

# 3

# Mechanical Properties of Materials

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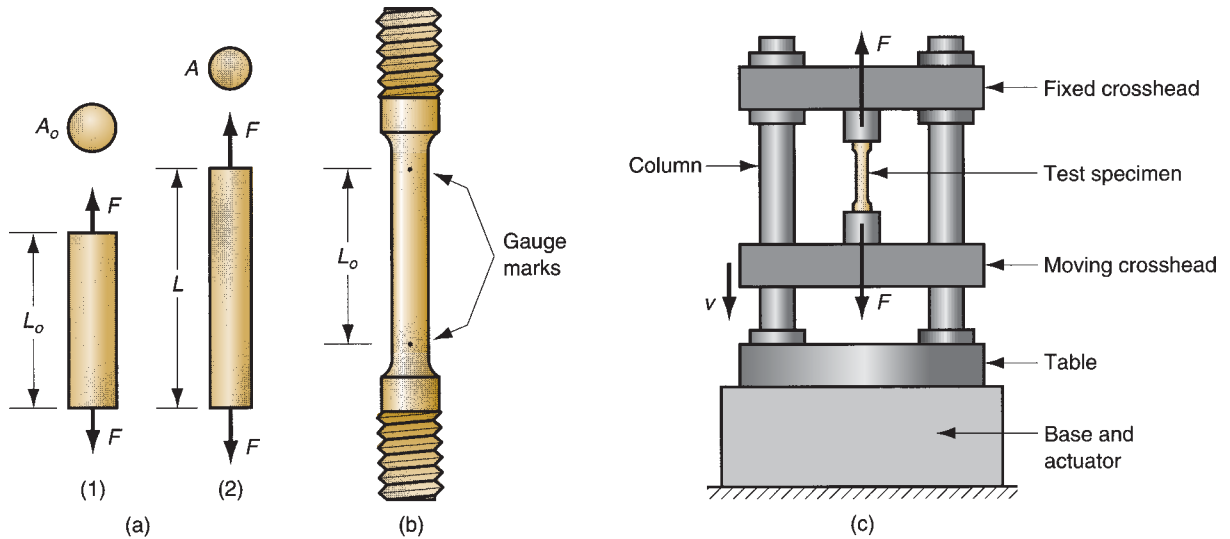
### 3.5 Viscoelastic Behavior of Polymers

Mechanical properties of a material determine its behavior when subjected to mechanical stresses. These properties include elastic modulus, ductility, hardness, and various measures of strength. Mechanical properties are important in design because the function and performance of a product depend on its capacity to resist deformation under the stresses encountered in service. In design, the usual objective is for the product and its components to withstand these stresses without significant change in geometry. This capability depends on properties such as elastic modulus and yield strength. In manufacturing, the objective is just the opposite. Here, stresses that exceed the yield strength of the material must be applied to alter its shape. Mechanical processes such as forming and machining succeed by developing forces that exceed the material's resistance to deformation. Thus, there is the following dilemma: Mechanical properties that are desirable to the designer, such as high strength, usually make the manufacture of the product more difficult. It is helpful for the manufacturing engineer to appreciate the design viewpoint and for the designer to be aware of the manufacturing viewpoint.

This chapter examines the mechanical properties of materials that are most relevant in manufacturing.

## 3. Stress–Strain Relationships

There are three types of static stresses to which materials can be subjected: tensile, compressive, and shear. Tensile stresses tend to stretch the material, compressive stresses tend to squeeze it, and shear involves stresses that tend to cause adjacent portions of the material to slide against each other. The stress–strain curve is the basic relationship that describes the mechanical properties of materials for all three types.



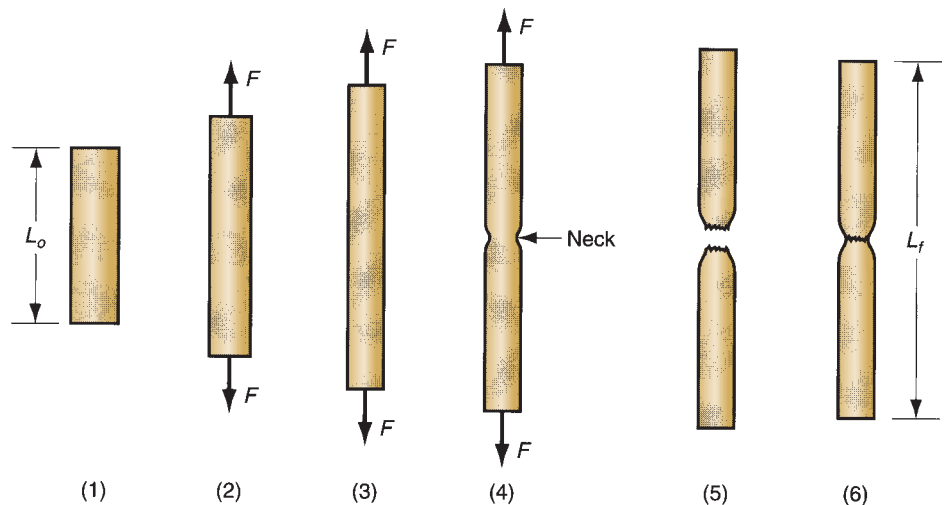
**FIGURE 3.1** Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material; (b) typical test specimen; and (c) setup of the tensile test.

### 3.1.1 TENSILE PROPERTIES

The tensile test is the most common procedure for studying the stress–strain relationship, particularly for metals. In the test, a force is applied that pulls the material, tending to elongate it and reduce its diameter, as shown in Figure 3.1(a). Standards by ASTM (American Society for Testing and Materials) specify the preparation of the test specimen and the conduct of the test itself. The typical specimen and general setup of the tensile test is illustrated in Figure 3.1(b) and (c), respectively.

The starting test specimen has an original length  $L_o$  and area  $A_o$ . The length is measured as the distance between the gage marks, and the area is measured as the (usually round) cross section of the specimen. During the testing of a metal, the specimen stretches, then necks, and finally fractures, as shown in Figure 3.2.

**FIGURE 3.2** Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.



The load and the change in length of the specimen are recorded as testing proceeds, to provide the data required to determine the stress–strain relationship. There are two different types of stress–strain curves: (1) engineering stress–strain and (2) true stress–strain. The first is more important in design, and the second is more important in manufacturing.

**Engineering Stress–strain** The engineering stress and strain in a tensile test are defined relative to the original area and length of the test specimen. These values are of interest in design because the designer expects that the strains experienced by any component of the product will not significantly change its shape. The components are designed to withstand the anticipated stresses encountered in service.

A typical engineering stress–strain curve from a tensile test of a metallic specimen is illustrated in Figure 3.3. The **engineering stress** at any point on the curve is defined as the force divided by the original area:

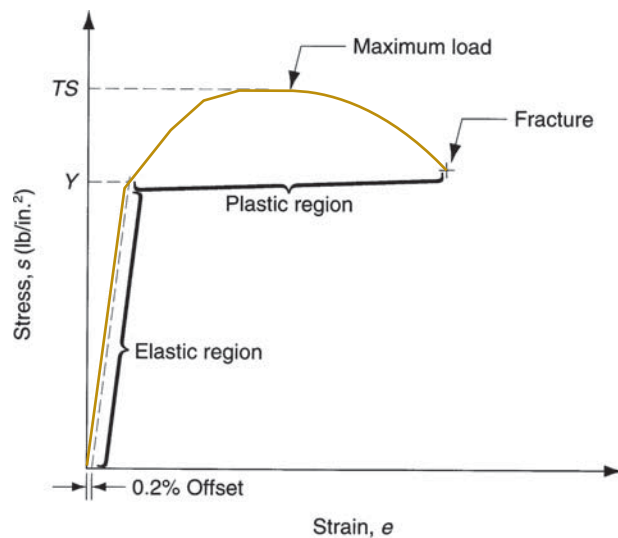
$$s = \frac{F}{A_o} \quad (3.1)$$

where  $s$  = engineering stress, MPa (lb/in<sup>2</sup>);  $F$  = applied force in the test, N (lb); and  $A_o$  = original area of the test specimen, mm<sup>2</sup> (in<sup>2</sup>). The **engineering strain** at any point in the test is given by

$$e = \frac{L - L_o}{L_o} \quad (3.2)$$

where  $e$  = engineering strain, mm/mm (in/in);  $L$  = length at any point during the elongation, mm (in); and  $L_o$  = original gage length, mm (in). The units of engineering strain are given as mm/mm (in/in), but think of it as representing elongation per unit length, without units.

The stress–strain relationship in Figure 3.3 has two regions, indicating two distinct forms of behavior: (1) elastic and (2) plastic. In the elastic region, the relationship between stress and strain is linear, and the material exhibits elastic behavior by



**FIGURE 3.3** Typical engineering stress–strain plot in a tensile test of a metal.

returning to its original length when the load (stress) is released. The relationship is defined by **Hooke's law**:

$$s = Ee \quad (3.3)$$

where  $E$  = **modulus of elasticity** (also known as **Young's modulus**), MPa (lb/in<sup>2</sup>), a measure of the inherent stiffness of a material. It is a constant of proportionality whose value is different for different materials. Table 3.1 presents typical values for several materials, metals and nonmetals.

As stress increases, some point in the linear relationship is finally reached at which the material begins to yield. This **yield point**  $Y$  of the material can be identified in the figure by the change in slope at the end of the linear region. Because the start of yielding is usually difficult to see in a plot of test data (it does not usually occur as an abrupt change in slope),  $Y$  is typically defined as the stress at which a strain offset of 0.2% from the straight line has occurred. More specifically, it is the point where the stress–strain curve for the material intersects a line that is parallel to the straight portion of the curve but offset from it by a strain of 0.2%. The yield point is a strength characteristic of the material, and is therefore often referred to as the **yield strength** (other names include **yield stress** and **elastic limit**).

The yield point marks the transition to the plastic region and the start of plastic deformation of the material. The relationship between stress and strain is no longer guided by Hooke's law. As the load is increased beyond the yield point, elongation of the specimen proceeds, but at a much faster rate than before, causing the slope of the curve to change dramatically, as shown in Figure 3.3. Elongation is accompanied by a uniform reduction in cross-sectional area, consistent with maintaining constant volume. Finally, the applied load  $F$  reaches a maximum value, and the engineering stress calculated at this point is called the **tensile**

**TABLE • 3.1** Elastic modulus for selected materials.

Metals	Modulus of Elasticity		Ceramics and Polymers	Modulus of Elasticity	
	MPa	lb/in <sup>2</sup>		MPa	lb/in <sup>2</sup>
Aluminum and alloys	69 × 10 <sup>3</sup>	10 × 10 <sup>6</sup>	Alumina	345 × 10 <sup>3</sup>	50 × 10 <sup>6</sup>
Cast iron	138 × 10 <sup>3</sup>	20 × 10 <sup>6</sup>	Diamond <sup>a</sup>	1035 × 10 <sup>3</sup>	150 × 10 <sup>6</sup>
Copper and alloys	110 × 10 <sup>3</sup>	16 × 10 <sup>6</sup>	Silicon <sup>a</sup>	185 × 10 <sup>3</sup>	27 × 10 <sup>6</sup>
Iron	209 × 10 <sup>3</sup>	30 × 10 <sup>6</sup>	Plate glass	69 × 10 <sup>3</sup>	10 × 10 <sup>6</sup>
Lead	21 × 10 <sup>3</sup>	3 × 10 <sup>6</sup>	Silicon carbide	448 × 10 <sup>3</sup>	65 × 10 <sup>6</sup>
Magnesium	48 × 10 <sup>3</sup>	7 × 10 <sup>6</sup>	Tungsten carbide	552 × 10 <sup>3</sup>	80 × 10 <sup>6</sup>
Nickel	209 × 10 <sup>3</sup>	30 × 10 <sup>6</sup>	Nylon	3.0 × 10 <sup>3</sup>	0.40 × 10 <sup>6</sup>
Steel	209 × 10 <sup>3</sup>	30 × 10 <sup>6</sup>	Phenol formaldehyde	7.0 × 10 <sup>3</sup>	1.00 × 10 <sup>6</sup>
Titanium	117 × 10 <sup>3</sup>	17 × 10 <sup>6</sup>	Polyethylene (low density)	0.2 × 10 <sup>3</sup>	0.03 × 10 <sup>6</sup>
Tungsten	407 × 10 <sup>3</sup>	59 × 10 <sup>6</sup>	Polyethylene (high density)	0.7 × 10 <sup>3</sup>	0.10 × 10 <sup>6</sup>
Zinc	108 × 10 <sup>3</sup>	16 × 10 <sup>6</sup>	Polystyrene	3.0 × 10 <sup>3</sup>	0.40 × 10 <sup>6</sup>

<sup>a</sup>Compiled from [8], [10], [11], [15], [16], and other sources.

Although diamond and silicon are not ceramics, they are often compared with the ceramic materials.

**TABLE • 3.2** Yield strength and tensile strength for selected metals.

Metal	Yield Strength		Tensile Strength		Metal	Yield Strength		Tensile Strength	
	MPa	lb/in <sup>2</sup>	MPa	lb/in <sup>2</sup>		MPa	lb/in <sup>2</sup>	MPa	lb/in <sup>2</sup>
Aluminum, annealed	28	4,000	69	10,000	Nickel, annealed	150	22,000	450	65,000
Aluminum, CW <sup>a</sup>	105	15,000	125	18,000	Steel, low C <sup>a</sup>	175	25,000	300	45,000
Aluminum alloys <sup>a</sup>	175	25,000	350	50,000	Steel, high C <sup>a</sup>	400	60,000	600	90,000
Cast iron <sup>a</sup>	275	40,000	275	40,000	Steel, alloy <sup>a</sup>	500	75,000	700	100,000
Copper, annealed	70	10,000	205	30,000	Steel, stainless <sup>a</sup>	275	40,000	650	95,000
Copper alloys <sup>a</sup>	205	30,000	410	60,000	Titanium, pure	350	50,000	515	75,000
Magnesium alloys <sup>a</sup>	175	25,000	275	40,000	Titanium alloy	800	120,000	900	130,000

Compiled from [8], [10], [11], [16], and other sources.

<sup>a</sup>Values given are typical. For alloys, there is a wide range in strength values depending on composition and treatment (e.g., heat treatment, work hardening).

**strength** or **ultimate tensile strength** of the material. It is denoted as *TS* where  $TS = F_{\max}/A_o$ . *TS* and *Y* are important strength properties in design calculations. (They are also used in certain manufacturing calculations.) Some typical values of yield strength and tensile strength are listed in Table 3.2 for selected metals. Conventional tensile testing of ceramics is difficult, and an alternative test is used to measure the strength of these brittle materials (Section 3.1.3). Polymers differ in their strength properties from metals and ceramics because of viscoelasticity (Section 3.5).

To the right of the tensile strength on the stress–strain curve, the load begins to decline, and the test specimen typically begins a process of localized elongation known as **necking**. Instead of continuing to strain uniformly throughout its length, straining becomes concentrated in one small section of the specimen. The area of that section narrows down (necks) significantly until failure occurs. The stress calculated immediately before failure is known as the **fracture stress**.

