000 km.

The results in Table 8.11 show the predominant influence of EI_{use} compared to the other environmental impact components. Because of its lightweight and subsequent savings in fuel consumption, AlMC has lower EI_{LC} in spite of its higher EI_{prod} and lower EI_{eol} recovery.

TABLE 8.11
Comparison of GCI and AlMC as Motorcar Brake Disk Materials

	Volume (dm^3)	Weight (kg)	EI_{prod} (mPt)	EI_{eol} (mPt)	EI_{use} (mPt)	EI_{LC} (mPt)
GCI	0.83	6.00	208.9	−165.4	2,729,884	2,729,927
AlMC	1.36	3.83	2293.3	−21.1	2,719,201	2,721,479

Source: Data based on Giudice, F. et al., *Mater. Des.*, 26, 9, 2005.

Conclusion

This case study illustrates the importance of including all the components of EI_{LC} when comparing the environmental impact of materials in a product.

8.13 RECYCLABILITY OF ENGINEERING MATERIALS AND RECYCLING ECONOMICS

The public concern for the environment and the increasing cost of landfill fees provide major incentives for reuse of components and recycling of materials. Recyclability describes the ease with which a material can be recycled and the quality of the recycled material relative to the virgin material. Most metals and their alloys have good recyclability if remelted separately from other alloys or materials. To maintain this level of recyclability, products need to be dismantled and scrap separated. Joining of dissimilar metals and coatings can lead to contamination on remelting.

Glasses can be recycled and used for new products provided they are separated by color and type. This is usually done by the consumer at collection points. Ceramics on the other hand are seldom recycled into new products but can be crushed and used as fillers for building materials and lower-grade products.

Thermoplastics can be easily recycled provided they are separated into different types. This is made easy by the labeling system discussed in Chapter 1, where 1 is PET, 2 is HDPE, 3 is PVC, etc. Thermosetting plastics and rubbers are not recyclable but can be crushed and used as fillers for lower-grade products. Composite and laminated materials are difficult to recycle as it is not usually possible to separate their constituent phases. In some cases these materials can be shredded and used as fillers for some plastics and building materials.

The recycling process of relatively large products normally starts with the last owner delivering the retired product to a dismantler who then separates reusable components and shreds the rest. Metals and other useful materials are then separated from the shredded material and the remainder is sent to the landfill. Economic incentives for those taking part in this process would ensure that it would work. For example, the dismantler has to sell the materials salvaged at a sufficient price to make a net profit after compensating the last owner for bringing in the product, paying the expenses of shredding, and paying the landfill fees. This net financial gain can also be used as a factor in selecting the most economic material for a given component. Case study 8.12 is used to illustrate the important role played by recycling in determining the total cost of a product and is based on studies by Sanders et al. (1990) and Berry (1992).

Case Study 8.12: Recycling Economics of Aluminum Beverage Containers

Metal Content

The aluminum industry has been trying to reduce the metal content of beverage containers through innovative designs and material selection. This is because the metal value constitutes about 70% of the container cost. The early two-piece seamless aluminum 12 oz (355 mL) beverage container was 15–20 g. Today, the can weights

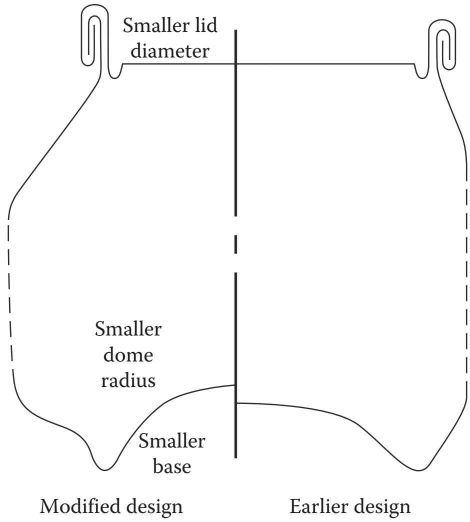

FIGURE 8.6 Design changes to reduce the weight of the aluminum beverage can.

only about 10–11 g. This reduction is achieved by reducing the starting thickness of the can stock sheet from 0.38 mm (0.015 in.) to about 0.3 mm (0.012 in.). The can is required to withstand an internal pressure of 90 psi. This reduction in thickness was made possible by reducing the can neck diameter, that is, the can lid. The neck diameter of early lids was 68.3 mm (2 11/16 in.) but today it is 60.3 mm (2 6/16 in.). Cans with smaller lid diameter withstand more internal pressure without buckling; therefore, lid thickness can be reduced. As the lid diameter was reduced, the base diameter was also reduced to maintain stackability of the cans. This has also allowed the thickness of the base metal to be reduced. Figure 8.6 shows the changes in lid and base design of the aluminum beverage can. No change in the can alloy composition was necessary. The can body is made of 3004 alloy (0.18 Si, 0.45 Fe, 0.13 Cu, 1.1 Mn, and 1.1 Mg), and the lid is made of 5182 alloy (0.10 Si, 0.24 Fe, 0.03 Cu, 0.35 Mn, and 4.5 Mg). These alloys are compatible in composition, which is an important factor in recycling. With small adjustments in composition, the recycled material can be reused in making either the body or lid stock.

Cost Analysis

Decreasing the metal weight in the can through the design changes and higher recovery rates of used cans for recycling have allowed the aluminum can to remain competitive in relation to other packaging materials as shown in Table 8.12.

Conclusion

Table 8.12 shows that the aluminum raw material used in a beverage can costs more than any of the alternative materials. This explains the motive for design changes to reduce the weight of material in the can. An aluminum can has an advantage in manufacturing cost over other materials and its distribution cost is

TABLE 8.12
Comparison of Costs Involved in Manufacturing of 355 mL

Cost Element	Aluminum	Glass	Plastic	Steel
Raw material	4.6	1.7	1.71	3.18
Manufacturing cost	3.19	7.8	6.27	3.81
Distribution cost	0.05	0.50	0.05	0.08
Recycling credit	(1.29)	(2.25)	(0.00)	(0.33)
Total net cost	6.55	7.75	8.03	6.74

Source: Based on Berry, D., *JOM*, 44, 21, 1992.
Note: Containers (in Cents) in 1987.

as low as that of plastic in view of its lightweight. The other major cost advantage of aluminum is derived from its recyclability. The recycling credit is the result of recycling manufacturing scrap, skeletons and stampings, and postconsumer scrap, that is, used cans. At present, 63% of used aluminum cans are collected and recycled. This value contrasts to 33% for glass beverage bottles and 24.7% for steel beverage cans. Without this higher recycling credit, the aluminum can would be more expensive than the steel can.

8.14 LIFE CYCLE COST

LCC gives the total cost of a product throughout its life and includes

- The selling price of the product
- Running cost
- Postuse cost

The elements of cost that determine the selling price of a product were discussed in Section 1.7. Running costs include all the costs paid by the owner throughout the life of the product. These include cost of energy used, maintenance cost, and cost of spare parts. Postuse costs include disposal cost minus resale and returns from recycling. Other LCCs include support, training, site preparation, and operating costs generated by the acquisition.

LCCs can be estimated for new projects either at total plant level or at equipment item level. The main aims of LCC are the following:

1. To provide a comprehensive understanding of the total commitment of asset ownership
2. To identify areas of the life cycle where improvement can be achieved through redesigning or reallocation of resources
3. To improve profitability and industrial efficiency

The applications of LCC in industry include comparing mutually exclusive projects, checking future performance of an asset, and trade-offs between design and operation parameters. Case study 8.13 illustrates how LCC is used to decide whether or not aluminum alloys should replace steel in making the body of motorcars.

Case Study 8.13: LCC Comparison of the Use of Aluminum and Steel in Making Motorcar Body

Problem

Motorcar manufacturers are facing the challenge of increasingly stringent regulations on levels of emission and fuel consumption. The challenge can be met by increasing the power train efficiency or reducing the weight by either downsizing or using lighter materials. Of these alternatives, weight reduction by using lighter materials is the most promising. This case study explores the possibility of substituting the lighter aluminum alloys for steel in the motorcar body, made of a structure covered by panels.

Analysis

Table 8.13 gives the parameters involved in the LCC analysis as presented for a rate of production of 200,000 units per year by Dieffenbach and Mascarin (1993).

The steel unibody represents today's motorcar. The aluminum unibody is similarly manufactured with the main difference being the use of aluminum sheets instead of steel. Because the same processes are used in fabrication and assembly of the two materials, the costs are roughly the same. The cost differences are, therefore, due to difference in material prices only. Figure 8.7 shows that the cost of the aluminum unibody is about 1.4 times that of steel.

However, the operating cost in the case of aluminum is about 0.6 times that of steel. The main operating cost difference between the two bodies is due to fuel

TABLE 8.13
Comparison of LCC Parameters for Steel and Aluminum Unibodies at a Rate of 200,000 Units per Year

Parameter	Steel Unibody	Aluminum Unibody
Weight of structure (kg)	225	135
Weight of panels (kg)	79	39
Steel content of structure (%)	100	60
Steel content of panels (%)	100	50
Fabrication	Stamping	Stamping
Assembly	Spot welding	Spot welding
Relative cost of extrusions and castings	1	2
Relative cost of sheets	1	4
Relative selling cost of scrap	1	10

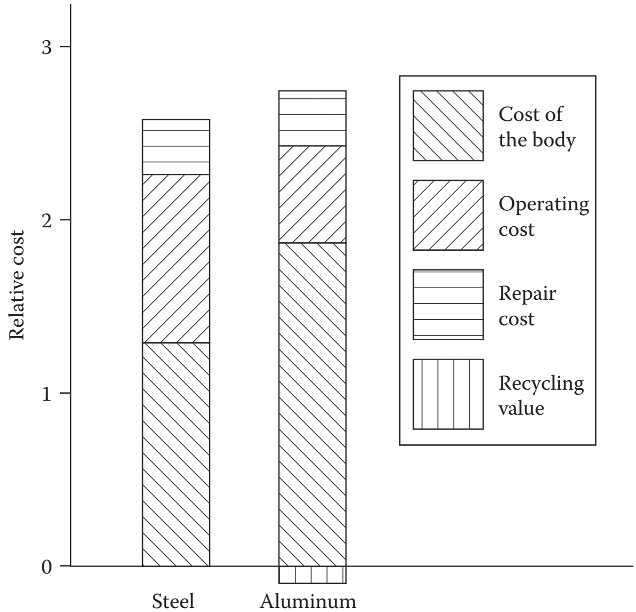

FIGURE 8.7 LCC comparison of steel and aluminum in motorcar body. (From Dieffenbach, J.R. and Mascarin, A.E., *JOM*, 45, 16, 1993.)

consumption. Repair costs do not vary significantly from one material to another since labor and insurance costs are predominant.

The recycling value of steel is very small compared to manufacturing costs and is ignored here. The recycling value of aluminum is about 10 times higher than steel and is shown in Figure 8.7 as credit, below the zero line.

The total LCC is arrived at by subtracting the recycling value from the costs above the zero line. The LCC ratio of steel to aluminum is about 1:1.02, that is, 2% in favor of steel. This result indicates that manufacturers will continue to use steel for the motorcar body. Aluminum unibody, however, holds promise if additional importance is placed on weight and fuel economy.

8.15 SUMMARY

1. In addition to designing and manufacturing products at the required level of quality, manufacturers must also be able to sell their products at competitive prices and make profits. It is, therefore, important that the different materials and processes involved in the design and manufacture should be evaluated in terms of their economic as well as their technical merits.
2. The cost of materials and manufacturing usually represents about 30%–70% of the total product cost in a wide range of engineering industries. As the cost of materials is so important, efforts should be made to optimize their use to achieve an overall reduction of the product cost. However, selecting a

cheaper material may not always be the answer to a less-expensive product. In some cases it may be more economical to pay the extra cost of higher strength since less material will be needed to carry the load. It may also be more economical to select a more expensive material with better machinability than to select a cheaper material that is difficult to machine.

3. The main elements that make up the cost of materials include cost of ore preparation, cost of extraction from the ore, cost of alloying, cost of conversion to semifinished products, and cost of conversion to finished product.
4. Plain-carbon steels and cast irons are less expensive than other materials when compared on the basis of cost per unit weight. However, plastics become less expensive if compared on the basis of cost per unit volume.
5. FFT is the time between picking up a part to load on the machine and depositing it after unloading from the machine. FFT includes loading time, manipulation time, machining or processing time, and unloading time. Allowance for tool setup and changes, fatigue allowance, and delays are added to the FFT to give the basic production time for the operation.
6. Processing cost consists of direct labor cost, cost of using equipment, cost of tooling and production aids, and overheads.
7. Time-saving devices can be expensive and should be justified economically by the saving in production time that will result from their use.
8. Cost–benefit and cost-effectiveness analyses are methods that are used to evaluate projects or products taking into account both economic value and service provided by the project or product. Cost–benefit analysis is used when the service can be measured in monetary terms, while cost-effectiveness analysis is more convenient when the service is not measurable monetarily and can only be measured in other units appropriate to the project or product.
9. The energy content of materials (H_p) can be used to assess the environmental impact of a product. The parameter $H_p\rho$/YS, where ρ is the density and YS the yield strength, can be taken as a measure of the environmental impact of the material in a tensile member.
10. LCA of the impact of a product over its entire life consists of the energy used in its production phase, use or operation phase, and end-of-life phase.
11. Recycling economics play an important role in determining the total cost of a product, especially if high-cost materials are involved in its manufacture.
12. LCC of a product includes the selling price of the product, running cost, and postuse cost.

REVIEW QUESTIONS

8.1 Explain why stainless steels are more expensive than plain-carbon steels.

8.2 Why has the price of titanium decreased in the last 20 years?

8.3 What are the economic reasons for the increased use of carbon fiber-reinforced materials?

8.4 Although plastics are more expensive than many metals, on the basis of cost per unit weight, plastic products are generally less expensive. Discuss this statement.

8.5 Although powdered alloys are more expensive than similar solid alloys, powder metallurgy products are competitive on a cost basis.

8.6 Why is aluminum more expensive than carbon steel, although its raw material is more abundant in nature?

8.7 A company that manufactures shelving units for libraries is considering the possibility of replacing steel shelves with a composite material (epoxy—75% glass fabric). Shelves are 150 cm long and 40 cm wide with the thickness depending on the type of material used in making it. The company is expecting to make 200,000 shelves per year. Given the information, determine whether the substitution is economically justified.

8.8 Using a drill jig is expected to reduce the drilling time from 25 to 15 min. If a jig is not used, a skilled worker will be needed with an hourly rate of $15. Using the jig makes it possible to use a less-skilled worker with an hourly rate of $11. The hourly rate for using the drilling machine is $8. The cost of designing and making the jig is $1500. The expected number of parts to be produced during the lifetime of the jig is 500. The interest on the capital can be ignored, as the duration of the job is short. Is the use of the jig economically justifiable?

8.9 Design a simple jig for drilling three holes in a rectangular workpiece that is 250 mm long, 150 mm wide, and 50 mm thick.

8.10 Calculate the number of parts that will justify introducing the jig in Question 8.9 given the following information:

Labor rate without jig = $12/h
Labor rate with jig = $10/h
Production time per part without jig = 15 min
Production time per part with jig = 10 min
Machine cost/h = $20
Cost of designing and making the jig = $500
The expected length of production run = 7 months
Rate of interest = 12%
(Answer: number of parts = 173)

8.11 The manufacture of a given component requires eight operations in the machine shop. The average setup time per operation is 2.5 h. Average operation time per machine is 7 min. The average nonoperation time needed for handling of workpieces and tools, inspection, delays, and temporary storage is 50 min per operation. Estimate the total time required to get a batch of 100 components through the workshop. (Answer: 120 h)

8.12 The component in Question 8.9 is required in batches of 500, and a turret lathe is being considered for manufacturing the component. The machining time will be unchanged, but the total handling time will be reduced to 1.5 min per operation. If the setup time of the turret lathe is estimated as 6 h, calculate the following:

a. Total time to process the batch on the engine lathe
b. Total time to process the batch on the turret lathe
c. Average production time in both cases

(Answers: (a) 493.3 h, (b) 478.87 h, and (c) 59.2 min for engine lathe, 57.5 for turret lathe)

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9 Materials Selection Process

9.1 INTRODUCTION

Selecting the appropriate material and manufacturing process is an important requisite for the development of a product that will perform successfully in service. It is estimated that there are more than 40,000 currently useful metallic alloys and probably close to that number of nonmetallic engineering materials such as plastics, ceramics and glasses, composite materials, and semiconductors. This large number of materials and the many manufacturing processes available to the engineer often make the selection process a difficult task. If the selection process is carried out haphazardly, there will be the risk of overlooking a possible attractive alternative solution. This risk can be reduced by adopting a systematic selection procedure. A rigorous and thorough approach to materials selection is, however, often not followed in industry, and much selection is based on past experience—"when in doubt make it stout out of the stuff you know about." Although it is unwise to totally ignore past experience, since what worked before is obviously a solution, such solution may not be the optimum solution. The increasing pressure to produce more economic and competitive products, in addition to the frequent introduction of new materials and manufacturing processes, makes it necessary for the engineer to be always on the lookout for possible improvement.

This chapter analyzes the nature of the selection process and proposes procedures for gradually narrowing down the available choices until an optimum combination of material and manufacturing process is identified. Because of the large amount of data involved in the selection process, a variety of quantitative selection procedures have been developed to analyze such data so that a systematic evaluation can be easily made. Several of the quantitative procedures can be adopted to computer-aided selection from a bank of material properties and process characteristics.

Although the materials and process selection is most often thought of in terms of new product development, there are many other reasons for reviewing the type of materials and processes used in manufacturing an existing product. These reasons include taking advantage of new materials or processes; improving service performance, including longer life and higher reliability; meeting new legal requirements, accounting for changed operating conditions; reducing cost; and making the product more competitive. The issues involved in materials substitution are discussed in Chapter 10.

The overall goal of this chapter is to illustrate how systematic selection procedures can be used to select optimum materials and processes for a given component.

The main objectives are to illustrate how to

1. Analyze material performance requirements for a given application
2. Create alternative solutions, screen them, and then rank the viable candidates
3. Use quantitative methods in materials selection
4. Incorporate computer methods in the selection process
5. Find reliable sources of material properties

9.2 NATURE OF THE SELECTION PROCESS

Unlike the exact sciences, where a problem normally has one single correct solution, materials selection processes are open-ended and normally lead to several possible solutions to the same problem. This is illustrated by the fact that similar components performing similar functions, but produced by different manufacturers, are often made from different materials and even by different manufacturing processes. However, selecting the optimum combination of material and process is not a simple task that can be performed at one certain stage in the history of a project; it should gradually evolve during the different stages of product development. Figure 9.1 shows that ideas developed on the basis of marketing surveys are first translated into industrial design, leading to broad description of the product in terms of the following parameters:

- What is it?
- What does it do?
- How does it do it?
- How much should it be?

As discussed in Chapters 1 and 5, answering these questions allows the product development team to formulate the product specifications, develop various concepts, and then select the optimum solution. After that, the product is decomposed into subassemblies and the different components of each subassembly are then identified. Experience in most industries has shown that it is desirable to adopt the holistic decision-making approach of concurrent engineering in product development. With concurrent engineering, materials and manufacturing processes are considered in the early stages of design and are more precisely defined as the design progresses from the concept to the embodiment and finally the detail stages, as shown in Figure 9.1.

Although each material and process selection decision has its own individual character and its own sequence of events, there is a general pattern common to the selection process. In the first stages of development of a new component, questions such as the following are posed:

What are the important, or primary, design and material requirements?
What are the secondary requirements and are they necessary?

Answering these questions makes it necessary to specify the performance requirements of the component and to broadly outline the main material

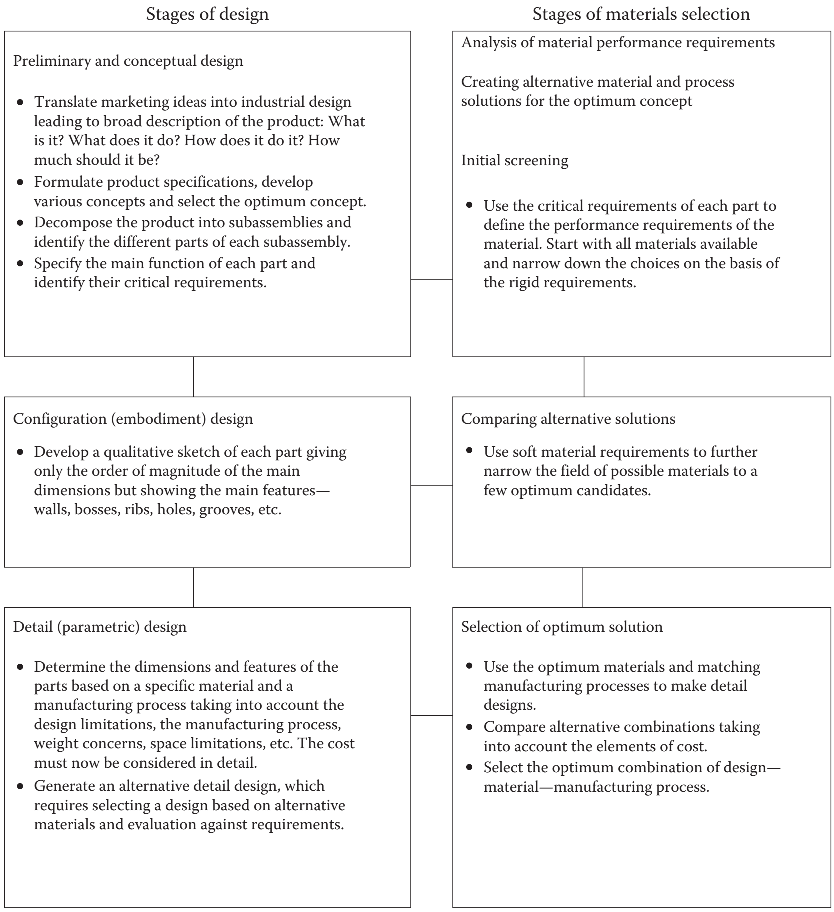


FIGURE 9.1 Major stages of design and the related stages of materials selection.

characteristics and processing requirements. On this basis, certain classes of materials and manufacturing processes may be eliminated and others chosen as likely candidates for making the component. The relevant material properties are then identified and ranked in the order of importance. Candidate materials that possess these properties are then graded according to their expected performance and cost. Processing details are also examined at this stage. Optimization techniques may then be used to select the optimum material and processing route. This may result in design modifications to achieve production economy or to suit the available production facilities and equipment. Even in the stage of product manufacture, some changes in materials may be necessary. Processing problems may arise causing the replacement of an otherwise satisfactory material. For example, heat treating, joining, or finishing difficulties may require materials substitution that, in turn, may result in different service performance characteristics requiring some redesign.

The processes discussed can generally be grouped into the following four steps:

1. Analysis of the performance requirements and creating alternative solutions
2. Initial screening of solutions
3. Comparing and ranking alternative solutions
4. Selecting the optimum solution

The four steps mentioned are discussed in Sections 9.3 through 9.6.

9.3 ANALYSIS OF THE MATERIAL PERFORMANCE REQUIREMENTS AND CREATING ALTERNATIVE SOLUTIONS

The material performance requirements can be divided into five broad categories, namely, functional requirements, processability requirements, cost, reliability, and resistance to service conditions.

9.3.1 Functional Requirements

Functional requirements are directly related to the required characteristics of the component, subassembly, or the product. Such requirements can generally be categorized as technical and esthetic. Technical requirements can be related to physical, mechanical, and chemical characteristics. For example, if the component carries a uniaxial tensile load, the YS of a candidate material can be directly related to the load-carrying capacity of the product. However, some technical characteristics of the component or product may not have simple correspondence with measurable material properties, as in the case of thermal shock resistance, and reliability. Under these conditions, the evaluation process can be quite complex and may depend upon predictions based on simulated service tests, upon the most closely related material properties. For example, thermal shock resistance can be related to thermal expansion coefficient, thermal conductivity, modulus of elasticity, ductility, and tensile strength.

Esthetic characteristics can be related to color, texture, tactile feel, fashion, or impression of warmth, which largely depend on consumer impressions about certain materials in a given application. For example, stainless steel conveys the impression of durability and precision, but it also appears cold. Designers can use this impression to convey advanced technology and high engineering quality of the product. Although esthetics are not easy to quantify, they need to be included as selection criteria in external components that are seen or touched by the user. Examples of such components include upholstery, external casing of watches, frames of glasses, and working surfaces in kitchens. Case study 11.6 in Chapter 11 illustrates how esthetics can be included in the selection of the door panel of a motorcar.

As discussed in Section 1.2.2, the HOQ approach provides a structured process for translating customer requirements and results of market research into quantifiable functional product requirements. The HOQ also gives the relative importance of the technical parameters in meeting customer needs and indicates the levels of performance to be achieved in the new product. The following case study illustrates the use of HOQ approach in arriving at the functional requirements of a step ladder.

Case Study 9.1: Determine the Functional Requirements of a Step Ladder

Problem

A company is considering the introduction of a new line of step ladders for domestic use. As a first step in this process, the company needs to determine the main functional requirements and target design parameters of the ladder.

Solution

The HOQ approach is used to translate the customer requirement function as shown in Table 9.1. According to the customer requirements, the ladder should be safe to use, long enough to reach the ceiling, lightweight, easy to store when not in use, convenient to use and easy to climb on and off, durable, and inexpensive. As part of the process, customers are also asked to rank these requirements in order of importance and the results are shown in Table 9.1. The customer requirements are correlated to a set of product functional requirements that need to be satisfied by the design. Most importantly, the ladder must have a handrail above the top step for safety, a height of 2 m, and five treads in addition to rubber feet and nonslip tread surfaces. The maximum weight, dimensions, and maximum cost were also identified.

Conclusion

The HOQ approach is a useful tool in developing functional requirements on the basis of customer needs.

9.3.2 Processability Requirements

The processability of a material is a measure of its ability to be worked and shaped into a finished component. With reference to a specific manufacturing method, processability can be defined as castability, weldability, machinability, etc. Ductility and hardenability can be relevant to processability if the material is to be deformed or hardened by heat treatment, respectively. The closeness of the stock form to the required product form can be taken as a measure of processability in some cases.

It is important to remember that processing operations will almost always affect the material properties so that processability considerations are closely related to functional requirements.

9.3.3 Cost

Cost is usually a controlling factor in evaluating materials, because in many applications there is a cost limit for a given component. When the cost limit is exceeded, the design may have to be changed to allow for the use of a less expensive material or manufacturing process sequence. The cost of processing often exceeds the cost of the stock material. In some cases, a relatively more expensive material may

TABLE 9.1
Using the HOQ Approach in Correlating Customer Needs to Performance Requirements

Technical Parameters → / Customer Requirements ↓	Importance to Customer	Maximum Height	Number of Treads	Nonslip Legs and Treads	Maximum Weight	Maximum Dimensions When Folded	Large Platform	Non-Rusting	Handrail on Top	Maximum Price
Safe to use	5	1	3	9			1		9	
Allows reaching the ceiling	4	9	3	1		3			3	
Lightweight	4				9					
Easy to store when not in use	3	3			3	9				
Platform to place items and tools	3						9			
Easy to climb on and off	4	3	9	1			1		3	
Long lasting	2							9		
Inexpensive	4									9
Importance		62	63	53	45	39	36	18	69	36
Relative importance		15%	15%	13%	10%	9%	9%	4%	16%	9%
Target design parameters		2 m	5 treads	Rubber feet and nonslip tread surfaces	6 kg	$H = 2$ m $W = 0.5$ m $D = 0.15$ m	45 × 20 cm	Non-rusting coating or corrosion resistant material	Handrail at 0.6 m from top tread	$50

eventually yield a less expensive product than a low-priced material, which is more expensive to process, as discussed in Section 8.5.

9.3.4 Reliability Requirements

Reliability of a material can be defined as the probability that it will perform the intended function for the expected life without failure. Material reliability is difficult to measure, because it is not only dependent upon the material's inherent properties, but it is also greatly affected by its production and processing history. Generally, new and nonstandard materials will tend to have lower reliability than established, standard materials.

Despite difficulties of evaluating reliability, it is often an important selection factor that must be taken into account. Failure analysis techniques are usually used to predict the different ways in which a product can fail and can be considered as a systematic approach to reliability evaluation. The causes of failure of a component in service can usually be traced back to defects in materials and processing, faulty design, unexpected service conditions, or misuse of the product. Failure of materials in service is discussed in Chapters 2 and 3. Reliability of components is discussed in Section 5.7.

9.3.5 Resistance to Service Conditions

The environment in which the product or component will operate plays an important role in determining the material performance requirements. High or low temperatures, as well as corrosive environments, can adversely affect the performance of most materials in service, as discussed in Chapters 2 and 3, respectively. Whenever more than one material is involved in an application, compatibility becomes a selection consideration. In a thermal environment, for example, the coefficients of thermal expansion of all the materials involved may have to be similar to avoid thermal stresses. In wet environments, materials that will be in electrical contact should be chosen carefully to avoid galvanic corrosion. In applications where relative movement exists between different parts, wear resistance of the materials involved should be considered. The design should provide access for lubrication; otherwise, self-lubricating materials have to be used. The selection of materials to resist failure under different service conditions is discussed in Chapter 4.

9.3.6 Creating Alternative Solutions

Having specified the material requirements, the rest of the selection process involves the search for the material that would best meet those requirements. The starting point is the entire range of engineering materials. At this stage, creativity is essential to open up channels in different directions and not let traditional thinking interfere with the exploration of ideas. Steel may be the best material for one design concept, whereas plastic is best for a different concept, although the two designs provide similar functions. The importance of this phase is that it creates alternatives without much regard to their feasibility.

9.4 INITIAL SCREENING OF SOLUTIONS

After all the alternatives have been suggested, the ideas that are obviously unsuitable are eliminated and attention is concentrated on those that look practical. Quantitative methods can be used for initial screening to narrow down the choices to a manageable number for subsequent detailed evaluation. Following are some of the quantitative methods for initial screening of materials and manufacturing processes.

9.4.1 Rigid Materials and Process Requirements

Initial screening of materials can be achieved by first classifying their performance requirements into two main categories:

- Rigid, or go-no-go, requirements
- Soft, or relative, requirements

Rigid requirements are those that must be met by the material if it is to be considered at all. Such requirements can be used for the initial screening of materials to eliminate the unsuitable groups. For example, metallic materials are eliminated when selecting materials for an electrical insulator. If the insulator is to be flexible, the field is narrowed further as all ceramic materials are eliminated. Other examples of the material rigid requirements include behavior under operating temperature, resistance to corrosive environment, ductility, electrical and thermal conductivity or insulation, and transparency to light or other waves.

Examples of manufacturing process rigid requirements include batch size, production rate, product size and shape, tolerances, and surface finish. Whether or not the equipment or experience for a given manufacturing process exists in a plant can also be considered as a hard requirement in many cases. Compatibility between the manufacturing process and the material is also an important screening parameter. For example, cast irons are not compatible with sheet metal-forming processes and steels are not easy to process by die casting. In some cases, eliminating a group of materials results in automatic elimination of some manufacturing processes. For example, if plastics are eliminated because service temperature is too high, injection and transfer molding should be eliminated as they are unsuitable for other materials. Compatibility between materials and manufacturing processes is discussed in Section 7.3.

Soft, or relative, requirements are those that are subject to compromise and trade-offs. Examples of soft requirements include mechanical properties, specific gravity, and cost. Soft requirements can be compared in terms of their relative importance, which depends on the application under study.

9.4.2 Cost per Unit Property Method

The cost per unit property method is suitable for initial screening in applications where one property stands out as the most critical service requirement. As an example, consider the case of a bar of a given length (L) to support a tensile force (F). The cross-sectional area (A) of the bar is given by

$$A = \frac{F}{S} \tag{9.1}$$

where S is the working stress of the material, which is related to its YS divided by an appropriate factor of safety.

The cost of the bar (C') is given by

$$C' = C\rho AL = \frac{C\rho FL}{S} \tag{9.2}$$

where

C is the cost of the material per unit mass
ρ is the density of the material

Since F and L are constant for all materials, comparison can be based on the cost of unit strength, which is the quantity $(C\rho)/S$.

Materials with lower cost per unit strength are preferable. If an upper limit is set for the quantity $(C\rho)/S$, then materials satisfying this condition can be identified and used as possible candidates for more detailed analysis in the next stage of selection.

The working stress of the material in Equations 9.1 and 9.2 is related to the static YS of the material since the applied load is static. If the applied load is alternating, it is more appropriate to use the fatigue strength of the material. Similarly, the creep strength should be used under loading conditions that cause creep.

Equations similar to Equation 9.2 can be used to compare materials on the basis of cost per unit stiffness when the important design criterion is the deflection in the bar. In such cases, S is replaced by the elastic modulus of the material, E. Equations 9.1 and 9.2 can also be modified to allow comparison of different materials under loading systems other than uniaxial tension. Table 9.2 gives some formulas for the cost per unit property under different loading conditions based on either YS or stiffness. Case study 9.1 illustrates the use of the cost per unit property method.

TABLE 9.2
Formulas for Estimating Cost per Unit Property

Cross Section and Loading Condition	Cost per Unit Strength	Cost per Unit Stiffness
Solid cylinder in tension or compression	$C(\rho/S)$	$C(\rho/E)$
Solid cylinder in bending	$C(\rho/S)^{2/3}$	$C(\rho/E)^{1/2}$
Solid cylinder in torsion	$C(\rho/S)^{2/3}$	$C(\rho/G)^{1/2}$
Solid cylindrical bar as slender column	—	$C(\rho/E)^{1/2}$
Solid rectangle in bending	$C(\rho/S)^{1/2}$	$C(\rho/E)^{1/3}$
Thin-walled cylindrical pressure vessel	$C(\rho/S)$	—

Case Study 9.2: Selecting a Beam Material for Minimum Cost

Problem

Consider a structural member in the form of a simply supported beam of rectangular cross section. The length of the beam is 1 m (39.37 in.), the width is 100 mm (3.94 in.), and there is no restriction on the depth of the beam. The beam is subjected to a concentrated load of 20 kN (4409 lb), which acts on its middle. The main design requirement is that the beam should not suffer plastic deformation as a result of load application. Use the information given in Table 9.3 to select the least expensive material for the beam.

Solution

Based on Table 9.3 and the appropriate formula from Table 9.2, the cost of unit strength for the different materials is calculated and the results are given in the last column of Table 9.3. The results show that steels AISI 1020 and 4140 are equally suitable, whereas aluminum 6061 and epoxy glass are more expensive. This answer is reasonable since steels are usually used in structural applications unless special features, such as lightweightedness or corrosion resistance, are required. If the weight of the beam that can carry the given load is calculated for the different materials, it can be shown that the 1020 steel beam is the heaviest, followed by 4140 steel, then aluminum, with epoxy glass being the lightest. In some cases, as in aerospace applications, it may be worth paying the extra cost of the lighter structural member. This issue is discussed in more detail in the case study of materials substitution in aerospace industry (Chapter 11).

9.4.3 Ashby's Method

Ashby's materials selection charts are useful for the initial screening of materials. Figure 9.2 plots the elastic modulus and strength against density for a variety of

TABLE 9.3
Characteristics of Candidate Materials for the Beam

Material	Working Stress[a] MPa	Working Stress[a] ksi	Specific Gravity	Relative Cost[b]	Cost of Unit Strength
Steel AISI 1020, normalized	117	17	7.86	1	0.73
Steel AISI 4140, normalized	222	32	7.86	1.38	0.73
Aluminum 6061, T6 temper	93	13.5	2.7	6	1.69
Epoxy + 70% glass fibers	70	10.2	2.11	9	2.26

[a] The working stress is computed from YS using a factor of safety of 3.
[b] The relative cost per unit weight is based on AISI 1020 steel as unity. Material and processing costs are included in the relative cost.

materials. For simple axial loading, the relationships are E/ρ or S/ρ. For other types of loading and component geometry, different $E-\rho$ and $S-\rho$ relationships apply, as shown in Table 9.2. Lines with the appropriate slopes are shown in Figure 9.2 to represent the different conditions. All the materials that lie on a given line will perform equally well, those above the line are better, and those below it are worse.

9.4.4 Dargie's Method

The initial screening of materials and processes can be a tedious task if performed manually from handbooks and supplier catalogs. This difficulty has prompted the introduction of several computer-based systems for materials and process selection

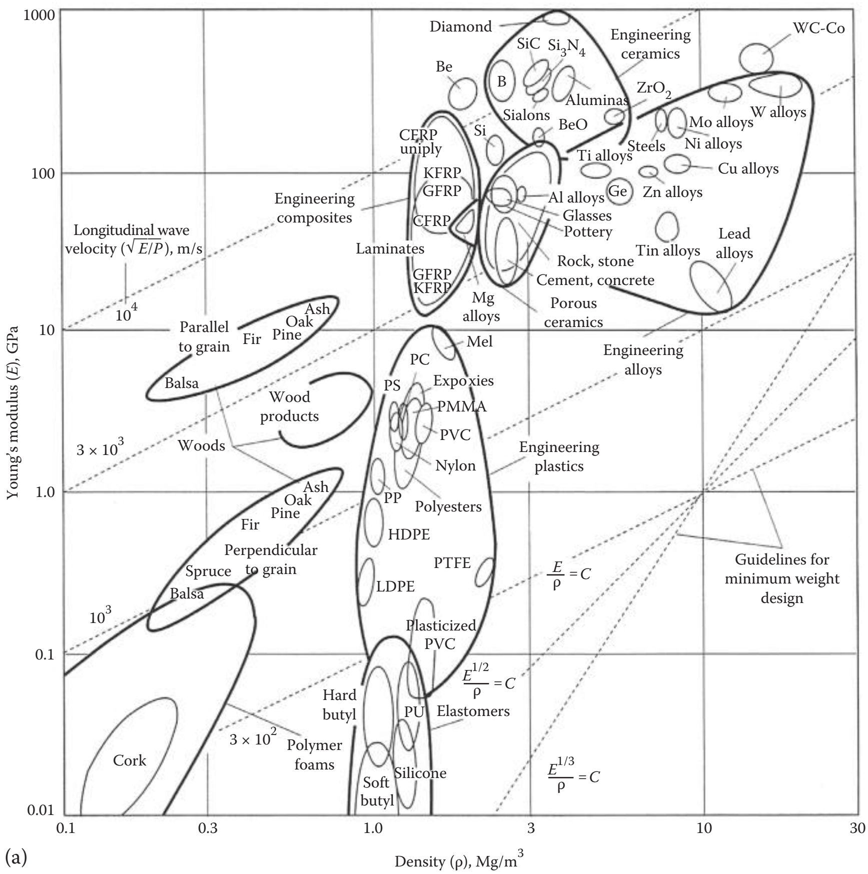
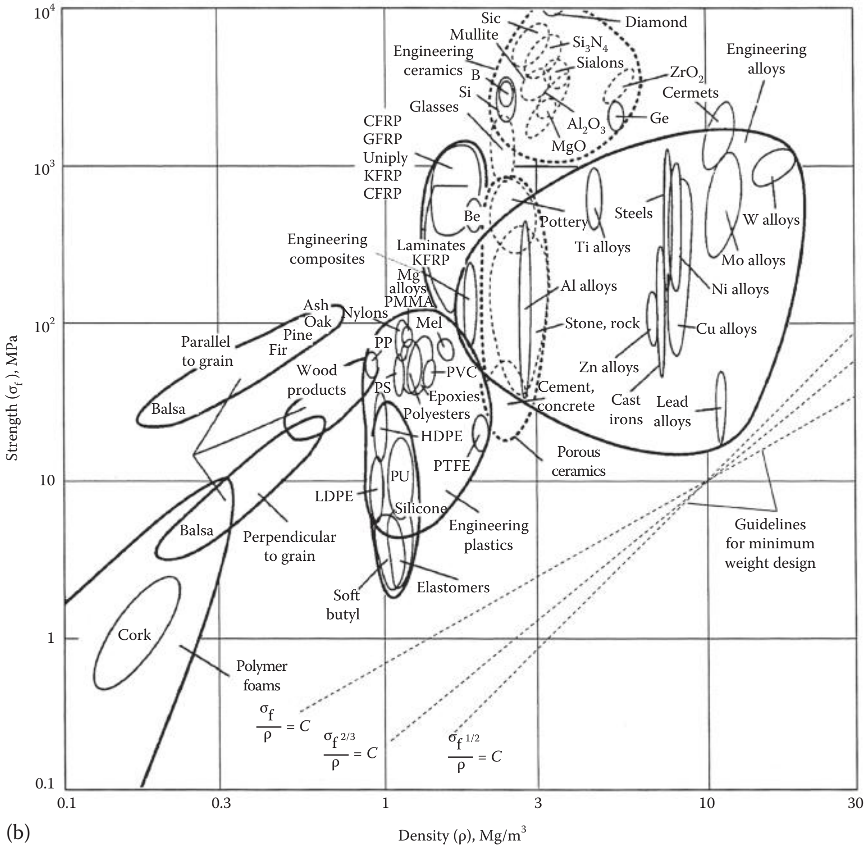


FIGURE 9.2 An example of Ashby's materials selection charts. The heavy envelopes enclose data for a given class of material. (a) Young's modulus, E, plotted against density, ρ, for various engineered materials. The guidelines of constant E/ρ, $E^{1/2}/\rho$, and $E^{1/3}/\rho$ allow selection of materials for minimum weight, deflection-limited design.

(*continued*)



(b)

FIGURE 9.2 (continued) An example of Ashby's materials selection charts. The heavy envelopes enclose data for a given class of material. (b) Strength, σ_f, plotted against density, ρ, for various engineered materials. Strength is YS for metals and polymers, compressive strength for ceramics, tear strength for elastomers, and tensile strength for composites. The guidelines of constant σ_f/ρ, $\sigma_f^{2/3}/\rho$, and $\sigma_f^{1/2}/\rho$ are used in minimum weight, yield limited, and design. (Reprinted from Ashby, M.F., Materials selection charts, in *ASM Metals Handbook*, Vol. 20, *Materials Selection and Design*, Dieter, G., Volume Chair. ASM International, Materials Park, OH, 1997, pp. 266–280. With permission.)

(Dargie, Esawi and Ashby, and Weiss are examples). The system proposed by Dargie et al. (1982) (MAPS 1) will be briefly described here and the method proposed by Esawi and Ashby in the next section. Dargie's system proposes a part classification code similar to that used in group technology. The first five digits of the MAPS 1 code are related to the elimination of unsuitable manufacturing processes. The first digit is related to the batch size. The second digit characterizes the bulk and depends on the major dimension and whether the part is long, flat, or compact. The third digit characterizes the shape, which is classified on the basis of being prismatic, axisymmetric, cup-shaped, nonaxisymmetric, and nonprismatic. The fourth digit is related to tolerance and the fifth digit is related to surface roughness.

The next three digits of the MAPS 1 code are related to the elimination of unsuitable materials. The sixth digit is related to service temperature. The seventh digit is related to the acceptable corrosion rate. The eighth digit characterizes the type of environment to which the part is exposed. The system uses two types of databases for preliminary selection:

- The suitability matrices
- The compatibility matrix

The suitability matrices deal with the suitability of processes and materials for the part under consideration. Each of the code digits has a matrix. The columns of the matrix correspond to the value of the digit and the rows correspond to the processes and materials in the database. The elements of the matrix are either 0, indicating unsuitability, or 2 indicating suitability. The compatibility matrix expresses the compatibility of the different combinations of processes and materials. The columns of the matrix correspond to the materials, whereas the rows correspond to the processes. The elements of the matrix are either 0 for incompatible combinations, 1 for difficult or unusual combinations, or 2 for combinations used in usual practice.

Based on the part code, the program generates a list of candidate combinations of materials and processes to produce it. This list helps the designer to identify possible alternatives early in the design process and to design for ease of manufacture.

9.4.5 Esawi and Ashby's Method

Another quantitative method of initial screening is proposed by Esawi and Ashby. The method compares the approximate cost of resources of materials, energy, capital, time, and information needed to produce the component using different combinations of materials and manufacturing processes. The method can be used early in the design process and is capable of comparing combinations of materials and processes such as the cost of a polymer component made by injection molding with that of a competing design in aluminum made by die casting.

According to this method, the total cost of a component has three main elements—material cost, tooling cost, and overhead cost. The material cost is a function of the cost per unit weight of the material and the amount of the material needed. Since the cost of tooling (dies, molds, jigs, fixtures, etc.) is normally assigned to a given production run, the tooling cost per component varies as the reciprocal of the number of components produced in that run. The overhead per component varies as the reciprocal of the production rate. Application of this method in initial screening requires a database, such as Cambridge Engineering Selector (CES) 4, which lists material prices, attributes of different processes, production rates, tool life, and approximate cost of equipment and tooling. CES 4 software contains records for 112 shaping processes such as vapor deposition, casting, molding, metal forming, machining, and composite forming. The software output can be in the form of graphs giving the variation of cost with the batch size for competing process/material combinations. Another type of output is relative cost per unit when a given component is made by different processing routes.

9.5 COMPARING AND RANKING ALTERNATIVE SOLUTIONS

After narrowing down the field of possible materials using one or more of the quantitative initial screening methods described in Section 9.4, quantitative methods can then also be used to further narrow the field of possible materials and matching manufacturing processes to a few promising candidates, which have good combinations of soft requirements. The following is a description of some such methods. It should be emphasized at this stage that none of the proposed quantitative methods is meant to replace the judgment and experience of the engineer. The methods are only meant to help the engineer in ensuring that none of the viable solutions are neglected and in making sounder choices and trade-offs for a given application.

9.5.1 Weighted Property Method

In the weighted property method, each material requirement, or property, is assigned a certain weight, depending on its importance to the performance of the part in service. A weighted property value is obtained by multiplying the numerical value of the property by the weighting factor (α). The individual weighted property values of each material are then summed to give a comparative material performance index (γ). Materials with the higher performance index (γ) are considered more suitable for the application.

9.5.2 Digital Logic Method

In the cases where numerous material properties are specified and the relative importance of each property is not clear, determinations of the weighting factors, α, can be largely intuitive, which reduces the reliability of selection. The digital logic approach can be used as a systematic tool to determine α. In this procedure, evaluations are arranged such that only two properties are considered at a time. Every possible combination of properties or goals is compared, and no shades of choice are required, only a yes or no decision for each evaluation. To determine the relative importance of each property or goal, a table is constructed, the properties or goals are listed in the left-hand column, and comparisons are made in the columns to the right, as shown in Table 9.4.

In comparing two properties or goals, the more important goal is given numerical one (1) and the less important is given zero (0). The total number of possible decisions $N = n(n-1)/2$, where n is the number of properties or goals under consideration. A relative emphasis coefficient or weighting factor, α, for each goal is obtained by dividing the number of positive decisions for each goal (m) into the total number of possible decisions (N). In this case $\Sigma\alpha = 1$.

To increase the accuracy of decisions based on the digital logic approach, the yes–no evaluations can be modified by allocating gradation marks ranging from 1 (no difference in importance) to 3 (large difference in importance). In this case, the total gradation marks for each selection criterion are reached by adding up the individual gradation marks. The weighting factors are then found by dividing these total gradation marks by their grand total. A simple interactive computer program can be written to help in determining the weighting factors. A computer program

TABLE 9.4
Determination of the Relative Importance of Goals Using the Digital Logic Method

Goals	Number of Positive Decisions, $N=n(n-1)/2$										Positive Decisions	Relative Emphasis Coefficient, α
		2	3	4	5	6	7	8	9	10		
1	1	1	0	1							3	0.3
2	0				1	0	1				2	0.2
3		0			0			1	0		1	0.1
4			1			1		0		0	2	0.2
5				0			0		1	1	2	0.2
	Total number of positive decisions										10	$\Sigma\alpha=1.0$

will also make it easier to perform a sensitivity analysis, whereby several runs of the process are performed to test the sensitivity of the final ranking to changes in some of the decisions.

9.5.3 Performance Index

In its simple form, the weighted property method has the drawback of having to combine unlike units, which could yield irrational results. This is particularly true when different mechanical, physical, and chemical properties with widely different numerical values are combined. The property with higher numerical value will have more influence than is warranted by its weighting factor. This drawback is overcome by introducing scaling factors. Each property is so scaled that its highest numerical value does not exceed 100. When evaluating a list of candidate materials, one property is considered at a time. The best value in the list is rated as 100 and the others are scaled proportionally. Introducing a scaling factor facilitates the conversion of normal material property values to scaled dimensionless values. For a given property, the scaled value, B, for a given candidate material is equal to

$$B=\text{Scaled property}=\frac{\text{Numerical value of property}\times 100}{\text{Maximum value in the list}} \tag{9.3}$$

For properties such as cost, corrosion or wear loss, and weight gain in oxidation, a lower value is more desirable. In such cases, the lowest value is rated as 100 and B is calculated as

$$B=\frac{\text{Minimum value in the list}\times 100}{\text{Numerical value of property}} \tag{9.4}$$

For material properties that can be represented by numerical values, application of the procedure discussed is simple. However, with properties such as corrosion and wear resistance, machinability and weldability, and esthetic quality, numerical values are rarely given and materials are usually rated as very good, good, fair, poor, etc. In such cases, the rating can be converted to numerical values using a relative scale. For example, corrosion resistance ratings of excellent, very good, good, fair, and poor can be given numerical values of 5, 4, 3, 2, and 1, respectively. After scaling the different properties, the material performance index (γ) can be calculated as

$$\text{Material performance index, } \gamma = \sum_{i=1}^{n} B_i \alpha_i \tag{9.5}$$

where i is summed over all the n relevant properties.

Cost (stock material, processing, finishing, etc.) can be considered as one of the properties and then given the appropriate weighting factor. However, if there are a large number of properties to consider, the importance of cost may be emphasized by considering it separately as a modifier to the material performance index (γ). In the cases where the material is used for space filling, cost can be introduced on per unit volume basis. A figure of merit (M) for the material can then be defined as

$$M = \frac{\gamma}{C\rho} \tag{9.6}$$

where

C is the total cost of the material per unit weight (stock, processing, finishing, etc.)
ρ is the density of the material

When an important function of the material is to bear stresses, it may be more appropriate to use the cost of unit strength instead of the cost per unit volume. This is because higher strength will allow less material to be used to bear the load and the cost of unit strength may be a better representative of the amount of material actually used in making the part. In this case, Equation 9.6 is rewritten as

$$M = \frac{\gamma}{C'} \tag{9.7}$$

where C' is determined from Table 9.2 depending on the type of loading.

This argument may also hold in other cases where the material performs an important function such as electrical conductivity or thermal insulation. In these cases, the amount of the material and consequently the cost are directly affected by the value of the property.

When a large number of materials with a large number of specified properties are being evaluated for selection, the weighted property method can involve a large number of tedious and time-consuming calculations. In such cases, the use of a computer would facilitate the selection process. The steps involved in the weighted property method can be written in the form of a simple computer program to select materials from a bank. The type of material information needed for computer-assisted ranking of alternative solution is normally structured in the form of databases of properties such as those published by ASM, as will be described in Section 9.8. An interactive program can also include the digital logic method to help in determining the weighting factors.

Case study 9.3 illustrates the use of the weighted property method.

Case Study 9.3: Selecting the Optimum Material for a Cryogenic Storage Tank

Problem

It is required to select the optimum material for a large cryogenic storage tank to be used in transporting liquid nitrogen gas.

