# Chapter 1 Introduction


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A familiar item fabricated from three different material types is the beverage container. Beverages are marketed in aluminum (metal) cans (top), glass (ceramic) bottles (center), and plastic (polymer) bottles (bottom).


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**Learning Objectives**

**After studying this chapter, you should be able to do the following:**

1. **List six different property classifications of materials that determine their applicability.**
2. **Cite the four components that are involved in the design, production, and utilization of materials, and briefly describe the interrelationships between these components.**
3. **Cite three criteria that are important in the materials selection process.**
4. **(a) List the three primary classifications of solid materials, and then cite the distinctive chemical feature of each.**
   **(b) Note the four types of advanced materials and, for each, its distinctive feature(s).**
5. **(a) Briefly define *smart material/system*.**
   **(b) Briefly explain the concept of *nanotechnology* as it applies to materials.**

## 1.1 HISTORICAL PERSPECTIVE

Please take a few moments and reflect on what your life would be like without all of the materials that exist in our modern world. Believe it or not, without these materials we wouldn't have automobiles, cell phones, the internet, airplanes, nice homes and their furnishings, stylish clothes, nutritious (also "junk") food, refrigerators, televisions, computers . . . (and the list goes on). Virtually every segment of our everyday lives is influenced to one degree or another by materials. Without them our existence would be much like that of our Stone Age ancestors.

Historically, the development and advancement of societies have been intimately tied to the members' ability to produce and manipulate materials to fill their needs. In fact, early civilizations have been designated by the level of their materials development (Stone Age, Bronze Age, Iron Age).[1]

The earliest humans had access to only a very limited number of materials, those that occur naturally: stone, wood, clay, skins, and so on. With time, they discovered techniques for producing materials that had properties superior to those of the natural ones; these new materials included pottery and various metals. Furthermore, it was discovered that the properties of a material could be altered by heat treatments and by the addition of other substances. At this point, materials utilization was totally a selection process that involved deciding from a given, rather limited set of materials, the one best suited for an application by virtue of its characteristics. It was not until relatively recent times that scientists came to understand the relationships between the structural elements of materials and their properties. This knowledge, acquired over approximately the past 100 years, has empowered them to fashion, to a large degree, the characteristics of materials. Thus, tens of thousands of different materials have evolved with rather specialized characteristics that meet the needs of our modern and complex society, including metals, plastics, glasses, and fibers.

The development of many technologies that make our existence so comfortable has been intimately associated with the accessibility of suitable materials. An advancement in the understanding of a material type is often the forerunner to the stepwise progression of a technology. For example, automobiles would not have been possible without the availability of inexpensive steel or some other comparable substitute. In the contemporary era, sophisticated electronic devices rely on components that are made from what are called *semiconducting materials*.

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[1] The approximate dates for the beginnings of the Stone, Bronze, and Iron ages are 2.5 million BC, 3500 BC, and 1000 BC, respectively.

## 1.2 MATERIALS SCIENCE AND ENGINEERING

Sometimes it is useful to subdivide the discipline of materials science and engineering into *materials science* and *materials engineering* subdisciplines. Strictly speaking, materials science involves investigating the relationships that exist between the structures and properties of materials (i.e., why materials have their properties). In contrast, materials engineering involves, on the basis of these structure–property correlations, designing or engineering the structure of a material to produce a predetermined set of properties. From a functional perspective, the role of a materials scientist is to develop or synthesize new materials, whereas a materials engineer is called upon to create new products or systems using existing materials and/or to develop techniques for processing materials. Most graduates in materials programs are trained to be both materials scientists and materials engineers.

*Structure* is, at this point, a nebulous term that deserves some explanation. In brief, the structure of a material usually relates to the arrangement of its internal components. Structural elements may be classified on the basis of size and in this regard there are several levels:

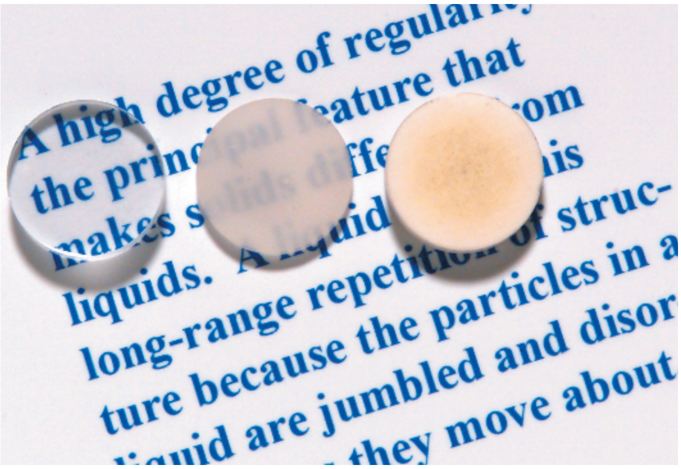
- Subatomic structure—involves electrons within the individual atoms, their energies and interactions with the nuclei.
- Atomic structure—relates to the organization of atoms to yield molecules or crystals.
- Nanostructure—deals with aggregates of atoms that form particles (nanoparticles) that have nanoscale dimensions (less that about 100 nm).
- Microstructure—those structural elements that are subject to direct observation using some type of microscope (structural features having dimensions between 100 nm and several millimeters).
- Macrostructure—structural elements that may be viewed with the naked eye (with scale range between several millimeters and on the order of a meter).

Atomic structure, nanostructure, and microstructure of materials are investigated using microscopic techniques discussed in Section 4.10.

The notion of *property* deserves elaboration. While in service use, all materials are exposed to external stimuli that evoke some types of responses. For example, a specimen subjected to forces experiences deformation, or a polished metal surface reflects light. A property is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus. Generally, definitions of properties are made independent of material shape and size.

Virtually all important properties of solid materials may be grouped into six different categories: mechanical, electrical, thermal, magnetic, optical, and deteriorative. For each, there is a characteristic type of stimulus capable of provoking different responses. These are noted as follows:

- Mechanical properties—relate deformation to an applied load or force; examples include elastic modulus (stiffness), strength, and resistance to fracture.
- Electrical properties—the stimulus is an applied electric field; typical properties include electrical conductivity and dielectric constant.
- Thermal properties—are related to changes in temperature or temperature gradients across a material; examples of thermal behavior include thermal expansion and heat capacity.
- Magnetic properties—the responses of a material to the application of a magnetic field; common magnetic properties include magnetic susceptibility and magnetization.
- Optical properties—the stimulus is electromagnetic or light radiation; index of refraction and reflectivity are representative optical properties.