The amount of strain that the material can endure before failure is also a mechanical property of interest in many manufacturing processes. The common measure of this property is **ductility**, the ability of a material to plastically strain without fracture. This measure can be taken as either elongation or area reduction. Elongation is defined as

$$EL = \frac{L_f - L_o}{L_o} \quad (3.4)$$

where *EL* = elongation, often expressed as a percent; *L<sub>f</sub>* = specimen length at fracture, mm (in), measured as the distance between gage marks after the two parts of the specimen have been put back together; and *L<sub>o</sub>* = original specimen length, mm (in). Area reduction is defined as

$$AR = \frac{A_o - A_f}{A_o} \quad (3.5)$$

where *AR* = area reduction, often expressed as a percent; *A<sub>f</sub>* = area of the cross section at the point of fracture, mm<sup>2</sup>(in<sup>2</sup>); and *A<sub>o</sub>* = original area, mm<sup>2</sup> (in<sup>2</sup>). There are problems with both of these ductility measures because of necking that occurs in

**TABLE • 3.3** Ductility as % elongation (typical values) for various selected materials.

Material	Elongation	Material	Elongation
<b>Metals</b>		<i>Metals, continued</i>	
Aluminum, annealed	40%	Steel, low C <sup>a</sup>	30%
Aluminum, cold worked	8%	Steel, high C <sup>a</sup>	10%
Aluminum alloys, annealed <sup>a</sup>	20%	Steel, alloy <sup>a</sup>	20%
Aluminum alloys, heat treated <sup>a</sup>	8%	Steel, stainless, austenitic <sup>a</sup>	55%
Aluminum alloys, cast <sup>a</sup>	4%	Titanium, nearly pure	20%
Cast iron, gray <sup>a</sup>	0.6%	Zinc alloy	10%
Copper, annealed	45%	<b>Ceramics</b>	0 <sup>b</sup>
Copper, cold worked	10%	<b>Polymers</b>	
Copper alloy: brass, annealed	60%	Thermoplastic polymers	100%
Magnesium alloys <sup>a</sup>	10%	Thermosetting polymers	1%
Nickel, annealed	45%	Elastomers (e.g., rubber)	1% <sup>c</sup>

Compiled from [8], [10], [11], [16], and other sources.

<sup>a</sup>Values given are typical. For alloys, there is a range of ductility that depends on composition and treatment (e.g., heat treatment, degree of work hardening).

<sup>b</sup>Ceramic materials are brittle; they withstand elastic strain but virtually no plastic strain.

<sup>c</sup>Elastomers endure significant elastic strain, but their plastic strain is very limited, only around 1% being typical.

metallic test specimens and the associated nonuniform effect on elongation and area reduction. Despite these difficulties, percent elongation and percent area reduction are the most commonly used measures of ductility in engineering practice. Some typical values of percent elongation for various materials (mostly metals) are listed in Table 3.3.

### Example 3.1 Engineering stress and strain

A tensile test specimen has a starting gage length = 50 mm and a cross-sectional area = 200 mm<sup>2</sup>. During the test, the specimen yields under a load of 32,000 N (this is the 0.2% offset) at a gage length of 50.2 mm. The maximum load of 65,000 N is reached at a gage length of 57.7 mm just before necking begins. Final fracture occurs at a gage length of 63.5 mm. Determine (a) yield strength, (b) modulus of elasticity, (c) tensile strength, (d) engineering strain at maximum load, and (e) percent elongation.

**Solution:** (a) Yield strength  $Y = 32,000/200 = 160 \text{ MPa}$ .

(b) Subtracting the 0.2% offset, engineering strain  $e = (50.2 - 50.0)/50.0 - 0.002 = 0.002$

Rearranging Equation (3.3), modulus of elasticity  $E = s/e = 160/0.002 = 80,000 \text{ MPa}$ .

(c) Tensile strength = maximum load divided by original area:  
 $TS = 65,000/200 = 325 \text{ MPa}$ .

(d) By Equation (3.2), engineering strain at maximum load  $e = (57.7 - 50)/50 = 0.154$ .

(e) Defined in Equation (3.4), percent elongation  $EL = (59.5 - 50)/50 = 0.19 = 19\%$ .

**True Stress–Strain** Thoughtful readers may be troubled by the use of the original area of the test specimen to calculate engineering stress, rather than the actual (instantaneous) area that becomes increasingly smaller as the test proceeds. If the actual area were used, the calculated stress value would be higher. The stress value obtained by dividing the instantaneous value of area into the applied load is defined as the **true stress**:

$$s = \frac{F}{A} \quad (3.6)$$

where  $s$  = true stress, MPa (lb/in<sup>2</sup>);  $F$  = force, N (lb); and  $A$  = actual (instantaneous) area resisting the load, mm<sup>2</sup> (in<sup>2</sup>).

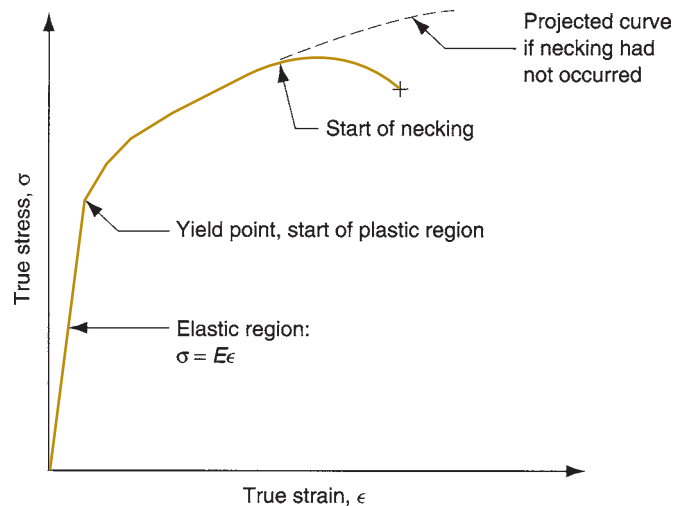
Similarly, **true strain** provides a more realistic assessment of the “instantaneous” elongation per unit length of the material. The value of true strain in a tensile test can be estimated by dividing the total elongation into small increments, calculating the engineering strain for each increment on the basis of its starting length, and then adding up the strain values. In the limit, true strain is defined as

$$e = \int_{L_o}^L \frac{dL}{L} = \ln \frac{L}{L_o} \quad (3.7)$$

where  $L$  = instantaneous length at any moment during elongation. At the end of the test (or other deformation), the final strain value can be calculated using  $L = L_f$ .

When the engineering stress–strain data in Figure 3.3 are plotted using the true stress and strain values, the resulting curve would appear as in Figure 3.4. In the elastic region, the plot is virtually the same as before. Strain values are small, and true strain is nearly equal to engineering strain for most metals of interest. The respective stress values are also very close to each other. The reason for these near equalities is that the cross-sectional area of the test specimen is not significantly reduced in the elastic region. Thus, Hooke’s law can be used to relate true stress to true strain:  $s = Ee$ .

The difference between the true stress–strain curve and its engineering counterpart occurs in the plastic region. The stress values are higher in the plastic region because the instantaneous cross-sectional area of the specimen, which has been continuously reduced during elongation, is now used in the computation. As in the



**FIGURE 3.4** True stress–strain curve for the previous engineering stress–strain plot in Figure 3.3.

previous curve, a downturn finally occurs as a result of necking. A dashed line is used in the figure to indicate the projected continuation of the true stress–strain plot if necking had not occurred.

As strain becomes significant in the plastic region, the values of true strain and engineering strain diverge. True strain can be related to the corresponding engineering strain by

$$e = \ln(1 + e) \quad (3.8)$$

Similarly, true stress and engineering stress can be related by the expression

$$s = S(1 + e) \quad (3.9)$$

In Figure 3.4, note that stress increases continuously in the plastic region until necking begins. When this happened in the engineering stress–strain curve, its significance was lost because an admittedly erroneous area value was used to calculate stress. Now when the true stress also increases, it cannot be dismissed so lightly. What it means is that the metal is becoming stronger as strain increases. This is the property called **strain hardening** that was mentioned in the previous chapter in the discussion of metallic crystal structures, and it is a property that most metals exhibit to a greater or lesser degree.

### Example 3.2 True stress and strain

For the data given in Example 3.1, determine (a) true stress and (b) true strain at the maximum load of 65,000 N.

**Solution:** (a) True stress is defined as the load divided by the instantaneous area. To find the instantaneous area, we assume uniform elongation prior to necking. Thus,  $AL = A_oL_o$ , and  $A = A_oL_o/L = 200(50)/57.7 = 173.3 \text{ mm}^2$ .

$$s = F/A = 65,000/173.3 = \mathbf{375 \text{ MPa}}$$

(b) By Equation (3.7), true strain  $e = \ln(L/L_o) = \ln(57.7/50) = \ln(1.154) = \mathbf{0.143}$ .

**Check:** Use Equations (3.8) and (3.9) to check these values:

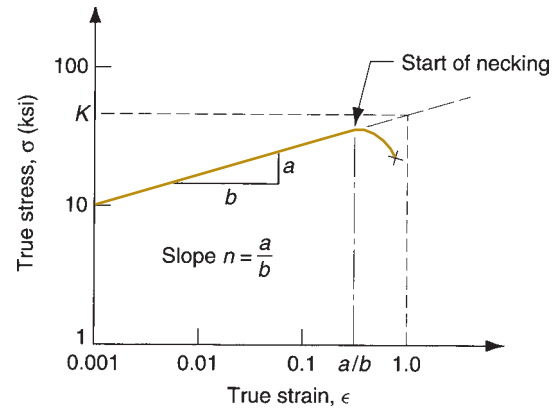
Using Equation (3.8) and the value of  $e$  obtained in Example 3.1,  $e = \ln(1 + 0.154) = 0.143$ .

Using Equation (3.9) and the value of  $TS$  obtained in Example 3.1,  $s = 325(1 + 0.154) = 375 \text{ MPa}$ .

**Comment:** Note that true stress is always greater than engineering stress, and true strain is always less than engineering strain.

Strain hardening, or **work hardening** as it is often called, is an important factor in certain manufacturing processes, particularly metal forming. Accordingly, it is worthwhile to examine the behavior of a metal as it is affected by this property. If the portion of the true stress–strain curve representing the plastic region were plotted on a log–log scale, the result would be a linear relationship, as shown in Figure 3.5.





**FIGURE 3.5** True stress–strain curve plotted on log–log scale.

Because it is a straight line in this transformation of the data, the relationship between true stress and true strain in the plastic region can be expressed as

$$s = Ke^n \quad (3.10)$$

This equation is called the **flow curve**, and it provides a good approximation of the behavior of metals in the plastic region, including their capacity for strain hardening. The constant  $K$  is called the **strength coefficient**, MPa (lb/in<sup>2</sup>), and it equals the value of true stress at a true strain value equal to one. The parameter  $n$  is called the **strain hardening exponent**, and it is the slope of the line in Figure 3.5. Its value is directly related to a metal's tendency to work harden. Typical values of  $K$  and  $n$  for selected metals are given in Table 3.4.

**TABLE • 3.4** Typical values of strength coefficient  $K$  and strain hardening exponent  $n$  for selected metals.

Material	Strength Coefficient, $K$		Strain Hardening Exponent, $n$	Material	Strength Coefficient, $K$		Strain Hardening Exponent, $n$
	MPa	lb/in <sup>2</sup>			MPa	lb/in <sup>2</sup>	
Aluminum, pure, annealed	175	25,000	0.20	Steel, low C, annealed <sup>a</sup>	500	75,000	0.25
Aluminum alloy, annealed <sup>a</sup>	240	35,000	0.15	Steel, high C, annealed <sup>a</sup>	850	125,000	0.15
Aluminum alloy, heat treated	400	60,000	0.10	Steel, alloy, annealed <sup>a</sup>	700	100,000	0.15
Copper, pure, annealed	300	45,000	0.50	Steel, stainless, austenitic, annealed	1200	175,000	0.40
Copper alloy: brass <sup>a</sup>	700	100,000	0.35				

Compiled from [9], [10], [11], and other sources.

<sup>a</sup>Values of  $K$  and  $n$  vary according to composition, heat treatment, and work hardening.

### Example 3.3 Flow curve parameters

For the data given in Example 3.1, determine the strength coefficient and strain hardening exponent in the flow curve equation:  $s = Ke^n$ .

**Solution:** We have two points on the flow curve from which the flow curve parameters can be determined: (1) at the yield point and (2) at the maximum load.

(1) At the yield point, engineering stress is very close to the value of true stress. Thus, from Example 3.1,  $s = Y = 160$  MPa. True strain is calculated using the gage length at yielding and adjusting for the 0.2% offset:  $e = \ln(50.2/50 - .002) = 0.001998$ . The corresponding flow curve equation is  $160 = K(0.001998)^n$ .

(2) At the maximum load, the values of true stress and true strain are available from the solution of Example 3.2:  $e = 0.143$  and  $s = 375$  MPa. The corresponding flow curve equation is  $375 = K(0.143)^n$ .

Solving for  $n$  and  $K$ ,

$$(1) K = 160/(0.001998)^n \text{ and } (2) K = 375/(0.143)^n$$

$$160/(0.001998)^n = 375/(0.143)^n$$

$$\ln(160) - n \ln(0.001998) = \ln(375) - n \ln(0.143)$$

$$5.0752 - (-6.2156)n = 5.9269 - (-1.9449)n$$

$$5.0752 + 6.2156n = 5.9269 + 1.9449n$$

$$(6.2156 - 1.9449)n = 5.9269 - 5.0752$$

$$4.2707n = 0.8517 \quad n = 0.1994$$

$$\text{Substituting back into (1): } K = 160/(0.001998)^{0.1994} = 552.7.$$

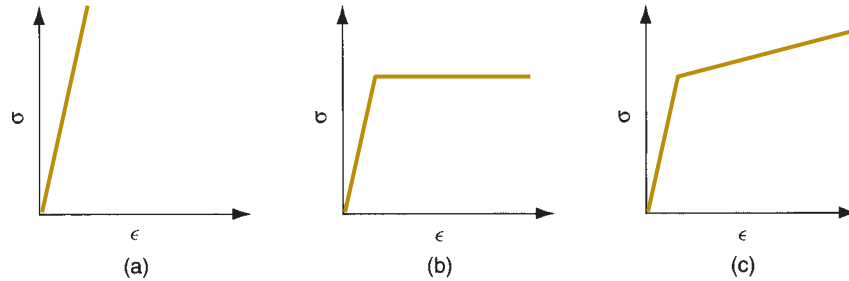
$$\text{Check: Using (2): } K = 375/(0.143)^{0.1994} = 552.7.$$

$$\text{The flow curve equation is } s = 552.7e^{0.1994}.$$

Necking in a tensile test and in metal forming operations that stretch the work part is closely related to strain hardening. As the test specimen is elongated during the initial part of the test (before necking begins), uniform straining occurs throughout the length because if any element in the specimen becomes strained more than the surrounding metal, its strength increases by work hardening, thus making it more resistant to additional strain until the surrounding metal has been strained an equal amount. Finally, the strain becomes so large that uniform straining cannot be sustained. A weak point in the length develops (from buildup of dislocations at grain boundaries, impurities in the metal, or other factors), and necking is initiated, leading to failure. Empirical evidence reveals that necking begins for a particular metal when the true strain reaches a value equal to the strain-hardening exponent  $n$ . Therefore, a higher  $n$  value means that the metal can be strained further before the onset of necking during tensile loading.

**Types of Stress–Strain Relationships** Much information about elastic–plastic behavior is provided by the true stress–strain curve. As indicated, Hooke’s law ( $s = Ee$ ) governs the metal’s behavior in the elastic region, and the flow curve

**FIGURE 3.6** Three categories of stress–strain relationship: (a) perfectly elastic, (b) elastic and perfectly plastic, and (c) elastic and strain hardening.