Analysis

An important rigid requirement for materials used in cryogenic applications is that the material must not suffer ductile–brittle transition at the operating temperature, which is about −196°C (−320.8°F) in this case. This rules out all carbon and low-alloy steels and other bcc materials, which suffer ductile–brittle transformation at low temperatures, as discussed in Section 4.5. Fcc materials do not usually become unduly brittle at low temperatures. Many plastics are also excluded on this basis.

Processability is another rigid requirement. As welding is normally used in manufacturing metal tanks, good weldability becomes a rigid requirement. Availability of materials in the required plate thickness and size is also another screening factor.

As a first step, the performance requirements of the storage tank should be translated into material requirements. In addition to having adequate toughness at the operating temperature, the material should be sufficiently strong and stiff. With a stronger material, thinner walls can be used, which means a lighter tank and lower cooldown losses. Thinner walls are also easier to weld. Lower specific gravity is also important as the tank is used in transportation. Lower specific heat reduces cooldown losses, lower thermal expansion coefficient reduces thermal stresses, and lower thermal conductivity reduces heat losses. The cost of material and processing will be used as a modifier to the material performance index, as given in Equation 9.7.

The digital logic method is used to determine the weighting factors. With seven properties to evaluate, the total number of decisions $= N(N-1)/2 = 7(6)/2 = 21$. The different decisions are given in Table 9.5.

The weighting factor can be calculated by dividing the number of positive decisions given to each property by the total number of decisions. The resulting weighting factors are given in Table 9.6.

Toughness is given the highest weight followed by density. The least important properties are Young's modulus, thermal conductivity, and specific heat; other properties are in between.

The properties of a sample of the candidate materials are listed in Table 9.7. The YS and Young's modulus correspond to room temperature that is conservative as they generally increase with decreasing temperature.

The next step in the weighted property method is to scale the properties given in Table 9.7. For the present application, materials with higher mechanical properties are more desirable, and highest values in toughness, YS, and Young's modulus are considered as 100. Other values in Table 9.7 are rated in proportion. However, lower values of specific gravity, thermal expansion coefficient, thermal conductivity, and

TABLE 9.5
Application of Digital Method to Cryogenic Tank Problem

	Decision Numbers																				
Property	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Toughness	1	1	1	1	1	1															
YS	0						1	0	0	1	1										
Young's modulus		0					0					0	0	0	1						
Density			0					1				1				1	1	1			
Expansion				0					1				1			0			1	1	
Conductivity					0					0				1			0		0		0
Specific heat						0					0				0			0		0	1

TABLE 9.6
Weighting Factors for Cryogenic Tank

Property	Positive Decisions	Weighting Factor
Toughness	6	0.28
YS	3	0.14
Young's modulus	1	0.05
Density	5	0.24
Expansion	4	0.19
Conductivity	1	0.05
Specific heat	1	0.05
Total	21	1.00

TABLE 9.7
Properties of Candidate Materials for Cryogenic Tank

	1	2	3	4	5	6	7
Material	Toughness Index[a]	YS (MPa)	Young's Modulus (GPa)	Specific Gravity	Thermal Expansion[b]	Thermal Conductivity[c]	Specific Heat[d]
Al 2014-T6	75.5	420	74.2	2.8	21.4	0.37	0.16
Al 5052-O	95	91	70	2.68	22.1	0.33	0.16
SS 301-FH	770	1365	189	7.9	16.9	0.04	0.08
SS 310–3/4H	187	1120	210	7.9	14.4	0.03	0.08
Ti–6Al–4V	179	875	112	4.43	9.4	0.016	0.09
Inconel 718	239	1190	217	8.51	11.5	0.31	0.07
70Cu–30Zn	273	200	112	8.53	19.9	0.29	0.06

Note: SS, stainless steel.

[a] Toughness index (TI) is based on UTS, YS, and ductility e, at −196°C (−321.8°F) $TI = (UTS + YS)e/2$.

[b] Thermal expansion coefficient is given in 10^{-6}/°C. The values are averaged between RT and −196°C.

[c] Thermal conductivity is given in cal/cm^2/cm/°C/s.

[d] Specific heat is given in cal/g/°C. The values are averaged between RT and −196°C.

specific heat are more desirable for this application. Accordingly, the lowest values in the table were considered as 100 and other values rated in proportion according to Equation 9.4. The scaled values are given in Table 9.8. The table also gives the performance index that is calculated according to Equation 9.5.

The performance index shows the technical capability of the material without regard to the cost. In this case, stainless steels are the optimum materials. It now remains to consider the cost aspects by calculating the figure of merit (M). In the present case, it is more appropriate to use Equation 9.7 as the primary function of the tank material is to bear stresses. The formula for a thin-walled pressure vessel is given in Table 9.2 as

TABLE 9.8
Scaled Values of Properties and Performance Index

	Scaled Properties							Performance
Material	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Index (γ)**
Al 2014–T6	10	30	34	96	44	4.3	38	42.2
Al 5052-O	12	6	32	100	43	4.8	38	40.1
SS 301-FH	100	100	87	34	56	40	75	70.9
SS 310–3/4H	24	82	97	34	65	53	75	50.0
Ti–6Al–4V	23	64	52	60	100	100	67	59.8
Inconel 718	31	87	100	30	82	5.2	86	53.3
70Cu–30Zn	35	15	52	30	47	5.5	100	35.9

Note: SS, stainless steel.

$$\text{Cost of unit strength} = \frac{C\rho}{S}$$

where S is the YS.

The values of the relative cost, cost of unit strength, performance index, figure of merit, M, and the ranking of the different materials are shown in Table 9.9. The results show that full hard stainless steel grade 301 is the optimum material followed by Al 2014-T6.

In the procedure discussed, the strength and density were considered twice: once in calculating the performance index (γ) and another time in calculating the

TABLE 9.9
Cost, Figure of Merit, and Ranking of Candidate Materials

Material	Relative Cost[a]	Cost of Unit Strength × 100	Performance Index	Figure of Merit	Rank
Al 2014-T6	1	0.67	42.2	62.99	2
Al 5052-O	1.05	3.09	40.1	12.98	6
SS 301-FH	1.4	0.81	70.9	87.53	1
SS 310–3/4H	1.5	1.06	50.0	47.17	3
Ti–6Al–4V	6.3	3.20	59.8	18.69	4
Inconel 718	5.0	3.58	53.3	14.89	5
70Cu–30Zn	2.1	8.96	35.9	4.01	7

Note: SS, stainless steel.

[a] The cost includes stock materials and processing cost. The relative cost is obtained by considering the cost of Al 2014 as unity and relating the cost of other materials to it.

cost of unit strength. This procedure may have overemphasized their effect on the final selection. This could be justifiable in this case as higher strength and lower density are advantageous from the technical and economic points of view.

Case Study 9.4: Materials Selection for Gas Turbine Blades

Introduction

The relatively high fuel efficiency and lower initial installed cost of advanced combustion turbines have made them in increasingly important source of power generation. Relatively high operating temperatures in the various stages of the turbine are among the main reasons for their superior thermal efficiency. Of all the turbine parts, the blades are subjected to the most severe conditions, and the development of better materials for their manufacture has always been a challenge to the materials engineer. As shown in Case studies 3.7 and 4.5, a turbine blade material must satisfy several criteria in order to perform well in the severe environment in which it operates. These include creep resistance, thermal stability of properties, high toughness to resist thermal shock, resistance to environmental attack at high temperatures, and resistance to erosion and wear. Although good resistance to creep deformation and rupture has often been the prime requirement, achievement of creep strength alone does not present the major problem. The greatest difficulty is avoidance of undue deterioration in other properties of the material as creep resistance is improved. Toughness, oxidation and hot corrosion resistance, as well as processability usually suffer when alloying elements are added to improve creep strength. In addition to traditional turbine blade materials, some new materials are now being developed, as discussed in Case study 4.5. This case study compares the traditional and new materials for use in two types of applications, aerospace and auxiliary power gas turbines.

Performance Requirements

As discussed in Section 9.3, the material performance requirements can be divided into the following categories:

Functional requirements and reliability: Resistance to creep and rupture, thermal stability, and density can represent the functional requirements, and toughness can be used to represent reliability. Table 9.10 gives the properties of some traditional and new turbine blade materials. Thermal stability is graded on a five-point scale of excellent (5), very good (4), good (3), fair (2), and poor (1).

Resistance to service conditions: Oxidation, corrosion, and abrasion. This factor will not be included in the present analysis as appropriate coatings can now be used to protect most materials.

Processability: This material property depends on the intended means of shaping the blade. Hot working, casting, and powder metallurgy are the main processing methods. Wrought alloys should exhibit sufficient

TABLE 9.10
Properties of Traditional and New Materials for Gas Turbine Blades

Material	Maximum Temperature (°C)	Thermal Stability	Toughness MPa (m)$^{1/2}$	Density (g/cm^3)	Installed Cost
Traditional blade materials					
IN 713	970	3	100	7.91	5
IN 100	1000	3	100	7.75	5
MAR-M-200 (DS)	920	3	120	8.53	4
M 247 (DS)	1035	3.5	100	8.95	4
PWA 1484 (SX)	1095	3.5	100	8.5	4
CMSX10 (SX)	1125	4	100	9.05	4
New materials					
Intermetallic TiAl	750	3	40	3.9	3
Monolithic ceramic SiC	1400	5	3.5	3.2	3
Monolithic ceramic Si_3N_4	1400	5	5	3.1	3
Monolithic ceramic Al_2O_3	1460	5	4.2	3.98	3
MMC (Ti–SiC)	800	1	30	2.82	1
MMC (Ni–SiC)	1150	3.5	30	3.5	1
CMC (Si_3N_4–30%SiC)	1500	4	10	3.2	2
CMC (Al_2O_3–30%SiC)	1640	3.5	9	3.75	2
SiC/SiC	1400	4	22.7	3.2	2

ductility at the working temperature, while cast alloys should be free from porosity and segregation. The presence of complex internal cooling channels represents an additional challenge to the production engineer. To simplify the present analysis, processability will be included as part of the cost.

Cost: The major installed cost elements of a turbine blade include material, processing, coating, and inspection. A more accurate comparison of the cost would take into account the length of service and repair costs, which is the life cycle cost. In this analysis, materials are compared on the basis of an estimate of the installed cost and a five-point scale is used for comparison, with the least expensive being 5 and the most expensive being 1, as shown in Table 9.10.

Selection among Blade Materials

The weighted property method is used to compare materials based on the performance requirements. The digital logic method is used to estimate the relative importance (weighting factors) of the different material properties for two applications:

- Turbine blades for engines used in aerospace applications with the main requirements of high maximum power, reliability, and lightweight. Relatively shorter lifetime and higher cost can be tolerated.

TABLE 9.11
Weighting Factors for Two Blades in Aerospace and Auxiliary Power Engines

Property	Maximum Temperature	Thermal Stability	Toughness	Density	Cost
Relative importance in aerospace engines	0.35	0.10	0.10	0.35	0.10
Relative importance in engines for auxiliary power units	0.10	0.30	0.30	0.05	0.30

- Turbine blades for gas engines for auxiliary power units with the main requirements of long life, tolerance to changeable loading, and reliability. Engine weight is not an issue, but low cost is important.

Table 9.11 gives the weighting factors that were obtained using the digital logic method.

Following the procedure outlined in Section 9.5.1, the properties in Table 9.10 are normalized such that the highest values of maximum temperature, thermal stability, and toughness are given 100 and other values are scaled relative to it as in Equation 9.3. In the case of density and cost, the lowest value is given 100 and other values are scaled relative to it as in Equation 9.4. The performance index of the different materials is calculated using Equation 9.5, and the results are shown in Table 9.12 for the two applications.

Conclusion

The results in Table 9.12 show that monolithic ceramic SiC and monolithic ceramic Si3N4 receive the best ranking for aerospace applications, with CMC (Si3N4–30%SiC) and SiC/SiC as close second. On the other hand, CMSX10 single crystal is the highest-ranking material for auxiliary power engine applications, with IN 713 and IN 100 as close second.

9.5.4 Limits on Property Method

In the limits on property method, the performance requirements are divided into three categories:

- Lower-limit properties
- Upper-limit properties
- Target value properties

For example, if it is desired to have a strong light material, a lower limit on the strength and an upper limit on the density are specified. When compatibility between materials is important, a target value for the thermal expansion coefficient or for the

TABLE 9.12
Ranking of Materials for Use in Aerospace and Auxiliary Power Engines

Material	Engines for Aerospace Applications		Engines for Auxiliary Power Units	
	Performance Index	Rank	Performance Index	Rank
Traditional blade materials				
IN 713	57.5		81.5	2
IN 100	57.5		81.5	2
MAR-M-200 (DS)	55		79.5	3
M 247 (DS)	58.5		79	3
PWA 1484 (SX)	58.5		79	3
CMSX10 (SX)	60.5		83.5	1
New materials				
Intermetallic TiAl	56.5		55.5	
Monolithic ceramic SiC	78.3	1	62.5	
Monolithic ceramic Si_3N_4	78.4	1	62.5	
Monolithic ceramic Al_2O_3	73.3	3	62	
MMC (Ti–SiC)	59.5		29.5	
MMC (Ni–SiC)	63.5		45.5	
CMC (Si_3N_4–30% SiC)	77.0	2	53	
CMC (Al_2O_3–30% SiC)	73.0	3	50	
SiC/SiC	76.0	2	55.5	

position in the galvanic series may be specified to control thermal stresses or galvanic corrosion, respectively. Whether a given property is specified as an upper or lower limit may depend upon the application. For example, when selecting materials for an electrical cable, the electrical conductivity will be specified as a lower-limit property for the conducting core and as an upper-limit property for the insulation outer layer.

The limits on property method is usually suitable for optimizing material and process selection when the number of possible alternatives is relatively large. This is because the limits that are specified for the different properties can be used for eliminating unsuitable materials from a data bank. The remaining materials are those whose properties are above the lower limits, below the upper limits, and within the limits of target values of the respective specified requirements. After the screening stage, the limits on property method can then be used to optimize the selection from among the remaining materials.

As in the case of weighted property method, each of the requirements or properties is assigned a weighting factor, α, which can be determined using the digital logic method, as discussed earlier. A merit parameter, m, is then calculated for each material according to the following relationship:

$$m = \left(\sum_{i=1}^{n_\mathrm{l}} \alpha_i \frac{Y_i}{X_i}\right)_\mathrm{l} + \left(\sum_{j=1}^{n_\mathrm{u}} \alpha_j \frac{X_j}{Y_j}\right)_\mathrm{u} + \left(\sum_{k=1}^{n_\mathrm{t}} \alpha_k \left|\frac{X_k}{Y_k} - 1\right|\right)_\mathrm{t} \tag{9.8}$$

where
l, u, and t are the lower-limit, upper-limit, and target value properties, respectively
n_l, n_u, and n_t are the numbers of lower-limit, upper-limit, and target value properties, respectively
α_i, α_j, and α_k are the weighting factors for the lower-limit, upper-limit, and target value properties, respectively
X_i, X_j, and X_k are the candidate material lower-limit, upper-limit, and target value properties, respectively
Y_i, Y_j, and Y_k are the specified lower limits, upper limits, and target values, respectively

According to Equation 9.8, the lower the value of the merit parameter, m, the better the material.

As in the weighted property method, the cost can be considered in two ways:

1. Cost is treated as an upper-limit property and is given the appropriate weight. When the number of properties under consideration is large, this procedure may obscure its importance.
2. Cost is included as a modifier to the merit parameter as follows:

$$m' = \frac{\mathrm{CX}}{\mathrm{CY}} m \tag{9.9}$$

where
CY and CX are the specified cost upper limit and the candidate material cost, respectively
m is the merit parameter calculated without taking the cost into account

In this case, the material with the lowest cost-modified merit parameter, m', is the optimum.

Case study 9.5 illustrates the use of the limits on property method in selection.

Case Study 9.5: Selecting an Insulating Material for a Flexible Electrical Conductor

Problem

Consider the case of selecting an insulating material for a flexible electrical conductor for a computer system. Space saving and adaptability to special configurations are important. Service temperature will not exceed 75°C (167°F). Cost is an important consideration because large quantities of these cables will be used in installing the system.

Analysis

Rigid requirements in this case are flexibility, or ductility, of the insulating material and operating temperature. The requirement for ductility eliminates all ceramic insulating materials, and the operating temperature eliminates some plastics such as LDPE.

The next step is to analyze the electrical and physical design requirements. They are as follows:

1. Dielectric strength, which is related to the breakdown voltage, is a lower-limit property in this case. Owing to space limitations, the dielectric strength should be more than 10,000 V/mm.
2. Insulating resistance depends on both the resistivity of the material and the geometry of the insulator; it is the lower-limit property. The minimum acceptable value is 10^{14} Ω/cm.
3. Dissipation factor affects the power loss in the material due to the alternating current and is an upper-limit property. The maximum acceptable value is 0.0015 at 60 Hz.
4. Dielectric constant is a measure of the electrostatic energy stored in the material and affects the power loss. This property is an upper-limit requirement in this case, although it is taken as a lower-limit property in applications such as capacitors. The maximum allowable value is 3.5 at 60 Hz.
5. Thermal expansion coefficient is a target value to ensure compatibility between the conductor and insulator at different temperatures. As the conductor is made of aluminum, the target value for the expansion coefficient is 2.3×10^{-5}/°C.
6. Specific gravity is an upper-limit property to ensure lightweight. This property will not be considered here because weight is not critical.

Table 9.13 gives the properties of some candidate materials, which do not violate the rigid requirements of ductility and operating temperature and also satisfy the upper or lower limits of design.

The first step is to determine the weighting factors for the different properties. Because the number of properties is relatively small, the cost will be included as one of the properties. The digital logic method is used as shown in Table 9.14. The number of properties under consideration is 6 and the total number of decisions $= 6(6-1)/2 = 15$.

The next step in the selection process is to calculate the merit parameter *m*, using Equation 9.8 for the different materials. In the present case, the dielectric strength and volume resistance are lower-limit properties; dissipation factor, dielectric constant, and cost are upper-limit properties; and thermal expansion coefficient is a target value. In calculating the relative merit of the different materials, the log value of the volume resistivity was used. As no upper limit is given to the cost, the cost of the most expensive material in Table 9.13 is taken as the upper limit. The relative merit parameter, *m*, and the rank of the different materials are given in Table 9.15.

TABLE 9.13
Properties of Some Candidate-Insulating Materials

Material	Dielectric Strength (V/mm)	Volume Resistance (Ω/cm)	Dissipation Factor (60 Hz)	Dielectric Constant (60 Hz)	Thermal Expansion (10^{-5}/°C)	Relative Cost[a]
PTFE	14,820	10^{18}	0.0002	2.1	9.5	4.5
CTFE	21,450	10^{18}	0.0012	2.7	14.4	9.0
ETFE	78,000	10^{16}	0.0006	2.6	9.0	8.5
Polyphenylene oxide	20,475	10^{17}	0.0006	2.6	6.5	2.6
Polysulfone	16,575	10^{14}	0.0010	3.1	5.6	3.5
Polypropylene	21,450	10^{16}	0.0005	2.2	8.6	1.0

Note: CTFE, Chlorotrifluoroethylene; PTFE, Polytetrafluoroethylene; ETFE, Ethylene tetrafluoroethylene.

[a] Cost includes material and processing cost. Relative cost is based on the cost of material and processing of polypropylene.

TABLE 9.14
Weighting Factors for an Electrical Insulator

	Decision Numbers																
Property	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total	Weighting Factor
Dielectric strength	0	1	1	0	1											3	0.20
Volume resistance	1					1	1	1	1							5	0.33
Dissipation factor		0				0				1	1	0				2	0.13
Dielectric constant			0				0			0			1	0		1	0.07
Thermal expansion				1				0			0		0		0	1	0.07
Cost					0				0			1		1	1	3	0.20
Total																15	1.00

Conclusion

The results show that polypropylene and polyphenylene oxides have equal merit parameters. The final selection between the two materials may depend on availability and possibility of coloring.

TABLE 9.15
Evaluation of Insulating Materials

Material	Merit Parameter, *m*	Rank
PTFE	0.78	3
CTFE	1.07	6
ETFE	0.81	5
Polyphenylene oxide	0.66	1
Polysulfone	0.78	3
Polypropylene	0.66	1

Note: CTFE, Chlorotrifluoroethylene; PTFE, Polytetrafluoroethylene; ETFE, Ethylene tetrafluoroethylene.

9.5.5 Analytic Hierarchy Process

Because arriving at an optimum material involves decision making in the presence of multiple and often conflicting criteria, the models of multiple-criteria decision making can be adopted for solving materials selection problems. Such models require complex hierarchical comparisons among candidates, which make it necessary for the decision maker to adopt one of several decision support tools and methodologies such as statistical techniques, outranking techniques, and analytic hierarchy process (AHP). The AHP was developed by Thomas Saaty in 1980 and provides an effective tool to solving multiple-criteria decision-making problems where there are a limited number of alternatives but each has a number of attributes, which make it suitable for adoption to materials selection problems. AHP is particularly suited for the cases where some or all of the selection criteria (decision elements) are difficult to quantify.

AHP starts by building a hierarchy consisting of a goal and subordinate elements of the problem. The alternatives among which the choice is to be made are placed at the lowest level in the hierarchy. Starting from the top of the hierarchy, pairwise comparisons are then made among all the elements at a particular level in the hierarchy. This is achieved by comparing each possible pair of the performance requirements on a scale of 9 to 1 as follows:

9 is given to one requirement when it is judged to be extremely more important to the performance than the other.
7 when it is very strongly more important.
5 when it is strongly more important.
3 when it is moderately more important.
1 when it is equally important or when comparing a requirement to itself.

Intermediate values can be used for intermediate preferences.

Case study 9.6 gives a simple example to illustrate how the processes involved in AHP can be used in materials selection. A more realistic example of using

AHP in selection is given in a case study in Chapter 11—selection of materials for tennis rackets.

Case Study 9.6: Using AHP to Select the Optimum Material for a Roof Truss

Problem

It is required to select the optimum material for a roof truss of a small warehouse. The candidate materials are AISI 1020, AISI 4130, AA 6061, and a composite material (epoxy–70% glass fabric). The performance requirements for the truss material are assumed to be high strength (σ), high elastic modulus (E), low density (ρ), and low cost (C). The properties of the candidate materials are given in Table 9.16.

The hierarchy diagram for this example is shown in Figure 9.3.

Table 9.17 illustrates the pairwise comparison for the material requirements of truss. The table is constructed by comparing each of the requirements to all others noting that when the importance of E relative to σ is 5, then the importance of σ relative to E is 1/5.

The next step is to construct the table of weights (Table 9.18) by normalizing the pairwise comparisons in the table of preferences (Table 9.17) by dividing the number in a given cell by the sum of the numbers in its column, for example, the number in the cell $\sigma-\sigma$ is $[1/(1+5+3+2)=0.091]$. With no inconsistency in

TABLE 9.16
Properties of the Candidate Materials for the Truss

	YS (σ), MPa	Elastic Modulus (E), GPa	Density (ρ), g/cc	Cost Category (C)[a]
AISI 1020	280	210	7.8	5
AISI 4130	1520	212	7.8	3
AA 6061	275	70	2.7	4
Epoxy–70% glass fabric	1270	28	2.1	2

[a] 5, Very inexpensive; 4, inexpensive; 3, moderate price; 2, expensive; 1, very expensive.

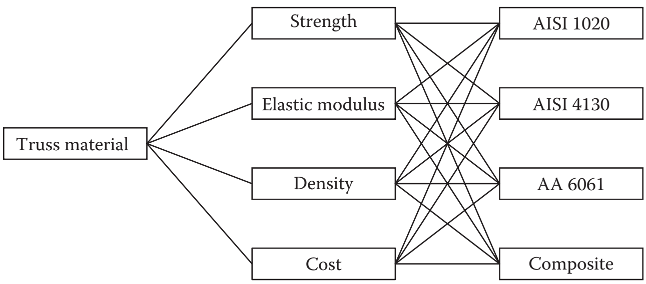


FIGURE 9.3 A simple AHP diagram for selecting a material for a truss.

TABLE 9.17
Pairwise Comparison of Material Requirements

	σ	E	ρ	C
σ	1	1/5	1/3	1/2
E	5	1	2	4
ρ	3	1/2	1	3
C	2	1/4	1/3	1

TABLE 9.18
Calculation of Weights

	σ	E	ρ	C	Average/ Weight	Consistency Measure
σ	0.091	0.102	0.091	0.059	0.086	4.02
E	0.455	0.513	0.545	0.471	0.496	4.07
ρ	0.273	0.256	0.273	0.353	0.289	4.09
C	0.182	0.128	0.091	0.118	0.129	4.04
Total/average	1.001	0.999	1.000	1.001	1.000	4.055

decision making, the numbers in a given row should be equal and represent the weight of the property. The sum of each column should also be 1.00. Averaging the values of each row should result in a better estimate of the weight of the property in this row, and the sum of all the weights should be 1.00.

One of the advantages of AHP is that it allows subjective decisions to be formalized and gives the degree of consistency of such decisions. In the present case, the consistency of the pairwise comparison can be assured before adopting the estimated weights. Consistency measures for the weights allocated to the different properties is calculated as

Consistency, measure for

$$\sigma = \frac{(0.086\times 1+0.496\times 1/5+0.289\times 1/3+0.129\times 1/2)}{0.086} = 4.02$$

Consistency measure for

$$E = \frac{(0.086\times 5+0.496\times 1+0.289\times 2+0.129\times 4)}{0.496} = 4.07$$

Consistency measure for

$$\rho = \frac{(0.086\times 3+0.496\times 1/2+0.289\times 1+0.129\times 3)}{0.289} = 4.09$$

Consistency measure for

$$C = \frac{(0.086\times 2 + 0.496\times 1/4 + 0.289\times 1/3 + 0.129\times 1)}{0.129} = 4.04$$

If the decision-making process is perfectly consistent, each consistency measure will equal the number of properties, which is 4 in this case. The foregoing results show that there is some inconsistency. Whether this inconsistency is acceptable depends on the value of the consistency index (CI) and consistency ratio (CR), which are calculated as follows:

$$\text{CI} = \frac{\lambda - n}{n-1} \quad \text{and} \quad \text{CR} = \frac{\text{CI}}{\text{RI}} \tag{9.10}$$

where

λ is the average consistency measure for all properties, equal to 4.055 in this case

n is the number of properties, equal to 4 in this case

RI is the random index, which depends on n as shown in Table 9.19

RI values in Table 9.19 give the average values of CI if the preference entries in the table of preferences were chosen at random. If the decision-making process is perfectly consistent, $\lambda = n$ and $\text{CR} = 0$. Normally, $\text{CR} < 0.10$ is considered acceptable. With $\text{CR} > 0.10$, the AHP may not give meaningful results.

For the present case,

$$\text{CI} = \frac{4.055-4}{4-1} = 0.018 \quad \text{and} \quad \text{CR} = \frac{0.018}{0.9} = 0.02$$

These results show that the consistency of the pairwise comparison in Table 9.17 is acceptable and that the weights allocated to the different properties are, therefore, consistent.

Comparing Alternatives

The final step in the AHP is to compare each of the alternative materials with respect to each of the properties. In this case, a matrix similar to Table 9.17 is

TABLE 9.19
Random Index as a Function of the Number of Properties (*n*)

n	2	3	4	5	6	7	8	9	10
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

constructed in which the materials are compared pairwise relative to each of the properties to determine their relative priorities. The total score for a given material is obtained by summing up its priorities with respect to the properties, taking the weight of each of the properties into account. The material with highest total score is selected.

Conclusion

As this simple example shows, the decision-making process using AHP can involve a large number of tedious calculations, especially in the cases where the number of properties/alternatives is large. Fortunately, however, such calculations can be performed on a spreadsheet (e.g., as described by Ragsdale), or using one of several of the free web-based (e.g., easymind) or commercial software products (e.g., DecisionPlus by InfoHarvest or Hiview by Catalyze).

A student version of DecisionPlus software, which is available at no cost from InfoHarvest, is used to solve this case study. The properties given in Table 9.16 and the weights that were calculated in Table 9.18 were used. The results are given in Table 9.20 and show that AISI 4130 achieved the highest score; its main assets are high strength and elastic modulus. A close second is AISI 1020; its main assets are high elastic modulus and low cost.

9.6 SELECTING THE OPTIMUM SOLUTION

Having ranked alternative materials using one of the methods in Section 9.5, the final step is selection of the optimum material. Candidates that have the most promising performance indices can now be used to develop a detail design each. Each detail design will exploit the points of strength of the material, avoid the weak points, and reflect the requirements of the manufacturing processes needed for the material. The type of material information needed for detail design is different from that needed for initial screening and ranking. What is needed at this stage is detailed high-quality information about the highest-ranking candidates. As shown in Section 9.8, such information is usually unstructured and can be obtained from handbooks,

TABLE 9.20
Results of AHP for the Truss Materials

			Major Contributions to the Score			
Material	**Rank**	**Score**	**σ (%)**	***E* (%)**	**ρ (%)**	***C* (%)**
AISI 1020	2	0.286		77		23
AISI 4130	1	0.293	16	76		8
AA 6061	3	0.231		22	59	19
Composite	4	0.191	20		80	

publications of trade organizations, and technical reports in the form of text, pdf files, tables, graphs, photographs, etc. There are instances where some of the desired may not be available or may be available for slightly different test conditions. In such cases educated judgment is required.

After completing the different designs, solutions are then compared, taking the cost elements into consideration to arrive at the optimum design–material–process combination, as illustrated in Case study 9.7.

Case Study 9.7: Reaching a Final Decision on the Optimum Material for a Sailing-Boat Mast Component

Problem

Select the least expensive component that satisfies the requirements for a simple structural component for a sailing-boat mast in the form of a hollow cylinder of length 1000 mm, which is subjected to compressive axial forces of 153 kN. Because of space and weight limitations, the outer diameter of the component should not exceed 100 mm, the inner diameter should not be less than 84 mm, and the mass should not exceed 3 kg. The component will be subjected to mechanical impact and spray of water. Assembly to other components requires the presence of relatively small holes.

Material Performance Requirements

Analysis in this case study is based on the paper by Farag and El-Magd (1992). Possible modes of failure and the corresponding material properties that are needed to resist failure for the present component include the following:

- Catastrophic fracture due to impact loading, especially near assembly holes, is resisted by high fracture toughness of the material. This is a rigid material requirement and will be used for initial screening of materials.
- Plastic yielding is resisted by high YS. This is a soft material requirement but a lower limit will be determined by the limitation on the outer diameter.
- Local and global buckling is resisted by high elastic modulus. This is a soft material requirement but a lower limit will be determined by the limitation on the outer diameter.
- Internal fiber buckling for fiber-reinforced materials is resisted by high modulus of elasticity of the matrix and high volume fraction of fibers in the loading direction. This is a soft material requirement but a lower limit will be determined by the limitation on the outer diameter.
- Corrosion that can be resisted either by selecting materials with inherently good corrosion resistance or by protective coating.
- Reliability of the component in service. A factor of safety of 1.5 is taken for the axial loading, that is, the working axial force will be taken as 230 kN to improve reliability.

In addition to the mentioned requirements, the limitations set on dimensions and weight should be observed.

Initial Screening of Materials

The requirement for fracture toughness of the material is used to eliminate ceramic materials. Because of the limitations set on the outer and inner diameters, the maximum possible cross section of the component is about 2300 mm^2. To avoid yielding under the axial working load, the YS of the material should be more than 100 MPa, which excludes engineering polymers, woods, and some of the lower strength engineering alloys (see Figure 9.2). Corrosion resistance is desirable but will not be considered as a factor for screening, since the possibility of protection for less corrosion materials exists, but will be considered as a soft requirement.

Comparing and Ranking Alternative Solutions

Table 9.21 shows a sample of materials that satisfy the conditions set in the initial screening stage. In a real-life situation the list in the table could be much longer, but the intent here is to illustrate the procedure. The YS, elastic modulus, specific gravity, corrosion resistance, and cost category are given for each of the materials. At this stage, it is sufficient to classify materials into very inexpensive, inexpensive, etc. Better estimate of the material and manufacturing cost will be needed in making the final decision in selection. Because the weight of the component is important in this application, specific strength and specific modulus would be better indicators of the suitability of the material (Table 9.22). The relative importance of the material properties is given in Table 9.23, and the performance indices of the different materials, as determined by the weighted property method, are given in Table 9.24. The seven candidate materials with high-performance indices ($\gamma > 45$) are selected for making actual component designs.

Selecting the Optimum Solution

As shown earlier, the possible modes of failure of a hollow cylinder include yielding, local buckling and global buckling, and internal fiber buckling. These four failure modes are used to develop the design formulas for the mast component. For more details on the design and optimization procedure or more details about Equations 9.11 through 9.14, please refer to the paper by Farag and El-Magd (1992).

Condition for yielding

$$\frac{F}{A} < \sigma_y \tag{9.11}$$

where

σ_y is the YS of the material
F is the external working axial force
A is the cross-sectional area

TABLE 9.21
Properties of Sample Candidate Materials

Material	YS (MPa)	Elastic Modulus (GPa)	Specific Gravity	Corrosion Resistance[a]	Cost Category[b]
AISI 1020 (UNS G10200)	280	210	7.8	1	5
AISI 1040 (UNS G10400)	400	210	7.8	1	5
ASTM-A242 type 1 (UNS K11510)	330	212	7.8	1	5
AISI 4130 (UNS G41300)	1520	212	7.8	4	3
AISI 316 (UNS S31600)	205	200	7.98	4	3
AISI 416 Ht. Treated (UNS S41600)	440	216	7.7	4	3
AISI 431 Ht. Treated (UNS S43100)	550	216	7.7	4	3
AA 6061 T6 (UNS A96061)	275	69.7	2.7	3	4
AA 2024 T6 (UNS A92024)	393	72.4	2.77	3	4
AA 2014 T6 (UNS A92014)	415	72.1	2.8	3	4
AA 7075 T6 (UNS A97075)	505	72.4	2.8	3	4
Ti–6Al–4V	939	124	4.5	5	1
Epoxy–70% glass fabric	1270	28	2.1	4	2
Epoxy–63% carbon fabric	670	107	1.61	4	1
Epoxy–62% aramid fabric	880	38	1.38	4	1

Source: Based on Farag, M.M. and El-Magd, E., *Mater. Des.*, 13, 323, 1992.
[a] 5, excellent; 4, very good; 3, good; 2, fair; 1, poor.
[b] 5, very inexpensive; 4, inexpensive; 3, moderate price; 2, expensive; 1, very expensive.

Condition for local buckling

$$\frac{F}{A} < 0.121\frac{ES}{D} \tag{9.12}$$

where
- D is the outer diameter of the cylinder
- S is the wall thickness of the cylinder
- E is the elastic modulus of the material

TABLE 9.22
Properties of Sample Candidate Materials

Material	Specific Strength (MPa)	Specific Modulus (GPa)	Corrosion Resistance[a]	Cost Category[b]
AISI 1020 (UNS G10200)	35.9	26.9	1	5
AISI 1040 (UNS G10400)	51.3	26.9	1	5
ASTM-A242 type 1 (UNS K11510)	42.3	27.2	1	5
AISI 4130 (UNS G41300)	194.9	27.2	4	3
AISI 316 (UNS S31600)	25.6	25.1	4	3
AISI 416 Ht. Treated (UNS S41600)	57.1	28.1	4	3
AISI 431 Ht. Treated (UNS S43100)	71.4	28.1	4	3
AA 6061 T6 (UNS A96061)	101.9	25.8	3	4
AA 2024 T6 (UNS A92024)	141.9	26.1	3	4
AA 2014 T6 (UNS A92014)	148.2	25.8	3	4
AA 7075 T6 (UNS A97075)	180.4	25.9	3	4
Ti–6Al–4V	208.7	27.6	5	1
Epoxy–70% glass fabric	604.8	28	4	2
Epoxy–63% carbon fabric	416.2	66.5	4	1
Epoxy–62% aramid fabric	637.7	27.5	4	1

[a] 5, excellent; 4, very good; 3, good; 2, fair, 1, poor.
[b] 5, very inexpensive; 4, inexpensive; 3, moderate price; 2, expensive; 1, very expensive.

TABLE 9.23
Weighting Factors

Property	Specific Strength (MPa)	Specific Modulus (GPa)	Corrosion Resistance	Relative Cost
Weighting factor (α)	0.3	0.3	0.15	0.25

Condition for global buckling

$$\sigma_y > \frac{F}{A}\left[1+\left(\frac{LDA}{1000\,I}\right)\sec\left\{\left(\frac{F}{EI}\right)^{1/2}\frac{L}{2}\right\}\right] \tag{9.13}$$

where
I is the second moment of area
L is the length of the component

TABLE 9.24
Calculation of the Performance Index

Material	Scaled-Specific Strength × 0.3	Scaled-Specific Modulus × 0.3	Scaled Corrosion Resistance × 0.15	Scaled Relative Cost × 0.25	Performance Index
AISI 1020 (UNS G10200)	1.7	12.3	3	25	42
AISI 1040 (UNS G10400)	2.4	12.3	3	25	42.7
ASTM-A242 type 1 (UNS K11510)	2	12.3	3	25	42.3
AISI 4130 (UNS G41300)	9.2	12.3	6	15	42.5
AISI 316 (UNS S31600)	1.2	11.3	12	15	39.5
AISI 416 Ht. Treated (UNS S41600)	2.7	12.7	12	15	42.4
AISI 431 Ht. Treated (UNS S43100)	3.4	12.7	12	15	43.1
AA 6061 T6 (UNS A96061)	4.8	11.6	9	20	45.4
AA 2024 T6 (UNS A92024)	6.7	11.8	9	20	47.5
AA 2014 T6 (UNS A92014)	7	11.6	9	20	47.6
AA 7075 T6 (UNS A97075)	8.5	11.7	9	20	49.2
Ti–6Al–4V	9.8	12.5	15	5	42.3
Epoxy–70% glass fabric	28.4	12.6	12	10	63
Epoxy–63% carbon fabric	19.6	30	12	5	66.6
Epoxy–62% aramid fabric	30	12.4	12	5	59.4

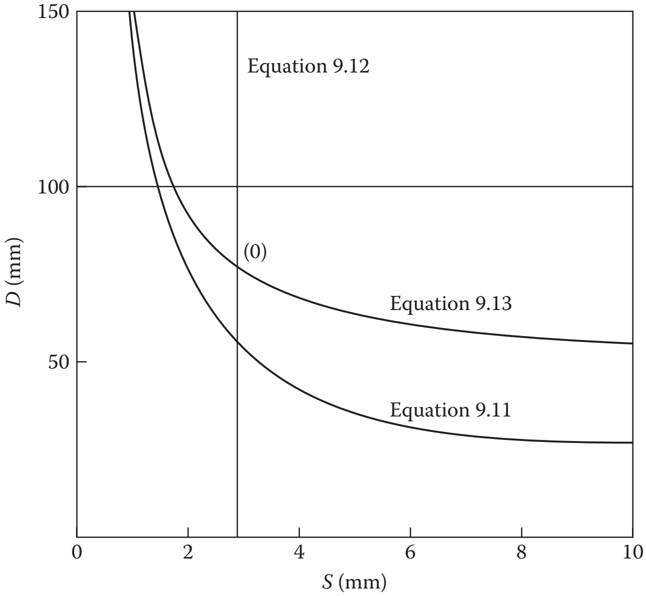


FIGURE 9.4 Design range as predicted by Equations 9.11 through 9.13 for AA 7075 aluminum alloy. (Based on Farag M.M. and El-Magd E., *Mater. Des.*, 13, 323, 1992.)

Condition for internal fiber buckling

$$\frac{F}{A} < \left[\frac{E_m}{4(1+\upsilon_m)(1-V_f^{1/2})} \right] \tag{9.14}$$

where

E_m is the elastic modulus of the matrix material
υ_m is the Poisson's ratio of the matrix material
V_f is the volume fraction of the fibers parallel to the loading direction

Figure 9.4 shows the optimum design range of component diameter and wall thickness as predicted by Equations 9.11 through 9.14 for AA 7075 aluminum alloy. Point (*O*) represents the optimum design. Similar figures were developed for the different candidate materials to determine the mast component's optimum design dimensions when made of the materials and the results are shown in Table 9.25. Although all the materials in Table 9.25 can be used to make safe components that comply with the space and weight limitations, AA2024 T6 is selected since it gives the least expensive solution.

9.7 COMPUTER ASSISTANCE IN MAKING FINAL SELECTION

9.7.1 CAD/CAM Systems

Integrating material property database with design algorithms and CAD/CAM programs has many benefits including homogenization and sharing of the different

TABLE 9.25
Designs Using Candidate Materials with Highest Performance Indices

Material	D_a (mm)	S (mm)	A (mm²)	Mass (kg)	Cost/kg ($)	Cost of Component ($)
AA 6061 T6 (UNS A96061)	100	3.4	1065.7	2.88	8	23.2
AA 2024 T6 (UNS A92024)	88.3	2.89	801.1	2.22	8.3	18.4
AA 2014 T6 (UNS A92014)	85.6	2.89	776.6	2.17	9	19.6
AA 7075 T6 (UNS A97075)	78.1	2.89	709.1	1.99	10.1	20
Epoxy–70% glass fabric	78	4.64	1136.3	2.39	30.8	73.6
Epoxy–63% carbon fabric	73.4	2.37	546.1	0.88	99	87.1
Epoxy–62% aramid fabric	75.1	3.99	941.6	1.30	88	114.4

Source: Based on Farag, M.M. and El-Magd, E., *Mater. Des.*, 13, 323, 1992.

departments, decreased redundancy of effort, and decreased cost of information storage and retrieval. Several such systems have been cited by Boardman and Kaufman (2000), and the following is a sample:

- The computerized application and reference system (CARS) is developed by the AISI *Automotive Steel Design Manual* and performs first-order analysis of design using different steels.
- Aluminum design system (ADS) is developed by the Aluminum Association (United States) and performs design calculations and conformance checks of aluminum structural members with the design specifications for aluminum and its alloys.
- Materials selection and design for fatigue life predictions is developed by ASM International and aids in the design of machinery and engineering structures using different engineering materials.
- Machine design's materials selection, developed by Penton Media (United States), combines the properties for a wide range of materials and the set for design analysis.

9.7.2 Expert Systems

Expert systems, also called knowledge-based systems, are computer programs, which simulate the reasoning of a human expert in a given field of knowledge. Expert systems rely on heuristics, or rules of thumb, to extract information from a large knowledge base. Expert systems typically consist of three main components:

- Knowledge base, which contains facts and expert level heuristic rules for solving problems in a given domain. The rules are normally introduced to the system by domain experts through a knowledge engineer.
- Inference engine, which provides an organized procedure for sifting through the knowledge base and choosing applicable rules to reach the recommended solutions. The inference engine also provides a link between the knowledge base and the user interface.
- User interface, which allows the user to input the main parameters of the problem under consideration. It also provides recommendations and explanations of how such recommendations were reached.

A commonly used format for the rules in the knowledge base is in the following form:

IF (condition 1) and/or (condition 2)
THEN (conclusion 1)

For example, in the case of FRP selection,

IF: required elastic modulus, expressed in GPa, is more than 150 and specific gravity less than 1.7.
THEN: oriented carbon fibers at 60% by volume.

Expert systems are finding many applications in industry including the areas of design, troubleshooting, failure analysis, manufacturing, materials selection, and materials substitution. When used to assist in materials selection, expert systems provide impartial recommendations and are able to search large databases for optimum solutions. Another important advantage of expert systems is their ability to capture valuable expertise and make it available to a wider circle of users. An example is the chemical corrosion expert system, which is produced by the National Association of Corrosion Engineers (NACE) in the United States, as reported by Boardman and Kaufman (2000). The system prompts the user for information on the environmental conditions and configuration of the component and then recommends candidate materials.

9.8 USING MATLAB® IN MATERIALS AND PROCESS SELECTION

9.8.1 Multicriteria Decision Making

Several quantitative methods for screening and selection of materials were discussed in Sections 9.4 through 9.7. The discussion showed that compromises and tradeoffs are often needed in view of the complex relationship between performance requirements of components and characteristics of available engineering materials and processes. This indicates that the selection process can be considered as a multicriteria decision-making problem, which lends itself to a variety of mathematical treatments, as reviewed by Jahan et al. (2010). Such mathematical treatments include multi-attribute utility analysis, neural networks, fuzzy multicriteria decision making, and multi-objective optimization methods.

The fuzzy set approach deals with vague and imprecise material properties, such as weldability, corrosion resistance, and wear resistance. Properties of this type are normally given discrete values. For example, excellent (5), very good (4), good (3), fair (2), or poor (1). Fuzzy logic on the other hand allows for values between the discreet numbers. In other words, the value of a classical variable can be restricted to either 1 or 0, which is either accept or reject; a fuzzy variable can have any value between 0 and 1, which corresponds to various shades of acceptance or rejection.

Multi-objective optimization methods can be used readily in selecting materials and processes for a given design. The goal in selecting a material is to optimize a number of metrics of performance in the product for which it is intended. Such metrics can include weight, cost, and environmental impact.

9.8.2 MATLAB® Programming Environment

MATLAB® is a commercial "Matrix Laboratory" package that operates as an interactive programming environment and provides a tool for doing numerical computations with matrices and vectors. MATLAB is particularly suited for solving systems of linear equations, computing eigenvalues and eigenvectors, factoring matrices, etc. In addition, it has a variety of graphical capabilities. MATLAB is designed to solve problems numerically in finite-precision arithmetic, which makes its solutions approximate rather than exact.

MATLAB features a family of application-specific solutions called toolboxes. There are a variety of toolboxes of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and optimization. Representative examples of using neural networks, fuzzy logic, and optimization toolboxes in materials selection and substitution include Jahan et al. (2010), Khabbaz et al. (2009), and Zhou et al. (2009).

Fuzzy logic toolbox provides an environment for building fuzzy inference systems and viewing and analyzing the results. Building and simulating a fuzzy logic system start with defining the desired output, formulating membership functions, creating the fuzzy inference rules, and then simulating the resulting fuzzy logic system. Membership functions define ranges for classifying each of the properties into high and low or poor, good and excellent, etc. The rules are in the form of IF-THEN and can be generated according to the knowledge base of the problem under consideration. Both the membership functions and the rules can be created using the command language or the graphical user interface of the fuzzy logic toolbox.

Optimization toolbox provides widely used algorithms for standard and large-scale optimization. These algorithms solve constrained and unconstrained continuous and discrete problems. The toolbox's optimization software includes functions for linear programming, quadratic programming, binary integer programming, nonlinear optimization, nonlinear least squares, systems of nonlinear equations, and multi-objective optimization. Such functions can be used to find optimal solutions, perform trade-off analyses, balance multiple design alternatives, and incorporate optimization methods into algorithms and models.

The following case study illustrates the use of the fuzzy toolbox of MATLAB software in ranking candidate materials for the cryogenic tank discussed in Case study 9.2. The use of the optimization toolbox of MATLAB in materials substitution is discussed in Chapter 10, Case study 10.6.

Case Study 9.8: Using the Fuzzy Toolbox in MATLAB® for Material Selection

Problem

The weighted properties method was used for materials selection for a cryogenic tank as shown in Case study 9.2. The case study identifies seven properties as being relevant to the performance of a material in the cryogenic tank. The seven properties are as follows: toughness index, yield strength, Young's modulus, specific gravity, thermal expansion, thermal conductivity, and specific heat. The ranking of the candidate materials according to their performance index is shown in Table 9.8 with stainless steel 301-FH receiving the highest rank. Khabbaz et al. (2009) solved the same problem using the fuzzy logic toolbox of MATLAB to see if better outcome of the selection process can be obtained.

Analysis

Khabbaz et al. started by defining the desired outputs, for example, low specific gravity, low thermal expansion coefficient, high toughness, and high strength are desirable. They then defined the membership functions for each of the seven properties. For example, the yield strength was defined as poor for values less than about 400 MPa, good for values in the range of about 600–900 MPa, and excellent for values higher than about 1000 MPa. In the case of specific gravity, excellent was assigned to values lower than about 1.7, good for values between about 2 and 4, and poor to values above about 6. Khabbaz et al. then created 14 fuzzy rules to cover the different combinations of membership functions and properties. For example, for all conditions of toughness, Young's modulus, thermal expansion, conductivity, and specific heat, IF yield strength is poor and specific gravity is poor, THEN the performance index is poor. Another example: For all conditions except poor Young's modulus, conductivity, and specific heat, IF toughness index is excellent, yield strength is good, specific gravity is excellent, and thermal expansion is good, THEN the performance index is excellent. Khabbaz et al. then used the Mamdani method, described in the fuzzy logic toolbox, to estimate the performance index of the candidate materials.

Result

The ranking of the top four materials according to the fuzzy logic method was the same as obtained in Table 9.8 with the weighted properties method. The rankings of the fifth, sixth, and seventh candidates were different, which is not very important since only one of the top ranking three or four candidates is normally adopted. However, the fuzzy logic method has an advantage of assigning smaller scores to the lower ranking candidate materials, which reduces the possibility of their selection as viable candidates.

9.9 SOURCES OF INFORMATION FOR MATERIALS SELECTION

9.9.1 Locating Material Property Data

One essential requisite to successful materials selection is a source reliable and consistent on material properties. There are many sources of information that include governmental agencies, trade associations, engineering societies, textbooks, research institutes, and material producers. Locating the appropriate type of information is not easy and may require several cycles of iteration until the information needed is gathered. According to Kirkwood, the steps involved in each cycle are as follows: define the question, set up a strategy to locate the needed information, use the resources you know best, go to less-known sources when necessary, evaluate the quality of information resources, and start again if needed using the new information to help define the question better. To locate useful sources of materials, it is important to identify the intended use of the type of data required and the quality of data required. In general, progressively higher quality of data is needed as the selection process progresses from initial screening to ranking and finally to selecting the optimum solution.

The ASM International has recently published a directory of material property databases (Boardman and Kaufman, 2000), which contains more than 500 data sources, including both specific databases and data centers. For each source, the directory gives a brief description of the available information, address, telephone number, e-mail, website, and approximate cost if applicable. The directory also has indices by material and property to help the user in locating the most appropriate source of material information. Much of the information is available on CD-ROM or PC disk, which makes it possible to integrate the data source in computer-assisted selection systems. Other useful reviews of the sources of material property data and information are also given in Westbrook (1997) and Price (1993).

9.9.2 Types of Material Information

According to Cebon and Ashby, material information can be classified into structured information from either reference sources or developed in-house and unstructured information from either reference sources or developed in-house. Structured information is normally in the form of databases of properties and is most suited for initial screening and for comparing and ranking of materials. Examples of structured reference sources of information material properties include ASM, Materials Universe, and MatWeb databases. These databases, in addition to several others, are collected online under the Material Data Network (www.matdata.net).

Unstructured information gives details about performance of specific materials and is normally found in handbooks, publications of trade organizations, and technical reports in the form of text, pdf files, tables, graphs, photographs, etc. Such information is most suited for detailed consideration of the top-ranking candidates who were selected in the initial screening and the ranking stages, as discussed in Section 9.6.