William D. Callister Jr./ Specimen preparation, P.A. Lessing

**Figure 1.1** Three thin disk specimens of aluminum oxide that have been placed over a printed page in order to demonstrate their differences in light-transmittance characteristics. The disk on the left is *transparent* (i.e., virtually all light that is reflected from the page passes through it), whereas the one in the center is *translucent* (meaning that some of this reflected light is transmitted through the disk). The disk on the right is *opaque*—that is, none of the light passes through it. These differences in optical properties are a consequence of differences in structure of these materials, which have resulted from the way the materials were processed.

- Deteriorative characteristics—relate to the chemical reactivity of materials; for example, corrosion resistance of metals.

The chapters that follow discuss properties that fall within each of these six classifications.

In addition to structure and properties, two other important components are involved in the science and engineering of materials—namely, *processing* and *performance*. With regard to the relationships of these four components, the structure of a material depends on how it is processed. Furthermore, a material's performance is a function of its properties.

We present an example of these processing-structure-properties-performance principles in Figure 1.1, a photograph showing three thin disk specimens placed over some printed matter. It is obvious that the optical properties (i.e., the light transmittance) of each of the three materials are different; the one on the left is transparent (i.e., virtually all of the reflected light from the printed page passes through it), whereas the disks in the center and on the right are, respectively, translucent and opaque. All of these specimens are of the same material, aluminum oxide, but the leftmost one is what we call a *single crystal*—that is, has a high degree of perfection—which gives rise to its transparency. The center one is composed of numerous and very small single crystals that are all connected; the boundaries between these small crystals scatter a portion of the light reflected from the printed page, which makes this material optically translucent. Finally, the specimen on the right is composed not only of many small, interconnected crystals, but also of a large number of very small pores or void spaces. These pores scatter the reflected light to a greater degree than the crystal boundaries and render this material opaque. Thus, the structures of these three specimens are different in terms of crystal boundaries and pores, which affect the optical transmittance properties. Furthermore, each material was produced using a different processing technique. If optical transmittance is an important parameter relative to the ultimate in-service application, the performance of each material will be different.

This interrelationship among processing, structure, properties, and performance of materials may be depicted in linear fashion as in the schematic illustration shown in Figure 1.2. The model represented by this diagram has been called by some the *central paradigm of materials science and engineering* or sometimes just the *materials paradigm*. (The term "paradigm" means a model or set of ideas.) This paradigm, formulated in the 1990s is, in essence, the core of the discipline of materials science and engineering. It describes the protocol for selecting and designing materials for specific and well-defined

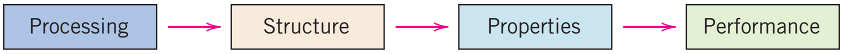


**Figure 1.2** The four components of the discipline of materials science and engineering and their interrelationship.

applications, and has had a profound influence on the field of materials.[2] Previous to this time the materials science/engineering approach was to design components and systems using the existing palette of materials. The significance of this new paradigm is reflected in the following quotation: ". . . whenever a material is being created, developed, or produced, the properties or phenomena the material exhibits are of central concern. Experience shows that the properties and phenomena associated with a material are intimately related to its composition and structure at all levels, including which atoms are present and how the atoms are arranged in the material, and that this structure is the result of synthesis and processing."[3]

Throughout this text, we draw attention to the relationships among these four components in terms of the design, production, and utilization of materials.

## 1.3 WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

Why do engineers and scientists study materials? Simply, because things engineers design are made of materials. Many an applied scientist or engineer (e.g., mechanical, civil, chemical, electrical), is at one time or another exposed to a design problem involving materials—for example, a transmission gear, the superstructure for a building, an oil refinery component, or an integrated circuit chip. Of course, materials scientists and engineers are specialists who are totally involved in the investigation and design of materials.

Many times, an engineer has the option of selecting a best material from the thousands available. The final decision is normally based on several criteria. First, the in-service conditions must be characterized, for these dictate the properties required of the material. Only on rare occasions does a material possess the optimum or ideal combination of properties. Thus, it may be necessary to trade one characteristic for another. The classic example involves strength and ductility; normally, a material having a high strength has only a limited ductility. In such cases, a reasonable compromise between two or more properties may be necessary.

A second selection consideration is any deterioration of material properties that may occur during service operation. For example, significant reductions in mechanical strength may result from exposure to elevated temperatures or corrosive environments.

Finally, probably the overriding consideration is that of economics: What will the finished product cost? A material may be found that has the optimum set of properties but is prohibitively expensive. Here again, some compromise is inevitable. The cost of a finished piece also includes any expense incurred during fabrication to produce the desired shape.

The more familiar an engineer or scientist is with the various characteristics and structure–property relationships, as well as the processing techniques of materials, the more proficient and confident he or she will be in making judicious materials choices based on these criteria.

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[2] This paradigm has recently been updated to include the component of material sustainability in the "Modified Paradigm of Materials Science and Engineering," as represented by the following diagram:

Processing → Structure → Properties → Performance → Reuse/Recyclability

[3] "*Materials Science and Engineering for the 1990s*," p. 27, National Academies Press, Washington, DC, 1998.

## CASE STUDY 1.1

### *Liberty Ship Failures*

The following case study illustrates one role that materials scientists and engineers are called upon to assume in the area of materials performance: analyze mechanical failures, determine their causes, and then propose appropriate measures to guard against future incidents.

The failure of many of the World War II Liberty ships[4] is a well-known and dramatic example of the brittle fracture of steel that was thought to be ductile.[5] Some of the early ships experienced structural damage when cracks developed in their decks and hulls. Three of them catastrophically split in half when cracks formed, grew to critical lengths, and then rapidly propagated completely around the ships' girths. Figure 1.3 shows one of the ships that fractured the day after it was launched.

Subsequent investigations concluded one or more of the following factors contributed to each failure:[6]

- When some normally ductile metal alloys are cooled to relatively low temperatures, they become susceptible to brittle fracture—that is, they experience a ductile-to-brittle transition upon cooling through a critical range of temperatures.

