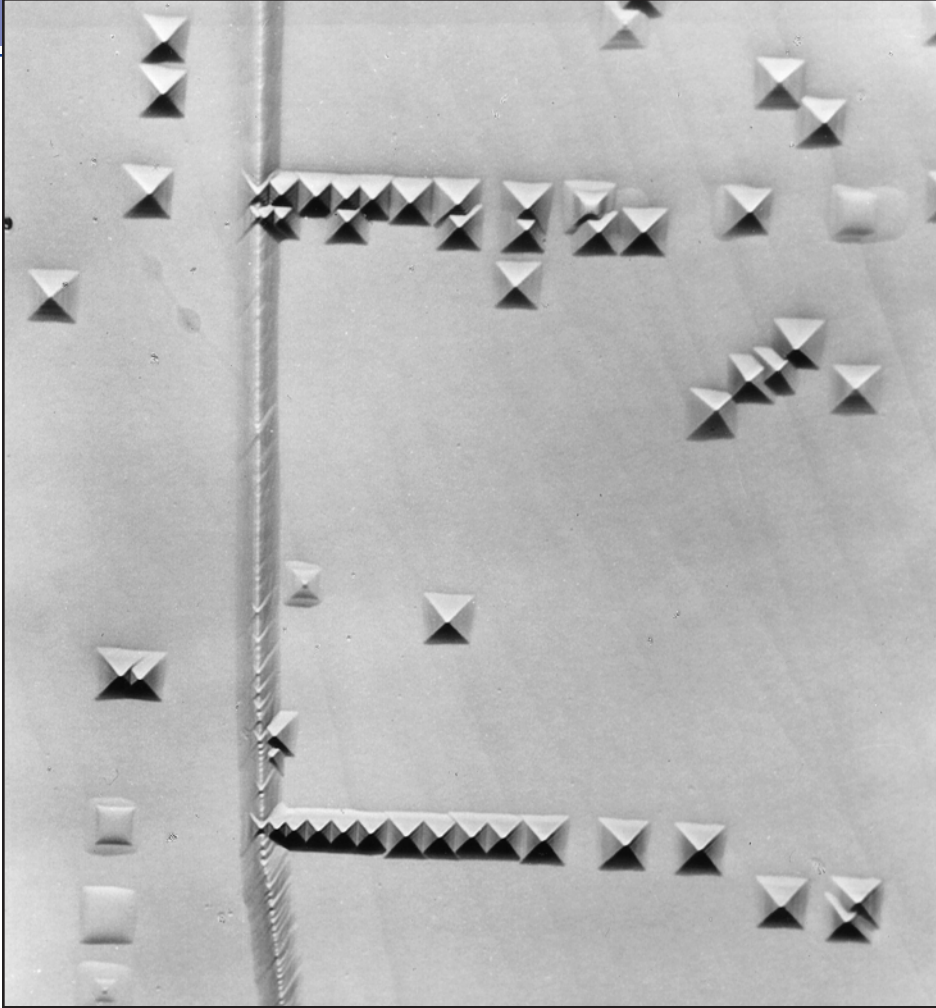


Chapter 7 Dislocations and Strengthening Mechanisms



In this photomicrograph of a lithium fluoride (LiF) single crystal, the small pyramidal pits represent those positions at which dislocations intersect the surface. The surface was polished and then chemically treated; these “etch pits” result from localized chemical attack around the dislocations and indicate the distribution of the dislocations. 750 $\times$. (Photomicrograph courtesy of W. G. Johnston, General Electric Co.)

WHY STUDY *Dislocations and Strengthening Mechanisms*?

With a knowledge of the nature of dislocations and the role they play in the plastic deformation process, we are able to understand the underlying mechanisms of the techniques that are used to strengthen and

harden metals and their alloys. Thus, it becomes possible to design and tailor the mechanical properties of materials—for example, the strength or toughness of a metal–matrix composite.

Learning Objectives

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

1. Describe edge and screw dislocation motion from an atomic perspective.
2. Describe how plastic deformation occurs by the motion of edge and screw dislocations in response to applied shear stresses.
3. Define slip system and cite one example.
4. Describe how the grain structure of a polycrystalline metal is altered when it is plastically deformed.
5. Explain how grain boundaries impede dislocation motion and why a metal having small grains is stronger than one having large grains.
6. Describe and explain solid-solution strengthening for substitutional impurity atoms in terms of lattice strain interactions with dislocations.
7. Describe and explain the phenomenon of strain hardening (or cold working) in terms of dislocations and strain field interactions.
8. Describe recrystallization in terms of both the alteration of microstructure and mechanical characteristics of the material.
9. Describe the phenomenon of grain growth from both macroscopic and atomic perspectives.

7.1 INTRODUCTION

Chapter 6 explained that materials may experience two kinds of deformation: elastic and plastic. Plastic deformation is permanent, and strength and hardness are measures of a material's resistance to this deformation. On a microscopic scale, plastic deformation corresponds to the net movement of large numbers of atoms in response to an applied stress. During this process, interatomic bonds must be ruptured and then reformed. In crystalline solids, plastic deformation most often involves the motion of dislocations, linear crystalline defects that were introduced in Section 4.5. This chapter discusses the characteristics of dislocations and their involvement in plastic deformation. Twinning, another process by which some metals plastically deform, is also treated. In addition, and probably most importantly, several techniques are presented for strengthening single-phase metals, the mechanisms of which are described in terms of dislocations. Finally, the latter sections of this chapter are concerned with recovery and recrystallization—processes that occur in plastically deformed metals, normally at elevated temperatures—and, in addition, grain growth.

Dislocations and Plastic Deformation

Early materials studies led to the computation of the theoretical strengths of perfect crystals, which were many times greater than those actually measured. During the 1930s it was theorized that this discrepancy in mechanical strengths could be explained by a type of linear crystalline defect that has since come to be known as a dislocation. It was not until the 1950s, however, that the existence of such dislocation defects was established by direct observation with the electron microscope. Since then, a theory of dislocations has evolved that explains many of the physical and mechanical phenomena in metals [as well as crystalline ceramics (Section 12.10)].

7.2 BASIC CONCEPTS

Edge and screw are the two fundamental dislocation types. In an edge dislocation, localized lattice distortion exists along the end of an extra half-plane of atoms, which also defines the dislocation line (Figure 4.3). A screw dislocation may be thought of

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Edge

as resulting from shear distortion; its dislocation line passes through the center of a spiral, atomic plane ramp (Figure 4.4). Many dislocations in crystalline materials have both edge and screw components; these are mixed dislocations (Figure 4.5).

Plastic deformation corresponds to the motion of large numbers of dislocations. An edge dislocation moves in response to a shear stress applied in a direction perpendicular to its line; the mechanics of dislocation motion are represented in Figure 7.1. Let the initial extra half-plane of atoms be plane *A*. When the shear stress is applied as indicated (Figure 7.1*a*), plane *A* is forced to the right; this in turn pushes the top halves of planes *B*, *C*, *D*, and so on, in the same direction. If the applied shear stress is of sufficient magnitude, the interatomic bonds of plane *B* are severed along the shear plane, and the upper half of plane *B* becomes the extra half-plane as plane *A* links up with the bottom half of plane *B* (Figure 7.1*b*). This process is subsequently repeated for the other planes, such that the extra half-plane, by discrete steps, moves from left to right by successive and repeated breaking of bonds and shifting by interatomic distances of upper half-planes. Before and after the movement of a dislocation through some particular region of the crystal, the atomic arrangement is ordered and perfect; it is only during the passage of the extra half-plane that the lattice structure is disrupted. Ultimately this extra half-plane may emerge from the right surface of the crystal, forming an edge that is one atomic distance wide; this is shown in Figure 7.1*c*.

slip

The process by which plastic deformation is produced by dislocation motion is termed **slip**; the crystallographic plane along which the dislocation line traverses is the *slip plane*, as indicated in Figure 7.1. Macroscopic plastic deformation simply corresponds to permanent deformation that results from the movement of dislocations, or slip, in response to an applied shear stress, as represented in Figure 7.2*a*.