9.9.3 Computerized Materials Databases

Computerized materials databases are an important part of any computer-aided system for selection. With an interactive database, as in the case of ASM metal selector, the user can define and redefine the selection criteria to gradually sift the materials and isolate the candidates that meet the requirements. In many cases, sifting can be carried out according to different criteria such as

1. Specified numeric values of a set of material properties
2. Specified level of processability such as machinability, weldability, formability, availability, and processing cost
3. Class of material, for example, fatigue-resistant, corrosion-resistant, heat-resistant, and electrical materials
4. Forms like rod, wire, sheet, tube, cast, forged, and welded
5. Designations such as UNS numbers, AISI numbers, common names, material group, or country of origin
6. Specifications, which allow the operator to select the materials that are acceptable to organizations such as ASTM and SAE
7. Composition, which allows the operator to select the materials that have certain minimum or maximum values of alloying elements

More than one of these sifting criteria mentioned can be used to identify suitable materials. Sifting can be performed in the AND or OR modes. The AND mode narrows the search since the material has to conform to all the specified criteria. The OR mode broadens the search since materials that satisfy any of the requirements are selected.

The number of materials that survive the sifting process depends on the severity of the criteria used. At the start of sifting, the number of materials shown on the screen is the total in the database. As more restrictions are placed on the materials, the number of surviving materials gets smaller and could reach 0, that is, no materials qualify. In such cases, some of the restrictions have to be relaxed and the sifting restarted.

The Material Data Network (www.matdata.net) is an online search engine for material information and is sponsored by ASM International and Granta Design Limited. Sources of information that are linked to the network, member sites, include ASM International, The Welding Institute, National Physical Laboratory (United Kingdom), National Institute of Materials Science (Japan), U.K. Steel Association "Steel Specifications," Cambridge Engineering Selector, MatWeb, and IDES plastics data. Member sites can be searched simultaneously with one search string for all classes of materials. The information provided is both quantitative and qualitative, with tables, graphs, micrographs, etc. Some of the sites are freely available and do not require registration, whereas others require registration to access the information.

9.10 SUMMARY

1. Experience has shown that it is desirable for product development teams to adopt the concurrent engineering approach, where materials and manufacturing processes are considered in the early stages of design and are more precisely defined as the design progresses from the concept to the embodiment and finally the detail stage.
2. Stages of the selection process can be summarized into analysis of the performance requirements and creating alternative solutions, initial screening of solutions, comparing and ranking alternative solutions, and selecting the optimum solution. The HOQ approach can be helpful in identifying the customer requirements and correlating them to performance requirements of the product.
3. Cost per unit property method can be used for the initial screening of alternative solutions. In its simplest form, this is equal to the cost per unit weight multiplied times the density of the material and divided by the property that is considered to be most important to the application. Ashby's selection charts, Dargie's method, and Esawi and Ashby's method are computer-based alternative ways of initial screening.
4. Weighted property method of selection can be used for comparing and ranking alternative solutions. Each material requirement is assigned a certain weight depending on its importance to the function of the product. The individual weighted properties of each material are summed to give a material performance index. The material with the highest performance index is considered as the optimum for the application. The limits on property method and the AHP are two additional methods that can be used for comparing and ranking alternatives.
5. After ranking of alternatives, candidates that have the most promising performance indices can each now be used to develop a detail design. Each detail design will exploit the points of strength of the material, avoid the weak points, and reflect the requirements of the manufacturing processes needed for the material. After completing the different designs, solutions are then compared, taking the cost elements into consideration to arrive at the optimum design–material–process combination.
6. Fuzzy Logic Toolbox of the MATLAB provides an environment for building fuzzy inference systems, which can be adapted for selecting and ranking materials. Building and simulating a fuzzy logic system starts with defining the desired output, formulating membership functions, creating the fuzzy inference rules, and then simulating the resulting fuzzy logic system. The rules are in the form of IF–THEN and can be generated according to the knowledge base of the problem under consideration. Both the membership

functions and the rules can be created using the command language or the graphical user interface of the fuzzy logic toolbox.

7. Computers can be used to assist in materials selection. Several CAD/CAM programs and expert systems are available for such purposes.
8. Reliable and consistent sources of material information are essential for successful materials selection. More detail and higher accuracy of information are needed as the selection process progresses from the initial screening to the final selection stage. Several databases and Internet sources are cited for these purposes.

REVIEW QUESTIONS

9.1 What are the main functional requirements and corresponding material properties for the following products: (a) milk containers, (b) gas turbine blades, (c) sleeve for sliding journal bearing, (d) piston for an internal combustion engine, and (e) airplane wing structure?

9.2 What are the main reasons why graphite-reinforced epoxy is now widely used in sports equipment?

9.3 (a) What are the main design requirements for an elevator hoisting cable (the cable from which the elevator is pulled up and let down)? (b) Select the optimum material out of the following candidates for use in making the elevator hoisting cable:

Material	UTS (MPa)	Yield (MPa)	Elongation (%)	Relative Cost
ASTM-A675, 45	350	155	33	1
ASTM-A675, 70	540	240	18	1.5
ASTM-A242 Type 1	450	320	21	2.1
ASTM-A717 Grade 70	550	485	19	5.0

9.4 The following three materials are being considered for manufacturing a welded structure in an industrial atmosphere. The structure is expected to be subjected to alternating stresses in addition to the static loading.

Material	A	B	C
Relative weldability (0.15)	5	1	3
Relative tensile strength (0.15)	3	5	2
Relative fatigue strength (0.25)	5	3	3
Relative corrosion resistance (0.20)	3	5	3
Relative cost (0.25)	2	5	3

Taking the weighting factors for the different properties as shown in parentheses after each property, what would be the best material? (Answer: material B)

9.5 If the weighting factors used in Question 9.4 are changed to 0.25, 0.10, 0.2, 0.25, and 0.2 for weldability, tensile strength, fatigue strength, corrosion resistance, and cost, respectively, find the new optimum material. (Answer: material A)

9.6 The following three materials are being considered for making the frame of a racing car. Give appropriate weighting factors for each of the properties and apply the weighted property method to select the appropriate material. If the cost is to be considered, what would be the appropriate way of doing so?

Material	Al-2014 T6	Steel AISI 1015	Epoxy–70% Glass Fabric
YS (MPa)	248	329	680
Young's modulus (GPa)	70	207	22
Weldability index (5 = excellent, 4 = very good, 3 = good)	3	5	4
Specific gravity	2.8	7.8	2.1

9.7 The boiler shell in a power-generating plant is made of welded sheets. It is required to select materials for the shell. (a) What are the main functional requirements of the material used in making the shell? (b) Translate the functional requirements into material properties. (c) Suggest the weighting factors for the different properties. (d) What are the possible modes of failure of the shell? Suggest possible remedies for the different modes of failure. (e) Suggest possible materials for the shell.

9.8 The following three materials are being considered for making the sleeves for the shaft of a centrifugal pump. Taking the weighting factors for the different properties as shown in parentheses after each property, what would be the best material?

Material	Al-770	Bronze ASTM B22	Tin Alloy ASTM B23
YS (MPa) (0.2)	173	168	40
Wear resistance (0.11)	2	5	2
Fatigue strength (MPa) (0.14)	150	120	32
Corrosion resistance (0.11)	3	2	5
Thermal conductivity (W/m K) (0.2)	167	42	50

9.9 It is required to produce a pair of scissors for kitchen use in household applications. Draw neat sketches showing the different elements and the main dimensions of the pair of scissors. Give the functional requirements and corresponding material requirements for each element. Suggest candidate materials and matching manufacturing processes for each of the elements as well as the method of assembly, knowing that the volume of production is 10,000 units per year.

9.10 It is required to design a screwdriver set for household use. The set is composed of five screwdrivers of different sizes for various applications in the household. Draw a neat sketch of a screwdriver and give the possible range of dimensions for the different screwdrivers in the set. Give the functional requirements and the corresponding material requirements for the different parts of the screwdriver. Suggest the different materials, manufacturing processes, and methods of assembly if the required number of sets is 10,000 per year.

9.11 It is required to design and select materials for a suitcase for air travel. (a) What are the main structural elements of the suitcase? (b) What are the main functional requirements of each structural element? (c) Translate the functional requirements into material properties. (d) Give weighting factors to the different properties. (e) Suggest possible materials for each structural element of the suitcase.

9.12 It is required to design and select materials for an overhead pedestrian crossing to connect two parts of a company. (a) What are the main design features and structural elements? (b) What are the main functional requirements of each structural element? (c) What are the corresponding material requirements for each element? (d) Use the digital logic method to determine the relative importance of each property for the different structural elements. (e) Recommend the possible materials that may be used as candidates for the final selection of the optimum material for each structural element.

9.13 The following three materials are being considered for making the outer body of a freshwater valve in a power-generating plant. Select the optimum material.

Material	AA-770 Aluminum Alloy	Bronze ASTM B22	AISI 302 Stainless Steel
Yield strength (MPa)	173	168	280
Wear resistance	2	5	5
Fatigue strength (MPa)	150	120	315
Corrosion resistance	2	4	4
Processability	3	5	3
Cost relative to aluminum	1	2	3

9.14 Draw a neat sketch of a bicycle for use by children aged 3–5. It is required to produce the frame of this bicycle (the frame is part of the bicycle to which the front- and back-wheel pedals and seat are attached). Select a reasonable shape for the frame and give the possible dimensions of each element of the frame. Give the functional requirements and corresponding material requirements for the frame. Suggest candidate materials and possible matching manufacturing processes for the elements of the frame as well as possible methods of assembling the elements to make the frame. Expected volume of production is 100,000 frames per year.

9.15 It is required to select the material for a structural member in a tensile-testing machine. The member is 2 m long and will carry a maximum tensile load of 50 kN. The maximum extension should not exceed 0.5 mm. Select the optimum material out of the following candidates:

Material	UTS (MPa)	Yield (MPa)	Young's Modulus (GPa)	Elongation (%)	Relative Cost
ASTM-A675, 45	350	155	212	33	1
ASTM-A675,70	540	240	212	18	1.5
ASTM-A242 type 1	450	320	212	21	2.1
ASTM-A717 grade 70	550	485	212	19	5.0

9.16 The following three materials are being considered for making the frame of a racing car:

Material	Al-2014 T6	Steel AISI 1015	Epoxy–70% Glass Fabric
YS (MPa)	248	329	680
Young's modulus (GPa)	70	207	22
Weldability index (5 = excellent, 4 = very good, 3 = good)	3	5	4
Specific gravity	2.8	7.8	2.1

Give appropriate weighting factors for each of the properties and apply the weighted property method to select the appropriate material. If the cost is to be considered, what would be the appropriate way of doing so?

9.17 Case study: Packaging materials, types, and selection.

Background information: Packaging is an important and fast-growing industry, which utilizes modern design, materials, and manufacturing technology. The shape of the package can range from a simple box, as in the case of industrial packages, to a complex design, as in the case of cosmetics. The materials used in making the package cover a wide variety of engineering materials, which include paper, wood, glass, metal, plastic, and composites of various materials. Manufacturing techniques used in making the package range from manual cutting and assembly to fully automatic processing and filling. The cost of the package can represent a considerable portion of the total cost of the product, especially in the case of consumer products. For example, the cost of packaging is about 30% of the selling price of cosmetics, 25% for drugs and pharmaceuticals, 20% for foods, and 10% for toys.

A well-designed package in the consumer industry should satisfy the following requirements:

1. Does not adulterate the contents, especially in the case of food and pharmaceutical packages
2. Maintains quality of the contents after it has been opened and until the consumer finishes the contents

3. Protects contents against environment and handling during shipping from manufacturer to consumer
4. Provides a convenient and efficient means of storage and handling at the wholesaler's warehouse, retailer's store room, and consumer's home
5. Conforms to the specifications of the transportation company or post office
6. Allows clear labeling and identification of the type, composition, and amount of the contents
7. Provides an attractive visual appearance and a high value as a sales tool
8. Does not endanger public safety at any stage of its life
9. Is easy to dispose of and recycle after the contents have been consumed
10. Has reasonable cost

The relative importance of the requirements mentioned depends on the contents of the package, expected shelf life, distance between manufacturer and consumer and method of delivery, as well as local and international laws.

In the present case study, a large manufacturer of instant coffee is in the process of reviewing the packaging policy. It is required to analyze the requirements, design the package, select the materials, and propose the method of manufacturing of coffee packages for the following cases:

1. Package for a single cup of coffee, 2 g (0.07 oz)
2. Small container for household use, 50 g (1.75 oz)
3. Medium-size container for household use, 100 g (3.5 oz)
4. Large-size container for household use, 200 g (7 oz)
5. Commercial-size container for cafeteria and restaurant use, 1000 g (2.2 lb)

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10 Materials Substitution

10.1 INTRODUCTION

Manufacturers and engineers are always on the lookout for new materials and improved processes to use in manufacturing better products and thus maintain their competitive edge and increase their profit margin. For example, in the automotive industry, the effort to reduce weight to improve fuel economy and to comply with tighter governmental regulations on safety and emission has led to the introduction of increasing amounts of plastics and composite materials in place of the traditionally used steels. However, suppliers of the traditional materials are trying to regain some of the lost ground by introducing higher-strength steels and prefinished sheets. This competition among materials makes it necessary to periodically perform a materials audit to determine whether the material used in making a given component should be substituted.

Reaching a decision on substitution can be complicated and may involve materials engineers, designers, manufacturing engineers, as well as marketing and purchasing personnel. The process can be further complicated if future investment plans for new plants and equipments are involved. Unless the substitution process is carried out methodically, it can lead to confusion, delays, unnecessary expense, or even the wrong decision being made.

The goal of this chapter is to analyze the various incentives and constraints involved in substituting one material for another in making an existing component.

The main objectives are to get a better understanding about

1. Materials audit
2. Constraints and incentives in materials substitution
3. Life cycle energy impact of materials substitution
4. Financial implications of materials substitution
5. Some quantitative methods of initial screening, comparing alternatives, and making final decision for materials substitution

10.2 MATERIALS AUDIT

The audit process could start by asking the following questions:

- When were the materials last selected and specified?
- Who initiated the last changes in materials? Was it company, personnel, or materials suppliers?

- Why was the material changed? Was it legislation, lack of availability, or increased cost of the established material or the possibility of improved performance and reduced cost? If it were performance, then which properties dictated the change?
- What feedback do you have on the performance of your product? Product failures and returns are an obvious source of information but user survey may be necessary.
- What progress has been made by the materials manufacturers since the last change?
- Have new manufacturing processes been introduced since the last change?
- Have the new materials been developed with your product in mind? When materials manufacturers develop new or improved grades, they normally have a number of specific targets in mind. Is your product among them? If not, how do you ascertain that the new material is optimized for your application? Have you consulted the materials supplier?
- Is the advantage of adopting a new and untried material worth the risk of abandoning the current and established material?
- Is the cost of conversion to the new material less than the benefits?
- Would new equipments and plants be needed?
- Assuming that the substitution has been made, what are the implicates of that substitution on the system at large?
- What are the institutional, legal, social, and environmental consequences?

Answers to the preceding questions provide the background against the decision to explore materials substitution and the driving force required to overcome the resistance to substitution and the tendency to continue doing what has been done in the past. The degree of resistance to substitution of one material by another depends on the following:

1. Company policy.
2. Availability of design guidelines and in-service experience for new materials.
3. Cost of redesign and investment required for new production facilities and equipment.
4. Increased inventory required for more than one spare replacement.
5. Type of product and the extent to which the new material is being used. When the market share of a new material is small, resistance to substitution is high. As market share increases, resistance to change decreases, therefore increasing the rate of substitution.

There are powerful arguments for not changing the *status quo* unless the benefits can be seen to be considerable. However, engineering products are subject to continual evolution to meet increased performance demands and to lower manufacturing costs. To stand still is to invite the competition to overtake. New and improved materials and processes can make a vital contribution to improved competitiveness, and the opportunities should be continuously assessed.

10.3 CONSIDERATIONS IN MATERIALS SUBSTITUTION

If a decision is taken to substitute a new material for an established one, care must be taken to ensure that all the characteristics of the new material are well understood. A large number of product failures have resulted from new materials being used before their long-term properties were fully known. Another source of failure results from substituting a new material without reviewing the design. As an example, consider the case where thinner HSLA steel sheets are substituted for the currently used thicker steel sheets in motorcar bodies. Having overcome the processing problems, the substitution appears attractive in view of the weight saving. It should be remembered, however, that although the strength of HSLA steel is higher, corrosion resistance and elastic modulus are essentially the same as those for low-carbon steel. Thinner HSLA sheets will be damaged by corrosion in shorter time and get dented more easily, and undesirable vibrations can be more of a problem.

Generally, a simple substitution of one material for another (part-for-part substitution) does not provide optimum utilization of the new material. This is because it is not possible to realize the full potential of a new material unless the component is redesigned to exploit its properties and manufacturing characteristics. This is illustrated in Figure 10.1. Wood and steel wire are used in making the clothes hangers 1 and 2. Hanger 3 is mostly made of plastic but uses a steel hook and is styled in the

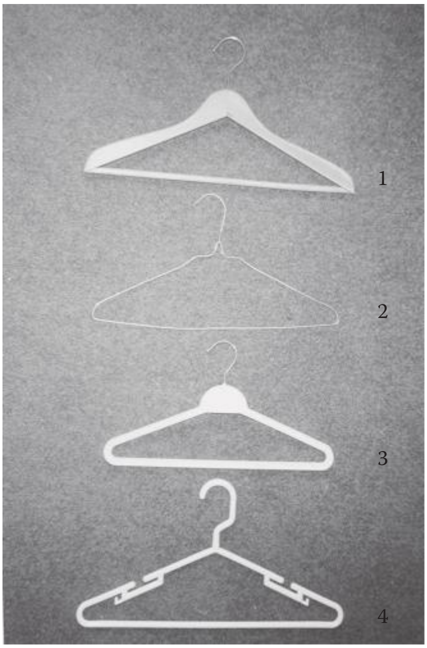

FIGURE 10.1 An example of how materials substitution affects the design and manufacturing processes of clothes hangers. Wood is shaped by cutting, the steel wire is shaped by bending, and the plastic is shaped by injection molding. Injection molding allows the flexibility of introducing useful features as in the bottom hanger.

same way as hangers 1 and 2. Hanger 4 is all plastic and introduces additional useful features that are only possible with injection molding.

In making a substitution, the new material should be mechanically, physically, and chemically compatible with the surrounding materials. For example, replacing steel with plastic may cause changes in deflection, thermal conduction, and thermal expansion due to differences in modulus of elasticity and thermal properties. Replacing steel with aluminum may cause galvanic corrosion with neighboring steel components. This means that changing the material of one component may entail several changes in the neighboring components. In some applications, the currently used material may have inherent characteristics that are not specified but are useful. For example, the high damping capacity of cast iron will be lost to the system if it is replaced by steel to save weight. System replacement provides the designer with the opportunity of integrated design to gain maximum benefit.

The main parameters that need to be examined for materials substitution can be grouped as follows:

1. Technical performance advantage, as a result of introducing a stronger, stiffer, tougher, or lighter material.
2. Economic advantage over the total life cycle of the product. This can be achieved as a result of introducing cheaper material, more cost-effective use of material, lower cost of processing, better recyclability and lower cost of disposal, or lower running cost of the product.
3. Changing the character of the product by incorporating a material that is esthetically more attractive, with a different feel, or that can provide more comfort to the user through sound or heat insulation, for example.
4. Environmental and legislative considerations including less damage to the environment over the life cycle of the product, better recycling or reuse, and compliance with environmental regulations.

10.4 SCREENING OF SUBSTITUTION ALTERNATIVES

In some cases, the need to search for a substitute material is recognized, but no definite alternative is presented. Under these conditions, it may be useful to start with a brainstorming session to identify a variety of alternatives that can then be screened to narrow the choices down to a few promising solutions. The method described by Pugh (1991) can be useful for initial screening of alternatives in the early stages of materials substitution. In this method, the performance requirements are first defined and the corresponding material properties are identified as described in Section 9.3. A decision matrix is then constructed as shown in Table 10.1. Each of the properties of possible alternative new materials is compared with the corresponding property of the currently used material, and the result is recorded in the decision matrix as (+) if more favorable, (–) if less favorable, and (0) if the same. The decision on whether a new material is better than the currently used material is based on the analysis of the result of comparison, that is, the total number of (+), (–), and (0). New materials with more favorable properties than drawbacks are selected as serious candidates for substitution and can be ranked using one of the two quantitative methods described in Section 10.5.

TABLE 10.1
Example of the Use of the Pugh Decision Matrix for Materials Substitution

Property	Currently Used Material	New Material (1)	New Material (2)	New Material (3)
Property (1)	C1	—	+	+
Property (2)	C2	+	+	+
Property (3)	C3	+	+	—
Property (4)	C4	0	+	—
Property (5)	C5	—	0	—
Property (6)	C6	0	0	0
Property (7)	C7	—	—	0
Property (8)	C8	—	+	0
Property (9)	C9	—	0	0
Total (+)		2	5	2
Total (−)		5	1	3
Total (0)		2	3	4

10.5 COMPARING AND RANKING OF ALTERNATIVE SUBSTITUTES

After narrowing down the field of possible substitute materials as described in Section 10.4, quantitative methods can be used to rank the most feasible alternatives. The following is a description of two methods of ranking alternative substitutes.

10.5.1 Cost of Performance Method of Substitution

In this method, the performance index, γ, and the total cost, C_t, of the candidate materials are separately compared against the currently used material. The performance index, γ, covers all requirements of the material except cost and is estimated using one of the ranking procedures outlined in Section 9.5. Various scenarios of substitution can be developed in this method by assigning different weighting factors to the performance requirements.

The total cost, C_t, is considered to consist of several cost elements as follows:

$$C_t = C_1 + C_2 + C_3 + C_4 \tag{10.1}$$

where

C_1 is the cost of material used in making the component

C_2 is the cost of manufacturing and finishing the component including cost of redesign and new tools

C_3 is the running cost over the entire life of the component

C_4 is the cost of disposal and recycling

If the purpose of substitution is to reduce the total cost of the component, an acceptable candidate must perform and the current material, that is, has similar performance index, γ, but at a lower total cost, C_t. If several candidates fulfill this condition, the one that gives the most cost reduction is selected.

If, however, the purpose is to improve performance, acceptable candidates must perform at a higher level than the currently used material. If cost is not the objective, the candidate with the highest performance index, γ, can be selected. In most situations, however, it is more realistic to calculate the percentage increase in performance ($\Delta\gamma\%$) and the corresponding percentage increase in cost ($\Delta C_t\%$) as follows:

$$\Delta\gamma\% = \frac{100(\gamma_n - \gamma_o)}{\gamma_o} \tag{10.2}$$

$$\Delta C_t\% = \frac{100(C_{tn} - C_{to})}{C_{to}} \tag{10.3}$$

where

γ_n and γ_o are the performance indices of the new and original materials, respectively

C_{tn} and C_{to} are the cost of the new and original materials, respectively

The substitute material that gives the highest ($\Delta\gamma\%/\Delta C_t\%$) can be selected if it has a clear advantage over the currently used material. Otherwise, further detailed analysis may be performed as discussed in Section 10.6.

The use of the cost of performance method is illustrated in Case study 10.1.

10.5.2 Compound Performance Function Method

This method compares the compound performance function (CPF) of the candidate materials against the currently used material. CPF is defined as the weighted sum of all the normalized material performance requirements, including total cost (C_t), and is estimated using one of the ranking procedures outlined in Section 9.5. Various scenarios of substitution can be developed in this method by assigning different weighting factors to the performance requirements.

For a successful substitution, the candidate material must have a higher CPF than the currently used material. The process may stop at this stage if the top-ranking alternative has a clear advantage over the currently used material. Otherwise, a more detailed analysis may be necessary as described in Section 10.6. The use of the CPF method in materials substitution is illustrated in Case studies 10.1 and 10.2.

Case Study 10.1: Materials Substitution in a Tennis Racket

Introduction

In this case study, a manufacturer of tennis rackets is considering the introduction of a new, more powerful model. The main evaluation criteria for the racket can be grouped into power, damping, and cost. The power of a racket allows the delivery of faster balls with less effort. Damping is the ability of the racket material to reduce the vibrations in the strings after hitting the ball and thus reduce the possibility of the player developing tennis elbow.

Analysis

The current material is epoxy –50% CF. Possible substitute materials to increase the power are shown in Table 10.2. For the purpose of this case study, power is taken as equal to (E/ρ), where E is the elastic modulus and ρ the density. Damping is taken as inversely proportional to E, and the material with the lowest E is given a damping of 10. The cost is taken as cost of the material per unit mass. The normalized values in Table 10.2 were obtained as described in the weighted property method given in Section 9.5.

Cost of Performance Method

The performance index, γ, in Table 10.3 is calculated by giving weights of 0.7 for power and 0.3 for damping. $\Delta\gamma$ and $\Delta C\%$ are percentage increases in γ and cost relative to the base material, respectively. The table shows that epoxy + 65% CF is a preferable substitution material as it has the highest ($\Delta\gamma\%/\Delta C\%$). Epoxy + 60% CF comes as a close second best.

TABLE 10.2
Characteristics of Tennis Racket Materials

Material	E (GPa)	Density ρ (g/cc)	Cost ($/kg)	Power	Damping	NP	ND	NC
Epoxy + 50% CF	136	1.87	93	73	10	82	100	100
Epoxy + 55% CF	146.4	1.873	101	78	9.3	88	93	92
Epoxy + 60% CF	156.8	1.876	109	84	8.7	94	87	85
Epoxy + 65% CF	167.2	1.879	117	89	8.1	100	81	80

Source: Based on Esawi, A.M.K. and Farag, M.M., Carbon nanotube reinforced composites: Potential and current challenges, *Mater. Des.*, 28(9), 2394, 2007.
Note: NP, normalized power; ND, normalized damping; NC normalized cost.

TABLE 10.3
Cost of Performance Method

Material	γ	$\Delta\gamma\%$	$\Delta C\%$	$\Delta\gamma\%/\Delta C\%$
Epoxy + 50% CF	87.4	—	—	—
Epoxy + 55% CF	89.5	2.40	8.6	0.28
Epoxy + 60% CF	91.9	5.15	17.2	0.3
Epoxy + 65% CF	94.3	7.9	25.8	0.31

TABLE 10.4
Compound Performance Function Method

Material	0.55 NP	0.20 ND	0.25 NC	CPF
Epoxy + 50% CF	45.1	20	25	90.1
Epoxy + 55% CF	48.4	18.6	23	90.1
Epoxy + 60% CF	51.7	17.4	21.25	90.35
Epoxy + 65% CF	55	16.2	20	91.2

Note: NP, normalized power; ND, normalized damping; NC, normalized cost.

Compound Performance Function Method

The CPF in Table 10.4 is calculated by giving the weights of 0.55 for power, 0.2 for damping, and 0.25 for cost. The table shows that epoxy + 65% CF is a preferable substitution material as it has the highest CPF. Epoxy + 60% CF comes as a close second best.

Conclusion

The results obtained using the cost of performance and CPF methods agree that epoxy +65% CF is an optimum substitute material with epoxy +60% CF as a close second best.

Case Study 10.2: Materials Substitution for a Cryogenic Tank

Problem

Consider the case of the cryogenic tank discussed in Case study 9.2 in Section 9.5. The results of the analysis show that SS 301-FH is the optimum material and is therefore used in making the tank. Suppose that at a later date a new fiber-reinforced material is available and it is proposed to manufacture the tank from the new material by the filament-winding technique. The properties of the new fiber-reinforced material are given in Table 10.5 together with the properties of SS 301-FH.

Analysis

Following the procedure in Section 9.5, the properties are first scaled. Using the same weighting factors as in Table 9.6, the performance index is calculated and the results in Table 10.6 show that the composite material is technically better than the stainless steel.

Final comparison between the original and candidate materials will be carried out according to the CPF method. The basis of comparison is chosen as the

TABLE 10.5
Properties of Candidate Materials for Cryogenic Tank

	1	2	3	4	5	6	7
Material	**Toughness Index**	**Yield Strength**	**Young's Modulus**	**Specific Gravity**	**Thermal Expansion**	**Thermal Conductivity**	**Specific Heat**
SS 310-FH	770	1365	189	7.9	16.9	0.04	0.08
Composite	175	1500	200	2.0	12	0.005	0.1

TABLE 10.6
Scaled Values of Properties and Performance Index

	Scaled Properties							Performance
Material	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Index (γ)**
SS 301-FH	100	91	95	25	71	12.5	100	70.9
Composite	23	100	100	100	100	100	80	77.4

TABLE 10.7
Relative Cost and Cost of Unit Strength for Candidate Materials

Material	Relative Cost	Cost of Unit Strength × 100	Figure of Merit (γ/Cost of Unit Strength) 10^{-2}
SS 301-FH	1.4	0.81	87.53
Composite	7	0.93	83.23

figure of merit, as described in Section 9.5. Following the same procedure of Section 9.5, the cost of unit strength is calculated as shown in Table 10.7.

Conclusion

As the figure of merit of SS 301-FH is higher than that of the composite material, the basis material still gives better value than the new material and no substitution is required.

If, however, the increasing use of the new composite material causes its relative cost to decrease to 6.6 instead of 7 (Table 10.7), the cost of unit property becomes 0.837×100 instead of 0.93×100. In this case, the figure of merit of the composite material becomes 92.5×10^{-2}, which means that it gives better value and is, therefore, a viable substitute.

10.6 REACHING A FINAL DECISION

A final step in the materials substitution process is to perform a detailed comparison of the technical and economic implications of adopting the substitute material. The following cost–benefit analysis procedure is a possible rational way of arriving at a final decision.

10.6.1 Cost–Benefit Analysis

The cost–benefit analysis is more suitable for the detailed analysis involved in making the final materials substitution decision. In cases where the new material is technically better but more complex and requires closer control and new technologies for its processing, components made from it would have better performance but would also be more expensive. In such cases, if materials substitution is to be economically feasible, the economic gain as a result of improved performance, $\Delta\gamma_e$, should be more than the additional cost, ΔC_t, incurred as a result of substitution:

$$\Delta\gamma_e - \Delta C_t > 1 \tag{10.4}$$

10.6.2 Economic Advantage of Improved Performance

The economic gain as a result of improved performance, $\Delta\gamma_e$, can be estimated based on the expected improved performance of the component, which can be related to the increase in performance index of the new material compared with the currently used material, γ_n and γ_o, respectively. The performance index, γ, can be calculated using one of the ranking procedures outlined in Section 9.5. The increase in performance can include the saving gained as a result of weight reduction, increased service life of the component, and reduced cost of disposal:

$$\Delta\gamma_e = A(\gamma_n - \gamma_o) \tag{10.5}$$

where

γ_n and γ_o are the performance indices of the new and original materials, respectively

A is the benefit of improved performance of the component expressed in dollars per unit increase in material performance index, γ

The use of the parameter A in the substitution process is illustrated in Case study 10.3.

Case Study 10.3: Reaching a Final Decision on Materials Substitution for the Sailing-Boat Mast Component

Problem

In Case study 9.5 that was discussed in Chapter 9, the aluminum alloy AA 2024 T6 was selected for the sailing-boat mast component since it gives the least-expensive solution. Of the seven materials in Table 9.22, AA 6061 T6, epoxy –70% glass fabric, and epoxy –62% aramid fabric result in components that are heavier and more expensive than those of the other four materials and will be rejected as they offer no advantage. Of the remaining four materials, AA 2024 T6 results in the least-expensive but the heaviest component. The other three materials—AA 2014 T6, AA 7075 T6, and epoxy –63% carbon fabric—result in progressively lighter components at progressively higher cost.

Analysis

For the cases where it is advantageous to have a lighter component, the cost-benefit analysis can be used in finding a suitable substitute for AA 2024 T6 alloy. For this purpose, Equation 10.5 is used with the performance index, γ, being considered as the weight of the component; ΔC the difference in cost of component; and A the benefit expressed in dollars, of reducing the mass by 1 kg. Comparing the materials in pairs shows that:

For A < \$7/kg saved,	AA2024 T6 is the optimum material.
For A = \$7–\$60.5/kg saved,	AA 7075 T6 is a better substitute.
For A > \$60.5/kg saved,	Epoxy-63% carbon fabric is optimum.

10.6.3 Total Cost of Substitution

The additional cost (ΔC_t) incurred as a result of substitution can be divided into the following:

Cost of redesign and testing. Using new materials usually involves design changes and testing of components to ensure that their performance meets the requirements. The cost of redesign and testing can be considerable in the case of critical components.

Cost differences in materials used. When smaller amounts of a new, more expensive material are used to make the product, the increase in direct material cost may not be as great as it would appear at first.

Cost differences in labor. This may not be an important factor in substitution if the new materials do not require new processing techniques and assembly procedures. This element of cost can be a source of cost saving if the new material does not require the same complex treatment or finishing processes used for the original material. If, however, new processes are needed, new cycle times may result and the difference in productivity has to be carefully assessed.

Cost of new tools and equipment. Changing materials can have considerable effect on the life and cost of tools, and it may influence the heat treatment and finishing processes. The cost of equipment needed to process new materials can be considerable if the new materials require new production facilities as in the case of replacing metals with plastics.

Based on this analysis, the total cost, ΔC_t, of substituting a new material, n, in place of an original material, o, in a given part is

$$\Delta C_t = (P_n M_n - P_o M_o) + f(C_1/N) + (C_2/N) + (T_n - T_o) + (L_n - L_o) \tag{10.6}$$

where

P_n and P_o are the price/unit mass of new and original materials used in the part
M_n and M_o are the masses of new and original materials used in the part
f is the capital recovery factor; it can be taken as 15% in the absence of information
C_1 is the cost of transition from original to new materials including cost of new equipment
C_2 is the cost of redesign and testing
N is the total number of new parts produced
T_n and T_o are the tooling cost per part for new and original materials
L_n and L_o are the labor cost per part using new and old materials

The use of cost analysis in substitution is illustrated in Case study 10.4.

Case Study 10.4: Materials Substitution of a Panel in Aerospace Industry

Introduction

The main driving force for materials substitution in aerospace industry is weight reduction at a reasonable cost while maintaining reliability and safety standards. Reducing the weight of the structure allows lifting a greater payload and traveling longer distances without refueling. In addition, weight saving could allow reduction of structures such as wing area, which would lead to further weight reduction. The outstanding values of strength/weight and stiffness/weight of FRPs make them prime challengers to the traditionally used aluminum alloys. As CFRPs offer the highest potential for weight saving, their use for panels in the upper wing surface of a civilian aircraft is discussed here.

This case study gives an analysis of the different factors involved in materials substitution in aerospace industry. The merits and drawbacks of substituting CFRP for the traditionally used aluminum alloys are examined. Body panels are used to illustrate the procedure, but similar analysis may be used for other parts of the structure of the aircraft. This case study was prepared when the author visited Massachusetts Institute of Technology (MIT). The help extended by Professor Thomas Eagar is acknowledged.

Analysis of Candidate Materials

Aluminum Alloys

Aluminum alloys are the traditional materials for civilian aircraft panels. Aluminum alloys in the 5xxx, 2xxx, and 7xxx series can be used for panel applications in the aerospace industry.

Fiber-Reinforced Plastics

FRPs are being increasingly used in aerospace industry as a result of their superior strength/weight and stiffness/weight. In low production volumes, composite panels containing continuous fibers can be made by stacking the required number of layers of preimpregnated fibers, prepregs, in the form of tapes or fabrics and then shaping them into matched dies. Stacking of the prepregs can be done manually or by using tape-laying machines. Composite structures are easily joined using structural adhesives, but machining and drilling are difficult as a result of the widely different properties of their constituents.

Required Mechanical Properties

Body panels of an aircraft can be subjected to a variety of loading conditions depending on their position and function. For example, the loading conditions on the wing of an airplane in flight can be approximately represented by a uniformly distributed load acting in the upward direction on a cantilever beam. In such a case, the load on a panel in the upper wing surface can be approximated to uniform in-plane compression. A major requirement for such a panel is resistance to buckling. However, a major requirement for a panel in the lower wing surface is resistance to static and fatigue tensile stresses. A panel in the control surfaces, for example, rudder, spoilers, and elevators, is not highly stressed but must be provided with adequate stiffness to keep its shape under wind forces. For such panels, it can be shown that $E^{1/3}/\rho$ is the major design parameter for comparing the candidate materials, where E is the modulus of elasticity and ρ is the density (Farag 1997, 2007).

Comparison of Candidate Materials

In the present case study, the upper wing panel is considered to be a flat rectangle of width, $b = 50$ cm, and length, $l = 100$ cm. Although the main load on such a panel is in-plane compression, some transverse and torsional loading may occur in maneuvering the aircraft or as a result of unfavorable weather conditions. Such secondary loads are not serious when isotropic materials, such as aluminum alloys, are used for the panel. CFRP, however, is not isotropic, and if all the fibers are oriented in the direction of the compressive load, the panel could easily fail under relatively small loads at right angles to the fibers. This can be avoided by placing some of the fibers at 90° or arranging them in the +45°/−45° directions, depending on the required degree of isotropy. In the present case study, the epoxy matrix will be strengthened using 33% carbon fabric +30% CFs. Composites with this arrangement of fibers are not as strong as those where all the CFs (63% by volume) are oriented in the same direction, but it provides the required strength in the 90° direction. Table 10.8 shows the superior structural efficiency of CFRP in comparison with the aluminum alloys. For a simply supported thin rectangular panel of thickness (t) and width (b) under in-plane compressive load (P), buckling will occur when

TABLE 10.8
Properties of Candidate Materials for Aircraft Body Panels

	Modulus of Elasticity		Density		$E^{1/3}/\rho$	Cost	
Material	**(GPa)**	**(ksi)**	**(Mg/m³)**	**(lb/in.³)**	**(SI Units)**	**($/kg)**	**($/lb)**
Aluminum alloy (average of 2xxx and 7xx series)	71	10,000	2.7	0.097	71.2	4.3	1.95[a]
Epoxy–33% carbon fabric + 30% CFs	100	14,286	1.61	0.058	134.65	110	50

Source: Adapted from Charles, J.A. and Crane, F.A.A., *Selection and Use of Engineering Materials*, Butterworths, London, U.K., 1989; McAffee, A.P., On the appropriate level of automation for advanced structural composites manufacturing for commercial aerospace applications, MSc thesis, Department of Mechanical Engineering and Sloan School of Management, MIT, Cambridge, MA, 1990.

[a] Aluminum alloys' cost is based on the average of 2024 and 7075 alloys, 1987 prices.

$$P = S_B tb = \frac{\pi^2 E}{3(1-\nu^2)}\left(\frac{t}{b}\right)^2 tb \tag{10.7}$$

where
S_B is the buckling stress
ν is Poisson's ratio (about 0.3 for most materials)

From Equation 10.7, the thickness is written as

$$t = \left(\frac{Pb}{3.62E}\right)^{1/3} \tag{10.8}$$

The mass of a panel (M) of length (l) is

$$M = \rho tbl$$

According to Charles and Crane (1989), a typical compressive end load for an aluminum alloy panel is about 3.5 MN/m, that is, $P/b = 3.5$ MN/m. This value is used to calculate the thicknesses of aluminum and CFRP panels according to Equation 10.8. The masses and costs of materials are then calculated using the information in Table 10.8 and the results are given in Table 10.9.

Shipp (1990) analyzed the nonrecurring cost of transition from aluminum of CFRP for the spoilers of model 737–200/300 at Boeing Commercial Airplanes. The cost was $948,198 for 150 shipsets, weighing 151 lb (68.6 kg) each. Dividing this sum by the total weight of the spoilers gives the cost of transition as $41.86/lb ($92.1/kg) of CFRP. This relatively high value reflects the man-hours needed to design the unfamiliar material and the extensive amount of testing required to

TABLE 10.9
Estimates for Aircraft Panel Substitution

	Aluminum	CFRP
Thickness for equal buckling resistance, in. (mm)	0.59 (15)	0.53 (13.4)
Mass of panel, lb (kg)	44.64 (20.25)	23.79 (10.79)
Cost of material in panel ($)	87.08	1186.90
Cost of transition per panel ($)	—	1002.51
Cost of labor per pound of panel material ($)	10–50[a]	50–300
Cost of labor per panel ($)	446.4–2232	1189.5–7137
Cost savings per panel due to less weight ($)	—	5671.20

Source: Adapted from Shipp, C.T., Cost-effective use of advanced composite materials in commercial aircraft manufacture, MSc thesis, Department of Mechanical Engineering and Sloan School of Management, MIT, Cambridge, MA, 1990.

[a] Estimated.

verify its reliability. This value is used to calculate the cost of transition from aluminum to CFRP in the present case study, as shown in Table 10.9.

According to Shipp (1990), American Airlines literature shows that a DC 10–10 airplane cuts its operating costs by about $29/year for a 1 lb (450 g) decrease in weight at the fuel prices of 1989. Assuming an expected life of 20 years for the airplane and a 10% cost of capital, Shipp estimated the present total value of the cost savings as $272/lb ($598/kg) decrease in weight. Cost savings are expected to depend on the size and function of the aircraft, current fuel prices, and the general economic conditions; they can range from $100 to $500/lb ($220–$1100/kg). Similar values of cost savings were reported by Charles and Crane (1989). In the present case study, a cost saving of $272/lb ($598/kg) is used to calculate the cost saving per panel due to less mass as shown in Table 10.9.

In a survey of several aerospace firms involved in manufacturing with advanced composites, Shipp found that the cost of labor involved in making a given part depends on its weight. Smaller parts are relatively more labor intensive. Components weighing more than 10 lb (4.54 kg) are found to need 0.8–4.6 h/lb (1.76–10.1 h/kg) of direct labor. Using an industry average of $65/h for fully burdened labor rate, Shipp estimated the cost of labor as $50–$300/lb ($110–$660/kg) of advanced composite materials. Aluminum labor cost is expected to be lower than the figures mentioned, as its manufacture is less labor intensive. For the present case study, a labor cost in the range $10–$50/lb ($22–$110/kg) is assumed.

Because the labor cost represents a large proportion of the cost (see Table 10.9), relatively small variations in the labor rate can affect the economic feasibility of substitution. The effect of labor rate variations on the total cost of substitution (ΔC_t) for a panel in the upper wing surface is shown in Figure 10.2. As would be expected, lowering the labor rate for one material makes it more attractive economically. For example, at a labor rate of $200/lb ($440/kg) for CFRP, aluminum is more attractive if its labor rate is $20/lb ($44/kg), but not attractive if

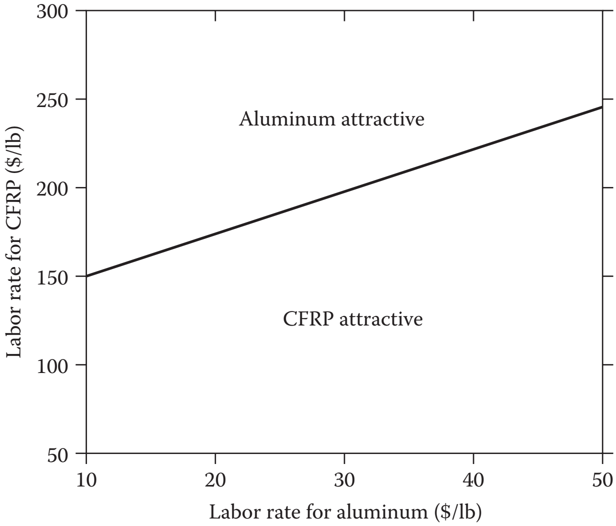

FIGURE 10.2 Effect of labor rate variations on the total cost of substitution for a panel in the upper wing surface of an aircraft.

its labor rate is $40/lb ($88/kg). Similarly, at a labor rate of $20/lb ($44/kg) for aluminum, CFRP is more attractive if its labor rate is $150/lb ($330/kg), but not attractive if its labor rate is $200/lb ($440/kg).

Conclusion

As the long-range behavior of the new materials is not well established, the present design codes require higher factors of safety in design and extensive testing programs when adopting FRP for critical components. This adds to the economic disadvantage of FRP. Such difficulty can only be solved gradually because engineers need to be more familiar with the unusual behavior of the new materials and need to gain more confidence in their long-range performance.

Case Study 10.5: Technical and Economic Feasibility of Using CNT-Based Composites in Aerospace Applications

Introduction

As discussed in Case study 10.4, the main driving force for materials substitution in aerospace industry is weight reduction at a reasonable cost while maintaining reliability and safety standards. This case study explores the merits and drawbacks of using CNTRP as a replacement for the traditionally used aluminum alloys and is based on A.M.K. Esawi and M.M. Farag, Chapter 15—Polymer nanotube composites: Promises and current challenges in *Polymer Nanotube Nanocomposites: Synthesis, Properties and Applications*, Mittal, V., Ed., M M Scrivener Press, Beverly, MA, 2010.

CNTs can be used in reinforcing polymer–matrix composites in two ways:

1. As the sole reinforcing phase (CNTRP)
2. As an additional reinforcing phase in conjunction with CFs (CF+CNT) in a hybrid composite

Required Mechanical Properties

As shown in Case study 10.4, a major requirement for such panel is resistance to buckling, and it was shown that ($E^{1/3}/\rho$) is the major design parameter for comparing the candidate materials, where E is modulus of elasticity and ρ is density. It was also shown that the weight of the panel is proportional to ($\rho/E^{1/3}$). In addition to the in-plane compression, some transverse and torsional loading may occur in maneuvering the aircraft or as a result of unfavorable weather conditions. Such secondary loads are not serious when isotropic materials, such as aluminum alloys, are used for the panel. In the case CFRP isotropy can be achieved by placing some of the fibers at 90° or arranging them in the +45°/−45° directions or with the random orientation of CNTs in CNTRP.

The rule of mixtures can be used to estimate upper bound values to the different properties (P_c) of the resulting composites as follows:

$$P_c = K_1V_1P_1 + K_2V_2P_2 + (1-(V_1+V_2))P_m \tag{10.9}$$

where

V_1 and V_2 are the volume fractions of phases 1 and 2, representing CNTs and CFs, respectively
P_1 and P_2 are the properties of phases 1 and 2, representing CNTs and CFs respectively
P_m is the property of the polymer–matrix
K_1 is the CNT efficiency parameter, which will be assumed equal to 1
K_2 is the CF efficiency parameter, which is equal to 1 for continuous aligned fibers in the direction of alignment, as is the case here

In calculating the upper bound values here, K_1 will be assumed equal to 1. It should, however, be noted that in the great majority of cases, a value of K_1 that is much lower than unity needs to be assumed in the case of CNT if the calculated values are to match experimentally measured values. This is particularly true in the case of mechanical properties and elastic modulus.

Using the same panel as in Case study 10.4, the mass of an aluminum panel that can bear the load in a civilian aircraft is 20.25 kg. The masses of CFRP and CNTRP panels of equivalent stiffness can be estimated from the proportionality of the weight to ($\rho/E^{1/3}$) and the values in Tables 10.10 and 10.11. The values for the aluminum alloy and epoxy 33% carbon fabric +30% CFs are based on Case study 10.4. The calculated values are given in Table 10.12. The calculations show that the aluminum panel is heaviest. The cost of material in a panel is calculated from its mass and the cost of material per kg, from Table 10.10. The results show that the aluminum panel is the least expensive.

TABLE 10.10
Assumptions Made in Calculating the Values in Table 10.11

Parameter	Value Used in Calculations
E of epoxy matrix	2.4 GPa
E of SWNT	1000 GPa
E of CVD-MWNT	300 GPa
Price of epoxy matrix	\$2.3 per kg
Price of SWNT (2009)	\$15,000–\$10,000 per kg depending on method of manufacture and purity
Price of CVD-MWNT (2009)	\$400–\$1,500 per kg depending on the quality and purity
Density of epoxy matrix	1.26 g/cc
Density of SWNT	1.4 g/cc
Density of MWNT	1.9 g/cc

Source: Based on Esawi, A.M.K. and Farag, M.M., Chapter 15—Polymer nanotube composites: Promises and current challenges, in *Polymer Nanotube Nanocomposites: Synthesis, Properties and Applications*, Mittal, V., Ed., M M Scrivener Press, Beverly, MA, 2010.

TABLE 10.11
Calculated Properties of Different Model Composites

Material	E_c (GPa)	Density ρ_c (g/cc)	$(E_c^{1/3}/\rho_c)$	Cost Cc (\$/kg)
Aluminum alloy (average of 2xxx and 7xxx series)	71	2.7	1.53	4.3
Epoxy 33% carbon fabric + 30% CFs	100	1.61	2.88	110
Epoxy + 1%SWNT	12.376	1.26	1.82	218.9
Epoxy + 20%ArcMWNT	201.92	1.39	4.15	8573.3
Epoxy + 20%CVD-MWNT	61.92	1.39	2.81	81.84
Epoxy 33% carbon fabric + 30% CFs + 1% SWNT	110	1.61	2.98	325.6
Epoxy 33% carbon fabric + 30% CFs + 3% SWNT	130	1.61	3.15	756.7
Epoxy 33% carbon fabric + 30% CFs + 1% CVD-MWNT	102	1.62	2.88	112.9
Epoxy 33% carbon fabric + 30% CFs + 3% CVD-MWNT	106	1.62	2.92	118.7

Source: Based on Esawi, A.M.K. and Farag, M.M., Chapter 15—Polymer nanotube composites: Promises and current challenges, in *Polymer Nanotube Nanocomposites: Synthesis, Properties and Applications*, Mittal, V., Ed., M M Scrivener Press, Beverly, MA, 2010.

Cost savings in fuel consumption, or the extra payload, as a result of reducing the weight of aircraft by 1 kg is estimated at \$1000 (see Case study 10.4). This value is used to calculate the cost saving due to a lighter panel in Table 10.12. The net cost saving as a result of substituting a composite material for the aluminum panel is given in Table 10.12. The results of Table 10.12 show that the hybrid composite [epoxy 33% carbon fabric +30% CFs +3% catalytic

TABLE 10.12
Feasibility of Panel Materials Substitution

	Mass of Panel (kg)	Cost of Material in Panel ($)	Additional Cost Due to More Expensive Material ($)	Cost Saving Due to Lighter Panel ($)	Net Cost Saving per Panel ($)	Ranking
Aluminum alloy (average of 2xxx and 7xxx series)	20.25	87.1	—	—	—	Base material
Epoxy 33% carbon fabric + 30% CFs	10.77	1184.7	1079.6	9480	8400.4	2
Epoxy + 1% SWNT	17.02	3725.7	3645.2	3230	–415.2	Reject
Epoxy + 20%ArcMWNT	7.47	64042.6	63955.5	12680	–51275.5	Reject
Epoxy + 20%CVD-MWNT	11.03	902.7	815.6	9220	8404.4	2
Epoxy 33% carbon fabric + 30% CFs + 1% SWNT	10.39	3382.98	3295.88	9860	6564.1	4
Epoxy 33% carbon fabric + 30% CFs + 3% SWNT	9.84	7445.93	7358.83	10410	3051.17	5
Epoxy 33% carbon fabric + 30% CFs + 1% CVD-MWNT	10.76	1214.56	1127.56	9490	8362.44	3
Epoxy 33% carbon fabric + 30% CFs + 3% CVD-MWNT	10.61	1259.46	1172.36	9640	8467.64	1

Source: Based on Esawi, A.M.K. and Farag, M.M., Chapter 15—Polymer nanotube composites: Promises and current challenges, in *Polymer Nanotube Nanocomposites: Synthesis, Properties and Applications*, Mittal, V., Ed., M M Scrivener Press, Beverly, MA, 2010.

chemical vapor deposition (CVD)-multi-wall nanotube (MWNT)] gives the maximum cost saving and is, therefore, given top ranking. Of the two second best materials (epoxy + 20% CVD-MWNT and epoxy +33% carbon fabric +30% CFs), the latter is a more likely contender. This is because CNT composite manufacturing techniques have to be considerably improved in order to incorporate 20% CNT, which cannot be achieved at present. This ranking shows that CVD-MWNT is more cost-effective in reinforcing composites than single-wall nanotube (SWNT). With the available preparation techniques and at the current prices, it can be effectively used as an additional strengthening phase in hybrid composites.