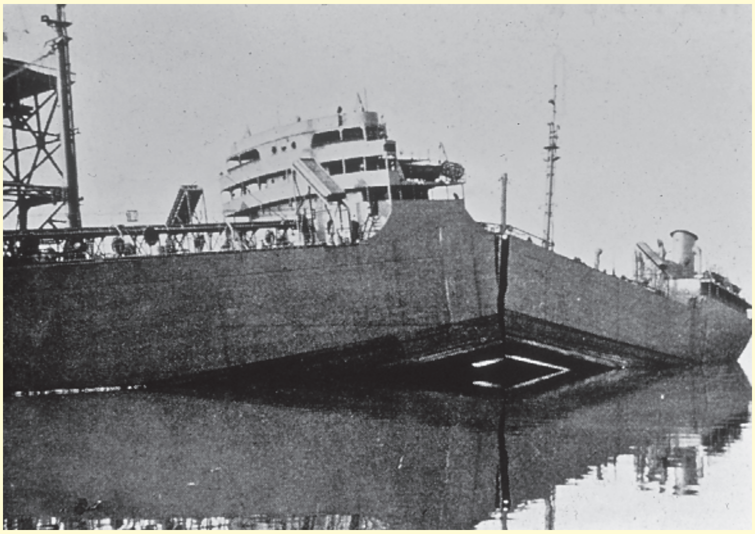

**Figure 1.3** The Liberty ship *S.S. Schenectady,* which, in 1943, failed before leaving the shipyard.
(Reprinted with permission of Earl R. Parker, *Brittle Behavior of Engineering Structures,* National Academy of Sciences, National Research Council, John Wiley & Sons, New York, 1957.)

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[4] During World War II, 2,710 Liberty cargo ships were mass-produced by the United States to supply food and materials to the combatants in Europe.

[5] Ductile metals fail after relatively large degrees of permanent deformation; however, very little if any permanent deformation accompanies the fracture of brittle materials. Brittle fractures can occur very suddenly as cracks spread rapidly; crack propagation is normally much slower in ductile materials, and the eventual fracture takes longer. For these reasons, the ductile mode of fracture is usually preferred. Ductile and brittle fractures are discussed in Sections 8.3 and 8.4.

[6] Sections 8.2 through 8.6 discuss various aspects of failure.

These Liberty ships were constructed of steel that experienced a ductile-to-brittle transition. Some of them were deployed to the frigid North Atlantic, where the once ductile metal experienced brittle fracture when temperatures dropped to below the transition temperature.[7]

- The corner of each hatch (i.e., door) was square; these corners acted as points of stress concentration where cracks can form.
- German U-boats were sinking cargo ships faster than they could be replaced using existing construction techniques. Consequently, it became necessary to revolutionize construction methods to build cargo ships faster and in greater numbers. This was accomplished using prefabricated steel sheets that were assembled by welding rather than by the traditional time-consuming riveting. Unfortunately, cracks in welded structures may propagate unimpeded for large distances, which can lead to catastrophic failure. However, when structures are riveted, a crack ceases to propagate once it reaches the edge of a steel sheet.
- Weld defects and *discontinuities* (i.e., sites where cracks can form) were introduced by inexperienced operators.

Remedial measures taken to correct these problems included the following:

- Lowering the ductile-to-brittle temperature of the steel to an acceptable level by improving steel quality (e.g., reducing sulfur and phosphorus impurity contents).
- Rounding off hatch corners by welding a curved reinforcement strip on each corner.[8]
- Installing crack-arresting devices such as riveted straps and strong weld seams to stop propagating cracks.
- Improving welding practices and establishing welding codes.

In spite of these failures, the Liberty ship program was considered a success for several reasons, the primary reason being that ships that survived failure were able to supply Allied Forces in the theater of operations and in all likelihood shortened the war. In addition, structural steels were developed with vastly improved resistances to catastrophic brittle fractures. Detailed analyses of these failures advanced the understanding of crack formation and growth, which ultimately evolved into the discipline of fracture mechanics.

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[7] This ductile-to-brittle transition phenomenon, as well as techniques that are used to measure and raise the critical temperature range, are discussed in Section 8.6.

[8] The reader may note that corners of windows and doors for all of today's marine and aircraft structures are rounded.

## 1.4 CLASSIFICATION OF MATERIALS

**Tutorial Video:** What Are the Different Classes of Materials?

Solid materials have been conveniently grouped into three basic categories: metals, ceramics, and polymers, a scheme based primarily on chemical makeup and atomic structure. Most materials fall into one distinct grouping or another. In addition, there are the composites that are engineered combinations of two or more different materials. A brief explanation of these material classifications and representative characteristics is offered next. Another category is advanced materials—those used in high-technology applications, such as semiconductors, biomaterials, smart materials, and nanoengineered materials; these are discussed in Section 1.5.

### Metals

*Metals* are composed of one or more metallic elements (e.g., iron, aluminum, copper, titanium, gold, nickel), and often also nonmetallic elements (e.g., carbon, nitrogen, oxygen) in relatively small amounts.[9] Atoms in metals and their alloys are arranged in a

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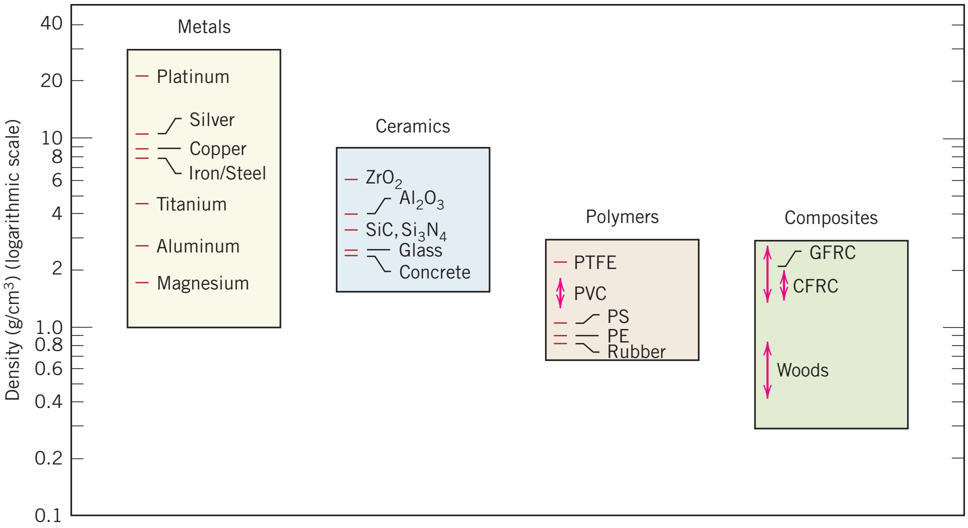
[9] The term *metal alloy* refers to a metallic substance that is composed of two or more elements.