Dislocation motion is analogous to the mode of locomotion employed by a caterpillar (Figure 7.3). The caterpillar forms a hump near its posterior end by pulling in its last pair of legs a unit leg distance. The hump is propelled forward by repeated lifting and shifting of leg pairs. When the hump reaches the anterior end,

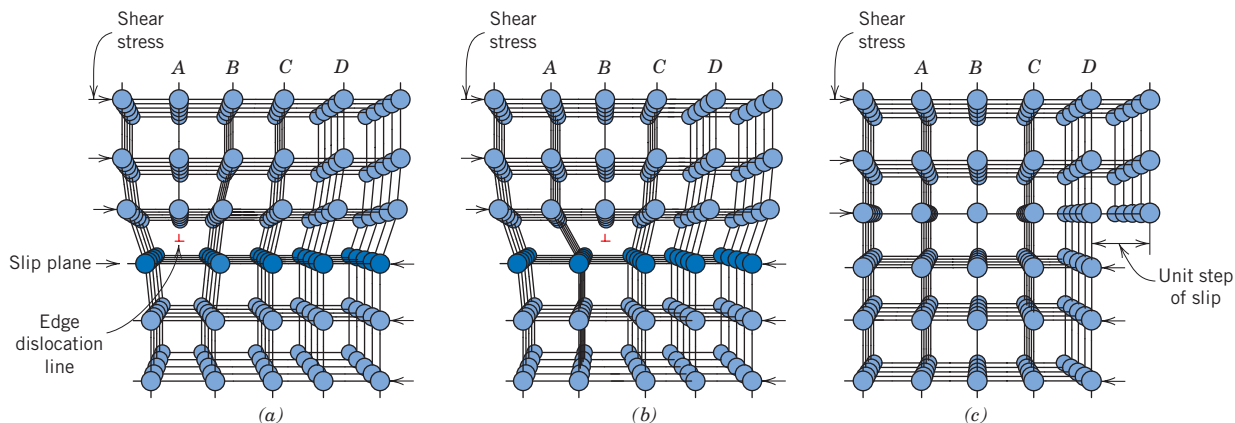
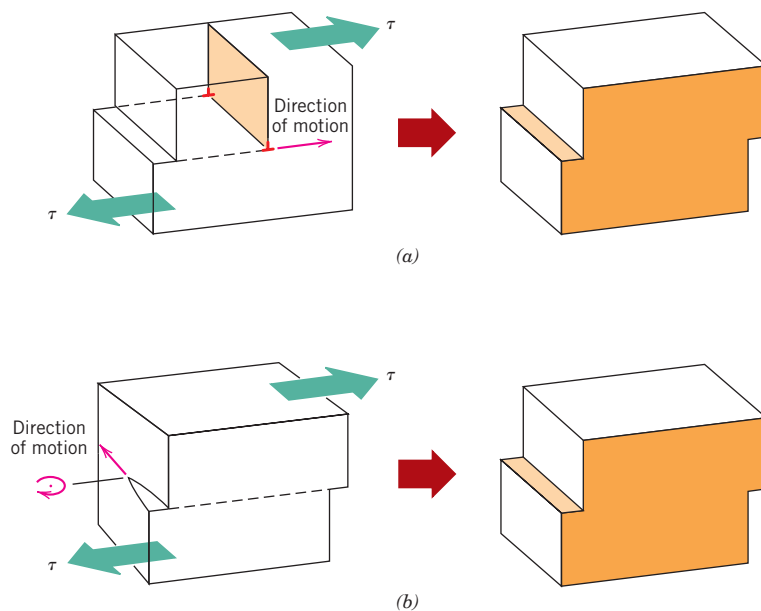


Figure 7.1 Atomic rearrangements that accompany the motion of an edge dislocation as it moves in response to an applied shear stress. (a) The extra half-plane of atoms is labeled *A*. (b) The dislocation moves one atomic distance to the right as *A* links up to the lower portion of plane *B*; in the process, the upper portion of *B* becomes the extra half-plane. (c) A step forms on the surface of the crystal as the extra half-plane exits. (Adapted from A. G. Guy, *Essentials of Materials Science*, McGraw-Hill Book Company, New York, 1976, p. 153.)

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Figure 7.2 The formation of a step on the surface of a crystal by the motion of (a) an edge dislocation and (b) a screw dislocation. Note that for an edge, the dislocation line moves in the direction of the applied shear stress τ ; for a screw, the dislocation line motion is perpendicular to the stress direction. (Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 70. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



the entire caterpillar has moved forward by the leg separation distance. The caterpillar hump and its motion correspond to the extra half-plane of atoms in the dislocation model of plastic deformation.



Screw Mixed

dislocation density

The motion of a screw dislocation in response to the applied shear stress is shown in Figure 7.2b; the direction of movement is perpendicular to the stress direction. For an edge, motion is parallel to the shear stress. However, the net plastic deformation for the motion of both dislocation types is the same (see Figure 7.2). The direction of motion of the mixed dislocation line is neither perpendicular nor parallel to the applied stress, but lies somewhere in between.

All metals and alloys contain some dislocations that were introduced during solidification, during plastic deformation, and as a consequence of thermal stresses that result from rapid cooling. The number of dislocations, or **dislocation density** in a material, is expressed as the total dislocation length per unit volume or, equivalently, the number of dislocations that intersect a unit area of a random section. The units of dislocation density are millimeters of dislocation per cubic millimeter or just per square millimeter. Dislocation densities as low as 10^3 mm^{-2} are typically found in carefully solidified metal crystals. For heavily deformed metals, the density may run as high as 10^9 to 10^{10} mm^{-2} . Heat treating a deformed metal specimen

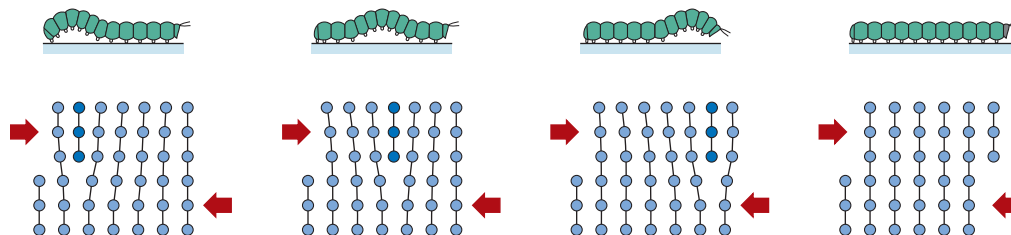


Figure 7.3 Representation of the analogy between caterpillar and dislocation motion.

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can diminish the density to on the order of 10^5 to 10^6 mm^{-2} . By way of contrast, a typical dislocation density for ceramic materials is between 10^2 and 10^4 mm^{-2} ; also, for silicon single crystals used in integrated circuits the value normally lies between 0.1 and 1 mm^{-2} .