10.7 USING MATLAB® IN MATERIALS SUBSTITUTION

MATLAB® is a commercial "Matrix Laboratory" package that operates as an interactive programming environment and provides a tool for doing numerical computations with matrices and vectors. It can also display information graphically. MATLAB has a variety of add-ons and toolboxes. Some of the toolboxes of relevance to materials selection and substitution were briefly given in Section 9.8. Case study 9.8 was used to illustrate the use of the fuzzy logic toolbox in materials selection and the following case study illustrates the use of the optimization toolbox in materials substitution.

Case Study 10.6: Using the Optimization Toolbox in MATLAB® for Materials Substitution

Introduction

The motorcar and aerospace industries are always on the lookout for designs and materials that allow weight reduction of components and products. Several ways of weight reduction were discussed in Case studies 10.4 and 10.5 for the aerospace industry and in Case 11.6 for the motorcar industry. In the case of motorcar industry, aluminum alloys provide an opportunity to reduce weight at an increased cost. In these case studies, relatively simple ways were used to compare solid panels made of sheets of different materials on the basis of their weight and cost.

Weight reduction can be taken another step further by using sandwich panels, where a core of lightweight material is placed between facing sheets. Section 6.18 discussed sandwich materials and Case study 6.11 explored the possibility of substituting a steel sheet with a steel-faced sandwich panel. The results show that the steel sheet is 6.86 times heavier than the sandwich panel with equivalent stiffness. Arriving at the optimum sandwich structures for a given application is complicated since the relative thickness and properties of the core and facing materials as well as the total thickness of the panel affect its performance. The substitution process in this case is considered as a multicriteria optimization problem and the optimization toolbox of MATLAB is used in the solution. The floor panel of a motorcar is used for illustration. The following analysis is based on a paper by Aly, Hamza, and Farag; see bibliography.

Problem Formulation

This case study considers the replacement of a solid aluminum sheet of thickness t_o by a sandwich panel made of a lightweight core material of thickness t_c and two thin aluminum facing sheets of thickness t_f. The total thickness of the sandwich panel is t_s and is equal to (t_o+2t_f). The multicriteria optimization task is formulated as the optimization of a single utility function. Given a candidate material combination for the facing and core of the sandwich panel, a linear utility function is used for optimization and is expressed as

$$\text{Maximize} \quad f(\bar{t}_o, \bar{t}_r) = \sum_{i=1}^{n} w_i \; p_i(\bar{t}_o, \bar{t}_r) \tag{10.10}$$

$$\text{Subject to} \quad \boldsymbol{g}(\bar{t}_o, \bar{t}_r) = \left\{H_i\left(1 - p_i(\bar{t}_o, \bar{t}_r)\right)\right\} \le \mathbf{0} \tag{10.11}$$

$$\bar{t}_{o,\min} \le \bar{t}_o \le \bar{t}_{o,\max} \tag{10.12}$$

$$\varepsilon \le \bar{t}_r \le 1 - \varepsilon \tag{10.13}$$

where $\bar{t}_o$ and $\bar{t}_r$ are design variables in the optimization problem and represent, respectively, the ratio of overall thickness of the sandwich panel to that of the base material normal panel and the volume fraction of facing material to the overall volume of the sandwich panel:

$$\bar{t}_o = \frac{t_s}{t_o} \tag{10.14}$$

$$\bar{t}_r = \frac{2t_f}{t_s} \tag{10.15}$$

ε is a small number, set to 0.01 in this case (since less than 1% thickness differences are not considered significant).

$f(\bar{t}_o, \bar{t}_r)$ is the utility objective function to be maximized.

$p_i(\bar{t}_o, \bar{t}_r)$, $i=1$ to n, are dimensionless design attributes of the sandwich panel relative to the base material normal panel (with n being the number of design attributes). Formulation is such that $p_i > 1.0$ implies the sandwich panel is "better" than the base solid panel in terms of the attribute i.

w_i, $i=1$ to n, are weights assigned to the design attributes depending on their importance.

$g_i(\bar{t}_o, \bar{t}_r)$, $i=1$ to n, are optional constraints on the value of design attributes. While the utility objective function seeks to improve the value of all attributes in the sandwich panel, some attributes may be getting better while others may be getting slightly compromised. When no compromise is permissible for some attribute i, setting the value of $H_i=1$ "activates" a hard constraint corresponding to that attribute such that a design with $p_i<1$ becomes unfeasible. Setting $H_i=0$ turns off the constraint corresponding to an attribute.

Equations 10.10 through 10.15 formulate the optimization problem for one material selection combination of facing and core of the sandwich panel and can be solved more than once for different alternative combinations.

Design Attributes

The design attributes that need to be optimized for the case of the floor panel of a motorcar include bending stiffness, buckling resistance, strength, weight, and cost. As an example of the formulations of the design attributes, the bending stiffness is given here assuming a unit length and unit width of the floor panel:

$$\alpha_{1o} = \frac{1}{12} E_o t_o^3 \tag{10.16}$$

Adapting Equation 6.18 to the current notations the bending stiffness of the sandwich panel is calculated as

$$\alpha_{1s} = \frac{1}{6} E_f t_f^3 + \frac{1}{2} E_f t_f t_{fc}^2 + \frac{1}{12} E_c t_c^3 \tag{10.17}$$

where

E_o, E_f, and E_c are Young's modulus values of the original panel, facing, and core materials, respectively

t_{fc} is the distance between the mid-planes of the two facing material layers, calculated as

$$t_{fc} = t_c + t_f \tag{10.18}$$

The design attribute for bending stiffness is then calculated as

$$p_1 = \frac{\alpha_{1s}}{\alpha_{1o}} \tag{10.19}$$

The design procedure is implemented into a MATLAB code using both exhaustive search (examining all combinations of $\overline{t}_o$, $\overline{t}_r$ in increments equal to 1% of their ranges), as well as multi-start sequential quadratic programming (via running the MATLAB function `fmincon()` from 100 random starting points within the search ranges of $\overline{t}_o$, $\overline{t}_r$).

Results

Table 10.13 gives the optimization results of substituting an aluminum 6160-T6 panel of thickness 2.4 mm with sandwich panels under two scenarios:

1. Scenario 1 considers weight reduction as the only objective and keeping the other design attribute as equal to or higher than the aluminum panel.
2. Scenario 2 considers weight reduction and cost reduction at the relative importance of 100:60, respectively, and keeping the other design attributed as equal to or higher than the aluminum panel.

TABLE 10.13
Best Sandwich Panel Designs for Vehicle Floor Panel under Different Scenarios

		Scenario 1	Scenario 2
Performance weighing	w_1 (bending stiffness)	0	0
	w_2 (static bending strength)	0	0
	w_3 (buckling resistance)	0	0
	w_4 (weight)	100	100
	w_5 (cost)	0	60
Core material		Polypropylene	Polypropylene
Facing material		Al 6160-T6	Al 6160-T6
$\bar{t}_o^*$		1.2000	1.2200
$\bar{t}_r^*$		0.3138	0.2844
f		112.9	173.1
Stiffness increase		23.1%	22.4%
Strength increase		2.6%	0.3%
Buckling resistance increase		0.3%	0.4%
Weight reduction		11.4%	11.2%
Cost reduction		0.3%	0.5%

The results show that sandwich panels provide a viable alternative as they are 11% lighter and are slightly less expensive than the solid aluminum sheet.

10.8 SUMMARY

1. Materials substitution is an ongoing process and materials used for a given product should be reviewed on a regular basis through a materials audit process. The audit process answers questions related to when the material was last selected, feedback on performance, and progress made in the area of materials and manufacturing.
2. If a decision is taken to substitute a new material for an established one, care must be taken to ensure that the characteristics of the new material are well understood and that advantages outweigh drawbacks of adopting it. Risk, cost of conversion, equipment needed, and the environmental impact need to be carefully evaluated.
3. The economic parameters involved in materials substitution include direct material and labor, cost of redesign and testing, cost of new tools and equipment, cost of change in performance, and overheads.
4. The major stages of materials substitution include screening of alternatives, comparing and ranking alternative substitutes, and reaching a final decision. The initial stages involve only rough estimates, which become more elaborate as the substitution process progresses to the screening and then the final selection stages.

5. Several quantitative methods of substitution are described in this chapter. The use of quantitative methods ensures that decisions are made rationally and that no viable alternative is ignored. These methods include Pugh's method for initial screening, cost of performance and CPF methods for ranking alternative solutions, and cost–benefit analysis for reaching a final decision.
6. The substitution process in the case of sandwich panels can be considered as a multi-criteria optimization problem and the optimization toolbox of MATLAB is used in the solution.

REVIEW QUESTIONS

10.1 Compare the following materials as possible replacement for glass in containers for apple juice drink: plastic and carton laminate. Consider the following factors in your discussion: whether the container is disposable or returnable, shelf life, weight, cost, environmental impact, and sales appeal.

10.2 What are the main materials that can be used to replace glass for packaging fresh milk? Compare the advantages and disadvantages of each material and give the milk distribution system that is most suitable for each material.

10.3 Materials B and C are being considered as replacement for material A in manufacturing a welded structure to serve in an industrial atmosphere. The structure is expected to be subjected to alternating stresses in addition to the static loading.

Material	A	B	C
Relative weldability (0.15)	5	1	3
Tensile strength (MPa) (0.15)	300	500	200
Fatigue strength (MPa) (0.25)	150	90	90
Relative corrosion resistance (0.20)	3	5	3
Relative cost (0.25)	2	5	3

Taking the weighing factors for the different properties as shown in parentheses after each property, what would be the best substitute material?

10.4 Aluminum alloy and GFRP are being considered for replacing steel in making the frame of a firefighting ladder to be fixed to a fire engine.

Material	Steel AISI 1015	Al-2014 T6	Epoxy –70% Glass Fabric
Yield strength (MPa)	329	248	680
Young's modulus (GPa)	207	70	22
Weldability index (5 = excellent, 4 = very good, 3 = good)	5	3	4
Specific gravity	7.8	2.8	2.1
Relative cost	1	4	5

Give appropriate weighing factors for each of the properties and decide whether any of the alternative materials can serve as a successful substitute.

10.5 Develop various scenarios of the solution to the problem in Case study 10.1 by changing the weights given to the power, damping, and cost. Comment on the results.

10.6 Currently a company is making the frame of a racing bicycle out of medium-carbon steel (the frame is part of the bicycle to which the front- and back-wheel pedals and seat are attached). Select a reasonable shape for the frame and give the possible dimensions of each element of the frame. Give the functional requirements and corresponding material requirements for the frame. Suggest candidate materials and possible matching manufacturing processes for replacing steel in making the frame. Expected volume of production is 10,000 frames/year.

10.7 Develop various scenarios of the solution in Case study 10.2 by changing the weights allocated to the power, damping, and cost. Comment on the results and the relative merits of the two methods, cost of performance, and CPF.

10.8 Term Project

Objective. The objectives of the term project are to train students to work in teams and to present an integrated study of the design, materials, and process selection of an engineering product.

Project teams. Project teams consist of about five members who will organize themselves so that each member will carry out a fair share of the work. The team will submit one final report, but all members of the team will participate in an oral presentation of the project.

Guidelines for project work.

1. Select a product or an engineering system in consultation with the course instructor.
2. Define the uses and function of the product or system.
3. Identify the different components, assemblies, or subassemblies. Define their function, operating conditions, and expected performance level.
4. Select one component for detailed analysis.
5. Define the principles of design calculations.
6. Define the material and manufacturing processes that are currently used in making the component.
7. Deduce the mechanical, physical, and chemical properties of the materials that could be used in making the component.
8. Classify possible materials and manufacturing processes.
9. Rank the alternative materials and processes based on the required characteristics.
10. Make final design for the component using the optimum candidate material and matching processes.
11. Compare expected performance of alternative component with that of the current component.
12. Submit a written report and give an oral presentation if required.

Note: These steps are only meant as guidelines. The team may change them to suite the project.

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11 Case Studies in Material Selection and Substitution

11.1 INTRODUCTION

Different chapters of this book have discussed various issues related to material selection and substitution and how they fit with customer needs and design limitations. Illustrative examples in the form of design examples and case studies were used to explain the points of discussion, whenever possible. However, such examples had to be kept simple and to just address the point under discussion in order not to disrupt the continuity of the subject matter. This chapter tries to address this limitation by presenting more detailed case studies that are hopefully more representative of real-world material selection and substitution problems.

Six case studies are presented in this chapter:

1. Design and selection of materials for a turnbuckle (Section 11.2).
2. Design and selection of materials for surgical implants (Section 11.3).
3. Design and material selection for lubricated journal bearings (Section 11.4).
4. Analysis of the requirements and substitution of materials for tennis racket (Section 11.5).
5. Material substitution in automotive industry (Section 11.6).
6. Can CNTs replace constantan alloy in strain sensors? (Section 11.7).

Each of the case studies starts by an introduction that provides background information about the product under consideration, followed by an analysis of its functional requirements and design. Possible materials and manufacturing processes are then briefly presented and compared using an appropriate quantitative method. Final conclusions are then drawn based on the results of the comparison.

11.2 DESIGN AND SELECTION OF MATERIALS FOR A TURNBUCKLE

11.2.1 Introduction

A turnbuckle is a loop with opposite internal threads in each end for the threaded end of two ringbolts, forming a coupling that can be turned to tighten or loosen the tension in the members attached to the ringbolts. Figure 11.1 shows an assembly of a typical turnbuckle. The turnbuckle is used in different applications involving

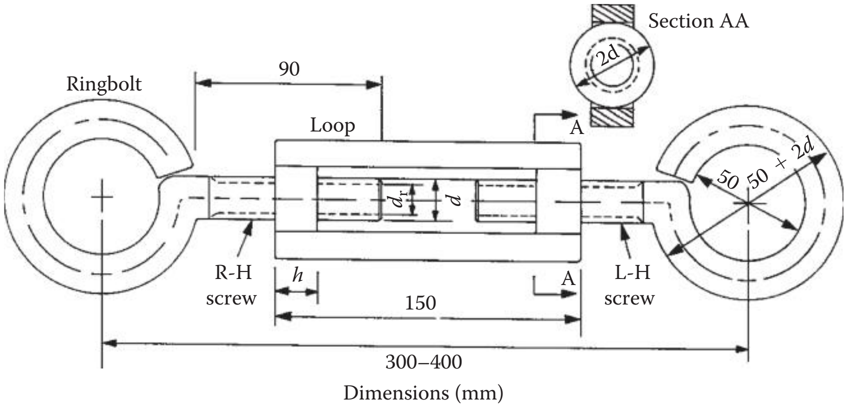

FIGURE 11.1 Assembly and material-independent dimensions of the turnbuckle.

widely different requirements of forces, reliability, and service conditions. Examples include guy wires for telegraph poles, ship rigs, sports equipment, and camping gear. The main functional requirements of a turnbuckle are to apply and maintain tensile forces to the members attached to the ringbolts. It should be possible for an operator to release and reapply the tensile forces when needed.

11.2.2 Factors Affecting Performance in Service

The forces acting on the turnbuckle are usually tensile, although fatigue and impact loading can be encountered. Corrosion becomes a problem in aggressive environments, especially if the loop is made from a different material other than the ringbolt material. The possible modes of service failure and their effect on the performance of the turnbuckle are the following:

1. Yielding of the loop or one of the ringbolts. This will release the tensile forces in the system and could make operation unsafe.
2. Shearing, or stripping, of threads on the loop or on one of the ringbolts. This will release the tensile forces in the system and would make it impossible to reapply the required forces.
3. Fatigue fracture of the loop or one of the ringbolts. Fatigue fracture could start at any of the points of stress concentration in the turnbuckle assembly.
4. Creep strain in the loop or one of the ringbolts. This will relax the tensile forces in the system and could make operation unsafe.
5. Fracture of the loop or one of the ringbolts. This could take place as a result of excessive loading of the system or as a result of impact loading if materials lose their toughness in service.
6. Corrosion as a result of environmental attack and galvanic action between ringbolt and loop if they are made of widely different materials. Excessive corrosion will make it difficult to apply and release the tension in the system and could reduce the cross-sectional area to dangerous limits. SCC can also occur in this system.

One or more of the mentioned failure modes could prove to be critical, depending on the materials used in making the turnbuckle components, type of loading, and service environment. For example, fatigue is expected to be critical if the load is fluctuating, whereas creep should be considered for high-temperature service.

General specifications

- The tensile force to be applied by the turnbuckle consists of a static component, $L_m = 20$ kN, and an alternating component, $L_a = 5$ kN.
- Inner diameter of the rings at the end of ringbolts = 50 mm.
- The shortest distance between centers of rings on ringbolts = 300 mm.
- The longest distance between centers of rings on ringbolts = 400 mm.
- Other dimensions of the turnbuckle, which are material independent, are shown in Figure 11.1.
- Service environment is industrial atmosphere.

11.2.3 Design Calculations

Figure 11.1 shows that the threaded length of the ringbolt is critical in view of the reduction in diameter involved in manufacturing the thread and the stress concentration at the roots of the teeth. It will, therefore, be assumed that if the threaded part can carry the service loads, the rest of the ringbolt will be safe.

In calculating the axial stress carried by a threaded bolt, an effective cross-sectional area, called tensile stress area (A_s), is used. The tensile stress area for standard metric threads is given by

$$A_s = 0.25\pi(d - 0.9382p)^2 \tag{11.1}$$

where

d is the major diameter of the bolt (see Figure 11.1)

p is the pitch of the thread

Table 11.1 gives the values of A_s for some standard metric threads.

11.2.4 Design for Static Loading

The tensile stress on the threaded part of the ringbolt (S_t) is given by

$$S_t = \frac{LK_t}{A_s} = \frac{\mathrm{YS_b}}{n_b} \tag{11.2}$$

where

L is the applied load

$\mathrm{YS_b}$ is the yield strength of the ringbolt material

n_b is the factor of safety used for the ringbolt calculations

K_t is the stress concentration factor

TABLE 11.1
Stress Areas for Some Standard Metric Threads

Major Diameter and Pitch (mm)		Tensile Stress Area (A_s) (mm^2)	Thread Shear Area per Millimeter of Engaged Threads	
			AS_b (mm^2)	AS_l (mm^2)
M4	0.7	8.78	5.47	7.77
M5	0.8	14.20	7.08	9.99
M6	1.0	20.10	8.65	12.20
M8	1.25	36.60	12.20	16.80
M10	1.5	58.00	15.60	21.50
M12	1.75	84.30	19.00	26.10
M14	2.0	115	22.40	31.00
M16	2.0	157	26.10	35.60
M18	2.5	192	29.70	40.50
M20	2.5	245	33.30	45.40
M22	2.5	303	37.00	50.00
M24	3.0	353	40.50	55.00
M27	3.0	459	46.20	62.00
M30	3.5	561	51.60	69.60
M36	4.0	817	61.30	84.10
M42	4.5	1120	74.30	99.20

If a ductile material is used for making the ringbolt, there will be no need to introduce a stress concentration factor in Equation 11.2 and K_t can be ignored. However, with brittle materials, such as cast iron, the stress concentration at the roots of the threads should be taken into consideration.

In the case of the loop, the combined area of the two sides ($2 \times A_l$) should withstand the applied load L without failure. Thus,

$$\frac{L}{2A_l} = \frac{\mathrm{YS}_l}{n_l} \tag{11.3}$$

where

YS_l is the yield strength of the loop material
n_l is the factor of safety used for the loop calculations

Stripping of threads on the ringbolt will occur when its threads fail in shear at the minor diameter (d_r) (Figure 11.1). The shear stress in the ringbolt threads (τ) is given by

$$\tau = \frac{L}{\mathrm{AS}_b \times h} \tag{11.4}$$

where

AS_b is the shear stress area per unit length of the ringbolt
h is the length of engagement between the ringbolt and loop

The values of AS_b for some standard metric threads are given in Table 11.1.

Similarly, stripping of the internal threads in the loop will occur when its threads fail in shear at the major diameter of the ringbolt (*d*). The shear stress in the loop threads (τ) is given by

$$\tau = \frac{L}{\mathrm{AS_l} \times h} \tag{11.5}$$

where $\mathrm{AS_l}$ is the shear stress area per unit length of the loop thread.

The values of $\mathrm{AS_l}$ for some standard metric threads are given in Table 11.1.

As Table 11.1 shows, the shear area of internal threads on the loop is greater than that of the external threads on the ringbolt. This means that if the ringbolt and loop materials have the same shear strengths, stripping of the ringbolt threads will normally occur before stripping of the internal threads on the loop. For this reason, the material selected for the loop can be weaker than that of the ringbolt.

11.2.5 Design for Fatigue Loading

When the turnbuckle is subjected to fatigue loading, the procedure outlined in Section 6.5 can be used. Equation 6.12 can be used to calculate the ringbolt tensile stress area A_s. Thus,

$$\frac{n_m K_t L_m}{\mathrm{UTS} A_s} = \frac{n_a K_f L_a}{S_e A_s} = 1 \tag{11.6}$$

where

- n_m and n_a are the factors of safety for static and fatigue strengths, respectively
- L_m and L_a are the static and alternating loads, respectively
- K_t and K_f are the static and fatigue stress concentration factors, respectively (K_t can be ignored for ductile materials)
- UTS and S_e are the tensile strength and modified endurance limit, respectively

According to Equation 6.10, S_e can be calculated by multiplying the endurance limit of the material by a set of modifying factors. For the present case study, all the modifying factors will be grouped as one modifying factor k_i.

A similar procedure can be used to calculate the length of engagement between the ringbolt and loop *h*.

For the ringbolt,

$$\frac{n_m K_t L_m}{\tau_{bu} \mathrm{AS_b} h} = \frac{n_a K_f L_a}{\tau_{be} \mathrm{AS_b} h} = 1 \tag{11.7}$$

where

- τ_{bu} and τ_{be} are the static and fatigue shear strengths of the ringbolt material, respectively
- K_t can be ignored for ductile materials, as in the case of tensile stress calculations

For the loop,

$$\frac{n_m K_t L_m}{\tau_{lu} AS_1 h} = \frac{n_a K_f L_a}{\tau_{le} AS_1 h} = 1 \tag{11.8}$$

where τ_{lu} and τ_{le} are the static and fatigue shear strengths of the loop material, respectively.

The values of h calculated from Equations 11.7 and 11.8 are compared and the larger one is selected.

For the present case study, the maximum-shear-stress theory will be used to predict the shear strengths of the ringbolt and loop materials. Thus, $\tau_u = 0.5$ UTS and $\tau_e = 0.5\ S_e$.

11.2.6 Candidate Materials and Manufacturing Processes

As shown in the design calculations, the strength of the loop material need not be as high as the ringbolt material. At the same time, the two materials should not be far apart in the galvanic series to avoid failure due to galvanic corrosion, as discussed in Section 6.7. For the present case, the ringbolt and loop materials will be selected with guidance from Table 3.1.

The ringbolt can be manufactured by the following methods:

1. From bar stock by first threading and then forming the ring by bending. Threading can be done by cutting or rolling.
2. From bar stock by upset forging to form a head, flattening the head and forming the ring by forging, and then threading as mentioned.
3. Sand casting and then thread cutting.
4. Shell molding and then thread cutting.
5. Die casting and then thread cutting.

For the present case study, it is assumed that the available facilities favor the first method of manufacturing the ringbolt, where a bar stock is threaded by rolling and then bent around a die at room temperature to form the ring. The main processing requirement in this case is ductility. A minimum elongation of 15% is assumed to be necessary. This figure can be arrived at from experience with similar products or by performing development experiments.

The loop can be manufactured by the following methods:

1. Sand casting using wooden or metal pattern and then thread cutting
2. Shell molding using metal pattern and then thread cutting
3. Die casting and then thread cutting
4. Die forging of a bar stock and then thread cutting
5. Machining from a bar stock and then thread cutting
6. Welding of the threaded ends to round or square bars

For the present case study, it is assumed that the available facilities favor the first method of manufacturing the loop.

Table 11.2 lists the properties of some candidate wrought alloys for the ringbolt and cast alloys for the loop materials. The values of K_f in the table are calculated according to Equation 4.9 using the given values of q and assuming that $K_t = 2.5$, which is reasonable for coarse threads.

11.2.7 Sample Calculations

The procedure for calculating the dimensions, weight, and cost of the turnbuckle will be illustrated here. The calculations are based on steel AISI 1015 as the ringbolt material and nodular cast iron ASTM A536 60–40–18 as the loop material. These two materials are compatible from the galvanic corrosion point of view.

As the turnbuckle is subjected to combined static and fatigue loading, Equation 11.6 will be used to calculate a preliminary value for A_s. According to Shigley and Mitchell (1983), the factors of safety can be taken as $n_m = 1.5$ for static loading, and $n_a = 3.0$ for fatigue loading. As the ringbolt material is ductile, the static stress concentration factor, K_t, can be taken as unity. Using the values in Table 11.2 for steel AISI 1015, Equation 11.6 can be written as

$$\frac{1.5 \times 1 \times 20{,}000}{430 \times A_s} + \frac{3.0 \times 1.15 \times 5{,}000}{195 \times 0.7 \times A_s} = 1 \tag{11.9}$$

which gives $A_s = 196.14\ \text{mm}^2$.

From Table 11.1, it can be seen that the M18 standard metric thread has an A_s of 192 mm^2, which is close to the calculated A_s. This means that the major diameter of the bolt is 18 mm.

The mass of the ringbolt

w_b = density (volume of the straight part + volume of the ring) = 603 g

The next step is to calculate the length of engagement between the ringbolt and the loop using Equations 11.7 and 11.8. According to Equation 11.7 and using the same values n_m, n_a, K_t, and K_f as before,

$$\frac{1.5 \times 1 \times 20{,}000 \times 2}{430 \times 29.7 \times h} + \frac{3.0 \times 1.15 \times 5{,}000 \times 2}{195 \times 0.7 \times 29.7 \times h} = 1 \tag{11.10}$$

This gives $h = 13.2$ mm.

In the case of the loop, K_t will be taken as unity since the nodular cast iron used is ductile. Factors of safety similar to those used for the ringbolt calculations will be used for the loop. According to Equation 11.8,

$$\frac{1.5 \times 1 \times 20{,}000 \times 2}{420 \times 40.5 \times h} + \frac{3.0 \times 1.3 \times 5{,}000 \times 2}{210 \times 0.6 \times 40.5 \times h} = 1 \tag{11.11}$$

This gives $h = 11.14$ mm, which is smaller than the value given by Equation 11.10.

The larger value of h is taken as the design value.

The two webs that connect the threaded ends of the loop have to resist the combined effects of the static and alternating loads. Equation 11.6 can be used to

TABLE 11.2
Candidate Materials for the Ringbolt and Loop Materials

Material	UTS (MPa)	YS (MPa)	$S_{e'}$ (MPa)	k_i	q	K_f	ρ	C	Relative Cost[a] Mat.	Mfr.
Ringbolt materials (minimum elongation 15%)										
Steels										
AISI 1015	430	329	195	0.7	0.1	1.15	7.8	1	1	1
AISI 1040	599	380	270	0.6	0.2	1.30	7.8	1	1.1	4
AISI 1340	849	567	420	0.5	0.7	2.05	7.8	3	2.2	4
AISI 4820	767	492	385	0.55	0.6	1.90	7.8	3	2.5	8
Aluminum alloys										
AA 3003 O	112	42	56	0.7	0.1	1.15	2.73	4	5	1
AA 5052 O	196	91	90	0.65	0.4	1.60	2.68	4	7	1
AA 6061 O	126	56	55	0.6	0.3	1.45	2.7	3	7	1
Copper-based alloys										
Al bronze	420	175	147	0.7	0.4	1.60	8.1	4	12	6
Si bronze	441	210	175	0.6	0.5	1.75	8.5	4	12	6
70/30 brass	357	133	145	0.75	0.3	1.45	8.5	4	10	4
Loop materials (cast alloys)										
Gray cast irons ASTM A48–74										
Grade 20	140	140	70	0.5	0.2	1.30	7.5	4	1.2	1
Grade 40	280	280	130	0.45	0.2	1.30	7.5	4	1.25	1
Grade 60	420	420	168	0.4	0.2	1.30	7.5	4	1.3	1
Nodular cast irons ASTM A536										
60–40–18	420	280	210	0.6	0.2	1.30	7.5	4	1.9	4
80–55–06	560	385	280	0.55	0.2	1.30	7.5	4	2	4
120–90–02	840	630	420	0.5	0.2	1.30	7.5	4	2.1	4
Aluminum alloys										
AA 208.0	147	98	44	0.6	0.4	1.60	2.8	3	5	1
AA 356.0 T6	231	168	79	0.5	0.5	1.75	2.68	4	5	1
AA B443.0	133	56	40	0.6	0.7	2.05	2.7	4	4	1
Copper-based alloys										
Al bronze	590	120	200	0.55	0.4	1.60	8.1	4	12	6
Si bronze	420	125	120	0.6	0.4	1.60	8.3	4	12	6
Mn bronze	640	340	300	0.5	0.5	1.75	8.3	4	11	6

Note: k_i, endurance limit modifying factor; ρ, specific gravity; C, corrosion resistance; Mat., material; Mfr., manufacturing: 1 = poor, 2 = fair, 3 = good, 4 = very good.

[a] Relative materials and processing costs are based on the cost of steel AISI 1015, which is taken as unity.

calculate the total cross-sectional area of the webs, A_w. Using the same factors of safety as mentioned,

$$\frac{1.5\times1\times20}{420\times A_w}+\frac{3.0\times1.3\times5}{210\times A_w}=1 \tag{11.12}$$

This gives $A_w = 164.3\ \text{mm}^2$:

$$\begin{aligned}\text{The mass of the loop } w_l &= \text{density(volume of threaded ends}\\ &\quad+\text{volume of webs)} = 336\ \text{g}\end{aligned}$$

$$\begin{aligned}\text{Total mass of the turnbuckle} = w_{tb} &= 2\times\text{weight of ringbolt} + \text{weight of loop}\\ &= 1542\ \text{g} = 1.542\ \text{kg}\end{aligned}$$

$$\begin{aligned}&\text{Relative cost of materials and processing}\\ &\quad= C_m = 2\times\text{relative cost of each ringbolt} + \text{relative cost of loop}\\ &\quad= 2\times0.603(1+1)+0.336(1.9+4) = 4.39 \text{ units of relative cost}\end{aligned}$$

To arrive at the optimum pair of materials for the turnbuckle, the calculations mentioned should be repeated for all possible combinations of ringbolt and loop materials given in Table 11.2. For example, each one of the three aluminum ringbolt alloys represents a possible candidate for each one of the three aluminum loop alloys, which involves nine combinations. However, aluminum alloys do not represent possible candidates for copper-based or ferrous alloys, as they are too far apart in the galvanic series, which could cause galvanic corrosion. From Table 11.2, it can be shown that there are 42 possible material combinations (24 combinations for ferrous alloys, 9 combinations for aluminum alloys, and 9 combinations for copper alloys).

It would be tedious and time consuming to perform all these required calculations manually. One of the screening methods discussed in Chapter 9 can be used to reduce the number of candidate materials in Table 11.2. Another approach, which is adopted here, is to write a computer program in a programming language, C++, for example, to perform the calculations. For each possible pair of materials, the program calculates the total weight of the turnbuckle and its relative cost.

To select the optimum pair of materials for the turnbuckle under consideration, the weighted property method, which was discussed in Section 9.5, is used. When the corrosion resistances of the two materials in a turnbuckle are different, the lower value is taken to represent the corrosion resistance of the turnbuckle.

For the present case study, the weighting factors are taken as 0.5, 0.3, and 0.2 for the cost, corrosion resistance, and weight, respectively. The performance index (γ) of a turnbuckle made of a pair of materials is calculated as follows:

$$\begin{aligned}\gamma &= 0.5(\text{scaled relative cost}) + 0.3(\text{scaled corrosion resistance})\\ &\quad+0.2(\text{scaled total weight})\end{aligned}$$

TABLE 11.3
Comparison of Turnbuckle Materials

Material Pair				
Ringbolt	**Loop**	**Relative Total Weight**	**Relative Cost**	**Merit Value**
AISI 1340	Nodular CI 120–90–02	1.082	2.264	1.748
AISI 1340	Gray CI grade 60	1.221	2.504	1.896
AISI 1015	Gray CI grade 60	1.220	1.000	1.944
AISI 1340	Gray CI grade 40	1.313	2.580	1.952
AISI 1340	Nodular CI 80–55–06	1.117	2.717	1.982
AISI 1015	Nodular CI 120–90–02	1.091	1.157	1.997
AISI 1015	Gray CI grade 40	1.314	1.076	2.001
AISI 1340	Nodular CI 60–40–18	1.152	2.790	2.025
AISI 1015	Nodular CI 80–55–06	1.126	1.232	2.041
AISI 1015	Nodular CI 60–40–18	1.161	1.305	2.085

Scaling was performed such that a turnbuckle with lower weight and cost was given a lower scaled value. To be consistent, material combinations with higher corrosion resistance were given a lower scaled value. With this method of scaling, turnbuckles with lower numerical value of the performance index (γ) are preferable to those with higher numerical value of the performance index.

The calculated relative total weight, relative cost, and performance index for 10 turnbuckles with the lowest numerical values of the performance index (γ) are given in Table 11.3. The results show that, with the present selection criteria, ferrous alloys are preferable. The main reasons for this are their lower cost and higher strengths. The higher strengths are reflected in the total weight of the turnbuckle as shown in Table 11.3. If the weighting factor given to corrosion resistance was increased at the expense of that given to cost, turnbuckles made of nonferrous alloys would be preferable.

11.3 DESIGN AND SELECTION OF MATERIALS FOR SURGICAL IMPLANTS

11.3.1 Introduction

Surgical implant materials are used in repairing many parts of the human body. The number of materials in current use as implant materials is large and includes metallic, polymeric, ceramic, and composite materials. Both hard tissues such as bones and soft tissues such as skin can be restored or replaced with implants of similar mechanical properties, texture, and color. For example, rigid metallic, ceramic, and composite materials are used for fixing or replacing bones and joints, foams and gels are used for soft tissue supplementation, and elastic materials are used for replacement of skin and blood vessels. Although the mechanical requirements of implant materials are relatively simple, the biocompatibility requirements are

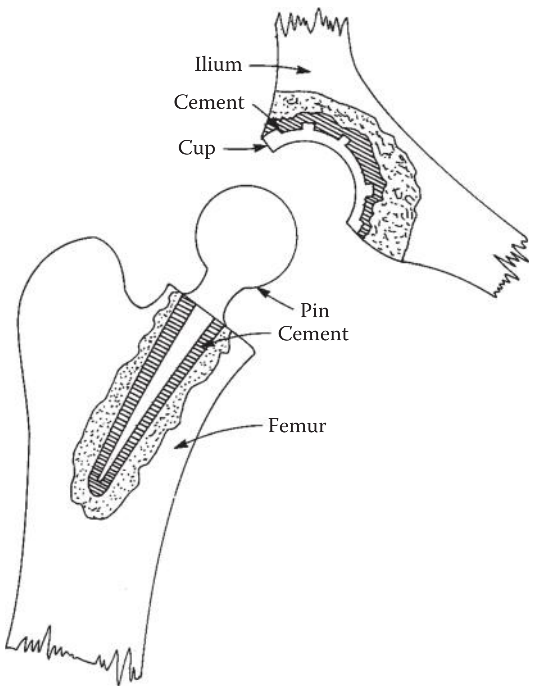

FIGURE 11.2 Components of a complete hip joint prosthesis.

stringent and more difficult to meet. Biocompatibility means that the material and its possible degradation products must be tolerated and cause no tissue dysfunction at any time.

This case study discusses the design and selection of materials for a hip joint prosthesis. Figure 11.2 shows the components used for a complete hip joint. In this case, the femoral head is replaced by a rigid pin that is installed in the shaft of the femur, whereas the pelvic socket (acetabulum) is replaced by a rigid or soft cup that is fixed to the ilium. Both the pin and cup can be fixed to the surrounding bone with an adhesive. In recent designs, natural bone growth is used to provide the bond.

11.3.2 Main Dimensions and External Forces

As the prosthesis is intended to replace the bone structure of the hip joint, it is important to study the bone structure and properties. Bone is a living tissue composed of inorganic and organic materials in dynamic equilibrium with the body fluids. Although the proportions vary from one part of the skeleton to another, water-free bone contains about two-thirds of inorganic and one-third of organic materials. The inorganic phase, primarily hydroxyapatite crystals, is hard and brittle and represents the main load-bearing component of the bone structure. The organic phase, primarily collagen fibers, is a gelatin-like protein and its presence makes the bone tough, in addition to its biological functions. These phases are generally arranged in a complex structure to give maximum strength in the required direction. Figure 11.3

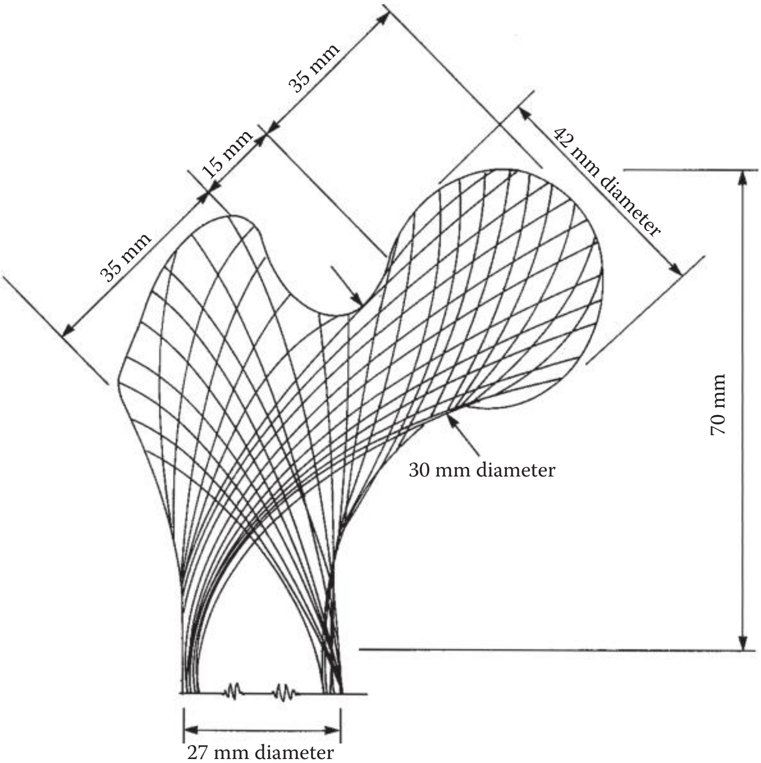

FIGURE 11.3 Main average dimensions and distribution of load-bearing phases in the head of the femur bone.

shows how the load-bearing phase is arranged in the direction of maximum stress in the head of the femur bone.

The compressive strength of compact bone is about 140 MPa, and the elastic modulus is about 14 GPa in the longitudinal direction and about one-third of that in the radial direction. These properties are modest in comparison with those of most engineering metallic and composite materials. However, live healthy bone is self-healing and has great resistance to fatigue loading. The implant material, however, does not have this ability to repair itself and usually has a finite fatigue life. For this reason, the implant material must be stronger than bone especially under fatigue loading.

In the case of the hip joint, carrying the repeated loading caused by walking and similar activities is an important part of its function. The loading frequency ranges from 1 to 2.5 million cycles per year, depending on the activity and movement of the individual. Stress analysis of the forces acting on the hip joint shows that the fatigue loading is usually equal to 2.5–3 times the body weight and can possibly be higher depending on posture of the individual. In addition to the repeated loading, the joint is subjected to a static loading as a result of muscle action, which keeps the parts of the joint together. This static load is normally much smaller than the repeated loading. As the hip joint prosthesis is generally intended to be permanent, it is expected to resist fatigue fracture for years or decades.

11.3.3 Fatigue-Loading Considerations

In designing the hip joint prosthesis, it should be borne in mind that, regardless of the strength of the implant material properties, the dimensions of the prosthesis must match the dimensions of the original bone. The design calculations in the present case study will be based on the dimensions given in Figure 11.3, which represent approximate average values for an adult. Assuming that the weight of the person is 75 kg (165 lb), and taking the alternating load as three times the weight, it can be shown that the hip prosthesis will be subjected to an alternating load of 2205 N. The maximum stress occurs in the prosthesis neck, which is about 30 mm in diameter according to Figure 11.3. From these values, the alternating stress is estimated as 3.1 MPa. Assuming that the static load due to muscle contraction is about 300 N, the static stress at the neck of the prosthesis is estimated as 0.42 MPa. Using the modified Goodman relationship as given by Equation 6.12,

$$\left(\frac{n_m K_t S_m}{\text{UTS}}\right)+\left(\frac{n_a K_f S_a}{S_e}\right)=1$$

where

n_m is the factor of safety for static load, taken as 2 in this case
n_a is the factor of safety for alternating load, taken as 3 in this case
K_t is the stress concentration factor for static load, taken as 2.2
K_f is the stress concentration factor for alternating stress, taken as 3.5
S_m (static stress) = 0.42 MPa, as calculated
S_a (alternating stress) = 3.1 MPa, as calculated
UTS is the ultimate tensile strength of the prosthesis material
S_e is the endurance limit of the prosthesis material

Taking the endurance ratio of the prosthesis material as 0.35, the value of S_e = 0.35 UTS.

Substituting these values in the mentioned Goodman relationship, UTS is found to be about 95 MPa. From the assumed value of endurance ratio of 0.35, S_e is estimated as 33.25 MPa. These values represent the minimum strengths that an implant material must have to be considered for making the pin of the hip joint prosthesis. Using materials with higher strengths will not make it possible to reduce the cross-sectional area of the prosthesis but will have the advantage of being less likely to fail in service.

11.3.4 Wear Considerations

Wear of the prosthesis parts (cup and pin) should also be considered when designing a hip joint prosthesis. Wear debris are often found in tissue surrounding joints and could cause adverse effects due to sensitivity of the patient to the material. In addition, material wear in the total hip prosthesis, especially the enlargement of the cup (acetabular concavity), causes poor articulation of the joint. The pressure between the mating surfaces of the prosthesis can be estimated by dividing the maximum force by the projected area of the cup. In the present case, the maximum force is given by $2205+300=2505$ N, and the projected area of the cup is 1385 mm^2. This gives an average pressure of 1.8 MPa. If both the pin and cup are made of metallic materials, the high friction coefficient could lead to mechanical difficulties. For this reason, the cup is usually made of a low-friction plastic such as HDPE and PTFE. The compressive strengths of most polymeric materials are higher than the calculated contact pressure, which means that selecting the material of the cup is mostly based on their biocompatibility.

11.3.5 Analysis of Implant Material Requirements

Earlier discussion has shown that the total hip joint prosthesis consists of a pin, which replaces the head of the femur bone, and a cup, which replaces the acetabular concavity. The pin and cup are fixed to the surrounding bone structure by an adhesive cement. As would be expected, the requirements for each of these components are different as they perform different functions. In the present case study, only the material requirements for pin will be discussed. Similar procedure can be applied to the cup and cement.

11.3.5.1 Tissue Tolerance

In general, biological requirements represent the major constraints in selecting implant materials. The action of the implant material on the body tissues can range from toxicity, in which case the implant material is totally rejected, to inertness. Even with inert material, their presence impedes the normal healing sequence at the implant site and leads to fibrocartilaginous membrane of low cellularity, which isolates the implant from normal tissue. This membrane is the body's response to the stimulus of an inert foreign material that is impervious to body fluids. The thickness of the membrane is proportional to the degree of implant material dissolution. Toxicity is usually signaled by a large population of inflammatory cells. This requirement is usually called tissue tolerance and is difficult to quantify. For the sake of comparison, materials are given a rating of 10 for the best material and 1 for the worst. Only materials with tissue tolerance of 7 or more will be considered in the present case study. The tissue tolerance requirements apply equally well to the pin, cup, and cement materials.

11.3.5.2 Corrosion Resistance

Another important implant material requirement is corrosion resistance. This is because body fluids are aqueous salt solutions with concentrations roughly comparable to seawater and with a pH value of 7.4. This environment is hostile and could cause corrosion of many metallic materials. Such corrosion should be avoided as it may induce deleterious effects in the surrounding tissues or even distant organs. The combination of corrosive action of the body fluids and fatigue loading could result in SCC, which imposes strict limitations on the implant material surface finish and structural homogeneity. As in the case of tissue tolerance, corrosion resistance is rated according to a scale of 10–1. Only materials with a corrosion resistance rating of 7 or better are considered in this case study. The corrosion resistance requirements apply equally well to the pin, cup, and cement materials.

11.3.5.3 Mechanical Behavior

The preceding design analysis shows that the strength requirements of implant materials are relatively easy to meet. Other material requirements include toughness, wear resistance, elastic compatibility, and specific gravity. Brittle materials are undesirable in hip joint prosthesis in view of the possible shock loading that may result in service. High wear resistance is necessary to avoid the accumulation of wear debris in the surrounding tissue or other organs of the body. Both toughness and wear resistance will be rated on a scale of 10–1, as in the case of tissue tolerance and corrosion resistance. Only materials with a wear resistance equal to or better than 7 and toughness equal to or better than 2 are considered in the present application.

11.3.5.4 Elastic Compatibility

Elastic compatibility of an implant material with the surrounding bone structure is also an important requirement. This is because large mismatches can lead to deterioration of the interface between the two materials. Unfortunately, the elastic moduli of the currently available materials for bone replacement are much higher than that of bone. Although this problem can be partially overcome by selecting the appropriate cementing agents, it is preferable for the implant material to be elastically compatible with the bone. The elastic modulus of bone (14 GPa) will be taken as a target value when candidate implant materials are evaluated.

11.3.5.5 Weight

Similarity between the specific gravity of the implant material and bone is also desirable to keep the weight of the implant material as close as possible to that of the original bone. The specific gravity of compact bone is about 2.1, which is less than that of the metallic implant materials in current use. The specific gravity of bone will be taken as a target value when candidate implant materials are evaluated.

11.3.5.6 Cost

Reasonable cost is another requirement for the hip joint prosthesis. The total cost includes the cost of the stock material and the cost of processing and finishing. As the volume of the prosthesis is independent of the material, it is more appropriate to compare materials on the basis of the cost per unit volume rather than the cost per unit mass. In view of the small numbers produced, mass production method cannot be used in making the hip joint prosthesis. This means that the

TABLE 11.4
Main Requirements and Weighting Factors for the Pin of the Hip Joint Prosthesis

Property	Weighting Factor
Tissue tolerance (lower-limit property)	0.2
Corrosion resistance (lower-limit property)	0.2
Tensile strength (lower-limit property)	0.08
Fatigue strength (lower-limit property)	0.12
Toughness (lower-limit property)	0.08
Wear resistance (lower-limit property)	0.08
Elastic modulus (target-value property)	0.08
Specific gravity (target-value property)	0.08
Cost (upper-limit property)	0.08

costs of processing and finishing are expected to represent a large proportion of the total cost.

Based on the preceding discussion, the material requirements for the pin of the hip joint prosthesis can be summarized as shown in Table 11.4. Higher values of the first six properties are more desirable and should comply with the lower limits outlined in the discussion. According to the limits on properties method, which is discussed in Section 9.5, these properties are lower-limit properties. Elastic modulus and specific gravity are target-value properties, as materials should match the bone as closely as possible. The cost is an upper-limit property.

The relative importance of the different material requirements is given in Table 11.4. The digital logic method can be used to assist in allocating the weighting factors.

11.3.6 Classification of Materials and Manufacturing Processes for the Prosthesis Pin

A survey of the literature shows that possible materials for the pin of the hip joint prosthesis include stainless steels, cobalt- and chromium-based alloys, titanium alloys, tantalum, and FRP. The latter materials have been under study for several years and are now being considered for approval by the Food and Drug Administration (FDA) for use in the United States. Although several ceramic materials have been developed for surgical implants, their use as hip joint prosthesis is still in the experimental stage. These materials should be seriously considered when their performance is better characterized.

When the pin is made of a metallic material, it can be manufactured either by casting or by forging. In both cases, the part is finished to the required final dimensions and given a mirror finish. This means that both cast and wrought alloys can be considered for the pin of the hip joint prosthesis. In the case of FRP, a processing method should be devised to orient the fibers in the direction of maximum loading. The matrix material can then be cast to infiltrate the fibers.

Table 11.5 gives the properties of representative examples of possible candidates for the pin of the hip joint prosthesis.

11.3.7 Evaluation of Candidate Materials

The limits of property method, discussed in Section 9.5, are used to evaluate the candidate materials listed in Table 11.5. Following the notations of Equation 9.8, the lower limits, Y_i; upper limits, Y_j; and target values, Y_k, used in the calculations were as follows:

1. Tissue tolerance, lower limit, $Y_i = 7$.
2. Corrosion resistance, lower limit, $Y_i = 7$.
3. Tensile strength, lower limit, $Y_i = 95$ MPa.
4. Fatigue strength, lower limit, $Y_i = 33.25$ MPa.
5. Toughness, lower limit, $Y_i = 2$.
6. Wear resistance, lower limit, $Y_i = 7$.
7. Elastic modulus, target value, $Y_k = 14$ GPa.
8. Specific gravity, target value, $Y_k = 2.1$.
9. Relative total cost, upper limit, $Y_j = 10$.

11.3.8 Results

Equation 9.8 and the preceding limits were used to calculate the merit parameter (m) for the candidate materials, and the results are shown in Table 11.6. The table shows that the Ti–6Al–4V alloy ranks as number one followed by Co–Cr alloy. Stainless steels, although commonly used as metal plates for repairing fractures, ranked 4–7, for the present application. If less weight is given to corrosion resistance and more weight is given to the cost of the prosthesis, as in the case of temporary implants, stainless steels would occupy top ranks.

11.4 DESIGN AND SELECTION OF MATERIALS FOR LUBRICATED JOURNAL BEARINGS

11.4.1 Introduction

A journal bearing is a machine element designed to transmit loads or reaction forces from a rotating shaft to the bearing support. Besides carrying loads, the bearing material is subjected to the sliding movement of the shaft. The friction forces that result from the sliding motion are normally reduced by lubrication. In the case of lubricated journal bearings, a continuous oil film is formed between the shaft and the bearing as shown in Figure 11.4. When the shaft is at rest, metal-to-metal contact occurs at point (x). As the shaft rotates slowly, the point of contact moves to position (y). A thin adsorbed film of lubricant may partially separate the surfaces, but a continuous film will not exist because of the slow speed. With the increasing speed of rotation, a continuous lubricant film is established and the center of the shaft is moved so that the minimum film thickness is at (z). The wedge shape of the film

TABLE 11.5
Properties of Selected Surgical Implant Materials

Material	Tissue Tolerance	Corrosion Resistance	Tensile Strength (MPa)	Fatigue Strength (MPa)	Elastic Modulus (GPa)	Relative Toughness	Relative Wear Resistance	ρ	*C*
Stainless steels									
316	10	7	517	350	200	8	8.0	8.0	1.0
317	9	7	630	415	200	10	8.5	8.0	1.1
321	9	7	610	410	200	10	8.0	7.9	1.1
347	9	7	650	430	200	10	8.4	8.0	1.2
Co–Cr alloys									
Cast alloy (1)	10	9	655	425	238	2	10.0	8.3	3.7
Wrought alloy (2)	10	9	896	600	242	10	10.0	9.1	4.0
Titanium alloys									
Unalloyed titanium	8	10	550	315	110	7	8.0	4.5	1.7
Ti–6Al–4V	8	10	985	490	124	7	8.3	4.4	1.9
Composites (fabric reinforced)									
Epoxy–70% glass	7	7	680	200	22	3	7.0	2.1	3
Epoxy–63% carbon	7	7	560	170	56	3	7.5	1.6	10
Epoxy–62% aramid	7	7	430	130	29	3	7.5	1.4	5

Note: ρ is the specific gravity; *C* is total relative cost and includes cost of material per unit volume, processing cost, and finishing cost; cast alloy (1): 27–30 Cr, 2.5 Ni, 5–7 Mo, 0.75 Fe, and 0.36 max C and Si, Rem. Co.; wrought alloy (2): 20 Cr, 10 Ni, 15 W, 0.13 Mo, 3 max Fe, 0.1 C, 2 max Mn, and 0.48 Si, Rem. Co.

