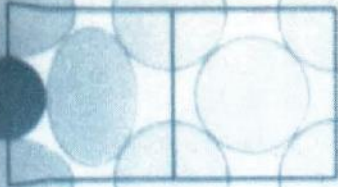*Sixth Edition*

STRUCTURE   ←→   PROPERTIES   ←→   PERFORMANCE

ELEMENTS OF MATERIALS SCIENCE AND ENGINEERING

Lawrence H. Van Vlack

UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

1

This book is in the
Addison-Wesley Series in Metallurgy and Materials Engineering

Consulting Editors
Morris Cohen
Merton C. Flemings

Sponsoring Editor: Don Fowley
Production Supervisor: Bette J. Aaronson
Copy Editor: Lyn Dupré
Text Designer: Deborah Schneck
Technical Art Consultant: Joseph Vetere
Illustrators: Dick Morton and C & C Associates, Inc.
Cover Designer: Marshall Henrichs
Production Coordinators: Helen Wythe and Sheila Bendikian
Manufacturing Supervisor: Hugh Crawford

To Today's Students, who will be Tomorrow's Engineers

Elements of Materials Science and Engineering

SIXTH EDITION
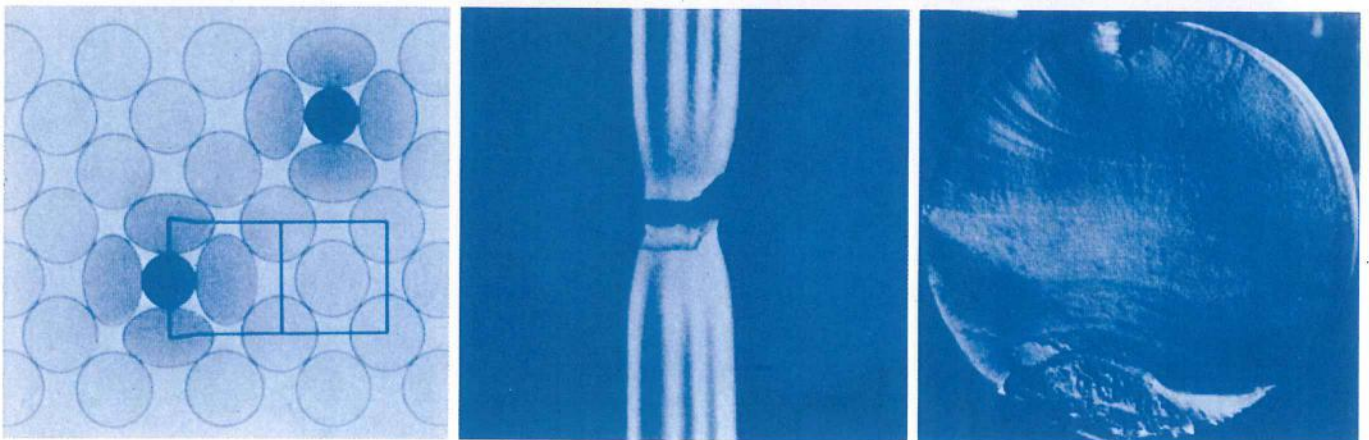
Lawrence H. Van Vlack

Sixth Edition

STRUCTURE — PROPERTIES — PERFORMANCE

ELEMENTS OF MATERIALS SCIENCE AND ENGINEERING

Lawrence H. Van Vlack

UNIVERSITY OF MICHIGAN
Ann Arbor, Michigan

*This Book Belongs
To Professor D.R. Clarke.
Please Return So Others
May Borrow It.*

WORLD STUDENT SERIES EDITION

This book is in the
Addison-Wesley Series in Metallurgy and Materials Engineering

Consulting Editors
Morris Cohen
Merton C. Flemings

Chapter 8

DEFORMATION AND FRACTURE

Most materials are subjected to stresses and the accompanying deformation during processing and use. Plastic deformation is required in processing most metals. Furthermore, the engineer must provide for elastic deformation of structural parts in designs. Even electrical materials, such as a wire, undergo deformation during manufacture and use. Normally, the originally intended role of any material is terminated if there is fracture, whether it is from an overload, from a sudden impact, or from sharp thermal gradients.

In this chapter, we shall consider the nature and mechanism of deformation— both elastic and plastic (recoverable and permanent). Then, we shall be in a better position to anticipate the rigidity and deformation strength of materials for processing and design. When we design to avoid fracture, we must consider stress concentrations and toughness.

8-1

ELASTIC DEFORMATION

Elastic deformation is a reversible strain. If a stress is applied in tension, the material becomes slightly longer; removal of the load permits the material to return to its original dimension. Conversely, when it is under compression, the material becomes slightly shorter. The dimensions of the unit cells change when the material undergoes elastic strain (Fig. 8–1.1).

Elastic Moduli

When only elastic deformation exists, the strain is proportional to the applied stress (Fig. 8–1.2). The ratio of stress to strain is the *modulus of elasticity* (Young's modulus), and is a property of the material (Eq. 1–2.3). The greater the forces of attraction between atoms in a material, the higher the modulus of elasticity (Fig. 2–6.1).

Any lengthening or compression of the crystal structure in one direction, due to a uniaxial force, produces an adjustment in the dimensions at right angles to the force. In Fig. 8–1.1(a), for example, a small contraction is indicated at right angles to the tensile force. The negative ratio between the lateral strain e_y and the direct tensile strain e_z is called *Poisson's ratio, v*:

$$v = -\frac{e_y}{e_z} \tag{8–1.1}$$

Engineering materials may be loaded in shear as well as in tension (and compression). In shear loading, the two forces are parallel but are not aligned (Fig. 8–1.3b). As a result, the *shear stress, τ*, is the shear force, F_s divided by the sheared area, A_s:

$$\tau = F_s/A_s \tag{8–1.2}$$

FIG. 8–1.1

Elastic Normal Strain (Greatly Exaggerated). Atoms are not permanently displaced from their original neighbors. (a) Tension (+). (b) No strain. (c) Compression (−).
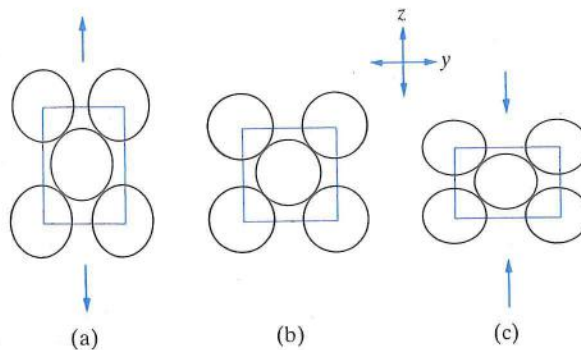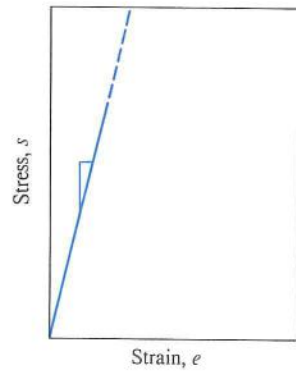
FIG. 8-1.2

Stress Versus Strain (Elastic). With only elastic strain, the two are proportional, and Eq. (1-2.3) applies. The slope of the curve is the modulus of elasticity (Young's modulus), $E = s/e$.

A shear stress produces an angular displacement, α. We define *shear strain, γ,* as the tangent of that angle; that is, as x/y in Fig. 8-1.3(b). The recoverable or elastic shear strain is proportional to the shear stress:

$$G = \tau/\gamma \qquad (8-1.3)$$

where G is the *shear modulus.* Also called the modulus of rigidity, the shear modulus is different from the modulus of elasticity, E; however, the two are related at small strains by

$$E = 2G(1 + v) \qquad (8-1.4)$$

Since Poisson's ratio v is normally between 0.25 and 0.5, the value of G is approximately 35 percent of E.

A third elastic modulus is the *bulk modulus, K.* It is the reciprocal of the compressibility β of the material and is equal to the hydrostatic pressure P_h per unit

(a)   (b)
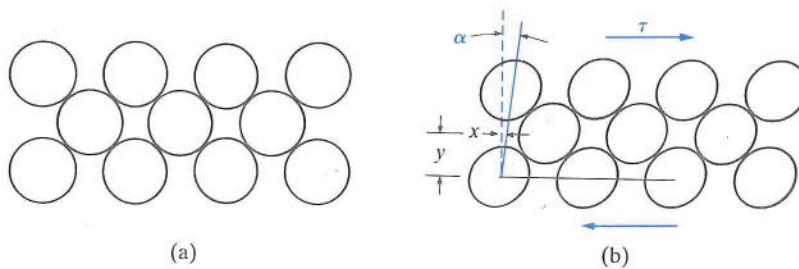
FIG. 8-1.3

Elastic Shear Strain. Shear couples produce a relative displacement of one plane of atoms past the next. This strain is elastic as long as atoms keep their original neighbors. (a) No strain. (b) Shear strain.

of volume compression, $\Delta V/V$:

$$K = \frac{P_h V}{\Delta V} = \frac{1}{\beta} \qquad (8-1.5)$$

The bulk modulus is related to the modulus of elasticity as follows:

$$K = \frac{E}{3(1 - 2\nu)} \qquad (8-1.6)$$

You will derive this equation in Problem 817.

Elastic Moduli Versus Temperature

Elastic moduli decrease as temperature increases, as shown in Fig. 8–1.4 for four common metals. In terms of Fig. 2–5.2(a), a thermal expansion reduces the value of dF/da, and therefore decreases the modulus of elasticity. The discontinuity in the curve for iron in Fig. 8–1.4 is due to the change from bcc to fcc at 912° C (1673° F). Not surprisingly, the more densely packed fcc polymorph requires greater stresses for a given strain; that is, the elastic modulus is greater for fcc. Also note from Fig. 8–1.4 that higher-melting-temperature metals have greater elastic moduli.

Elastic Moduli Versus Crystal Direction

Elastic moduli are *anisotropic* within materials; that is, they vary with crystallographic direction. As an example, iron has an average modulus of elasticity of about 205 GPa (30,000,000 psi); however, the actual modulus of a crystal of iron varies from 280 GPa (41,000,000 psi) in the [111] direction to only 125 GPa (18,000,000 psi) in the [100] direction (Table 8–1.1). The consequence of any such anisotropy becomes significant in polycrystalline materials. Assume, for example, that Fig. 8–1.5(a) represents the cross-section of a steel wire in which the average stress is 205 MPa (30,000 psi). If the grains are randomly oriented, the

FIG. 8–1.4

Modulus of Elasticity Versus Temperature. (Adapted from A. G. Guy and J. J. Hren, *Elements of Physical Metallurgy*, Addison-Wesley.)
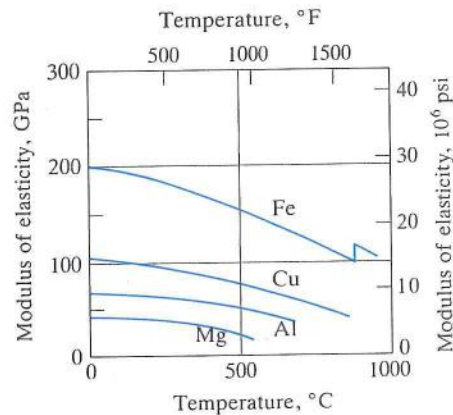
TABLE 8-1.1 Moduli of Elasticity (Young's Modulus)*

METAL	MAXIMUM		MINIMUM		RANDOM	
	GPa	10^6 psi	GPa	10^6 psi	GPa	10^6psi
Aluminum	75	11	60	9	70	10
Gold	110	16	40	6	80	12
Copper	195	28	70	10	110	16
Iron (bcc)	280	41	125	18	205	30
Tungsten	345	50	345	50	345	50

* Adapted from E. Schmid and W. Boas, *Plasticity in Crystals*. English translation, London: Chapman Hall.

elastic strain is 0.001, because the average modulus of elasticity is 205 GPa (30,000,000 psi). However, in reality, the stress varies from 125 MPa (18,000 psi) to 280 MPa (41,000 psi) as shown in Fig. 8-1.5(b), because grains have different orientations, but each is strained equally (0.001). Of course, this means that some grains will exceed their yield strength before other grains reach their yield strength.

(a)

(b)
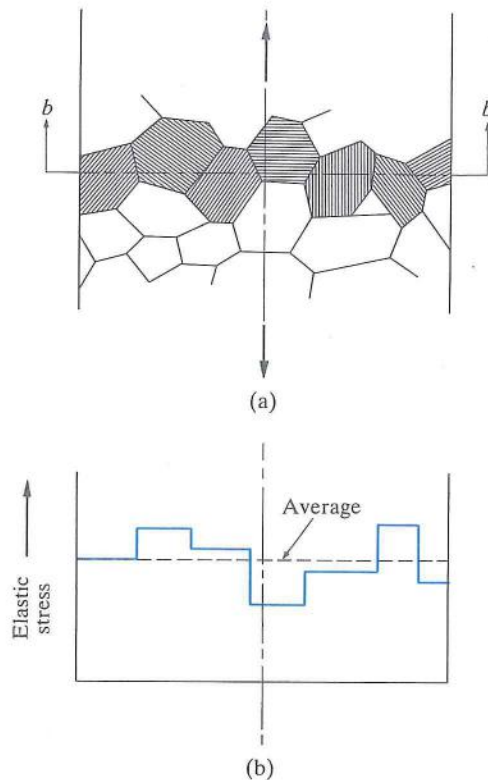
FIG. 8-1.5

Stress Heterogeneities (Schematic). Elastic stresses vary with grain orientation, because the moduli of elasticity are not isotropic.

Example 8-1.1

A plate of steel has a 100.0-cm × 100.0-cm square scribed on its surface. It is loaded in one direction (perpendicular to opposite sides of the square) with a 200-MPa (29,000-psi) stress.
(a) What are the dimensions of the scribed area? (Poisson's ratio of steel = 0.29).
      Without the initial stress being removed, a second tension stress of 410 MPa (60,000 psi) is applied at right angles to the first—that is, perpendicular to the other edges of the square.
(b) What are the new dimensions of the scribed area?

Procedure Since no preferred orientation is indicated, we shall assume the random grain value of the modulus of elasticity (Table 8-1.1). The strains are additive when the two stresses are applied.

Calculation

(a) From Eq. (1-2.3): $e_z = 200$ MPa/205,000 MPa = 0.000975

  From Eq. (8-1.1): $e_y = -0.29(0.000975) = -0.00028$

  1000 mm $(1 + 0.000975) \times 1000$ mm $(1 - 0.00028) = 1001.0$ mm × 999.7 mm

(b) $e_y = -0.00028 + 410$ MPa/205,000 MPa = 0.00172

  $e_z = 0.000975 - 0.29(410/205,000) = 0.00040$

  1000 mm $(1 + 0.0004) \times 1000$ mm $(1 + 0.00172) = 1000.4$ mm × 1001.7 mm

Additional information We can write a general equation for elastic deformation in three dimensions from Eqs. (1-2.3 and 8-1.1):

$$e_x = \frac{S_x}{E} - \frac{vS_y}{E} - \frac{vS_z}{E} \qquad (8-1.7)$$

Example 8-1.2

What is the percentage volume change in iron if it is hydrostatically compressed with 1400 MPa (200,000 psi)? (Poisson's ratio = 0.29.)

Procedure We need the bulk modulus $(= P_h/(\Delta V/V))$ which is obtainable from E and v (Eq. 8-1.6). An alternative solution makes use of Eq. (8-1.7). Since $e_x = e_y = e_z (= \Delta L/L)$, and with $\Delta V/V \approx 3(\Delta L/L)$, we get the same answer.

