

# 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

→ Materials are probably more **deep seated** in our culture than most of us realize. Transportation, housing, clothing, communication, recreation, and food production—virtually every segment of our everyday lives is influenced to **one degree or another** by materials. 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).<sup>1</sup>

**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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## 1.2 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

<sup>1</sup>The approximate dates for the beginnings of the Stone, Bronze, and Iron ages are 2.5 million BC, 3500 BC, and 1000 BC, respectively.

properties of materials. **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.<sup>2</sup> 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.

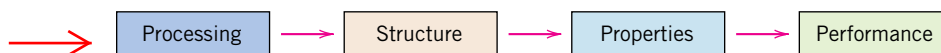
*Structure* is, at this point, a nebulous term that deserves some explanation. In brief, the structure of a material usually relates to the arrangement of its internal components. *Subatomic structure* involves electrons within the individual atoms and interactions with their nuclei. On an atomic level, structure encompasses the organization of atoms or molecules relative to one another. The next larger structural realm, which contains large groups of atoms that are normally agglomerated together, is termed *microscopic*, meaning that which is subject to direct observation using some type of microscope. Finally, structural elements that can be viewed with the naked eye are termed *macroscopic*.

The notion of *property* deserves elaboration. While in service use, all materials are exposed to external stimuli that evoke some type of response. 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. Mechanical properties relate deformation to an applied load or force; examples include elastic modulus (stiffness), strength, and toughness. For electrical properties, such as electrical conductivity and dielectric constant, the stimulus is an electric field. The thermal behavior of solids can be represented in terms of heat capacity and thermal conductivity. Magnetic properties demonstrate the response of a material to the application of a magnetic field. For optical properties, the stimulus is electromagnetic or light radiation; index of refraction and reflectivity are representative optical properties. Finally, deteriorative characteristics relate to the chemical reactivity of materials. 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. Thus, the interrelationship among processing, structure, properties, and performance is as depicted in the schematic illustration shown in Figure 1.1. Throughout this text, we draw attention to the relationships among these four components in terms of the design, production, and utilization of materials.

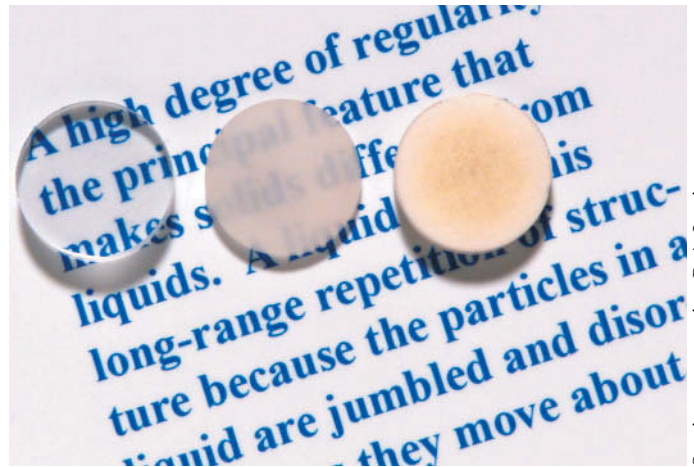
We present an example of these processing-structure-properties-performance principles in Figure 1.2, a photograph showing three thin disk specimens placed over some printed matter. It is obvious that the optical properties (i.e., the light transmittance) of each of the three materials are different; the one on the left is transparent (i.e., virtually all of the



**Figure 1.1** The four components of the discipline of materials science and engineering and their interrelationship.

<sup>2</sup>Throughout this text, we draw attention to the relationships between material properties and structural elements.

→ **Figure 1.2** 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.



Specimen preparation, P. A. Lessing

reflected light 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 also effectively scatter the reflected light 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.

### 1.3 WHY STUDY MATERIALS SCIENCE AND ENGINEERING?

→ Why do we study materials? Many an applied scientist or engineer, whether mechanical, civil, chemical, or electrical, is at one time or another exposed to a design problem involving materials, such as 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, a materials problem is one of selecting the right 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. On only rare occasions does a material possess the maximum 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 ideal 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.