TABLE 11.6
Merit Parameter (*m*) and Ranking of Candidate Materials for the Pin of a Hip Joint Prosthesis

Material	Merit Parameter (*m*)	Rank
Ti–6Al–4V	0.554	1
Co–Cr wrought alloy	0.555	2
Unalloyed titanium	0.563	3
316 stainless steel	0.593	4
347 stainless steel	0.597	5
317 stainless steel	0.607	6
321 stainless steel	0.608	7
Epoxy–70% glass fabric	0.615	8
Co–Cr cast alloy	0.622	9
Epoxy–62% aramid fabric	0.649	10
Epoxy–63% carbon fabric	0.720	11

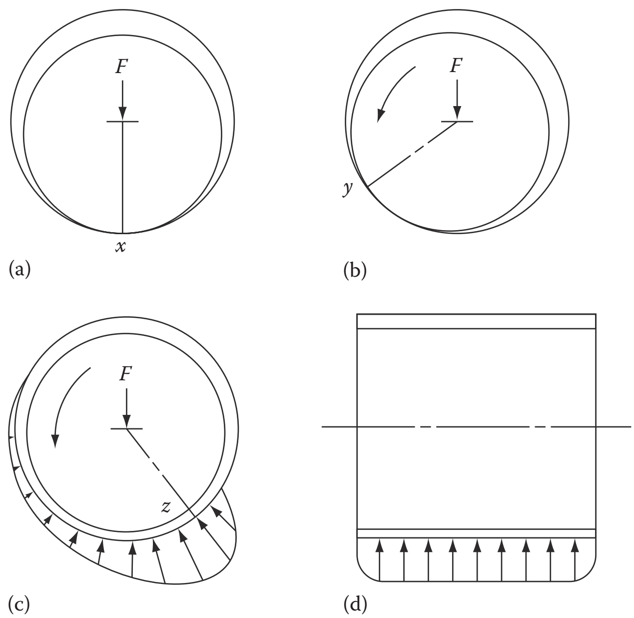

FIGURE 11.4 Position of the shaft in relation to the bearing and the pressure distribution in a lubricated journal bearing. (a) Shaft at rest, (b) shaft rotating at slow speed, (c) shaft rotating at high speed, and (d) distribution of pressure in the axial direction.

helps to build up sufficient pressure to support the external force. The pressure distribution in both the radial and axial directions is shown in Figure 11.4c and d. The drop in pressure at the edges of the bearing in the axial direction is due to the leakage of the lubricant from the sides.

Experience shows that higher lubricant pressure builds up in the bearing as the clearance between the shaft and bearing decreases. In addition, the bearing gives better guidance to the shaft as the clearance decreases. However, allowance must be made for manufacturing tolerances in the journal and sleeve, deflection of the shaft, and space to permit foreign particles to pass through the bearing. The clearance (c) is usually related to the diameter of the shaft (d) and usually ranges between $c/d = 0.001$ and 0.0025.

The bearing length should be as long as possible to reduce the compressive stresses on the bearing material. Also a longer bearing will reduce the side leakage of the lubricant from the bearing, thus allowing higher loads to be supported without suffering metal-to-metal contact between the journal and bearing. However, space requirements, manufacturing tolerances, and shaft deflection are better met with a shorter bearing length. The length of the bearing is usually related to the diameter of the shaft and usually ranges between $L/d = 0.8$ and 2.0.

In the present case study, it is required to design and select the materials for the two journal bearings that support the rotor of a centrifugal pump in its casing. The mass of the rotor is equally distributed between the two bearings, which carry a load of 7500 N each. The diameter of the rotor shaft is 80 mm and its speed of rotation is 1000 rpm.

11.4.2 Design of the Journal Bearing

The magnitude and nature of the load are the main factors that affect the bearing design and the performance of the bearing material. Heavy loads require high compressive YS to avoid plastic deformation, whereas cyclic loads require high fatigue strength to avoid fracture. An approximate value of the mean compressive stress (S_c) acting on the bearing material is given by

$$S_c = \frac{F}{LD} \tag{11.13}$$

where
- F is the force acting on the bearing (7500 N)
- L is the axial length of the bearing
- D is the diameter of the bearing ($d + c$)
- d is the shaft diameter (80 mm)
- c is the clearance

For the present case study, it is reasonable to assume that L/d is 1.25, that is, $L = 100$ mm, and c/d is 0.001. These values are within the practical limits discussed. Based on these assumptions, it can be shown that the compressive stress acting on the bearing material is about 0.93 MPa. This value is within 0.6 and 1.2, which are the limits recommended by Shigley and Mitchell (1983) for centrifugal pumps.

The coefficient of friction (f) is an important parameter in bearing design as it affects both the power loss and temperature rise due to friction. The coefficient of friction for a well-lubricated journal bearing can be expressed by the McKee empirical relation (reported by Black and Adams, 1983):

$$f = \frac{K(ZNd)}{S_c c} + K' \tag{11.14}$$

where
- Z is the viscosity of the lubricant (cP)
- N is the rotational speed of the shaft (rpm)
- K is a constant whose value depends on the system of units used
- K' is a constant to account for end leakage of the lubricant (0.002 for L/d in the range 0.75–2.8)

The quantity ZN/S_c is called the bearing characteristic number and is dimensionless if the quantities are expressed in a consistent system of units. Higher values of this parameter ensure the continuity of the lubricant film and avoid metal-to-metal contact between the bearing material and the journal. The value of Z depends on the grade of the oil and its temperature at the bearing–journal interface. This temperature is a function of the heat balance between the heat generated due to friction, H_1, and the heat dissipated by the bearing to the surroundings, H_2. Under the thermal equilibrium, heat will be dissipated at the same rate that it is generated in the lubricant.

The usual procedure in bearing design is to assume a bearing temperature and then estimate H_1 and H_2. If thermal equilibrium is indicated, then the assumed bearing temperature is correct. If H_1 and H_2 are not approximately equal, the designer must assume a different operating temperature, a different oil, or different values of L and d. For the present case study, it is reasonable to assume an ambient temperature, t_a, of 20°C (68°F) and a bearing surface temperature, t_b, of 70°C (158°F). Black and Adams (1983) reported that experimental work shows that

$$t_b - t_a = 0.5(t_o - t_a) \tag{11.15}$$

where t_o is the temperature of the oil film.

Using the preceding assumptions and Equation 11.15, $t_o = 120$°C (248°F). Selecting a lubricating oil of grade SAE No. 30 gives $Z = 5.5$ cP at 120°C. Under these conditions, the bearing characteristic number is

$$\frac{ZN}{S_c} = 5.5 \times \frac{1000}{0.93} = 5914$$

This value is within the range 4,300–14,300, which is recommended by Jain (1983) for centrifugal pumps.

From Equation 11.14,

$$f = 0.00395$$

The heat generated due to friction, H_1, is given by

$$H_1 = fFV \tag{11.16}$$

where

F (force acting on the bearing) = 7500 N

V (rubbing velocity) (m/s) = $\pi dN/60$ = 4.187 m/s

From Equation 11.16,

$$H_1 = 0.00395 \times 7500 \times 4.187 = 124 \text{ W}$$

According to Black and Adams (1983), the heat dissipated by the bearing, H_2, is given by the empirical relationship

$$H_2 = CA(t_b - t_a) = \frac{1}{2}CA(t_o - t_a) \tag{11.17}$$

where

A is the projected area of the bearing (Ld)

C is the heat-dissipation coefficient

C = 3.75 ft. lb/min/in.^{2}/°F (244 W/m^2/°C) for average industrial unventilated bearings

C = 5.8 ft. lb/min/in.^{2}/°F (377 W/m^2/°C) for well-ventilated bearings

Using the assumed values of temperature and Equation 11.17, it can be shown that

Under average industrial unventilated conditions, H_2 = 97.6 W.

Under well-ventilated conditions, H_2 = 150.8 W.

Comparing the calculated values of H_1 and H_2 shows that thermal balance can be achieved under moderate ventilation conditions.

Having determined the bearing loads, lubricant, and operating temperatures, it is now possible to select the optimum material for the bearing.

11.4.3 Analysis of Bearing Material Requirements

The preceding discussion shows that the compressive strength of the bearing material at the operating temperature (120°C or 248°F in the present case) must be sufficient to support the load acting on the bearing. If the material is not strong enough, it could suffer considerable plastic deformation by extrusion. Fatigue strength also becomes important under conditions of fluctuating load. Both compressive and fatigue strengths are known to increase as the thickness of the bearing material decreases. This is achieved in practice by bonding a thin layer of the bearing material (0.05–0.15 mm or 0.002–0.006 in.) to a strong backing material to form a bimetal structure. Common examples include lead and tin alloys on steel or bronze backs.

An intermediate layer of copper or aluminum alloys may also be introduced between the bearing material and the steel back to produce a trimetal structure. In such cases, the bearing material can be made as thin as 0.013 mm (0.0005 in.).

Conformability of the bearing material allows it to change its shape to compensate for slight deflections, misalignments, and inaccuracies in the journal and bearing housing. Bearing materials with lower Young's modulus will undergo larger deflections under lower loads and are, therefore, more desirable.

Embeddability is the ability of the bearing material to embed grit, sand, hard metal particles, or similar foreign materials and thus prevents them from scoring and wearing the journal. Such foreign materials can be introduced with the lubricant or ventilating air. Materials with lower hardness are expected to have better embeddability.

Wear resistance of bearing materials is an important parameter in cases where the position of the journal is to be kept within narrow tolerances or where the bearing material is a thin layer on a hard backing. Generally, the wear rate depends on the tendency of the system toward adhesive weld formation and on the resistance of the bearing material to abrasion by asperities on the journal surface. The rate of wear can be an important factor in determining the bearing life.

Thermal conductivity becomes an important factor in selecting bearing materials under conditions of high speeds or high loads, where heat is generated at high rates (see Equation 11.16). The ability of the bearing material to conduct heat away from friction surfaces reduces the operating temperature and thus reduces the possibility of lubricant-film failure, melting of the bearing material, and seizure of the bearing.

Corrosion resistance of the bearing material becomes an important parameter when the lubricating oil is likely to contain acidic products or to be contaminated by corrosive materials.

As many of the bearing materials contain expensive elements, the cost may become a deciding factor in selection. Using a thin layer of the expensive bearing material in bimetal or trimetal structures can reduce the total cost of the bearing.

The preceding discussion shows that the main requirements for a bearing material are

1. Compressive strength at the operating temperature. This is a lower-limit property, which means that for a candidate material to be considered, its strength should exceed a given minimum value. This value is determined from the bearing design. In the present case study, the minimum strength of the bearing material at the operating temperature of 120°C (24°F) is

$$S_m = S_c n$$

where
S_m is the minimum compressive strength of the bearing
n is the factor of safety, which can be taken as 2 in the present case

From the preceding design calculations,

$$S_m = 1.86 \text{ MPa}$$

As information on the strength of bearing materials at 120°C is not readily available, comparison between the different materials will be based on room-temperature properties. For the present case study, the minimum allowable room-temperature compressive strength will be taken as 20 MPa. Most available metallic bearing alloys can meet this requirement.

2. Fatigue strength at the operating temperature. As in the case of the compressive strength, this is a lower-limit property. As fatigue is not expected to be the main selection criterion in the present case study, no special calculations are needed. It will be assumed that materials that satisfy the lower limit of the compressive strength will also satisfy the lower limit of the fatigue strength. Using a similar reasoning as in the case of compressive strength, the minimum allowable fatigue strength will be taken as 20 MPa.
3. Hardness is an upper-limit property, which means that for a candidate material to be considered, its hardness should be below a given maximum value. This maximum value depends on the hardness of the journal material. For the present case study, it will be assumed that the maximum allowable bearing material hardness is 100 BHN. This will allow the use of most well-known bearing materials except the hardest copper-based alloys.
4. Young's modulus is also an upper-limit property. In this case, the maximum allowable Young's modulus will be taken as 100 GPa, which will allow most well-known bearing materials to be considered.
5. Wear resistance is a lower-limit property that is system dependent. It depends on the journal materials, lubricant, surface roughness of the journal, and cleanliness of the service environment. This property is usually given as excellent (5), very good (4), good (3), fair (2), and poor (1). In the present case study, materials with a rating of poor will not be considered.
6. Corrosion resistance is a lower-limit property and is usually described by a rating system similar to that used for wear resistance. In the present case study, materials with a corrosion resistance rating of poor will not be considered.
7. Thermal conductivity is a lower-limit property and, in view of the high rotational speeds of the shaft, a relatively high minimum conductivity of 20 W/mK will be specified, and this means that all nonmetallic bearing materials are excluded.
8. Cost of the bearing material, backing material, and fabrication should be considered. In the present case study, a single value for the cost of the material on the job, which includes all the mentioned factors, will be given. For the present case study, the maximum allowable cost will be taken as that of tin-based ASTM B23 grade 5.

11.4.4 Classification of Bearing Materials

Many alloy systems have been specially developed to accommodate the conflicting requirements that have to be satisfied by bearing materials. They are used in relatively small quantities and are produced by a relatively small number of manufacturers. Although the composition and processing methods of most commercial

TABLE 11.7
Composition of Some Bearing Alloys (%)

Alloy Grade	Sn	Sb	Pb	Cu	Fe	Zn	A	Others
White metals ASTM B23 (tin based)								
1	91	4.5	0.35	4.5	0.08	0.005	0.005	0.08 Bi, 0.1 As
2	89	7.5	0.35	3.5	0.08	0.005	0.005	0.08 Bi, 0.1 As
3	84	8.0	0.35	8.0	0.08	0.005	0.005	0.08 Bi, 0.1 As
4	75	12	10	3.0	0.08	0.005	0.005	0.15 As
5	65	15	18	2.0	0.08	0.005	0.005	0.15 As
White metals ASTM 23 (lead based)								
6	20	15	63.5	1.5	0.08	—	—	0.15 As
7	10	15	75.0	0.5	0.1	—	—	0.6 As
8	5	15	80.0	0.5	—	—	—	0.2 As
10	2	15	83.0	0.5	—	—	—	0.2 As
11	—	15	Rem.	0.5	—	—	—	0.25 As
15	1	15	Rem.	0.5	—	—	—	1.4 As
Copper-based alloys SAE (copper–lead)								
48	0.25	—	28	Rem.	0.35	0.1	—	1.5 Ag, 0.025 P
49	0.5	—	24	Rem.	0.35	—	—	
480	0.5	—	35	Rem.	0.35	—	—	15 Ag
Copper-based alloys ASTM B22 (bronze)								
A	19	—	0.25	Rem.	0.25	0.25	—	1 P
B	16	—	0.25	Rem.	0.25	0.25	—	1 P
C	10	—	10	Rem.	0.15	0.75	—	0.1 P, 1 Ni
Aluminum-based alloys								
770	6	—	—	1	0.7	—	Rem.	1 Ni, 0.7 Si
780	6	—	—	1	0.7	—	Rem.	0.5 Ni, 1.5 Si
MB7	7	—	—	1	0.6	—	Rem.	1.7 Ni, 0.6 Si

Note: Rem., remainder.

systems are of proprietary nature, widely used bearing materials can be classified as follows:

1. White metals (babbitt alloys). These are either tin- or lead-based alloys with additions of antimony and copper. Iron, aluminum, zinc, and arsenic are also usually present in small amounts, as shown in Table 11.7. The relevant properties of a selected number of these alloys are given in Table 11.8.
2. Copper-based bearing alloys offer a wider range of strengths and hardness than white metals. Lead and tin are the main alloying elements, but silver, iron, zinc, phosphorus, and nickel are sometimes found in small quanti-

TABLE 11.8
Properties of Some Bearing Materials

Alloy Grade	YS (MPa)	Fatigue Strength (MPa)	Hardness (BHN)	Corrosion Resistance	Wear Resistance	Thermal Conduction (W/m K)	Young's Modulus (GPa)	Relative Cost
White metals ASTM B23 (tin based)								
1	30.0	27	17	5	2	50.2	51	7.3
2	42.7	34	25	5	2	50.2	53	7.3
3	46.2	37	37	5	2	50.2	53	7.3
4	38.9	31	25	5	2	50.2	53	7.3
5	35.4	28	23	5	2	50.2	53	7.5
White metals ASTM 23 (lead based)								
6	26.6	22	21	4	3	23.8	29.4	1.3
7	24.9	28	23	4	3	23.8	29.4	1.2
8	23.8	27	20	4	3	23.9	29.4	1.1
10	23.8	27	18	4	3	23.9	29.4	1.0
11	21.4	22	15	4	3	23.9	29.4	1.0
15	28.0	30	21	4	3	23.9	29.4	1.0
Copper-based alloys SAE (copper–lead)								
48	40	45	28	3	5	41.8	75	1.5
49	45	50	35	3	5	41.8	75	1.5
480	38	42	26	3	5	41.8	75	1.5
Copper-based alloys ASTM B22 (bronze)								
A	168	120	100	2	5	41.8	95	1.8
B	126	100	100	2	5	41.8	95	1.8
C	119	91	65	2	3	42.0	77	1.6
Aluminum-based alloys								
770	173	150	70	3	2	167	73	1.5
780	158	135	68	3	2	167	73	1.5
MB7	193	170	73	3	2	167	74	1.5

ties. Tables 11.7 and 11.8 give the composition and properties of a selected number of copper-based bearing alloys.

3. Aluminum-based bearing alloys are suitable for high-duty bearings in view of their high strengths and thermal conductivities. They can be used in single metal, bimetal, or trimetal systems. Tables 11.7 and 11.8 also give the composition and properties of selected aluminum-based bearing alloys.
4. Nonmetallic bearing alloys are mostly based on polymers or polymer–matrix composites. They are widely used under conditions of light loading. The major disadvantage of this group of bearing materials is their low thermal conductivities. In view of the high speed of rotation encountered in the present case study, this group will not be considered further.

11.4.5 Selection of the Optimum Bearing Alloy

Based on the preceding analysis and design considerations, the weighting factors were estimated using the digital logic approach described in Section 9.5. Table 11.9 gives the different weighting factors for the present case study.

The table shows that the YS is considered as one of the most important requirements. Ensuring that extensive yielding will not take place in the bearing material will ensure the uniformity of the lubricant film and would avoid vibrations at the high operating speeds of the pump. The thermal conductivity is considered equally important to the YS to ensure adequate conduction of heat away from the bearing–journal interface. With the relatively high speeds in the present case, sharp temperature rise as a result of temporary failure of the lubricant film could be serious. As no mention of excessive load fluctuating was made, it was assumed that fatigue is not expected to represent a serious problem and was, therefore, given a lower weighting factor than YS.

Corrosion and wear resistances were given moderate weighting factors as the danger of contamination and foreign particles was not emphasized in the service conditions. Hardness was given one of the lowest weights as it is expected that the rotor shaft will be adequately hardened. Young's modulus is treated similarly as misalignment, and deflection of the rotor shaft is not expected to be excessive. As the cost of the bearing material is expected to represent a small part of the total cost of the centrifugal pump, this factor was given a low weighting factor.

The candidate bearing materials of Tables 11.7 and 11.8 were evaluated using the limits on properties method described in Section 9.5. The lower and upper limits for the different properties were discussed earlier and can be summarized as follows:

- Lower limit of YS = 20 MPa.
- Lower limit of fatigue strength = 20 MPa.
- Lower limit on thermal conductivity = 20 W/mK.
- Lower limit on corrosion resistance = 2.

TABLE 11.9
Weighting Factors of the Selection Criteria for the Bearing Material of Centrifugal Pump

Property	Weighting Factor
YS	0.20
Fatigue strength	0.14
Hardness	0.08
Corrosion resistance	0.11
Wear resistance	0.11
Thermal conductivity	0.20
Young's modulus	0.08
Cost	0.08
Total	1.00

TABLE 11.10
Merit Parameter and Suitability of Bearing Materials

Material	Merit Parameter (m)	Suitability
White metals ASTM B23 (tin based)		
1	0.59	8
2	0.54	5
3	0.54	5
4	0.56	6
5	0.56	7
White metals ASTM 23 (lead based)		
6	0.63	11
7	0.61	9
8	0.62	10
10	0.61	9
11	0.66	12
15	0.58	6
Copper-based alloys SAE (copper–lead)		
48	0.47	3
49	0.47	3
480	0.49	4
Copper-based alloys ASTM B22 (bronze)		
B	0.49	4
C	0.49	4
Aluminum-based alloys		
770	0.37	1
780	0.38	2
MB7	0.37	1

- Lower limit on wear resistance = 2.
- Upper limit on hardness = 100 BHN.
- Upper limit on Young's modulus = 100 GPa.
- Upper limit on relative cost = 7.5.

The mentioned lower and upper limits were used to calculate the merit parameters (m) of the different materials using Equation 9.8. The results of evaluation are given in Table 11.10.

11.4.6 Conclusion

The results in Table 11.10 show that aluminum-based alloys are most suitable for the present application and were given suitability ratings of 1 and 2. The high conductivity, high compressive and fatigue strengths, and moderate cost are their main attractions. Copper-based alloys would also be adequate and were given suitability ratings of 3 and 4.

11.5 ANALYSIS OF THE REQUIREMENTS AND SUBSTITUTION OF MATERIALS FOR TENNIS RACKETS

11.5.1 Introduction

Leading sports and recreational industries are now using sophisticated materials and high-technology production methods to manufacture their products. In addition, biomechanics is also being used to gain better understanding of the human body to enhance player comfort and to optimize equipment performance. As a result, the shape and the materials used in making many sports equipment and leisure products have undergone considerable change. For example, tennis rackets are now available in many shapes and sizes, as shown in Figure 11.5, although they all comply with the International Tennis Federation (ITF) rules, which limit the total length to a maximum of 32 in. (81.3 cm) and the strung surface, called the head, to a maximum of 15.5 in. (39.4 cm) in length and 11.5 in. (29.2 cm) in width. Although there are no limitations on the racket weight, it usually ranges between 13 and 15 oz (368.5 and 425 g).

11.5.2 Analysis of the Functional Requirements of the Tennis Racket

From an engineering point of view, a tennis racket can be considered as an implement for transmitting power from the arm of the player to the ball. This should be done as efficiently as possible to allow the player to deliver the fastest balls with the least effort. Tennis players usually call this characteristic the power of the racket. In addition to power, players evaluate rackets in terms of playability, which is a subjective evaluation of the overall performance of the racket. For a more objective evaluation, playability may be considered as a function of control and vibrations.

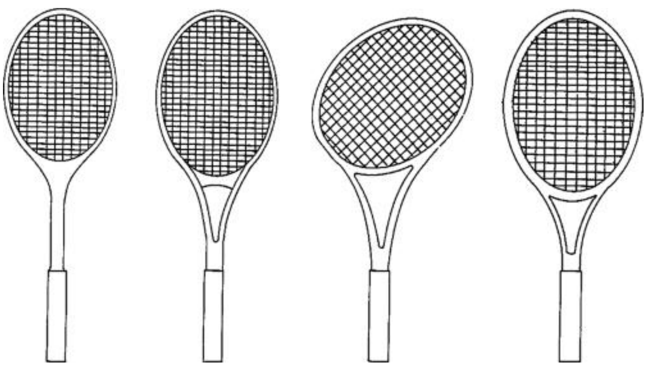

FIGURE 11.5 Examples of different tennis racket shapes.

Control is the ability to give the ball the desired speed and spin and to place it in the desired area of the court. Control can be considered a function of weight, balance, stability, and area of the sweet spot. These parameters are mainly affected by the material, shape, and design of the racket. The weight of the racket is mainly a function of the cross-sectional area of the racket, the shape, and the density of the material. Balance is a function of the position of the center of gravity of the racket in relation to the player's hand. Stability can be defined as the ability of the racket to resist twisting due to off-center hits. It depends primarily on the weight distribution in the racket head. In some cases, balancing weights are added to the sides of the racket head to improve stability. The sweet spot is defined as the area of maximum ball rebound velocity. The size of this area depends on the size and shape of the racket head.

Vibrations take place in the strings as a result of hitting the ball and are then transmitted to the player's arm through the racket frame. If the racket material does not sufficiently dampen the vibrations, the player may develop tennis elbow.

In addition to the shape and the frame material, the performance of the racket is influenced by the material of the strings and the tension in the strings. With higher tension, the strings will absorb less power in deflection and deliver more power to the ball. The limiting value of the tension in the strings is decided by their own strength and will not be taken as a factor in selecting the material of the racket frame. The present case study will only consider the effect of the racket design and material of the frame on the performance of the racket.

11.5.3 Design Considerations

From the stress analysis point of view, the tennis racket can be modeled as a cantilever with the handle as the fixed end, as shown in Figure 11.6. The stiffness of the racket, that is, deflection as a result of hitting the ball, will determine the power of the racket. A stiffer racket will absorb less energy in deflection and will deliver more power to the ball. The maximum deflection will take place when the ball is hit with the outermost tip of the head. As the cross-sectional area and dimensions of the racket head are normally much smaller than those of the handle, it can be assumed that most of the deflection will take place in the head, as shown in Figure 11.6. The maximum deflection (y) is given by

$$y = \frac{\left(Fl^3\right)}{(3EI)} \tag{11.18}$$

where

F is the force acting on one side of the racket head as a result of hitting the ball, assumed to be constant for all racket designs and materials

l is the length of the racket head

E is Young's modulus of the racket material

I is the moment of inertia of the cross section of the racket head in the direction of the applied force

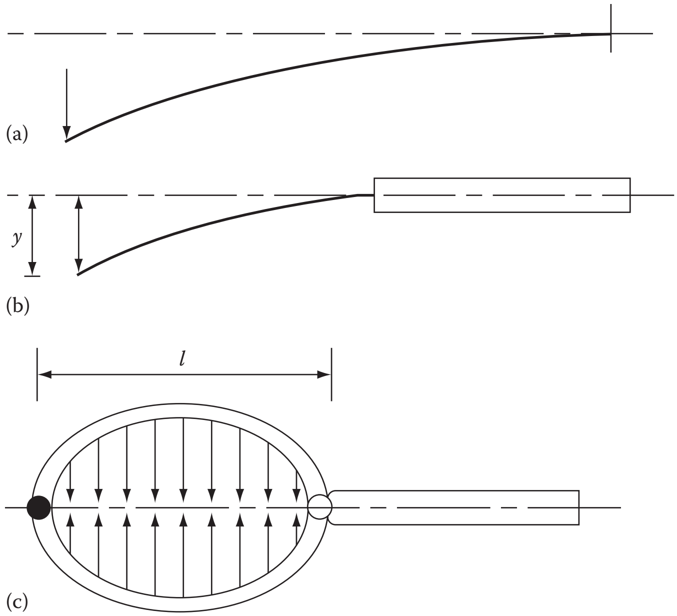

FIGURE 11.6 Simple modeling of tennis racket as a cantilever. (a) Deflection of a cantilever beam of uniform cross section under a concentrated load acting on its end, (b) deflection of tennis racket as a result of hitting the ball with its tip, and (c) forces acting on the racket head as a result of tension in the strings.

The cross-sectional area of the racket frame can be complex, especially in the case of hollow sections. For simplicity of analysis, it will be considered as a rectangle with outer dimensions of H and B and inner dimensions of h and b for all materials. From Table 4.4,

$$I = \frac{(BH^3 - bh^3)}{12}$$

Equation 11.18 shows that rackets with larger head lengths will suffer larger deflection, that is, will be less powerful, unless materials with higher E are used in their manufacture. Larger heads mean larger sweet spot and better control.

As shown, balance is a function of the position of the center of gravity. Changing the size of the racket head is expected to change the position of the center of gravity. This means that the density of the materials has to be taken into account when designing the shape of the racket. The density also affects the balance of the racket. Using lighter materials will allow the use of balancing weights at the appropriate points of the head without increasing the total weight of the racket.

Combining the stiffness and low weight requirements, it can be concluded that materials with higher specific stiffness will allow the design of rackets with higher power and better control. From the vibration damping point of view, materials with lower elastic modulus provide better damping.

Cost is an important consideration in selecting a tennis racket, especially when catering for beginners and amateur players. In this case, the cost can be considered as a function of the cost of materials and processing.

11.5.4 Classification of Racket Materials

Tennis rackets can be made of several widely different materials including various types of wood, aluminum alloys, steels, and fiber-reinforced composite materials. With their much better performance at reasonable price, CFRPs currently represent the favorable material for the great majority of tennis rackets.

11.5.5 Material Substitution

To continue to improve the performance of their sports equipment, manufacturers are currently examining CNTRPs as possible substitutes for CFRP. CNTRPs provide better properties but are more expensive. This case study, which is based on a paper by Esawi and Farag (2007), uses the cost–benefit analysis to evaluate CNTRP as a possible substitute for CFRP in tennis rackets. In this case, the cost is taken as cost of the material per unit mass, whereas the benefit is considered to consist of two elements, power and damping. As shown earlier, materials with higher specific modulus provide higher power, whereas materials with lower elastic modulus provide better damping.

11.5.6 Ranking of Alternative Substitutes

Table 11.11 gives the properties of the traditional epoxy + 65%CF as well as some experimental CNTRP composites, which are being considered as possible substitutes. For the present analysis, the AHP is used to assess the cost–benefit analysis of the materials in Table 11.11 in making tennis rackets. As discussed in Section 9.5, AHP is an approach to solving multicriteria decision-making problems that depend on pairwise comparison of alternatives with respect to the selection criteria. The Criterium DecisionPlus version 3.04 by InfoHarvest was used to build a decision tree as shown in Figure 11.7. The cost is taken to be directly related to the price of the material in dollars per kilogram, as shown in Table 11.11, since the cost of processing is expected to be similar for the different materials. The benefit side consists of improved power, which is taken to linearly increase with the specific modulus, and improved damping, which is categorized as high, medium, and low for elastic modulus values less than 200, 200–300, and above 300 GPa, respectively. Various scenarios for material substitution are developed by allocating different weights to the cost, power, and damping. The resulting rankings are shown in Table 11.12.

11.5.7 Conclusion

Table 11.12 shows that the material ranking is sensitive to the importance and weight, allocated to each of the main variables: cost, power, and damping. Higher

TABLE 11.11
Properties of Candidates for Making a Tennis Racket

	E_c (GPa)	Density ρ_c (g/cc)	Specific Modulus (E_c/ρ_c) (GPa)/(g/cc)	Cost C_c^a (\$/kg)
Epoxy + 5% CNT	130.4	1.843	70.75421	2152.357
Epoxy + 20% CNT	425.6	1.852	229.8056	8579.429
Epoxy + 30% CNT	622.4	1.858	334.9839	12864.14
Epoxy + 50% CF	136.0	1.870	72.72727	92.5
Epoxy + 55% CF	146.4	1.873	78.16337	100.75
Epoxy + 60% CF	156.8	1.876	83.58209	109
Epoxy + 65% CF	167.2	1.879	88.9835	117.25
Epoxy + 1% CNT + 64% CF	184.8	1.879	98.35019	544.0714
Epoxy + 3% CNT + 62% CF	220.0	1.879	117.0836	1397.714
Epoxy + 5% CNT + 60% CF	255.2	1.879	135.8169	2251.357
Epoxy + 10% CNT + 55% CF	343.2	1.879	182.6503	4385.464
Epoxy + 15% CNT + 50% CF	431.2	1.879	229.4838	6519.571

Source: Esawi, A.M.K. and Farag, M.M., Carbon nanotube reinforced composites: Potential and current challenges, *Mater. Des.*, 28, 2394, 2007.

[a] Cost C_c is calculated using the cost of individual components and applying the rule of mixtures.

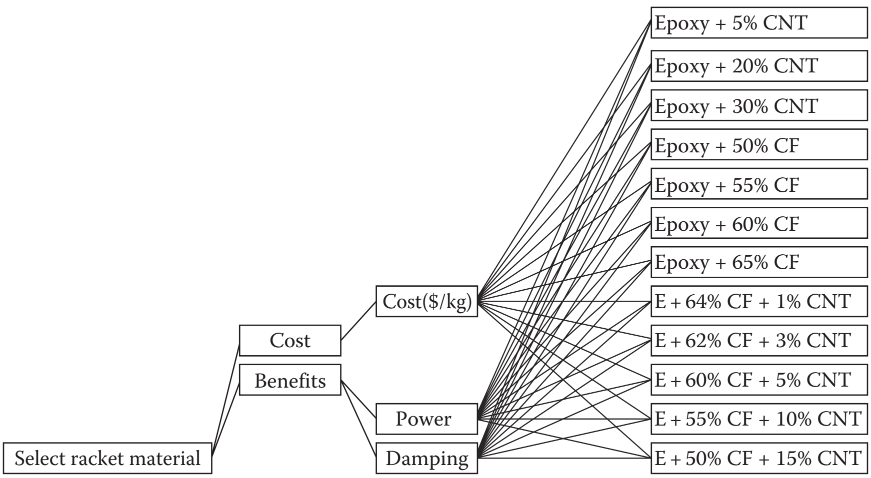

FIGURE 11.7 Decision tree for AHP analysis. (Based on Esawi, A.M.K. and Farag, M.M., *Mater. Des.*, 28, 2394, 2007.)

TABLE 11.12
Ranking of Materials According to AHP

	Weights		Top-Ranking Materials			
Alternative	Cost/Benefit	Power/Damping	Highest	Second	Third	Fourth
1	50%/50%	50%/50%	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 1% CNT + 64% CF Epoxy + 55% CF	Epoxy + 50% CF
2	30%/70%	60%/40%	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF
3		70%/30%	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF
4	25%/75%	60%/40%	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF
5		70%/30%	Epoxy + 1% CNT+ 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF
6	20%/80%	60%/40%	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF
7		70%/30%	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF	Epoxy + 55% CF Epoxy + 30% CNT
8	15%/85%	70%/30%	Epoxy + 30% CNT	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF
9	10%/90%	70%/30%	Epoxy + 30% CNT	Epoxy + 1% CNT + 64% CF	Epoxy + 65% CF	Epoxy + 60% CF

Source: Esawi, A.M.K. and Farag, M.M., *Mater. Des.*, 28, 2394, 2007.

weight for the cost and less emphasis on power tend to favor the traditional epoxy–CF composites. Epoxy–CF–CNT hybrid composites become more viable as the weight allocated to cost is reduced and the emphasis on power is increased. The epoxy–CNT composites become viable alternatives only at the two lowest weights for cost, and the consequent highest emphasis on benefits, with higher emphasis on power.

11.6 MATERIAL SUBSTITUTION IN THE AUTOMOTIVE INDUSTRY

11.6.1 Introduction

The materials used in making a motorcar cover almost all classes of engineering materials including metals and alloys, polymers and composites, elastomers, and ceramics. The relative amounts of these materials have changed over the years and Kandelaars and van Dam (1998) have shown that the percentage of the lighter materials, aluminum and plastics, in the total car weight has steadily increased compared with the heavier material, steel, during the period 1960–1992. For example, in 1960, aluminum and plastics constituted 2% and 1% of the total weight, respectively, whereas in 1986, these fractions increased to 4% and 7%.

The major driving forces behind material substitution in the automotive industry are cost reduction, better fuel economy, improved esthetics and comfort, and compliance to new legislation such as the End-of-Life Vehicle Directive, European Directive 2000/53/EC. An important factor in improving fuel efficiency, which is defined as the distance driven divided by energy used, is weight reduction by using higher-performance materials or substituting lightweight materials for the traditional ferrous materials used in the body, chassis, and power train components. Such substitution must be made cost-effectively while conforming to the increasingly severe safety and quality standards, and without unduly restricting the freedom of the stylist.

This case study, which is based on a paper by Farag (2007), gives an analysis of the different factors involved in materials substitution in automotive components. An interior panel is used for illustration, but the procedure can be applied to other parts of the motorcar. PVC is assumed to be the currently used material for the panel in this case study.

11.6.2 Materials and Manufacturing Processes for Interior Panels

PVC, which is assumed to be the currently used material for the interior panel, is one of the cheapest and most versatile polymers. This explains its wide use in a wide variety of applications ranging from pipes and fittings, flexible and rigid packaging, and artificial leather and car upholstery to cladding panels for flooring, doors, and windows. PVC can be easily shaped by injection or compression molding. However, there are environmental concerns about the chloride monomer.

FRPs are being increasingly used in automotive industries as a result of their superior strength/weight and stiffness/weight ratios. The fibers in the composite can either be long in the form of continuous roving, woven fabrics, or preimpregnated tapes and sheets, or short in the form of chopped mats. The matrix can either be thermosetting plastic or thermoplastic. Both the matrix and fibers have strong influence on the properties of the composite and its manufacturing processes. Although thermosetting epoxy resins are normally used as the matrix material in advanced composites, there is increasing interest in thermoplastics such as PP, PEEK, PPS, and polyetherimide (PEI). The main advantages of thermoplastics are better damage and environmental tolerance rather than improved mechanical performance. In addition, thermoplastics are easier to form and recycle. Generally, however, FRPs containing carbon or glass fibers are not recyclable and their production is energy-intensive and polluting.

Recently, natural fibers such as flax, hemp, and jute have been considered for reinforcing plastics as they need much less energy to grow, are renewable, and are biodegradable after use. NFRPs have the potential of vehicle weight reduction while satisfying the increasingly stringent environmental criteria, and some auto manufacturers have already started using them in some of their models, as in the case of Mercedes Benz A-Class and Ford Model U hybrid-electric car.

Filament winding and hand or machine layup of continuous fibers are used for advanced composites with relatively short production runs. Resin transfer molding (RTM) is used for intermediate production volumes of about 30,000 parts annually. Larger production volumes can be achieved using sheet-molding compound (SMC), which is a mixture of chopped fiber roving and matrix material. SMC can be shaped using compression molding and is increasingly used for making panels in the automotive industry. Reinforced reaction injection molding (RRIM) is also suitable for large-scale production of motorcar body panels.

Wood and cork, being natural materials, are renewable sources that require little energy for their production and are easy to recycle. In addition to its good stiffness to weight ratio, wood has excellent tactile and texture qualities and is perceived to be warmer and softer than many other materials (Ashby and Johnson, 2002). Cork has similar esthetic qualities to wood in addition to having excellent sound-damping qualities. Currently, wood is used for panels and veneer of several interior components in luxury motorcars such as the Rolls-Royce Phantom and the Jaguar xj6. Granulated cork and laminated wood can be pressed into sheets and panels, but they both need to be polished and sealed if they are to be used for motorcar interior applications.

11.6.3 Performance Indices of Interior Panels

Performance indices for a motorcar interior panel can be divided into four groups as follows: (1) technical characteristics, (2) cost considerations, (3) esthetics and comfort issues, and (4) environmental considerations. Following is an analysis of the performance indices under each group.

11.6.3.1 Technical Characteristics

Technical characteristics of interior panels include rigidity and resistance to buckling, light weight, resistance to thermal distortion, and resistance to weather conditions and direct sunlight.

For simplicity of analysis in the present case study, the body panel is considered to be relatively flat and rectangular with the following dimensions: length, $l = 100$ cm (39.4 in.), and width, $b = 50$ cm (19.7 in.). The thickness of the currently used PVC panel is 3.7 mm.

The material performance index (m) for a stiff light structural member can be represented as

$$m = \frac{E^{1/3}}{\rho} \tag{11.19}$$

where
E is the elastic modulus
ρ is the density

The thickness of another panel of equal stiffness and resistance to buckling is given as

$$t_n = t_o \left(\frac{E_o}{E_n} \right)^{1/3} \tag{11.20}$$

where
t_n and t_o are the thickness of new and currently used panels, respectively
E_n and E_o are the elastic constants of new and currently used materials, respectively

The values of the elastic modulus, the density, and the weight of the panels, based on the thickness calculated using Equation 11.20, are given in Table 11.13 for the different candidate materials.

The mass (M) of the panel is

$$M = \rho tbl \tag{11.21}$$

where
ρ is the density of the panel material
l, b, and t are the length, width, and thickness of the panel, respectively

For the internal panel, Matos and Simplicio (2006) gave the thermal distortion index $M2$ as a function of thermal conductivity divided by thermal expansion coefficient. Materials with higher $M2$ are preferred as they are expected to suffer less thermal distortion. The values of thermal conductivity and thermal expansion coefficient are taken from Matos and Simplicio (2006) and Ashby and Johnson (2002) or calculated using the rule of mixtures in the case of composite materials. The calculated values of $M2$ for the different candidate materials are given in Table 11.13.

The candidate materials under consideration are expected to satisfy the resistance to weather conditions and direct sunlight and will not be ranked according to this requirement.

TABLE 11.13
Technical, Cost, and Environmental Considerations

Material	*E* (GPa)	Density (g/cc)	Weight of Panel (kg)	Material Cost (USD)	Manufacturing Cost (USD)	Running Cost (USD)	*M*2 (W/m)
PVC	2.00	1.30	2.4	3.3	2.0	12.2	250,000
PP+glass fibers (40%)	7.75	1.67	3.3	6.0	2.0	21.8	60,000
Epoxy+CFs (60%)	69	1.60	1.46	27.2	5.0	9.6	700,000
Cork	0.02	0.20	1.74	14.0	17.0	11.5	400
Wood (ash/willow)	10	0.85	0.927	1.18	17.0	6.12	60,000
PP+flax fibers (40%)	4.65	1.19	1.67	1.9	2.0	11.0	50,000
PP+hemp fibers (40%)	6.00	1.236	1.60	1.8	2.0	10.6	50,000
PP+jute fibers (40%)	3.96	1.174	1.76	1.9	2.0	11.6	50,000

Source: Ashby, M. and Johnson, C., *Materials and Design: The Art and Science of Material Selection in Product Design*, Butterworth-Heinemann, Oxford, U.K., 2002; Ermolaeva et al., *Mater. Des.*, 25, 689, 2004; Matos, M.J. and Simplicio, M.H., *Mater. Des.*, 27, 74, 2006.

11.6.3.2 Cost Considerations for Interior Panel

The total cost (C_t) of a panel is considered to consist of four elements:

$$C_t = C_1 + C_2 + C_3 + C_4 \tag{11.22}$$

where
- C_1 is the cost of material
- C_2 is the cost of manufacturing and finishing
- C_3 is the cost over the entire life of the component
- C_4 is the cost of disposal and recycling

The cost of the material in the panel is based on its weight and the price of material per unit weight. The manufacturing cost is roughly estimated assuming that compression molding is used for PVC, GFRP, and NFRP; hand or machine layup for CFRP; and cutting, shaping, sealing, and polishing for wood and cork.

The weight of a motorcar plays a major role in determining its fuel efficiency as measured by the distance traveled per unit volume of fuel (km/L). Reducing the weight of a given component or a subsystem (primary weight reduction) is expected to result in a secondary weight reduction in other supporting components or subsystems. According to Das (2005), a ratio of 2:1 can be assumed for primary to secondary weight savings. Das (2005) also found that reducing the vehicle curb weight by 10% results in a 6.6% increase in fuel efficiency, measured in kilometers per liter. Taking the life of the car to be 5 years, the total distance traveled as 200,000 km, the cost of fuel as \$3/gal, and using the figures provided by Das (2005) of 8.62 km/L for a 1782 kg vehicle, the saving in fuel cost over the entire life of the vehicle can be estimated as about \$6.6/kg reduction in curb weight of the vehicle. This amount can also be taken as the share in the running cost of a component weighing 1 kg over the entire life of the vehicle. For simplicity, the cost of disposal and recycling will not be considered in the present case study.

The different cost items for the candidate materials are shown in Table 11.13.

11.6.3.3 Esthetics and Comfort

This group of indices evaluates materials according to their esthetic and tactile characteristics as well as comfort considerations, which include heating and cooling insulation, and vibration and sound damping. For the present case study, esthetics are considered as a combined function of the tactile feel and warmth of the material, as defined by Ashby and Johnson (2002). Wood, being the material of choice for the interior panels of the Rolls-Royce Phantom, is considered to have the optimum combination and is given a value of 100 units. Other materials are ranked according to their distance from it on a tactile warmth–tactile softness chart provided by Ashby and Johnson (2002), and the values are given in Table 11.14.

Thermal insulation of a material is a function of its thermal conductivity and thermal diffusivity. According to Matos and Simplicio (2006), the thermal insulation

TABLE 11.14
Esthetic and Comfort Characteristics of Candidate Materials

Indices	Esthetics	*M*1 (W s$^{1/2}$/m^2 K) (Normalized)	Sound Damping/Loss Coefficient (Normalized)
PVC	80	780 (19.2)	0.08 (40)
PP + glass fibers (40%)	75	1460 (10.3)	0.03 (15)
Epoxy + CFs (60%)	70	1460 (10.3)	0.03 (15)
Cork	85	150 (100)	0.20 (100)
Wood (ash/willow)	100	730 (20.5)	0.05 (25)
PP + flax fibers (40%)	80	1460 (10.3)	0.08 (40)
PP + hemp fibers (40%)	80	1460 (10.3)	0.08 (40)
PP + jute fibers (40%)	80	1460 (10.3)	0.08 (40)

Source: Ashby, M. and Johnson, C., *Materials and Design: The Art and Science of Material Selection in Product Design*, Butterworth-Heinemann, Oxford, U.K., 2002; Ermolaeva et al., *Mater. Des.*, 25, 689, 2004; Matos, M.J. and Simplicio, M.H., *Mater. Des.*, 27, 74, 2006.

index $M1$ is given by the thermal conductivity divided by the square root of thermal diffusivity. Materials with lower values of $M1$ are considered to provide better comfort for the motorcar passenger when used for making the interior panels. The values of $M1$ for the different candidate materials are shown in Table 11.14 and have been calculated based on the values in a thermal conductivity–thermal expansion chart provided by Ashby and Johnson (2002) and the values given by Matos and Simplicio (2006) or estimated using the rule of mixtures in the case of composite materials.

Sound and vibration damping for a candidate material is represented by its ability to absorb energy from a falling object on its surface, loss coefficient in an elastic modulus–loss coefficient chart provided by Ashby and Johnson (2002). Materials with higher values of loss coefficient are considered better for the interior panel application. In the case of composite materials, the rule of mixtures was used to estimate this property. The values of sound and vibration damping for the candidate materials are given in Table 11.14.

11.6.3.4 Environmental Considerations

Environmental considerations are becoming increasingly a more influential factor in material selection and substitution as a result of the increasing awareness of the public and the legislation on environmental impact, as in the case of "EI 99," for example. According to ISO 14001, LCA, which evaluates the environmental impact of a given product over its entire life cycle, can be divided into three main phases:

1. Production phase including energy requirements for primary and secondary materials used and all the processes involved in manufacturing them into a finished product
2. Use or operation phase including the energy, fuel, and emissions over the entire lifetime of the product
3. End-of-life phase including the energy used in disposal of the discarded product and whatever energy is gained from its recycling

Ermolaeva et al. (2004) calculated the environmental impact of the three phases for the case of motorcars, LCA, and the results show that the energy consumed during the vehicle operation phase is about 85%–92% of the total depending on the environmental properties of the materials and the manufacturing process used in making the motorcar. This is also in agreement with Ashby and Johnson (2002), who showed that of the total energy consumed over the life cycle of a motorcar, 94% is consumed during the use phase, 4% in the production of the materials, 1% in manufacturing, and 1% in disposal. These figures indicate that reducing the weight of the motorcar is the most important factor in reducing the environmental impact, as it has a direct relation to increased fuel efficiency (distance traveled per unit of fuel) and reduction of the total energy consumption over its life cycle. To simplify the analysis in this case study, the environmental impact of a given panel will be taken as proportional to its weight.

11.6.4 Comparison of Candidate Materials

Having estimated the values of the different performance requirements of the candidate materials, the next step is to normalize them. The lowest value for weight, total cost, and thermal insulation index (*M*1) is given 100 and other values are given proportionate quantities. In the case of esthetics, sound and vibration damping, and thermal distortion index (*M*2), the highest value is given 100 and others are given proportionate quantities. Tables 11.14 and 11.15 give the normalized property values in brackets.

Both the performance/cost and the compound objective function (COF) methods (see Section 10.5) are used to rank the candidate substitute materials in Table 11.14. The digital logic method (see Section 9.5) is used to assign the weighting factors.

11.6.5 Performance/Cost Method of Substitution

The performance of a material in this method is taken as the weighted sum of the normalized values of its esthetics, thermal insulation index (*M*1), sound and vibration damping, weight, and thermal distortion (*M*2), as shown in Table 11.16. The performance values of the candidate materials are then compared with the currently used material, PVC, and categorized as lower, similar, or higher performance. The results in Table 11.16 show that PP + glass fibers (40%) gives lower performance at a higher cost and is, therefore, rejected.

PP + flax fibers (40%), PP + hemp fibers (40%), and PP + jute fibers (40%) give similar performance to PVC but at a lower cost. These candidates would be preferable if the main objective of substitution is cost reduction. Of the three candidates, PP + hemp fibers (40%) is given the top ranking as it has the highest performance/cost.

Epoxy + CFs (60%), cork, and wood give higher performance at a higher cost than PVC. They would be preferable if the object of substitution is to raise performance. Of the three candidates, wood is the best as it has the highest performance/cost.

TABLE 11.15
Weight and Cost of Panels and *M*2 of Materials

Material	Weight of Panel (kg) (Normalized)	Total Cost of Panel (USD) (Normalized)	*M*2 (W/m) (Normalized)
PVC	2.4 (38.6)	17.5 (82.3)	250,000 (35.7)
PP + glass fibers (40%)	3.3 (28.2)	29.8 (48.3)	60,000 (8.6)
Epoxy + CFs (60%)	1.46 (63.5)	41.8 (34.4)	700,000 (100)
Cork	1.74 (53.3)	42.5 (33.9)	400 (0.057)
Wood (ash/willow)	0.927 (100)	24.3 (59.3)	60,000 (8.6)
PP + flax fibers (40%)	1.67 (55.5)	14.9 (96.6)	50,000 (7.1)
PP + hemp fibers (40%)	1.6 (57.9)	14.4 (100)	50,000 (7.1)
PP + jute fibers (40%)	1.76 (52.7)	15.5 (92.9)	50,000 (7.1)

TABLE 11.16
Results of the Performance/Cost Method of Substitution

Index Weighting Factor	Esthetics 0.2	*M*1 0.2	Sound Damping 0.1	Weight of Panel 0.4	*M*2 0.1	Performance	Cost (USD)	Perform/Cost	Evaluation and Rank
PVC	16	3.8	4.0	15.5	3.6	42.9	17.5	2.5	Current material
PP + glass fibers (40%)	15	2.1	1.5	11.3	0.9	30.8	29.8	1.03	Lower performance and higher cost (reject)
Epoxy + CFs (60%)	14	2.1	1.5	25.4	10	53.0	41.8	1.3	Better performance rank 3
Cork	17	20	10	21.3	0.01	68.3	42.5	1.6	Better performance rank 2
Wood (ash/willow)	20	4.1	2.5	40.0	0.9	67.5	24.3	2.8	Better performance rank 1
PP + flax fibers (40%)	16	2.1	4.0	22.2	0.7	45.0	14.9	3.0	Lower cost rank 2
PP + hemp fibers (40%)	16	2.1	4.0	23.2	0.7	46.0	14.4	3.2	Lower cost rank 1
PP + jute fibers (40%)	16	2.1	4.0	21.1	0.7	43.9	15.5	2.8	Lower cost rank 3

11.6.6 Compound Objective Function Method

In applying this method, two substitution scenarios were created by changing the weighting factors as follows:

1. More emphasis on cost with less emphasis on esthetics and comfort, economy model, where technical and economic aspects represent 75% of the weight, whereas esthetic and comfort aspects represent 25%. The weights are allocated as follows: weight of panel (0.25), total cost (0.4), *M*2 (0.1), esthetics (0.1), *M*1 (0.08), and sound damping (0.07).
2. Less emphasis on cost and more emphasis on esthetics and comfort, luxury model, where technical and economic aspects represent 50% of the weight, whereas esthetic and comfort aspects represent 50%. The weights are allocated as follows: weight of panel (0.2), total cost (0.2), *M*2 (0.1), esthetics (0.25), *M*1 (0.15), and sound damping (0.1).