( $s = K\epsilon^n$ ) determines the behavior in the plastic region. Three basic forms of stress–strain relationship describe the behavior of nearly all types of solid materials, shown in Figure 3.6:

- (a) **Perfectly elastic.** The behavior of this material is defined completely by its stiffness, indicated by the modulus of elasticity  $E$ . It fractures rather than yielding to plastic flow. Brittle materials such as ceramics, many cast irons, and thermosetting polymers possess stress–strain curves that fall into this category. These materials are not good candidates for forming operations.
- (b) **Elastic and perfectly plastic.** This material has a stiffness defined by  $E$ . Once the yield strength  $Y$  is reached, the material deforms plastically at the same stress level. The flow curve is given by  $K = Y$  and  $n = 0$ . Metals behave in this fashion when they have been heated to sufficiently high temperatures that they recrystallize rather than strain harden during deformation. Lead exhibits this behavior at room temperature because room temperature is above the recrystallization point for lead.
- (c) **Elastic and strain hardening.** This material obeys Hooke’s law in the elastic region. It begins to flow at its yield strength  $Y$ . Continued deformation requires an ever-increasing stress, given by a flow curve whose strength coefficient  $K$  is greater than  $Y$  and whose strain-hardening exponent  $n$  is greater than zero. The flow curve is generally represented as a linear function on a natural logarithmic plot. Most ductile metals behave this way when cold worked.

Manufacturing processes that deform materials through the application of tensile stresses include wire and bar drawing (Section 18.6) and stretch forming (Section 19.6.1).

### 3.1.2 COMPRESSION PROPERTIES

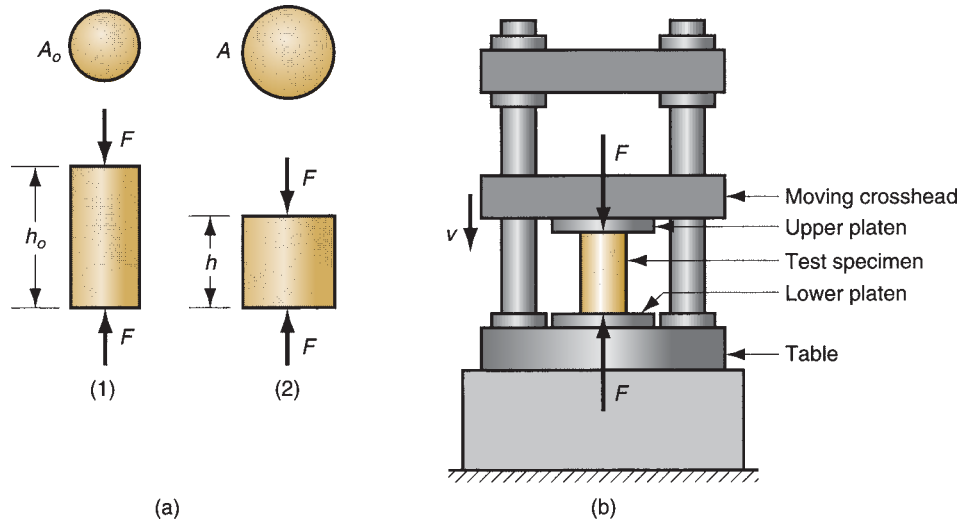
A compression test applies a load that squeezes a cylindrical specimen between two platens, as illustrated in Figure 3.7. As the specimen is compressed, its height is reduced and its cross-sectional area is increased. Engineering stress is defined as

$$s = \frac{F}{A_o} \quad (3.11)$$

where  $A_o$  = original area of the specimen. This is the same definition of engineering stress used in the tensile test. The engineering strain is defined as

$$e = \frac{h - h_o}{h_o} \quad (3.12)$$

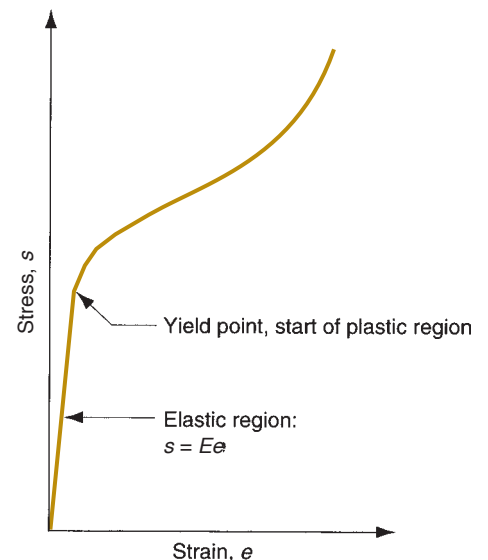
**FIGURE 3.7**  
Compression test:  
(a) compression force applied to test piece in (1), and (2) resulting change in height; and (b) setup for the test, with size of test specimen exaggerated.



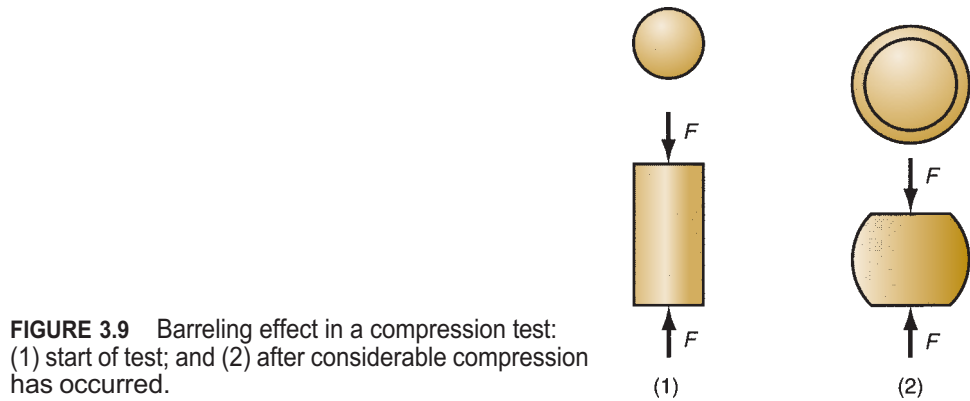
where  $h$  = height of the specimen at a particular moment into the test, mm (in); and  $h_o$  = starting height, mm (in). Because the height is decreased during compression, the value of  $e$  will be negative. The negative sign is usually ignored when expressing values of compression strain.

When engineering stress is plotted against engineering strain in a compression test, the results appear as in Figure 3.8. The curve is divided into elastic and plastic regions, as before, but the shape of the plastic portion of the curve is different from its tensile test complement. Because compression causes the cross section to increase (rather than decrease as in the tensile test), the load increases more rapidly than previously. This results in a higher value of calculated engineering stress.

Something else happens in the compression test that contributes to the increase in stress. As the cylindrical specimen is squeezed, friction at the surfaces in contact with the platens tends to prevent the ends of the cylinder from spreading. Additional



**FIGURE 3.8** Typical engineering stress–strain curve for a compression test.



**FIGURE 3.9** Barreling effect in a compression test: (1) start of test; and (2) after considerable compression has occurred.

energy is consumed by this friction during the test, and this results in a higher applied force. It also shows up as an increase in the computed engineering stress. Hence, owing to the increase in cross-sectional area and friction between the specimen and the platens, the characteristic engineering stress–strain curve in a compression test is obtained, as shown in the figure.

Another consequence of the friction between the surfaces is that the material near the middle of the specimen is permitted to increase in area much more than at the ends. This results in the characteristic **barreling** of the specimen, as seen in Figure 3.9.

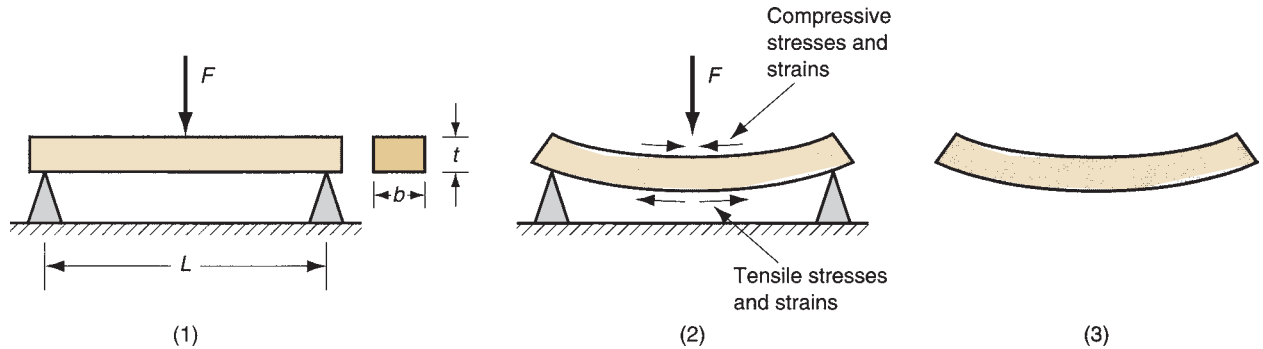
Although differences exist between the engineering stress–strain curves in tension and compression, when the respective data are plotted as true stress–strain, the relationships are nearly identical (for almost all materials). Because tensile test results are more abundant in the literature, values of the flow curve parameters ( $K$  and  $n$ ) can be derived from tensile test data and applied with equal validity to a compression operation. What must be done in using the tensile test results for a compression operation is to ignore the effect of necking, a phenomenon that is peculiar to straining induced by tensile stresses. In compression, there is no corresponding collapse of the work. In previous plots of tensile stress–strain curves, the data were extended beyond the point of necking by means of the dashed lines. The dashed lines better represent the behavior of the material in compression than the actual tensile test data.

Compression operations in metal forming are much more common than stretching operations. Important compression processes in industry include rolling, forging, and extrusion (Chapter 18).

### 3.1.3 BENDING AND TESTING OF BRITTLE MATERIALS

Bending operations are used to form metal plates and sheets. As shown in Figure 3.10, the process of bending a rectangular cross section subjects the material to tensile stresses (and strains) in the outer half of the bent section and compressive stresses (and strains) in the inner half. If the material does not fracture, it becomes permanently (plastically) bent as shown in (3) of Figure 3.10.

Hard, brittle materials (e.g., ceramics), which possess elasticity but little or no plasticity, are often tested by a method that subjects the specimen to a bending



**FIGURE 3.10** Bending of a rectangular cross section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part.

load. These materials do not respond well to traditional tensile testing because of problems in preparing the test specimens and possible misalignment of the press jaws that hold the specimen. The **bending test** (also known as the **flexure test**) is used to test the strength of these materials, using a setup illustrated in the first diagram in Figure 3.10. In this procedure, a specimen of rectangular cross section is positioned between two supports, and a load is applied at its center. In this configuration, the test is called a three-point bending test. A four-point configuration is also sometimes used. These brittle materials do not flex to the exaggerated extent shown in Figure 3.10; instead they deform elastically until immediately before fracture. Failure usually occurs because the ultimate tensile strength of the outer fibers of the specimen has been exceeded. This results in **cleavage**, a failure mode associated with ceramics and metals operating at low service temperatures, in which separation rather than slip occurs along certain crystallographic planes. The strength value derived from this test is called the **transverse rupture strength**, calculated from the formula

$$TRS = \frac{1.5FL}{bt^2} \quad (3.13)$$

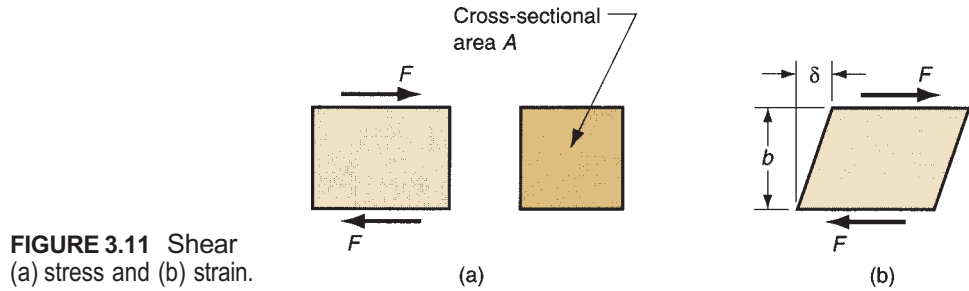
where  $TRS$  = transverse rupture strength, MPa (lb/in<sup>2</sup>);  $F$  = applied load at fracture, N (lb);  $L$  = length of the specimen between supports, mm (in); and  $b$  and  $t$  are the dimensions of the cross section of the specimen as shown in the figure, mm (in).

The flexure test is also used for certain nonbrittle materials such as thermoplastic polymers. In this case, because the material is likely to deform rather than fracture,  $TRS$  cannot be determined based on failure of the specimen. Instead, either of two measures is used: (1) the load recorded at a given level of deflection, or (2) the deflection observed at a given load.

### 3.1.4 SHEAR PROPERTIES

Shear involves application of stresses in opposite directions on either side of a thin element to deflect it as shown in Figure 3.11. The shear stress is defined as

$$\tau = \frac{F}{A} \quad (3.14)$$



**FIGURE 3.11** Shear  
(a) stress and (b) strain.

where  $t$  = shear stress, lb/in<sup>2</sup> (MPa);  $F$  = applied force, N (lb); and  $A$  = area over which the force is applied, in<sup>2</sup> (mm<sup>2</sup>). Shear strain can be defined as

$$g = \frac{d}{b} \quad (3.15)$$

where  $g$  = shear strain, mm/mm (in/in);  $d$  = the deflection of the element, mm (in); and  $b$  = the orthogonal distance over which deflection occurs, mm (in).

Shear stress and strain are commonly tested in a **torsion test**, in which a thin-walled tubular specimen is subjected to a torque as shown in Figure 3.12. As torque is increased, the tube deflects by twisting, which is a shear strain for this geometry.

The shear stress can be determined in the test by the equation

$$t = \frac{T}{2\pi R^2 t} \quad (3.16)$$

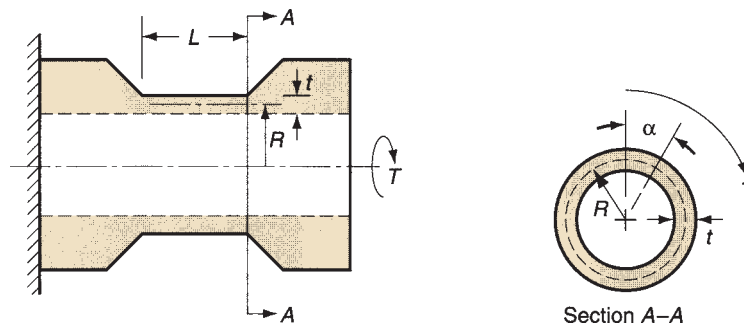
where  $T$  = applied torque, N-mm (lb-in);  $R$  = radius of the tube measured to the neutral axis of the wall, mm (in); and  $t$  = wall thickness, mm (in). The shear strain can be determined by measuring the amount of angular deflection of the tube, converting this into a distance deflected, and dividing by the gauge length  $L$ . Reducing this to a simple expression,

$$g = \frac{Ra}{L} \quad (3.17)$$

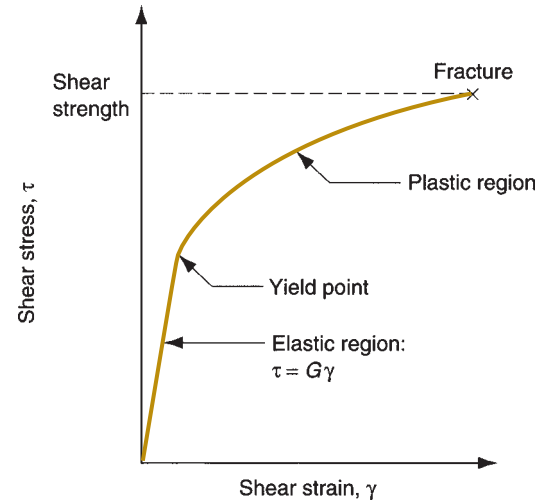
where  $a$  = the angular deflection (radians).