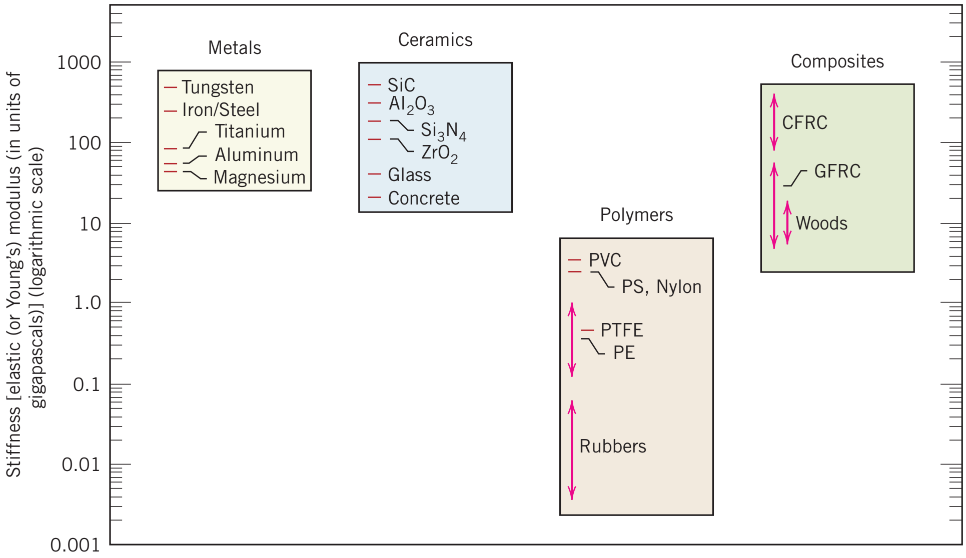
**Figure 1.4** Bar chart of room-temperature density values for various metals, ceramics, polymers, and composite materials.



very orderly manner (as discussed in Chapter 3) and are relatively dense in comparison to the ceramics and polymers (Figure 1.4). With regard to mechanical characteristics, these materials are relatively stiff (Figure 1.5) and strong (Figure 1.6), yet are ductile (i.e., capable of large amounts of deformation without fracture), and are resistant to fracture (Figure 1.7), which accounts for their widespread use in structural applications. Metallic materials have large numbers of nonlocalized electrons—that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. For example, metals are extremely good conductors of electricity (Figure 1.8) and heat, and are not transparent to visible light; a polished metal surface has a lustrous appearance. In addition, some of the metals (i.e., Fe, Co, and Ni) have desirable magnetic properties.

**Tutorial Video:** Metals

**Figure 1.5** Bar chart of room-temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.



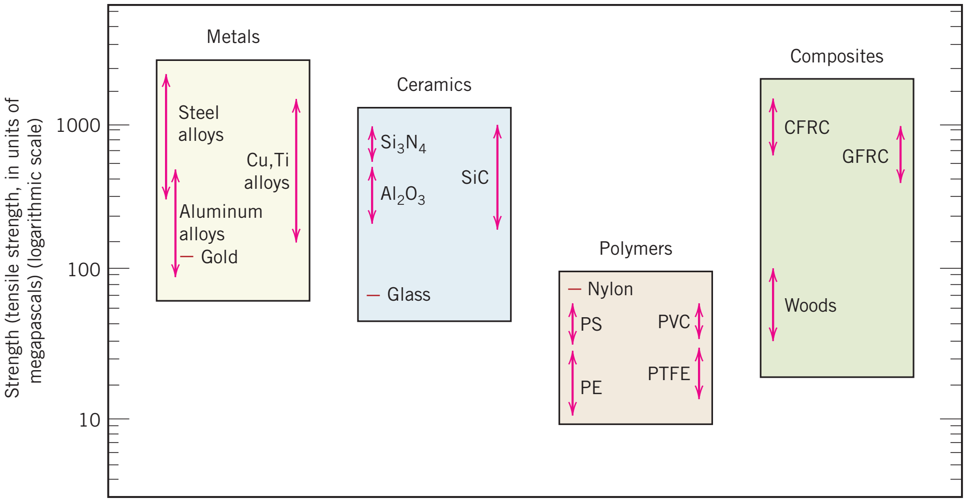


**Figure 1.6** Bar chart of room-temperature strength (i.e., tensile strength) values for various metals, ceramics, polymers, and composite materials.

Figure 1.9 shows several common and familiar objects that are made of metallic materials. Furthermore, the types and applications of metals and their alloys are discussed in Chapter 11.

## Ceramics

**Tutorial Video:** Ceramics

*Ceramics* are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, common ceramic materials include aluminum oxide (or *alumina,* $Al_2O_3$), silicon dioxide (or *silica,* $SiO_2$), silicon carbide (SiC), silicon nitride ($Si_3N_4$), and, in addition, what some refer to as the *traditional ceramics*—those composed of clay minerals (e.g., porcelain), as well as cement and glass. With regard to mechanical behavior, ceramic materials are relatively stiff and strong—stiffnesses and strengths are comparable to those of the metals (Figures 1.5 and 1.6). In addition, they are typically very hard. Historically, ceramics have exhibited extreme brittleness (lack of ductility) and are highly susceptible to fracture (Figure 1.7). However, newer ceramics are being engineered to have improved resistance to fracture; these materials are used for cookware, cutlery, and even automobile engine parts. Furthermore, ceramic materials are typically insulative to the

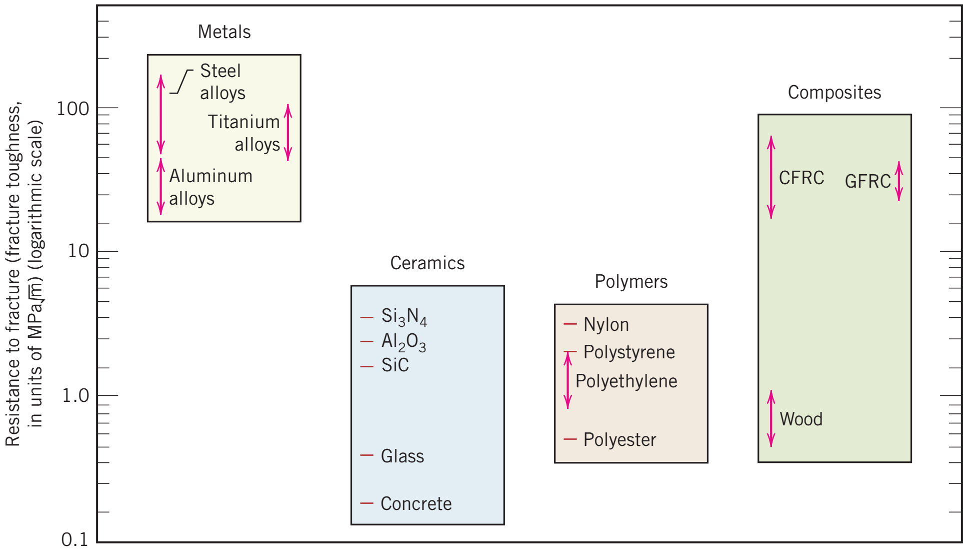


**Figure 1.7** Bar chart of room-temperature resistance to fracture (i.e., fracture toughness) for various metals, ceramics, polymers, and composite materials. (Reprinted from *Engineering Materials 1: An Introduction to Properties, Applications and Design,* third edition, M. F. Ashby and D. R. H. Jones, pages 177 and 178. Copyright 2005, with permission from Elsevier.)