Solution

  $K = (205,000$ MPa$)/3(1 - 0.58))$
      $= 162,700$ MPa.

  $\Delta V/V = -1400$ MPa/162,700 MPa $= -0.86$ v/o

Alternative solution

  $e_x = (1 - 2v)(-1400$ MPa$)/(205,000$ MPa$) = -0.00287$

  $\Delta V/V \approx 3e = -0.86$ v/o

Comment   The approximation $\Delta V/V = 3(\Delta L/L)$ originates from $1 + \Delta V/V = (1 + \Delta L/L)^3$, and it is valid when the Δs are small.

8–2

PLASTIC DEFORMATION

Figure 8–1.2 shows only elastic strain. This situation is typical of brittle (nonductile) materials such as cast iron, glass, and phenol–formaldehyde polymers. *Ductile* materials undergo some *plastic* (permanent) strain before fracture. For example, if a steel beam is loaded, it will first deflect elasticly. The deflection disappears when the load is removed. An overload will permanently bend the beam in the locations where the stresses exceed the yield strength of the steel. In this case, the bent beam has failed, but it has not fractured. In contrast, on a production line, the yield strength of a sheet of steel may be intentionally exceeded to bend the sheet into the shape of a car fender. At this stage, the metal has yielded, but it has not failed because production requires considerable plastic strain. It is necessary in both production and service to know (1) the critical stress requirements to initiate permanent deformation, and (2) the amount of plastic strain available before eventual fracture of a ductile material.

Strengths

The laboratory test bar of Fig. 8–2.1(a) was used to produce the accompanying *stress–strain diagram*. The *stress, s,* is the force per unit area expressed in N/m^2 (or $lb_f/in.^2$), but we more commonly expressed it in MPa (or psi). The *strain, e,* is $\Delta L/L$, and therefore is dimensionless. The increasing stress produces only elastic strain in the linear part of the test. Beyond the *proportional limit,* plastic strain accompanies and generally exceeds the elastic strain:

$$e = e_{el} + e_{pl} \qquad (8-2.1)$$

The *yield strength, S_y,* is the critical stress required to introduce yielding, or plastic strain. The point of deviation from the elastic slope is gradual in some materials, such as aluminum and zinc. It also may be abrupt, as it is in structural steels. In either case, continued loading produces *both* elastic and plastic strain.*

Inasmuch as the first increment of plastic strain that is detected is dependent on the sensitivity of the testing equipment, an unstandardized test procedure could

---

* In many steels, where initial yielding is pronounced, the engineer sometimes speaks of a *yield point,* or an elastic limit, rather than of the yield strength. Although used, the latter term is not fully appropriate, because continued loading produces additional elastic strain.

(a)

(b)
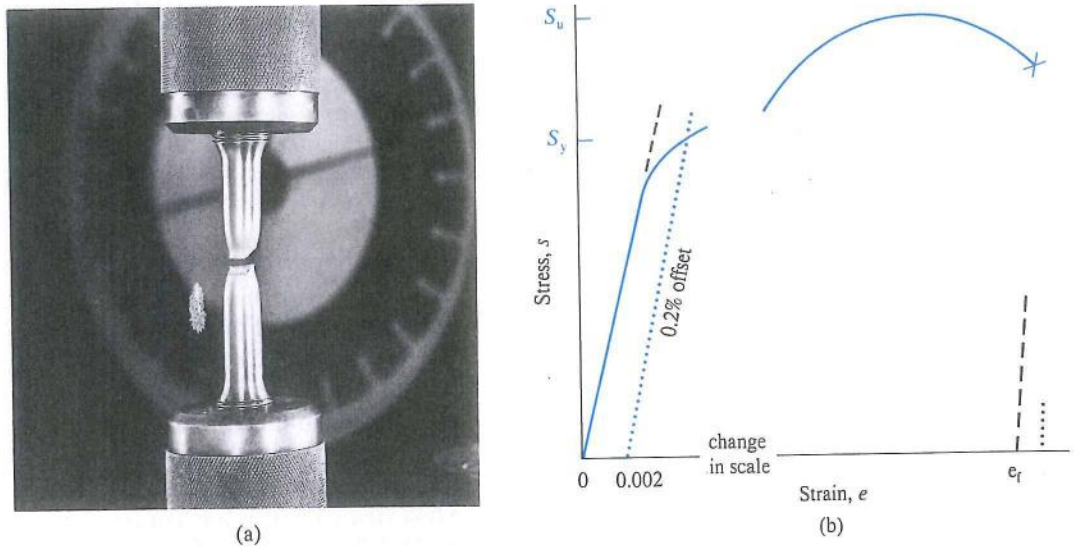
FIG. 8–2.1

Tensile Test. (a) Standardized test bar after ductile fracture. (Courtesy of U.S. Steel Corp.) (b) Stress–strain diagram (ductile material). The yield strength, S_y, is the stress that initiates plastic deformation (commonly defined by 0.2 percent permanent offset). The ultimate strength, S_u, is the maximum stress based on the original, or nominal, area.

lead to considerable data variability from test bar to test bar, and from laboratory to laboratory. Pragmatically, the engineer standardizes the testing by defining the yield strength as the stress required to produce a tolerable amount of strain — commonly 0.2 percent. This strength is obtained by plotting the 0.2 percent *offset* from the linear portion of the stress–strain curve, then reading the intercept (Fig. 8–2.1b).

Almost all ductile materials become stronger when they are deformed plasticly. We call this process *strain hardening*. It is used advantageously in the design of engineering materials (Section 9–3). This added strength appears in Fig. 8–2.1(b) as the concurrent increase in stress and strain beyond the yield strength.

As presented in the Fig. 8–2.1(b), the stress–strain curve reaches a maximum and then falls off. The maximum is called the ultimate tensile strength, or more simply the *ultimate strength, S_u*. The ultimate strength is the limiting stress used by the engineer. Beyond this point, the test bar shows a reduction in cross-sectional area, called *necking*. As a result, the load-carrying capability of the bar is reduced until the final fracture occurs. A *breaking strength, S_B*, can be calculated, but has little engineering significance because the nominal test-bar area is not pertinent at this stage.

Hardness

As we indicated in Section 1-2, *hardness* is the resistance to penetration. Various procedures are used to measure hardness. These depend on the material, its thickness, the indentor used, and the load applied. More common hardness indices are the Brinell Hardness Number (BHN), and the Rockwell hardnesses (R). The latter has several scales—R_c, R_b, R_f, and so on—which have appropriate loads and indentors for harder steels, softer brasses, and thin sheet metal. Although hardness is not a basic property of a material, we shall consider hardness data as useful indices of strength. For example, with steels, a rule of thumb is that the ultimate strength in psi is 500 times the BHN value. Since the hardness can be measured *in situ,* and does not require the machining of a test bar, its index is useful in quality control and service checking.

Ductility

We use the term *ductility* to define the permanent strain that is realized before the test bar fractures. As she does with strength, the engineer has more than one way to define this strain. *Elongation* is the linear plastic strain accompanying fracture:

$$El_{gage\,length} = (L_f - L_o)/L_o \qquad (8-2.2)$$

It is imperative that for the engineer to identify the gage length, because the plastic strain is almost invariably localized (Fig. 8-2.2).

A second measure of ductility is the *reduction of area,* R of A, at the point of fracture:

$$R\text{ of }A = (A_o - A_f)/A_o \qquad (8-2.3)$$

Gage length	Elongation
200 mm	20%
50 mm (2 in.)	50%
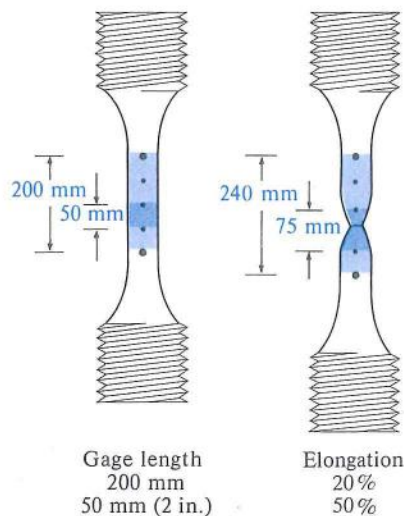
FIG. 8-2.2

Elongation Versus Gage Length. Since final deformation is localized, an elongation value is meaningless unless the gage length is indicated. For routine testing, a 50-mm (2-in.) gage length is common.

Both measures of ductility normally are expressed in percent. Values for these two measures of ductility parallel each other: both are high in ductile materials, and are nil in a brittle material. However, there is no established mathematical relationship between the two, because the final plastic deformation is highly localized.

True Stress and Strain

The stress–strain curve as commonly presented (Fig. 8–2.1b) is based on force per nominal, or *original, area.* As previously noted, however, necking occurs before a ductile material fractures. After necking starts, the *true stress, σ*, is higher than is the *nominal stress, s*. Likewise, the *true strain, ε*, differs from the *nominal strain, e*. We must modify the nominal stress–strain curve of Fig. 8–2.1(b) if we want a *true stress–strain* curve (Fig. 8–2.3).

The design engineer almost always uses the nominal *s/e* data, rather than the true *σ/ε* data. The nominal data are used partly because design calculations for engineering products are based on original dimensions. More important, it would be impractical to reduce the load as the material plasticly deforms during the last moments before complete failure.*

Although products are never designed on the basis of the true fracture strength, $σ_f$, (Fig. 8–2.3), knowledge of this stress is useful in the design of deformation processes. We shall observe in the next chapter that it is possible to make materials in which the ultimate strength, S_u, is raised toward that limit.

FIG. 8–2.3

True Stress and Strain. The true stress, σ, is based on the actual area rather than on the nominal (original) area. Therefore, the true fracture stress, $σ_f$, exceeds the nominal breaking strength, S_b. Also, because the strain is localized, the true strain at the point of fracture, $ε_f$, exceeds the nominal strain for fracture, e_f. (See Example 8–2.2.)

---
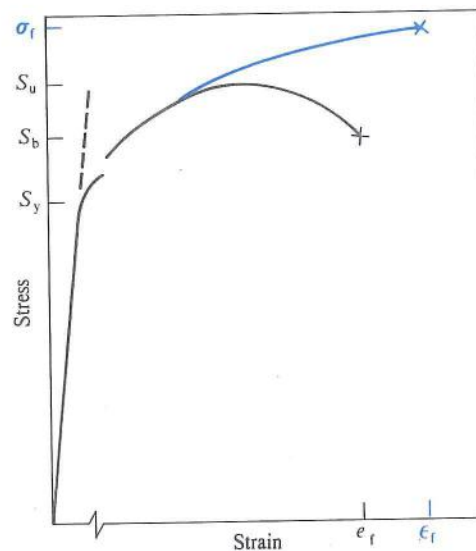
* In a facetious but illustrative vein, you as the design engineer will probably not volunteer to crawl out on the bridge to measure the diameter of a tie bar just before it breaks and the bridge falls into the river so that the *true* stress and strain are known. Sometimes, it does not pay to know the truth!

Example 8–2.1

A copper test bar has a 2.00-in. (51-mm) gage length. After testing, the gage marks are 2.82 in. (71.6 mm) apart. What is the ductility?

Calculation

$$\text{elongation}_{2.00-\text{in.}} = (2.82 \text{ in.} - 2.00 \text{ in.})/2.00 \text{ in.}$$
$$= 0.41 \qquad \qquad \text{(or 41\%)}$$

Comments The reduction of area is expected to be high, but it cannot be calculated from the elongation data. A calculation in SI units will give the same ductility.

Example 8–2.2

OPTIONAL

A copper wire has a nominal breaking strength of 300 MPa (43,000 psi). Its ductility is 77 percent reduction of area. Calculate the true stress σ_f for fracture.

Solution Based on the original area, A_o,

$$\frac{F}{A_o} = 300 \text{ MPa} \qquad F = (300 \times 10^6 \text{ N/m}^2)A_o$$

$$\sigma_f = \frac{F}{A_{tr}} = \frac{F}{(1 - 0.77)A_o} = \frac{(300 \times 10^6 \text{ N/m}^2)A_o}{0.23 A_o} = 1300 \text{ MPa}$$

or

$$\frac{F}{A_{tr}} = \frac{(43,000 \text{ psi})A_o}{0.23 A_o} = 187,000 \text{ psi}$$

Comment We can determine the *true strain* ϵ from the cross-sectional dimensions. If we define the true strain ϵ as

$$\epsilon \equiv \int_{l_o}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_o}\right)$$

and assume constant volume, $Al = A_o l_o$, then

$$\epsilon = \ln\left(\frac{l}{l_o}\right) = \ln\left(\frac{A_o}{A}\right) \qquad \qquad (8-2.4)$$

This equation gives a definition of true strain that holds for all strains and is independent of gage length.

Example 8–2.3

A 212-cm copper wire is 0.76 mm (0.03 in.) in diameter. Plastic deformation started when the load was 8.7 kg. (a) What was the force provided in N and lb$_f$? (b) When loaded to 15.2 kg (33.9 lb$_f$), the total strain was 0.011. The wire was then unloaded. What is the length of the wire after unloading? (c) What is the yield strength of the copper?

Procedure The yield strength is the critical stress to initiate plastic strain. Therefore, we must calculate the stress with the 8.7-kg load for (c). After yielding is initiated, any additional stress produces *both* elastic and plastic deformation. Thus, both are included in the 0.011 strain; we can calculate the elastic strain from the modulus of elasticity and the 15.2-kg load.

Calculation

(a) $(8.7 \text{ kg})(9.8 \text{ m/s}^2) = 85.25 \text{ N}$ $(8.7 \text{ kg})(2.2 \text{ lb}_f/\text{kg}) = 19.1 \text{ lb}_f$

   area $= \pi(0.76 \times 10^{-3} \text{ m})^2/4 = 0.45 \times 10^{-6} \text{ m}^2$

(b) Stress at 15.2 kg: $(15.2 \text{ kg})(9.8 \text{ m/s}^2)/(0.45 \times 10^{-6} \text{ m}^2) = 331 \text{ MPa}$

   Elastic strain at 15.2 kg: $(331 \text{ MPa})/(110,000 \text{ MPa}) = 0.003$

   Plastic strain at 15.2 kg: $0.011 - 0.003 = 0.008 \text{ permanent}$

   Wire length after unloading: $1.008(212 \text{ cm}) = 213.7 \text{ cm}$

(c) Yield strength: $S_y = (85.2 \text{ N})/(0.45 \times 10^{-6} \text{ m}^2) = 190 \text{ MPa}$

Comment Elastic strain continues to increase after plastic deformation starts, because the bonds of all atoms experience increased forces, even if they do not establish new neighbors by plastic deformation.

8–3
DEFORMATION MECHANISMS

Cubic metals and their nonordered alloys deform predominantly by *plastic shear,* or *slip,* in which one plane of atoms slides over the next adjacent plane. Plastic shear also is one of the methods of deformation in hexagonal metals, and in a few ceramic materials. Shear deformation even occurs when compression or tension forces are applied, because the stresses may be resolved into shear stresses.

Slip Systems

Slip occurs more readily along certain crystal directions and planes than along others. This is illustrated in Fig. 8–3.1, where a single crystal of an hcp metal was deformed plastically. The shear stress required to produce slip on a crystal plane is called the *critical shear stress,* τ_c.