A typical shear stress–strain curve is shown in Figure 3.13. In the elastic region, the relationship is defined by

$$t = Gg \quad (3.18)$$



**FIGURE 3.12** Torsion  
test setup.



**FIGURE 3.13** Typical shear stress–strain curve from a torsion test.

where  $G$  = the **shear modulus**, or **shear modulus of elasticity**, MPa (lb/in<sup>2</sup>). For most materials, the shear modulus can be approximated by  $G = 0.4E$ , where  $E$  is the conventional elastic modulus.

In the plastic region of the shear stress–strain curve, the material strain hardens to cause the applied torque to continue to increase until fracture finally occurs. The relationship in this region is similar to the flow curve. The shear stress at fracture can be calculated and this is used as the **shear strength**  $S$  of the material. Shear strength can be estimated from tensile strength data by the approximation:  $S = 0.7(TS)$ .

Because the cross-sectional area of the test specimen in the torsion test does not change as it does in the tensile and compression tests, the engineering stress–strain curve for shear derived from the torsion test is virtually the same as the true stress–strain curve.

Shear processes are common in industry. Shearing action is used to cut sheet metal in blanking, punching, and other cutting operations (Section 19.1). In machining, the material is removed by the mechanism of shear deformation (Section 20.2).

## 3.2 Hardness

The hardness of a material is defined as its resistance to permanent indentation. Good hardness generally means that the material is resistant to scratching and wear. For many engineering applications, including most of the tooling used in manufacturing, scratch and wear resistance are important characteristics. As the reader shall see later in this section, there is a strong correlation between hardness and strength.

### 3.2.1 HARDNESS TESTS

Hardness tests are commonly used for assessing material properties because they are quick and convenient. However, a variety of testing methods are appropriate because of differences in hardness among different materials. The best-known hardness tests are Brinell and Rockwell.



**Brinell Hardness Test** The Brinell hardness test is widely used for testing metals and nonmetals of low- to medium hardness. It is named after the Swedish engineer who developed it around 1900. In the test, a hardened steel (or cemented carbide) ball of 10-mm diameter is pressed into the surface of a specimen using a load of 500, 1500, or 3000 kg. The load is then divided into the indentation area to obtain the Brinell Hardness Number (BHN). In equation form,

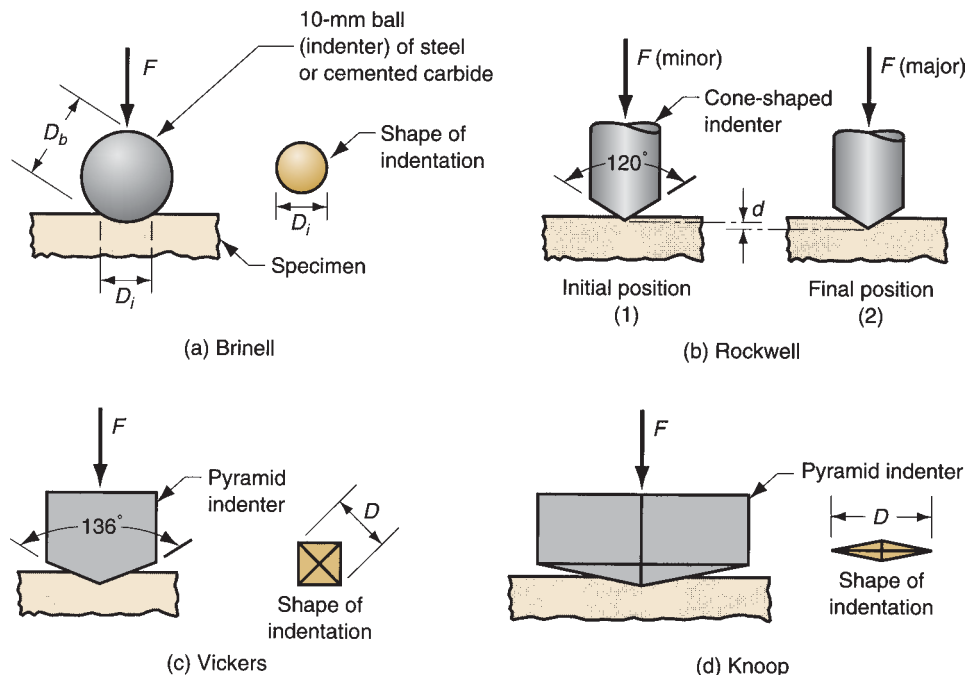
$$HB = \frac{2F}{\pi D_b (D_b - \sqrt{D_b^2 - D_i^2})} \quad (3.19)$$

where  $HB$  = Brinell Hardness Number (BHN);  $F$  = indentation load, kg;  $D_b$  = diameter of the ball, mm; and  $D_i$  = diameter of the indentation on the surface, mm.

These dimensions are indicated in Figure 3.14(a). The resulting BHN has units of  $\text{kg/mm}^2$ , but the units are usually omitted in expressing the number. For harder materials (above 500 BHN), the cemented carbide ball is used because the steel ball experiences elastic deformation that compromises the accuracy of the reading. Also, higher loads (1500 and 3000 kg) are typically used for harder materials. Because of differences in results under different loads, it is considered good practice to indicate the load used in the test when reporting  $HB$  readings.

**Rockwell Hardness Test** This is another widely used test, named after the metallurgist who developed it in the early 1920s. It is convenient to use, and several enhancements over the years have made the test adaptable to a variety of materials.

In the Rockwell Hardness Test, a cone-shaped indenter or small-diameter ball, with diameter = 1.6 or 3.2 mm (1/16 or 1/8 in) is pressed into the specimen using a minor load of 10 kg, thus seating the indenter in the material. Then, a major load of 150 kg (or other value) is applied, causing the indenter to penetrate into the



**FIGURE 3.14** Hardness testing methods: (a) Brinell; (b) Rockwell: (1) initial minor load and (2) major load, (c) Vickers, and (d) Knoop.

**TABLE • 3.5** Common Rockwell hardness scales.

Rockwell Scale	Hardness Symbol	Indenter	Load (kg)	Typical Materials Tested
A	HRA	Cone	60	Carbides, ceramics
B	HRB	1.6 mm ball	100	Nonferrous metals
C	HRC	Cone	150	Ferrous metals, tool steels

specimen a certain distance beyond its initial position. This additional penetration distance  $d$  is converted into a Rockwell hardness reading by the testing machine. The sequence is depicted in Figure 3.14(b). Differences in load and indenter geometry provide various Rockwell scales for different materials. The most common scales are indicated in Table 3.5.

**Vickers Hardness Test** This test, also developed in the early 1920s, uses a pyramid-shaped indenter made of diamond. It is based on the principle that impressions made by this indenter are geometrically similar regardless of load. Accordingly, loads of various size are applied, depending on the hardness of the material to be measured. The Vickers Hardness ( $HV$ ) is then determined from the formula

$$HV = \frac{1.854 F}{D^2} \quad (3.20)$$

where  $F$  = applied load, kg, and  $D$  = the diagonal of the impression made by the indenter, mm, as indicated in Figure 3.14(c). The Vickers test can be used for all metals and has one of the widest scales among hardness tests.

**Knoop Hardness Test** The Knoop test, developed in 1939, uses a pyramid-shaped diamond indenter, but the pyramid has a length-to-width ratio of about 7:1, as indicated in Figure 3.14(d), and the applied loads are generally lighter than in the Vickers test. It is a microhardness test, meaning that it is suitable for measuring small, thin specimens or hard materials that might fracture if a heavier load were applied. The indenter shape facilitates reading of the impression under the lighter loads used in this test. The Knoop hardness value ( $HK$ ) is determined according to the formula

$$HK = 14.2 \frac{F}{D^2} \quad (3.21)$$

where  $F$  = load, kg; and  $D$  = the long diagonal of the indenter, mm. Because the impression made in this test is generally very small, considerable care must be taken in preparing the surface to be measured.

**Scleroscope** The previous tests base their hardness measurements either on the ratio of applied load divided by the resulting impression area (Brinell, Vickers, and Knoop) or by the depth of the impression (Rockwell). The Scleroscope is an instrument that measures the rebound height of a “hammer” dropped from a certain distance above the surface of the material to be tested. The hammer consists of a weight with diamond indenter attached to it. The Scleroscope therefore measures the mechanical energy absorbed by the material when the indenter strikes the surface. The energy absorbed gives an indication of resistance to penetration, which is consistent with the definition of hardness. If more energy is absorbed, the rebound

will be less, meaning a softer material. If less energy is absorbed, the rebound will be higher—thus a harder material. The primary use of the Scleroscope seems to be in measuring the hardness of large parts of steel and other ferrous metals.

**Durometer** The previous tests are all based on resistance to permanent or plastic deformation (indentation). The durometer is a device that measures the elastic deformation of rubber and similar flexible materials by pressing an indenter into the surface of the object. The resistance to penetration is an indication of hardness, as the term is applied to these types of materials.

### 3.2.2 HARDNESS OF VARIOUS MATERIALS

This section compares the hardness values of some common materials in the three engineering material classes: metals, ceramics, and polymers.

**Metals** The Brinell and Rockwell hardness tests were developed at a time when metals were the principal engineering materials. A significant amount of data has been collected using these tests on metals. Table 3.6 lists hardness values for selected metals.

For most metals, hardness is closely related to strength. Because the method of testing for hardness is usually based on resistance to indentation, which is a form of compression, one would expect a good correlation between hardness and strength properties determined in a compression test. However, strength properties in a compression test are nearly the same as those from a tension test, after allowances for changes in cross-sectional area of the respective test specimens; so the correlation with tensile properties should also be good.

Brinell hardness ( $HB$ ) exhibits a close correlation with the ultimate tensile strength  $TS$  of steels, leading to the relationship [9], [15]:

$$TS = K_h(HB) \quad (3.22)$$

**TABLE • 3.6** Typical hardness of selected metals.

Metal	Brinell Hardness, HB	Rockwell Hardness, HR <sup>a</sup>	Metal	Brinell Hardness, HB	Rockwell Hardness, HR <sup>a</sup>
Aluminum, annealed	20		Magnesium alloys, hardened <sup>b</sup>	70	35B
Aluminum, cold worked	35		Nickel, annealed	75	40B
Aluminum alloys, annealed <sup>b</sup>	40		Steel, low C, hot rolled <sup>b</sup>	100	60B
Aluminum alloys, hardened <sup>b</sup>	90	52B	Steel, high C, hot rolled <sup>b</sup>	200	95B, 15C
Aluminum alloys, cast <sup>b</sup>	80	44B	Steel, alloy, annealed <sup>b</sup>	175	90B, 10C
Cast iron, gray, as cast <sup>b</sup>	175	10C	Steel, alloy, heat treated <sup>b</sup>	300	33C
Copper, annealed	45		Steel, stainless, austenitic <sup>b</sup>	150	85B
Copper alloy: brass, annealed	100	60B	Titanium, nearly pure	200	95B
Lead	4		Zinc	30	

Compiled from [10], [11], [16], and other sources.

<sup>a</sup>HR values are given in the B or C scale as indicated by the letter designation. Missing values indicate that the hardness is too low for Rockwell scales.

<sup>b</sup>HB values given are typical. Hardness values will vary according to composition, heat treatment, and degree of work hardening.

**TABLE • 3.7** Hardness of selected ceramics and other hard materials, arranged in ascending order of hardness.

Material	Vickers Hardness, HV	Knoop Hardness, HK	Material	Vickers Hardness, HV	Knoop Hardness, HK
Hardened tool steel <sup>a</sup>	800	850	Titanium nitride, TiN	3000	2300
Cemented carbide (WC - Co) <sup>a</sup>	2000	1400	Titanium carbide, TiC	3200	2500
Alumina, Al <sub>2</sub> O <sub>3</sub>	2200	1500	Cubic boron nitride, BN	6000	4000
Tungsten carbide, WC	2600	1900	Diamond, sintered polycrystal	7000	5000
Silicon carbide, SiC	2600	1900	Diamond, natural	10,000	8000

Compiled from [14], [16], and other sources.

<sup>a</sup>Hardened tool steel and cemented carbide are the two materials commonly used in the Brinell hardness test.

**TABLE • 3.8** Hardness of selected polymers.

Polymer	Brinell Hardness, HB	Polymer	Brinell Hardness, HB
Nylon	12	Polypropylene	7
Phenol formaldehyde	50	Polystyrene	20
Polyethylene, low density	2	Polyvinyl-chloride	10
Polyethylene, high density	4		

Compiled from [5], [8], and other sources.

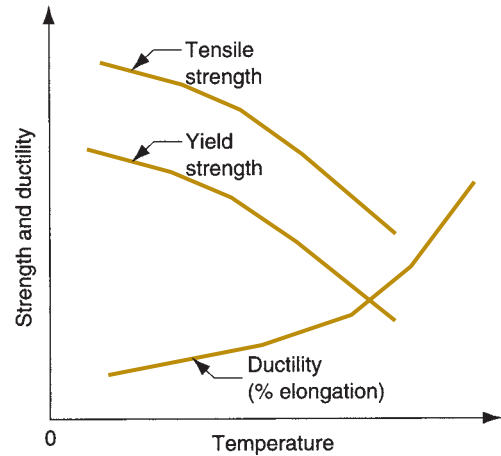
where  $K_h$  is a constant of proportionality. If  $TS$  is expressed in MPa, then  $K_h = 3.45$ ; and if  $TS$  is in lb/in<sup>2</sup>, then  $K_h = 500$ .

**Ceramics** The Brinell hardness test is not appropriate for ceramics because the materials being tested are often harder than the indenter ball. The Vickers and Knoop hardness tests are used to test these hard materials. Table 3.7 lists hardness values for several ceramics and hard materials. For comparison, the Rockwell C hardness for hardened tool steel is 65 HRC. The HRC scale does not extend high enough to be used for the harder materials.

**Polymers** Polymers have the lowest hardness among the three types of engineering materials. Table 3.8 lists several of the polymers on the Brinell hardness scale, although this testing method is not normally used for these materials. It does, however, allow comparison with the hardness of metals.

### 3.3 Effect of Temperature on Properties

Temperature has a significant effect on nearly all properties of a material. It is important for the designer to know the material properties at the operating temperatures of the product when in service. It is also important to know how temperature affects mechanical properties in manufacturing. At elevated temperatures, materials are lower in strength and higher in ductility. The general relationships for metals are depicted in Figure 3.15. Thus, most metals can be formed more easily at elevated temperatures than when they are cold.