7.3 CHARACTERISTICS OF DISLOCATIONS

Several characteristics of dislocations are important with regard to the mechanical properties of metals. These include strain fields that exist around dislocations, which are influential in determining the mobility of the dislocations, as well as their ability to multiply.

lattice strain

When metals are plastically deformed, some fraction of the deformation energy (approximately 5%) is retained internally; the remainder is dissipated as heat. The major portion of this stored energy is as strain energy associated with dislocations. Consider the edge dislocation represented in Figure 7.4. As already mentioned, some atomic lattice distortion exists around the dislocation line because of the presence of the extra half-plane of atoms. As a consequence, there are regions in which compressive, tensile, and shear **lattice strains** are imposed on the neighboring atoms. For example, atoms immediately above and adjacent to the dislocation line are squeezed together. As a result, these atoms may be thought of as experiencing a compressive strain relative to atoms positioned in the perfect crystal and far removed from the dislocation; this is illustrated in Figure 7.4. Directly below the half-plane, the effect is just the opposite; lattice atoms sustain an imposed tensile strain, which is as shown. Shear strains also exist in the vicinity of the edge dislocation. For a screw dislocation, lattice strains are pure shear only. These lattice distortions may be considered to be strain fields that radiate from the dislocation line. The strains extend into the surrounding atoms, and their magnitude decreases with radial distance from the dislocation.

The strain fields surrounding dislocations in close proximity to one another may interact such that forces are imposed on each dislocation by the combined interactions of all its neighboring dislocations. For example, consider two edge dislocations that have the same sign and the identical slip plane, as represented in Figure 7.5a. The compressive and tensile strain fields for both lie on the same side of the slip plane; the strain field interaction is such that there exists between these two isolated dislocations a mutual repulsive force that tends to move them apart. On the other hand, two dislocations of opposite sign and having the same slip plane will be attracted to one another, as indicated in Figure 7.5b, and dislocation

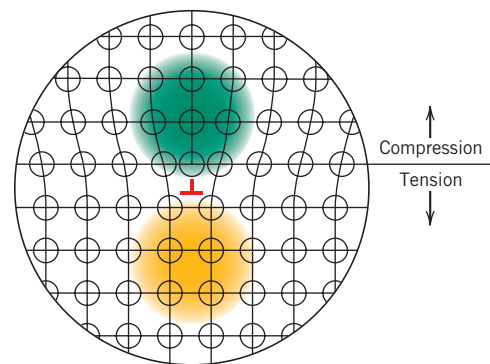
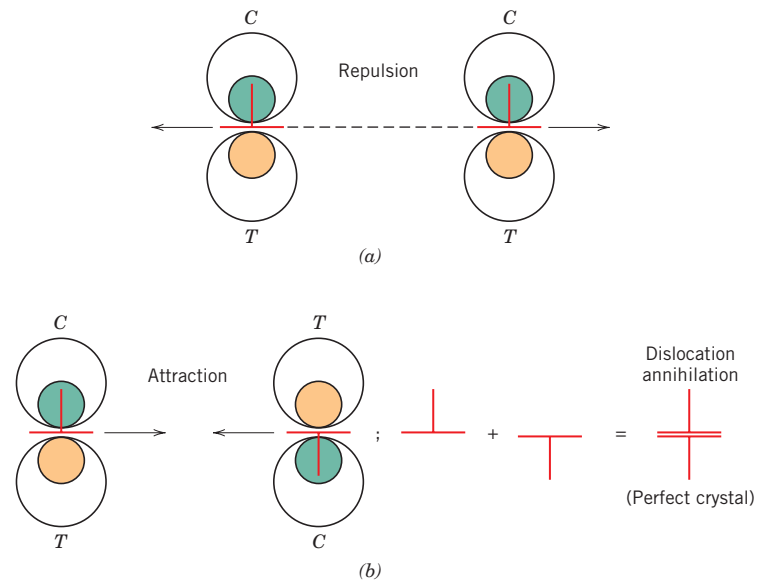


Figure 7.4 Regions of compression (green) and tension (yellow) located around an edge dislocation. (Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 85. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

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Figure 7.5 (a) Two edge dislocations of the same sign and lying on the same slip plane exert a repulsive force on each other; *C* and *T* denote compression and tensile regions, respectively. (b) Edge dislocations of opposite sign and lying on the same slip plane exert an attractive force on each other. Upon meeting, they annihilate each other and leave a region of perfect crystal. (Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, p. 75. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons.)



annihilation will occur when they meet. That is, the two extra half-planes of atoms will align and become a complete plane. Dislocation interactions are possible between edge, screw, and/or mixed dislocations, and for a variety of orientations. These strain fields and associated forces are important in the strengthening mechanisms for metals.

During plastic deformation, the number of dislocations increases dramatically. We know that the dislocation density in a metal that has been highly deformed may be as high as 10^{10} mm^{-2} . One important source of these new dislocations is existing dislocations, which multiply; furthermore, grain boundaries, as well as internal defects and surface irregularities such as scratches and nicks, which act as stress concentrations, may serve as dislocation formation sites during deformation.

7.4 SLIP SYSTEMS

slip system

Dislocations do not move with the same degree of ease on all crystallographic planes of atoms and in all crystallographic directions. Ordinarily there is a preferred plane, and in that plane there are specific directions along which dislocation motion occurs. This plane is called the *slip plane*; it follows that the direction of movement is called the *slip direction*. This combination of the slip plane and the slip direction is termed the **slip system**. The slip system depends on the crystal structure of the metal and is such that the atomic distortion that accompanies the motion of a dislocation is a minimum. For a particular crystal structure, the slip plane is the plane that has the most dense atomic packing—that is, has the greatest planar density. The slip direction corresponds to the direction, in this plane, that is most closely packed with atoms—that is, has the highest linear density. Planar and linear atomic densities were discussed in Section 3.11.

Consider, for example, the FCC crystal structure, a unit cell of which is shown in Figure 7.6a. There is a set of planes, the $\{111\}$ family, all of which are closely packed. A (111) -type plane is indicated in the unit cell; in Figure 7.6b, this plane is positioned within the plane of the page, in which atoms are now represented as touching nearest neighbors.

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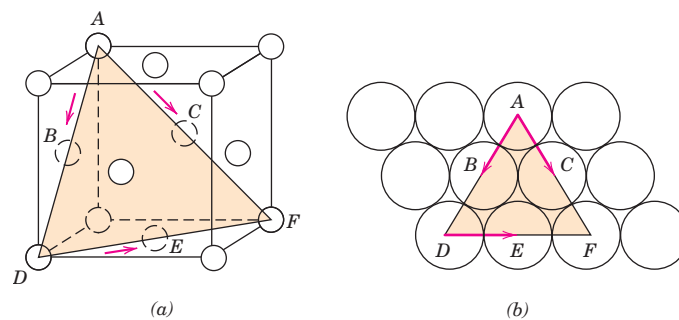


Figure 7.6 (a) A $\{111\}$ $\langle 110 \rangle$ slip system shown within an FCC unit cell. (b) The (111) plane from (a) and three $\langle 110 \rangle$ slip directions (as indicated by arrows) within that plane comprise possible slip systems.

Slip occurs along $\langle 110 \rangle$ -type directions within the $\{111\}$ planes, as indicated by arrows in Figure 7.6. Hence, $\{111\}\langle 110 \rangle$ represents the slip plane and direction combination, or the slip system for FCC. Figure 7.6b demonstrates that a given slip plane may contain more than a single slip direction. Thus, several slip systems may exist for a particular crystal structure; the number of independent slip systems represents the different possible combinations of slip planes and directions. For example, for face-centered cubic, there are 12 slip systems: four unique $\{111\}$ planes and, within each plane, three independent $\langle 110 \rangle$ directions.