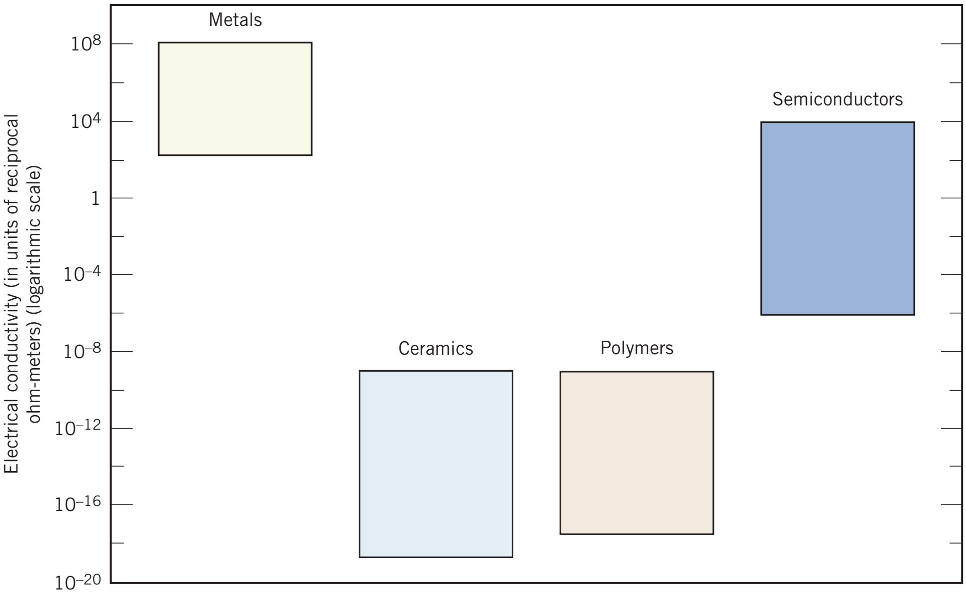


**Figure 1.8** Bar chart of room-temperature electrical conductivity ranges for metals, ceramics, polymers, and semiconducting materials.

passage of heat and electricity (i.e., have low electrical conductivities, Figure 1.8) and are more resistant to high temperatures and harsh environments than are metals and polymers. With regard to optical characteristics, ceramics may be transparent, translucent, or opaque (Figure 1.1), and some of the oxide ceramics (e.g., $Fe_3O_4$) exhibit magnetic behavior.

Several common ceramic objects are shown in Figure 1.10. The characteristics, types, and applications of this class of materials are also discussed in Chapters 12 and 13.

## Polymers

Polymers include the familiar plastic and rubber materials. Many of them are organic compounds that are chemically based on carbon, hydrogen, and other nonmetallic elements (i.e., O, N, and Si). Furthermore, they have very large molecular structures, often chainlike in nature, that often have a backbone of carbon atoms. Some common and familiar polymers are polyethylene (PE), nylon, poly(vinyl chloride) (PVC), polycarbonate (PC), polystyrene (PS), and silicone rubber. These materials typically have low densities (Figure 1.4), whereas their mechanical characteristics are generally dissimilar to those of the metallic and ceramic materials—they are not as stiff or strong as these

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**Figure 1.9** Familiar objects made of metals and metal alloys (from left to right): silverware (fork and knife), scissors, coins, a gear, a wedding ring, and a nut and bolt.

**Figure 1.10** Common objects made of ceramic materials: scissors, a china teacup, a building brick, a floor tile, and a glass vase.

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other material types (Figures 1.5 and 1.6). However, on the basis of their low densities, many times their stiffnesses and strengths on a per-mass basis are comparable to those of the metals and ceramics. In addition, many of the polymers are extremely ductile and pliable (i.e., plastic), which means they are easily formed into complex shapes. In general, they are relatively inert chemically and unreactive in a large number of environments. Furthermore, they have low electrical conductivities (Figure 1.8) and are nonmagnetic. One major drawback to the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use.

**Tutorial Video:** Polymers

Figure 1.11 shows several articles made of polymers that are familiar to the reader. Chapters 14 and 15 are devoted to discussions of the structures, properties, applications, and processing of polymeric materials.

**Figure 1.11** Several common objects made of polymeric materials: plastic tableware (spoon, fork, and knife), billiard balls, a bicycle helmet, two dice, a lawn mower wheel (plastic hub and rubber tire), and a plastic milk carton.

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## CASE STUDY 1.2

### *Carbonated Beverage Containers*

One common item that presents some interesting material property requirements is the container for carbonated beverages. The material used for this application must satisfy the following constraints: (1) provide a barrier to the passage of carbon dioxide, which is under pressure in the container; (2) be nontoxic, unreactive with the beverage, and, preferably, recyclable; (3) be relatively strong and capable of surviving a drop from a height of several feet when containing the beverage; (4) be inexpensive, including the cost to fabricate the final shape; (5) if optically transparent, retain its optical clarity; and (6) be capable of being produced in different colors and/or adorned with decorative labels.

All three of the basic material types—metal (aluminum), ceramic (glass), and polymer (polyester plastic)—are used for carbonated beverage containers (per the chapter-opening photographs). All of these materials are nontoxic and unreactive with beverages. In addition, each material has its pros and cons. For example, the aluminum alloy is relatively strong (but easily dented), is a very good barrier to the diffusion of carbon dioxide, is easily recycled, cools beverages rapidly, and allows labels to be painted onto its surface. However, the cans are optically opaque and relatively expensive to produce. Glass is impervious to the passage of carbon dioxide, is a relatively inexpensive material, and may be recycled, but it cracks and fractures easily, and glass bottles are relatively heavy. Whereas plastic is relatively strong, may be made optically transparent, is inexpensive and lightweight, and is recyclable, it is not as impervious to the passage of carbon dioxide as aluminum and glass. For example, you may have noticed that beverages in aluminum and glass containers retain their carbonization (i.e., "fizz") for several years, whereas those in two-liter plastic bottles "go flat" within a few months.