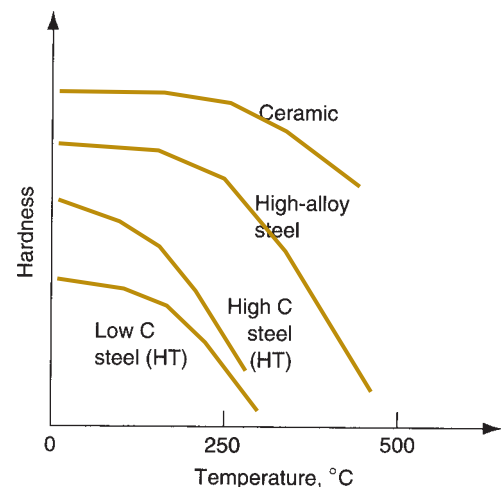


**FIGURE 3.15** General effect of temperature on strength and ductility.

**Hot Hardness** A property often used to characterize strength and hardness at elevated temperatures is hot hardness. *Hot hardness* is simply the ability of a material to retain hardness at elevated temperatures; it is usually presented as either a listing of hardness values at different temperatures or as a plot of hardness versus temperature, as in Figure 3.16. Steels can be alloyed to achieve significant improvements in hot hardness, as shown in the figure. Ceramics exhibit superior properties at elevated temperatures compared with other materials. They are often selected for high temperature applications, such as turbine parts, cutting tools, and refractory applications.

Good hot hardness is also desirable in the tooling materials used in many manufacturing operations. Significant amounts of heat energy are generated in most metalworking processes, and the tools must be capable of withstanding the high temperatures involved.

**Recrystallization Temperature** Most metals behave at room temperature according to the flow curve in the plastic region. As the metal is strained, it increases in strength because of strain hardening (the strain-hardening exponent  $n > 0$ ). However, if the metal is heated to a sufficiently elevated temperature and then deformed,



**FIGURE 3.16** Hot hardness—typical hardness as a function of temperature for several materials.

strain hardening does not occur. Instead, new grains are formed that are free of strain, and the metal behaves as a perfectly plastic material, that is, with a strain-hardening exponent  $n = 0$ . The formation of new strain-free grains is a process called **recrystallization**, and the temperature at which it occurs is about one-half the melting point ( $0.5 T_m$ ), as measured on an absolute scale (R or K). This is called the **recrystallization temperature**. Recrystallization takes time. The recrystallization temperature for a particular metal is usually specified as the temperature at which complete formation of new grains requires about 1 hour.

Recrystallization is a temperature-dependent characteristic of metals that can be exploited in manufacturing. By heating the metal to the recrystallization temperature before deformation, the amount of straining that the metal can endure is substantially increased, and the forces and power required to carry out the process are significantly reduced. Forming metals at temperatures above the recrystallization temperature is called **hot working** (Section 17.3).

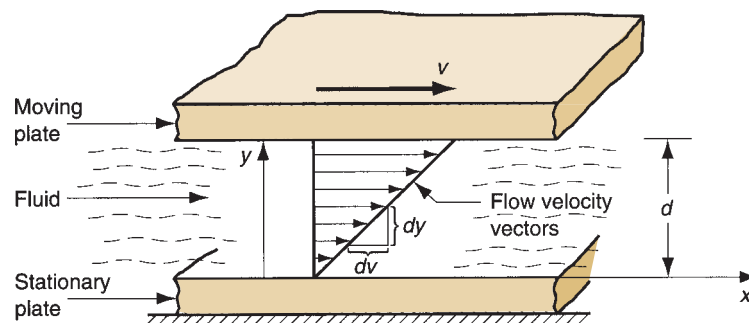
## 3.4 Fluid Properties

Fluids behave quite differently than solids. A fluid flows; it takes the shape of the container that holds it. A solid does not flow; it possesses a geometric form that is independent of its surroundings. Fluids include liquids and gases; the interest in this section is on the former. Many manufacturing processes are accomplished on materials that have been converted from solid to liquid state by heating. Metals are cast in the molten state; glass is formed in a heated and highly fluid state; and polymers are almost always shaped as thick fluids.

**Viscosity** Although flow is a defining characteristic of fluids, the tendency to flow varies for different fluids. Viscosity is the property that determines fluid flow. Roughly, **viscosity** can be defined as the resistance to flow that is characteristic of a fluid. It is a measure of the internal friction that arises when velocity gradients are present in the fluid—the more viscous the fluid is, the higher the internal friction and the greater the resistance to flow. The reciprocal of viscosity is **fluidity**—the ease with which a fluid flows.

Viscosity is defined more precisely with respect to the setup in Figure 3.17, in which two parallel plates are separated by a distance  $d$ . One of the plates is stationary while the other is moving at a velocity  $v$ , and the space between the plates is occupied by a fluid. Orienting these parameters relative to an axis system,  $d$  is in the  $y$ -axis direction and  $v$  is in the  $x$ -axis direction. The motion of the upper plate is

**FIGURE 3.17** Fluid flow between two parallel plates, one stationary and the other moving at velocity  $v$ .



resisted by force  $F$  that results from the shear viscous action of the fluid. This force can be reduced to a shear stress by dividing  $F$  by the plate area  $A$ :

$$\tau = \frac{F}{A} \quad (3.23)$$

where  $\tau$  = shear stress, N/m<sup>2</sup> or Pa (lb/in<sup>2</sup>). This shear stress is related to the rate of shear, which is defined as the change in velocity  $dv$  relative to  $dy$ . That is,

$$g' = \frac{dv}{dy} \quad (3.24)$$

where  $g'$  = shear rate, 1/s;  $dv$  = incremental change in velocity, m/s (in/sec); and  $dy$  = incremental change in distance  $y$ , m (in). The shear viscosity is the fluid property that defines the relationship between  $F/A$  and  $dv/dy$ ; that is,

$$\frac{F}{A} = h \frac{dv}{dy} \quad \text{or} \quad \tau = h g' \quad (3.25)$$

where  $h$  = a constant of proportionality called the coefficient of viscosity, Pa-s (lb-sec/in<sup>2</sup>). Rearranging Equation (3.25), the coefficient of viscosity can be expressed as follows:

$$h = \frac{\tau}{g'} \quad (3.26)$$

Thus, the viscosity of a fluid can be defined as the ratio of shear stress to shear rate during flow, where shear stress is the frictional force exerted by the fluid per unit area, and shear rate is the velocity gradient perpendicular to the flow direction. The viscous characteristics of fluids defined by Equation (3.26) were first stated by Newton. He observed that viscosity was a constant property of a given fluid, and such a fluid is referred to as a **Newtonian fluid**.

The units of coefficient of viscosity require explanation. In the International System of units (SI), because shear stress is expressed in N/m<sup>2</sup> or Pascals and shear rate in 1/s, it follows that  $h$  has units of N-s/m<sup>2</sup> or Pascal-seconds, abbreviated Pa-s. In the U.S. customary units, the corresponding units are lb/in<sup>2</sup> and 1/sec, so that the units for coefficient of viscosity are lb-sec/in<sup>2</sup>. Other units sometimes given for viscosity are poise, which = dyne-sec/cm<sup>2</sup> (10 poise = 1 Pa-s and 6895 Pa-s = 1 lb-sec/in<sup>2</sup>). Some typical values of coefficient of viscosity for various fluids are given in Table 3.9.

**TABLE • 3.9** Viscosity values for selected fluids.

Material	Coefficient of Viscosity		Material	Coefficient of Viscosity	
	Pa-s	lb-sec/in <sup>2</sup>		Pa-s	lb-sec/in <sup>2</sup>
Glass <sup>b</sup> , 540 C (1000 F)	10 <sup>12</sup>	10 <sup>8</sup>	Pancake syrup (room temp)	50	73 × 10 <sup>-4</sup>
Glass <sup>b</sup> , 815 C (1500 F)	10 <sup>5</sup>	14	Polymer <sup>a</sup> , 151 C (300 F)	115	167 × 10 <sup>-4</sup>
Glass <sup>b</sup> , 1095 C (2000 F)	10 <sup>3</sup>	0.14	Polymer <sup>a</sup> , 205 C (400 F)	55	80 × 10 <sup>-4</sup>
Glass <sup>b</sup> , 1370 C (2500 F)	15	22 × 10 <sup>-4</sup>	Polymer <sup>a</sup> , 260 C (500 F)	28	41 × 10 <sup>-4</sup>
Mercury, 20 C (70 F)	0.0016	0.23 × 10 <sup>-6</sup>	Water, 20 C (70 F)	0.001	0.15 × 10 <sup>-6</sup>
Machine oil (room temp.)	0.1	0.14 × 10 <sup>-4</sup>	Water, 100 C (212 F)	0.0003	0.04 × 10 <sup>-6</sup>

Compiled from various sources.

<sup>a</sup>Low-density polyethylene is used as the polymer example here; most other polymers have slightly higher viscosities.

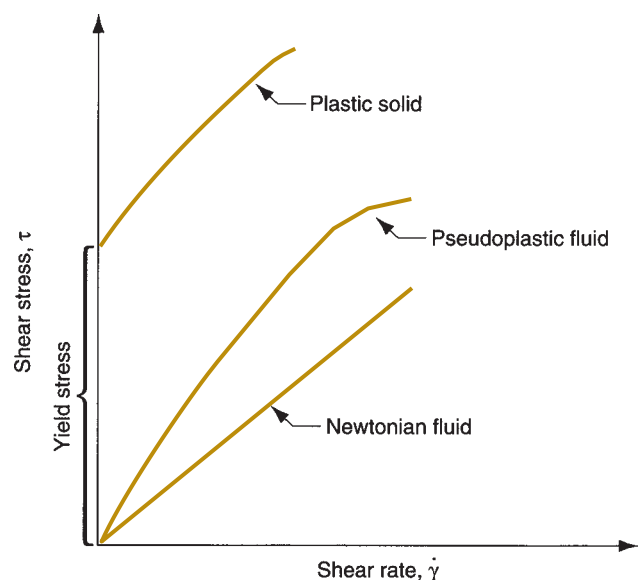
<sup>b</sup>Glass composition is mostly SiO<sub>2</sub>; compositions and viscosities vary; values given are representative.

One can observe in several of the materials listed that viscosity varies with temperature.

**Viscosity in Manufacturing Processes** For many metals, the viscosity in the molten state compares with that of water at room temperature. Certain manufacturing processes, notably casting and welding, are performed on metals in their molten state, and success in these operations requires low viscosity so that the molten metal fills the mold cavity or weld seam before solidifying. In other operations, such as metal forming and machining, lubricants and coolants are used in the process, and again the success of these fluids depends to some extent on their viscosities.

Glass ceramics exhibit a gradual transition from solid to liquid states as temperature is increased; they do not suddenly melt as pure metals do. The effect is illustrated by the viscosity values for glass at different temperatures in Table 3.9. At room temperature, glass is solid and brittle, exhibiting no tendency to flow; for all practical purposes, its viscosity is infinite. As glass is heated, it gradually softens, becoming less and less viscous (more and more fluid), until it can finally be formed by blowing or molding at around 1100°C (2000°F).

Most polymer-shaping processes are performed at elevated temperatures, at which the material is in a liquid or highly plastic condition. Thermoplastic polymers represent the most straightforward case, and they are also the most common polymers. At low temperatures, thermoplastic polymers are solid; as temperature is increased, they typically transform first into a soft rubbery material, and then into a thick fluid. As temperature continues to rise, viscosity decreases gradually, as in Table 3.9 for polyethylene, the most widely used thermoplastic polymer. However, with polymers the relationship is complicated by other factors. For example, viscosity is affected by flow rate. The viscosity of a thermoplastic polymer is not a constant. A polymer melt does not behave in a Newtonian fashion. Its relationship between shear stress and shear rate can be seen in Figure 3.18. A fluid that exhibits this decreasing viscosity with increasing shear rate is called *pseudoplastic*. This behavior complicates the analysis of polymer shaping.



**FIGURE 3.18** Viscous behaviors of Newtonian and pseudoplastic fluids. Polymer melts exhibit pseudoplastic behavior. For comparison, the behavior of a plastic solid material is shown.



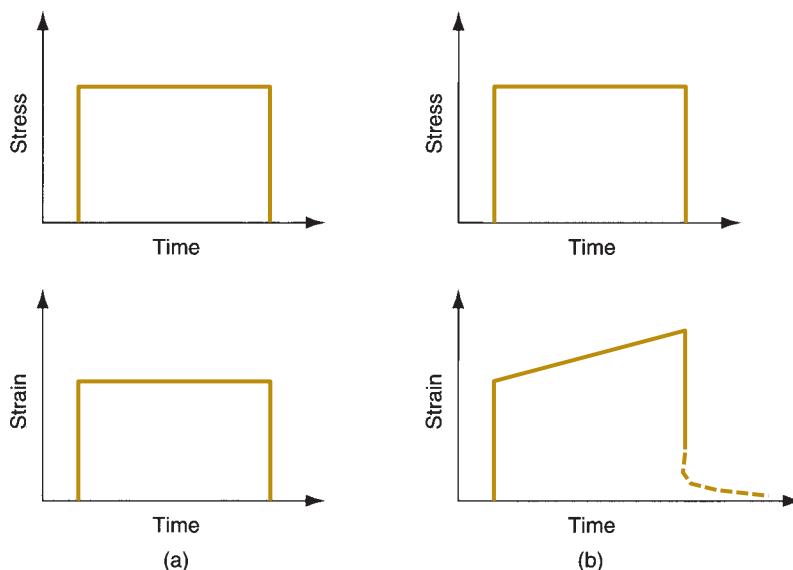
### 3.5 Viscoelastic Behavior of Polymers

Another property that is characteristic of polymers is viscoelasticity. **Viscoelasticity** is the property of a material that determines the strain it experiences when subjected to combinations of stress and temperature over time. As the name suggests, it is a combination of viscosity and elasticity. Viscoelasticity can be explained with reference to Figure 3.19. The two parts of the figure show the typical response of two materials to an applied stress below the yield point during some time period. The material in (a) exhibits perfect elasticity; when the stress is removed, the material returns to its original shape. By contrast, the material in (b) shows viscoelastic behavior. The amount of strain gradually increases over time under the applied stress. When stress is removed, the material does not immediately return to its original shape; instead, the strain decays gradually. If the stress had been applied and then immediately removed, the material would have returned immediately to its starting shape. However, time has entered the picture and played a role in affecting the behavior of the material.

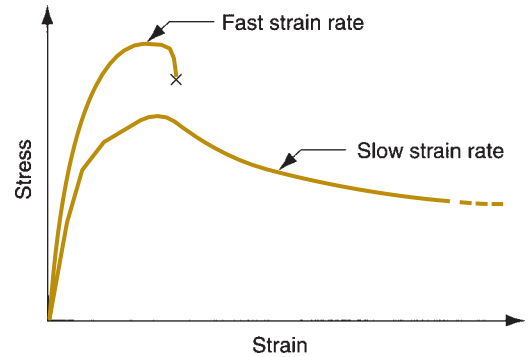
A simple model of viscoelasticity can be developed using the definition of elasticity as a starting point. Elasticity is concisely expressed by Hooke's law,  $s = Ee$ , which simply relates stress to strain through a constant of proportionality. In a viscoelastic solid, the relationship between stress and strain is time dependent; it can be expressed as

$$s(t) = f(t)e \quad (3.27)$$

The time function  $f(t)$  can be conceptualized as a modulus of elasticity that depends on time. It might be written  $E(t)$  and referred to as a viscoelastic modulus. The form of this time function can be complex, sometimes including strain as a factor. Without getting into the mathematical expressions for it, the effect of the time dependency can nevertheless be explored. One common effect can be seen in Figure 3.20, which shows the stress–strain behavior of a thermoplastic polymer under different strain



**FIGURE 3.19** Comparison of elastic and viscoelastic properties: (a) perfectly elastic response of material to stress applied over time; and (b) response of a viscoelastic material under same conditions. The material in (b) takes a strain that is a function of time and temperature.