The COFs for each of the materials for the two scenarios were calculated using the values in Tables 11.14 and 11.15, and the results are given in Table 11.17.

The results of Table 11.17 show that for the economy model, PP + hemp fibers (40%) and PP + flax fibers (40%) receive first and second ranks, respectively; their biggest asset is their low cost. This is in agreement with Marsh (2003), who reported that PP + flax fiber composites replaced GFRP in underbody components in vehicles such as the Mercedes Benz A-Class and the Ford Model U hybrid-electric car. For the luxury model, the results show that cork and wood have close COF values and, therefore, share the top rank. Their biggest asset is excellent esthetic qualities and heat insulation. As discussed earlier, wood is used for body panels and veneers in the Rolls-Royce Phantom.

TABLE 11.17
Results of the Compound Objective Function Method of Substitution

	Scenario I (Economy Model)		Scenario II (Luxury Model)	
Material	**COF**	**Rank**	**COF**	**Rank**
PVC	58.5	5	54.7	6
PP + glass fibers (40%)	36.6	8	38.1	8
Epoxy + CFs (60%)	48.6	7	50.5	7
Cork	50.3	6	63.8	1
Wood (ash/willow)	63.0	3	63.4	1
PP + flax fibers (40%)	64.8	2	56.7	4
PP + hemp fibers (40%)	66.8	1	57.9	3
PP + jute fibers (40%)	62.7	4	55.4	5

11.6.7 Conclusion

The two proposed methods are used to examine the case of material substitution for interior motorcar panels and they yielded consistent results. In both methods, PP + hemp fibers (40%) and PP + flax fibers (40%) rank highest for the economy models, where cost is important, whereas wood and cork rank highest for the luxury models, where esthetics and comfort are important. These results are consistent with the current trends in industry.

Based on the results of the case study presented here, it is expected that NFRP would be increasingly used as automotive materials. More research needs to be done on how to improve the performance and economics of these emerging materials, as they also have excellent potential for wider industrial applications.

Case Study 11.7: Can Carbon Nanotubes Replace Constantan Alloy in Strain Sensors?

Introduction

This case study explores the possibility of replacing the traditional strain sensors that are based on constantan alloys with CNT-based strain sensors. A strain gauge is designed to give accurate and reliable strain measurements under specific operating conditions. In addition, it should be easy to install and of low cost. As CNTs offer higher performance at a higher cost, the cost–benefit analysis method, discussed in Section 10.6, is used. This case study is based on Amal M. K. Esawi and Mahmoud M. Farag, Chapter 15—Polymer Nanotube Composites: Promises and Current Challenges, in Polymer Nanotube Nanocomposites: Synthesis, Properties and Applications, Mittal, V. (editor), M M Scrivener Press, Salem, MA, 2010.

Performance Requirements of Strain Sensors

Although the gauge factor, which is related to the strain sensitivity of the sensor, is an important requirement for a strain gauge material, several other performance requirements must also be considered. These include

a. High strain sensitivity
b. Insensitivity to strain level and temperature
c. High fatigue life
d. Ability to stand high elongation
e. Minimum temperature-induced strain over a wide temperature range
f. Self-temperature compensation to match the test material's thermal expansion coefficient
g. Ability to measure very large strains 5% (50,000 $\mu\varepsilon$)
h. High fatigue life for dynamic applications
i. Excellent stability for accurate static strain measurements over long periods of time.

Materials and Manufacturing Processes for Strain Sensors

The most widely used alloy for strain gauges is constantan alloy, which is known to have the best overall combination of the aforementioned properties. Strain gauges based on constantan alloy offer wide static, dynamic, and temperature ranges, and gauge factors in the range 2–3.2. However, they lack versatility and flexibility as they only measure strain at the location where they are bonded and along the direction of the grid.

CNT is considered as a potential strain sensor material because of its structural and electrical characteristics. A long continuous CNT-based sensor is envisaged to measure strain over a large structure and thus can be used for structural health monitoring. When selecting a polymer for a CNT-based strain gauge, ductility and ease of processing are the key requirements. Such requirements are exhibited by PMMA. Strain sensors in the form of PMMA polymer with 1 wt% MWNT composite film can have a gauge factor of about 15. Another possible alternative is PMMA polymer with 10 wt% CWNT, which exhibits relatively high electrical conductivity and a gauge factor of about 5.

Cost-Benefit Analysis of Conventional Foil Gauges versus CNT-Based Composite Gauges

The gauge sensitivity to changes in strain (gauge factor, G) represents the major selection criterion for a strain gauge material when evaluating the technical performance of one material relative to another. Therefore, for the purpose of this analysis, the incremental relative performance index ($\Delta\gamma$), representing the increase in performance when using the new CNT-based gauge, will be defined as

$$\Delta\gamma = \frac{\left((G)_{\mathrm{CNT}} - (G)_{\mathrm{base}}\right)}{(G)_{\mathrm{base}}} \tag{11.23}$$

The relative incremental cost (ΔC), representing the increased cost due to the more expensive CNT-based gauge, is taken as

$$\Delta C = \frac{(C_{\mathrm{CNT}} - C_{\mathrm{base}})}{C_{\mathrm{base}}} \tag{11.24}$$

where C_{CNT} and C_{base} are the costs of the CNT-based gauge and the conventional gauge, respectively.

The benefit/cost can be measured as

$$\frac{\Delta\gamma\,\alpha_{\mathrm{T}}}{\Delta C\,\alpha_{\mathrm{c}}} \tag{11.25}$$

where

α_{T} is a weighting factor to account for technical performance
α_{c} is a weighting factor to account for the importance of cost

TABLE 11.18
Properties and Cost of Strain Gauges Based on Constantan Alloy and CNT

			Maximum Allowed Cost of CNT-Based Gauge (C_{CNT}) Relative to the Constantan Foil Gauge (C_{base}), Which Is Taken as Unity		
Material	**Gauge Factor**	**$\Delta\gamma$**	**$\alpha_T/\alpha_c = 1$**	**$\alpha_T/\alpha_c = 3$**	**$\alpha_T/\alpha_c = 5$**
Constantan alloy foil gauge	2–3.2	—	$C_{base} = 1$	$C_{base} = 1$	$C_{base} = 1$
PMMA–1 wt% MWNT gauge	15	5	$C_{CNT} \le 6$	$C_{CNT} \le 16$	$C_{CNT} \le 25$
PMMA–10 wt% SWNT gauge	5	1	$C_{CNT} \le 2$	$C_{CNT} \le 4$	$C_{CNT} \le 6$

For the CNT-based gauge to be competitive relative to current gauge materials, the value of ($\Delta\gamma\ \alpha_T/\Delta C\ \alpha_c$) needs to be greater than 1. Table 11.18 gives the results of applying Equation 11.25 under three different conditions:

1. Technical performance is equally weighted to cost, $\alpha_T/\alpha_c = 1$.
2. Technical performance is more important than cost, $\alpha_T/\alpha_c = 3$.
3. Technical performance is much more important than cost, $\alpha_T/\alpha_c = 5$.

The results show that the PMMA–1 wt% MWNT gauge offers a more feasible alternative as its price is allowed to be six times that of the constantan alloy foil gauge for equal weights of technical performance and cost. When more importance is assigned to technical performance, the price of the PMMA–1 wt% MWNT gauge is allowed to be close to 25 times the cost of the constantan alloy foil gauge. Such restrictions are easy to meet and the PMMA–1 wt% MWNT gauge is, therefore, competitive. This is not the case with the PMMA–10 wt% SWNT gauge where the relative cost is restricted to less than six times that of the constantan alloy foil gauge, even when high importance is assigned to technical performance.

Conclusion

The analysis shows that the PMMA–1 wt% MWNT gauge competes favorably with the commercially available metallic foil gauges. It is expected to become even more competitive as the cost of CNTs decreases with the progress of their development and the increase in their production volume. MWNTs are now available in kg quantities with purities reaching 99% and their prices in 2009 were 10 times cheaper than in 2006. The introduction of the catalytic chemical vapor deposition (CCVD) process allows industrial scale production of relatively low-cost MWNTs. In 2009, the price of CCVD MWNTs ranged from $500 to 1500 per kg. The use of SWNTs on an industrial large scale is expected to remain more limited as their price is more than 50 times the price of MWNTs.

Such sensors can also be used as a conductive coating to measure strains over large areas. The CNT-based strain sensors have the added advantages that their strain sensitivity can be controlled by varying the CNT weight percent in the composite and that they can measure strain in all directions since the CNTs are randomly dispersed within the polymer matrix.

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Part IV

Appendices

INTRODUCTION

Materials have evolved with mankind since the dawn of civilization. Stone followed by bronze and then iron marked the main materials that shaped the early ages of civilization. The number of materials in the service of man has increased slowly over the years. It has been reported that there are more than 40,000 currently useful metallic alloys and probably close to that number of nonmetallic engineering materials, such as plastics, ceramics, composite materials, and semiconductors and advanced materials. One of the distinguishing features of modern industry is the extensive use of this expanding range of materials, many of which are usually combined to make the final product. As an example, consider the case of an average motor car where almost all types of engineering materials are used in its manufacture. For example, steel is used for the body; aluminum for the engine; copper for the wiring; lead for the battery; chromium and nickel as alloying elements for the exhaust system; platinum, palladium, and rhodium in the catalytic converter; ceramics for the spark plugs; glass for the windscreen; plastics for body interior panels and headlamps; natural and synthetic rubber for tires and timing belts; and composite materials for bumpers. Materials are generally based on the gaseous, liquid, and solid elements found in nature, and Table P.1 gives the physical and chemical data for such elements.

Engineering materials can be conveniently classified into ferrous and nonferrous metals and alloys, nonmetallic organic and inorganic materials, composite materials, and semiconductors. Figure P.1 illustrates this classification. Although there are large variations in the properties of materials within a given class, there are also similarities. Metallic materials are conductors of heat and electricity, whereas all nonmetallic materials are generally insulating, as shown in Table P.2. Ceramics are hard and corrosion resistant but are generally brittle. Plastics are generally lighter than metals and

TABLE P.1
Physical and Chemical Data for Selected Elements

Element	Symbol	Atomic Mass (amu)	Density of Solid (at 20°C) ($mg/m^3 = g/cm^3$)	Crystal Structure (at 20°C)	Melting Point (°C)	Atomic Number
Hydrogen	H	1.008	—	—	−259.34 (TP)	1
Helium	He	4.003	—	—	−271.69	2
Lithium	Li	6.941	0.533	bcc	180.6	3
Beryllium	Be	9.012	1.85	hcp	1289	4
Boron	B	10.81	2.47	—	2092	5
Carbon	C	12.01	2.27	Hex.	3826 (SP)	6
Nitrogen	N	14.01	—	—	−210.0042 (TP)	7
Oxygen	O	16.00	—	—	−218.789 (TP)	8
Fluorine	F	19.00	—	—	−219.67 (TP)	9
Neon	Ne	20.18	—	—	−248.587 (TP)	10
Sodium	Na	22.99	0.966	bcc	97.8	11
Magnesium	Mg	24.31	1.74	hcp	650	12
Aluminum	Al	26.98	2.70	fcc	660.452	13
Silicon	Si	28.09	2.33	Dia.cub.	1414	14
Phosphorus	P	30.97	1.82 (white)	Ortho.	44.14 (white)	15
Sulfur	S	32.06	2.09	Ortho.	115.22	16
Chlorine	Cl	35.45	—	—	−100.97 (TP)	17
Argon	Ar	39.95	—	—	−189.352 (TP)	18
Potassium	K	39.10	0.862	bcc	63.71	19
Calcium	Ca	40.08	1.53	fcc	842	20
Scandium	Sc	44.96	2.99	fcc	1541	21
Titanium	Ti	47.90	4.51	hcp	1670	22
Vanadium	V	50.94	6.09	bcc	1910	23
Chromium	Cr	52.00	7.19	bcc	1863	24
Manganese	Mn	54.94	7.47	Cubic	1246	25
Iron	Fe	55.85	7.87	bcc	1538	26
Cobalt	Co	58.93	8.8	hcp	1495	27
Nickel	Ni	58.71	8.91	fcc	1455	28
Copper	Cu	63.55	8.93	fcc	1084.87	29
Zinc	Zn	65.38	7.13	hcp	419.58	30
Gallium	Ga	69.72	5.91	Ortho.	29.7741 (TP)	31
Germanium	Ge	72.59	5.32	Dia cub.	938.3	32
Arsenic	As	74.92	5.78	Rhomb.	603 (SP)	33
Selenium	Sc	78.96	4.81	He2x.	221	34
Bromine	Br	79.90	—	—	−7.25 (TP)	35
Krypton	Kr	83.80	—	—	−157.385	36
Rubidium	Rb	85.47	1.53	bcc	39.48	37
Strontium	Sr	87.62	2.58	fcc	769	38
Yttrium	Y	88.91	4.48	hcp	1522	39
Zirconium	Zr	91.22	6.51	hcp	1855	40
Niobium	Nb	92.91	8.58	bcc	2469	41

TABLE P.1 (continued)
Physical and Chemical Data for Selected Elements

Element	Symbol	Atomic Mass (amu)	Density of Solid (at 20°C) ($mg/m^3 = g/cm^3$)	Crystal Structure (at 20°C)	Melting Point (°C)	Atomic Number
Molybdenum	Mo	95.94	10.22	bcc	2623	42
Technetium	Tc	98.91	11.50	hcp	2204	43
Ruthenium	Ru	101.07	12.36	hcp	2334	44
Rhodium	Rh	102.91	12.42	fcc	1963	45
Palladium	Pd	106.4	12.00	fcc	1555	46
Silver	Ag	107.87	10.50	fcc	961.93	47
Cadmium	Cd	112.4	8.65	hcp	321.108	48
Indium	In	114.82	7.29	fct	156.634	49
Tin	Sn	118.69	7.29	bct	231.9681	50
Antimony	Sb	121.75	6.69	Rhomb.	630.755	51
Tellurium	Te	127.60	6.25	Hex.	449.57	52
Iodine	I	126.90	4.95	Ortho.	113.6 (TP)	53
Xenon	Xe	131.30	—	—	−111.7582(TP)	54
Cesium	Cs	132.91	1.91 (−10°)	bcc	28.39	55
Barium	Ba	137.33	3.59	bcc	729	56
Lanthanum	La	138.91	6.17	Hex.	918	57
Cerium	Ce	140.12	6.77	fcc	798	58
Praseodymium	Pr	140.91	6.78	Hex.	931	59
Neodymium	Nd	144.24	7.00	Hex.	1021	60
Promethium	Pm	(145)	—	Hex.	1042	61
Samarium	Sm	150.4	7.54	Rhomb.	1074	62
Europium	Eu	151.96	5.25	bcc	822	63
Gadolinium	Gd	157.25	7.87	hcp	1313	64
Terbium	Tb	158.93	8.27	hcp	1356	65
Dysprosium	Dy	162.50	8.53	hcp	1412	66
Holmium	Ho	164.93	8.80	hcp	1474	67
Erbium	Er	167.26	9.04	hcp	1529	68
Thulium	Tm	168.93	9.33	hcp	1545	69
Ytterbium	Yb	173.04	6.97	fcc	819	70
Lutetium	Lu	174.97	9.84	hcp	1663	71
Hafnium	Hf	178.49	13.28	hcp	2231	72
Tantalum	Ta	180.95	16.67	bcc	3020	73
Tungsten	W	183.85	19.25	bcc	3422	74
Rhenium	Re	186.2	21.02	hcp	3186	75
Osmium	Os	190.2	22.58	hcp	3033	76
Iridium	Ir	192.22	22.55	fcc	2447	77
Platinum	Pt	195.09	21.44	fcc	1769.0	78
Gold	Au	196.97	19.28	fcc	1064.43	79
Mercury	Hg	200.59	—	—	−38.836	80
Thallium	Tl	204.37	11.87	hcp	304	81
Lead	Pb	207.2	11.34	fcc	327.502	82
Bismuth	Bi	208.98	9.80	Rhomb.	327.502	83
Uranium	U	238.03	19.05	Ortho.	1135	92

Source: Shackelford, J.F., *Introduction to Materials Science for Engineers*, Macmillan, New York, 1992.

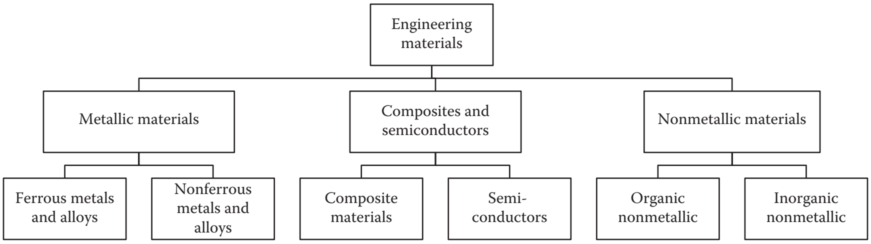

FIGURE P.1 Classes of engineering materials.

TABLE P.2
Comparison of Thermal Conductivity and Linear Thermal Expansion Coefficient for Selected Materials

Material	Thermal Conductivity (W/m°C)	Linear Expansion (106/°C)
Aluminum	230	22.5
Copper	400	17
Steel 1020	50	11.7
Al_2O_3	29	9
SiC	12	4.68
Fireclay	0.8	4.5
Soda-lime glass	0.96	9.2
LDPE	0.34	198
PVC	0.12	144

ceramics, and they are corrosion resistant, but they are softer and have much lower elastic moduli. Composites combine two or more material groups, which allows them to combine the attractive properties of the constituencies. Professional societies and organizations issue designation systems to help users identify materials. Such designations identify a given material class by a number, letter, symbol, name, or a combination thereof. Designations are normally based on either the chemical composition or the mechanical properties. Table P.3 gives some examples. The UNS has been developed by the ASTM, the SAE, and several other technical societies, trade associations, and the US government agencies. The UNS number is a designation of chemical composition and consists of a letter and five numerals. The letter indicates the broad class of alloys, and the numerals define specific alloys within that class.

It should be noted that the designation systems are not specifications but are often incorporated into specifications describing products that are made of the designated materials. A standard specification is a published document that describes the characteristics a product must have to be suitable for a certain application.

TABLE P.3
Classification and Designation of Some Metallic Materials

Name	Number	Example	
Ferrous Materials	**AISI–SAE**		**UNS**
Plain-carbon steel	10xx	1015	G10150
Free machining steel	11xx	1118	G11180
Manganese steel	13xx	1335	G13350
Molybdenum steel	40xx	4027	G40270
Chromium–molybdenum steel	41xx	4118	G41180
Nickel–chromium steel	43xx	4320	G43200
Chromium steel	50xx	5015	G50150
Chromium–vanadium steel	61xx	6118	G61180
Wrought Aluminum Alloys	**AA**		
Aluminum 99% and greater	1xxx	1060	A91060
Two-phase Al–Cu alloys	2xxx	2014	A92014
One-phase Al–Mn alloys	3xxx	3003	A93003
Two-phase Al–Si alloys	4xxx	4032	A94032
One-phase Al–Mg alloys	5xxx	5052	A95052
Two-phase Al–Mg–Si alloys	6xxx	6061	A96061
Two-phase Al–Zn alloys	7xxx	7075	A97075
Cast Aluminum Alloys	**AA**		
Al–Cu alloys	2xx.x	108.0	A02080
Al–Si–Cu alloys	3xx.x	333.0	A03330
Al–Si alloys	4xx.x	B443.0	A24430
Al–Mg alloys	5xx.x	520	A05200
Al–Zn alloys	7xx.x	A712.0	A17120
Al–Sn alloys	8xx.x	850.0	A08500

The appendices in this part of the book are intended to give background information and some reference information about engineering materials that should be helpful to the reader in

- Identifying the composition and properties of some commonly used engineering materials (Appendices A through E)
- Conversion from one system of units to another and from one hardness scale to another (Appendix F)
- Finding the meaning of technical terms in the area of materials and manufacturing in the glossary (Appendix G)

Appendix A: Metallic Materials–Classification, General Characteristics, and Properties

A.1 INTRODUCTION

Pure metallic elements have a wide range of properties, and their alloys are even more versatile and form a large proportion of the engineering materials used in industry. Metallic materials can be divided into ferrous and nonferrous alloys. Ferrous alloys occupy more than 90% of world production of metallic materials. Ferrous alloys have iron as the base metal and range from plain-carbon steels, containing more than 98% iron, to high-alloy steels containing up to about 50% of a variety of alloying elements. All other metallic materials fall into the nonferrous category, which can be subdivided into light metals, for example, aluminum, magnesium, and titanium; low-melting-point metals, for example, bismuth, lead, and tin; refractory metals, for example, molybdenum, niobium, tantalum, and tungsten; and precious metals, for example, gold, silver, and platinum. Within each group of alloys, classification can be made according to

a. Chemical composition, for example, carbon content and alloy content in steels
b. Finishing method, for example, hot rolled or cold rolled
c. Product form, for example, bar, plate, sheet, tubing, or structural shape

The method of producing the alloy can be used for further subdivision. For example, carbon steels can be classified into rimmed, semikilled, or killed, depending on the deoxidation practice.

Metallic materials can also be divided according to the method of production into cast alloys and wrought alloys. Cast alloys form about 20% of all industrial metallic materials and are cast directly into shape. Wrought alloys are usually shaped by hot or cold working into semifinished products like plates, sheets, rods, wires, or tubes. These semifinished materials provide a starting point for the fabrication of finished components by further forming or machining processes. A third type, which has gained industrial favor in recent years, is powder metals and alloys. The powders are compacted and sintered to produce ready-to-use components that need very little further machining.

A.2 STRENGTHENING OF METALLIC MATERIALS

Mechanical behavior of metallic materials represents an important reason for their selection in engineering applications where relatively high strength and reasonable toughness are needed. Higher strength means thinner sections and lighter components, while higher toughness means less likelihood of sudden failure in service. For many engineering alloys, however, an increase in strength is accompanied by a reduction in toughness, and the optimum combination of these properties should be selected to meet the service requirements.

Within the elastic range, the behavior of the material is mainly a function of its modulus of elasticity, which is a characteristic of the material and is not markedly affected by alloying or heat treatment. Most steels, for example, have elastic moduli within the relatively narrow range of 190–220 GPa (27–31 million psi), and aluminum and most of its alloys have a modulus of elasticity of about 69,000 MPa (10 million psi) at room temperature. The modulus of elasticity is an important design parameter as its value affects the deflection of components and structures under load (stiffness).

In contrast to modulus of elasticity, other mechanical properties are sensitive to the material composition and its thermomechanical history. Strengthening by alloy addition is used in practice for many alloys. In the case of steels, increasing the carbon content increases the iron carbide volume fraction, which increases the strength and hardness but decreases the ductility and toughness. Heat treatment is also commonly used to strengthen metallic materials. For example, a large variety of properties can be obtained in steels by varying the cooling on quenching from high temperatures. Another form of heat treatment is precipitation hardening, where a hard phase is finely dispersed in a soft matrix. For example, the strength of precipitation-hardened 2014 aluminum alloy is more than double the strength of the annealed alloy. Cold working of wrought alloys is another important method of strengthening engineering alloys. The strength can usually be increased by reducing grain size. For example, in ultra-fine-grained steels, special treatments produce grain sizes of about 1 μm and increase the strength by approximately a factor of 2.

It should be noted that increasing the strength of metallic alloys by any of the earlier methods usually leads to reduction in ductility and toughness, except for the grain size reduction, where ductility increases as the strength increases.

A.3 STEELS AND CAST IRON

Ferrous materials, of which steels are the major alloys, represent about 90% of the total usage of metallic materials in the world. The main reasons for this overwhelming preference for ferrous materials are their versatile properties and low cost.

A.3.1 Carbon Steels

Plain-carbon steels constitute the major bulk of steels used in industry and Table A.1 gives some examples. Plain-carbon steels, or simply carbon steels, are defined as those in which carbon is the alloying element that essentially controls the properties

TABLE A.1
Mechanical Properties of Some Carbon Steels

Specification and Grade		Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	Elongation (%)
Hot-rolled sheet and strip structural-quality low-carbon steel						
ASTM A570	A	310	45	170	25	23–27
	B	340	49	205	30	21–25
	C	360	52	230	33	18–23
	D	380	55	275	40	15–21
	E	400	58	290	42	13–19
Special-quality hot-rolled steel bars						
ASTM A675	45	310–380	45–55	155	22.5	33
	50	345–415	50–60	170	25	30
	60	415–495	60–72	205	30	22
	70	485–585	70–85	240	35	18
	80	550 min	80 min	275	40	17
Steel castings						
ASTM A27-77	60–30	415	60	205	30	24
	70–36	485	70	250	37	22
A148-73	80–40	552	80	276	40	18
	90–60	621	90	414	60	20
	120–95	827	120	655	95	14
	175–145	1207	175	1000	145	6

Source: Shackelford, J.F., *Introduction to Materials Science for Engineers*, Macmillan, New York, 1992.

and in which the amount of manganese does not exceed 1.65%. These steels can be divided according to composition into

1. Low carbon, less than 0.3% C
2. Medium carbon, between 0.3% C and 0.6% C
3. High carbon, more than 0.6% C

The strength of plain-carbon steels increases as the carbon content increases, but the ductility decreases. Also, plain-carbon steels lose most of their strength at high temperatures, become too brittle at low temperatures, and are subject to corrosion in most environments. These limitations can be eliminated by adding the appropriate alloying elements, as will be discussed in the following section.

A.3.2 Alloy Steels

Alloy steels are usually defined as those that contain more than any of the following amounts: 1.65% manganese, 0.60% silicon, 0.60% copper, or specified amounts

TABLE A.2
Mechanical Properties of Selected HSLA Steels

ASTM No. and Type	UNS Designation	Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	Elongation (%)
A242 type 1	K11510	435–480	63–70	290–345	42–50	21
A572 grade 50	—	450	65	345	50	21
A607 grade 60	—	520	75	415	60	16–18
Grade 70	—	590	85	485	70	14
A618 grade 1	K02601	483	70	345	50	22
A717 grade 60	—	485	70	415	60	20–22
Grade 70	—	550	80	485	70	18–20
Grade 80	—	620	90	550	80	16–18

of one or more other alloying elements. Steels that do not contain more than a 5% total of combined alloying elements are called low-alloy steels. Alloy additions may be intended to enhance mechanical, physical, or chemical properties; hardenability, weldability, or other fabrication characteristics; or some other attribute of the steel. Since there are more elements to be kept within specified limits, better quality control is required, and consequently alloy steels are expected to be more expensive than plain-carbon steels.

In many specifications, acceptance for a given steel is based more on physical or mechanical properties than on chemical composition as in the case of ASTM specifications. This makes it possible for the producer to supply a cheaper proprietary material that will meet the desired properties as in the case of HSLA steels. These steels have yield strengths in excess of about 300 MPa (43 ksi) and usually contain from 0.05% to 0.33% C and 0.2% to 1.65% Mn with small additions of Cr, Mo, or Ni. Table A.2 gives the mechanical properties of selected HSLA steels.

Another group with even higher strength than HSLA steels is the ultrahigh-strength steels with yield strengths of about 1400 MPa (200 ksi) or higher, as shown in Table A.3.

A.3.3 Stainless Steels

Stainless steel is the generic name for more than 70 types of corrosion-resistant steels that contain a minimum of 12% chromium. Increasing chromium content gives additional corrosion resistance. Stainless steels can be divided into five groups: (1) austenitic, (2) martensitic, (3) ferritic, (4) precipitation hardening, and (5) duplex stainless steels. The names of these categories reflect the microstructure of the steel, and this depends on the balance between the alloying elements present and the heating and cooling cycle to which the steel has been subjected. Carbon, nickel, nitrogen, and manganese are among the alloying elements that enhance the retention of austenite, while chromium and the strong carbide formers enhance the retention of ferrite. The martensitic steels contain balanced amounts of austenite and ferrite

TABLE A.3
Mechanical Properties of Some Ultrahigh-Strength Steels

Designation or Grade	Tempering Temp. °C	Tempering Temp. °F	Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	Elongation (%)
Medium-carbon low-alloy water quenched and tempered							
4130	205	400	1765	256	1520	220	10
	315	600	1570	228	1340	195	13
	425	800	1380	200	1170	170	16.5
4340	205	400	1980	287	1860	270	11
	315	600	1760	255	1620	235	12
	425	800	1500	217	1365	198	14
Medium-alloy air-hardening steel							
H13	527	980	1960	284	1570	228	13
	593	1100	1580	229	1365	198	14.4
18Ni maraging steels (solution treated for 1 h at 820°C (1500°F), then aged for 3 h at 480°C (900°F))							
l8Ni(200)			1500	218	1400	203	10
l8Ni(250)			1800	260	1700	247	8
l8Ni(300)			2050	297	2000	290	7

stabilizers so that upon heating, the structure becomes austenitic, and upon cooling at a suitable rate, it becomes martensitic. Precipitation hardening stainless steels have either austenitic, martensitic, or semiaustenitic microstructures. Hardening is accomplished by precipitation of titanium or copper in the martensitic microstructures, aluminum in the semiaustenitic microstructures, and carbides in the austenitic microstructures. The composition and properties of some stainless steels are given in Table A.4.

A.3.4 Tool Steels

Tool steels constitute a class of high-carbon alloy steels that are used to cut or form other materials. To perform its requirements efficiently, a tool steel is required to have excellent wear and abrasion resistance, high hardness at moderate or elevated temperatures, and high toughness. The AISI has an identification and type classification of tool steels, which is based on the end use, common properties, or manner of heat treatment. The compositions and properties of some of these steels are given in Table A.5. High-speed steels retain enough hardness to cut metals at rapid rates that generate tool temperatures up to about 630°C (1166°F) and yet return to their original hardness when cooled to room temperature. Of the different compositions, four grades, T1, M1, M2, and M10, make up a large proportion of the tool steels used for production machining and are the most readily available.

TABLE A.4
Composition and Properties of Selected Stainless Steels

AISI	Nominal Composition (%) C	Cr	Ni	Mn	Si	Others[a]		Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	Elongation (%)	Hardness (BHN)
Austenitic													
201	0.15	17	4.5	6.50	1.0	—	—	805	117	385	56	55	185
301	0.15	17	7	2.0	1.0	—	—	770	112	280	41	60	162
302	0.15	18	9	2.0	1.0	—	—	630	91	280	41	50	162
304	0.08	19	9.5	2.0	1.0	—	—	588	85	294	43	55	150
316	0.08	17	12	2.0	1.0	2.5	Mo	588	85	294	43	50	145
330	0.08	18.5	35.5	2.0	1.0	—	—	630	91	266	39	45	150
Ferritic													
405	0.08	13	—	1.0	1.0	0.2	Al	490	71	280	41	30	150
430	0.12	17	—	1.0	1.0	—	—	525	76	315	46	30	155
442	0.2	21.5	—	1.0	1.0	—	—	560	81	315	46	20	185

Martensitic													
403	0.15	12.5	—	1.0	0.5	—	—	525	76	280	41	35	153
416	0.15	13	—	1.25	1.0	0.6	Mo	525	76	280	41	30	153
431	0.2	16	2.0	1.0	1.0	—	—	875	127	665	97	20	260
502	0.1	5	—	1.0	1.0	0.55	Mo	455	66	175	25	30	150
Precipitation hardening													
17—7 PH[b]	0.07	17	7	—	—	1.0	Al	1484	215	1346	195	9	465
PH 13—8Mo[b]	0.05	14	8.5	—	—	2.5	Mo	1552	225	1414	205	12	465
						1.0	Al						
AM 350[c]	1.0	16.5	4.3	—	—	2.75	Mo	1518	220	1311	190	13	450

[a] Most steels contain 0.035 and 0.04–0.06 P except for type 416, which contains 0.15 S.

[b] Aged at 510°C.

[c] Aged at 450°C.

TABLE A.5
Composition and Mechanical Properties of Some Tool Steels

	Composition (%)						Hardness (RC)		Toughness	
Grade	C	Cr	V	W	Mo	Others	Room Temperature	(560°C) (1040°F)	J	ft lb
Water hardening										
W1	0.6–1.4	—	—	—	—	—	63	10	68	50.2
W2	0.6–1.4	—	0.25	—	—	—	63	10	68	50.2
Shock resisting										
S1	0.50	1.5	—	2.5	—	—	60	20	95	70.1
S2	0.50	—	—	—	0.50	1.0 Si	63	20	95	70.1
Oil hardening										
O1	0.9	0.5	—	0.5	—	1.0 Mn	63	20	54	39.9
Air hardening										
A2	1.0	5.0	—	—	1.0	—	63	30	48	35.4
Tungsten high speed										
T1	0.70	4.0	1.0	18.0	—	—	66	52	61	45
T2	0.85	4.0	2.0	18.0	—	—	65	52	61	45
Molybdenum high speed										
M2	0.85	4.0	2.0	6.25	5.00	—	65	52	68	50.2
M3	1.00	4.0	2.4	6.00	5.00	—	67	52	48	35.4
M4	1.3	4.0	4.0	5.50	4.50	—	67	52	48	35.4
M10	0.85	4.0	2.0		8.00	—	65	52	68	50.2

A.3.5 Cast Iron

Cast irons are a group of materials that are basically ternary alloys of iron, carbon, and silicon, which contain more than 2% carbon and from 1% to 3% silicon. Wide variations in properties can be achieved by varying the balance between carbon and silicon, by alloying with various metallic or nonmetallic elements, and by varying melting, casting, and heat-treating practices. The group of cast irons includes gray, white, ductile, and malleable irons. Ductile irons exhibit measurable ductility, in contrast with white and gray irons that exhibit brittle behavior in tension. Malleable iron is initially cast as white iron and then malleablized by heat treatment to give it the required ductility. Nodular cast irons, also known as ductile irons or spheroidal-graphite (SG) cast irons, contain graphite in the form of tiny spheres instead of flakes as in gray irons. Nodular cast iron is competing with steels in many applications, as in the case of crankshafts of motorcar engines, for example. The composition and properties of some grades of cast iron are given in Table A.6.

A.4 LIGHT NONFERROUS METALS AND ALLOYS

Nonferrous metals and alloys are relatively more expensive than steels and are usually considered in the category of special materials to meet special needs. They are selected only when the relatively high cost per unit weight can be justified by one or more of their special properties, such as lightweight, high strength/weight ratio, high electric and thermal conductivity, or corrosion resistance. Table A.7 gives some physical properties of selected nonferrous metals and alloys.

A.4.1 Aluminum Alloys

Among the commercial metals, aluminum is second only to iron in production and consumption on a weight as well as a volume basis. Pure aluminum, specific gravity 2.7, and its alloys are the most important light nonferrous metallic materials, and their selection is usually based on one or more of the following considerations:

1. High strength/weight ratio that allows the design and construction of strong lightweight structures. This is particularly advantageous for portable equipment, vehicles, and aircraft applications.
2. Resistance to corrosion in atmospheric environments, in fresh and salt waters, and in many chemicals and their salts. Aluminum has no toxic salts, which makes it suitable for processing, handling, storing, and packaging of foods and beverages.
3. High electric and heat conductivity, especially when lightweight is important.

The AA designation system used to describe wrought aluminum alloys is given in Table P.3. The composition and properties of representative alloys are given in Table A.8.

TABLE A.6
Composition and Properties of Selected Cast Irons

Specification	Class or Grade	UNS No.	Composition (CE =% C + 0.3[%Si + P])	Tensile Strength		Yield Strength		Average (BHN)	Elongation (%)
				MPa	ksi	MPa	ksi		
Gray iron									
ASTM A48–74	20	—	CE = 4.34	140	20.3	140	20.3	170	—
	25	—	CE = 4.08	175	25.38	175	25.38	190	—
	35	—	CE = 3.77	245	35.53	245	35.53	220	—
	40	—	CE = 3.65	280	40.6	280	40.6	225	—
	50	—	CE = 3.45	350	50.76	350	50.76	250	—
	60	—	CE = 3.37	420	60.9	420	60.91	270	—
Nodular (ductile) iron									
ASTM A536	60–40–18	F32800	Chemical composition is subordinate to mechanical properties. However, the content of any chemical element may be specified by mutual agreement.	420	60.9	280	40.6	170	18
	65–45–12	F33100		455	65.98	315	45.68		12
	80–55–06	F33800		560	81.2	385	55.8	215	6
	100–70–03	F34800		700	101.5	490	71.06		3
	120–90–02	F36200	—	840	121.8	630	91.36	270	2
ASTM A395	60–40–18	F32800	CE = 3.77	420	60.9	280	40.6	165	18
AS1M A476	80–60–03	F34100	CE = 3.8–4.5	560	81.21	420	60.9	201 min	3
Malleable iron									
ASTM	32510	—	TC, 2.5%; Si, 1.3%; S, 0.11%; P, 0.18% max	350	50.76	230	33.35	110–145	10
A47 (ferritic)	35018	—	TC, 2.3%; Si, 1.2%; S, 0.11%, P, 0.18% max	370	53.66	245	35.5	—	18
ASTM A220 (pearlitic)	40010	—	TC, 2.3%; Si, 1.3%; S, 0.11%; P, 0.18% max	420	60.9	280	40.6	180–240	10

TABLE A.7
Some Physical Properties of Selected Nonferrous Metals and Alloys

Metal/Alloy	Density (kg/m^3)	Melting Point (°C)	Cost[a] (Relative to Mild Steel)
Light metals and alloys			
Mg	1,700	650	3–4
Mg alloys	1,750–1,800	610–660	—
Al	2,700	660	3–4
Al alloys	2,600–2,800	475–660	
Ti	4,500	1670	20–30
Ti alloys	4,400–4,700	1550–1650	—
Copper and alloys			
Cu	8,930	1085	5–6
Cu alloys	7,400–8,950	880–1260	—
High-temperature metals and alloys			
Ni	8,910	1453	20–30
Ni alloys	7,750–8,900	1100–1450	—
Co	8,832	1495	35–40
Mo	1,022	2610	150–200
Nb	8,570	2468	100–150
Ta	16,600	2996	—
W	19,250	3410	50
Low-melting metals and alloys			
Zn	7,113	420	3–4
Zn alloys	6,640–7,200	385–525	—
Pb	11,350	327	2
Pb alloys	8,850–11,350	180–327	—
Sn	5,765	232	20–30
Cd	8,642	321	5–6
Bi	9,808	271	10–20
In	7,286	157	100–150
Precious metals and alloys			
Ag	10,490	962	500–800
Au	19,302	1064	$5–8 \times 10^4$
Pt	21,450	1769	$8–10 \times 10^4$

[a] Costs vary significantly, depending on supply and demand, quantity purchased, size and shape, delivery time, and several other factors.

TABLE A.8
Composition and Properties of Selected Aluminum Alloys

			Tensile Strength		Yield Strength		Elongation	Hardness
Alloy	Temper	Nominal Composition (%)	MPa	ksi	MPa	ksi	(%)	(BHN)
Wrought alloys								
1060	0	99.6+A1	70	10	28	4	43	19
	H18		133	19	126	18	6	35
2014	0	4.4 Cu, 0.8 Si, 0.8 Mn, 0.4 Mg	189	27	98	14	18	45
	T6		490	71	420	61	13	135
3003	0	1.2 Mn	112	16	42	6	40	28
	H18		203	29	189	27	10	55
4032	T6	12.5 Si, 1.0 Mg, 0.9 Cu, 0.9 Ni	385	56	322	47	9	120
5052	0	2.5 Mg, 0.25 Cr	196	28	91	13	30	47
	H38		294	43	259	38	8	77
6061	0	1.0 Mg, 0.6 Si, 0.25 Cu, 0.25 Cr	126	18	56	8	30	30
	T6		315	46	280	41	17	95
7075	0	5.5 Zn, 2.5 Mg, 1.5 Cu, 0.3 Cr	231	34	105	15	16	60
	T6		581	84	511	74	11	150
Casting alloys								
208.0	Sand cast	4 Cu, 3 Si	147	21	98	14	2.5	55
356.0	T51	7 Si, 0.3 Mg	175	25	140	20	2	60
	T6		231	34	168	24	3.5	70
B443.0	Sand cast	5 Si	133	19	56	8	8	40
	Die cast		231	34	112	16	9	50
520.0	T4	10 Mg	336	49	182	26	16	75
850.0	T5	6.5 Sn, 1 Cu, 1 Ni	161	23	77	11	10	45

A.4.2 Magnesium Alloys

Magnesium, with a specific gravity of only 1.74, is the lightest metal available for use by engineers. Table A.9 gives the composition and properties of selected magnesium alloys. Because of their relatively low melting point, magnesium casting alloys are widely used in making die-cast products.

A.4.3 Titanium Alloys

Titanium has a specific gravity of 4.5 and is considered as one of the light metals. Titanium alloys are also among the strongest of the light alloys, especially at elevated temperatures (540°C or 1000°F), which gives them the highest strength/weight ratio among structural alloys. Titanium alloys also have excellent corrosion resistance to atmospheric and sea environments as well as to a wide range of chemicals. The mechanical properties of titanium alloys cover a wide range of strength and ductility. The composition and mechanical properties of some commercial purity titanium and its alloys are given in Table A.10.

A.5 HEAVY NONFERROUS METALS AND ALLOYS

A.5.1 Copper Alloys

Copper and its alloys have a unique combination of high thermal and electric conductivity, high corrosion resistance, generally high ductility, and wide range of interesting colors. Compared with other nonferrous alloys, copper alloys exhibit a wider range of ductility and strength combinations. The composition and properties of selected copper alloys are given in Table A.11.

A.5.2 Low-Melting-Point Alloys

Low-melting metals include zinc, lead, tin, bismuth, antimony, cadmium, and indium. Zinc is a relatively inexpensive metal and is the fourth most widely used metallic material after iron, aluminum, and copper. Almost half of the zinc production is used in galvanizing steel to protect it against corrosion. Another major use for zinc is die-casting alloys. Table A.12 gives the composition and properties of some zinc die-casting alloys.

A.5.3 High-Temperature Metals and Alloys

High-temperature materials normally cover nickel and its alloys and cobalt and its alloys, in addition to tungsten, molybdenum, tantalum, and niobium. Nickel and cobalt are also used for applications that require corrosion resistance in addition to high-temperature resistance. Superalloys contain large amounts of alloying elements, which improve the high-temperature strength, creep resistance, and oxidation resistance. As shown in Tables A.13 and A.14, superalloys fall into the three categories of iron–nickel-based, nickel-based, and cobalt-based alloys. Typical applications

TABLE A.9
Composition and Properties of Selected Magnesium Alloys

Alloy	Temper	Nominal Composition (%)	Tensile Strength		Yield Strength		Elongation (%)	Hardness (BHN)
			MPa	ksi	MPa	ksi		
Wrought alloys								
AZ31B	0	3.0 Al, 0.2 Mn, 1.0 Zn	224	33	115	17	11	56
	H24		255	37	165	24	7	73
AZ61A	F	6.5 Al, 0.15 Mn, 1.0 Zn	266	39	140	20	8	55
HK31A	H24	0.7 Zr, 3.2 Th	235	34	175	25	4	57
HM21A	T8	0.8 Mn, 2.0 Th	224	33	140	20	6	55
ZK40A	T5	4.0 Zn, 0.45 Zr	280	41	250	36	4	60
Casting alloys								
AM 00A	F	10.0 Al, 0.1 Mn	140	20	70	10	6	53
	T4		238	35	70	10	6	52
	T6		238	35	105	15	2	52
AZ63A	F	6.0 Al, 0.15 Mn, 3.0 Zn	182	26	77	11	4	50
	T6		238	35	112	16	3	73
EZ33A	T5	2.6 Zn, 0.7 Zr, 3.2 Re	140	20	98	14	2	50
HK31A	T6	0.7 Zr, 3.2 Th	189	27	91	13	4	55
HZ32A	T5	2.1 Zn, 0.7 Zr, 3.2 Th	189	27	91	13	4	55
ZK61A	T6	6.0 Zn, 0.8 Zr	280	41	182	26	5	70

TABLE A.10
Properties and Applications of Selected Wrought Titanium Alloys

Alloy and Composition	Tensile Strength MPa	Tensile Strength ksi	Yield Strength MPa	Yield Strength ksi	Elongation (%)	Hardness (RC)	Application
Unalloyed							
ASTM grade 1	240	35	170	25	—	—	Excellent corrosion resistance
ASTM grade 4	550	80	480	70	—	—	
Alpha alloys							
5 Al, 2.5 Sn	875	127	819	119	16	36	Weldable, aircraft engine compressor blades and ducts, steam turbine blades
8 Al, 1 Mo, 1 V	1029	149	945	137	16	—	—
Alpha + beta alloys							
3 Al, 2.5 V	700	101	595	86	20	—	Aircraft hydraulic tubes
6 Al, 4 V	1008	146	939	136	14	36	Rocket motor cases, blades, and disks for turbines
7 Al, 4 Mo	1120	162	1050	152	16	38	Airframes and jet engine parts
6 Al, 2 Sn, 4 Zr, 6 Mo	1288	187	1190	173	10	42	Components for advanced jet engines
							Airframe structures requiring toughness and strength
10 V, 2 Fe, 3 Al	1295	188	1218	177	10	—	—
Beta alloys							
13 V, 11 Cr, 3 Al	1239	180	1190	173	8	—	High-strength fasteners
8 Mo, 8 V, 2 Fe, 3 Al	1330	193	1260	183	8	40	Aerospace components
3 Al, 8 V, 6 Cr, 4 Mo, 4 Zr	1470	213	1400	203	7	42	High-strength fasteners
11.5 Mo, 6 Zr, 4.5 Sn	1407	204	1337	194	11	—	High-strength sheets for aircraft

TABLE A.11
Composition and Properties of Selected Wrought Copper Alloys

Alloy	Nominal Composition (%)	Treatment	Tensile Strength		Yield Strength		Elongation (%)	Rockwell Hardness
			MN/m²	psi	MN/m²	psi		
Pure copper								
C10200	99.95 Cu	—	221–455	33–66	69–365	10–53	55	—
Dilute copper alloys								
Beryllium copper	97.9 Cu, 1.9 Be	Annealed	490	71	—	—	35	RB 60
	0.2 Ni or Co	HT (hardened)	1400	203	1050	152	2	RC 42
Brass								
Gilding, 95%	95 Cu, 5 Zn	Annealed	245	36	77	11	45	RF 52
		Hard	392	57	350	51	5	RB 64
Red brass, 85%	85 Cu, 15 Zn	Annealed	280	41	91	13	47	RF 64
		Hard	434	63	406	59	5	RB 73
Cartridge brass, 70%	70 Cu, 30 Zn	Annealed	357	52	133	19	55	RF 72
		Hard	532	77	441	64	8	RB 82
Muntz metal	60 Cu, 40 Zn	Annealed	378	55	119	17	45	RF 80
		Half-hard	490	71	350	51	15	RB 75

High-lead brass	65 Cu, 33 Zn, 2 Pb	Annealed	350	51	119	17	52	RF 68
		Hard	318	46	420	61	7	RB 89
Phosphor bronze, 5%	95 Cu, 5 Sn	Annealed	350	51	175	25	55	RB 40
		Hard	588	85	581	84	9	RB 90
Phosphor bronze, 10%	90 Cu, 10 Sn	Annealed	483	70	250	36	63	RB 62
		Hard	707	103	658	95	16	RB 96
Aluminum bronze	95 Cu, 5 Al	Annealed	420	61	175	25	66	RB 49
		Cold rolled	700	102	441	64	8	RB 94
Aluminum bronze (2)	81.5 Cu, 9.5 Al, 5 Ni, 2.5 Fe, 1 Mn	Soft	630	91	—	—	12	—
		Hard	735	107	420	61	12	RB 105
High-silicon bronze	96 Cu, 3 Si	Annealed	441	64	210	31	55	RB 66
		Hard	658	95	406	59	8	RB 93
Copper nickel								
Cupronickel, 30%	70 Cu, 30 Ni	Annealed	385	56	126	18	36	RB 40
		Cold rolled	588	85	553	80	3	RB 86
Nickel silver								
Nickel silver	65 Cu, 23 Zn, 12 Ni	Annealed	427	62	196	28	35	RB 55
(German silver)		Hard	595	86	525	76	4	RB 89

TABLE A.12
Composition and Properties of Some Zinc Die-Casting Alloys

Material	Zamak 3 ASTM AG40A(XXIII)	Zamak 5 ASTM AG41A(XXV)
Composition (%)		
Copper	0.25	0.75–1.25
Aluminum	3.50–4.30	3.50–4.30
Magnesium	0.02–0.05	0.03–0.08
Iron (max)	0.10	0.10
Zinc	Rem	Rem
Properties		
Tensile strength MPa (ksi)	287 (42)	329 (48)
Elongation (%)	10.00	7.00
Charpy impact (J) (ft lb)	58.3 (43)	66 (49)
Hardness (BHN)	82	91
Specific gravity	6.6	6.7

Note: Rem, remainder.

include vanes and blades for turbine and jet engines, heat exchangers, vessels for chemical plants, and heat-treating equipment.

Refractory metals have melting points above 1630°C (2966°F). Tungsten, molybdenum, tantalum, and niobium are important members of this group. The most advanced applications of these metals and their alloys are in the manufacture of rocket motors and turbojet engines. Table A.15 gives the composition and properties of selected refractory metals and alloys.