The predominant sets of *slip systems* in several familiar metals are summarized in Table 8–3.1. A slip system includes the *slip plane* (*hkl*),* and a *slip direction* [*uvw*]. There are a number of slip systems, because of the multiple planes in a family of planes and the multiple directions in a family of directions (Sections 3–6 and 3–7). Two facts stand out in Table 8–3.1.

---

* See Section 3–7 for (*hkil*) indices of hexagonal crystals.

(a)   (b)   (c)
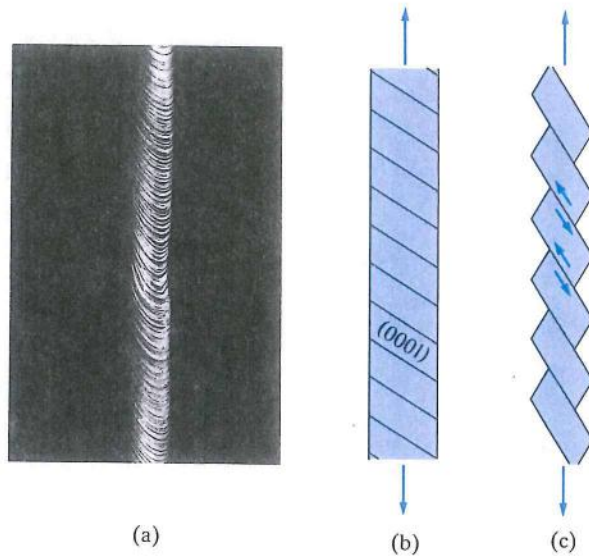
FIG. 8-3.1

Slip in a Single Crystal (hcp). Slip paralleled the (0001) plane, which contains the shortest slip vector. (See Section 3-7 for (hkil) indices of hexagonal crystals.) (Constance Elam, *Distortion of Metal Crystals,* Oxford: Clarendon Press.)

1. The slip direction in each metal crystal is the direction with the highest linear density of lattice points, or the shortest distance between lattice points

2. The slip planes are planes that have wide interplanar spacings and, therefore, high planar densities (Section 3-8)

Mechanism of Slip

Figure 8-3.2 shows a simplified mechanism of slip. If we were to calculate the strength of metals on this basis, the result would indicate that the strength of metals should be approximately $G/6$, where G is the shear modulus. Since metals have only a fraction of that strength, a different slip mechanism must be operative. All experimental evidence supports a mechanism involving dislocation movements.

TABLE 8-3.1 Predominant Slip Systems in Metals

STRUCTURE	EXAMPLES	SLIP DIRECTIONS	SLIP PLANES	NUMBER OF INDEPENDENT SLIP SYSTEMS
bcc	α-Fe, Mo, Na, W	$\langle \bar{1}11 \rangle$	$\{101\}$	12
bcc	α-Fe, Mo, Na, W	$\langle \bar{1}11 \rangle$	$\{211\}$	12
fcc	Ag, Al, Cu, γ-Fe, Ni, Pb	$\langle \bar{1}10 \rangle$	$\{111\}$	12**
hcp	Cd, Mg, α-Ti, Zn	$\langle 11\bar{2}0 \rangle$	$\{0001\}$*	3
hcp	α-Ti	$\langle 11\bar{2}0 \rangle$	$\{10\bar{1}0\}$*	3

* See Section 3-7 for (hkil) indices of hexagonal crystals. ** See Example 8-3.1 and Fig. 8-3.10.

(a)   (b)

(c)
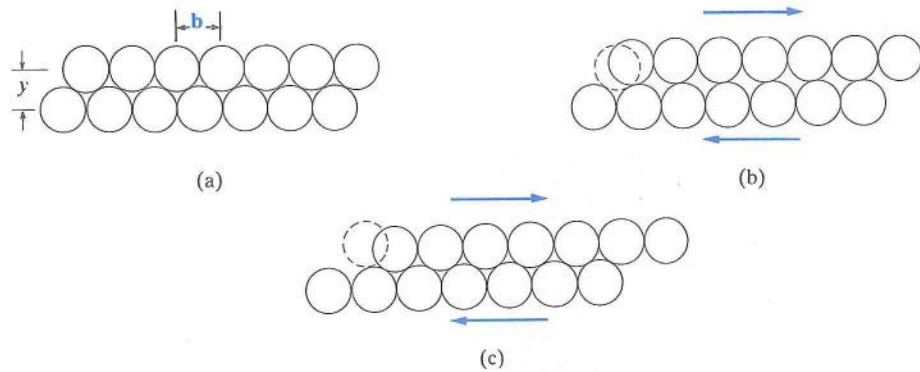
FIG. 8–3.2

An Assumed Mechanism of Slip (Simplified). Metals actually deform with less shear stress than this mechanism would require.

If we use Fig. 8–3.3 as a model of a dislocation and place a shear stress along the horizontal direction, the dislocation can be moved (Fig. 8–3.4) with a shearing displacement within the crystal. (See also Fig. 4–1.5.) The shear stress required for this type of deformation is a small fraction of the previously cited value of $G/6$, and it matches observed shear strengths.

OPTIONAL
The mechanism of slip requires the growth and movement of a dislocation line; therefore, energy is required. The energy, E, of a dislocation line is proportional to the length of the dislocation line, l, the product of the shear modulus, G, and the square of the unit slip vector $\mathbf{b}$ (Section 4–1):

$$E \propto lG\mathbf{b}^2 \qquad\qquad (8\text{–}3.1)$$

Thus, the easiest dislocations to generate and expand for plastic deformation are those with the shortest unit slip vector, $\mathbf{b}$ (Fig. 4–1.2), particularly since the $\mathbf{b}$ term
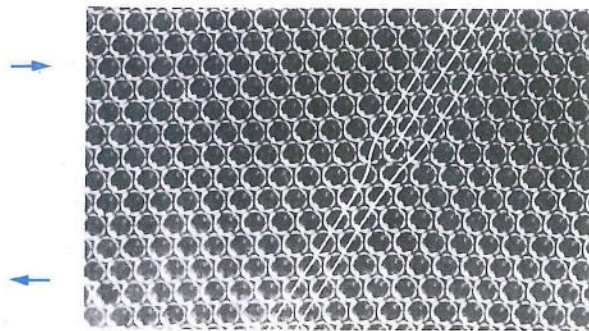
FIG. 8–3.3

Edge Dislocation. "Bubble-raft" model of an imperfection in a crystal structure. Note the extra row of atoms. (Bragg and Nye, *Proc. Roy. Soc. (London).*)

(a)

(b)

(c)

(d)
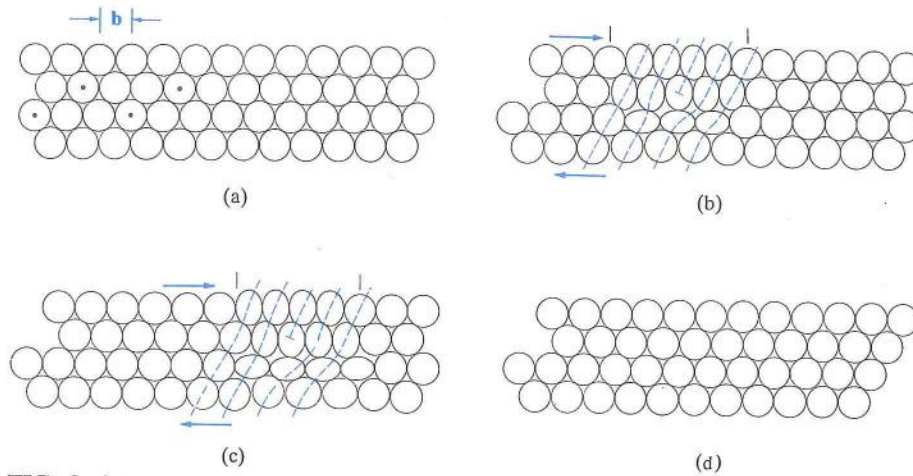
FIG. 8-3.4

Slip by Dislocations. In this model, only a few atoms at a time are moved from their low-energy positions. Less stress is therefore required to produce slip than would be needed if all the atoms moved at once as proposed in Fig. 8-3.2.

is squared. The directions in a metal with the shortest slip vector will be the directions with the greatest linear density of atoms. The lowest value for the shear modulus, G, accompanies the planes that are farthest apart and hence have the greatest planar density of atoms. Thus, we can develop the rule of thumb that predicts that the lowest critical shear stresses will occur *on the most densely packed planes and in the most densely packed directions.*

Dislocation Movements in Solid Solutions

The energy associated with an edge dislocation (Fig. 4-1.3) is the same whether the dislocation is located at (b) or at (c) in Fig. 8-3.4. Therefore, no net energy is required for the movement between the two.* Such is not the case when solute atoms are present. As shown in Fig. 8-3.5, when an impurity atom is present, the energy associated with a dislocation is less than it is in a pure metal. Thus, when a dislocation encounters foreign atoms, its movement is restrained because energy must be supplied to release it for further slip. As a result, solid-solution alloys always have higher strengths than do pure metals (Fig. 8-3.6). We call this process *solution hardening* (Section 9-2).

---

* This statement does not apply if (1) the movement includes an increase in the length of the dislocation, or (2) there is a pile-up of dislocations.

(a) Larger impurity atom   (b) Smaller impurity atom   (c) Same size atom
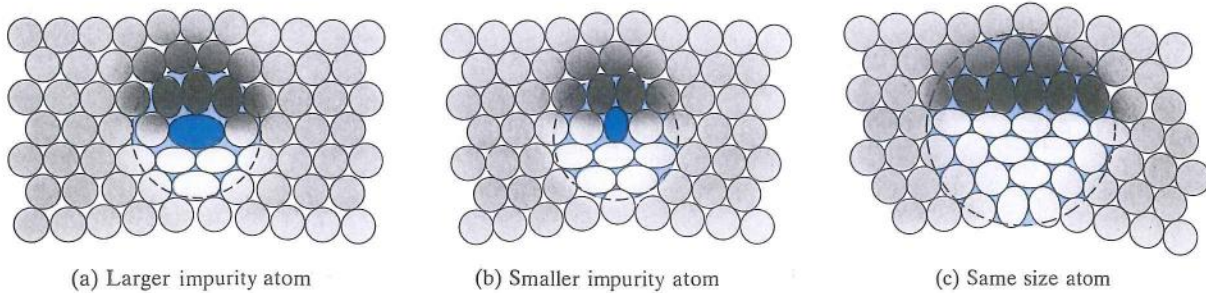
FIG. 8–3.5

Solid Solution and Dislocations. An odd-sized atom decreases the stress around a dislocation. As a result, energy must be supplied and additional stress applied to detach the dislocation from the solute atom. This process accounts for solution hardening.
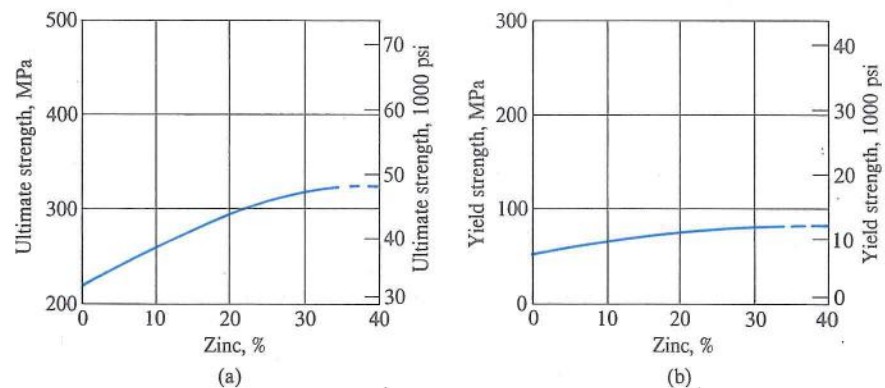
FIG. 8–3.6

Solution Hardening (Annealed α-Brass). The addition of zinc to copper increases both the yield and the ultimate strengths. (Thirty-five percent zinc is the practical limit for commercial brasses. See Fig. 5–6.1.)

Plastic Deformation of Compounds

An atom in a single-component metal always has like atoms for neighbors, even during deformation. A compound, however, has two or more types of atoms with a preference for unlike neighbors (see, for example, Fig. 3–1.1). On many potential slip planes, deformation brings together like atoms and separates a fraction of the unlike atoms (Fig. 8–3.7). Within a compound, this means higher energy, which shows up as a resistance to shear. Consequently, the critical shear stresses on some planes are sufficiently high that slip is essentially impossible. In effect, the number

Ni Ni Ni Ni Ni Ni^{2+} O^{2-} Ni^{2+} O^{2-} Ni^{2+} O^{2-}

Ni Ni Ni Ni Ni O^{2-} Ni^{2+} O^{2-} Ni^{2+} O^{2-} Ni^{2+}

⟶ Ni Ni Ni Ni Ni   ⟶ Ni^{2+} O^{2-} Ni^{2+} O^{2-} Ni^{2+} O^{2-}

Ni Ni Ni Ni Ni ⟵ O^{2-} Ni^{2+} O^{2+} Ni^{2+} O^{2-} Ni^{2+} ⟵

        (a)   (b)
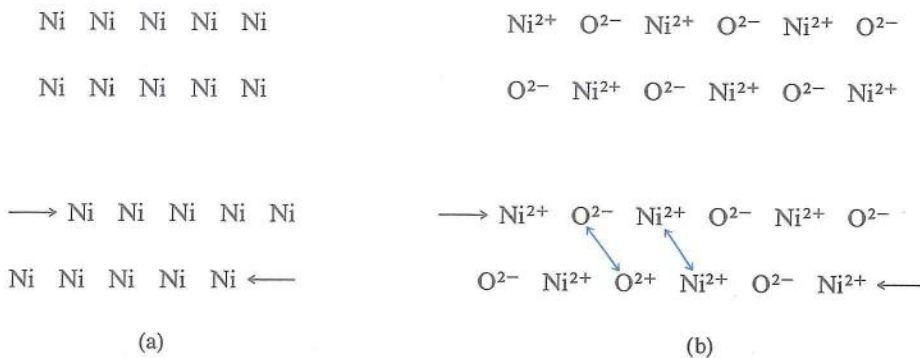
FIG. 8-3.7

Comparison of Slip Processes (Metallic Nickel and Nickel Oxide). More force is
required to displace the ions in NiO than is needed for the atoms in nickel. The strong
repulsive forces between like ions become siginificant. Nickel also has more slip systems
than does nickel oxide.

of possible slip systems is reduced, and ductility decreases. This result is revealed in
Table 8-3.2, which cites the slip systems for several relatively simple compounds.
For example, only six sets are operative in MgO. In more complex compounds—
such as in $Ni_8Fe_{16}O_{24}$, used in magnet ceramics, and in $PbZrO_3$, used in piezoe-
lectric transducers—the possibility of slip is negligible at normal temperatures;
hence, the materials behave in a brittle manner.

As revealed in Fig. 3-1.1, the shortest repeating distance (i.e., the slip vector) in
an NaCl-type crystal is along the several ⟨110⟩ directions. Quite expectedly, there-
fore, the ⟨110⟩ directions have been found by experiment to be the slip directions.
The most common slip plane for NaCl-type crystals is one of those in the {110}
form. This is particularly true in those compounds, such as LiF and MgO, that
have small, "nondeformable" ions. Other NaCl-type compounds with large ions,
such as PbS and MnSe, possess other slip planes, but still have the ⟨110⟩ slip
directions (Table 8-3.2).