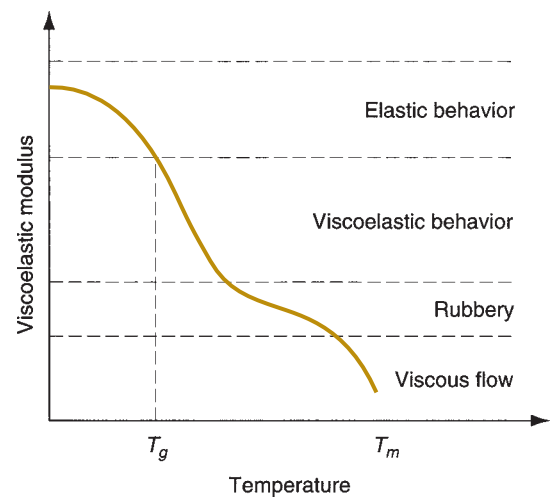


**FIGURE 3.20** Stress–strain curve of a viscoelastic material (thermoplastic polymer) at high and low strain rates.

rates. At low strain rate, the material exhibits significant viscous flow. At high strain rate, it behaves in a much more brittle fashion.

Temperature is a factor in viscoelasticity. As temperature increases, the viscous behavior becomes more and more prominent relative to elastic behavior. The material becomes more like a fluid. Figure 3.21 illustrates this temperature dependence for a thermoplastic polymer. At low temperatures, the polymer shows elastic behavior. As  $T$  increases above the glass transition temperature  $T_g$ , the polymer becomes viscoelastic. As temperature increases further, it becomes soft and rubbery. At still higher temperatures, it exhibits viscous characteristics. The temperatures at which these modes of behavior are observed vary, depending on the plastic. Also, the shapes of the modulus versus temperature curve differ according to the proportions of crystalline and amorphous structures in the thermoplastic. Thermosetting polymers and elastomers behave differently than shown in the figure; after curing, these polymers do not soften as thermoplastics do at elevated temperatures. Instead, they degrade (char) at high temperatures.

Viscoelastic behavior manifests itself in polymer melts in the form of shape memory. As the thick polymer melt is transformed during processing from one shape to another, it “remembers” its previous shape and attempts to return to that geometry. For example, a common problem in extrusion of polymers is die



**FIGURE 3.21** Viscoelastic modulus as a function of temperature for a thermoplastic polymer.

swell, in which the profile of the extruded material grows in size, reflecting its tendency to return to its larger cross section in the extruder barrel immediately before being squeezed through the smaller die opening. The properties of viscosity and viscoelasticity are examined in more detail in Chapter 13 on plastic-shaping processes.

- 6.2 For the preceding problem, use the inverse lever rule to determine the proportions of liquid and solid phases present in the alloy.
- 6.3 In the iron-iron carbide phase diagram of Figure 6.4, identify the phase or phases present at the following temperatures and nominal compositions: (a) 650°C (1200°F) and 2% Fe<sub>3</sub>C, (b) 760°C (1400°F) and 2% Fe<sub>3</sub>C, and (c) 1095°C (2000°F) and 1% Fe<sub>3</sub>C.

## Chapter Contents

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### 7.5 Some Important Elements Related to Ceramics

- 7.5.1 Carbon
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Metals are usually thought to be the most important class of engineering materials. However, it is of interest to note that ceramic materials are actually more abundant and widely used. Included in this category are clay products (e.g., bricks and pottery), glass, cement, and more modern ceramic materials such as tungsten carbide and cubic boron nitride. This is the class of materials discussed in this chapter. Several elements related to ceramics are also covered because they are sometimes used in similar applications. These elements are carbon, silicon, and boron.

The importance of ceramics as engineering materials derives from their abundance in nature and their mechanical and physical properties, which are quite different from those of metals. A **ceramic** material is an inorganic compound consisting of a metal (or semi-metal) and one or more nonmetals. The word **ceramic** traces from the Greek *keramos* meaning potter's clay or wares made from fired clay. Important examples of ceramic materials are **silica**, or silicon dioxide ( $\text{SiO}_2$ ), the main ingredient in most glass products; **alumina**, or aluminum oxide ( $\text{Al}_2\text{O}_3$ ), used in applications ranging from abrasives to artificial bones; and more complex compounds such as hydrous aluminum silicate ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ ), known as **kaolinite**, the principal ingredient in most clay products. The elements in these compounds are the most common in Earth's crust; see Table 7.1. The group includes many additional compounds, some of which occur naturally while others are manufactured.

The general properties that make ceramics useful in engineered products are high hardness, good electrical and thermal insulating characteristics, chemical stability, and high melting temperatures. Some ceramics are translucent—window glass being the clearest example. They are also brittle and possess virtually no ductility, which can cause problems in both processing and performance of ceramic products.

**TABLE • 7.1** Most common elements in the earth's crust, with approximate percentages.

Oxygen	Silicon	Aluminum	Iron	Calcium	Sodium	Potassium	Magnesium
50%	26%	7.6%	4.7%	3.5%	2.7%	2.6%	2.0%

Compiled from [6].

The commercial and technological importance of ceramics is best demonstrated by the variety of products and applications that are based on this class of material. The list includes:

- **Clay construction products**, such as bricks, clay pipe, and building tile
- **Refractory ceramics**, which are capable of high temperature applications such as furnace walls, crucibles, and molds
- **Cement used in concrete**, used for construction and roads (concrete is a composite material, but its components are ceramics)
- **Whiteware products**, including pottery, stoneware, fine china, porcelain, and other tableware, based on mixtures of clay and other minerals
- **Glass** used in bottles, glasses, lenses, window panes, and light bulbs
- **Glass fibers** for thermal insulating wool, reinforced plastics (fiberglass), and fiber optics communications lines
- **Abrasives**, such as aluminum oxide and silicon carbide
- **Cutting tool materials**, including tungsten carbide, aluminum oxide, and cubic boron nitride
- **Ceramic insulators**, which are used in applications such as electrical transmission components, spark plugs, and microelectronic chip substrates
- **Magnetic ceramics**, for example, in computer memories
- **Nuclear fuels** based on uranium oxide ( $\text{UO}_2$ )
- **Bioceramics**, which include materials used in artificial teeth and bones

For purposes of organization, ceramic materials are classified into three basic types: (1) **traditional ceramics**—silicates used for clay products such as pottery and bricks, common abrasives, and cement; (2) **new ceramics**—more recently developed ceramics based on nonsilicates such as oxides and carbides, and generally possessing mechanical or physical properties that are superior or unique compared to traditional ceramics; and (3) **glasses**—based primarily on silica and distinguished from the other ceramics by their noncrystalline structure. In addition to the three basic types, there are **glass ceramics**—glasses that have been transformed into a largely crystalline structure by heat treatment.

## 7. Structure and Properties of Ceramics

Ceramic compounds are characterized by covalent and ionic bonding. These bonds are stronger than metallic bonding in metals, which accounts for the high hardness and stiffness but low ductility of ceramic materials. Just as the presence of free electrons in the metallic bond explains why metals are good conductors of heat and

electricity, the presence of tightly held electrons in ceramic molecules explains why these materials are poor conductors. The strong bonding also provides these materials with high melting temperatures, although some ceramics decompose, rather than melt, at elevated temperatures.

Most ceramics take a crystalline structure. The structures are generally more complex than those of most metals. There are several reasons for this. First, ceramic molecules usually consist of atoms that are significantly different in size. Second, the ion charges are often different, as in many of the common ceramics such as  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ . Both of these factors tend to force a more complicated physical arrangement of the atoms in the molecule and in the resulting crystal structure. In addition, many ceramic materials consist of more than two elements, such as  $(\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4)_n$ , also leading to further complexity in the molecular structure. Crystalline ceramics can be single crystals or polycrystalline substances. In the more common second form, mechanical and physical properties are affected by grain size; higher strength and toughness are achieved in the finer-grained materials.

Some ceramic materials tend to assume an amorphous structure or *glassy* phase, rather than a crystalline form. The most familiar example is, of course, glass. Chemically, most glasses consist of fused silica. Variations in properties and colors are obtained by adding other glassy ceramic materials such as oxides of aluminum, boron, calcium, and magnesium. In addition to these pure glasses, many ceramics that have a crystal structure use the glassy phase as a binder for their crystalline phase.

### 7.1.1 MECHANICAL PROPERTIES

Basic mechanical properties of ceramics are presented in Chapter 3. Ceramic materials are rigid and brittle, exhibiting a stress-strain behavior best characterized as perfectly elastic (see Figure 3.6). As seen in Table 7.2, hardness and elastic modulus

**TABLE • 7.2** Selected mechanical and physical properties of ceramic materials.

Material	Hardness (Vickers)	Elastic modulus, $E$		Specific Gravity	Melting Temperature	
		GPa	(lb/in <sup>2</sup> )		°C	°F
Traditional ceramics						
Brick-fireclay	N.A.	95	$14 \times 10^6$	2.3	N.A.	N.A.
Cement, Portland	N.A.	50	$7 \times 10^6$	2.4	N.A.	N.A.
Silicon carbide ( $\text{SiC}$ )	2600 HV	460	$68 \times 10^6$	3.2	2700 <sup>a</sup>	4892 <sup>a</sup>
New Ceramics						
Alumina ( $\text{Al}_2\text{O}_3$ )	2200 HV	345	$50 \times 10^6$	3.8	2054	3729
Cubic boron nitride (cBN)	6000 HV	N.A.	N.A.	2.3	3000 <sup>a</sup>	5430 <sup>a</sup>
Titanium carbide ( $\text{TiC}$ )	3200 HV	300	$45 \times 10^6$	4.9	3250	5880
Tungsten carbide (WC)	2600 HV	700	$100 \times 10^6$	15.6	2870	5198
Glass						
Silica glass ( $\text{SiO}_2$ )	500 HV	69	$10 \times 10^6$	2.2	7 <sup>b</sup>	7 <sup>b</sup>

Compiled from [3], [4], [5], [6], [9], [10], and other sources. Key: N.A. = Not available or not applicable.

<sup>a</sup>The ceramic material chemically dissociates or, in the case of diamond and graphite, sublimates (vaporizes), rather than melts.

<sup>b</sup>Glass, being noncrystalline, does not melt at a specific melting point. Instead, it gradually exhibits fluid properties with increasing temperature. It becomes liquid at around 1400°C (2500°F).

for many of the new ceramics are greater than those of metals (see Tables 3.1, 3.6, and 3.7). Stiffness and hardness of traditional ceramics and glasses are significantly less than for new ceramics.

Theoretically, the strength of ceramics should be higher than that of metals because of their atomic bonding. The covalent and ionic bonding types are stronger than metallic bonding. However, metallic bonding has the advantage that it allows for slip, the basic mechanism by which metals deform plastically when subjected to high stresses. Bonding in ceramics is more rigid and does not permit slip under stress. The inability to slip makes it much more difficult for ceramics to absorb stresses. Yet ceramics contain the same imperfections in their crystal structure as metals—vacancies, interstitialcies, displaced atoms, and microscopic cracks. These internal flaws tend to concentrate the stresses, especially when a tensile, bending, or impact loading is involved. As a result of these factors, ceramics fail by brittle fracture under applied stress much more readily than metals. Their tensile strength and toughness are relatively low. Also, their performance is much less predictable due to the random nature of the imperfections and the influence of processing variations, especially in products made of traditional ceramics.

The frailties that limit the tensile strength of ceramic materials are not nearly so operative when compressive stresses are applied. Ceramics are substantially stronger in compression than in tension. For engineering and structural applications, designers have learned to use ceramic components so that they are loaded in compression rather than tension or bending.

Various methods have been developed to strengthen ceramics, nearly all of which have as their fundamental approach the minimization of surface and internal flaws and their effects. These methods include [7]: (1) making the starting materials more uniform; (2) decreasing grain size in polycrystalline ceramic products; (3) minimizing porosity; (4) introducing compressive surface stresses; for example, through application of glazes with low thermal expansions, so that the body of the product contracts after firing more than the glaze, thus putting the glaze in compression; (5) using fiber reinforcement; and (6) heat treatments, such as quenching alumina from temperatures in the slightly plastic region to strengthen it.

### 7.1.2 PHYSICAL PROPERTIES

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Several of the physical properties of ceramics are presented in Table 7.2. Most ceramic materials are lighter than metals and heavier than polymers (see Table 4.1). Melting temperatures are higher than for most metals, some ceramics preferring to decompose rather than melt.

Electrical and thermal conductivities of most ceramics are lower than for metals; but the range of values is greater, permitting some ceramics to be used as insulators while others are electrical conductors. Thermal expansion coefficients are somewhat less than for the metals, but the effects are more damaging in ceramics because of their brittleness. Ceramic materials with relatively high thermal expansions and low thermal conductivities are especially susceptible to failures of this type, which result from significant temperature gradients and associated volumetric changes in different regions of the same part. The terms *thermal shock* and *thermal cracking* are used in connection with such failures. Certain glasses (for example, those containing high proportions of  $\text{SiO}_2$ ) and glass ceramics are noted for their low thermal expansion and are particularly resistant to these thermal failures (*Pyrex* is a familiar example).



These materials are based on mineral silicates, silica, and mineral oxides. The primary products are fired clay (pottery, tableware, brick, and tile), cement, and natural abrasives such as alumina. These products, and the processes used to make them, date back thousands of years (Historical Note 7.1). Glass is also a silicate ceramic material and is often included within the traditional ceramics group [5], [6] Glass is covered in a later section because it is distinguished from the above crystalline materials by its amorphous or vitreous structure (the term *vitreous* means glassy, or possessing the characteristics of glass).

Making pottery has been an art since the earliest civilizations. Archeologists examine ancient pottery and made in China, where fine white stoneware was first similar artifacts to study the cultures of the ancient crafted as early as 1400 B.C.E. By the ninth century, world. Ceramic pottery does not corrode or disintegrate the Chinese were making articles of porcelain, which with age nearly as rapidly as artifacts made of wood, was fired at higher temperatures than earthenware or metal, or cloth. stoneware to partially vitrify the more complex mixture of raw materials and produce translucency in the final product. Dinnerware made of Chinese porcelain. Somehow, early tribes discovered that clay is transformed into a hard solid when placed near an open fire. Burnt clay articles have been found in the Middle East was highly valued in Europe; it was called "china." It that date back nearly 10,000 years. Earthenware pots contributed significantly to trade between China and similar products became an established commerce- Europe and influenced the development of European cial trade in Egypt by around 4000 B.C.E. culture.

**Silica** ( $\text{SiO}_2$ ) is another major raw material for the traditional ceramics. It is the principal component in glass, and an important ingredient in other ceramic products including whiteware, refractories, and abrasives. Silica is available naturally in various forms, the most important of which is **quartz**. The main source of quartz is **sandstone**. The abundance of sandstone and its relative ease of processing means

that silica is low in cost; it is also hard and chemically stable. These features account for its widespread use in ceramic products. It is generally mixed in various proportions with clay and other minerals to achieve the appropriate characteristics in the final product. Feldspar is one of the other minerals often used. **Feldspar** refers to any of several crystalline minerals that consist of aluminum silicate combined with either potassium, sodium, calcium, or barium. The potassium blend, for example, has the chemical composition  $\text{KAlSi}_3\text{O}_8$ . Mixtures of clay, silica, and feldspar are used to make stoneware, china, and other tableware.