## CASE STUDY

### *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<sup>3</sup> is a well-known and dramatic example of the **brittle fracture** of steel that was thought to be ductile.<sup>4</sup> 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<sup>5</sup>:

- 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. 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.<sup>6</sup>

- 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.

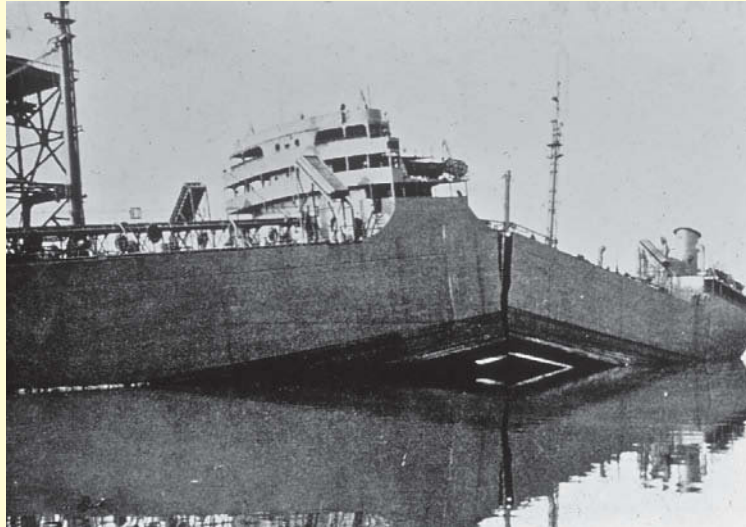
<sup>3</sup>During World War II, 2,710 Liberty cargo ships were mass-produced by the United States to supply food and materials to the combatants in Europe.

<sup>4</sup>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.

<sup>5</sup>Sections 8.2 through 8.6 discuss various aspects of failure.

<sup>6</sup>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.





**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.)

**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.<sup>7</sup>
- 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.

<sup>7</sup>The reader may note that corners of windows and doors for all of today's marine and aircraft structures are rounded.

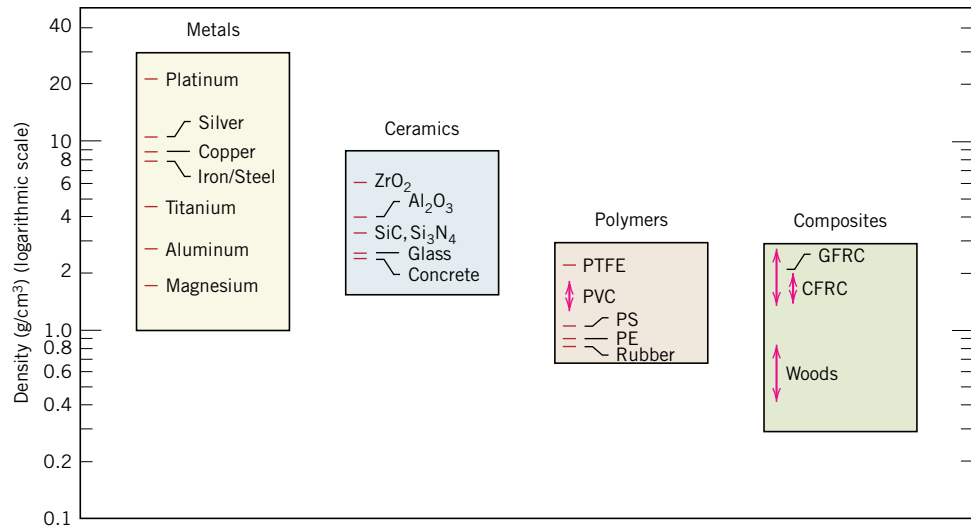
## 1.4 CLASSIFICATION OF MATERIALS

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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.