TABLE 8-3.2 Slip Systems in Simple Compounds

STRUCTURE	EXAMPLES	SLIP DIRECTIONS	SLIP PLANES	NUMBER OF COMBINATIONS
NaCl	LiF, MgO, MnS, TiC	⟨110⟩	{1$\bar{1}$0}	6
NaCl	PbS	⟨110⟩	{001}	6
NaCl	MnSe	⟨110⟩	{$\bar{1}$11}	12
CsCl	CsCl	⟨100⟩	{001}	6
Al_2O_3	Al_2O_3	⟨11$\bar{2}$0⟩	{0001}	3

We conclude that both intermetallic and ceramic compounds are inherently less deformable than are pure metals and their solid solution phases, because critical shear stresses are high and the number of slip planes is small. Consequently, fracture stresses are commonly exceeded before plastic deformation is initiated (Section 8–4).

OPTIONAL

Deformation by Twinning

A crystal is *twinned* if it possesses a mirror boundary. In Fig. 8–3.8, the (110) plane of a bcc metal is sketched in two dimensions in the plane of the paper. Vertical to this plane is a twin boundary, across which the atoms are arranged in the same, but reflected, pattern.

Twinning can be induced by shear stresses, as indicated in Fig. 8–3.9. This twinning produces a permanent displacement, but is limited to relatively low strains, because, once repositioned, the atoms cannot move farther by twinning. For this reason, twinning deformation is overshadowed in most materials by

FIG. 8–3.8

Twin (Bcc). The (110) plane is shown. The boundary is a ($\bar{1}$12) plane emerging perpendicularly through the plane of the sketch. The two parts are mirror images of one another, and the ($\bar{1}$12) plane is common to both parts of the twin. The (110) and ($\bar{1}$12) planes intersect along the [1$\bar{1}$1] direction. (From L. H. Van Vlack, *Materials Science for Engineers,* Addison-Wesley, Reading, Mass., Fig. 6–22, with permission.)
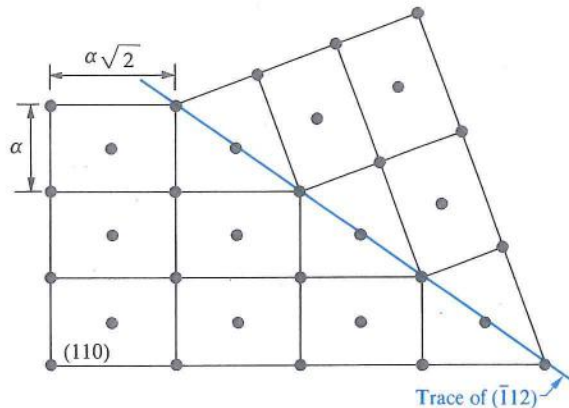
FIG. 8–3.9

Mechanical Twinning [Bcc—(110) Plane]. A shear stress in the [1$\bar{1}$1] direction produces strain by twinning. Deformation by twinning is significant in hcp metals, because there are fewer hexagonal slip systems (Table 8–3.1).
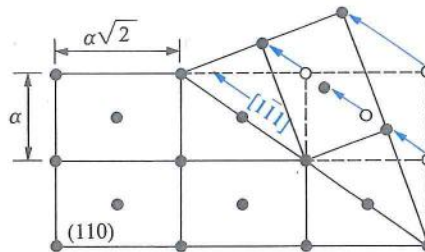
plastic slip. However, hexagonal materials have only a few slip systems (Table 8–3.1). In magnesium, zirconium, zinc, and a few other hcp metals, twinning strain is the predominant mechanism for processing to final shapes and dimensions.

Example 8–3.1

With a sketch, show the 12 slip systems that are included in the $\langle \bar{1}10 \rangle \{111\}$ slip systems of fcc metals.

Answers See Fig. 8–3.10. Each of the four planes of the $\{111\}$ family has three slip directions. Thus, we have

$[\bar{1}10](111)$	$[1\bar{1}0](11\bar{1})$	$[110](1\bar{1}1)$	$[110](\bar{1}11)$
$[10\bar{1}](111)$	$[101](11\bar{1})$	$[10\bar{1}](1\bar{1}1)$	$[101](\bar{1}11)$
$[0\bar{1}1](111)$	$[011](11\bar{1})$	$[011](1\bar{1}1)$	$[01\bar{1}](\bar{1}11)$

Comment The rear planes are parallel to the front planes and therefore involve the same slip systems; for example, $[110](\bar{1}11)$ is the same slip system as $[110](1\bar{1}\bar{1})$. Likewise, $[\bar{1}10](111)$ and $[1\bar{1}0](111)$ are the same slip system, but of opposite sense.
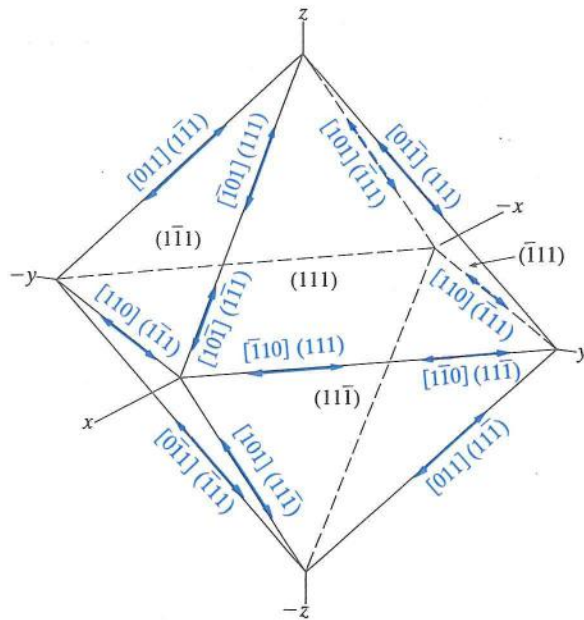
FIG. 8–3.10

The 12 Slip Systems of $\langle 1\bar{1}0 \rangle \{111\}$**. (See Example 8–3.1).**

FIG. 8–3.11

Slip Vectors on (111).
See Example 8–3.2.
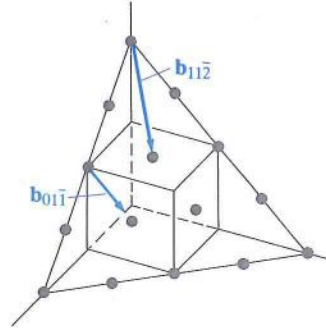
OPTIONAL

Example 8–3.2

Both $[01\bar{1}]$ and $[11\bar{2}]$ lie in the (111) plane of fcc aluminum. Therefore, both $[01\bar{1}](111)$ and $[11\bar{2}](111)$ slip are conceivable. (a) Make a sketch of the (111) plane and show the $[01\bar{1}]$ and $[11\bar{2}]$ unit slip vectors. (b) Compare the energies of the dislocation lines that have these two displacement vectors.

Solution

(a) See sketch (Fig. 8–3.11).

(b) Refer to Eq. (8–3.1):

$$\frac{E_{01\bar{1}}}{E_{11\bar{2}}} = \frac{lGb_{01\bar{1}}^2}{lGb_{11\bar{2}}^2}$$

Both involve the same slip plane (111); therefore, the same shear modulus applies. Based on unit length l,

$$\frac{E_{01\bar{1}}}{E_{11\bar{2}}} = \left(\frac{b_{01\bar{1}}}{b_{11\bar{2}}}\right)^2 = \left(\frac{a/\sqrt{2}}{a\sqrt{6}/2}\right)^2 = \frac{1}{3}$$
$$E_{01\bar{1}} = \tfrac{1}{3}E_{11\bar{2}}$$

Comment With this $\tfrac{1}{3}$ ratio, slip occurs appreciably more readily with the first of the two potential slip systems for fcc metals.

8–4

FRACTURE

The ultimate mechanical failure is fracture. We commonly categorize fracture as being either ductile or brittle (i.e., nonductile). Little energy is required to break brittle materials, such as glass, polystyrene, and some of the cast irons. Conversely, tough materials, such as rubber and many steels, absorb considerable energy in the

fracture process. The contrast is important, since the service limit in many engineering products is not the yield or ultimate strength; rather it may be the energy associated with fracture propagation.

Brittle fracture requires energy to separate atoms and to expose new surface along the fracture path. *Ductile fracture* requires not only the energy just cited, but much additional energy to deform plastically the material adjacent to the fracture path.

One measure of toughness is the area under the stress–strain curve (Fig. 8–4.1). With no plastic deformation, that area is $se/2$, or $s^2/2E$, and the energy is solely elastic. The calculation is not as simple for the ductile material in Fig. 8–4.1(b), because the plastic strain of the deformable material far exceeds the limited elastic strain. The result is a much higher energy consumption before fracture. The units of energy as just described are the product of stress and strain:

$$(N/m^2)(m/m) = joule/m^3 \qquad\qquad (or\ ft \cdot lbs/in^3)$$

that is, joules per unit volume. In reality, the energy consumption is very nonuniform within the fractured test piece; negligible energy is absorbed in undeformed regions, whereas a major quantity is absorbed in the vicinity of the fracture. Furthermore, this distribution is markedly affected by the size and shape of the test specimen. Notches are especially critical in determining the energy requirements for fracture.
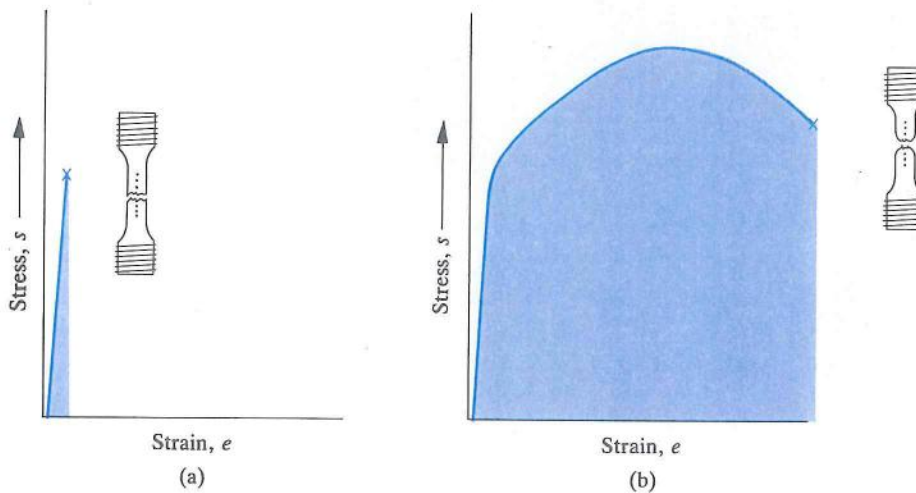
FIG. 8–4.1

Fracture. (a) Brittle fracture involves little or no plastic deformation. (b) Ductile fracture requires energy for plastic deformation. Toughness, the energy requirement, is equal to the area under the s–e curve.

Toughness Tests

Figure 8–4.2 shows an impact tester that has been widely used to obtain toughness data. The energy absorbed in the fracture is calculated from the height of the followthrough swing of the heavy pendulum (Example 8–4.1). A Charpy V-notch test specimen (Fig. 8–4.2b) is commonly used for comparative purposes. Note, however, that these values are a function of size and shape, as well as of the materials being compared.

Ductility-Transition Temperature

Many materials exhibit an abrupt drop in ductility and toughness as the temperature is lowered. In glass and other amorphous materials, this change corresponds to the glass-transition temperature. Of course, metals are crystalline and do not

(a)

(b)

(c)
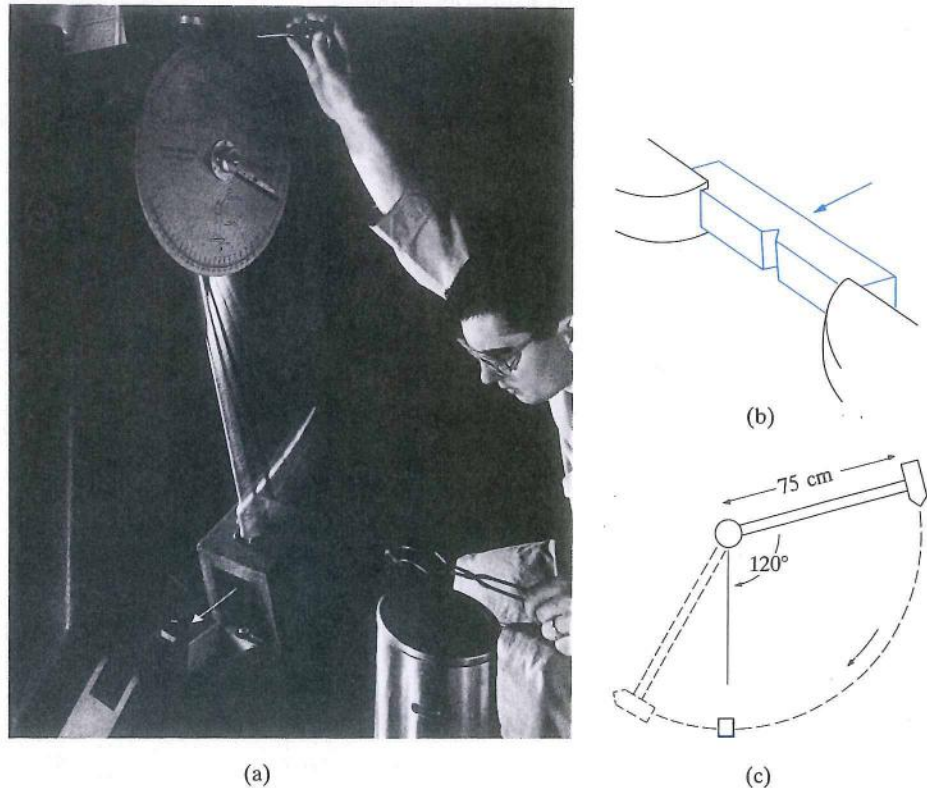
FIG. 8–4.2

Toughness Test. The notched test specimen—arrow in (a) and sketched in (b)—is broken by the impact of the swinging pendulum (c). The amount of energy absorbed is calculated from the arc of the followthrough swing (Example 8–4.1). (Courtesy of U.S. Steel Corp.)
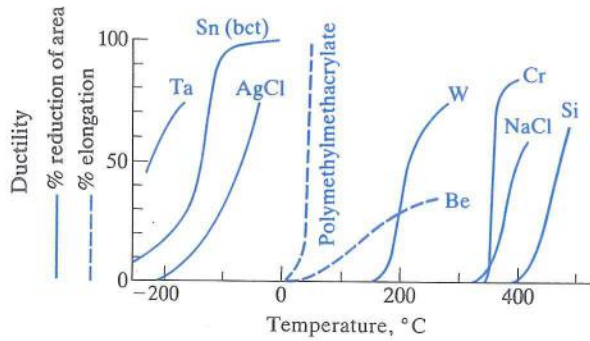
FIG. 8-4.3

Ductility Versus Temperature (Tensile Tests). Except for fcc metals, most materials lose ductility abruptly at decreasing temperatures. For a given material, the transition temperature is higher for higher strain rates—for example, in impact loading. (After data by A. H. Cottrell, *The Mechanical Properties of Matter*, Wiley.)

have a glass-transition temperature. However, they may have a *ductility-transition temperature, T_{dt}* (Fig. 8–4.3), that divides a lower temperature regime where the fracture is said to be nonductile from a higher temperature range where considerable plastic deformation accompanies failure.