Still another important raw material for traditional ceramics is **alumina**. Most alumina is processed from the mineral **bauxite**, which is an impure mixture of hydrous aluminum oxide and aluminum hydroxide plus similar compounds of iron or manganese. Bauxite is also the principal ore in the production of aluminum metal. A purer but less common form of  $\text{Al}_2\text{O}_3$  is the mineral **corundum**, which contains alumina in massive amounts. Slightly impure forms of corundum crystals are the colored gemstones sapphire and ruby. Alumina ceramic is used as an abrasive in grinding wheels and as a refractory brick in furnaces.

**Silicon carbide**, also used as an abrasive, does not occur as a mineral. Instead, it is produced by heating mixtures of sand (source of silicon) and coke (carbon) to a temperature of around  $2200^\circ\text{C}$  ( $3900^\circ\text{F}$ ), so that the resulting chemical reaction forms SiC and carbon monoxide.

### 7.2.2 TRADITIONAL CERAMIC PRODUCTS

The minerals discussed above are the ingredients for a variety of ceramic products. The coverage is organized by major categories of traditional ceramic products. A summary of these products, and the raw materials and ceramics out of which they are made, is presented in Table 7.3. The coverage is limited to materials commonly used in manufactured products, thus omitting certain commercially important ceramics such as cement.

**Pottery and Tableware** This category is one of the oldest, dating back thousands of years; yet it is still one of the most important. It includes tableware products that we all use: earthenware, stoneware, and china. The raw materials for these products are clay usually combined with other minerals such as silica and feldspar. The wetted mixture is shaped and then fired to produce the finished piece.

**Earthenware** is the least refined of the group; it includes pottery and similar articles made in ancient times. Earthenware is relatively porous and is often glazed. **Glazing** involves application of a surface coating, usually a mixture of oxides such

TABLE • 7.3 Summary of traditional ceramic products.

Product	Principal Chemistry	Minerals and Raw Materials
Pottery, tableware	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ , $\text{SiO}_2$ , $\text{KAlSi}_3\text{O}_8$	Clay + silica + feldspar
Porcelain	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ , $\text{SiO}_2$ , $\text{KAlSi}_3\text{O}_8$	Clay + silica + feldspar
Brick, tile	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ , $\text{SiO}_2$ plus fine stones	Clay + silica + other
Refractory	$\text{Al}_2\text{O}_3$ , $\text{SiO}_2$ Others: $\text{MgO}$ , $\text{CaO}$	Alumina and silica
Abrasive: silicon carbide	SiC	Silica + coke
Abrasive: aluminum oxide	$\text{Al}_2\text{O}_3$	Bauxite or alumina

as silica and alumina, to make the product less pervious to moisture and more attractive to the eye. **Stoneware** has lower porosity than earthenware, resulting from closer control of ingredients and higher firing temperatures. **China** is fired at even higher temperatures, which produces the translucence in the finished pieces that characterize their fine quality. The reason for this is that much of the ceramic material has been converted to the glassy (vitrified) phase, which is relatively transparent compared to the polycrystalline form. Modern **porcelain** is nearly the same as china and is produced by firing the components, mainly clay, silica, and feldspar, at still higher temperatures to achieve a very hard, dense, glassy material. Porcelain is used in a variety of products ranging from electrical insulation to bathtub coatings.

**Brick and Tile** Building brick, clay pipe, unglazed roof tile, and drain tile are made from various low-cost clays containing silica and gritty matter widely available in natural deposits. These products are shaped by pressing (molding) and firing at relatively low temperatures.

**Refractories** Refractory ceramics, often in the form of bricks, are critical in many industrial processes that require furnaces and crucibles to heat and/or melt materials. The useful properties of refractory materials are high temperature resistance, thermal insulation, and resistance to chemical reaction with the materials (usually molten metals) being heated. As mentioned, alumina is often used as a refractory ceramic, together with silica. Other refractory materials include magnesium oxide (MgO) and calcium oxide (CaO). The refractory lining often contains two layers, the outside layer being more porous because this increases the insulation properties.

**Abrasives** Traditional ceramics used for abrasive products, such as grinding wheels and sandpaper, are **alumina** and **silicon carbide**. Although SiC is the harder material (hardness of SiC is 2600 HV vs. 2200 HV for alumina), the majority of grinding wheels are based on  $\text{Al}_2\text{O}_3$  because it gives better results when grinding steel, the most widely used metal. The abrasive particles (grains of ceramic) are distributed throughout the wheel using a bonding material such as shellac, polymer resin, or rubber. The use of abrasives in industry involves material removal, and the technology of grinding wheels and other abrasive methods to remove material is presented in Chapter 24.

## 7.3 New Ceramics

The term new ceramics refers to ceramic materials that have been developed synthetically over the last several decades and to improvements in processing techniques that have provided greater control over the structures and properties of ceramic materials. In general, new ceramics are based on compounds other than variations of aluminum silicate (which form the bulk of the traditional ceramic materials). New ceramics are usually simpler chemically than traditional ceramics; for example, oxides, carbides, nitrides, and borides. The dividing line between traditional and new ceramics is sometimes fuzzy, because aluminum oxide and silicon carbide are included among the traditional ceramics. The distinction in these cases is based more on methods of processing than chemical composition.

The new ceramics are organized into chemical compound categories: oxides, carbides, and nitrides, discussed in the following sections. More complete coverage of new ceramics is presented in references [3], [5], and [8].

### 7.3.1 OXIDE CERAMICS

The most important oxide new ceramic is *alumina*. Although also discussed in the context of traditional ceramics, alumina is today produced synthetically from bauxite, using an electric furnace method. Through control of particle size and impurities, refinements in processing methods, and blending with small amounts of other ceramic ingredients, strength and toughness of alumina have been improved substantially compared to its natural counterpart. Alumina also has good hot hardness, low thermal conductivity, and good corrosion resistance. This is a combination of properties that promote a wide variety of applications, including [13]: abrasives (grinding wheel grit), bioceramics (artificial bones and teeth), electrical insulators, electronic components, alloying ingredients in glass, refractory brick, cutting tool inserts (Section 22.3.1), spark plug barrels, and engineering components. Figure 7.1 shows a collection of new ceramic parts, most of which are made of alumina.

### 7.3.2 CARBIDES

The carbide ceramics include silicon carbide (SiC), tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC), and chromium carbide (Cr<sub>3</sub>C<sub>2</sub>). Silicon carbide was discussed previously. A part made of SiC is also shown in Figure 7.1. Although it is a man-made ceramic, the methods for its production were developed a century ago, and therefore it is generally included in the traditional ceramics group. In addition to its use as an abrasive, other SiC applications include resistance heating elements and additives in steelmaking.



**FIGURE 7.1**  
A collection of ceramic components. The white parts are alumina and the black parts are silicon carbide and silicon nitride. (Photo courtesy of Insaco Inc.)

WC, TiC, and TaC are valued for their hardness and wear resistance in cutting tools and other applications requiring these properties. **Tungsten carbide** was the first to be developed (Historical Note 7.2) and is the most important and widely used material in the group. WC is typically produced by carburizing tungsten powders that have been reduced from tungsten ores such as **wolframite** ( $\text{FeMnWO}_4$ ) and scheelite ( $\text{CaWO}_4$ ). **Titanium carbide** is produced by carburizing the minerals **rutile** ( $\text{TiO}_2$ ) or **ilmenite** ( $\text{FeTiO}_3$ ). And **tantalum carbide** is made by carburizing either pure tantalum powders or tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ ) [11]. **Chromium carbide** is more suited to applications where chemical stability and oxidation resistance are important.  $\text{Cr}_3\text{C}_2$  is prepared by carburizing chromium oxide ( $\text{Cr}_2\text{O}_3$ ) as the starting compound. Carbon black is the usual source of carbon in all of these reactions.

### Historical Note 7.2 Tungsten carbide

The compound WC does not occur in nature. It was first fabricated in the late 1890s by the Frenchman Henri Moissan. However, the technological and commercial importance of the development was not recognized for two decades.

Tungsten became an important metal for incandescent lamp filaments in the early 1900s. Wire drawing was required to produce the filaments. The traditional tool steel draw dies of the period were unsatisfactory for drawing tungsten wire due to excessive wear. There was a need for a much harder material. The compound WC was known to possess such hardness. In 1914 Germany, H. Voigtlander and H. Lohmann developed a fabrication process for hard carbide draw dies by sintering parts pressed from powders of tungsten carbide tool grades with WC and TiC were developed for steel and/or molybdenum carbide. Lohmann is credited with the first commercial production of sintered carbides.

The breakthrough leading to the modern technology of cemented carbides is linked to the work of K. Schroter in Germany in the early and mid-1920s. He used WC powders mixed with about 10% of a metal from the iron group, finally settling on cobalt as the best binder, and sintering the mixture at a temperature close to the melting point of the metal. The hard material was first marketed in Germany as "Widia" in 1926. The Schroter patents were assigned to the General Electric Company under the trade name "Carboloy"—first produced in the United States around 1928.

Widia and Carboloy were used as cutting tools for machining cast iron and many nonferrous metals, but not in the cutting of steel. When steel was machined, the tools would wear rapidly by cratering. In the early 1930s, carbide cutting tool grades with WC and TiC were developed for steel and/or molybdenum carbide. Lohmann is credited with the introduction of Widia X, which had a composition 84% WC, 10% TiC, and 6% Co. And Carboloy Grade 831 was introduced in the United States in 1932; it contained 69% WC, 21% TiC, and 10% Co.

Except for SiC, each carbide discussed here must be combined with a metallic binder such as cobalt or nickel in order to fabricate a useful solid product. In effect, the carbide powders bonded in a metal framework creates what is known as a ***cemented carbide***—a composite material, specifically a ***cermet*** (reduced from ***ceramic*** and ***metal***). Cemented carbides and other cermets are discussed in Section 9.2. The carbides have little engineering value except as constituents in a composite system.

### 7.3.3 NITRIDES

The important nitride ceramics are silicon nitride ( $\text{Si}_3\text{N}_4$ ), boron nitride (BN), and titanium nitride (TiN). As a group, the nitride ceramics are hard and brittle, and they melt at high temperatures (but not generally as high as the carbides). They are usually electrically insulating, except for TiN.

**Silicon nitride** shows promise in high temperature structural applications.  $\text{Si}_3\text{N}_4$  oxidizes at about  $1200^\circ\text{C}$  ( $2200^\circ\text{F}$ ) and chemically decomposes at around  $1900^\circ\text{C}$

(3400°F). It has low thermal expansion, good resistance to thermal shock and creep, and resists corrosion by molten nonferrous metals. These properties have provided applications for this ceramic in gas turbines, rocket engines, and melting crucibles.

**Boron nitride** exists in several structures, similar to carbon. The important forms of BN are (1) hexagonal, similar to graphite; and (2) cubic, same as diamond; in fact, its hardness is comparable to that of diamond. This latter structure goes by the names **cubic boron nitride** and **borazon**, symbolized cBN, and is produced by heating hexagonal BN under very high pressures. Owing to its extreme hardness, the principal applications of cBN are in cutting tools (Section 22.2.5) and abrasive wheels (Section 24.1.1). Interestingly, it does not compete with diamond cutting tools and grinding wheels. Diamond is suited to nonsteel machining and grinding, while cBN is appropriate for steel.

**Titanium nitride** has properties similar to those of other nitrides in this group, except for its electrical conductivity; it is a conductor. TiN has high hardness, good wear resistance, and a low coefficient of friction with the ferrous metals. This combination of properties makes TiN an ideal material as a surface coating on cutting tools. The coating is only around 0.006 mm (0.0003 in) thick, so the amounts of material used in this application are low. The gold color of titanium nitride makes it suitable for decorative coatings. Finally, its non-toxic properties allow its use in medical applications as a coating material for implants.

A new ceramic material related to the nitride group, and also to the oxides, is the oxynitride ceramic called **sialon**. It consists of the elements silicon, aluminum, oxygen, and nitrogen; and its name derives from these ingredients: Si-Al-O-N. Its chemical composition is variable, a typical composition being  $\text{Si}_4\text{Al}_2\text{O}_2\text{N}_6$ . Properties of sialon are similar to those of silicon nitride, but it has better resistance to oxidation at high temperatures than  $\text{Si}_3\text{N}_4$ . Its principal application is for cutting tools, but its properties may make it suitable for other high temperature applications in the future.

## 7.4 Glass

The term glass is somewhat confusing because it describes a state of matter as well as a type of ceramic. As a state of matter, the term refers to an amorphous, or non-crystalline, structure of a solid material. The glassy state occurs in a material when insufficient time is allowed during cooling from the molten condition for the crystalline structure to form. It turns out that all three categories of engineering materials (metals, ceramics, and polymers) can assume the glassy state, although the circumstances for metals to do so are quite rare.

As a type of ceramic, **glass** is an inorganic, nonmetallic compound (or mixture of compounds) that cools to a rigid condition without crystallizing; it is a ceramic that is in the glassy state as a solid material. This is the material discussed in this section—a material that dates back 4500 years (Historical Note 7.3).

### Historical Note 7.3 History of glass

The oldest glass specimens, dating from around 2500 B.C.E., are glass beads and other simple shapes found in Mesopotamia and ancient Egypt. These were made

by painstakingly sculpturing glass solids, rather than by molding or shaping molten glass. It was a thousand years before the ancient cultures exploited the fluid



properties of hot glass, by pouring it in successive tube, and then blown into shape by an artisan either layers over a sand core until sufficient thickness and freely in air or into a mold cavity. Other simple tools rigidity had been attained in the product, a cup-shaped were utilized to add the stem and/or base to the object. vessel. This pouring technique was used until around The ancient Romans showed great skill in their 200 B.C.E., when a simple tool was developed that rev- use of various metallic oxides to color glass. Their olutionized glassworking—the blowpipe.

**Glassblowing** was probably first accomplished in cathedrals and churches of the Middle Ages in Italy Babylon and later by the Romans. It was performed and the rest of Europe. The art of glassblowing is using an iron tube several feet long, with a mouthpiece still practiced today for certain consumer glassware; on one end and a fixture for holding the molten glass and automated versions of glassblowing are used for on the other. A blob of hot glass in the required initial mass-produced glass products such as bottles and shape and viscosity was attached to the end of the iron light bulbs (Chapter 12).

### 7.4.1 CHEMISTRY AND PROPERTIES OF GLASS

The principal ingredient in virtually all glasses is **silica** ( $\text{SiO}_2$ ), most commonly found as the mineral quartz in sandstone and silica sand. Quartz occurs naturally as a crystalline substance; but when melted and then cooled, it forms vitreous silica. Silica glass has a very low thermal expansion coefficient and is therefore quite resistant to thermal shock. These properties are ideal for elevated temperature applications; accordingly, Pyrex and chemical glassware designed for heating are made with high proportions of silica glass.

In order to reduce the melting point of glass for easier processing, and to control properties, the composition of most commercial glasses includes other oxides as well as silica. Silica remains as the main component in these glass products, usually comprising 50% to 75% of total chemistry. The reason  $\text{SiO}_2$  is used so widely in these compositions is because it is the best **glass former**. It naturally transforms into a glassy state upon cooling from the liquid, whereas most ceramics crystallize upon solidification. Table 7.4 lists typical chemistries for some common glasses. The additional ingredients are contained in a solid solution with  $\text{SiO}_2$ , and each has a function: (1) acting as flux (promoting fusion) during heating; (2) increasing fluidity in the molten glass for processing; (3) retarding **devitrification**—the tendency to crystallize from the glassy state; (4) reducing thermal expansion in the final product; (5) improving the chemical resistance against attack by acids, basic substances, or water; (6) adding color to the glass; and (7) altering the index of refraction for optical applications (e.g., lenses).