TABLE A.13
Chemical Composition of Selected Ni-Based and Co-Based Alloys

Material	Nominal Composition (wt%)										Others
	C	Mn	Si	Cr	Ni	Co	W	Nb	Zr	Fe	
Fe–Ni-based alloys											
Incoloy 80	0.05	0.8	0.5	21	32.5	—	—	—	—	45.7	0.38 Al, 0.38 Ti
Inconel 718	0.08	—	—	19	52.5	—	—	5.1	—	18.5	3 Mo, 0.9 Ti, 0.5 Al, 0.15 Cu
Nickel-based alloys											
DS-nickel	—	—	—	—	bal	—	—	—	—	—	2.1 ThO_2
Hastelloy X	0.1	1.0	1.0	21.8	bal	1.5	0.6	—	—	18.5	—
Inconel 600	0.08	0.5	0.2	15.5	76	—	—	—	—	8.0	—
Inconel 617	0.1	0.5	0.5	22.0	52	12.5	—	—	—	1.5	9 Mo, 0.3 Ti, 1.2 Al, 0.2 Cu
MAR-M200, c	0.15	—	—	9.0	bal	10	12.5	1.8	0.05	—	2Ti, 5 Al, 0.015 B
TRW VI A, c	0.13	—	—	6.0	bal	7.5	5.8	0.5	0.13	—	2 Mo, 1 Ti, 0.02 B, 5.4 Al, 9 Ta, 0.5 Re, 0.4 Hf
Cobalt-based alloys											
AiResist 13, c	0.45	0.5	—	21	1	bal	11	2	—	2.5	3.5 Al, 0.1 Y
X-40, c	0.5	0.5	0.5	25	10	bal	7.5	—	—	1.5	—
MAR-M302, c	0.85	0.1	0.2	21.5	—	bal	10	—	0.15	—	9 Ta, 0.005 B
MAR-M918	0.05	0.2	0.2	20	20	bal	—	—	0.1	0.5	7.5 Ta

Note: bal, balance; c, cast alloy.

TABLE A.14
Rupture Strength of Selected Nickel-Based and Cobalt-Based Alloys

	Rupture Strength (MPa) (ksi)					
	650°C (1200°F)		851°C (1500°F)		1093°C (2000°F)	
Material	**100 h**	**1000 h**	**100 h**	**1000 h**	**100 h**	**1000 h**
Nickel-based alloys						
DS-nickel	162	155	131	120.6	61.3	51
	(23.5)	(22.5)	(19)	(17.5)	(8.9)	(7.4)
Hastelloy X	330	234	96	69	8.2	4.1
	(48)	(34)	(14)	(10)	(1.2)	(0.6)
Inconel 600	—	—	55.2	38.6	9.6	6.2
			(8)	(5.6)	(1.4)	(0.9)
Inconel 617	414	324	145	96	18.6	10.3
	(60)	(47)	(21)	(14)	(2.7)	(1.5)
MAR-M200, c	—	—	524	414	75.8	44.8
	—	—	(76)	(60)	(11)	(6.5)
TRW VI A, c	1000	896	552	420.6	82.7	—
	(145)	(130)	(80)	(61)	(12)	—
Cobalt-based alloys						
AiResist 13, c	—	—	172.4	117.2	30.3	—
	—	—	(25)	(17)	(4.4)	—
X-40, c	390	339	179.3	137.9	27.6	—
	(57)	(49)	(26)	(20)	(4)	—
MAR-M302, c	—	—	276	206.9	41.4	27.6
	—	—	(40)	(30)	(6)	(4)
MAR-M918	462	—	206.9	137.9	17.2	—
	(67)	—	(30)	(20)	(2.5)	—

Note: c, cast alloy.

TABLE A.15
Composition and Properties of Some Refractory Metals and Alloys

Alloy	Nominal Additions (%)	Test Temperature °C	Test Temperature °F	UTS at Test Temperature MPa	UTS at Test Temperature ksi	10 h Rupture Stress MPa	10 h Rupture Stress ksi
Niobium and alloys							
Unalloyed Nb	—	1366	2491	70	10	38	5.5
SCB 291	10 Ta, 10 W	1366	2491	224	33	63	9.1
C129Y	10 W, 10 Hf, 0.1 Y	1590	2894	182	26	105	15.2
FS85	28 Ta, 11 W, 0.8 Zr	1590	2894	161	23	84	12.2
Molybdenum and alloys							
Unalloyed Mo	—	1366	2491	182	26	102	14.8
TZM	0.5 Ti, 0.08 Zr, 0.015 C	1590	2894	371	54	154	22.3
WZM	25 W, 0.1 Zr, 0.03 C	1590	2894	504	73	105	15.2
Tantalum and alloys							
Unalloyed	—	1590	2894	60	8.7	17.5	2.5
Ta-10 W	10 W	1590	2894	350	50.8	140	20.3
T-222	9.6 W, 2.4 Hf, 0.01 C	1590	2894	280	40.6	266	38.6
Tungsten and alloys							
Unalloyed	—	1922	3492	175	25.4	48	7.0
W-2 ThO_2	2 ThO_2	1922	3492	210	30.5	126	18.3
W-15 Mo	15 Mo	1922	3492	252	36.6	84	12.2
GE 218	Doped	1922	3492	406	58.9	—	—

Appendix B: Polymers—Classification, General Characteristics, and Properties

B.1 INTRODUCTION

Polymers are organic materials and are characterized by their low density, good thermal and electric insulation, high resistance to most chemicals, ability to take different colors and opacities, and ease of manufacturing into complicated shapes with excellent surface finish in one step. Compared with structural metals and alloys, unreinforced bulk polymers have high thermal expansion coefficients, are mechanically weaker, and exhibit lower elastic moduli. These drawbacks can be greatly overcome by reinforcing polymers with a variety of fibrous materials to form composite materials.

Plastics are composed of a mixture of polymeric materials and additives. Polymers can be classified into thermoplastics and thermosets. Thermoplastics soften when heated and harden when cooled, no matter how often the process is repeated. Thermosets, on the other hand, have strong intermolecular bonding, which prevents the fully cured materials from softening when heated. The additives are intended to give the plastic desirable properties such as color, flexibility, rigidity, flame resistance, weathering resistance, and processability.

Rubbers are similar to plastics in structure, and the difference is largely based on the degree of extensibility or stretching. Rubbers can be stretched to at least twice their original length and, upon release of the stress, return to approximately the original dimensions. Some grades of plastics approach this definition of rubber.

B.2 STRUCTURE OF POLYMERS

The structure of a polymeric material is intimately related to the polymerization mechanism involved in forming it. During polymerization, a monomer, or other small molecules, attaches itself to a growing molecule in order to produce the polymeric molecule. In addition to polymerization, molecules of the monomer are usually subjected to heat and pressure, in the presence of a catalyst, to induce polymerization. The resulting molecules are chain-like with secondary weak bonds between them that allow them to slide easily relative to each other. These polymers are described as linear polymers. When the arrangement of linear molecules is completely random, the structure is amorphous. Certain amount of crystallinity is achieved when adjacent chains become aligned, creating regions of regular structure. The frequency and distribution of these regions are determined by the structure of the molecules and by the processing techniques applied to the material. Increasing crystallinity tends to increase the static and fatigue strengths and softening temperature but decreases ductility, as in the case of HDPE. Amorphous polymers, on the other hand, shrink less in molding, which simplifies the design of molds for large parts.

The optical properties of polymers are also influenced by the extent of crystallinity. Crystalline polymers are essentially two-phase systems, with the denser crystalline phase having a higher refractive index than the amorphous matrix. This difference in refractive index makes crystalline polymers either opaque or translucent. Completely amorphous polymers can be transparent, for example, acrylic and polycarbonate.

Addition-type polymers can also be polymerized with branched molecules that have side chains protruding from the main chain, thus forming a structure resembling the branched shape of a tree. Polyethylene is an example of a polymer in which branching can occur. With increasing length of side chains, the average distance between the main chains increases. This reduces the secondary bonds and is accompanied by a decrease in crystallinity and lower density and stiffness. When the repeating unit in the polymer is the same as that of the monomer, the resulting polymer is known as a homopolymer. Another type of addition polymers can be made to contain more than one kind of monomer, and the resulting structure, called a copolymer, is comparable to a solid solution in metallic materials. The properties of the copolymer depend on the type and arrangement of monomers used in building it. Copolymers tend to be less crystalline than homopolymers, and they are, therefore, tougher and more flexible. An example of a copolymer is ABS, which is made from acrylonitrile, butadiene, and styrene. The members of the ABS group are strong and tough with properties that can be tailored to different requirements by varying the proportions of the constituents and the molecular weight.

In contrast to addition reactions, which are primarily a summation of individual molecules into a polymer, condensation reactions form in steps between two or more different molecules, which make them slower processes. Furthermore, there is usually a by-product that must condense, hence the name of the reaction. This by-product is usually water or some other molecules, such as HCl or CH_3OH. Condensation reactions can produce either a chain-like molecule such as 6/6 nylon or a network structure such as phenol formaldehyde.

B.3 GENERAL CHARACTERISTICS OF PLASTICS

B.3.1 Mechanical Behavior of Polymers

When a polymer is subjected to a continuously applied load, it undergoes both elastic deformation, which occurs instantaneously on application of load, and viscous deformation, which increases with time. The latter component of deformation is usually not fully recoverable on unloading. The recovery of dimensions after load removal is dependent on the loading time and is generally more rapid after short periods of time at low strains than after long periods of time at high strains. The recovery time is an important parameter in applications involving intermittent loading. This behavior is called viscoelastic. Generally, increasing the molecular weight of the polymer, by increasing the average chain length and cross-linking, causes the viscous deformation to decrease.

The impact strength of polymers can be measured in a similar way to metals and is usually presented in joule or foot-pound per unit width of specimen or notch depth. The impact strength generally decreases with decreasing temperature, and many polymers become very brittle at their glass-transition temperatures. Plastics that are considered tough include polycarbonates, PTFE, ABS, nylon, polyethylene, and high-impact polypropylene. On the other hand, acrylics and general-purpose polystyrene are among the brittle plastics.

Unlike steels, which can resist an infinite number of fatigue cycles if the applied stress is below their endurance limit, plastics do not have well-defined fatigue limits. Also, because of the viscoelastic nature of plastics, high-frequency cyclic loading can cause temperature rise and further reduction in strength.

Generally, plastics are much softer than many other engineering materials, and their hardness is usually expressed by special scales of Rockwell and shore hardness. Because of their low hardness, plastics are usually susceptible to abrasive damage from other harder materials. However, there are exceptions to this rule, and some plastics have considerable resistance to abrasion, even compared with metallic materials. Polyurethane is particularly good in this regard.

B.3.2 Physical Properties of Polymers

Low specific gravity is one of the important features of plastics and ranges from 0.9 to 1.1 for polyethylene and polystyrene, 1.2–1.55 for PVC, and 2.1–2.2 for Teflon. Plastics are also nonconductors of heat and electricity and some are among the best available insulators. Plastics are usually transparent or translucent unless additives mask these properties. Among the optically clear polymers are acrylic, allylic, and cellulosic. Among the polymers that can be translucent are epoxy, polycarbonate, polyester, polyethylene, polypropylene, polystyrene, polysulfone, polyurethane, PVC, and silicone. Generally, the coefficient of expansion of bulk polymers is approximately 2–20 times as great as that of metals and is usually not linear. This means that if a plastic material is to replace a metallic material in a part with close tolerances, due allowance should be made. Fillers can be added to reduce thermal expansion.

The heat deflection temperature is usually considered as an indication of the suitability of polymers to high-temperature service. According to ASTM standards, this temperature is determined as follows. A sample of the plastic to be tested is shaped as a bar and placed in a liquid medium and loaded to a known level. The temperature of the liquid is raised steadily (1.1°C/min or 2°F/min) until the bar has distorted by a predetermined amount (0.25 mm or 0.010 in.). The temperature at which this distortion is reached is the heat distortion temperature. The data from such tests give reasonably good indication of the maximum temperature for short-term service for amorphous thermoplastics. For crystalline plastics, however, the deflection temperature usually gives a poor indication of the upper temperature limit for use of the material. Exposure to high temperatures can cause degradation of polymers as a result of the oxidation. Examples of antioxidant additives include phenols, aromatic amines, aminophenols, aldehydes, and ketones.

UV radiation and oxidation can both cause the primary covalent bonds in polymer chains to break, giving rise to molecular chain fragments known as free radicals. Free radicals can recombine to form cross-links between the polymer chains, which increases rigidity and decreases ductility of the material. They can also recombine to form smaller polymer molecules and lead to loss of strength. A certain degree of protection against radiation can be achieved by the addition of suitable UV absorbers. A typical example of protection against UV radiation is the addition of carbon black to rubber.

B.3.3 Chemical Properties of Polymers

Generally, plastics can exhibit excellent resistance to many forms of chemical attack, especially in weak acids or alkalis. They are, however, attacked by strong oxidizing acids. Thermoplastics can also be dissolved by various organic solvents. The solubility in a particular solvent generally decreases as the molecular weight and crystallinity increase. Fuels, fats, oils, and even water may cause some plastics to swell and soften. Immersing stressed thermoplastics in some liquids could cause stress cracking.

B.4 THERMOPLASTICS

Thermoplastics are more widely used than thermosetting plastics and occupy about 78% of the market. Polyethylenes are the most widely used group of plastics and occupy 28% of the total world market of plastics. Polyethylenes are relatively cheap, tough, and resistant to chemicals. They have excellent dielectric strength and are easy to process. Their largest drawbacks are their poor heat resistance and dimensional stability. The different types of polyethylenes can be classified according to their density into low, medium, and high density, as shown in Tables B.1 and B.2. Typical applications include high-frequency insulators, piping, housewares, blow-molded bottles and containers, battery parts, toys, and flexible film packaging.

Polystyrenes are second only to polyethylenes in volume of use and occupy about 17% of the total market share of plastics. They are based on the styrene monomer with low crystallinity and considerable branching. Various modifications create a wide range of structures and properties. Polystyrenes are generally rigid, have low cost, and have exceptional insulating properties. Although they have reasonable tensile strength, they are subject to creep and their maximum service temperature is limited to about 77°C (ca. 170°F) (Tables B.1 and B.2). The impact grades and glass-filled types are used widely for engineering parts, and polystyrene foams are highest in volume use of all the plastics. They can be easily processed by common methods. Typical applications include housings for appliances like TV and radios, automobile dashboards, containers, housewares, luggage and furniture parts, fan blades, and foam products.

Vinyls are a very widely used group of plastics and occupy about the same market share as polystyrenes. Like polyethylenes and polystyrenes, they are versatile and low in cost. Plasticizers can change the vinyls from a stiff and rigid state to a flexible and rubberlike one (Tables B.1 and B.2). Vinyls have excellent chemical resistance,

TABLE B.1
Some Mechanical Properties of Selected Plastics

	Tensile Strength		Tensile Modulus				Izod Impact	
Material	**MN/m²**	**ksi**	**MN/m²**	**ksi**	**Elongation (%)**	**Hardness**	**J**	**ft lb**
I. Thermoplastics								
Polyethylene								
Low density	7–21	1.0–3.0	140	20.0	50–800	Rr 10	27	19.93
Medium density	14–21	2.0–3.0	280	40.0	50.800	Rr 14	2.7–22	1.99–16.24
High density	21–35	3.0–5.0	700–1,400	100–200	1030	Rr 65	1.36–6.8	1–5.02
Polypropylene								
Homopolymers	35	5.0	1,200	171.4	150	Rr 90	0.54–2.0	0.4–1.48
High-impact copolymers	27	3.8–6	—	—	400	Rr 65	5.4–8.1	4–5.98
Talc filled, 40%	35	5.0	3,600	514.2	5.0	Rr 95	0.54	0.4
Polystyrene								
General purpose	35–56	5.0–8.0	3,300	471.4	1.5–4.0	Rm 74	0.27–0.54	0.2–0.4
High impact	23–32	3.3–4.6	2,200	314.2	25–60	Rm 60	1.36–3.8	2.8
30% glass fiber	77–100	11.0–14.3	8,800	1257.1	—	Rm 90	3.8	2.8
PVC								
General purpose	7–28	1.0–4.0	20	2.8	400	Sa 75	—	—
Flexible PVC	14–21	2.0–3.0	15	2.1	250	Sa 85	—	—
Rigid PVC	35–63	5.0–9.0	200–4,200	285.7–600	100	Rr 115	1.4–2.7	1.03–1.99
Acrylic (MMA)								
Cast, general purpose	42–84	6.0–12.0	2,800	400	—	Rm 91	0.68	0.5
Molding grade	63–77	9.0–11.0	2,800	400	—	Rm 95	0.5	0.37
High impact	42–63	6.0–9.0	2,100	300	25–40	Rm 45	1.4–5.4	1.0–3.99

(continued)

TABLE B.1 (continued)
Some Mechanical Properties of Selected Plastics

Material	Tensile Strength		Tensile Modulus		Elongation (%)	Hardness	Izod Impact	
	MN/m²	ksi	MN/m²	ksi			J	ft lb
Nylons								
Nylon 6/12	62	8.8	21,000	3,000	150–340	Rr 114	1.36–2.7	1–1.99
Acetal								
Homopolymer	70	10.0	3,700	528.6	25–75	Rm 94	1.9–3.1	1.4–2.29
Homopolymer 22% TFE fiber	53	7.5	2,800	400.0	12–21	Rm 78	0.95–2.3	0.7–1.7
Copolymer	62	8.8	2,900	414.2	60–75	Rm 80	1.63–3.5	1.2–2.58
Polycarbonate								
Unfilled	63	9.0	2,400	342.8	110	Rm 70	16–22	11.81–16.24
ABS								
Medium impact	46	6.6	2,500	357.1	6–14	Rr 111	5.4	3.99
High impact	42	6.0	2,300	328.5	10–35	Rr 103	8.8	6.49
Very high impact	33.6	4.8	1,750	250.0	15–50	Rr 88	10.8	7.97
Heat resistant	50.4	7.2	2,450	350.0	5–20	Rr 111	3.12	2.3
Fluoroplastics								
PCTFE	28–42	4.0–6.0	1,400	200.0	160	Sd 76	4	2.95
PTFE	14–49	2.0–7.0	700	100.0	100–450	Sd 58	6.1	4.5
High-temperature plastics								
Polyamide unfilled	91	13.0	3,150	450.0	7–9	Rm 97	1.36	1
Polyamide 40% graphite	53	7.6	5,300	757	2–3	Rm 73	—	—
Polysulfone	71.4	10.2	2,500	357	50–100	Rr 120	1.63	1.2

II. Thermosetting plastics								
Phenolic								
General purpose	35–63	5.0–9.0	800	114.2	—	Re 95	0.44	0.32
Shock and heat	28–63	4.0–9.0	14,000	2,000	—	Re 85	2.17	1.6
Heat (mineral)	35–49	5.0–7.0	11,000	1571.4	—	Re 85	0.54	0.4
Electric (mineral)	28–56	4.0–8.0	6,000	857.1	—	Re 87	0.41	0.59
Epoxy								
Cast rigid	63–105	9.0–15.0	3,200	457.1	—	Rm 106	0.5	0.37
Molded	56–140	8.0–20.0	14,000	2,000	—	B78	1.3–5.5	0.96–4.06
High-strength laminate	350–490	50.0–70.0	32,000	4571.4	—	B71	1.36–41	1–30.26
Polyester								
Unfilled	56	8.0	2,400	342.8	200–300	Rm 117	1.63	1.2
30% glass fiber	123	17.6	7,700	1100	3	Rm 90	2.3	1.7
Alkyd								
Granular (mineral)	42–63	6.0–9.0	16,000	2285.7	—	Re 85	0.42	0.31
Silicone								
30% glass fiber	42	6	17,500	2,500	—	Rm 90	4–20.3	2.95–14.98
Silica reinforced	28	4	11,000	1571.4	—	Rm 82	0.41	0.3

TABLE B.2
Some Physical Properties and Uses of Selected Plastics

Material	Expansion Coefficient ×10⁵ m/m/°C	Expansion Coefficient ×10⁵ in./in./°F	Heat Deflection Temperature °C	Heat Deflection Temperature °F	Specific Gravity	Relative Cost
I. Thermoplastics						
Polyethylene						
Low density	19.8	11	36	96.8	0.92	1.0
Medium density	16.2	9	44.4	111.92	0.93	1.0
High density	13.5	7.5	49	120.2	0.96	1.0
Polypropylene						
Homopolymers	8.6	4.78	57	134.6	0.91	0.8
High-impact copolymers	—	—	50	122	0.9	1.1
Talc filled, 40%	—	—	81	177.8	1.23	1.0
Polystyrene						
General purpose	7.4	4.11	67–100	152.6–212	1.05	1.0
High impact	7.0	3.89	67–97	152.6–206.6	1.04	1.0
30% glass fiber	3.2	1.78	97	206.6	1.29	1.75
Polycarbonate						
Unfilled	6.75	3.75	132	269-6	1.2	3.6
ABS						
Medium impact	8.46	4.7	94	201.2	1.05	1.4
High impact	9.5	5.28	99	210.2	1.04	1.6
Very high impact	11.0	6.11	96	204.8	1.02	1.7
Heat resistant	6.7	3.72	114	237.2	1.05	1.8
Fluoroplastics						
PCTFE	4.5	2.5	—	—	2.1	20
PTFE	9.9	5.5	—	—	2.16	10
High-temperature plastics						
Polyamide unfilled	5.0	2.78	360	680	1.43	—
Polyamide 40% graphite	3.2	1.78	360	680	1.65	—
Polysulfone	5.6	3.11	174	345.2	1.24	6.3
PVC						
General purpose	14.4	8	—	—	1.40	1.6
Flexible PVC	14.4	8	—	—	1.35	1.6
Rigid PVC	9–11	5–6.11	72	161.6	1.40	1.3
Acrylic (MMA)						
Cast, general purpose	5.4–7.2	3–4	99	210.2	1.19	1.4
Molding grade	5.4–7.2	3–4	88	190.4	1.18	1.7
High impact	7.2–11	4–6.11	77	170.6	1.11	2.2

TABLE B.2 (continued)
Some Physical Properties and Uses of Selected Plastics

Material	Expansion Coefficient ×10^5 m/m/°C	Expansion Coefficient ×10^5 in./in./°F	Heat Deflection Temperature °C	Heat Deflection Temperature °F	Specific Gravity	Relative Cost
Nylons						
Nylon 6/12	9	5	82	179.6	1.07	5.8
Acetal						
Homopolymer	9–14.4	5–8	124	255.2	1.42	2.5
Homopolymer 22% TFE fiber	9–14.4	5–8	100	212	1.52	15
Copolymer	8.46	4.7	110	230	1.41	1.9
II. Thermosetting plastics						
Phenolic						
General purpose	3.8	2.11	174	345.2	1.38	—
Shock and heat	2.3	1.28	154	309.2	1.83	—
Heat (mineral)	1.8	1	177	350.6	1.53	—
Electric (mineral)	3.96	2.2	154–204	309.2–399.2	1.52–1.67	—
Epoxy						
Cast rigid	5.6	3.11	166	330.8	1.20	1.3
Molded	3.6	2	191	375.8	1.91	1.3
High-strength laminate	3.6	2	—	—	1.84	1.3
Polyester						
Unfilled	11.3	6.28	54	129.2	1.31	2.7
30% glass fiber	2.3–9.7	1.28–5.39	213	415.4	1.54	2.9
Alkyd						
Granular (mineral)	2.9	1.61	146–191	294.8–375.8	2.2	1.4
Silicone						
30% glass fiber	5.76	3.2	482	899.6	1.88	—
Silica reinforced	4–8	2.22–4.44	482	899.6	1.93	—

high abrasion resistance, and good electric resistivity. Their maximum useful temperature is about 77°C (ca. 170°F) (Tables B.1 and B.2). The most widely used vinyls are PVC and PVC-acetate copolymer. Vinyls can be easily processed by common methods. Typical applications include rigid PVC for construction industry such as pipes, conduits, fume hoods, and various building components. Flexible PVC is used in communication and low-tension cables, flexible tubing, footwear, imitation leather, upholstery, records, and film and sheet for chemical tanks and other applications.

Polypropylenes are the fourth largest group of thermoplastics and they occupy about 5% of the total market share of plastics. They are similar in many respects to HDPEs and can be classified into three basic groups: homopolymers, copolymers, and reinforced, as shown in Tables B.1 and B.2. Copolymers are produced by adding other types of olefin monomers to improve properties like low-temperature toughness. The mechanical properties can be further improved by adding fillers, glass fibers, or asbestos. The ability of polypropylenes to withstand fatigue loading has made them popular for surgical implant hinges. Although polypropylenes have low creep resistance, reinforcing them with asbestos can raise their maximum service temperature to about 125°C (ca. 260°F). They are easily processed by common methods. Typical applications include housewares, luggage and furniture, automotive components, medical devices, piping, mechanical parts, housings, TV cabinets, containers, ropes, and film and fibers.

The ABS plastics have a good balance of toughness, hardness, and rigidity, which they maintain over the range of temperatures −40°C to 107°C (ca. −40°F to 225°F). ABS have low water absorption, hence good dimensional stability. They also exhibit high abrasion resistance. As shown in Tables B.1 and B.2, ABS polymers are available in medium, high, and very high impact grades, as well as heat resistant, transparent, flame retardant, and expanded grades. ABS plastics are readily processed by all manufacturing methods for thermoplastics. ABS chromium-plated components are in wide use as a replacement for metals, for example, in automobiles and appliances. Other applications include piping and fittings, appliance housings, telephone housings, refrigerator components, fume hoods and ducts, automotive components, and tool handles.

Acrylic plastics are mostly based on methyl methacrylate polymers (PMMA) modified by copolymerization or blending with other monomers. They have high optical clarity, can acquire glossy surface, and are available in brilliant transparent colors. Acrylics are strong, hard, and stiff, but regular grades are brittle (Tables B.1 and B.2). High impact grades are produced by blending with rubber stock. Acrylics are available as cast sheets, rods, tubes, or blocks and as powders for injection molding and extrusion. They can be processed by machining, molding, and thermoforming. Molding compounds can be extruded or injection molded. Typical applications include transparent enclosures and optical uses such as lenses, signs, displays, window glazing, lighting fixtures, protective goggle lenses, reflectors, pump parts, control knobs, and tool handles.

Polyamides, nylons, have basically linear molecular structures with a relatively high degree of crystallinity, which gives them good mechanical properties, as shown in Tables B.1 and B.2. They also have a very high abrasion resistance and good frictional characteristics. Nylons also have excellent electric properties and chemical resistance. Their major disadvantage is their relatively high cost and moisture absorption, which results in dimensional changes. Nylons are processed mainly by molding and extruding, but small parts can be processed by powder sintering. Polyamides are used in applications where precision is not the first requirement and where high wear resistance and low friction are required. Typical applications include bearings, gears, housings, bushings, tubing, pump housings, rollers, fasteners, zippers, and electric parts.

Acetals are highly crystalline and among the strongest and stiffest thermoplastics (Tables B.1 and B.2). Their excellent creep resistance and low moisture absorption give them excellent dimensional stability, and they retain most of their properties in hot water. Acetals also have excellent resistance to vibration fatigue. They have low coefficient of friction and good abrasion resistance. They are useful for continuous service up to about 105°C (ca. 220°F). Typical applications include mechanical parts such as gears, bushings, bearings, cams, rollers, impellers, latches, wear surfaces, and housings where high performance is required over a long period.

Polycarbonate (Tables B.1 and B.2) is a linear, noncrystalline, transparent plastic. Polycarbonate is tough and has excellent electric resistivity as well as outdoor stability. Its maximum service temperature is about 140°C (ca. 285°F) and has good creep resistance under load. Although it has negligible moisture absorption, it is easily attacked by organic solvents. Typical applications include safety helmets, safety shields, window glazing, windshields, lenses, load-bearing electric parts, electric insulators, battery cases, tool housings, medical apparatus, and parts requiring dimensional stability.

Fluoroplastics (Tables B.1 and B.2) are composed basically of linear molecules with fluorine replacing some or all of the hydrogen atoms. They are highly crystalline with high molecular weight. As a class, fluoroplastics rank among the best plastics for chemical resistance and for high-temperature performance up to about 260°C (500°F). PTFE is the most widely used fluoroplastic because of its high service temperature. Typical applications include linings for chemical processing equipment, chemical pipes, pump parts, valves, coatings for home cookware, insulation for high-temperature wire and cable, gaskets, and low-friction surfaces.

Several groups of thermoplastics have been developed to withstand temperatures in excess of 200°C (ca. 390°F) for extended periods. These include polyimide, polysulfone, polyphenylene sulfide, and polyarylsulfone (Tables B.1 and B.2). In addition to their high-temperature resistance, these plastics have high strength and tensile modulus and excellent resistance to solvents. Their major disadvantage is the difficulty in processing them. Their high-price limits their use to specialized applications where resistance to high temperature is important.

B.5 THERMOSETTING PLASTICS

Although thermosetting plastics are fewer in number and their manufacturing processes are more limited than thermoplastics, their special characteristics make them indispensible in some applications, and at present they occupy about 14% of the total market share of plastics. The presence of the network of strong covalent bonds, which are developed due to cross-linking between molecules, in thermosetting plastics makes them react quite differently to temperature and mechanical stresses than thermoplastics. Thermosetting plastics generally resist higher temperatures and are harder but more brittle than thermoplastics. They also have better dimensional stability, creep resistance, chemical resistance, and electric properties. Thermosetting plastics are generally more difficult to process than thermoplastics, and once cured, that is, cross-linked, they will not return to their original state. Before curing, thermosetting plastics are composed of a resin system and fillers. Sometimes reinforcements are also added. Thermosetting plastics are usually classified according to the resin component, which consists of a polymer, curing agents, hardeners, inhibitors, and plasticizers. The resin component influences the dimensional stability, heat and chemical resistance, electric properties, and flammability. The fillers usually have a major effect on mechanical properties, especially when in the form of fibers. Tables B.1 and B.2 list some properties of selected thermosetting plastics.

Phenolics (phenol formaldehyde) are the most widely used group of thermosetting plastics and occupy about 6% of the total market share of plastics. Although brittle, phenolic resins have high resistance to heat, water, and chemicals. They are relatively cheap and are readily molded with good stiffness and impact resistance. Phenolics can be classified as general purpose with wood flour fillers, shock resistant with paper or fabric fillers, heat resistant with mineral or glass fillers, electric grade with mineral fillers, chemical grade with no fillers, and rubber phenolics. Typical applications include motor housings, pulleys, wheels, appliance connector plugs, ignition parts, condenser housings, electric insulators, handles, and knobs.

Epoxies (Tables B.1 and B.2) are some of the most versatile plastics and are used in high-performance applications where their high cost is justified. They are available in a wide variety of forms, both liquid and solid, and are cured into the finished product by catalysts. The epoxy resins give good chemical resistance and electric properties in addition to excellent bonding properties. They also have exceptionally high strength, especially when reinforced with glass fiber or other similar fibers. Typical uses of epoxies include adhesives, components requiring high strength and thermal insulation, encapsulation of electronic components, and tools and dies.

Polyester thermosetting resins (Tables B.1 and B.2) are copolymers of a polyester and, usually, styrene. Unreinforced polyesters have limited use, and the majority of products are glass reinforced as either moldings or laminates. When reinforced, polyesters exhibit excellent balance of mechanical, electric, and chemical properties. They can be made in a large number of colors and give off no volatiles during curing. Polyesters have low moisture absorption. They are widely used to produce "fiberglass" boat hulls, swimming pools, chairs, automobile body panels, and other high-strength components.

Silicones (Tables B.1 and B.2) are semiorganic polymers composed of monomers in which oxygen atoms are attached to silicon atoms together with radicals. Silicones can be used in a wide range of temperatures from –73°C to +260°C (–100°F to +500°F). They have excellent electric properties and resistance to water and certain chemicals. They are also compatible with body tissues. Silicones are premium plastics and are used in critical or high-performance applications, such as aircraft, aerospace, and electronics.

B.6 ELASTOMERS

Elastomers are a large family of rubberlike polymers with the characteristic ability to undergo very large elastic deformations without rupture. They are soft and have a low elastic modulus and a low glass-transition temperature. All rubbers are elastomers, but not all elastomers are rubbers. An elastomer is defined as being capable of recovering substantially in shape and size after the load has been removed. Rubber is defined as being capable of recovering quickly from large deformations. Table B.3 lists some properties of selected rubbers.

TABLE B.3
Some Properties and Applications of Selected Rubbers

Material	Tensile Strength MN/m²	Tensile Strength ksi	Elongation (%)	Hardness (Shore A)	Specific Gravity
Natural rubber	28	40	700	30–90	0.92
Styrene butadiene	24.5	35	600	40–90	0.94
Neoprene	28	40	600	30–90	1.24
Butyl	21	30	800	40–80	0.92
Silicone	8.4	12	700	30–85	0.98
Fluorocarbon	17.5	25	300	60–90	1.85
Hypalon	21	30	500	50–90	1.18

Natural rubber is a homopolymer of the isoprene monomer. A number of grades of rubber are made from the raw material by adding fillers like carbon black, silica, and silicates. The soft grades have excellent resilience and good abrasion resistance, with low hysteresis and heat building up under repeated loading. They have low resistance to oil, heat ozone, and sunlight. Additives like carbon black improve the resistance to UV radiation. Major uses of natural rubber include conveyor belts, tire products, sound damping, and gaskets.

Styrene butadiene rubbers (SBRs) are copolymers of butadiene and styrene and are the most widely used group of rubbers because of their low cost and their use in automobile tires. A wide range of properties can be obtained by changing the butadiene to styrene ratio, and the grades containing more than 50% styrene are usually considered as plastics. SBRs have excellent impact and abrasion resistance but poor chemical resistance. Their major uses include motorcar tire treads, conveyor belts, gaskets, and sound damping.

Neoprene (chloroprene) is a synthetic rubber that is chemically and structurally similar to natural rubber. It has excellent resistance to oils, chemicals, sunlight, weathering, aging, and ozone and retains its properties at temperatures up to 115°C (ca. 240°F). In addition, it has excellent resistance to permeation by gases, but it is more expensive. Major applications include heavy-duty conveyor belts, V-belts, footwear, brake diaphragms, bridge mounts, and motor mounts.

Butyl rubbers consist of copolymers of isobutylene and isoprene and are one of the lowest priced synthetics. Because of their excellent dielectric strength and impermeability, they are widely used for cable insulation, encapsulating components, and similar electric applications. Other applications include coated fabrics, high-pressure steam hoses, inner tube linings, and machine mounts.

Some silicones can be considered as rubbers in view of their extensibility. Silicone rubbers are the most stable of all rubbers with excellent resistance to high and low temperatures, oils, and chemicals. They maintain their electric properties over the range of temperatures –73°C to +270°C (ca. –100°F to +520°F). All silicone rubbers can be classified as high-performance, high-price materials, and their major uses include seals, gaskets, O-rings, encapsulation of electronic components, and insulation for wire and cable.

B.7 ADHESIVES

One important application of polymers is as adhesives, which are being used to replace welding and riveting in several applications. The use of adhesives covers the range from aircraft and missile skins to food and beverage cans. This is because

1. Adhesive bonding can be effectively used to combine different materials while maintaining their integrity.
2. Stresses are uniformly distributed over the bonded area.
3. Adhesive joints provide sealing against the environment.
4. The fatigue behavior of adhesive-bonded structural assemblies is excellent.

Polymeric materials such as thermoplastic resins, thermosetting resins, and rubbers (elastomers) can be used as adhesives. Table B.4 gives the properties and method of preparation of some commonly used adhesives. The factors that affect the selection of an adhesive for a given joint include the service temperature, the chemical environment, the expected life of the joint, and the nature of the surfaces to be joined. The method of application and curing treatment can also play an important role in the selection of adhesives.

Epoxies consist of an epoxy resin plus a hardener and are available in both one-part, hot cure, and two-part, cold or warm cure, form. They allow great versatility in formulation since there are many resins and hardeners in this group.

Cyanoacrylates are one-part adhesives that consist of liquid monomers that polymerize through reaction with moisture on the surfaces to be bonded. They set very quickly, in a few seconds, but they require close-fitting surfaces because they do not fill large voids. Exposure to temperatures above 80°C (ca. 175°F) in high humidity can cause bond failure. Most consumer-oriented super glues are of this type.

Anaerobics are one-part polyester acrylic adhesives that harden when in contact with metal surfaces and when air is excluded. Rubber-modified anaerobics remove odor, flammability, and toxicity while speeding the curing operation. They can bond almost anything, including oily surfaces, and are often used to secure, seal, and retain threaded or similarly close-fitting parts.

Toughened acrylics are fast curing and give high strength and toughness. They are supplied in two parts, resin and catalyst, which can be applied as premixed or applied separately. In the latter case, the resin is applied to one surface and the catalyst to the other. Toughened acrylics tolerate minimal surface preparation and bond well to a variety of materials including oily metals and many plastics. As they often contain volatiles and flammable monomers, special vapor extraction systems may need to be installed if used on large scale.

Polyurethanes are either one-part or two-part adhesives that cure fast at room temperature. They provide strong resilient joints with high-impact resistance. Their

TABLE B.4
Properties and Preparation of Some Common Adhesives

Adhesive	Curing Temperature		Service Temperature		Lap-Shear Strength[a]		Peel Strength at RT	
	°C	°F	°C	°F	MPa at °C	ksi at °F	N/cm	lb/in.
Acrylics	RT	RT	Up to 120	Up to 250	17.2–37.9	2.5–5.5	17.5–105	10–60
Anaerobics	RT	RT	Up to 166	Up to 330	15.2–27.6	2.2–4.0	17.5	10
Butyral–phenolic	135–177	275–350	–51 to 79	–60 to 175	17.2 6.9(80)	2.5 1.0(175)	17.5	10
Cyanoacrylates	RT	RT	Up to 166	Up to 330	15.2–27.6	2.2–4.0	17.5	10
Epoxy (RT cure)	RT	RT	–51 to 82	–60 to 180	17.2 10.3(80)	2.5 1.5(175)	7	4
Epoxy (HT cure)	90–175	195–350	–51 to 175	–60 to 350	17.2 10.3(175)	2.5 1.5(350)	8.8	5
Epoxy–nylon	120–175	250–350	–250 to 82	–420 to 180	41 13.8(80)	6.0 2.0(180)	123	70
Epoxy–phenolic	120–175	250–350	–250 to 260	–420 to 500	21–28 6.9(80)	3.0–4.0 1.0(175)	8.8	5
Polyurethanes	149	300	Up to 66	Up to 150	24	3.5	123	70
Silicones	149	300	Up to 260	Up to 500	0.3	0.04	43.8	25
Hot melts (general) (polyamides)	—	—	Up to 120	Up to 250	1.4–4.8	0.2–0.7	35	20
	260–370	500–700	Up to 315	Up to 600	13.8	2.0	17.5	10

Note: RT, room temperature; HT, high temperature.

[a] RT if temperature is not specified.

TABLE B.5
Properties of Some Commercial Polystyrene Foams

	Density		Compressive Strength		Compressive Modulus	
Polymer	**kg/m³**	**lb/ft.³**	**kN/m²**	**psi**	**kN/m²**	**psi**
Polystyrene (molded)	16.0	1.0	138	20	1,725	250
	32.0	2.0	242	35	5,175	750
	64.0	4.0	483	70	12,075	1750
Polystyrene (extruded)	30.4	1.9	242	35	6,900	1000
	46.4	2.9	449	65	20,700	3000
	70.4	4.4	897	130	34,845	5050

fast cure and sensitivity to moisture in the uncured state usually necessitate machine application. They are weak in creep and should only be considered for nonstructural applications.

Hot melts are thermoplastic adhesives that are solid at room temperature but melt when heated. They are generally applied as heated liquids and form a bond as they cool. They are generally used in nonstructural applications.

B.8 FOAMS

Foamed materials are a class of lightweight cellular engineering materials. Foams can be classified according to their pore structure as open-cell or closed-cell foams. In the open-cell structures, the pores are connected to each forming an interconnected network. In the closed-cell foams, the pores are not connected. Compared with open-cell structures, the closed-cell foam materials have higher dimensional stability, lower moisture absorption, and higher compressive strength. Closed-cell foams also have higher density and are more expensive as they require more material. Foamed materials can be metallic, ceramic, or polymeric, but the latter is more widely used commercially.

Polystyrene foams are good thermal insulators and are therefore often used as building insulation materials and disposable food and drink containers. They also have good damping properties and are therefore used in packaging. Extruded closed-cell polystyrene foam is sold under the trade name Styrofoam. Table B.5 gives some properties of commercial polystyrene foams. It is noticed that the compressive strength and modulus increase as the density increases.

Appendix C: Ceramic Materials—Classification, General Characteristics, and Properties

C.1 INTRODUCTION

Ceramics cover a wide variety of materials of widely different compositions and properties. The characteristic feature of all ceramic materials is that they are inorganic compounds of one or more metals with a nonmetallic element. The nonmetallic elements are usually oxygen as in the case of aluminum oxide, carbon as in the case of silicon carbide, and nitrogen as in the case of silicon nitride. Ceramic materials are generally insulators to heat and electricity. They are also hard, stiff, and stable. Ceramic materials can have one of the following types of structures:

1. Noncrystalline structures, or glasses, where only the short-range arrangement of the atoms exists but which do not have the long-range repetitious crystalline pattern.
2. Crystalline structures where all the material is arranged according to a 3D long-range order. Crystalline ceramics generally have higher stability than glasses and on the average have higher melting points and hardness.
3. Crystalline material bonded together by a noncrystalline or glassy matrix. The glassy phase is usually the weaker of the two phases and reducing its volume fraction increases the strength of the material.

The American Ceramic Society has classified ceramics into the following groups: whitewares, glass, refractories, structural clay products, and enamels. Refractories and glasses will be discussed in the following sections.

C.2 GENERAL CHARACTERISTICS OF CERAMICS

C.2.1 Mechanical Properties of Ceramics

The most noticeable characteristic of ceramics is that they are hard and brittle at room temperature. High strength can be achieved in ceramics, provided no porosity or structural defects are present. In practice, however, structural irregularities such as microcracks, grain boundaries, and microporosity are difficult, if not impossible, to eliminate. While in ductile materials the stress concentrations around these structural defects may be relieved by plastic flow of the material, this is not possible in brittle materials and fracture occurs at stresses much lower than the theoretically possible strength. Once started, the fracture propagates readily under tension, because the stress concentration is intensified as the crack proceeds. Under compression, a crack will not be self-propagating as loads can be transferred across it; therefore, brittle materials are usually much stronger in compression than in tension. The ratios between tensile strength, modulus of rupture, and compressive strength can be roughly taken as 1:2:10. Tables C.1 and C.2 give numerical values of some properties for ceramics and glasses.

TABLE C.1
Some Properties of Oxide and Carbide Ceramics

		Thermal Expansion Coefficient		Tensile Strength		Compressive Strength		Young's Modulus	
Material	Specific Gravity	10^{-6}/°C	10^{-6}/°F	MPa	ksi	MPa	ksi	GPa	lb/in.$^2 \times 10^6$
I. Oxides									
Alumina (85%)	3.39	—	—	155	22.5	1930	280	221	32
(90%)	3.60	—	—	221	32	2482	360	276	40
(99.5%)	3.89	8.8	4.9	262	38	2620	380	372	54
Beryllia (98%)	2.90	9.0	5.0	85	12.3	1980	287	230	33
(99.5%)	2.88	9.0	5.0	98	14.2	2100	304	245	35.5
Magnesia	3.60	13.5	7.5	140	20.3	840	122	280	40.6
Zirconia	5.8	9.8	5.4	147	21.3	2100	304	210	30.4
Thoria	9.8	9.2	5.1	52	7.5	1400	203	140	20.3
II. Carbides									
SiC (silicate bond)	2.57	4.68	2.6	—	—	105	15.2	21	3.0
SiC (SiN bond)	2.62	4.68	2.6	—	—	150	21.7	44	6.4
SiC (self-bonded)	3.10	3.78	2.1	—	—	1400	203	175	25.4
Boron carbide	2.51	4.5	2.5	—	—	2900	420	308	44.6
Tungsten carbide	16.0	5.95	3.3	—	—	—	—	—	—

TABLE C.2
Typical Compositions and Properties of Commercial Glasses

	Fused Silica	96% Silica (Vycor)	Soda Lime–Silica	Borosilicate (Pyrex)	Aluminosilicate	Lead–Alkali
Chemical composition (%)						
SiO_2	99.5+	96	72.6	80.2	57	56.5
Al_2O_3			1.6	2.6	20.6	1.4
K_2O			0.9	0.3		8.25
Na_2O			13.1	4.5	1.0	4.25
CaO			3.7	0.1	5.4	
MgO			8.0		12.0	
B_2O_3		4		12.3	4	
PbO						29.6
Fe_2O_3			0.1			
Properties						
Young's modulus GPa (lb/in.$^2 \times 10^6$)	73.5 (10.7)	67.2 (9.8)	70 (10.2)	66.5 (9.6)	89.6 (13)	63 (9.1)
Poisson's ratio	0.17	0.18	0.24	0.20	0.26	—
Specific gravity	2.20	2.18	2.46	2.23	2.53	3.04
Linear expansion coefficient, ×(07)/°C(/°F)	5.6 (3.1)	8 (4.4)	92 (51)	32.5 (18)	42 (23)	90 (50)
Maximum service temperature (°C) (°F)	1197 (2187)	1097 (2007)	460 (860)	490 (914)	637 (1179)	380 (716)
Volume resistivity (Ω cm) at 250°C (482°F)	1.6×10^{12}	5×10^9	2.5×10^6	1.3×10^8	3.2×10^{13}	8×10^8
Dielectric constant	3.8	3.8	7.2	4.6	6.3	6.7
Refractive index	1.458	—	1.510	1.474	1.634	1.583

C.2.2 Physical Properties of Ceramics

Ceramic materials generally have higher melting points than commonly used metals, and their thermal conductivities fall between those of metals and those of polymers. The thermal conductivity of refractories depends on their composition, crystal structure, and texture. Simple crystalline structures, as in silicon carbide, usually have higher thermal conductivity. The variation of thermal conductivity with temperature usually depends on whether the material is crystalline or noncrystalline. For example, fireclay bricks show an increase of thermal conductivity with rising temperature, whereas the more crystalline forsterite and some high aluminas show a decrease in thermal conductivity with rising temperature.

Thermal shock resistance is a function of thermal conductivity and expansion coefficient in brittle materials. Ceramics generally have lower thermal expansion coefficients than metals and polymers. Ceramics with a lower thermal expansion coefficient and higher thermal conductivity usually exhibit better thermal shock resistance.

Ceramics are generally nonconducting to electricity and are considered to be dielectric. Most porcelains, aluminas, quartz, mica, and glasses have volume electrical resistivity values greater than 10^{15} ohm-cm and dielectric constants of up to 12 (1 kHz AC). The electrical resistivity of many ceramics decreases with the introduction of impurities in their structures.

Magnetic ceramics include a number of spinel structures commonly referred to as ferrites; for example, $MgFe_2O_4$, Fe_3O_4, $CoFe_2O_4$, and $CuFe_2O_4$. Ferrites find widespread applications in magnetic recording tape and disks, electron beam deflection coils, transformer cores, and computer memory parts.

The specific gravities of most ceramic materials range from 2 to 3, which makes them comparable to those of light metals.

C.2.3 Chemical Resistance of Ceramics

Ceramics are generally chemically very stable even at elevated temperatures. Almost all ceramic materials are resistant to chemical attack, except by hydrofluoric acid and, to some extent, by hot caustic solutions. They are not affected by organic solvents.

C.3 REFRACTORY CERAMICS

The most widely used common refractories are the alumina–silica type, with compositions ranging from nearly pure silica to nearly pure alumina, together with some impurities, such as iron and magnesium oxides. The structure usually consists of a glassy matrix binding the crystalline constituents. Silica bricks are made of at least 95% SiO_2. The refractory bricks based on silica are less expensive but are slightly acidic, that is, give acidic water solutions. Slags high in CaO and MgO, which are used to refine molten metals by removing phosphorous and sulfur, are basic and react with silica to form low-melting-point materials that erode the bricks. Under such basic slag conditions, basic refractories, such as those based on MgO and CaO, are used. Magnesia is susceptible to thermal shock and is less stable when in contact with most metals at temperatures above about 1700°C (ca. 3100°F) in reducing atmospheres.

Alumina is one of the most important commercial oxides. At moderately high temperatures, its strength is high, it is chemically stable, and it can be used either in oxidizing or reducing atmospheres up to about 1930°C (ca. 3500°F) for short periods. Pure alumina refractories can withstand higher temperatures than those containing binders. Alumina ceramics are successfully used in applications like cutting-tool inserts. However, their relatively high thermal expansion coefficient, coupled with high modulus of elasticity, makes them too prone to thermal shock to be used in applications like gas-turbine engines. Table C.1 lists numerical values of typical properties of some oxide ceramics.

Beryllia combines good electrical insulation with relatively higher thermal conductivity, which makes it useful for special electronic applications. Beryllia is stable to about 1700°C (ca. 3100°F) in air, reducing atmospheres, and in vacuum. Its resistance to chemical attack at high temperatures makes beryllia suitable as a crucible material for melting high-purity metals and alloys. However, it is expensive and difficult to work with and its dust particles are toxic. Table C.1 gives typical properties of beryllia.

Pure zirconia suffers an inversion in crystal structure at about 1000°C (ca. 1830°F), which causes a 7% contraction in volume with accompanying cracking. When stabilized with about 5% CaO, zirconia can be used at elevated temperatures and can be repeatedly heated above 2230°C (ca. 4040°F) without reversion. Zirconia is not wetted by most metals, and it is used for crucibles for melting platinum, palladium, ruthenium, and rhodium. It is also used for refractory bricks away from the slag line, as slags react severely with it. PSZ ceramics exhibit good thermal shock resistance, low coefficient of friction, excellent wear resistance, and a thermal expansion coefficient similar to that of steel. These characteristics make PSZ good candidates for applications in several parts of advanced diesel engines. PSZ is also used in applications where wear and thermal shock resistance are needed, as in the case of high-temperature metal extrusion dies. Table C.1 gives some properties of zirconia refractories.

Thoria has the highest melting point of all oxides, 3327°C (6021°F), and is stable under most conditions. Thoria crucibles have been used for melting titanium. Thoria is sensitive to thermal shock due to its high coefficient of thermal expansion and low thermal conductivity. It is also expensive and radioactive. Table C.1 lists some properties of thoria.

Carbides, as a family, contain materials with the highest melting points of all engineering materials. Hafnium and tantalum carbides both have melting points of 3944°C (7131°F). However, carbides cannot be used unprotected at high temperatures because of their poor oxidation resistance. The only exception is silicon carbide, which can be used at temperatures up to about 1680°C (ca. 3050°F). Silicon carbide combines high thermal conductivity, low thermal expansion, and high thermal shock resistance, which allows it to be used as a structural material for parts that are subjected to high mechanical and thermal stresses. As their density is only about one-third that of metallic superalloys, parts made from SiC have additional advantages where rotary and oscillating motion is involved. A SiC turbine rotor for an exhaust-operated turbocharger performed satisfactorily in an experimental diesel engine. Boron carbide is best known for its extreme hardness and its abrasion resistance. Table C.1 lists some properties of commonly used carbides.

Most nitrides are relatively brittle and have poor resistance to oxidation. The most widely used refractory nitrides are boron nitride (BN) and silicon nitride (Si_3N_4). Cubic boron nitride is best known as the synthetic diamond material, Borozon, and is stable in air up to 1730°C (ca. 3140°F) and has a hardness approaching that of diamond. It also has a thermal conductivity five times that of copper at room temperature, which makes it useful for very small heat-sink devices. Boron nitride is anisotropic, and its thermal expansion parallel to the direction of pressing is 10 times that in the perpendicular direction. Silicon nitride has outstanding resistance to wetting or reaction with molten nonferrous metals and is used for crucibles and boats for melting and refining semiconductor materials like germanium. It has excellent thermal shock resistance, which makes it useful for thin, thermocouple protection tubes and radiant heat shields. Its excellent erosion resistance at high temperatures makes it useful for rocket nozzle inserts.