## Composites

A *composite* is composed of two (or more) individual materials that come from the categories previously discussed—metals, ceramics, and polymers. The design goal of a composite is to achieve a combination of properties that is not displayed by any single material and also to incorporate the best characteristics of each of the component materials. A large number of composite types are represented by different combinations of metals, ceramics, and polymers. Furthermore, some naturally occurring materials are composites—for example, wood and bone. However, most of those we consider in our discussions are synthetic (or human-made) composites.

One of the most common and familiar composites is fiberglass, in which small glass fibers are embedded within a polymeric material (normally an epoxy or polyester).[10] The glass fibers are relatively strong and stiff (but also brittle), whereas the polymer is more flexible. Thus, fiberglass is relatively stiff, strong (Figures 1.5 and 1.6), and flexible. In addition, it has a low density (Figure 1.4).

**Tutorial Video:** Composites

Another technologically important material is the carbon fiber–reinforced polymer (CFRP) composite—carbon fibers that are embedded within a polymer. These materials are stiffer and stronger than glass fiber–reinforced materials (Figures 1.5 and 1.6) but more expensive. CFRP composites are used in some aircraft and aerospace applications, as well as in high-tech sporting equipment (e.g., bicycles, golf clubs, tennis rackets, skis/snowboards) and recently in automobile bumpers. The new Boeing 787 fuselage is primarily made from such CFRP composites.

Chapter 16 is devoted to a discussion of these interesting composite materials.

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[10] Fiberglass is sometimes also termed a *glass fiber–reinforced polymer* composite (GFRP).

There is an alternative and more illustrative way of presenting property values by material type than was portrayed by Figures 1.4 through 1.8—that is, if we plot the values of one property versus those of another property for a large number of different types of materials. Both axes are scaled logarithmically and usually span several (at least three) orders of magnitude, so as to include the properties of virtually all materials. For example, Figure 1.12 is one such diagram; here logarithm of stiffness (modulus of elasticity or Young's modulus) is plotted versus the logarithm of density. Here it may be noted that data values for a specific type (or "family") of materials (e.g., metals, ceramics, polymers) cluster together and are enclosed within an envelope (or "bubble") delineated with a bold line; hence, each of these envelopes defines the property range for its material family.

This is a simple, comprehensive, and concise display of the kind of information contained in both Figures 1.4 and 1.5 that shows how density and stiffness correlate with one another among the various kinds of materials. Charts such as Figure 1.12 may be constructed for any two material properties—for example, thermal conductivity versus electrical conductivity. Thus, a relatively large number of plots of this type are available given the possible combinations of pairs of the various material properties. They are

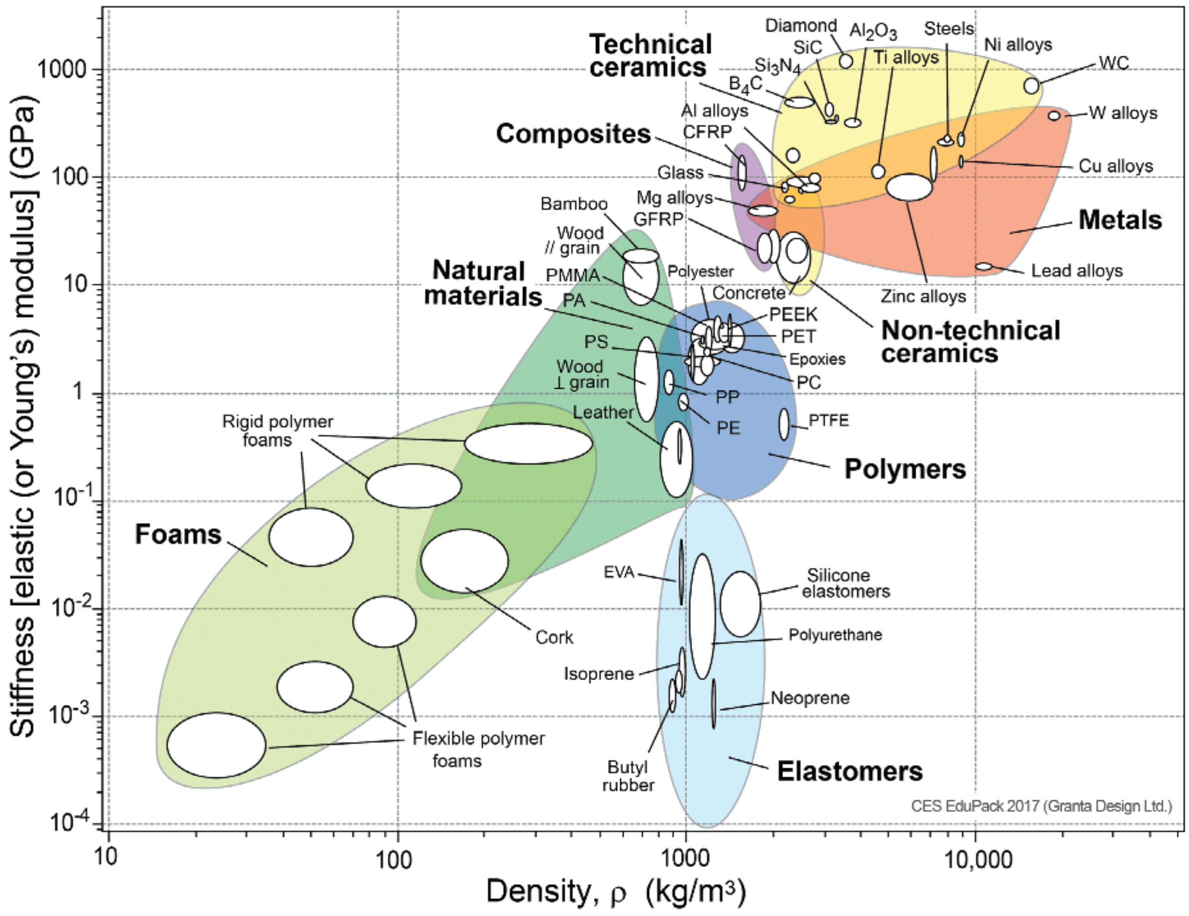

**Figure 1.12** Modulus of elasticity (stiffness) versus density materials selection chart.
(Chart created using CES EduPack 2017, Granta Design Ltd.)

often referred to as "materials property charts," "materials selection charts," "bubble charts," or "Ashby charts" (after Michael F. Ashby, who developed them).[11]

In Figure 1.12, envelopes for three important engineering material families are included that were not discussed previously in this section. These are as follows:

- Elastomers—polymeric materials that display rubbery-like behavior (high degrees of elastic deformation).
- Natural materials—those that occur in nature; for example, wood, leather, and cork.
- Foams—typically polymeric materials that have high porosities (contain a large volume fraction of small pores), which are often used for cushions and packaging.