The possible slip systems for BCC and HCP crystal structures are listed in Table 7.1. For each of these structures, slip is possible on more than one family of planes (e.g., $\{110\}$, $\{211\}$, and $\{321\}$ for BCC). For metals having these two crystal structures, some slip systems are often operable only at elevated temperatures.

Metals with FCC or BCC crystal structures have a relatively large number of slip systems (at least 12). These metals are quite ductile because extensive plastic deformation is normally possible along the various systems. Conversely, HCP metals, having few active slip systems, are normally quite brittle.

The Burgers vector concept was introduced in Section 4.5, and denoted by a $\mathbf{b}$ for edge, screw, and mixed dislocations in Figures 4.3, 4.4, and 4.5, respectively. With regard to the process of slip, a Burgers vector's direction corresponds to a dislocation's slip direction, whereas its magnitude is equal to the unit slip distance (or interatomic separation in this direction). Of course, both the direction and the magnitude of $\mathbf{b}$ will depend on crystal structure, and it is convenient to specify a Burgers vector in terms of unit cell edge length (a) and crystallographic direction indices.

Table 7.1 Slip Systems for Face-Centered Cubic, Body-Centered Cubic, and Hexagonal Close-Packed Metals

<i>Metals</i>	<i>Slip Plane</i>	<i>Slip Direction</i>	<i>Number of Slip Systems</i>
Face-Centered Cubic			
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle \bar{1}10 \rangle$	12
Body-Centered Cubic			
α -Fe, W, Mo	$\{110\}$	$\langle \bar{1}11 \rangle$	12
α -Fe, W	$\{211\}$	$\langle \bar{1}11 \rangle$	12
α -Fe, K	$\{321\}$	$\langle \bar{1}11 \rangle$	24
Hexagonal Close-Packed			
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0 \rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0 \rangle$	6

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Burgers vectors for face-centered cubic, body-centered cubic, and hexagonal close-packed crystal structures are given as follows:

$$\mathbf{b}(\text{FCC}) = \frac{a}{2} \langle 110 \rangle \quad (7.1a)$$

$$\mathbf{b}(\text{BCC}) = \frac{a}{2} \langle 111 \rangle \quad (7.1b)$$

$$\mathbf{b}(\text{HCP}) = \frac{a}{3} \langle 11\bar{2}0 \rangle \quad (7.1c)$$

**Concept Check 7.1**

Which of the following is the slip system for the simple cubic crystal structure? Why?

$$\{100\} \langle 110 \rangle$$

$$\{110\} \langle 110 \rangle$$

$$\{100\} \langle 010 \rangle$$

$$\{110\} \langle 111 \rangle$$

(Note: a unit cell for the simple cubic crystal structure is shown in Figure 3.23.)

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

7.5 SLIP IN SINGLE CRYSTALS**resolved shear stress**

Resolved shear stress—dependence on applied stress and orientation of stress direction relative to slip plane normal and slip direction

A further explanation of slip is simplified by treating the process in single crystals, then making the appropriate extension to polycrystalline materials. As mentioned previously, edge, screw, and mixed dislocations move in response to shear stresses applied along a slip plane and in a slip direction. As noted in Section 6.2, even though an applied stress may be pure tensile (or compressive), shear components exist at all but parallel or perpendicular alignments to the stress direction (Equation 6.4b). These are termed **resolved shear stresses**, and their magnitudes depend not only on the applied stress, but also on the orientation of both the slip plane and direction within that plane. Let ϕ represent the angle between the normal to the slip plane and the applied stress direction, and λ the angle between the slip and stress directions, as indicated in Figure 7.7; it can then be shown that for the resolved shear stress τ_R

$$\tau_R = \sigma \cos \phi \cos \lambda \quad (7.2)$$

where σ is the applied stress. In general, $\phi + \lambda \neq 90^\circ$, since it need not be the case that the tensile axis, the slip plane normal, and the slip direction all lie in the same plane.

A metal single crystal has a number of different slip systems that are capable of operating. The resolved shear stress normally differs for each one because the orientation of each relative to the stress axis (ϕ and λ angles) also differs. However, one slip system is generally oriented most favorably—that is, has the largest resolved shear stress, $\tau_R(\text{max})$:

$$\tau_R(\text{max}) = \sigma (\cos \phi \cos \lambda)_{\text{max}} \quad (7.3)$$

critical resolved shear stress

In response to an applied tensile or compressive stress, slip in a single crystal commences on the most favorably oriented slip system when the resolved shear stress reaches some critical value, termed the **critical resolved shear stress** τ_{crss} ; it represents the minimum shear stress required to initiate slip, and is a property of the

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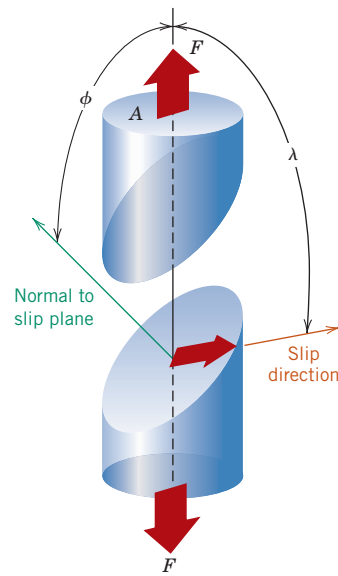


Figure 7.7 Geometrical relationships between the tensile axis, slip plane, and slip direction used in calculating the resolved shear stress for a single crystal.

material that determines when yielding occurs. The single crystal plastically deforms or yields when $\tau_R(\text{max}) = \tau_{\text{crss}}$, and the magnitude of the applied stress required to initiate yielding (i.e., the yield strength σ_y) is

$$\sigma_y = \frac{\tau_{\text{crss}}}{(\cos \phi \cos \lambda)_{\text{max}}} \quad (7.4)$$

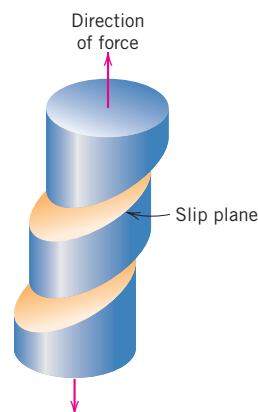
The minimum stress necessary to introduce yielding occurs when a single crystal is oriented such that $\phi = \lambda = 45^\circ$; under these conditions,

$$\sigma_y = 2\tau_{\text{crss}} \quad (7.5)$$

For a single-crystal specimen that is stressed in tension, deformation will be as in Figure 7.8, where slip occurs along a number of equivalent and most favorably oriented planes and directions at various positions along the specimen length. This slip deformation forms as small steps on the surface of the single crystal that are parallel to one another and loop around the circumference of the specimen as indicated in Figure 7.8. Each step results from the movement of a large number of

Yield strength of a single crystal—dependence on the critical resolved shear stress and the orientation of most favorably oriented slip system

Figure 7.8 Macroscopic slip in a single crystal.