### 7.4.2 GLASS PRODUCTS

Following is a list of the major categories of glass products. The roles played by the different ingredients are examined in Table 7.4 as these products are discussed.

**Window Glass** This glass is represented by two chemistries in Table 7.4: (1) soda-lime glass and (2) window glass. The soda-lime formula dates back to the glass-blowing industry of the 1800s and earlier. It was (and is) made by mixing soda ( $\text{Na}_2\text{O}$ ) and lime ( $\text{CaO}$ ) with silica ( $\text{SiO}_2$ ) as the major ingredient. The blending of ingredients has evolved empirically to achieve a balance between avoiding crystallization during

**TABLE • 7.4** Typical compositions of selected glass products.

Product	Chemical Composition (by weight to nearest %)								
	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	Al <sub>2</sub> O <sub>3</sub>	MgO	K <sub>2</sub> O	PbO	B <sub>2</sub> O <sub>3</sub>	Other
Soda-lime glass	71	14	13	2					
Window glass	72	15	8	1	4				
Container glass	72	13	10	2 <sup>a</sup>	2	1			
Light bulb glass	73	17	5	1	4				
Laboratory glass:									
Vycor	96			1				3	
Pyrex	81	4		2				13	
E-glass (fibers)	54	1	17	15	4			9	
S-glass (fibers)	64			26	10				
Optical glasses:									
Crown glass	67	8				12		12	ZnO
Flint glass	46	3				6	45		

Compiled from [4], [5] and [10], and other sources.

<sup>a</sup>May include Fe<sub>2</sub>O<sub>3</sub> with Al<sub>2</sub>O<sub>3</sub>

cooling and achieving chemical durability of the final product. Modern window glass and the techniques for making it have required slight adjustments in composition and closer control over its variation. Magnesia (MgO) has been added to help reduce devitrification.

**Containers** In previous times, the same basic soda-lime composition was used for manual glass-blowing to make bottles and other containers. Modern processes for shaping glass containers cool the glass more rapidly than older methods. Also, the importance of chemical stability in container glass is better understood today. Resulting changes in composition have attempted to optimize the proportions of lime (CaO) and soda (Na<sub>2</sub>O<sub>3</sub>). Lime promotes fluidity. It also increases devitrification, but since cooling is more rapid, this effect is not as important as in prior processing techniques with slower cooling rates. Soda reduces chemical instability and solubility of the container glass.

**Light Bulb Glass** Glass used in light bulbs and other thin glass items (e.g., drinking glasses, Christmas ornaments) is high in soda and low in lime; it also contains small amounts of magnesia and alumina. The chemistry is dictated largely by the economics of large volumes involved in light bulb manufacture. The raw materials are inexpensive and suited to the continuous melting furnaces used today.

**Laboratory Glassware** These products include containers for chemicals (e.g., flasks, beakers, glass tubing). The glass must be resistant to chemical attack and thermal shock. Glass that is high in silica is suitable because of its low thermal expansion. The trade name “Vycor” is used for this high-silica glass. This product is very insoluble in water and acids. Additions of boric oxide also produce a glass with low coefficient of thermal expansion, so some glass for laboratory ware contains B<sub>2</sub>O<sub>3</sub> in amounts of around 13%. The trade name “Pyrex” is used for the borosilicate glass



developed by the Corning Glass Works. Both Vicor and Pyrex are included in the listing as examples of this product category.

**Glass Fibers** Glass fibers are manufactured for a number of important applications, including fiberglass reinforced plastics, insulation wool, and fiber optics. The compositions vary according to function. The most commonly used glass reinforcing fibers in plastics are E-glass. It is high in CaO and  $\text{Al}_2\text{O}_3$  content, it is economical, and it possesses good tensile strength in fiber form. Another glass fiber material is S-glass, which has higher strength but is not as economical as E-glass. Compositions are indicated in the table.

Insulating fiberglass wool can be manufactured from regular soda-lime-silica glasses. The glass product for fiber optics consists of a long, continuous core of glass with high refractive index surrounded by a sheath of lower refractive glass. The inside glass must have a very high transmittance for light in order to accomplish long distance communication.

**Optical Glasses** Applications for these glasses include lenses for eyeglasses and optical instruments such as cameras, microscopes, and telescopes. To achieve their function, the glasses must have different refractive indices, but each lens must be homogenous in composition. Optical glasses are generally divided into: crowns and flints. **Crown glass** has a low index of refraction, while **flint glass** contains lead oxide ( $\text{PbO}$ ) that gives it a high index of refraction.

### 7.4.3 GLASS-CERAMICS

Glass-ceramics are a class of ceramic material produced by conversion of glass into a polycrystalline structure through heat treatment. The proportion of crystalline phase in the final product typically ranges between 90% and 98%, with the remainder being unconverted vitreous material. Grain size is usually between 0.1 and 1.0  $\mu\text{m}$  (4 and 40  $m$ -in), significantly smaller than the grain size of conventional ceramics. This fine crystal microstructure makes glass-ceramics much stronger than the glasses from which they are derived. Also, due to their crystal structure, glass-ceramics are opaque (usually gray or white) rather than clear.

The processing sequence for glass-ceramics is as follows: (1) The first step involves heating and forming operations used in glassworking (Section 12.2) to create the desired product geometry. Glass shaping methods are generally more economical than pressing and sintering to shape traditional and new ceramics made from powders. (2) The product is cooled. (3) The glass is reheated to a temperature sufficient to cause a dense network of crystal nuclei to form throughout the material. It is the high density of nucleation sites that inhibits grain growth of individual crystals, thus leading ultimately to the fine grain size in the glass-ceramic material. The key to the propensity for nucleation is the presence of small amounts of nucleating agents in the glass composition. Common nucleating agents are  $\text{TiO}_2$ ,  $\text{P}_2\text{O}_5$ , and  $\text{ZrO}_2$ . (4) Once nucleation is initiated, the heat treatment is continued at a higher temperature to cause growth of the crystalline phases.

Several examples of glass-ceramic systems and typical compositions are listed in Table 7.5. The  $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$  system is the most important commercially; it includes Corning Ware (Pyroceram), the familiar product of the Corning Glass Works.

**TABLE • 7.5** Several glass-ceramic systems.

Glass-Ceramic System	Typical Composition (to nearest %)						
	Li <sub>2</sub> O	MgO	Na <sub>2</sub> O	BaO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	TiO <sub>2</sub>
Li <sub>2</sub> O-Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub>	3				18	70	5
MgO-Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub>		13			30	47	10
Na <sub>2</sub> O-BaO-Al <sub>2</sub> O <sub>3</sub> -SiO <sub>2</sub>			13	9	29	41	7

Compiled from [5], [6], and [10].

The significant advantages of glass-ceramics include (1) efficiency of processing in the glassy state, (2) close dimensional control over the final product shape, and (3) good mechanical and physical properties. Properties include high strength (stronger than glass), absence of porosity, low coefficient of thermal expansion, and high resistance to thermal shock. These properties have resulted in applications in cooking ware, heat exchangers, and missile radomes. Certain systems (e.g., MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> system) are also characterized by high electrical resistance, suitable for electrical and electronics applications.

## 7.5

### Some Important Elements Related to Ceramics

In this section, several elements of engineering importance are discussed: carbon, silicon, and boron. These materials are encountered occasionally in subsequent chapters. Although they are not ceramic materials according to the definition, they sometimes compete for applications with ceramics. And they have important applications of their own. Basic data on these elements are presented in Table 7.6.

#### 7.5.1 CARBON

Carbon occurs in two alternative forms of engineering and commercial importance: graphite and diamond. They compete with ceramics in various applications: graphite in situations where its refractory properties are important, and diamond

**TABLE • 7.6** Some basic data and properties of carbon, silicon, and boron.

	Carbon	Silicon	Boron
Symbol	C	Si	B
Atomic number	6	14	5
Specific gravity	2.25	2.42	2.34
Melting temperature	3727°C <sup>a</sup> (6740°F)	1410°C (2570°F)	2030°C (3686°F)
Elastic modulus, GPa (lb/in <sup>2</sup> )	240 <sup>b</sup> (35 X 10 <sup>6</sup> ) <sup>c</sup> 10357 <sup>c</sup> (150 X 10 <sup>6</sup> ) <sup>c</sup>	N.A.	393 (57 X 10 <sup>6</sup> )
Hardness (Mohs scale)	1 <sup>b</sup> , 10 <sup>c</sup>	7	9.3

<sup>a</sup>Carbon sublimates (vaporizes) rather than melts.

<sup>b</sup>Carbon in the form of graphite (typical value given).

<sup>c</sup>Carbon in the form of diamond.

N.A. = not available.

in industrial applications where hardness is the critical factor (such as cutting and grinding tools).

**Graphite** Graphite has a high content of crystalline carbon in the form of layers. Bonding between atoms in the layers is covalent and therefore strong, but the parallel layers are bonded to each other by weak van der Waals forces. This structure makes graphite quite anisotropic; strength and other properties vary significantly with direction. It explains why graphite can be used both as a lubricant and as a fiber in advanced composite materials. In powder form, graphite possesses low frictional characteristics due to the ease with which it shears between the layers; in this form, graphite is valued as a lubricant. In fiber form, graphite is oriented in the hexagonal planar direction to produce a filament material of very high strength and elastic modulus. These graphite fibers are used in structural composites ranging from tennis rackets to fighter aircraft components.

Graphite exhibits certain high temperature properties that are both useful and unusual. It is resistant to thermal shock, and its strength actually increases with temperature. Tensile strength at room temperature is about 100 MPa (15,000 lb/in<sup>2</sup>), but increases to about twice this value at 2500°C (4500°F) [5]. Theoretical density of carbon is 2.22 gm/cm<sup>3</sup>, but apparent density of bulk graphite is lower due to porosity (around 1.7 gm/cm<sup>3</sup>). This is increased through compacting and heating. It is electrically conductive, but its conductivity is not as high as most metals. A disadvantage of graphite is that it oxidizes in air above around 500°C (900°F). In a reducing atmosphere it can be used up to around 3000°C (5400°F), not far below its sublimation point of 3727°C (6740°F).

The traditional form of graphite is polycrystalline with a certain amount of amorphous carbon in the mixture. Graphite crystals are often oriented (to a limited degree) in the commercial production process to enhance properties in a preferred direction for the application. Also, strength is improved by reducing grain size (similar to ceramics). Graphite in this form is used for crucibles and other refractory applications, electrodes, resistance heating elements, antifriction materials, and fibers in composite materials. Thus, graphite is a very versatile material. As a powder it is a lubricant. In traditional solid form it is a refractory. And when formed into graphite fibers, it is a high-strength structural material.

**Diamond** Diamond is carbon that possesses a cubic crystalline structure with covalent bonding between atoms, as shown in Figure 2.5(b). This structure is three-dimensional, rather than layered as in graphite carbon, and this accounts for the very high hardness of diamond. Single crystal natural diamonds (mined in South Africa) have a hardness of 10,000 HV, while the hardness of an industrial diamond (polycrystalline) is around 7000 HV. The high hardness accounts for most of the applications of industrial diamond. It is used in cutting tools and grinding wheels for machining hard, brittle materials, or materials that are very abrasive. For example, diamond tools and wheels are used to cut ceramics, fiberglass, and hardened metals other than steels. Diamond is also used in dressing tools to sharpen grinding wheels that consist of other abrasives such as alumina and silicon carbide. Similar to graphite, diamond has a propensity to oxidize (decompose) in air at temperatures above about 650°C (1200°F).

Industrial or synthetic diamonds date back to the 1950s and are fabricated by heating graphite to around 3000°C (5400°F) under very high pressures (Figure 7.2). This process approximates the geological conditions by which natural diamonds were formed millions of years ago.

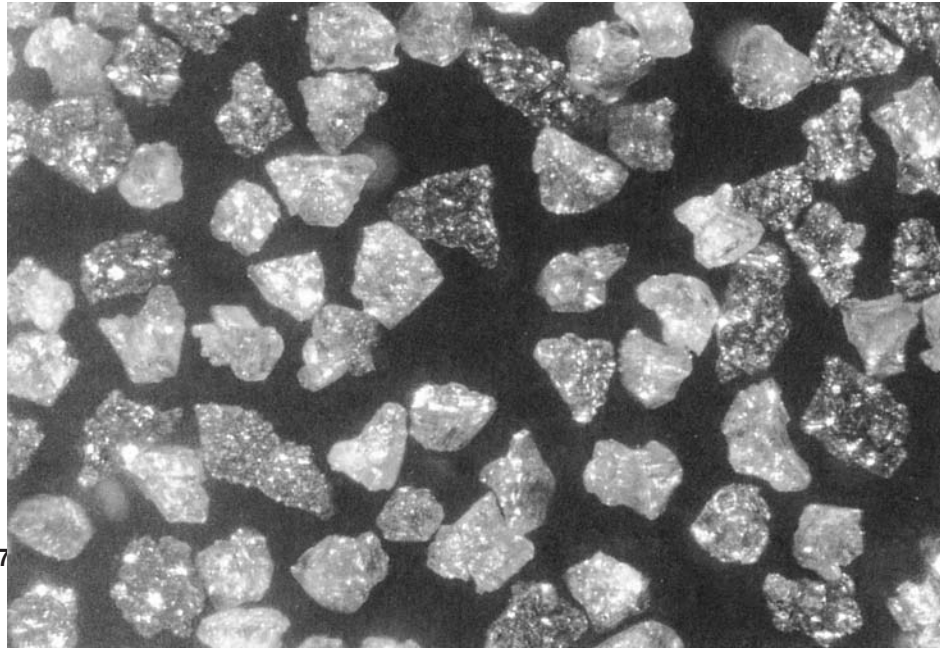


FIGURE 7

Synthetically produced diamond powders: (Photoc

### 7.5.2 SILICON

Silicon is a semimetallic element in the same group in the periodic table as carbon (Figure 2.1). Silicon is one of the most abundant elements in the Earth's crust, comprising about 26% by weight (Table 7.1). It occurs naturally only as a chemical compound—in rocks, sand, clay, and soil—either as silicon dioxide or as more complex silicate compounds. As an element it has the same crystalline structure as diamond, but its hardness is lower. It is hard but brittle, lightweight, chemically inactive at room temperature, and is classified as a semiconductor.

The greatest amounts of silicon in manufacturing are in ceramic compounds ( $\text{SiO}_2$  in glass and silicates in clays) and alloying elements in steel, aluminum, and copper alloys. It is also used as a reducing agent in certain metallurgical processes. Of significant technological importance is pure silicon as the base material in semiconductor manufacturing in electronics. The vast majority of integrated circuits produced today are made from silicon (Chapter 33).

### 7.5.3 BORON

Boron is a semimetallic element in the same periodic group as aluminum. It is only about 0.001% of the Earth's crust by weight, commonly occurring as the minerals **borax** ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ) and **kernite** ( $\text{Na}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$ ). Boron is lightweight and very stiff (high modulus of elasticity) in fiber form. In terms of electrical properties, it is classified as a semiconductor (its conductivity varies with temperature; it is an insulator at low temperatures but a conductor at high temperatures).

As a material of industrial significance, boron is usually found in compound form. As such, it is used as a solution in nickel electroplating operations, an ingredient ( $\text{B}_2\text{O}_3$ ) in certain glass compositions, a catalyst in organic chemical reactions, and as a nitride (cubic boron nitride) for cutting tools. In nearly pure form it is used as a fiber in composite materials (Sections 9.4.1 and 14.1).