These bubble charts are extremely useful tools in engineering design and are used extensively in the materials selection process in both academia and industry.[12] When considering materials for products, an engineer is often confronted with competing objectives (e.g., light weight and stiffness) and must be in a position to assess possible trade-offs among any competing requirements. Insights into the consequences of trade-off choices may be gleaned by using appropriate bubble charts. This procedure is demonstrated in the *Materials Selection for a Torsionally Stressed Cylindrical Shaft* case study found in both the "Library of Case Studies" [which may be found in WileyPLUS or at *www.wiley.com/college/callister* (Student Companion Site)] and the "Mechanical Engineering Online Support Module" [which may be found in all digital version of the text or at *www.wiley.com/college/callister (Student Companion Site)*].

## 1.5 ADVANCED MATERIALS

Materials utilized in high-technology (or high-tech) applications are sometimes termed *advanced materials.* By *high technology,* we mean a device or product that operates or functions using relatively intricate and sophisticated principles, including electronic equipment (cell phones, DVD players, etc.), computers, fiber-optic systems, high-energy density batteries, energy-conversion systems, and aircraft. These advanced materials are typically traditional materials whose properties have been enhanced and also newly developed, high-performance materials. Furthermore, they may be of all material types (e.g., metals, ceramics, polymers) and are normally expensive. Advanced materials include semiconductors, biomaterials, and what we may term *materials of the future* (i.e., smart materials and nanoengineered materials), which we discuss next. The properties and applications of a number of these advanced materials—for example, materials that are used for lasers, batteries, magnetic information storage, liquid crystal displays (LCDs), and fiber optics—are also discussed in subsequent chapters.

### Semiconductors

*Semiconductors* have electrical properties that are intermediate between those of electrical conductors (i.e., metals and metal alloys) and insulators (i.e., ceramics and polymers)—see Figure 1.8. Furthermore, the electrical characteristics of these materials are extremely sensitive to the presence of minute concentrations of impurity atoms, for which the concentrations may be controlled over very small spatial regions. Semiconductors have made possible the advent of integrated circuitry that has totally revolutionized the electronics and computer industries (not to mention our lives) over the past four decades.

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[11] A collection of these charts may be found at the following web address: www.teachingresources.grantadesign.com/charts.

[12] Granta Design's CES EduPack is an excellent software package for teaching the principles of materials selection in design using these bubble charts.

## Biomaterials

The length and the quality of our lives are being extended and improved, in part, due to advancements in the ability to replace diseased and injured body parts. Replacement implants are constructed of *biomaterials*—nonviable (i.e., nonliving) materials that are implanted into the body, so that they function in a reliable, safe, and physiologically satisfactory manner, while interacting with living tissue. That is, biomaterials must be *biocompatible*—compatible with body tissues and fluids with which they are in contact over acceptable time periods. Biocompatible materials must neither elicit rejection or physiologically unacceptable responses nor release toxic substances. Consequently, some rather stringent constraints are imposed on materials in order for them to be biocompatible.

Suitable biomaterials are to be found among the several classes of materials discussed earlier in this chapter—i.e., metal alloys, ceramics, polymers, and composite materials. Throughout the remainder of this book we draw the reader's attention to those materials that are used in biotechnology applications.

Over the past several years the development of new and better biomaterials has accelerated rapidly; today, this is one of the "hot" materials areas, with an abundance of new, exciting, and high-salary job opportunities. Example biomaterial applications include joint (e.g., hip, knee) and heart valve replacements, vascular (blood vessel) grafts, fracture-fixation devices, dental restorations, and generation of new organ tissues.

## Smart Materials

*Smart* (or *intelligent*) *materials* are a group of new and state-of-the-art materials now being developed that will have a significant influence on many of our technologies. The adjective *smart* implies that these materials are able to sense changes in their environment and then respond to these changes in predetermined manners—traits that are also found in living organisms. In addition, this *smart* concept is being extended to rather sophisticated systems that consist of both smart and traditional materials.

Components of a smart material (or system) include some type of sensor (which detects an input signal) and an actuator (which performs a responsive and adaptive function). Actuators may be called upon to change shape, position, natural frequency, or mechanical characteristics in response to changes in temperature, electric fields, and/or magnetic fields.

Four types of materials are commonly used for actuators: shape-memory alloys, piezoelectric ceramics, magnetostrictive materials, and electrorheological/magnetorheological fluids. *Shape-memory alloys* are metals that, after having been deformed, revert to their original shape when temperature is changed (see the Materials of Importance box following Section 10.9). *Piezoelectric ceramics* expand and contract in response to an applied electric field (or voltage); conversely, they also generate an electric field when their dimensions are altered (see Section 18.25). The behavior of *magnetostrictive materials* is analogous to that of the piezoelectrics, except that they are responsive to magnetic fields. Also, *electrorheological* and *magnetorheological fluids* are liquids that experience dramatic changes in viscosity upon the application of electric and magnetic fields, respectively.

Materials/devices employed as sensors include optical fibers (Section 21.14), piezoelectric materials (including some polymers), and microelectromechanical systems (MEMS; Section 13.10).

For example, one type of smart system is used in helicopters to reduce aerodynamic cockpit noise created by the rotating rotor blades. Piezoelectric sensors inserted into the blades monitor blade stresses and deformations; feedback signals from these sensors are fed into a computer-controlled adaptive device that generates noise-canceling antinoise.

## Nanomaterials

One new material class that has fascinating properties and tremendous technological promise is the *nanomaterials,* which may be any one of the four basic types—metals, ceramics, polymers, or composites. However, unlike these other materials, they are not distinguished on the basis of their chemistry but rather their size; the *nano* prefix denotes that the dimensions of these structural entities are on the order of a nanometer ($10^{-9}$ m)—as a rule, less than 100 nanometers (nm; equivalent to the diameter of approximately 500 atoms).