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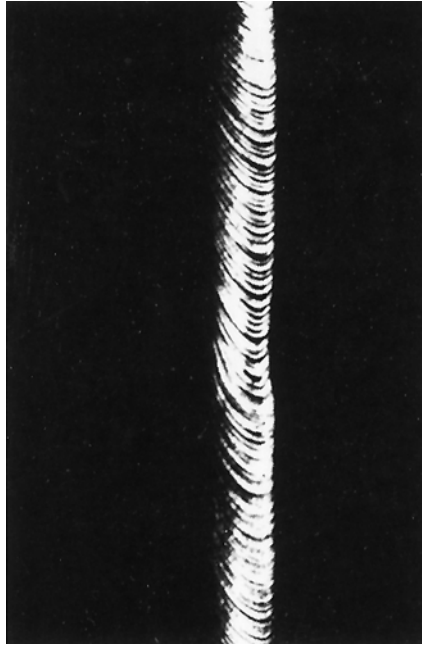


Figure 7.9 Slip in a zinc single crystal. (From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

dislocations along the same slip plane. On the surface of a polished single crystal specimen, these steps appear as lines, which are called *slip lines*. A zinc single crystal that has been plastically deformed to the degree that these slip markings are discernible is shown in Figure 7.9.

With continued extension of a single crystal, both the number of slip lines and the slip step width will increase. For FCC and BCC metals, slip may eventually begin along a second slip system, the system that is next most favorably oriented with the tensile axis. Furthermore, for HCP crystals having few slip systems, if the stress axis for the most favorable slip system is either perpendicular to the slip direction ($\lambda = 90^\circ$) or parallel to the slip plane ($\phi = 90^\circ$), the critical resolved shear stress will be zero. For these extreme orientations the crystal ordinarily fractures rather than deforming plastically.



Concept Check 7.2

Explain the difference between resolved shear stress and critical resolved shear stress.

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

EXAMPLE PROBLEM 7.1

Resolved Shear Stress and Stress-to-Initiate-Yielding Computations

Consider a single crystal of BCC iron oriented such that a tensile stress is applied along a $[010]$ direction.

- (a) Compute the resolved shear stress along a (110) plane and in a $[\bar{1}11]$ direction when a tensile stress of 52 MPa (7500 psi) is applied.

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(b) If slip occurs on a (110) plane and in a $[\bar{1}11]$ direction, and the critical resolved shear stress is 30 MPa (4350 psi), calculate the magnitude of the applied tensile stress necessary to initiate yielding.

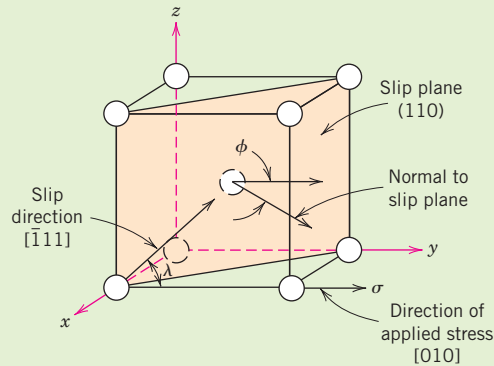
Solution

(a) A BCC unit cell along with the slip direction and plane as well as the direction of the applied stress are shown in the accompanying diagram. In order to solve this problem we must use Equation 7.2. However, it is first necessary to determine values for ϕ and λ , where, from the diagram below, ϕ is the angle between the normal to the (110) slip plane (i.e., the [110] direction) and the [010] direction, and λ represents the angle between $[\bar{1}11]$ and [010] directions. In general, for cubic unit cells, an angle θ between directions 1 and 2, represented by $[u_1v_1w_1]$ and $[u_2v_2w_2]$, respectively, is equal to

$$\theta = \cos^{-1} \left[\frac{u_1u_2 + v_1v_2 + w_1w_2}{\sqrt{(u_1^2 + v_1^2 + w_1^2)(u_2^2 + v_2^2 + w_2^2)}} \right] \quad (7.6)$$

For the determination of the value of ϕ , let $[u_1v_1w_1] = [110]$ and $[u_2v_2w_2] = [010]$ such that

$$\begin{aligned} \phi &= \cos^{-1} \left\{ \frac{(1)(0) + (1)(1) + (0)(0)}{\sqrt{[(1)^2 + (1)^2 + (0)^2][(0)^2 + (1)^2 + (0)^2]}} \right\} \\ &= \cos^{-1} \left(\frac{1}{\sqrt{2}} \right) = 45^\circ \end{aligned}$$



However, for λ , we take $[u_1v_1w_1] = [\bar{1}11]$ and $[u_2v_2w_2] = [010]$, and

$$\begin{aligned} \lambda &= \cos^{-1} \left[\frac{(-1)(0) + (1)(1) + (1)(0)}{\sqrt{[(-1)^2 + (1)^2 + (1)^2][(0)^2 + (1)^2 + (0)^2]}} \right] \\ &= \cos^{-1} \left(\frac{1}{\sqrt{3}} \right) = 54.7^\circ \end{aligned}$$

Thus, according to Equation 7.2,

$$\begin{aligned} \tau_R &= \sigma \cos \phi \cos \lambda = (52 \text{ MPa})(\cos 45^\circ)(\cos 54.7^\circ) \\ &= (52 \text{ MPa}) \left(\frac{1}{\sqrt{2}} \right) \left(\frac{1}{\sqrt{3}} \right) \\ &= 21.3 \text{ MPa} (3060 \text{ psi}) \end{aligned}$$

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(b) The yield strength σ_y may be computed from Equation 7.4; ϕ and λ will be the same as for part (a), and

$$\sigma_y = \frac{30 \text{ MPa}}{(\cos 45^\circ)(\cos 54.7^\circ)} = 73.4 \text{ MPa (10,600 psi)}$$

7.6 PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS

Deformation and slip in polycrystalline materials is somewhat more complex. Because of the random crystallographic orientations of the numerous grains, the direction of slip varies from one grain to another. For each, dislocation motion occurs along the slip system that has the most favorable orientation, as defined above. This is exemplified by a photomicrograph of a polycrystalline copper specimen that has been plastically deformed (Figure 7.10); before deformation the surface was polished. Slip lines¹ are visible, and it appears that two slip systems operated for most of the grains, as evidenced by two sets of parallel yet intersecting sets of lines. Furthermore, variation in grain orientation is indicated by the difference in alignment of the slip lines for the several grains.

Gross plastic deformation of a polycrystalline specimen corresponds to the comparable distortion of the individual grains by means of slip. During deformation, mechanical integrity and coherency are maintained along the grain boundaries; that is, the grain boundaries usually do not come apart or open up. As a consequence, each individual grain is constrained, to some degree, in the shape it may assume by its neighboring grains. The manner in which grains distort as a result of gross plastic deformation is indicated in Figure 7.11. Before deformation the grains are equiaxed, or have approximately the same dimension in all directions. For this particular deformation, the grains become elongated along the direction in which the specimen was extended.

Polycrystalline metals are stronger than their single-crystal equivalents, which means that greater stresses are required to initiate slip and the attendant yielding. This is, to a large degree, also a result of geometrical constraints that are imposed on the grains during deformation. Even though a single grain may be favorably oriented with the applied stress for slip, it cannot deform until the adjacent and less favorably oriented grains are capable of slip also; this requires a higher applied stress level.

7.7 DEFORMATION BY TWINNING

In addition to slip, plastic deformation in some metallic materials can occur by the formation of mechanical twins, or *twinning*. The concept of a twin was introduced in Section 4.6; that is, a shear force can produce atomic displacements such that on one side of a plane (the twin boundary), atoms are located in mirror-image positions of atoms on the other side. The manner in which this is accomplished is demonstrated

¹ These slip lines are microscopic ledges produced by dislocations (Figure 7.1c) that have exited from a grain and appear as lines when viewed with a microscope. They are analogous to the macroscopic steps found on the surfaces of deformed single crystals (Figures 7.8 and 7.9).