Figure 8–4.4 shows the energy absorbed during impact fracture by two different steels as a function of temperature. As with the glass-transition temperature (Section 4–2), the ductility-transition temperature is not fixed, but rather depends on size and shape, the rate of loading, presence of impurities, and so on. However, the engineer will be quick to choose steel C over steel B of Fig. 8–4.4, if it is to be used in a welded ship in the North Atlantic winter waters. A crack, once started in the steel with a high ductility transition temperature, could continue to propagate with a low energy fracture until the ship was broken apart. Several unfortunate naval catastrophies occurred before design engineers learned how to minimize stress concentrations, and metallurgists found that fine-grained steels have lower
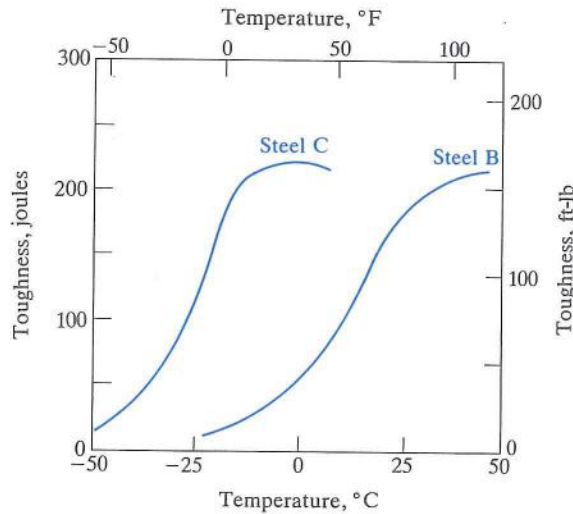
FIG. 8-4.4

Toughness Transitions. For each steel, there is a marked decrease in toughness at lower temperatures. The transition temperature is significantly lower for steel C (fine-grained) than for steel B (rimmed). (Adapted from Leslie, Rickett, and Lafferty, *Trans. AIME*.)

ductility-transition temperatures than do coarse-grained steels. Fortunately, fcc metals do not display an abrupt change in ductility as the temperature is lowered. Thus, aluminum, copper, and austenitic stainless steels can be used in cryogenic applications. Unfortunately, other properties and costs preclude the widespread use of these materials as replacements for large structures, pipelines, and so on.

Fracture Toughness, K_{Ic}

The impact tests that we described in the previous section have been available for several decades. They give qualitative data that may be used advantageously for comparative purposes; however, they do not give property data that can be used for design purposes. To obtain these values, we must consider *fracture mechanics*. Fracture always starts at some point of *stress concentration*, which may be adjacent to a rivet hole, along a keyway of a shaft, at some reentrant angle in the product or structure, along a scored line on a piece of window glass, or at a flaw in the material itself. In each of these cases, the stress is concentrated because the load cannot be uniformly distributed across the full area. The load must be redistributed around the end of the missing cross-section. This situation is illustrated schematically in Fig. 8–4.5(a) for an elliptical hole. As shown for the crack in Fig. 8–4.5(b), the

(a)   (b)
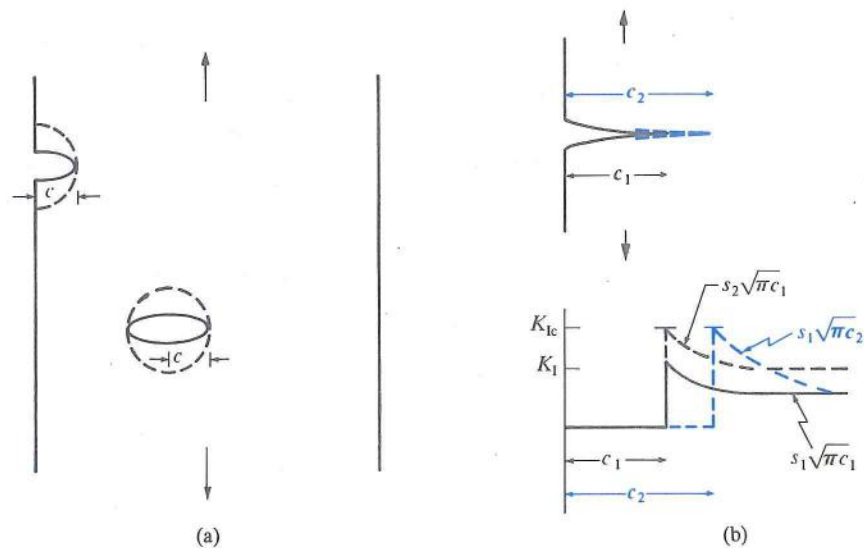
FIG. 8–4.5

Stress Intensification. (a) Elliptical hole. The stress is intensified adjacent to the hole because the load must be redistributed around the end of the hole. (b) Stress-intensity factor, K_I. Fracture occurs when the stress intensity attains the critical value, K_{Ic}, for the material. As indicated in Eq. (8–4.1), that value may be reached by either a greater stress or a deeper crack.

stress intensity is greatest at the tip. The intensity increases in proportion to the nominal stress, s (after correction for true area), and the square root of the crack's depth, c. More specifically,

$$K_I = Ys\sqrt{\pi c} \qquad\qquad (8\text{–}4.1)$$

where K_I is the *stress-intensity factor* that is independent of the nature of the material. (The term Y provides a correction for the thickness-to-width ratio of the material. For our purposes, it is slightly more than unity for metal plate products.) With the $s\sqrt{c}$ relationship of Eq. (8–4.1), the units of the stress-intensity factor are $MPa\cdot\sqrt{m}$ (or $Psi\cdot\sqrt{in}$.). With more intense stresses or with deeper cracks, the stress intensity becomes sufficient for the fracture to progress spontaneously. This threshold stress intensity is a property of the material. It is called the *critical stress-intensity factor*, K_{Ic}, or the *fracture toughness* of the material.

The loading in Figs. 8–4.5(a) and 8–4.6 is called mode I; hence the subscript to the symbol, K in Eq. (8–4.1). Other modes include II, shear forces parallel to the crack surface and perpendicular to the crack front, and III, shear forces parallel to the crack surface as well as to the crack front (tearing).

Design Considerations

There are several design implications from the relationships of the last section. Cracks can be tolerable, providing $Ys\sqrt{\pi c}$; that is, K_I, does not exceed the critical stress-intensity factor, K_{Ic}, for the material.* Conversely, the material will fracture if $Ys\sqrt{\pi c}$ exceeds K_{Ic}, even though S_y or S_u are not exceeded.

The engineer must consider both strength and fracture toughness because materials with higher strengths typically have low fracture toughness, and vice versa.
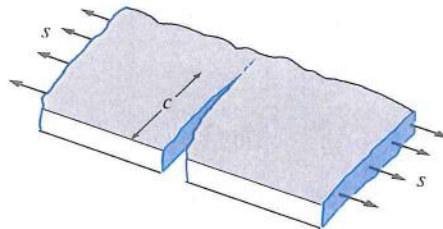
FIG. 8–4.6

Fracture Stresses (Mode I). Stresses that open an edge crack in tension introduce an intensity factor, K_I, that increases with $\sqrt{\pi c}$ as indicated in Eq. (8–4.1). If K_I exceeds a critical value, K_{Ic}, the crack will advance catastrophically.

---

* We can make a comparison with our previous observations on stress, which is a function of force and area ($s = F/a$), and is independent of the material. When the stress reaches a critical value for a given material, however, plastic deformation occurs. We call that critical stress for the material the yield strength, S_y. Here the critical value of *stress intensity*, K_{Ic}, is the fracture toughness of the material.

Thus, conditions for fracture may be encountered before the yield stress is reached, so full advantage cannot be taken of the high strength. Such considerations lead us to place a high value on careful design, as well as on materials that have no surface or internal imperfections.

Example 8–4.1

An impact pendulum on a testing machine weighs 10 kg and has a center of mass 75 cm from the fulcrum. It is raised 120° and released. After the test specimen is broken, the followthrough swing is 90° on the opposite side. How much energy did the test material absorb?

Calculation   Refer to Fig. 8–4.2.

$$\Delta E = 10 \text{ kg}(9.8 \text{ m/s}^2)(0.75 \text{ m})[\cos(-120°) - \cos 90°]$$
$$= -36.8 \text{ J} \qquad\qquad\qquad (lost \text{ by the pendulum})$$
$$= +36.8 \text{ J} \qquad\qquad\qquad (absorbed \text{ by the sample})$$

Comments   In general, materials have more toughness at high temperatures than they do at low ones. In fact, there is an abrupt decrease in the toughness of many steels as they are cooled below ambient temperatures. The temperature at which this discontinuous decrease occurs is called the *ductility–transition temperature* (Fig. 8–4.4).

Example 8–4.2

A steel has a yield strength, S_y, of 1100 MPa (160,000 psi), an ultimate strength, S_u, of 1200 MPa (174,000 psi), and a fracture toughness, K_{Ic}, of 90 MPa·$\sqrt{m}$ (82,000 psi·$\sqrt{in}$.). (a) A plate has a 2-mm (0.08-in.) edge crack. Will it fail by fracturing before it fails by yielding? (b) What are the deepest tolerable cracks that may be present without fracturing before yielding? [Assume that the geometric factor, Y, is equal to 1.1 for steel plates loaded in tension as in Fig. 8–4.6.]

Procedure   Determine the stress s required to raise the stress intensity factor K_I to the critical value of 90 MPa·$\sqrt{m}$. In (b) use 90 MPa·$\sqrt{m}$ and 1100 MPa (K_{Ic} and S_y, respectively) to calculate the critical limiting crack length.

Calculation   Use Eq. (8–4.1).

(a) $s = (90 \text{ MPa}·\sqrt{m})/(1.1\sqrt{0.002\pi \text{ m}})$
$= 1030 \text{ MPa}$

This stress of 1030 MPa (150,000 psi) to cause fracture is less than S_y; so this steel will fracture before it yields.

(b) $c\pi = [(90 \text{ MPa}·\sqrt{m})/(1100 \text{ MPa})(1.1)]^2$
$c = 0.0017 \text{ m}$ (or 1.7 mm)

Comment   Why should the answer be rounded down rather than up?

SUMMARY

1. Elastic deformation is a *reversible* strain, and is proportional to the applied stress. There are three elastic moduli: *Young's modulus, E,* is the axial stress per unit strain; the *shear modulus, G,* is the shear stress per unit strain, and the *bulk modulus, K,* is the hydrostatic stress (or pressure) per unit volume change. We can calculate one from another by using *Poisson's ratio, v.* The elastic moduli are generally anisotropic, and usually decrease with increasing temperatures.

2. *Plastic strain* is not reversible; it is permanent. The critical stress to initiate plastic strain is called the *yield strength, S*$_y$. Further stressing produces both elastic and plastic strains, with the latter predominant. The *ultimate strength, S*$_u$, is the maximum stress per unit of *original area. Ductility* is the plastic strain prior to fracture. True stress and true strain are calculated on the basis of the *true area.* They exceed the nominal stress and strain in ductile materials, because the plastic deformation reduces the cross-sectional area.

3. Plastic strain is not reversible. Plastic deformation occurs in crystalline materials predominantly by *dislo-cation movements* along slip planes. A minor amount of plastic deformation may arise from *twinning.* Those *slip systems* with the lowest *critical shear stresses* are the most densely packed directions on the most densely packed planes. Compounds have inherently high shear stengths. *Solution hardening* results from dislocations becoming anchored on solute atoms.

4. Fracture may be ductile or brittle; that is, it may occur with or without plastic deformation. The former is tougher. Toughness tests measure the energy required for fracture of standardized test specimens. Steel and a number of other materials exhibit a *ductility-transition temperature, T*$_{dt}$, below which fracture occurs with little energy absorption.

The *stress-intensity factor* (K_I of Eq. 8–4.1) relates the nominal stress and the depth of a crack to the stress concentration at the tip of the crack. *Fracture toughness, K*$_{Ic}$, is the critical value of K_I that permits crack propagation. It is a property of a material, and it commonly dictates the stress limits on high-strength materials that have low ductility.

KEY WORDS

Anisotropic
Annealing point
Bulk modulus (K)
Critical shear stress
Deformation, elastic
Deformation, plastic
Ductility
Ductility-transition temperature (T_{dt})
Elastic strain (e_{el})
Elastomer
Elongation (El.)
Fracture, brittle
Fracture, ductile

Fracture toughness
Hardness
Plastic strain (e_{pl})
Poisson's ratio (v)
Proportional limit
Reduction of area (R of A)
Shear modulus (G)
Shear strain (γ)
Shear stress (τ)
Slip direction
Slip plane
Slip system
Strain (e)

Strength (S)
Stress (s)
Stress-intensity factor (K_I)
Stress-intensity factor, critical (K_{Ic})
Stress–strain diagram
Toughness
True stress (σ)
True strain (ϵ)
Twin (crystal)
Ultimate strength (S_u)
Yield strength (S_y)
Young's modulus (E)

PRACTICE PROBLEMS

8–P11 A 7.6-mm (0.30-in.) diameter 1040 steel bar, which was initially 2.27 m (89.4 in.) long, supports a weight of 3963 N (890 lb$_f$). What is the difference in length if the steel bar is replaced by a 70–30 brass bar?

8–P12 What is the volume change of a rod of brass when it is loaded axially by a force of 233 MPa (33,800 psi)? (Poisson's ratio is 0.37.)

8–P13 What is the bulk modulus of the brass in Problem 8–P12? What is the shear modulus?

8–P14 If iron has an axial stress of 208 MPa (30,200 psi), what will be the highest local stress within a polycrystalline copper bar?

8–P15 A precisely machined steel rod has a specified diameter of 18.6 mm (0.732 in.). It is to be elastically loaded longitudinally with a force of 670,000 N (150,000 lb$_f$). (a) By what percentage will its diameter change? (b) By what percentage will the cross-sectional area change? (Poisson's ratio is 0.29.)

8–P16 The elastic modulus of copper drops from 110 GPa (16×10^6 psi) at 20° C (68° F) to 107 GPa (15.5×10^6 psi) at 50° C (122° F). What is the change in the total length of a 1575-mm (62-in.) bar if the stress is held constant at 165 MPa while the temperature rises those 30° C?

8–P17 Based on Problems 8–P12 and 8–P13, what shear angle, α, does a shear stress of 262 MPa (38,000 psi) produce in brass?

8–P18 Distinguish among the three elastic moduli.

8–P21 "The yield strength is the stress where strain switches from elastic to plastic." Comment on the validity of this statement.

8–P22 A wire of a magnesium alloy is 1.05 mm (0.04 in.) in diameter. Plastic deformation starts with a load of 10.5 kg (which is _____ N), or 23 lb$_f$. The total strain is 0.0081 after loading to 12.1 kg (26.6 lb$_f$). (a) How much permanent strain has occurred with a load of 12.1 kg (26.6 lb$_f$)? (b) Rework this problem with English units.

8–P23 A brass test specimen has a reduction of area of 35 percent. (a) What is the true strain, ϵ? (b) What is the ratio of the true stress, σ, to the nominal stress, s, for fracture, S_b?

8–P31 Identify the 12 $\langle \bar{1}11 \rangle \{101\}$ slip systems for a bcc metal.

8–P32 (a) Sketch the atomic arrangement on the (110) plane of MnS, which has the structure of NaCl (Fig. 3–2.5). (b) Identify the six $\langle 1\bar{1}0 \rangle \{110\}$ slip systems for this compound. (c) How long is the slip vector, **b**, in these systems?

8–P33 Differentiate between the terms *resolved shear stress* and *critical shear stress*.

8–P34 The engineer commonly defines the stress for yield strength after a 0.2 percent offset strain has occured (Fig. 8–2.1b). Based on Fig. 8–1.5, why is this offset necessary?