Prior to the advent of nanomaterials, the general procedure scientists used to understand the chemistry and physics of materials was to begin by studying large and complex structures and then investigate the fundamental building blocks of these structures that are smaller and simpler. This approach is sometimes termed *top-down science*. However, with the development of scanning probe microscopes (Section 4.10), which permit observation of individual atoms and molecules, it has become possible to design and build new structures from their atomic-level constituents, one atom or molecule at a time (i.e., "materials by design"). This ability to arrange atoms carefully provides opportunities to develop mechanical, electrical, magnetic, and other properties that are not otherwise possible. We call this the *bottom-up approach*, and the study of the properties of these materials is termed *nanotechnology*.[13]

Some of the physical and chemical characteristics exhibited by matter may experience dramatic changes as particle size approaches atomic dimensions. For example, materials that are opaque in the macroscopic domain may become transparent on the nanoscale; some solids become liquids, chemically stable materials become combustible, and electrical insulators become conductors. Furthermore, properties may depend on size in this nanoscale domain. Some of these effects are quantum mechanical in origin, whereas others are related to *surface phenomena*—the proportion of atoms located on surface sites of a particle increases dramatically as its size decreases.

Because of these unique and unusual properties, nanomaterials are finding niches in electronic, biomedical, sporting, energy production, and other industrial applications. Some are discussed in this text, including the following:

- Catalytic converters for automobiles (Materials of Importance box, Chapter 4)
- Nanocarbons—fullerenes, carbon nanotubes, and graphene (Section 13.10)
- Particles of carbon black as reinforcement for automobile tires (Section 16.2)
- Nanocomposites (Section 16.16)
- Magnetic nanosize grains that are used for hard disk drives (Section 20.11)
- Magnetic particles that store data on magnetic tapes (Section 20.11)

Whenever a new material is developed, its potential for harmful and toxicological interactions with humans and animals must be considered. Small nanoparticles have exceedingly large surface area–to–volume ratios, which can lead to high chemical reactivities. Although the safety of nanomaterials is relatively unexplored, there are concerns that they may be absorbed into the body through the skin, lungs, and digestive tract at relatively high rates, and that some, if present in sufficient concentrations, will pose health risks—such as damage to DNA or promotion of lung cancer.

## 1.6 MODERN MATERIALS' NEEDS

In spite of the tremendous progress that has been made in the discipline of materials science and engineering within the past few years, technological challenges remain, including the development of even more sophisticated and specialized materials, as well as consideration of the environmental impact of materials production. Some comment is appropriate relative to these issues so as to round out this perspective.

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[13] One legendary and prophetic suggestion as to the possibility of nanoengineered materials was offered by Richard Feynman in his 1959 American Physical Society lecture titled "There's Plenty of Room at the Bottom."

A number of today's important technological sectors involve energy. There is a recognized need to find new and economical sources of energy, especially renewable energy, and to use present resources more efficiently. Materials will undoubtedly play a significant role in these developments—for example, the direct conversion of solar power into electrical energy. Solar cells employ some rather complex and expensive materials. To ensure a viable technology, materials that are highly efficient in this conversion process yet less costly must be developed.

In conjunction with improved solar cell materials, there is also a marked need for new materials for batteries that provide higher electrical energy-storage densities than those presently available and at lower costs. The current cutting-edge technology uses lithium ion batteries; these offer relatively high storage densities, but also present some technological challenges.

Significant quantities of energy are involved in transportation. Reducing the weight of transportation vehicles (automobiles, aircraft, trains, etc.), as well as increasing engine operating temperatures, will enhance fuel efficiency. New high-strength, low-density structural materials remain to be developed, as well as materials that have higher-temperature capabilities, for use in engine components.

The hydrogen fuel cell is another very attractive and feasible energy-conversion technology that has the advantage of being nonpolluting. It is just beginning to be implemented in batteries for electronic devices and holds promise as a power plant for automobiles. New materials still need to be developed for more efficient fuel cells and also for better catalysts to be used in the production of hydrogen.

Nuclear energy holds some promise, but the solutions to the many problems that remain necessarily involve materials, such as fuels, containment structures, and facilities for the disposal of radioactive waste.

Furthermore, environmental quality depends on our ability to control air and water pollution. Pollution control techniques employ various materials. In addition, materials processing and refinement methods need to be improved so that they produce less environmental degradation—that is, less pollution and less despoilage of the landscape from the mining of raw materials. Also, in some materials manufacturing processes, toxic substances are produced, and the ecological impact of their disposal must be considered.

Many materials that we use are derived from resources that are nonrenewable—that is, not capable of being regenerated, including most polymers, for which the prime raw material is oil, and some metals. These nonrenewable resources are gradually becoming depleted, which necessitates (1) the discovery of additional reserves, (2) the development of new materials having comparable properties with less adverse environmental impact, and/or (3) increased recycling efforts and the development of new recycling technologies. As a consequence of the economics of not only production but also environmental impact and ecological factors, it is becoming increasingly important to consider the "cradle-to-grave" life cycle of materials relative to the overall manufacturing process.

The roles that materials scientists and engineers play relative to these, as well as other environmental and societal issues, are discussed in more detail in Chapter 22.

## SUMMARY

### Materials Science and Engineering

- Six different property classifications of materials determine their applicability: mechanical, electrical, thermal, magnetic, optical, and deteriorative.
- One important relationship in the science of materials is the dependence of a material's properties on its structural elements. By *structure*, we mean how the internal component(s) of the material is (are) arranged. In terms of (and with increasing) dimensionality, structural elements include subatomic, atomic, nanoscopic, microscopic, and macroscopic.

- With regard to the design, production, and utilization of materials, there are four elements to consider—processing, structure, properties, and performance. The performance of a material depends on its properties, which in turn are a function of its structure(s); structure(s) is (are) determined by how the material was processed. The interrelationship among these four elements is sometimes called the central paradigm of materials science and engineering.
- Three important criteria in materials selection are in-service conditions to which the material will be subjected, any deterioration of material properties during operation, and economics or cost of the fabricated piece.

**Classification of Materials**

- On the basis of chemistry and atomic structure, materials are classified into three general categories: metals (metallic elements), ceramics (compounds between metallic and nonmetallic elements), and polymers (compounds composed of carbon, hydrogen, and other nonmetallic elements). In addition, composites are composed of at least two different material types.

**Advanced Materials**

- Another materials category is the advanced materials that are used in high-tech applications, including semiconductors (having electrical conductivities intermediate between those of conductors and insulators), biomaterials (which must be compatible with body tissues), smart materials (those that sense and respond to changes in their environments in predetermined manners), and nanomaterials (those that have structural features on the order of a nanometer, some of which may be designed on the atomic/molecular level).

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