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



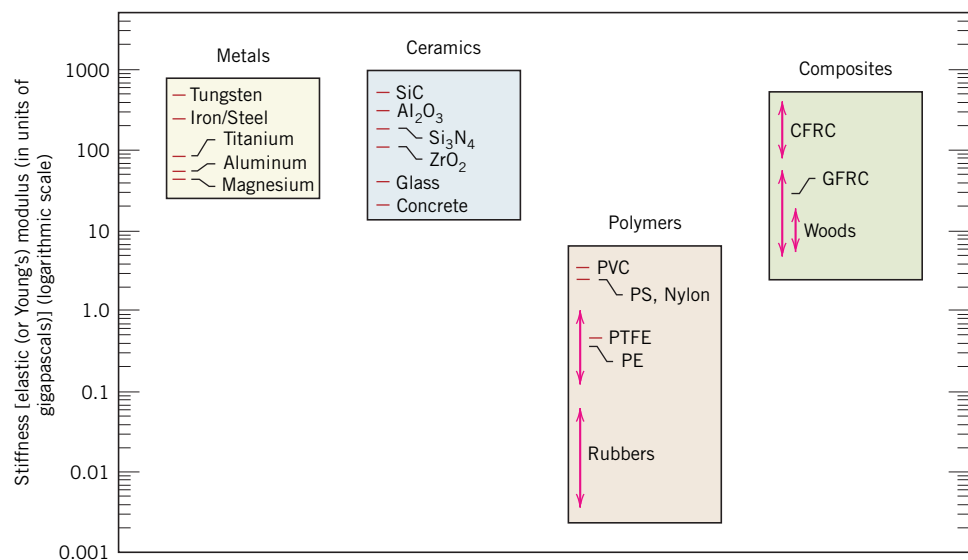
### Metals

**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.<sup>8</sup> Atoms in metals and their alloys are arranged in a 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

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Metals

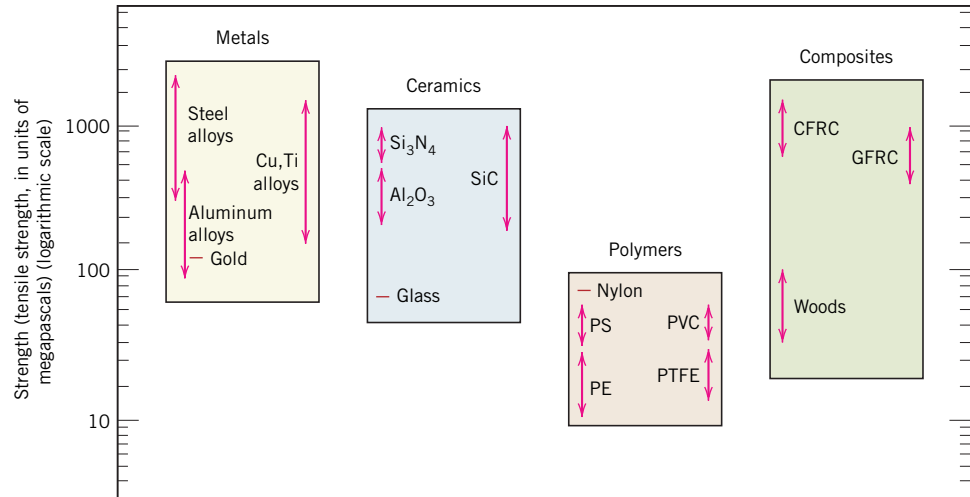
**Figure 1.5**  
Bar chart of room-temperature stiffness (i.e., elastic modulus) values for various metals, ceramics, polymers, and composite materials.



<sup>8</sup>The term *metal alloy* refers to a metallic substance that is composed of two or more elements.

**Figure 1.6**

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



(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.