8–P35 Alloys of zinc and of magnesium are more widely used as casting alloys than as wrought (plastically deformed) alloys. Suggest a valid reason why this is so.

8–P36 Refer to Table 8–3.2. Why are there $\langle 100 \rangle \{001\}$ slip systems in CsCl structures, and not $\langle 111 \rangle \{\bar{1}10\}$ slip systems? There are more atoms per mm in the $\langle 111 \rangle$ directions than in the $\langle 100 \rangle$ directions.

8–P41 What would the followthrough angle have been in Example 8–4.1 if, before testing the sample, the initial angle of the pendulum had been set at 105°?

8–P42 The value of K_{Ic} for a steel is 186 MPa·m$^{1/2}$ (169,000 psi·in$^{1/2}$). What is the maximum tolerable crack when the steel carries a nominal stress of 800 MPa (116,000 psi)? (The geometric factor, Y, is 1.1.)

8–P43 Convert $K_{Ic} = 135,000$ psi·in$^{1/2}$ to MPa·m$^{1/2}$.

8–P44 The testing machine of Fig. 8–4.2 is described in Example 8–4.1. What is its maximum capacity expressed in the amount of energy absorbed by a specimen?

8–P45 A small hole drilled through a steel plate ahead of a crack will stop the crack's progress until repairs can be made. Explain how the hole accomplishes this feat.

TEST PROBLEMS

811 Provide a ball-park figure for Young's elastic modulus (a) of chromium and (b) of gold.

812 An aluminum rod is stressed 210 MPa (30,000 psi) in tension. Its initial diameter was 24.02 mm (0.946 in.). What is the change in diameter as a result of the load? Its bulk modulus is 73 GPa.

813 Assume a material deforms elastically in tension with no change in volume; that is, $(1 + e_x)(1 + e_y)(1 + e_z) = 1$. Calculate Poisson's ratio.

814 Aluminum that has an elastic modulus of 70 GPa (10^7 psi) and a Poisson's ratio 0.34 is under hydrostatic pressure of 83 MPa (12,000 psi). What are the dimensions of the unit cell?

815 Which will have the greater compressibility, β, iron with a Poisson's ratio of 0.29, or brass with a ratio of 0.37?

816 A test bar 12.83 mm (0.5051 in.) in dia. with a 50-mm gage length is loaded axially with 200 kN (45,000 lb_f) and is stretched 0.458 mm (0.018 in.). Its diameter is 12.79 mm (0.5035 in.) under load. (a) What is the bulk modulus of the bar? (b) What is the shear modulus?

817 A precisely ground cube $(100.00 \text{ mm})^3$ of an aluminum alloy is compressed in the x direction 70 MPa. (a) What are the new dimensions if Poisson's ratio is 0.3? (b) A second compression of 70 MPa is concurrently applied in the y direction. Now, what are the dimensions? (c) Derive Eq. (8–1.7). [Hint: Consider that the cube is under a stress of $s_x = s_y = s_z = P_h$ and recall that $(1 + \Delta V/V) = (1 + \Delta L/L)^3 = 1 + 3e + \cdots$.]

818 A vulcanized rubber ball decreases 1.2 percent in diameter when it is under 1000 psi hydrostatic pressure. A test bar of the same type of rubber stretches 2.1 percent when it is stressed 175 psi in tension. What is Poisson's ratio of the rubber?

821 A hardened steel fractures with a stress of 1515 MPa (217,000 psi) and a total strain of 0.027. What is the ductility? (Elastic strain is recovered.)

822 A 70 Cu–30 Zn brass has an elastic modulus of 110 GPa (16,000,000 psi) and a yield strength of 140 MPa (20,000 psi). (a) How much load can a 2.74-mm (0.108-in.) wire of this alloy support without yielding? (b) If a load of 55 kg (121 lb_f) is

supported by a 30.5-m (100-ft) wire of this size, what is the total extension?

823 A 0.50-in. (12.7-mm) diameter test bar of the brass identical to that in Problem 822, had a 0.29-in. (7.4-mm) diameter at its fracture point. The testing machine recorded 1030 lb_f (468 kg) when the test bar broke. What were the (a) true stress, and the (b) true strain when the bar fractured?

824 A testing machine recorded a load of 53,000 lb_f when the deformation (2-in.) was 24 percent. The elongation (2-in.) at fracture was 47 percent, but the load was only 41,000 lb_f. Explain.

825 A 1040 steel wire has a diameter of 0.89 mm (0.035 in.). Its yield strength is 875 MPa (127,000 psi) and its ultimate strength is 1070 MPa (155,000 psi). An aluminum alloy also is available with a yield strength of 255 MPa (37,000 psi), and an ultimate strength of 389 MPa (56,400 psi). (a) How much (what percentage) heavier, or lighter, will an aluminum wire be than a steel wire to support a 35-kg (77-lb) load with the same elastic deformation as the steel wire? (b) How much (what percentage) heavier, or lighter, must an aluminum wire be to support the same maximum load without permanent deformation? (c) How much heavier or lighter must it be to support the load without breaking? (Hint: Establish a ratio of masses without calculating the actual areas.)

826 The percent reduction of area cannot be calculated from the percent elongation (nor vice versa). Why is this true, given that both are measures of ductility?

827 Change the experimental data for the standard test bar (diameter = 0.5051 in., or 12.7 mm) of Fig. 8–2.2 from 240 mm and 75 mm to 219 mm and 59 mm, respectively. The final diameter at the break is 9.3 mm. Calculate four ductility values.

831 Identify eight of the 12 $\langle \bar{1}11 \rangle \{211\}$ slip systems for bcc metals.

832 Select a (112) plane of a bcc metal. Sketch it such that you can illustrate a $\langle 111 \rangle$ slip direction that lies in that plane.

833 Under certain conditions, the $\langle 011 \rangle \{100\}$ slip systems can operate in NaCl-type structures to sup-

plement the $\langle 1\bar{1}0 \rangle\{110\}$ systems. (a) How many slip systems belong to this $\langle 011 \rangle\{100\}$ set? List them. (b) What is the slip vector in PbS, which has the NaCl-type structure and these two slip systems?

834 Impurity atoms inhibit dislocation movements. Explain.

835 A 95 Cu–5 Sn bronze has the same elastic modulus as does pure copper (Appendix C). This bronze, however, has a yield strength that is three times as great as that of pure copper. Discuss reasons for this difference.

836 Your company is about to make a bid on a contract for 1500 feet of metal rods that can support 2000 lb$_f$ loads without permanent deformation. Copper or a 70 Cu–30 Zn brass could be used. Assume that the purchase price per pound of copper is twice that of zinc. (a) What will the cost ratio be for purchasing the raw materials for the two metals? (Processing costs are to be calculated separately.) (b) Recalculate for $\$_{Cu} = 1.2 \, \$_{Zn}$.

841 A test specimen is expected to absorb two-thirds as much energy during fracture as did the specimen in Example 8–4.1—that is, 24.5 J. What angle of followthrough should be expected?

842 The steel of Problem 8–P42, with a 9-mm (0.35-in.) crack, can support what maximum nominal stress without the crack advancing?

843 A steel with a K_{Ic} value of 190 MPa·m$^{1/2}$ also has a yield strength of 900 MPa. How deep will a crack be before the steel is subject to fracture as a mode of failure? (The geometric factor, Y, is 1.05.)

844 A steel has a yield strength of 690 MPa (100,000 psi), and a K_{Ic} value of 70 MPa·m$^{1/2}$ (63,700 psi·in.$^{1/2}$). What will be the limiting design stress if the maximum tolerable crack is 2.5 mm (0.10 in.) and no plastic deformation is permitted? (The plate dimensions require a geometric factor of 1.1.)

845 Engineers who previously designed riveted ships paid little attention to transition temperatures, unlike those who currently design welded ships. Why?

846 Explain why rubber is brittle at liquid-nitrogen temperatures (77 K).

TERMS AND CONCEPTS

Acceptor An impurity that accepts electrons from the valence band and, therefore, produces electron holes in the valence band.

Acceptor saturation Filling of acceptor sites. As a consequence, additional thermal activation does not increase the number of intrinsic carriers.

Activation energy (E or Q) Energy barrier that must be met before a reaction can occur.

Additive (plastics) Minor addition for modifying properties or performance.

Age hardening See *precipitation hardening.*

Alloy A metal containing two or more elements.

Amorphous Noncrystalline, and without long-range order.

Anion Negative ion.

Anisotropic Having different properties in different directions.

Annealing point (glass) Stress-relief temperature ($\sim T_g$). This temperature provides a viscosity of $\sim 10^{12}$ Pa·s ($\sim 10^{13}$ poises).

Annealing (strain-hardened metal) Heating a cold-worked metal to produce recrystallization and therefore softening.

Annealing (steels) For a *full* anneal, austenite is formed, then the steel is cooled slowly enough to form pearlite. (Annealing to remove strain hardening is called *process* anneal. In that process, the steel is heated to just below the eutectoid temperature.)

Anode The electrode that supplies electrons to the external circuit. The electrode that undergoes corrosion. The negative electrode.

Anode reactions Electrochemical oxidation reactions.

Anodized Surface coated with an oxide layer; achieved by making the part an anode in an electrolytic bath.

Antiferromagnetism Magnetic coupling with balanced alignment of oppositely oriented spins; therefore, the net magnetism is zero.

Arrhenius equation Thermal activation relationship. (See comments with Example 6–4.2.)

ASTM grain size (G.S.#) Standardized grain counts. (See Eq. 7–1.3).

Atactic Lack of long-range repetition in a linear polymer (as contrasted to isotactic).

Atomic mass unit (amu) One-twelfth of the mass of C^{12}; also, g/(0.602 . . . $\times 10^{24}$).

Atomic number The number of electrons possessed by an uncharged atom. The number of protons per atom.

Atomic radius (R) One-half of the interatomic distance of like atoms.

Atomic weight Atomic mass expressed in atomic mass units, or in g per mole.

Attenuation (optical) Reduction of radiation intensity with distance.

Austempering Transformation of $\gamma \rightarrow (\alpha + \overline{C})$ below the "knee" of the I-T curve to form bainite, which is a dispersion of carbide in a ferrite matrix.

Austenite (γ) Face-centered cubic (fcc) iron, or an iron-rich, fcc solid solution.

Austenite decomposition Eutectoid reaction that changes austenite to (α + carbide).

Austenization Heat treatment to dissolve carbon into fcc iron, thereby forming austenite.

Bainite Microstructure of ($\alpha + \overline{C}$) formed isothermally below the "knee" of the I-T curve.

Band, conduction (CB) Band above the energy gap. Electrons become carriers when they are activated to this band.

Band, valence (VB) Filled energy band below the energy gap. Conduction in this band requires electron holes.

BH product Energy required for demagnetization. The maximum product of the second quadrant usually is used.

Bifunctional (molecule) Molecule with two reaction sites for joining with adjacent molecules.

Birefringence Difference in index of refraction with orientation.

Blow molding Processing by expanding a parison into a mold by air pressure.

Body-centered cubic (bcc) The center of the cube is identical to the cube corners. All translations of $\pm a/2, \pm b/2, \pm c/2$ from any location produce positions that are identical in every respect.

Boltzmann's constant (k) Thermal energy coefficient ($13.8 \ldots \times 10^{-24}$ J/K, or 86.1×10^{-6} eV/K).

Bond angle Angle between stereospecific bonds in molecules, or in covalent solids.

Bond energy Energy required to separate two chemically bonded atoms. Generally expressed as energy per mole of 0.6×10^{24} bonds.

Bond length Interatomic distance between centers of covalently bonded atoms.

Boundary stresses Shear stresses between phases that arise from differential dimensional changes.

Bragg's law Diffraction law for periodic structures (Eq. 3–8.2).

Branching Bifurcation of a polymer chain.

Brass An alloy of copper (>60 percent) plus zinc.

Bronze An alloy of copper and tin (unless otherwise specified; e.g., an aluminum bronze is an alloy of copper and aluminum).

Bulk modulus (K) Hydrostatic pressure per unit volume strain.

Butadiene-type compound Prototype for several rubbers based on $C{=}C{-}C{=}C$. (See Table 4–3.1.)

Carbide ($\overline{C}$) Compound of metal and carbon. (Unless specifically stated otherwise, refers to the iron-base carbide (Fe_3C) in this text, and is labeled $\overline{C}$.)

Carburize Introduction of carbon through the surface of a steel by diffusion. The purpose is to harden the surface.

Casting Shaping by solidifying a liquid or suspension.

Cathode The electrode that receives electrons from the external circuit. The electrode on which electroplating is deposited. The positive electrode.

Cathode reactions Electrochemical reduction reactions. (See Eqs. 14–2.2b, 14–2.4, 14–2.5, and 14–2.6.)

Cation Positive ion.

Cell, composition An electrochemical cell between electrodes of different compositions.

Cell, concentration An electrochemical cell arising from nonequal electrolyte concentrations. (The more dilute solution establishes the anode.)

Cell, galvanic An electrochemical cell containing two dissimilar metals in an electrolyte.

Cell, oxidation An electrochemical cell arising from unequal oxygen potentials. (The oxygen-deficient area becomes the anode.)

Cell, stress An electrochemical cell in which a plastically strained area produces an anode.

Ceramic A material that is a compound of metallic and nonmetallic elements.

Charge carriers Electrons in the conduction band provide n-type (negative) carriers. Electron holes in the valence band provide p-type (positive) carriers.

Charge density (D) Charge per unit area (e.g., on an electrode).

Cis Prefix denoting unsaturated positions on the same side of the polymer chain. (Also see *trans*.)

Coalescence Growth of dispersed particles within a microstructural matrix.

Coercive field (electric, $-\mathscr{E}_c$) Electric field required to remove remanent polarization.

Coercive field (magnetic, $-H_c$) Magnetic field required to remove remanent magnetic induction.

Cold work, percent Amount of cold working, calculated from the change in cross-sectional area, $100(A_0 - A_f)/A_0$.

Cold working Plastic deformation below the recrystallization temperature.

Component (phases) One of the basic chemical substances required to create a chemical mixture or solution.

Composite Unified combinations of two (or more) distinct materials.

Compounds, III–V Semiconducting compounds of Group III and Group V elements.

Compound A phase composed of two or more elements in a given ratio.

Concentration gradient (dC/dx) Change in concentration with distance. Concentration is expressed in number per unit volume.

Conductivity Transfer of thermal or electrical energy along a potential gradient.

Conductivity (electrical) Product of carrier density, carrier charge, and charge mobility. Reciprocal of

resistivity. Charge flux per unit voltage gradient.

Coordination number (CN) Number of closest ionic or atomic neighbors.

Copolymer Polymers with more than one type of mer.

Copolymer, block Copolymer with clustering of like mers along the chain.

Copolymer, graft Polymeric molecule with branches of a second type of polymer.

Coring Segregation during solidification (occurs because the initial solid does not equilibrate with the succeeding solid).

Corrosion Surface deterioration by electrochemical reaction.

Coulombic forces Forces between charged particles, particularly ions.

Covalent bond A pair of shared electrons that produces a bond between two adjacent atoms.

Creep Time-dependent strain that occurs as a result of mechanical stresses.

Creep rate Creep strain per unit time.

Crevice corrosion Localized corrosion in an oxidation cell.

Critical shear stress Minimum shear stress to initiate slip on a crystal plane.

Cross-linking The tying together of adjacent polymer chains.

Crystal A solid with a long-range repetitive pattern of atoms in the three coordinate directions.