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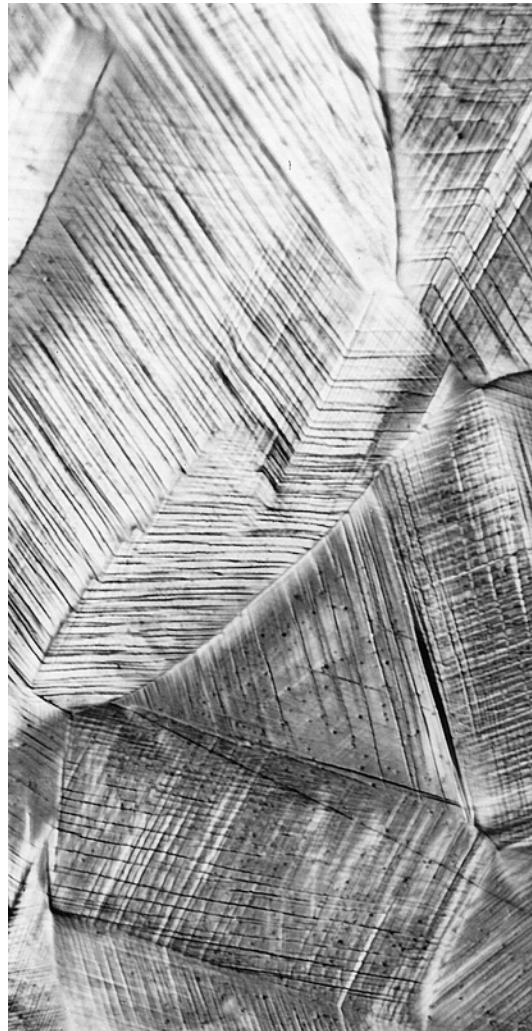
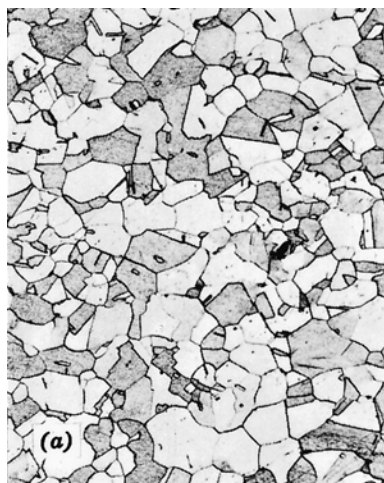


Figure 7.10 Slip lines on the surface of a polycrystalline specimen of copper that was polished and subsequently deformed. 173 $\times$. [Photomicrograph courtesy of C. Brady, National Bureau of Standards (now the National Institute of Standards and Technology, Gaithersburg, MD).]

Figure 7.11 Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (a) Before deformation the grains are equiaxed. (b) The deformation has produced elongated grains. 170 $\times$. (From W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



7.7 Deformation by Twinning • 187

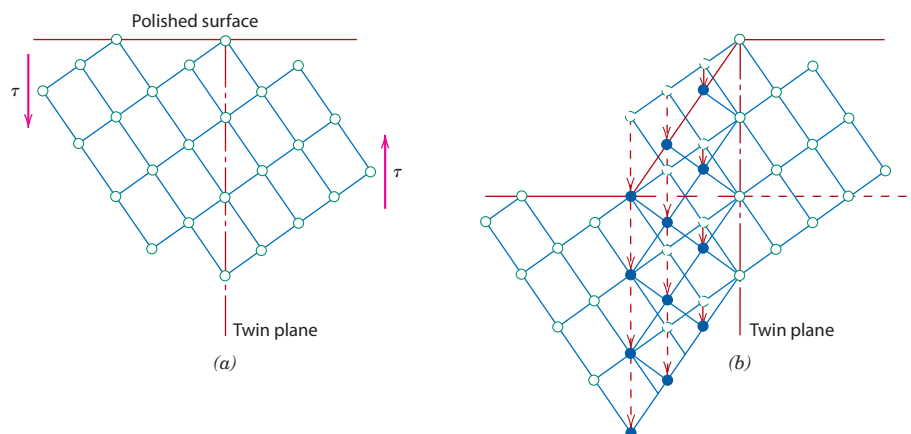


Figure 7.12 Schematic diagram showing how twinning results from an applied shear stress τ . In (b), open circles represent atoms that did not change position; dashed and solid circles represent original and final atom positions, respectively. (From G. E. Dieter, *Mechanical Metallurgy*, 3rd edition. Copyright © 1986 by McGraw-Hill Book Company, New York. Reproduced with permission of McGraw-Hill Book Company.)

in Figure 7.12. Here, open circles represent atoms that did not move, and dashed and solid circles represent original and final positions, respectively, of atoms within the twinned region. As may be noted in this figure, the displacement magnitude within the twin region (indicated by arrows) is proportional to the distance from the twin plane. Furthermore, twinning occurs on a definite crystallographic plane and in a specific direction that depend on crystal structure. For example, for BCC metals, the twin plane and direction are (112) and $[111]$, respectively.

Slip and twinning deformations are compared in Figure 7.13 for a single crystal that is subjected to a shear stress τ . Slip ledges are shown in Figure 7.13a, the formation of which was described in Section 7.5; for twinning, the shear deformation is homogeneous (Figure 7.13b). These two processes differ from each other in several respects. First, for slip, the crystallographic orientation above and below the slip plane is the same both before and after the deformation; for twinning, there will be a reorientation across the twin plane. In addition, slip occurs in distinct atomic spacing multiples, whereas the atomic displacement for twinning is less than the interatomic separation.

Mechanical twinning occurs in metals that have BCC and HCP crystal structures, at low temperatures, and at high rates of loading (shock loading), conditions under which the slip process is restricted; that is, there are few operable slip systems.

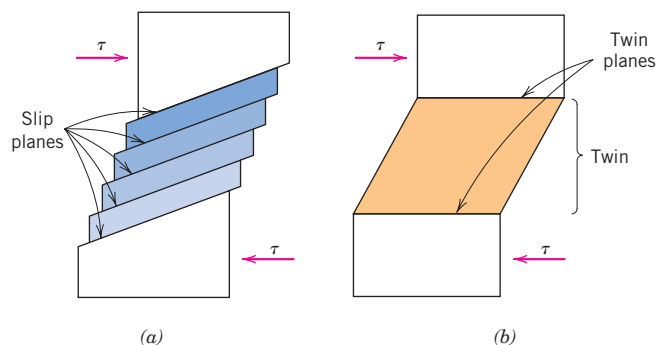


Figure 7.13 For a single crystal subjected to a shear stress τ , (a) deformation by slip; (b) deformation by twinning.

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The amount of bulk plastic deformation from twinning is normally small relative to that resulting from slip. However, the real importance of twinning lies with the accompanying crystallographic reorientations; twinning may place new slip systems in orientations that are favorable relative to the stress axis such that the slip process can now take place.

Mechanisms of Strengthening in Metals

Metallurgical and materials engineers are often called on to design alloys having high strengths yet some ductility and toughness; ordinarily, ductility is sacrificed when an alloy is strengthened. Several hardening techniques are at the disposal of an engineer, and frequently alloy selection depends on the capacity of a material to be tailored with the mechanical characteristics required for a particular application.