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

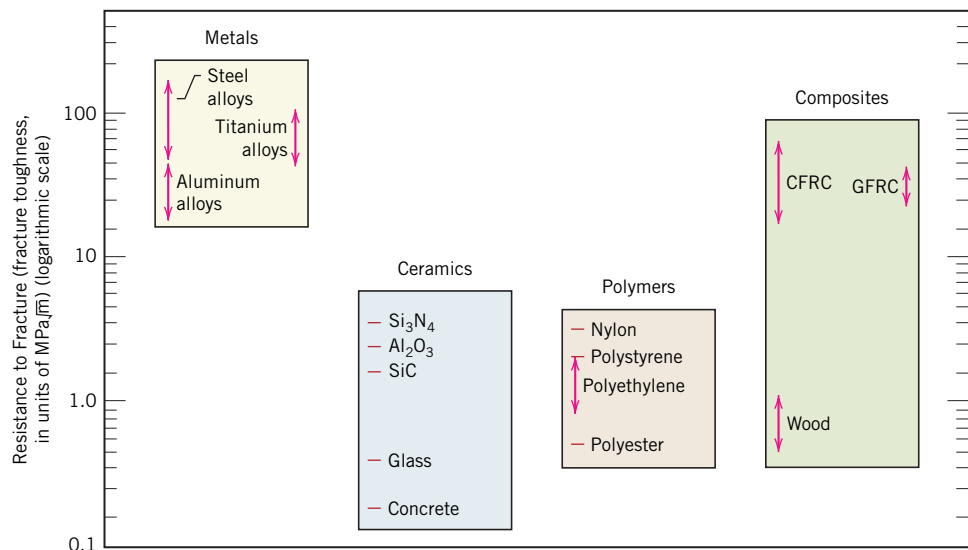
**Ceramics** are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. For example, common ceramic materials include aluminum oxide (or *alumina*, Al<sub>2</sub>O<sub>3</sub>), silicon dioxide (or *silica*, SiO<sub>2</sub>), silicon carbide (SiC), silicon nitride (Si<sub>3</sub>N<sub>4</sub>), 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

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Ceramics

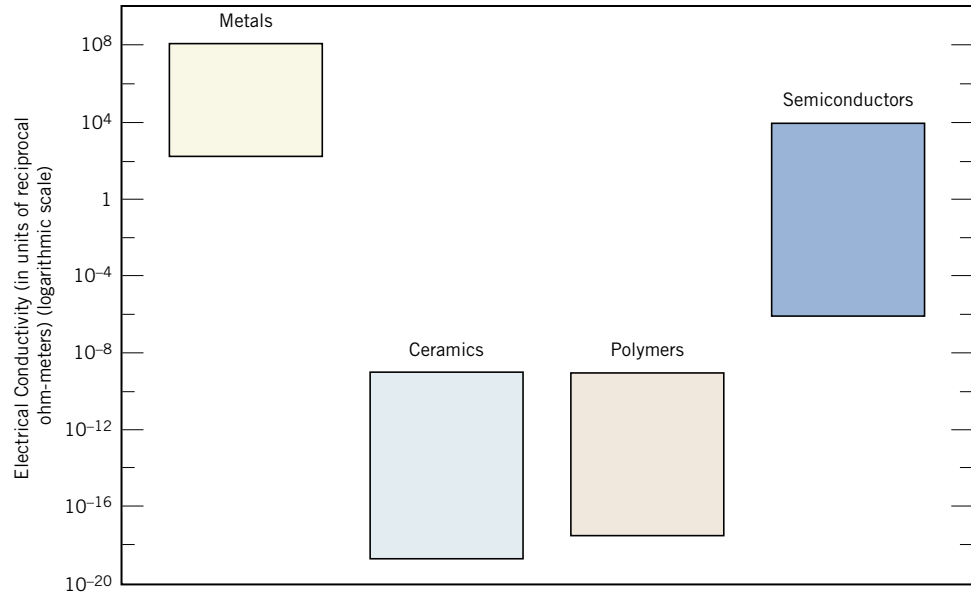
**Figure 1.7**

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.



even automobile engine parts. Furthermore, ceramic materials are typically insulative to the 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 1.2), and some of the oxide ceramics (e.g.,  $\text{Fe}_3\text{O}_4$ ) 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



**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. One major drawback to the polymers is their tendency to soften and/or decompose at modest temperatures, which, in some instances, limits their use. Furthermore, they have low electrical conductivities (Figure 1.8) and are nonmagnetic.

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**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

*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).<sup>9</sup> 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).

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.

**WileyPLUS****Tutorial Video:**  
Composites

<sup>9</sup>Fiberglass is sometimes also termed a *glass fiber–reinforced polymer* composite (GFRP).

## 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 (camcorders, CD/DVD players), computers, fiber-optic systems, spacecraft, aircraft, and military rocketry. 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, integrated circuits, 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 three decades.