Crystal direction [uvw] A line from an arbitrary origin through a selected unit-cell location. The indices are the lattice coefficients of that location.

Crystal plane (hkl) A two-dimensional array of ordered atoms. (See also *Miller indices*.)

Crystal pulling Method of growing single crystals by slowly pulling a seed crystal away from a molten pool.

Crystal system Categorization of unit cells by axial and dimensional symmetry.

Curie point (electric) Transition temperature between a symmetric crystal and polar crystal.

Curie temperature (magnetic, T_c) Transition temperature for magnetic-domain formation.

Debonding Uncoupling of reinforcement fibers from the matrix of a composite.

Decarburization Removal of carbon from the surface zone of steel by elevated temperature oxidation.

Defect semiconductor Nonstoichiometric compounds of elements that have more than one valence.

Defect structure Nonstoichiometric compounds that contain either vacancies or interstitials within the structure.

Deformation, elastic Reversible deformation without permanent atomic (or molecular) displacements.

Deformation, plastic Permanent deformation arising from the displacement of atoms (or molecules) to new surroundings.

Deformation, viscoelastic Concurrent viscous flow and elastic deformation.

Degradation Destruction of polymers to smaller molecules.

Degree of polymerization, n Mers per average molecule. Also, molecular mass/mer mass.

Delocalized electrons Valence electrons not bound to specific atoms.

Depleted zone The region adjacent to an n–p junction that lacks charge carriers. (A reverse voltage bias increases the width of this depleted zone.)

Devitrification Crystallization of glass. Process for producing "glass-ceramics."

Diamagnetism Repulsion of magnetic flux because the permeability is less than that of a vacuum. (Zero for superconductors.)

Diamond-cubic structure The fcc structure of an element with CN = 4. (See Fig. 3–2.6a.)

Dielectric An insulator. A material that can be placed between two electrodes without conduction.

Dielectric constant, relative (κ) Ratio of charge density arising from an electric field (1) with, and (2) without, the material present.

Dielectric strength Electrical breakdown potential of an insulator per unit thickness.

Diffraction line The diffracted beam from a crystal surface. (Detected photographically or with a Geiger-type counter.)

Diffraction (x-ray) Deviation of an x-ray beam by a periodic structure.

Diffusion The movement of atoms or molecules in a material.

Diffusion flux (J) Transport per unit area and time.

Diffusivity (D) Diffusion flux per unit concentration gradient.

Dipole An electrical couple with positively and negatively charged ends.

Dipole moment (p_e) Product of electric charge and charge separation distance.

Dislocation, edge ($\perp$) Linear defect at the edge of an extra crystal plane. The slip vector is perpendicular to the defect line.

Dislocation, screw (s) Linear defect with slip vector parallel to the defect line.

Dispersion Difference in index of refraction with wavelength.

Domain (electric) Microstructural region with coordinated alignment of electric dipoles.

Domain (magnetic) Microstructural region of coordinated magnetic alignments.

Domain boundary (Bloch wall) Transition zone between magnetic domains; moves during magnetization and demagnetization.

Domain boundary (ferroelectric) Transition zone between electrical domains.

Donor An impurity that donates carriers to the conduction band.

Donor exhaustion Depletion of donor electrons. When it occurs, additional thermal activation does not increase the number of extrinsic carriers.

Drawing Mechanical forming by tension through, or in, a die (e.g., wire drawing (Fig. 9–1.3), or sheet drawing). This process usually is carried out at temperatures below the recrystallization temperature.

Drift velocity ($\bar{v}$) Net velocity of electrons in an electric field.

Ductility Total permanent (plastic) strain prior to fracture; measured as elongation, or as reduction of area.

Ductility-transition temperature (T_{dt}) Temperature that separates the regime of brittle fracture from the higher temperature range of ductile fracture.

Earlywood First wood growth during the growing season. The part of the wood-growth ring that has larger, thinner walled cells. (Also called spring wood.)

Elastic modulus (E) Stress per unit of elastic strain.

Elastic strain (e_{el}) Strain that is recoverable when the load is removed.

Elastomer Polymer with a large elastic strain. This strain arises from the unkinking of the polymer chains.

Electric field ($\mathscr{E}$) Potential gradient, V/m.

Electrode potential (ϕ) Voltage developed at an electrode (referenced to a standard electrode).

Electrolyte Conductive ionic solution (liquid or solid).

Electron charge (q) The charge of 0.16×10^{-18} coul (or 0.16×10^{-18} A·s) carried by each electron.

Electron hole (p) Electron vacancy in the valence band that serves as a positive-charge carrier.

Electron–hole pair An electron in the conduction band and an accompanying electron hole in the valence band, which results when the electron jumps the energy gap in an intrinsic semiconductor.

Electronic repulsion Repelling force of too many electrons in the same vicinity.

Elongation (El.) Total plastic strain before fracture, measured as the percent of axial strain. (A gage length must be stated.)

End-quench test (Jominy bar) Standardized test, performed by quenching from one end only, for determining hardenability.

Endurance limit The maximum stress allowable for unlimited stress cycling.

Energy distribution Spectrum of energy levels arising from thermal activation.

Energy band Permissible range of energy levels for delocalized electrons in a material.

Energy gap (E_g) Forbidden energies between the valence band and the conduction band.

Energy well Potential energy minimum between two atoms.

Engineering The adaptation of materials and/or energy for society's needs. (Other definitions are possible.)

Equilibrium The state at which net reaction ceases (because the minimum free energy has been reached).

Eutectic, induced A eutectic reaction resulting from segregation during solidification.

Eutectic composition Composition of the liquid-solution phase that possesses a minimum melting temperature (at the intersection of two solubility curves).

Eutectic reaction $L_2 \rightleftharpoons S_1 + S_3$.

Eutectic temperature Temperature of the eutectic reaction at the intersection of two solubility curves.

Eutectoid composition Composition of the solid-solution phase that possesses a minimum decomposition temperature (at the intersection of two solid solubility curves).

Eutectoid reaction $S_2 \rightleftharpoons S_1 + S_3$.

Eutectoid temperature Temperature of the eutectoid reaction at the intersection of two solid solubility curves.

Extrusion Shaping by pushing the material through a die (Fig. 9–1.2c).

Face-centered cubic (fcc) A structure in which the centers of the cube faces are identical to one another and to the cube corners. All translations of $\pm a/2$, 0, $\pm c/2$ (and their permutations) from any location produce positions that are identical in every respect.

Family of directions $\langle uvw \rangle$ Crystal directions that are identical except for our arbitrary choice of axes.

Family of planes $\{hkl\}$ Crystal planes that are identical except for our arbitrary choice of axes.

Fatigue Time-delayed fracture; commonly occurs under cyclic loading or in a reactive environment.

Fatigue strength Design stress during the expected lifetime of a plastic.

Fermi distribution, $F(E)$ Probability of electron occupancy over the range of energy levels (Eq. 11–3.2).

Fermi energy (E_f) Energy level with a 50-percent probability of occupancy. Maximum filled energy level of a metal at 0° K.

Ferrimagnetism Net magnetism arising from unbalanced alignment of magnetic ions within a crystal.

Ferrite (α) Body-centered cubic iron; or an iron-rich, bcc solid solution.

Ferrites Compounds containing trivalent iron; commonly magnetic.

Ferroelectrics Materials with spontaneous electric-dipole alignment.

Ferromagnetism Metallic materials with spontaneous magnetic alignment.

Fiber debonding Loss of cohesion between fiber and matrix caused by shear stresses.

Fiber-reinforced plastic (FRP) A product with a polymer matrix and a fiber reinforcement (commonly glass).

Fick's first law Proportionality between diffusion flux and concentration gradient.

Filler Particulate or fibrous additive for reinforcement and dilution.

Floating zone Method of growing single crystals, which melts an isolated zone within a bar. The material solidifies as a single crystal on the bottom side of the rising molten zone.

Fluorescence Luminescence that occurs almost immediately after excitation.

Forward bias Potential direction that moves the charge carriers across the n–p junction.

Fracture, brittle Fracture with negligible plastic deformation and minimum energy absorption.

Fracture, ductile Fracture accompanied by plastic deformation and, therefore, by energy absorption.

Fracture toughness The critical stress intensity factor, K_{Ic}, for fracture propagation.

Galvanic protection Corrosion protection achieved by making the material cathodic.

Galvanic series Sequence (cathodic to anodic) of corrosion susceptibility for common metals. Varies with passivity and with electrolyte composition. (See also *electrode potentials*, which are for standard electrolytes.)

Galvanized steel Zinc-coated steel. The zinc serves as a sacrificial anode.

Glass An amorphous solid below its transition temperature. A glass lacks long-range crystalline order, but normally has short-range order.

Glass-transition temperature (T_g) Transition temperature between a supercooled liquid and its rigid glassy solid.

Grain Individual crystal in a polycrystalline microstructure.

Grain (wood) Seasonal growth pattern, alternating between earlywood and latewood.

Grain boundary The zone of crystalline mismatch between adjacent grains.

Grain boundary area (S_v) Intergranular area/unit volume; for example, in.^{2}/in.^{3} or mm^2/mm^3.

Half-cell reaction See Table 14–2.1.

Hall effect Cross-voltage induced by a current moving at 90° to a magnetic field.

Hardenability The ability to develop maximum hardness by avoiding the $\gamma \rightarrow (\alpha + \overline{C})$ reaction.

Hardenability curve Hardness profile of end-quench test bar.

Hardness Index of resistance to penetration (or to scratching if the indentor is moved). There are sev-

eral common test procedures—Brinnell, Rockwell, and so on.

Hardness traverse Profile of hardness values.

Heat of fusion (H_f) Energy per mole (or other stated unit) to melt a material.

Hexagonal close-packed metal (hcp) A hexagonal metal with CN = 12, and PF = 0.74.

High-stiffness composite Composite with a high elastic modulus–to-density ratio, E/ρ.

Homogenization (soaking) Heat treatment to equalize composition by diffusion.

Hot-working Deformation that is performed above the recrystallization temperature, so that annealing occurs concurrently.

Hydrogen bond Secondary bonds in which the hydrogen atom (proton) is attracted to electrons of neighboring atoms.

Hydrogen electrode Standard reference electrode with the following half-cell reaction:

$$H_2 \rightarrow 2H^+ + 2\ e^-$$

Hypereutectoid A composition with *more* solute than is found in the eutectoid composition.

Hypoeutectoid A composition with *less* solute than is found in the eutectoid composition.

Immiscibility Mutually insoluble phases.

Imperfection (crystal) Defect in a crystal; may be a point, a line, or a boundary.

Impressed current Direct current applied to make a metal cathodic during service.

Index of refraction (n) Ratio of light velocity in a vacuum to that in the material.

Induced compression Prestressing of the surface region of a material, commonly by differential thermal contraction.

Induction (magnetic, B) Flux density in a magnetic field.

Induction (remanent, B_r) Flux density remaining after the external magnetic field has been removed.

Induction hardening Hardening by heating the surface with high-frequencing induced currents.

Inhibitor An additive to an electrolyte that promotes passivation.

Injection molding Process of pressure molding a material in a closed die. For thermoplasts, the die must be cooled. For thermosets, the die is maintained at the curing temperature of the plastic.

Insulator (electrical) Material with a filled valence band and a large energy gap.

Interfacial stress Shear stresses that transfer the load between the matrix and the reinforcement.

Intergranular precipitation Nucleation and growth of a second phase along the boundaries of preexisting grains.

Internal reflection Surface reflection of light within the higher-index phase.

Interplanar spacing (d_{hkl}) Perpendicular distance between two adjacent planes with the same index.

Interrupted quench Two-stage quenching of steel that involves heating to form austenite, initial quenching to a temperature above the start of martensite formation, followed by a second (slower) cooling to room temperature.

Interstice Unoccupied space between atoms or ions.

Intragranular precipitation Nucleation and growth of a particulate phase within preexisting grains.

Ion An atom that possesses a charge because it has added or removed electrons.

Ion vacancy ($\square$) Unoccupied ion site within a crystal structure. The charge of the missing ion must be compensated appropriately.

Ionic bond Atomic bonding through coulombic attraction of unlike ions.

Ionic radius (r, R) Semiarbitrary radius assigned to ions. The sum of the radii of two adjacent ions is equal to their interatomic distance. Varies with coordination number. (See the footnote with Appendix B.)

Isotactic Long-range repetition in a polymer chain (in contrast to atactic).

Isotherm Line of constant temperature.

Isothermal precipitation Precipitation from supersaturation at constant temperature.

Isothermal Transformation (I-T) Transformation, with time, by holding at a constant temperature.

I-T curve Plot of reaction progress for isothermal transformation.

Jominy distance (D_{qe}) Cooling rate indexed to a distance from the quenched end of a Jominy bar.

Junction (n–p) Interface between an n-type and a p-type semiconductor.

Laser Light amplifications stimulated by emission of radiation.

Latewood The part of the wood grain that has smaller, thicker-walled cells. Formed late in the growing season. (Also called summer wood.)

Lattice A space arrangement with extended periodicity.

Lattice constants (a, b, c) Edge dimensions of a unit cell.

Lever rule (inverse) Equation for interpolation to determine the quantity of phases in an equilibrated mixture.

Light-emitting diode (LED) An $n-p$ junction device designed to produce photons by recombination.

Linear density Items (e.g., atoms) per unit length.

Liquidus The locus of temperatures above which there is only liquid.

Lone pair Electron pairs in a nonconnecting sp^3 orbital.

Long-range order A repetitive pattern over many atomic distances.

Luminescence Light emitted by the energy released as conduction electrons recombine with electron holes.

Macromolecules Molecules made up of hundreds to thousands of atoms.

Magnet, permanent (hard) Magnet with a large $(-BH)$ energy product, which therefore maintains domain alignment.

Magnet, soft Magnet that requires negligible energy for domain randomization.

Magnetization (M) Magnetic-moment density; that is, magnetic moment per unit volume.

Magneton, Bohr (β) Magnetic moment of an electron $(9.27 \times 10^{-24}$ A·m^2).

Martensite (M) A phase arising from a diffusionless, shearlike phase transformation. In steels containing >0.15 w/o carbon, martensite is a hard, brittle, body-centered tetragonal phase that is supersaturated with carbon.

Materials (engineering) Substances used for technical products. (These include metals, ceramics, polymers, semiconductors, glasses, and natural substances such as wood and stone, but generally exclude food, drugs, and related substances.)

Materials balance Mathematical calculation of "the whole is equal to the sum of its parts."

Matrix Principal material of a composite that envelopes the reinforcement.

Mean chord length, $\overline{L}$ A measure of grain size, based on the average boundary intercept distance.

Mer, ---( )--- The smallest repetitive unit in a polymer.

Metallic bond Interatomic bonds in metals characterized by delocalized electrons in the energy bands.

Metal (Chapter 1) Material characterized by its high electrical and thermal conductivities. (Chapter 2) Element located in the left and lower portions of the periodic table, as normally presented. (Chapter 11) Material with only a partially filled valence band.

Microfibrils Discrete filamentary units of the wood-cell wall.

Microcracking A multiplicity of cracks on a microscopic scale in the region of failure.

Microstructure Structure of grains and phases. Generally requires magnification for observation.

Miller index (hkl) Index relating a plane to the references axes of a crystal. *Reciprocals* of axial intercept, cleared of fractions and of common multipliers.

Mixture A combination of two, or more, phases.

Mobility (μ) The drift velocity of an electric charge per unit electric field, $\overline{v}/\mathscr{E} = $ (m/s)(V/m). Alternatively, the diffusion coefficient of a charge for a potential difference, $D/E = $ (m^2/s)/V.