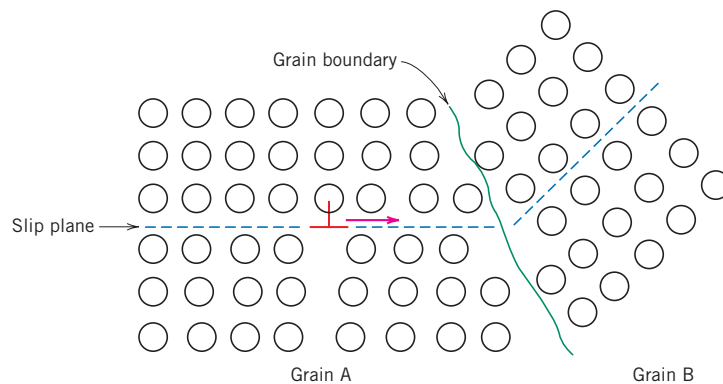
Important to the understanding of strengthening mechanisms is the relation between dislocation motion and mechanical behavior of metals. Because macroscopic plastic deformation corresponds to the motion of large numbers of dislocations, *the ability of a metal to plastically deform depends on the ability of dislocations to move*. Since hardness and strength (both yield and tensile) are related to the ease with which plastic deformation can be made to occur, by reducing the mobility of dislocations, the mechanical strength may be enhanced; that is, greater mechanical forces will be required to initiate plastic deformation. In contrast, the more unconstrained the dislocation motion, the greater is the facility with which a metal may deform, and the softer and weaker it becomes. Virtually all strengthening techniques rely on this simple principle: *restricting or hindering dislocation motion renders a material harder and stronger*.

The present discussion is confined to strengthening mechanisms for single-phase metals, by grain size reduction, solid-solution alloying, and strain hardening. Deformation and strengthening of multiphase alloys are more complicated, involving concepts beyond the scope of the present discussion; Chapter 10 and Section 11.9 treat techniques that are used to strengthen multiphase alloys.

7.8 STRENGTHENING BY GRAIN SIZE REDUCTION

The size of the grains, or average grain diameter, in a polycrystalline metal influences the mechanical properties. Adjacent grains normally have different crystallographic orientations and, of course, a common grain boundary, as indicated in Figure 7.14. During plastic deformation, slip or dislocation motion must take place

Figure 7.14 The motion of a dislocation as it encounters a grain boundary, illustrating how the boundary acts as a barrier to continued slip. Slip planes are discontinuous and change directions across the boundary. (From Van Vlack, *A Textbook of Materials Technology*, 1st edition, © 1973, p. 53. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)



7.8 Strengthening by Grain Size Reduction • 189

across this common boundary—say, from grain A to grain B in Figure 7.14. The grain boundary acts as a barrier to dislocation motion for two reasons:

1. Since the two grains are of different orientations, a dislocation passing into grain B will have to change its direction of motion; this becomes more difficult as the crystallographic misorientation increases.
2. The atomic disorder within a grain boundary region will result in a discontinuity of slip planes from one grain into the other.

It should be mentioned that, for high-angle grain boundaries, it may not be the case that dislocations traverse grain boundaries during deformation; rather, dislocations tend to “pile up” (or back up) at grain boundaries. These pile-ups introduce stress concentrations ahead of their slip planes, which generate new dislocations in adjacent grains.

A fine-grained material (one that has small grains) is harder and stronger than one that is coarse grained, since the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength σ_y varies with grain size according to

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \quad (7.7)$$

Hall-Petch
equation—
dependence of yield
strength on grain size

In this expression, termed the *Hall-Petch equation*, d is the average grain diameter, and σ_0 and k_y are constants for a particular material. Note that Equation 7.7 is not valid for both very large (i.e., coarse) grain and extremely fine grain polycrystalline materials. Figure 7.15 demonstrates the yield strength dependence on grain size for a brass alloy. Grain size may be regulated by the rate of solidification from the liquid phase, and also by plastic deformation followed by an appropriate heat treatment, as discussed in Section 7.13.

It should also be mentioned that grain size reduction improves not only strength, but also the toughness of many alloys.

Small-angle grain boundaries (Section 4.6) are not effective in interfering with the slip process because of the slight crystallographic misalignment across the boundary. On the other hand, twin boundaries (Section 4.6) will effectively block

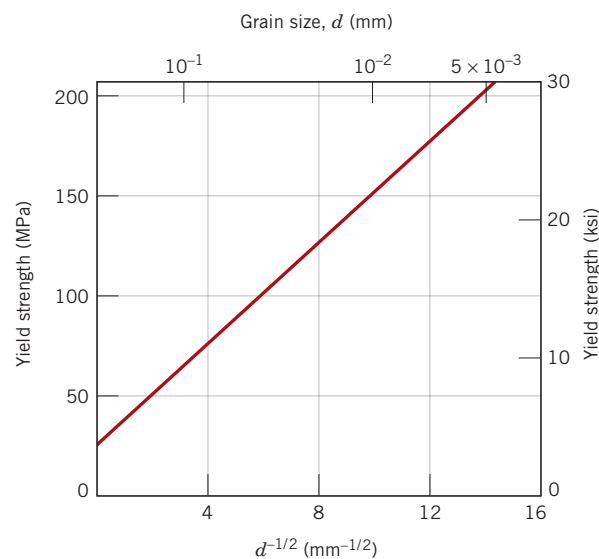


Figure 7.15 The influence of grain size on the yield strength of a 70 Cu–30 Zn brass alloy. Note that the grain diameter increases from right to left and is not linear. (Adapted from H. Suzuki, “The Relation Between the Structure and Mechanical Properties of Metals,” Vol. II, *National Physical Laboratory, Symposium No. 15*, 1963, p. 524.)

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slip and increase the strength of the material. Boundaries between two different phases are also impediments to movements of dislocations; this is important in the strengthening of more complex alloys. The sizes and shapes of the constituent phases significantly affect the mechanical properties of multiphase alloys; these are the topics of discussion in Sections 10.7, 10.8, and 16.1.

7.9 SOLID-SOLUTION STRENGTHENING

solid-solution
strengthening

Another technique to strengthen and harden metals is alloying with impurity atoms that go into either substitutional or interstitial solid solution. Accordingly, this is called **solid-solution strengthening**. High-purity metals are almost always softer and weaker than alloys composed of the same base metal. Increasing the concentration of the impurity results in an attendant increase in tensile and yield strengths, as indicated in Figures 7.16a and 7.16b for nickel in copper; the dependence of ductility on nickel concentration is presented in Figure 7.16c.