### Biomaterials

*Biomaterials* are employed in components implanted into the human body to replace diseased or damaged body parts. These materials must not produce toxic substances and must be compatible with body tissues (i.e., must not cause adverse biological reactions). All of the preceding materials—metals, ceramics, polymers, composites, and semiconductors—may be used as biomaterials.

### 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 13.9).

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*.<sup>10</sup>

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 13.9)
- 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)

<sup>10</sup>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.”



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.

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.

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.

Furthermore, there is a recognized need to find new and economical sources of 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 has been demonstrated. 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.

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.

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.

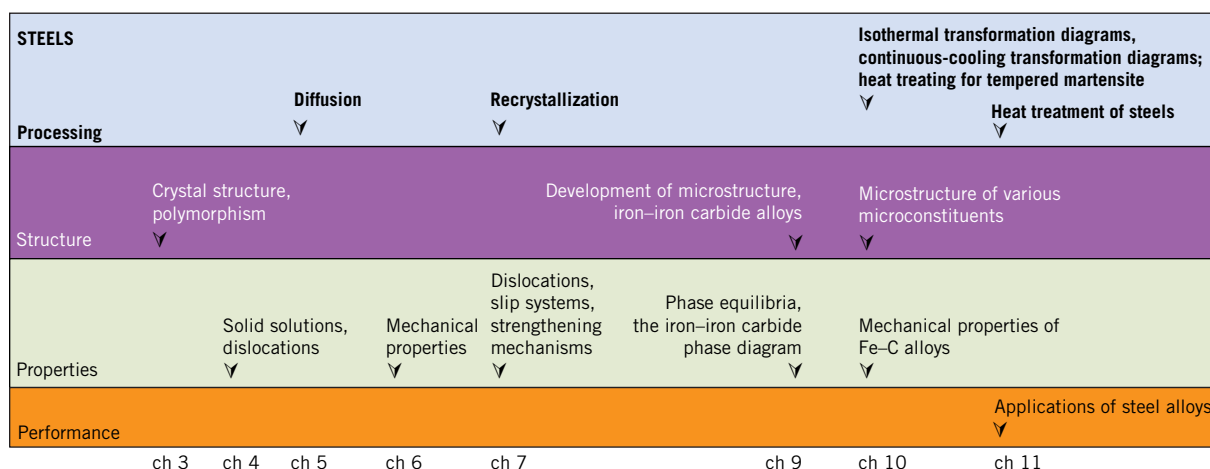
The roles that materials scientists and engineers play relative to these, as well as other environmental and societal issues, are discussed in more detail in Chapter 22.