Modulus of elasticity (elastic modulus, Young's modulus) Stress per unit elastic strain.

Mole Mass equal to the molecular weight of a material. Also, $0.602 . . . \times 10^{24}$ molecules.

Molecular crystal Crystals with molecules as basic units (as contrasted to atoms).

Molecular length ($\overline{L}$) End-to-end, root-mean length.

Molecular orientation Collective alignment of macromolecules, usually by an applied axial stress.

Molecular weight Mass of one molecule (expressed in amu), or the mass of $0.602 . . . \times 10^{24}$ molecules (expressed in grams). Mass of one formula weight.

Molecular weight (mass-average), $\overline{M}_m$ Average molecular size based on the mass fraction.

Molecular weight (number-average), $\overline{M}_n$ Average molecular size based on the number fraction.

Molecule Finite group of atoms bonded by strong attractive forces (primary bonds). Bonding between atoms is by weak, secondary bonds.

Monomer A molecule with a single mer.

NaCl structure The fcc structure of an AX compound with CN = 6. (See Figs. 3–1.1 and 3–2.5.)

Nernst equation Electrode potential as a function of electrolyte concentration and temperature (Eq. 14–2.3).

Network structure Molecular structure with primary bonds in three dimensions.

Nonstoichiometric compounds Compounds with noninteger atom (or ion) ratios.

Normalizing Heating of steel into the austenite range ($\sim 50°$ C, or $100°$ F) so that it will contain a uniform, fine-grained microstructure.

Nucleation The start of the growth of a new phase.

Nucleation, heterogeneous Nucleation on a preexisting surface (or by introduction of "seeds").

Nucleation, homogeneous Unaided nucleation within a preexisting phase.

Orbital Wave probabilities of atomic or molecular electrons.

Orthorhombic A crystal with three unequal, but mutually perpendicular, axes.

Overaging Aging continued until softening occurs.

Oxidation (general) The raising of the valence state of an element.

Paramagnetism Magnetic structure with the magnetic moments that are uncoupled, except in the presence of an applied magnetic field.

Passivation The condition in which normal corrosion is impeded by an absorbed surface film.

Pearlite (P) A lamellar mixture of ferrite and carbide formed by decomposing austenite of eutectoid composition.

Performance (materials) The behavior (and alteration) of materials during manufacture and or service.

Periodic table See Fig. 2–1.1.

Permeability (magnetic, μ) Ratio of induction to magnetic field, B/H.

Permittivity (ϵ) Ratio of charge density to electric field in a vacuum, 8.85×10^{-12} C/V · m.

Phase A physically homogeneous part of a materials system. (See Section 5–1.)

Phase, transition Metastable phase that forms as an intermediate step in a reaction.

Phase boundary Compositional or structural discontinuity between two phases.

Phase diagram Graph of phase-stability areas with composition and environment (usually temperature) as the coordinates.

Phase diagram, isothermal cut A constant-temperature section of a phase diagram.

Phase diagram, one-phase area Part of a phase diagram possessing a single unsaturated solution.

Phase diagram, two-phase area Part of a phase diagram beyond the solubility limit curves, such that a second phase is necessary. Temperature and phase compositions *cannot* be varied independently.

Phase diagram, three-phase temperature Invariant temperature in a binary system at which three phases can coexist.

Phases, chemical compositions of Phase compositions expressed in terms of chemical components.

Phases, quantities of Material compositions expressed in terms of phase fractions.

Phosphorescence Luminescence that is delayed by extended relaxation times.

Photoconduction Conduction arising from photon activation of electrons across the energy gap.

Photomultiplier Device that uses a photon to trigger an electron avalanche in a semiconductor. Thus, weak light signals can be amplified.

Photon A quantum of light.

Photovoltaic Production of an electrical potential by incident light.

Piezoelectric Dielectric materials with structures that are asymmetric, such that their centers of positive and negative charges are not coincident. As a result, the polarity is sensitive to pressures that change the dipole distance and therefore the polarization.

Pit corrosion Localized corrosion that penetrates a metal nonuniformly.

Planar density Items (e.g., atoms) per unit area.

Plastic Material composed primarily of polymers.

Plastic constraint Prevention of plastic deformation in a ductile material caused by the presence of an adjacent rigid material.

Plastic strain (e_{pl}) Permanent strain. It is not recoverable, since the atoms have moved to new neighbors.

Plasticizer An additive of small-molecular-weight molecules to a polymeric mix for the purpose of reducing the viscosity.

Point defect Crystal imperfections involving one (or a very few) atoms.

Poisson's ratio (v) Absolute ratio of lateral to axial strain.

Polar group A local electric dipole within a molecule.

Polarization, dielectric ($\mathscr{P}$) Electric dipole density; that is, dipole moment per unit volume.

Polarization, electronic (p_e) Dipole moment from electronic displacements.

Polarization, ionic (p_i) Dipole moment from ionic displacements.

Polarization, molecular (p_m) Dipole moment from molecular orientation.

Polarization, remanent ($\mathscr{P}_r$) Polarization remaining after the external electric field has been removed.

Polyblend A mixture of two or more polymeric phases.

Polycrystalline Material with multiple crystals and accompanying grain boundaries.

Polydispersity index, PDI The $\overline{M}_m/\overline{M}_n$ ratio. (Used as a measure of molecular-size distribution).

Polyfunctional Molecule with multiple (>2) reaction sites.

Polymer Nonmetallic material consisting of (large) macromolecules composed of many repeating units; the technical term for a plastic.

Polymorphism A composition with more than one crystal structure (allotrophic).

Precipitation Separation from a supersaturated solution.

Precipitation hardening Hardening by the formation of clusters prior to precipitation (also called age hardening).

Preferred orientation A nonrandom alignment of crystals or molecules.

Prestressing Introduced compressive stresses, usually obtained by tension rods or similar mechanical means.

Primary bond Strong (>200 kJ/mol) interatomic bonds of the covalent, ionic, and metallic types.

Proeutectoid A phase that separates from a solid solution *before* the latter decomposes into the eutectoid product.

Property Characteristic quality of a material. (Quantitative values are preferable.)

Proportional limit The limit of the proportional range of the stress–strain curve. (Elastic strain increases beyond this "limit," but is masked by plastic strain.)

Quench Process of accelerated cooling, usually in agitated water or oil.

Radiation damage Structural defects arising from exposure to radiation.

Rate ($R = t^{-1}$) Reaction per unit time.

Recombination Annihilation of electron–hole pairs.

Recovery Loss of resistivity, or related behaviors that originated during strain hardening, by annealing out point defects. (See also *recrystallization*.)

Recrystallization The formation of new annealed grains from previously strain-hardened grains.

Recrystallization temperature Temperature above which recrystallization is spontaneous.

Rectifier Electric "valve" that permits forward current and prevents reverse current.

Reduction Removal of oxygen from an oxide. Also, the lowering of the valence level of an element.

Reduction of area (R of A) Total plastic strain before fracture, measured as the percent decrease in cross-sectional area at the fracture point.

Refractory A material capable of withstanding extremely high temperatures.

Reinforcement Component of composites with a high elastic modulus and high strength.

Relaxation time (τ) Time required for exponential decay to $1/e$ of the initial value.

Repetition distance Translation vector between two identical lattice points.

Resistivity (ρ) Reciprocal of conductivity (usually expressed as ohm $\cdot$ m).

Resistivity coefficient, solutioin (y_x) Coefficient of resistivity versus solid solution content (atom fraction basis), $d\rho/dX$.

Resistivity coefficient, thermal (y_T) Coefficient of resistivity versus temperature, $d\rho/dT$.

Rolling Mechanical working through the use of two rotating rolls (Fig. 9–1.2).

Root mean square length ($\overline{L}$) Statistical end-to-end length of linear molecules.

Sacrificial anode Expendable metal that is anodic to the product that is to be protected.

Scale Surface layer of oxidized metal.

Scission Fragmentation of a polymer by radiation.

Secondary bonds Weak (<40 kJ/mol) interatomic

bonds arising from dipoles within the atoms or molecules.

Segregation Compositional nonuniformity due to delayed reactions.

Semiconductor A material with controllable conductivities, intermediate between an insulator and a conductor.

Semiconductor, extrinsic Semiconduction from impurity sources.

Semiconductor, intrinsic Semiconduction of a pure material. The electrons are excited across the energy gap.

Semiconductor, *n*-type Semiconductor in which impurities provide donor electrons to the conduction band. Electrons are the majority carriers.

Semiconductor, *p*-type Semiconductor in which impurities provide acceptor sites for electrons from the valence band. Electron holes are the majority carriers.

Shear modulus (*G*) Shear stress per unit shear strain.

Shear strain (*γ*) Tangent of shear angle, *α*, developed from shear stress.

Shear stress (*τ*) Shear force per unit area.

Sheet molding Thermal forming of plastic products from starting sheets of fiber-reinforced plastics.

Short-range order Specific first-neighbor arrangement of atoms, but random long-range arrangements.

Simple cubic (sc) A cubic unit cell with lattice points at the corners only. (It may contain atoms at other locations, which are not identical.)

Sintering Bonding by thermal means.

Slip direction Crystal direction of the displacement vector on which slip takes place.

Slip plane Crystal plane along which slip occurs.

Slip system Combination of slip directions on slip planes that have low critical shear stresses.

Slip vector (b) Displacement distance of a dislocation. It is parallel to a screw dislocation and perpendicular to an edge dislocation.

***S*-*N* curve** Plot of fatigue stress versus number of stress cycles.

Solder Metals that melt below approximately 425° C (800° F) and are used for joining. Commonly, these are Pb–Sn alloys; however, other alloys (even glass) may be used.

Solid solution A homogenous crystalline phase with more than one chemical component.

Solid solution, interstitial Crystals that contain a second component in their interstices. The basic structure is unaltered.

Solid solution, ordered A substitutional solid solution with a preference by each of the components for specific lattice sites.

Solid solution, substitutional Crystals with a second component substituted for solvent atoms in the basic structure.

Solidus The locus of temperatures below which only solids are stable.

Solubility limit Maximum solute addition without supersaturation (See Section 5–1).

Solute The minor component of a solution.

Solution hardening Increased strength present in solid solutions (from pinning of dislocation by solute atoms).

Solution treatment Heating to induce solid solutions.

Solvent The major component of a solution.

Space charge Polarization from conductive particles in a dielectric.

Spalling Cracking from thermal stresses.

Spheroidite A two-phase microstructure of spherelike carbides in a ferrite matrix.

Spheroidization Process of making spheroidite, generally by extensive overtempering to develop spherelike carbides.

Spinning (polymers) Fiber-making process by filament extrusion.

Stainless steel High-alloy steel (usually containing Cr, or Cr + Ni) designed for resistance to corrosion and or oxidation.

Static fatigue Delayed fracture arising from stress corrosion.

Steel, low-alloy Steel containing up to 5 percent alloying elements other than carbon. Phase equilibria are related to the $Fe-Fe_3C$ diagram.

Steel, plain-carbon Basically Fe–C alloys with minimal alloy content.

Stereoisomer Isomeric molecules differing in mer configurations along the molecular chain.

Stereospecific Covalent bonding (and hydrogen bridges) between specific atom pairs (in contrast to the omnidirectional coulombic attractions).

Sterling silver An alloy of 92.5 Ag and 7.5 Cu. (This corresponds to nearly the maximum solubility of copper in silver.)

Stoichiometric compounds Compounds with integer atom (or ion) ratios.

Strain (e) Unit deformation. Elastic strain is recoverable; plastic strain is permanent.

Strain hardening Increased hardness (and strength) arising from plastic deformation below the recrystallization temperature.

Strength (S) Critical stress to produce failure. Yield strength, S_y is the stress to initiate the first plastic deformation; ultimate tensile strength, S_u, is the maximum calculated stress on the basis of the original area.

Stress (s) Force per unit area. Nominal stress is based on the original design area; true stress is based on the actual area.

Stress corrosion Corrosion accentuated by stresses; or fracture accelerated by corrosion.

Stress intensity factor (K_I) Stress intensity (tension) at the root of a crack, $Pa \cdot m^{-1/2}$.

Stress intensity factor, critical (K_{Ic}) A value (for a given material) that relates the depth of a propagating crack to the design limit for the nominal stress (Eq. 8–4.1).

Stress relaxation Decay of stress at a constant strain (by molecular rearrangement).

Stress relief Removal of residual stresses by heating.

Stress rupture Time-dependent rupture resulting from constant load (usually at elevated temperatures).

Stress–strain diagram Plot of stress as a function of strain. (Stress normally is plotted on the basis of original area.)

Superconductivity Property of zero resistivity at temperatures approaching absolute zero.

Supercooled ( ) A phase cooled beyond its range of full equilibrium. In this text, we identify a supercooled phase with parentheses; for example, (γ).

Surface Boundary between a condensed phase and gas.

Tempered glass Glass with surface compressive stresses induced by heat treatment.

Tempered martensite A two-phase microstructure of ferrite and carbide obtained by decomposing martensite.

Tempering A toughening process in which martensite is heated to initiate a ferrite-plus-carbide microstructure.

Tetragonal Two of three axes equal; all three at right angles.

Thermal expansion coefficient (α) (Change in dimension)/(change in temperature).

Thermistor Semiconductor device with a high dependence on temperature. It may be calibrated as a thermometer.

Thermoplastic Softens with increased temperature, thus becoming moldable; rehardens on cooling.

Thermosetting Hardens with heating. Plastics that undergo further (three-dimensional) polymerization with heating.

Tie-line Isotherm across a two-phase field connecting the solubility limits of two equilibrated phases.

Toughness A measure of the energy required for mechanical failure.

Trans **(polymers)** Prefix denoting unsaturated positions on the *opposite* side of the polymer chain. (See also *cis*.)

Transducer A material or device that converts energy from one form to another, specifically electrical energy to, or from, mechanical energy.

Transistor Semiconductor device for the amplification of current. There are two principal types: field effect and junction.

Translation Vector displacement between lattice points.

True stress (σ) Stress based on the actual area.

True strain (ϵ) Strain based on the actual area at the point of fracture.

T-T-T curve Time-Temperature-Transformation curve (See *I-T curves*.)

Twin (crystal) Two parts of a crystal that possess a mirror image relationship.

Ultimate strength (S_u) Maximum stress, based on nominal area.

Unit cell A small (commonly the smallest) repetitive volume that possesses the maximum symmetry of a crystal lattice.

Vacancy (□) A normally occupied lattice site that is vacant.

Valence electrons Removable electrons from the outer shell(s) of an atom.

Vinyl compounds (C_2H_3R), where R is one of several atoms or radicals.

Viscoelastic deformation Combined deformation by viscous flow and elastic strain.

Viscoelastic modulus (M_{ve}) Ratio of shear stress to the sum of elastic deformation, γ_{el}, and viscous flow, γ_f.

Viscoelasticity Combination of viscous flow and elastic behavior.

Viscosity (η) Ratio of shear stress to the velocity gradient of flow. Reciprocal of fluidity.

Viscous flow Time-dependent, irreversible flow.

Vulcanization Treatment of rubber with sulfur to cross-link elastomer chains.

Yield strength (S_y) Resistance to initial plastic deformation.

Young's modulus (E) Modulus of elasticity (axial). Stress per unit elastic strain.

Zener diode An n–p junction that has a controlled breakdown voltage with a reverse bias.

Zone refining Purification performed by passing a molten zone along a bar of material. The liquid retains the solute; the solid crystallizes at the solidus composition.