C.4 GLASSES

Glasses include a large family of noncrystalline inorganic materials of widely different composition and properties. Silica is the most important constituent of glass, but other oxides are added to achieve certain characteristics. Table C.2 gives typical compositions and properties of some commercial glasses. The constituents of glass can be grouped into three categories:

1. Glass formers such as silica and boron oxide.
2. Modifiers such as sodium and potassium that are added to lower the melting temperature and improve processability.
3. Intermediate oxides that do not form glasses by themselves but affect the properties. An example is lead oxide that is added to improve the refractive index of the glass.

Fused silica and 96% silica glass have high softening temperature and low thermal expansion coefficient, which makes them resistant to heat and thermal shock. They also have very good chemical durability and electrical resistance. However, high cost and fabrication difficulties limit their applications to highly specialized products like furnace sight glasses, high-temperature thermocouple sheaths, and space and astronomical applications.

Soda-lime glass is the most widely used glass in terms of tonnage produced and variety of applications, because it is the least expensive and the easiest to fabricate. It is used for windows, bottles, jars, electric bulbs, and fluorescent tubes. However, its resistance to high temperature and thermal shock is poor and its resistance to chemical attack is only fair.

Lead glasses are somewhat more costly than soda-lime glasses but have excellent electrical resistivity and high refractive index. They are composed basically of silica, potash, and lead oxide. Glasses of this type are used for neon sign tubes and other applications requiring good electrical insulation. With higher lead content, these glasses are used for electric capacitors and for absorption of x-rays, gamma rays, and other forms of higher radiation. Lead glasses are also used for optical purposes where they are commonly called flint glass. Like soda-lime glasses, however, these glasses are not resistant to high temperatures or thermal shock.

Borosilicate glasses, Pyrex, are made by replacing most of the soda in soda-lime glass by boric oxide. This reduces the thermal expansion coefficient that improves the thermal shock resistance. Their resistance to heat and chemical attack is also better than soda-lime and lead glasses, but they are also more expensive and difficult to fabricate. Among its uses are laboratory glassware, industrial pipe lining sight glasses, boiler-gauge glasses, and domestic cookware. More recent applications include both flat-plate and tubular-type solar energy collectors.

Aluminosilicate glass is also resistant to thermal shock and stands higher temperatures than borosilicate glass; however, it is more expensive and more difficult to fabricate. Uses include halogen lamps for automobile head lamps, range-top cookware, and, when coated with electrically conducting film, resistors for electronic circuitry.

Appendix D: Composite Materials—Classification and Properties

D.1 INTRODUCTION

A composite material can be broadly defined as an assembly of two or more chemically distinct materials, having a distinct interface between them, and acting in concert to produce a desired set of properties. Composite materials can be classified as being either natural, as in the case of wood, or synthetic, as in the case of GFRPs. The different materials in a composite may be present as macroscopically distinct phases, as in the case of coatings, sandwich materials, and laminates, or they may be mixed on a microscopic scale, as in the case of dispersion, particulate, and fiber composites. In the latter group the matrix, the continuous phase, can be used to identify the composite, for example, MMC or PMC. The overall behavior of composite materials depends on

1. Properties of the constituents
2. Size and distribution of the constituents
3. Volume fraction of the constituents
4. Shape of the constituents
5. Nature and strength of bond between the constituents

PMCs are more widely used than MMCs. This is because a wider variety of reinforcing materials and better established manufacturing techniques are available for fiber-reinforced polymers. The demanding mechanical and chemical conditions that are usually encountered in MMCs allow only a narrow choice of reinforcing materials, and the techniques are often more complex and costly. The bulk of fiber-reinforced composites consists of plastics reinforced with continuous fibers. The reinforcing phase for polymers may be in the form of bundles of very fine glass fibers or other fibers such as graphite, aramid polymers, boron, or SiC. Applications of GRPs are varied and accordingly glass fibers are available in several commercial forms. Continuous strand fiber and roving, which resemble a ribbon or tape, are used for filament winding processes. Chopped fiber, 6–25 mm (1/4–1 in.) long, is utilized in manufacturing molded GRP shapes with randomly oriented fibers. Woven fabrics and nonwoven mats are also important and are produced as sheets, cloth, and roving. Unidirectional fabrics contain carbon fibers in the warp direction only and the weft is formed with glass, polyester, or aramid. Hybrid mixtures containing two types of fibers in the warp, for example, carbon–glass and carbon–aramid, are also used to combine the attractive properties of the different reinforcements. Bidirectional fabrics utilizing carbon in both warp and weft directions are available in different styles of weave, for example, plain, satin, and twill. Table D.1 gives some properties of selected composite materials.

Most composite materials have been developed to improve mechanical properties such as strength, stiffness, creep resistance, and toughness, but a few examples have been developed to achieve certain physical or chemical characteristics. Some properties of composite materials depend only on the amount of each phase, volume

TABLE D.1
Some Properties of Selected Composite Materials

Matrix Material	Fiber Material	ff (%)	Specific Gravity	Tensile Strength		Elastic Modulus	
				MPa	ksi	GPa	lb/in.$^2 \times 10^6$
Epoxy	S glass[a,b]	70	2.11	2100	304.4	62.3	9.0
	S glass[c]	70	2.11	680	98.6	22	3.2
	S glass[a,b]	14	1.38	500	72.5	—	—
	E glass[a,b]	73	2.17	1642	238	55.9	8.1
	E glass[a,b]	56	1.97	1028	149	42.8	6.2
	E glass[a,d]	56	1.97	34.5	5	10.4	1.5
	Carbon[a,b]	63	1.61	1725	250	158.7	23
	Carbon[a,d]	63	1.61	41.4	6	11.0	1.6
	Aramid[a,b]	62	1.38	1311	190	82.8	12
	Aramid[a,d]	62	1.38	39.3	5.7	5.5	0.8
Polyester	E glass[c]	65	1.8	340	49.3	19.6	2.8
	Glass[e]	40	1.55	140	20.3	8.9	1.3
Polystyrene	Glass[e]	30	1.28	97	14	8.2	1.2
Polycarbonate	Glass[e]	20	1.31	107	15.5	6.2	0.9
	Glass[e]	40	1.44	131	19	10.4	1.5
Nylon 66	Glass[e]	20	1.31	152	22	8.3	1.2
	Glass[e]	40	1.41	200	29	11.0	1.6
	Glass[e]	70	—	207	30	21.4	3.1
Aluminum	Carbon[a,b]	40		1242	180		
	SiO_2[a,b]	48		870	126		
	B[a,b]	10		297	43		
Nickel	B[a,b]	8		2650	384		
	W[a,b]	40		1100	159		
Copper	Carbon[a,b]	65		794	115		
	W[a,b]	77		1760	255		

[a] Continuous fibers.
[b] Fibers aligned in loading direction.
[c] Fabric.
[d] Fibers at 90° to loading direction.
[e] Discontinuous fibers.

fraction, and are insensitive to the microstructural geometry. These structure-insensitive properties may be determined by suitable weighted averages of the properties of each of the individual phases. Density and heat capacity are examples of such properties. The variation of structure-insensitive properties with the amount of phases can be represented by the rule of mixtures as

$$P_c = f_1 \times P_1 + f_2 \times P_2 + \cdots \tag{D.1}$$

where

P_c, P_1, and P_2 are the properties of the composite, phase 1 and phase 2, respectively
f_1 and f_2 are the volume fractions of phases 1 and 2, respectively; $f_1 + f_2 + \cdots = 1$

Composite material properties that are sensitive to the geometry of the phases as well as to their volume fractions are called structure-sensitive properties. Examples are elastic modulus, strength, and thermal and electrical conductivities. The variation of these properties with the volume fraction of constituent phases does not follow a unique relationship but usually falls between an upper limit and lower limit, depending on the arrangement of phases. This is particularly true in the case of fiber-reinforced composites. The upper limit is represented by the rule of mixtures of Equation D.1, while the lower limit is represented by the inverse rule of mixtures:

$$P_c = \frac{P_1 \times P_2}{(f_1 \times P_2) + (f_2 \times P_1)} \tag{D.2}$$

The upper limit represents the case where the fibrous constituents are arranged in parallel, while the lower limit is for the case where they are arranged perpendicular to the direction of measurement. The properties of the composite can be made more isotropic by orienting some of the fibers in the transverse direction, cross ply. However, this increased isotropy is achieved at the expense of reduced longitudinal properties. Anisotropy is not always undesirable and the load-carrying efficiency of structures can be increased by tailoring the material to provide greater local strength and stiffness where it is most needed.

D.2 DISPERSION AND PARTICULATE COMPOSITES

Dispersion composites are characterized by microstructures consisting of fine particles, of sizes less than 0.1 μm (4 μin.), and volume fractions are usually less than 15%, dispersed in a matrix. This type of composites are usually produced to improve the mechanical strength of the matrix, which is the load-carrying constituent.

Industrial examples of dispersion-strengthened composites are the aluminum–Al_2O_3 system, known as SAP, and the nickel–3%ThO_2 system, known as TD nickel. For high-temperature stability, the dispersed phase must not coarsen. This means that it should have low solubility and low rate of diffusion in the matrix, low interfacial energy and low reactivity with the matrix, high melting point, and high negative heat of formation.

The use of particulate fillers in polymeric materials is widespread. Inorganic particulate fillers may be used to raise the elastic modulus, increase the surface hardness, reduce shrinkage and eliminate crazing after molding, improve fire resistance, improve color and appearance, modify the thermal and electrical conductivities, and raise the viscosity for ease of molding. Also, the use of inorganic fillers can greatly reduce the cost without necessarily sacrificing other desirable properties. An important application of type of composites is in automotive tires, where particles of silica and carbon black are added to enhance the strength of the rubber matrix.

D.3 FIBER-REINFORCED COMPOSITES

Fibrous composites cover a wide variety of materials in which a matrix is used to bind together the fibers and to protect their surfaces from damage or chemical attack. Furthermore, the matrix separates the individual fibers and prevents brittle cracks from spreading across the composite. GFRPs account for over 75% of total fiber composite production. Although many types of plastics can be used as the matrix for GRPs, polyester and epoxy resins are the most widely used. Table D.1 lists the properties of selected fiber-reinforced composites.

D.3.1 Materials for Fiber Reinforcement

Glass fibers, in their various forms, are the most widely used form of reinforcement for plastics because of their low cost and availability. E glass, which is alumina borosilicate glass, is the most commonly used in plastic reinforcement. S glass was developed for higher strength, but it is more expensive than E glass. Table D.2 gives some properties of glass fibers.

Carbon and graphite fibers were developed to meet the need of aircraft industry for light materials with superior strength and stiffness. The scope of use of this material has now expanded and CFRPs are used in several non-aerospace areas, particularly in sports, leisure equipment, and industrial applications. Carbon fibers are usually classified into (1) high-modulus (HM or type I), (2) high-strength (HS or type II), and (3) general-purpose grade (A or type III). Table D.2 gives some characteristics of carbon fibers. Carbon fibers can be used with a variety of matrix materials, but epoxy resins represent the major part of CFRP products. Other matrix materials include (a) thermosets, such as polyesters, vinyl esters, phenolics, and polyimides; (b) thermoplastics, such as nylons, polycarbonates, polyesters, and polysulfones; and (c) metals, such as aluminum, magnesium, tin, and lead.

DuPont's Kevlar, an aramid, is lighter than carbon fibers and is available in different crystalline structures. More alignment of molecules results in higher crystallinity and higher elastic modulus. Kevlar 29 has an elastic modulus of about 62,000 GPa (9 million psi) with about 3.6% elongation. Kevlar 49 has an elastic modulus of 117,000 GPa (17 million psi) with about 2.5% elongation. Both types have strengths of about 3400 MPa (500,000 psi). Unlike carbon and glass fibers, which have similar elastic moduli in tension and compression, Kevlar exhibits a much lower modulus in compression than in tension. Table D.2 gives some properties of aramid fibers.

TABLE D.2
Some Properties of Selected Fiber Materials

Fiber Material	Specific Gravity	Tensile Strength GPa	Tensile Strength ksi	Elastic Modulus Gpa	Elastic Modulus lb/in.$^2 \times 10^6$	Relative Cost[a]
E glass	2.54	3.5	507	73.5	10.7	1
S glass	2.49	4.6	667	85.5	12.4	3–4
Carbon (HS)	1.9	2.5	263	240	34.8	20–40
Carbon (HM)	1.9	2.5	305	390	56.6	20–40
Aramid	1.5	2.8–3.4	406–493	66–130	9.6–18.8	4–12
Steel	7.8	4.2	609	207	30	
W	19.4	4.1	594	413	59.9	
Rene 41	8.26	2.0	290	168	24.3	
Mo	10.2	2.2	319	364	52.8	
Boron	2.6	3.5	507	420	60.9	
SiC	4	2.1	305	490	71	
Al_2O_3	3.15	2.1	305	175	25.4	
SiO_2	2.19	6	870	73.5	10.7	

[a] Cost of E glass is taken as unity.

Metal wires are reasonably strong, relatively ductile, and exhibit more consistent behavior than brittle fibers. Steel wires are normally used for reinforcing rubber and concrete. Other metallic fibers include tungsten, beryllium, molybdenum, and Rene 41, Table D.2. Nonmetallic fibers cover a wide variety of materials including boron, Al2O3, SiO2, SiC, and Si3N4. Many of these materials are also available as whiskers. Boron fibers are produced by vapor deposition of boron on a tungsten wire and they range from 0.1 to 0.15 mm (4–6 mils) in diameter. Typical properties of nonmetallic fibers are given in Table D.2.

D.4 LAMINATED COMPOSITES

Laminated composites, or layered materials, consist of two or more different layers bonded together. The layers can differ in material, orientation, or form. Clad metals are an example of metal–metal laminates where the outer layers are usually selected to give corrosion resistance or decorative appearance, while the inner layers are usually selected to give high strength. Other possible laminate combinations include metal–plastics as in the case of soft-packaging materials, elastomers–fabrics as in the case of V-belts and motorcar tires, and composite–metal as in the case of FRP faces–honeycomb core sandwich materials.

Laminates can also be built from fiber-reinforced layers with different fiber orientations. The properties of a given fiber-reinforced laminate in a certain direction can be determined on the basis of volume fraction and the properties of the different layers in that direction.

Sandwich materials can be classified as laminated composites. These materials usually consist of a thin facing material and a low-density core. Sandwich materials combine high section modulus with low density; for example, an aluminum-faced, honeycomb sandwich structure beam is about one-fifth the weight of a solid aluminum beam of equivalent rigidity. The facing material in a sandwich structure carries the major applied load and therefore determines the stiffness, stability, and strength of the composite. Examples of possible facing materials are aluminum, stainless steel, magnesium, titanium, plastics, and fiber-reinforced materials. The core forms the bulk of a sandwich structure. Therefore, it is usually of lightweight but must also be strong enough to withstand normal shear and compressive loads. The core can be in the form of foam or cells. Foam cores are usually made from plastics, especially polystyrene, urethane, cellulose acetate, phenolic, epoxy, and silicone. Foamed inorganic materials like glass, ceramics, and concrete can also be used. Cellular cores can have corrugated or honeycomb structures and are usually made from metal foils joined by welding, brazing, or adhesive bonding. Other core materials are GRPs, ceramics, or paper. Plastic-cored sandwiches faced with steel or aluminum have been shown to be weight-saving, cost-effective substitutes for automotive sheet steel. Thermal and sonic insulation of characteristics of these sandwiches provide secondary benefits, along with possibilities of using lower-capacity forming presses. However, sandwich materials suffer from lower in-plane strength, lower dent resistance, limited joining capability, and more difficulties in recycling.

Appendix E: Semiconductors and Advanced Materials

E.1 SEMICONDUCTORS

Semiconductors have electrical properties that are intermediate between the conducting metallic materials and the insulating nonmetallic materials. Small concentrations of impurity atoms in semiconductors are known to have substantial effect on their characteristics. Members of this group include single-crystal silicon, germanium, and gallium arsenide. Organic semiconductors are recent important additions to this group.

E.2 ADVANCED MATERIALS

Advanced materials cover both new high-performance materials as well as traditional materials whose properties have been enhanced to meet the more challenging demands of high-technology applications. Examples of such applications can be found in space travel, aircraft industry, military applications, sports equipment, biomedical applications, and electronic products. Advanced materials can be metals, ceramics, polymers, semiconductors, or composites. As advanced materials are normally more expensive than traditional materials, it is expected that the benefit of using them would more than outweigh the increased cost. Examples of advanced materials include the following.

E.3 NANOSTRUCTURED MATERIALS

Nanostructured materials can be metals, ceramics, polymers, or composites whose structures contain features smaller than 100 nm. Nanostructured materials can exhibit unusual mechanical, electrical, magnetic, or optical properties. An example of nanostructured materials is CNTs, which consist of one-atom thick graphite sheet rolled into a tube. The tube can be a single wall CNT (SWCNT) or MWCNT, depending on the number of sheets involved. The strength of an SWCNT can range between 50 and 200 GPa and their elastic modulus can be about 1000 GPa. Section 11.5 gives an example of the use of CNTs in sports equipment.

When the magnetically anisotropic Co–Cr alloy is in the form of nanoparticles of size in the range of 10 nm, it can be used for information storage on magnetic tapes and hard disk drives. This method of information storage is found in all computers, iPods, MP3 players, and credit/debit cards.

E.4 SMART MATERIALS

Smart materials are able to sense changes in their surroundings and then respond in a predetermined manner. Shape-memory materials, such as NiTi alloys, change their shape when their temperature changes. Piezoelectric materials, such as quartz and lead zirconate (PbZrO3), expand and contract in response to an applied electric field or voltage or conversely generate an electric field when their dimensions change. The behavior of magnetostrictive materials is similar to piezoelectric materials except that they are responsive to magnetic fields, rather than electric fields. Smart materials are used in building MEMSs, which integrate miniature mechanical devices with electronic circuits. The size of MEMS devices ranges from 20 μm to 1 mm and their applications range from accelerator/decelerator sensors that are used in airbag deployment systems in motorcars to gyroscopes and microphones that are used for military and aerospace applications.

Appendix F: Conversion of Units and Hardness Values

TABLE F.1
Conversions to SI Units

Quantity	Multiply Number Of	By	To Obtain Number Of
Length	Inches	25.4	mm
	Feet	0.3048	Meters (m)
	Yards	0.9144	m
Area	Square inches	645.16	mm^2
	Square feet	0.092903	m^2
	Square yards	0.836130	m^2
Volume	Cubic inches	16387.1	mm^3
	Cubic feet	0.0283168	m^3
	Cubic yards	0.764555	m^3
Mass	Ounces	0.0283495	Kilograms (kg)
	Pounds (lb)	0.45359237	kg
	Short tons	907.185	kg
	Long tons	1016.05	kg
Density	lb/in.^{3}	27679.9	kg/m^3
	lb/ft.^{3}	16.0185	Kg/m^3
Force	Pounds force (lbf)	4.44822	Newtons (N)
	Tons force (long)	9964.02	N
	Dynes	10^{-5}	N
	kgf	9.80665	N
Stress	lbf/in.^{2}	6894.76	N/m^2
	tonf/in.^{2}	15.4443×10^6	N/m^2
	kgf/cm^2	98.0665×10^3	N/m^2
Work	ft. lbf	1.35582	Joules (J)
	hp/h	2.68452×10^6	J
	BTU	1.05506×10^3	J
	kw/h	3.6×10^6	J
	kcal	4.1868×10^3	J
	kgf/m	9.80665	J
Power	ft./lbf s	1.35582	Watts (W)
	Horsepower (hp)	745.7	W
	Metric hp (CV)	735.499	W
	BTU/h	0.293071	W

(*continued*)

TABLE F.1 (continued)
Conversions to SI Units

Quantity	Multiply Number Of	By	To Obtain Number Of
Thermal conductivity	BTU/h ft. °F	1.73073	W/m^3
	BTU in./h ft.^{2} °F	0.144228	W (m K)
	Kcal/m h °C	1.163	

Note: Temperature $°C = \frac{5}{9}(°F - 32)$.

$$°F = \frac{9}{5}°C + 32.$$

TABLE F.2
Hardness Conversions: Soft Steel, Gray and Malleable Cast Iron, and Most Nonferrous Metals

Rockwell Scale			BHN 500 kg	VHN 10 kg and	Tensile Strength
B	A	30T	(10 mm Ball)	BHN 3000 kg	(MN/m^2)
100	61.5	82.0	201	240	800
98	60.0	81.0	189	228	752
96	59	80	179	216	710
94	57.5	78.5	171	205	676
92	56.5	77.5	163	195	641
90	55.5	76.0	157	185	614
88	54	75	151	176	586
86	53	74	145	169	559
84	52	73	140	162	538
82	50.5	71.5	135	156	517
80	49.5	70	130	150	497
78	48.5	69	126	144	476
74	46	66	118	135	448
70	44	63.5	110	125	420
66	42	60.5	104	117	392
62	40.5	58	98	110	—
58	38.5	55	92	104	—
54	37	52.5	87	98	—
50	35	49.5	83	93	—
46	33.5	47	79.5	88	—
42	31.5	44	76	86	—
38	30	41.5	73	—	—
34	28	38.5	70	—	—
30	26.5	36	67	—	—
20	22	29	61.5	—	—
10	—	22	57	—	—

TABLE F.3
Hardness Conversions: Hardened Steel and Hard Alloys

Rockwell Scale					
C	A	30T	VHN 10 kg	BHN 3000 kg	Tensile Strength (MN/m^2)
80	92	92	1865	—	—
75	89.5	89	1478	—	—
70	86.5	86	1076	—	—
65	84	82	820	—	—
64	83.5	81	789	—	—
62	82.5	79	739	—	—
60	81	77.5	695	614	2310
58	80	75.5	655	587	2205
56	79	74	617	560	2065
54	78	72	580	534	2006
52	77	70.5	545	509	1889
50	76	68.5	513	484	1758
48	74.5	66.5	485	460	1634
46	73.5	65	458	437	1524
44	72.5	63	435	415	1427
42	71.5	61.5	413	393	1338
40	70.5	59.5	393	372	1255
38	69.5	57.5	373	352	1179
36	68.5	56	353	332	1117
34	67.5	54	334	313	1054
32	66.5	52	317	297	992.9
30	65.5	50.5	301	283	937.7
28	64.5	48.5	285	270	889.4
26	63.5	47	271	260	848
24	62.5	45	257	250	807
22	61.5	43	246	240	772
20	60.5	41.5	236	230	745

Appendix G: Glossary

Abrasive wear: Occurs in a soft surface when the asperities of a hard surface rub against it.

Activation energy: The energy required to cause a reaction to occur.

Additive: Material added to a polymer to modify its characteristics.

Adhesive wear: Loss of material from a surface as a result of tearing off of its asperities when they form a bond with a stronger material.

Age hardening (precipitation hardening): Increase of hardness as a result of the precipitation of a hard phase from a supersaturated solid solution.

Allotropy (polymorphism): Change of lattice structure with temperature, for example, iron changes from bcc to fcc at 910°C.

Alloy: A metal containing one or more additional metallic or nonmetallic elements.

Amorphous (noncrystalline): Atoms or molecules of the material are not arranged according to a repetitive pattern or exhibit long-range order.

Anion: Negative ion that is formed when an atom gains one or more electrons.

Anisotropic: Exhibiting different properties in different directions.

Annealing (steels): Heating to the austenite range then cooling slowly enough to form ferrite and pearlite.

Annealing (strain-hardened metal): Heating a cold-worked metal to the recrystallization temperature to soften the material. In the case of steels, this is called process anneal.

Anode: The electrode that supplies electrons to the external circuit in an electrochemical cell. It is the electrode that undergoes corrosion or the negative electrode.

Anodizing: Electrochemically coating the surface with an oxide layer by making the part an anode in an electrolytic bath.

Artificial aging: Heating a solution-treated and solution-quenched precipitation-hardenable alloy in order to speed up the precipitation process.

Atomic mass unit (amu): One-twelfth of the mass of C12; also equal to 1.66×10^{-24} g.

Atomic number: The number of electrons possessed by an uncharged atom; also the number of protons per atom.

Atomic radius: One-half of the interatomic distance of like atoms.

Atomic weight: Atomic mass expressed in atomic mass units, or in gram per mole.

Austempering: Quenching steel from the austenite range to a temperature just above the martensitic transformation range and holding it long enough to form bainite, which is a dispersion of carbide in a ferrite matrix.

Austenite: Fcc iron (γ-phase) or an iron-rich, fcc solid solution.

Austenitic stainless steel: Corrosion-resistant alloy steel containing at least 11% chromium that is mainly γ-phase (austenite).

Austenization: Heating steel to the austenite range to dissolve carbon into fcc iron, thereby forming austenite.

Avogadro's number: The number of atoms in a gram mole. It is equal to 6.02×10^{23} atoms/g mole.

Bainite: Microstructure of steel consisting of fine needles of Fe_3C in α-iron. It is formed as a result of austempering treatment.

Binary alloy: Alloy composed of two elements.

Block copolymer: Mixture of polymers that form blocks along a single-molecule chain.

Blow molding: Processing polymers or glass by expanding a parison into a mold by air pressure. Usually used to make hollow containers and bottles.

Body-centered cubic (bcc): Arrangement of atoms in a cell such that one atom is at the center of a cube in addition to eight atoms at the cube corners.

Bond energy: Energy required to separate two bonded atoms.

Branching: Addition of molecules as branches to the sides of the main polymer molecular chain.

Brass: An alloy of copper containing up to about 40 wt% zinc.

Brinell hardness: Measurement of hardness obtained by indenting the surface with a 10 mm ball under a load of 3000 kg.

Brittle: Lacking in ductility. Brittle materials break without undergoing plastic deformation.

Bronze: An alloy of copper and tin, unless otherwise specified, for example, in the case of aluminum bronze that is an alloy of copper and aluminum.

Bulk modulus (*K*): Hydrostatic pressure per unit volume strain.

Carbide: Compound of metal and carbon, for example, iron carbide is Fe_3C.

Carbon fiber-reinforced plastic (CFRP): Composite material consisting of a polymer–matrix reinforced with carbon, or graphite, fibers.

Carburization: Increasing the carbon content of a steel surface by diffusion. The purpose is usually to harden the surface.

Cast iron: Ferrous alloy containing more than 2 wt% carbon.

Casting: Shaping by pouring a liquid material in a mold and allowing it to solidify, thus taking the shape of the mold.

Cathode: The electrode in an electrochemical cell that receives electrons from the external circuit. The electrode on which electroplating is deposited.

Cation: Positively charged ion.

Cementite: The iron carbide, Fe_3C, hard brittle phase in steel.

Ceramic: Inorganic nonmetallic insulating material usually based on compounds of metals with nonmetals. They are generally characterized by their resistance to high temperatures and poor ductility.

Charpy impact test: Test to measure the toughness of materials.

Cold working: Plastic deformation below the recrystallization temperature. Measured by the percent reduction in area or thickness.

Composite: Synthetic material made by adding particulate or fibrous phases to a matrix material to modify its properties.

Compression molding: Shaping of thermosetting plastics by applying pressure and heat to allow cross-linking, setting, to take place.

Coordination number (CN): Number of closest atomic or ionic neighbors.

Copolymer: Mixture of polymers containing more than one type of monomer. Block copolymer results from clustering of like mers along the chain. Graft copolymer results from attaching branches of a second type of polymer.

Coring: Segregation during solidification resulting from relatively fast cooling.

Corrosion: Surface deterioration as a result of electrochemical reaction.

Covalent bond: Attraction as a result of sharing of electrons between adjacent atoms.

Creep: Time-dependent plastic strain that occurs as a result of mechanical stresses at relatively high temperatures.

Creep rupture: Fracture as a result of creep.

Crevice corrosion: Localized corrosion in a corrosion cell near a restricted area or a crevice.

Critical stress intensity factor (K_{IC}): The stress at the root of a crack that is sufficient to cause crack propagation.

Cross-linking: Linking of adjacent polymer molecules by chemical bond.

Crystal: A solid with a long-range repetitive pattern of atoms.

Debonding in composite materials: Uncoupling of reinforcement phase from the matrix.

Decarburization: Loss of carbon from the surface of steel.

Deformation, elastic: Temporary deformation that is eliminated when the stress is removed. It occurs as a result of atomic or molecular movement without permanent displacements.

Deformation, plastic: Permanent deformation that persists after the stress is removed. It arises from the displacement of atoms or molecules to new positions.

Deformation, viscoelastic: Combined viscous flow and elastic deformation.

Degree of polymerization: Average number of mers in a polymer molecule.

Devitrification: Crystallization of glass. Process for producing "glass–ceramics."

Diffusion: The movement of atoms or molecules in a material.

Dislocation: Linear defect in a crystalline solid. Edge dislocation is at the edge of an extra crystal plane. The slip vector, which defines the direction and magnitude of deformation associated with the movement of dislocation, is perpendicular to the defect line. In screw dislocations, the slip vector is parallel to the defect line.

Dispersion strengthening: Increase of strength as a result of introducing fine particles in the material.

Drawing: Forming of wires or sheet metals by applying tension through a die as in wire drawing or sheet drawing.

Ductile iron: Type of cast iron in which the graphite phase is spheroidal rather than flakes as in gray cast iron.

Ductile–brittle transition temperature: Temperature that separates the mode of brittle fracture from the higher temperature range of ductile fracture.

Ductility: Ability to undergo plastic deformation without fracture. Measured as elongation in length or as reduction of area.

Edge dislocation: Linear defect in a crystalline solid at the edge of an extra crystal plane. The slip vector, which defines the direction and magnitude of deformation associated with the movement of dislocation, is perpendicular to the defect line.

Elastic modulus (*E*): Stress per unit of elastic strain. Measured by the slope of the elastic part of the stress–strain diagram.

Elastic strain: Strain that is recoverable when the load is removed.

Elastomer: Polymer with a large, more than 100%, elastic strain.

Electrochemical cell: System providing electrical connection of anode, cathode, and electrolyte.

Electrode potential: Voltage developed at an electrode in reference to a standard electrode.

Electrolyte: Conductive ionic liquid or solid solution.

Electron: Negatively charged subatomic particle moving in orbits around positively charged nucleus.

Element: Fundamental chemical species as given in the periodic table of elements.

Elongation: Change in length resulting from the application of external forces.

Elongation percent: Total plastic strain at fracture. A gauge length must be stated.

Enamel: Ceramic, usually vitreous, coating on a metal.

End-quench test (Jominy bar): Standardized test performed by quenching from one end only, for determining hardenability.

Endurance limit: The maximum stress allowable for unlimited stress cycling.

Endurance ratio: The endurance limit divided by the ultimate tensile strength of the material. It is about 0.5 for many of the steels.

Engineering strain: Elongation divided by the original length of sample.

Engineering stress: Load divided by the original cross-sectional area of sample.

Equilibrium: The state at which there is no net reaction because the minimum free energy has been reached.

Erosion: Wear caused by the movement of hard particles relative to the surface.

Eutectic alloy: Alloy with the lowest melting point compared with its neighboring alloys.

Eutectic reaction: Transformation of a liquid alloy to more than one solid phase simultaneously during solidification.

Eutectic temperature: Temperature of the eutectic reaction.

Eutectoid composition: Composition of the solid solution phase that possess a minimum decomposition temperature.

Eutectoid reaction: Transformation of a solid solution to more than one solid phase simultaneously on cooling.

Eutectoid temperature: Temperature of the eutectoid reaction.

Extrusion: Shaping by pushing the material through a die. Used for metals and plastics.

Face-centered cubic (fcc): Arrangement of atoms in a cell such that one atom is at the center of each of the faces in addition to eight atoms at the cube corners.

Fatigue curve (*S*–*N* curve): Plot of the alternating stress (*S*) versus number of cycles to failure (*N*).

Fatigue strength (endurance limit): The maximum stress allowable for unlimited stress cycling.

Ferrite (α): Bcc iron or an iron-rich, bcc solid solution.

Ferritic stainless steel: Corrosion-resistant alloy steel containing at least 11% chromium that is mainly α-phase.

Ferrous alloy: Iron-base alloy.

Fiber-reinforced plastic (FRP): Composite material consisting of a polymer–matrix reinforced with fibers of glass, carbon, aramid, or a combination.

Fiberglass: Composite material consisting of a polymer–matrix reinforced with glass fibers.

Filler: Particulate or fibrous additive to polymers for reinforcement, dimensional stability, or dilution.

Firing: Heating a ceramic material to create a bond between its constituents and particles.

Fracture: Breaking of materials under stress. Brittle fracture involves negligible plastic deformation and minimum energy absorption. Ductile fracture is accompanied by plastic deformation and, therefore, by energy absorption.

Fracture toughness: Critical value of the stress intensity factor, K_{IC}, for fracture propagation.

Free electrons: Electrons that are responsible for electrical conductivity in metals.

Galvanic cell: Electrochemical cell consisting of anode, cathode, and electrolyte.

Galvanic corrosion: Corrosion between dissimilar metals in electrical contact in the presence of an electrolyte.

Galvanic protection: Protection of a structure against corrosion by making it the cathode in a galvanic cell.

Galvanic series: Arrangement of metallic material in sequence (cathodic to anodic) of corrosion susceptibility in aqueous environment, such as seawater.

Galvanized steel: Steel coated with a layer of zinc. The zinc provides galvanic protection by serving as a sacrificial anode.

Glass: An amorphous (noncrystalline) solid below its transition temperature. A glass lacks long-range crystalline order but normally has short-range order.

Glass-ceramic: Crystalline ceramic material produced by controlled devitrification of glass.

Glass fiber-reinforced plastic (GFRP or fiberglass): Composite material consisting of a polymer–matrix reinforced with glass fibers.

Glass transition temperature: The temperature at which a supercooled liquid becomes a rigid glassy solid.

Glaze: Glass layer on a ceramic component.

Grain: Individual crystal in a polycrystalline microstructure.

Grain boundary: The zone of crystalline mismatch between adjacent grains.

Grain growth: Increase in the average size of the grains, usually as a result of prolonged heating.

Grain size: A measure of the average size of grains in a polycrystalline microstructure.

Gray cast iron: Type of cast iron in which the graphite phase is in the form of flakes in a matrix of ferrite, pearlite, or a mixture of the two.

Hardenability: The ease with which steel can be transformed to hard martensite by quenching.

Hardness: Resistance to indentation or scratching by a hard indentor. Common hardness tests include Brinell, Rockwell, and Vickers.

Heat treatment: Controlled heating and cooling of the material to control its microstructure and properties.

Hexagonal close-packed (hcp): Arrangement of atoms in a cell with a hexagonal top and bottom, each containing six atoms in the corners and one atom in the center in addition to three atoms in a plane between the top and bottom.

High-alloy steel: Steel containing a total of more than 5 wt% alloying elements.

High-strength low-alloy steels (HSLA): Steels containing a total of less than 5 wt% alloy additions but exhibiting relatively high strength.

Homogenization (soaking): Heat treatment to equalize composition by diffusion.

Hot isostatic pressing (HIP): Compacting powders under high temperatures to allow compaction and sintering to take place simultaneously.

Hot shortness: Melting of some parts of the alloy even though the temperature is below the equilibrium melting temperature. This is usually a result of segregation.

Hot working: Deformation of the material above the recrystallization temperature so that working and annealing occur concurrently.

Hydrogen embrittlement: Loss of ductility as a result of hydrogen diffusion in the material.

Hypereutectic: Composition greater than the eutectic composition.

Hypoeutectic: Composition less than the eutectic composition.

Hypoeutectoid: Composition less than the eutectoid composition.

Immiscibility: Mutually insoluble phases.

Impact strength (toughness): Resistance to fracture by impact loading and is measured by the Izod or Charpy tests that give the amount of energy required to fracture a standard sample.

Imperfection in crystals: Defects in crystals including point defects such as vacant atom sites and extra atoms (interstitials), line defects such as dislocations, or surface defects such as grain boundaries.

Impressed current: DC applied to protect a structure by making the metal cathodic during service.

Inhibitor: An additive to an electrolyte that decreases the rate of corrosion and promotes passivation.

Injection molding: Molding of polymers under pressure in a closed die.

Interrupted quench: Two-stage quenching of steel from austenitic phase, initial quenching to a temperature above the start of martensite formation, followed by a second (slower) cooling to room temperature.

Interstitial solid solution: An alloy in which the atoms of one of the constituents are small enough to fit in the spaces between the solvent atoms.

Ion: An atom that possesses a charge because it has added or removed electrons.

Ionic bond: A primary atomic bond involving transfer of electrons between unlike atoms.

Isotropic: Exhibiting properties that do not change with the direction of measurement.

Jominy end-quenching test: Test to measure the hardenability of steels using a standard specimen and test conditions.

Laminate: Composite material in which the phases are arranged in layers.

Larson–Miller parameter: A relationship between the stress, the temperature, and the rupture time in creep.

Lattice: Arrangement of atoms in a crystalline solid.

Lattice constants (lattice parameters): Dimensions of the edges of a unit cell.

Lever rule: Equation to determine the quantity of phases in an alloy under equilibrium conditions.

Long-range order: Repetition of the pattern of atomic arrangement in a crystalline solid over many atomic distances.

Low-alloy steel: Steel containing a total of less than 5 wt% alloying elements.

Macromolecules: Molecules made up of hundreds to thousands of atoms.

Malleable iron: Type of cast iron with some ductility. It is obtained by heat-treating white cast iron to change its iron carbide to nodular graphite.

Martempering: Quenching steel from the austenite range to a temperature just above the martensitic transformation range followed by a slow cool through martensitic transformation range to reduce the stresses associated with that transformation.

Martensite: A phase arising from quenching of steels from the austinite temperature range as a result of a diffusionless, shearlike phase transformation. It is a hard and brittle phase. Martensitic transformations also occur in some nonferrous alloys.

Martensitic stainless steels: Corrosion-resistant alloy steel containing at least 11% chromium and is mainly martensitic phase.

Materials: Engineering materials are substances used for manufacturing products and include metals, ceramics, polymers, composites, semiconductors, glasses, cement, and natural substances such as wood and stone.

Matrix: The continuous phase that envelops the reinforcing phase in a composite material.

Mer: The smallest repetitive unit in a polymer.

Metal: Material characterized by its high electrical and thermal conductivities as a result of the presence of the free electrons of the metallic bond.

Metal–matrix composites (MMC): Composites in which the reinforcing phase is enveloped in a metallic material.

Metallic bond: Interatomic bonds in metals characterized by the presence of electrons that are free to move and conduct electrical current.

Metastable: A state of material that does not change with time although it does not represent true equilibrium.

Microstructure: Arrangement and relationship between the grains and the phases in a material. Generally requires magnification for observation.

Modulus of elasticity (elastic modulus, Young's modulus): Stress per unit of elastic strain. Measured by the slope of the elastic part of the stress–strain diagram.

Modulus of rigidity (shear modulus): Shear stress per unit shear strain.

Mole: Mass equal to the molecular weight of a material.

Molecular weight: Mass of one molecule expressed in atomic mass units (amu).

Molecule: Group of atoms bonded by strong attractive forces, primary bonds.

Monomer: A molecule with a single mer. Monomers combine with similar molecules to form a polymeric molecule.

Natural aging: Allowing the solution-treated and solution-quenched precipitation-hardenable alloy to stay long enough at room temperature for precipitation to take place.

Neutron: Subatomic particle located in the nucleus and has a neutral charge.

Noncrystalline (amorphous): Atoms or molecules of the material that are not arranged according to a repetitive pattern or exhibit long-range order.

Nondestructive testing: Inspection of materials and components without impairing their integrity.

Nonferrous alloy: Metallic alloy with a base metal other than iron. Examples include aluminum-base alloys and copper-base alloys.

Normalizing: Heating of steel into the austenite range and cooling at a rate that is faster than that used for annealing but slower than that required for hardening. This treatment is used to produce a uniform, fine-grained microstructure.

Nucleation: The start of a new phase in phase transformation or the beginning of solidification from a liquid. Heterogeneous nucleation takes place on a preexisting surface or a "seed." Homogeneous occurs without the aid of a preexisting phase.

Nucleus: Central core of an atom about which electrons orbit. Also a small solid particle that forms from the liquid at the beginning of solidification.

Overaging: Continuing with the age-hardening treatment beyond the peak hardness thus causing the hardness to decrease as a result of precipitate coarsening.

Oxidation: Reaction of a metal with oxygen.

Particulate composite: Composite material consisting of particles imbedded in a matrix.

Passivation: Impeding the rate of corrosion due to the presence of an adsorbed protective film on the surface.

Pearlite: A lamellar mixture of ferrite and iron carbide formed by decomposing austenite of eutectoid composition.

Peritectic reaction: Reaction of a liquid phase with a solid phase to form a second solid phase.

Phase: A physically and/or chemically homogeneous part of the structure of a material.

Phase boundary: Compositional or structural discontinuity between two phases.

Phase diagram: Graphical representation of the phases present in equilibrium in an alloy system at different compositions and temperatures.

Pitting corrosion: Corrosion attack that is localized in narrow areas of the surface.

Plastic: Engineering material composed primarily of a polymer with additives.

Plastic strain: Permanent deformation that persists after the stress is removed. It arises from the displacement of atoms or molecules to new positions.

Plasticizer: An additive of small molecular weight molecules to a polymeric mix to reduce the rigidity.

Point defect: Crystal imperfection or disorders involving one or a small number of atoms.

Poisson's ratio: Ratio between lateral strain (contraction) and axial strain (extension) under tensile load.

Polycrystalline: Material with multiple grains and associated boundaries.

Polymer: Nonmetallic organic material consisting of macromolecules composed of many repeating units that are called mers.

Polymer–matrix composite: Composite material in which the reinforcing phase is held together by a polymer–matrix.

Polymorphism (allotropy): Change of lattice structure with temperature, for example, iron changes from bcc to fcc at 910°C.

Powder metallurgy technique: Processing powders by compaction and sintering to produce a solid product.

Precipitation: Separation of a second phase from a supersaturated solution.

Precipitation hardening (age hardening): Increase of hardness as a result of the precipitation of a hard phase from a supersaturated solid solution.

Preferred orientation: Alignment of grains or inclusions in a particular direction thus leading to anisotropy.

Primary bond: Strong interatomic bond. Examples are covalent, ionic, or metallic bonds.

Proeutectic: A phase that separates from a liquid before the latter undergoes eutectic transformation.

Proeutectoid: A phase that separates from a solid solution before the latter undergoes eutectoid transformation.

Proportional limit: The end of the range within which the strain increases linearly with stress level.

Prosthesis: Part used to replace a body part.

Protective coating: Layer on the surface to act as a barrier or protect the material from the surrounding environment.

Proton: Positively charged subatomic particle in the nucleus of the atom. The number of protons is equal to the number of electrons in a neutral atom.

Quenching: Fast cooling, usually in water or oil, to produce a nonequilibrium structure.

Radiation damage: Creation of structural defects as a result of exposure to radiation.

Recovery: A low-temperature anneal that involves heating the cold-worked material to partially reduce structural defects leading to a slight softening.

Recrystallization: The formation of new annealed soft grains in place of previously strain-hardened ones.

Recrystallization temperature: Temperature above which recrystallization is spontaneous. It is about 0.4 T_m, where T_m is the melting point of the material expressed in degrees Kelvin or Rankin.

Reduction: Removal of oxygen from an oxide.

Reduction of area percent: Total plastic strain at fracture expressed as percent decrease in cross-sectional area at the point of fracture.

Refractory: A material that can resist high temperatures.

Refractory metal: Metal with a melting point higher than about 1700°C.

Reinforcement: The component that provides a composite material with high elastic modulus and/or high strength.

Relaxation time: Time required for the stress resulting from a fixed value of strain to decrease to 0.37 (=1/*e*) of the initial value.

Residual stresses: Stresses stored in the material as a result of processing.

Rockwell hardness: A measure of hardness obtained by indenting the surface by applying a force to a hard ball or a diamond cone and measuring the depth of indention.

Rolling: Mechanical working through the use of two rolls that are rotating in opposite direction. The rolls may be cylindrical, as in the case of sheet rolling, or shaped, as in the case of section rolling.

Rupture time: The time required for a sample to fail by creep at a given temperature and stress.

Sacrificial anode: Expendable metal that is used to protect the more noble metal of a component or structure.

Scale: Surface layer of oxidized metal.

Screw dislocation: Linear defect in a crystalline solid where the slip vector, which defines the direction and magnitude of deformation associated with the movement of dislocation, is parallel to the defect line (see dislocation).

Secondary bonds: Weak interatomic bonds arising from dipoles within the atoms or molecules, for example, van der Waal's bond.

Segregation: Nonuniform distribution of alloying elements as a result of nonequilibrium conditions.

Shear modulus: Shear stress per unit shear strain.

Sheet molding: Thermal forming of sheets of FRPs.

Short-range order: Specific arrangement of atoms relative to their close neighbors but random long-range arrangements.

Sintering: Heating of compacted powders to induce bonding as a result of diffusion.

Slip: Deformation of a material by the movement of dislocations through the lattice.

Slip casting: Shaping of ceramic parts by pouring powder–water mixture, slip, into a porous mold that allows the water to escape leaving a dense mass behind, which is then extracted from the mold and dried.

Slip direction: Crystal direction of the displacement vector on which slip takes place.

Slip plane: Crystal plane along which slip occurs.

Slip system: Combination of slip directions and slip planes corresponding to dislocation movement.

Slip vector: Defines the direction and magnitude of deformation associated with the movement of a dislocation. It is parallel to a screw dislocation and perpendicular to an edge dislocation.

***S–N* curve:** Plot of the alternating stress versus number of cycles to fatigue failure.

Solder: Alloys whose melting points are below about 425°C and are used for joining. The Pb–Sn eutectic alloy, with a melting point of 183°C, is among the commonly used soldering alloys.

Solid solution: A homogeneous crystalline phase composed of more than one element. Substitutional solid solutions are obtained when the elements involved have similar atomic size. Interstitial solid solutions are obtained when the atomic size of one of the constituent elements is so small that it can fit in the spaces between the lager atoms of the parent metal.

Solubility limit: Maximum solute addition without supersaturation

Solute: The component that is dissolved in a solvent to form a solid solution.

Solution hardening: Increase in strength associated with the addition of alloying elements to form a solid solution.

Solution treatment: Heating a multiphase alloy to become a single phase.

Solvent: The main component of a solid solution in which the solute is dissolved.

Spalling: Cracking or flaking off of a material as a result of thermal stresses.

Stainless steel: Corrosion-resistant alloy steel containing at least 11% chromium and may also contain nickel. Depending on the composition and treatment, stainless steels can be ferritic, austenitic, or martensitic.

Steel: Basically an alloy of iron plus up to 2 wt% carbon and may contain additional elements. Plain-carbon steels are Fe–C alloys with minimal alloy content. Low-alloy steels contain up to 5% alloying elements other than carbon.

Strain: Deformation per unit length as a result of stress. Elastic strain is recoverable when the load is removed. Plastic strain results in a permanent deformation.

Strain hardening: Increase in strength as a result of plastic deformation below the recrystallization temperature.

Strength: Resistance to stress. Yield strength is the stress to initiate plastic deformation. Ultimate tensile strength is the maximum stress that can be borne by the material, calculated on the basis of the original area.

Stress: Force or load per unit area. Engineering stress is based on the original cross-sectional area. True stress is based on the actual area.

Stress corrosion: Accelerated corrosion due to the presence of stress.

Stress intensity factor (K_I): Stress intensity at the root of a crack.

Stress relaxation: Decrease with time of the stress at a fixed value of strain. See relaxation time.

Stress relief: Removal of internal stresses in a material by heat treatment.

Stress rupture: Time-dependent fracture resulting from constant load under creep conditions.

Stress–strain diagram: Plot of stress as a function of strain.

Superalloys: A group of alloys that retain their strength at high temperatures. Commonly used superalloys include iron-base, nickel-base, and cobalt-base alloys.

Superplasticity: The ability of a material to undergo very large amount of plastic deformation.

Tempered glass: Glass that has been heat treated to generate residual compressive stresses in the surface layers.

Tempered martensite: A microstructure composed of fine dispersion of carbide in ferrite and is obtained by heating martensite.

Tempering: Heating of martensite to increase its toughness by producing a microstructure composed of fine dispersion of carbide in ferrite.
Thermal shock: Failure of the material as a result of sudden change of temperature.
Thermoplastic: A polymer that softens with increased temperature, thus becoming moldable, and rehardens on cooling. Such polymer is usually soft and ductile at normal temperatures.
Thermosetting plastic: A polymer that hardens on heating as a result of cross-linking, that is, the formation 3D network of strongly bonded molecules. Such polymer is usually rigid and brittle.
Toughness: Resistance to fracture by impact loading and is measured by the Izod or Charpy tests that give the amount of energy required to fracture a standard sample. It can also be represented by the total area under the stress–strain diagram.
True strain: Elongation divided by the actual length of sample.
True stress: Load divided by the actual cross-sectional area of sample.
Ultimate strength: Maximum stress, based on the original area.
Unit cell: The smallest repetitive group of atoms that represents the arrangement of atoms in a crystal lattice. Common unit cells include bcc, fcc, and hcp.
Vacancy: A point defect in a crystalline structure that is associated with an unoccupied lattice site.
Valence electrons: Electrons in the outer shell(s) of an atom that take part in atomic bonding.
Van der Waal's bond: Weak interatomic secondary bonds arising from dipoles within the atoms or molecules.
Viscoelastic deformation: Deformation involving both fluidlike viscous flow and solid-like elastic strain.
Viscosity: Ratio of shear stress to the velocity gradient of flow.
Viscous flow: Time-dependent flow in polymers and glasses above their glass transition temperature.
Vulcanization: Treatment of rubber with sulfur to cross-link elastomer chains, that is, form a 3D network structure.
Wear: Loss of surface material as a result of mechanical action.
Welding: Joining of parts by local melting at the join.
Whisker: Very small nearly perfect fiber.
White cast iron: Type of cast iron in which the carbon is present as iron carbide. It is very hard and brittle.
Wrought alloy: Alloy that can be shaped by forming processes such as forging, rolling, extrusion, and drawing.
Yield strength: Stress that causes the material to reach its elastic limit, that is, resistance to the onset of plastic deformation.
Young's modulus (modulus of elasticity, elastic modulus): Stress per unit of elastic strain. Measured by the slope of the elastic part of the stress–strain diagram.

Materials Science

"Many of the topics in the book, especially the relationship between design, materials and manufacturing, are increasingly discussed in the curricula of materials engineering and mechanical engineering. This book explains these topics very clearly and would be of interest to many faculty members in these departments. ...The front matter explains what the book is all about very clearly and presents a strong case for why faculty members should adopt it for their course…"

—Theodoulos Z. Kattamis, University of Connecticut, Storrs, USA

"This book presents a broad range of topics important for material and process selection. This includes matters for which relevance has been growing in the recent past such as environmental and energy content aspects. The approach used is truly engineering- and realization-oriented and therefore particularly suited for mechanical, industrial, and design engineering students."

—Rémy Glardon, EPFL, Lausanne, Switzerland

Since the publication of the second edition of this book, changes have occurred in the fields of materials and manufacturing. Industries now place more emphasis on manufacturing products and goods locally, rather than outsourcing. Nanostructured and smart materials appear more frequently in products, composites are used in designing essential parts of civilian airliners, and biodegradable materials are increasingly used instead of traditional plastics. More emphasis is now placed on how products affect the environment, and society is willing to accept more expensive but eco-friendly goods. In addition, there has been a change in the emphasis and the way the subjects of materials and manufacturing are taught within a variety of curricula and courses in higher education.

This third edition of the bestselling **Materials and Process Selection for Engineering Design** has been comprehensively revised and reorganized to reflect these changes. In addition, the presentation has been enhanced and the book includes more real-world case studies.

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