## 1.7 PROCESSING/STRUCTURE/PROPERTIES/PERFORMANCE CORRELATIONS

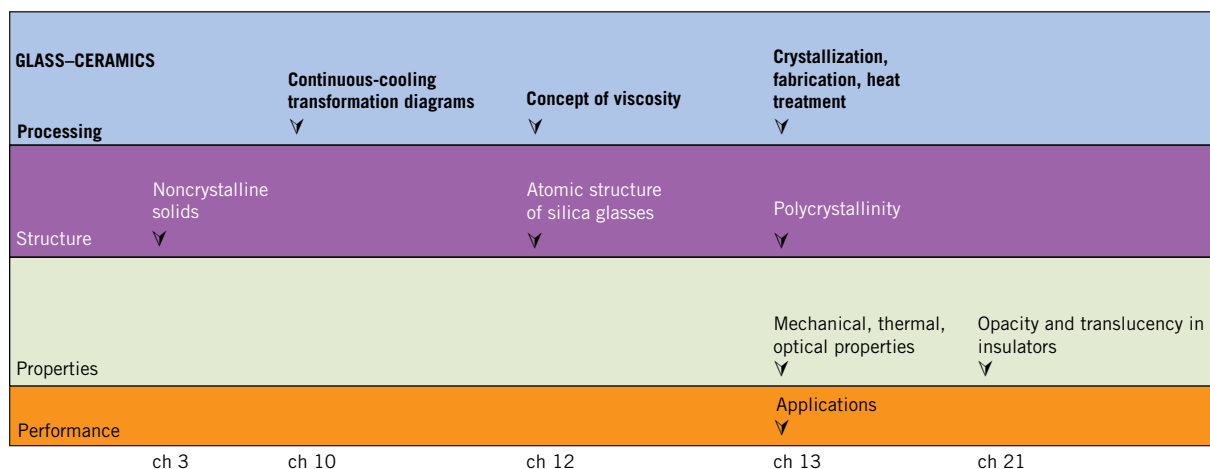
### WileyPLUS

**Tutorial Video:**  
Processing/  
Structure/  
Properties/  
Performance of  
Materials

As mentioned previously (Section 1.2), the science and engineering of materials involves four interrelated components: processing, structure, properties, and performance (Figure 1.1). Inasmuch as the remainder of this text discusses these components for the different material types, it has been decided to direct the reader's attention to the treatment of individual components for several specific materials. Whereas some of these discussions are found within single chapters, others are spread out over multiple chapters. For the latter, and for each material we have selected, a *topic timeline* has been created that indicates the locations (by sections) where treatments of the four components are to be found. Figure 1.12 presents topic timelines for the following materials: steels, glass–ceramics, polymer fibers, and silicon semiconductors. In addition, near the end of each chapter with some discussion of processing, structure,

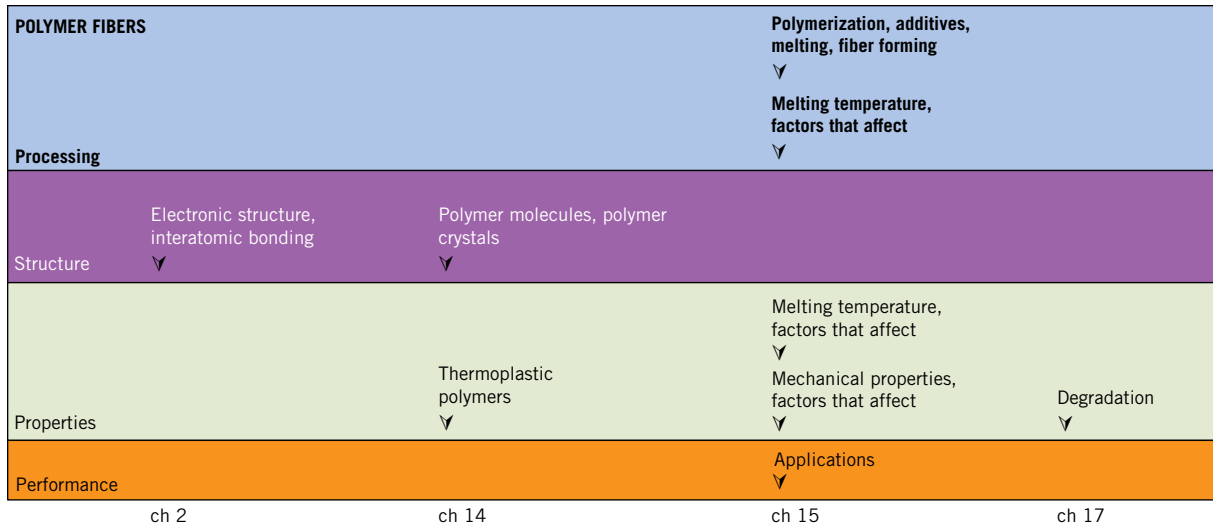


(a)

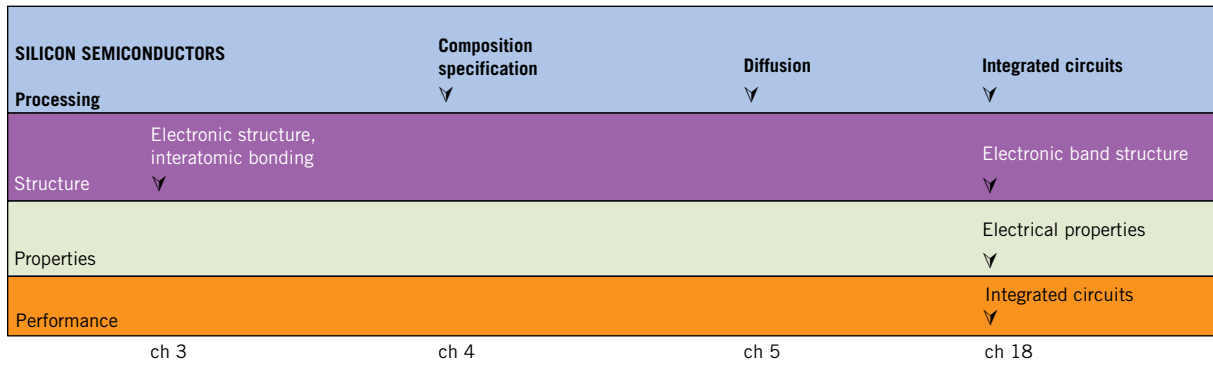


(b)

**Figure 1.12** Processing/structure/properties/performance topic timelines for (a) steels, (b) glass–ceramics, (c) polymer fibers, and (d) silicon semiconductors.



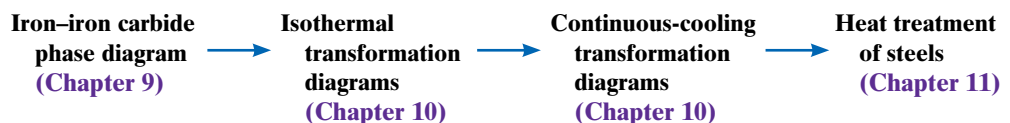
(c)



(d)

**Figure 1.12** (continued)

properties, and/or performance for at least one of these four materials, a summary is provided in the form of one or more concept maps. A *concept map* is a diagram that illustrates the relationships among concepts. We represent these relationships by connecting arrows (frequently horizontal); each arrow points (left to right) from one concept to another. The organization of these connections is *hierarchical*—that is, a concept to the left of an arrow should be mastered before a concept to the right can be understood. For each map, at least one of its concepts is discussed in its chapter; other concepts may be treated in previous and/or later chapters. For example, Figure 1.13 presents a portion of a concept map for the processing of steel alloys that appears in Chapter 10.

**Figure 1.13** Portion of a concept map for the processing of a steel alloy found in Chapter 10.

## SUMMARY

### Materials Science and Engineering

- There are six different property classifications of materials that determine their applicability: mechanical, electrical, thermal, magnetic, optical, and deteriorative.
- One aspect of materials science is the investigation of relationships that exist between the structures and properties of materials. By *structure*, we mean how some internal component(s) of the material is (are) arranged. In terms of (and with increasing) dimensionality, structural elements include subatomic, atomic, 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); furthermore, structure(s) is (are) determined by how the material was processed.
- 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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## QUESTIONS

+ Problem available (at instructor's discretion) in WileyPLUS

- 1.1** Select one or more of the following modern items or devices and conduct an Internet search in order to determine what specific material(s) is (are) used and what specific properties this (these) material(s) possess(es) in order for the device/item to function properly. Finally, write a short essay in which you report your findings.

Cell phone/digital camera batteries  
 Cell phone displays  
 Solar cells  
 Wind turbine blades  
 Fuel cells  
 Automobile engine blocks (other than cast iron)  
 Automobile bodies (other than steel alloys)  
 Space telescope mirrors  
 Military body armor  
 Sports equipment  
   Soccer balls  
   Basketballs  
   Ski poles  
   Ski boots  
   Snowboards  
   Surfboards

Golf clubs  
 Golf balls  
 Kayaks  
 Lightweight bicycle frames

- 1.2** List three items (in addition to those shown in Figure 1.9) made from metals or their alloys. For each item, note the specific metal or alloy used and at least one characteristic that makes it the material of choice.
- 1.3** List three items (in addition to those shown in Figure 1.10) made from ceramic materials. For each item, note the specific ceramic used and at least one characteristic that makes it the material of choice.
- 1.4** List three items (in addition to those shown in Figure 1.11) made from polymeric materials. For each item, note the specific polymer used and at least one characteristic that makes it the material of choice.
- 1.5** Classify each of the following materials as to whether it is a metal, ceramic, or polymer. Justify each choice: (a) brass; (b) magnesium oxide ( $\text{MgO}$ ); (c) Plexiglas®; (d) polychloroprene; (e) boron carbide ( $\text{B}_4\text{C}$ ); and (f) cast iron.