Alloys are stronger than pure metals because impurity atoms that go into solid solution ordinarily impose lattice strains on the surrounding host atoms. Lattice strain field interactions between dislocations and these impurity atoms result, and, consequently, dislocation movement is restricted. For example, an impurity atom that is smaller than a host atom for which it substitutes exerts tensile strains on the surrounding crystal lattice, as illustrated in Figure 7.17a. Conversely, a larger substitutional

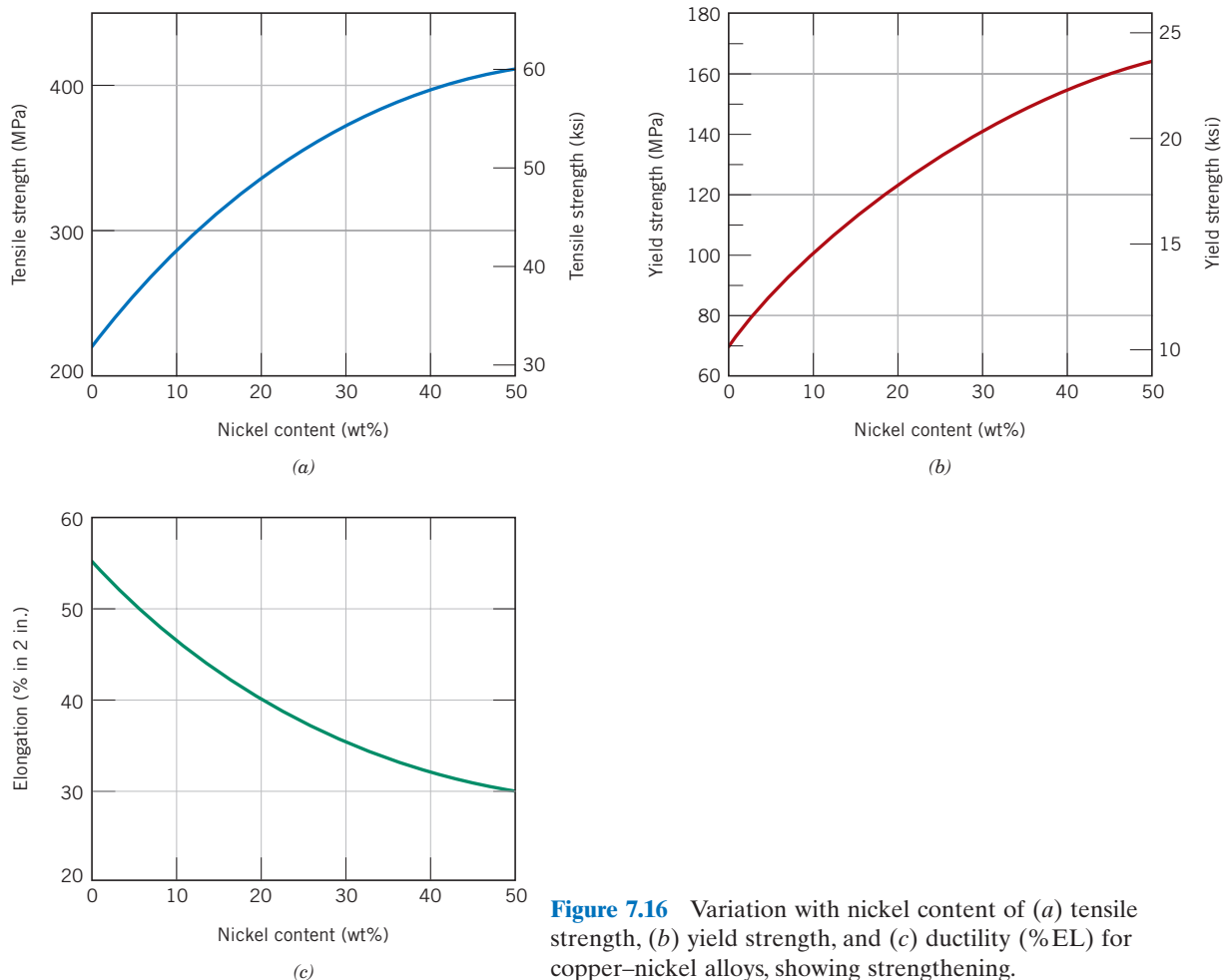


Figure 7.16 Variation with nickel content of (a) tensile strength, (b) yield strength, and (c) ductility (%EL) for copper–nickel alloys, showing strengthening.

7.10 Strain Hardening • 191

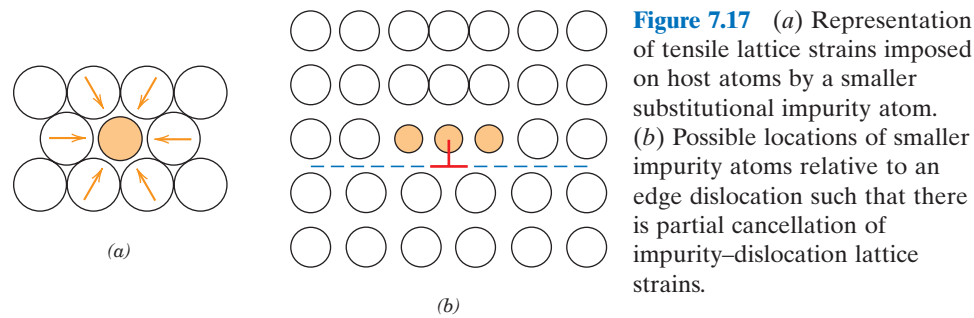


Figure 7.17 (a) Representation of tensile lattice strains imposed on host atoms by a smaller substitutional impurity atom. (b) Possible locations of smaller impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

atom imposes compressive strains in its vicinity (Figure 7.18a). These solute atoms tend to diffuse to and segregate around dislocations in a way so as to reduce the overall strain energy—that is, to cancel some of the strain in the lattice surrounding a dislocation. To accomplish this, a smaller impurity atom is located where its tensile strain will partially nullify some of the dislocation's compressive strain. For the edge dislocation in Figure 7.17b, this would be adjacent to the dislocation line and above the slip plane. A larger impurity atom would be situated as in Figure 7.18b.

The resistance to slip is greater when impurity atoms are present because the overall lattice strain must increase if a dislocation is torn away from them. Furthermore, the same lattice strain interactions (Figures 7.17b and 7.18b) will exist between impurity atoms and dislocations that are in motion during plastic deformation. Thus, a greater applied stress is necessary to first initiate and then continue plastic deformation for solid-solution alloys, as opposed to pure metals; this is evidenced by the enhancement of strength and hardness.

7.10 STRAIN HARDENING

strain hardening

cold working

Percent cold work—
dependence on
original and
deformed cross-
sectional areas

Strain hardening is the phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed. Sometimes it is also called *work hardening*, or, because the temperature at which deformation takes place is “cold” relative to the absolute melting temperature of the metal, **cold working**. Most metals strain harden at room temperature.

It is sometimes convenient to express the degree of plastic deformation as *percent cold work* rather than as strain. Percent cold work (%CW) is defined as

$$\% \text{CW} = \left(\frac{A_0 - A_d}{A_0} \right) \times 100 \quad (7.8)$$

where A_0 is the original area of the cross section that experiences deformation, and A_d is the area after deformation.

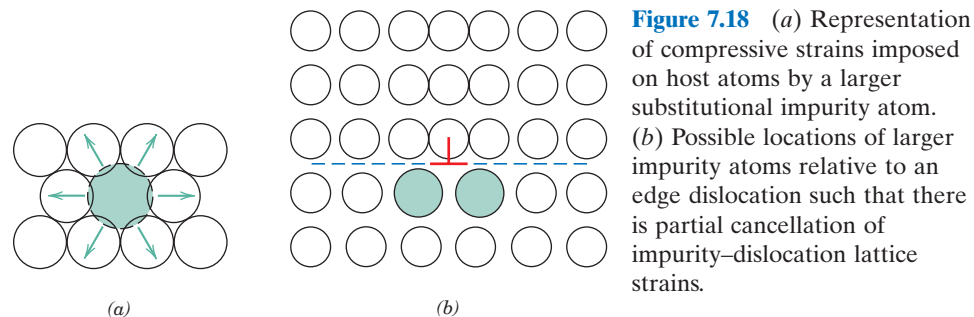


Figure 7.18 (a) Representation of compressive strains imposed on host atoms by a larger substitutional impurity atom. (b) Possible locations of larger impurity atoms relative to an edge dislocation such that there is partial cancellation of impurity–dislocation lattice strains.

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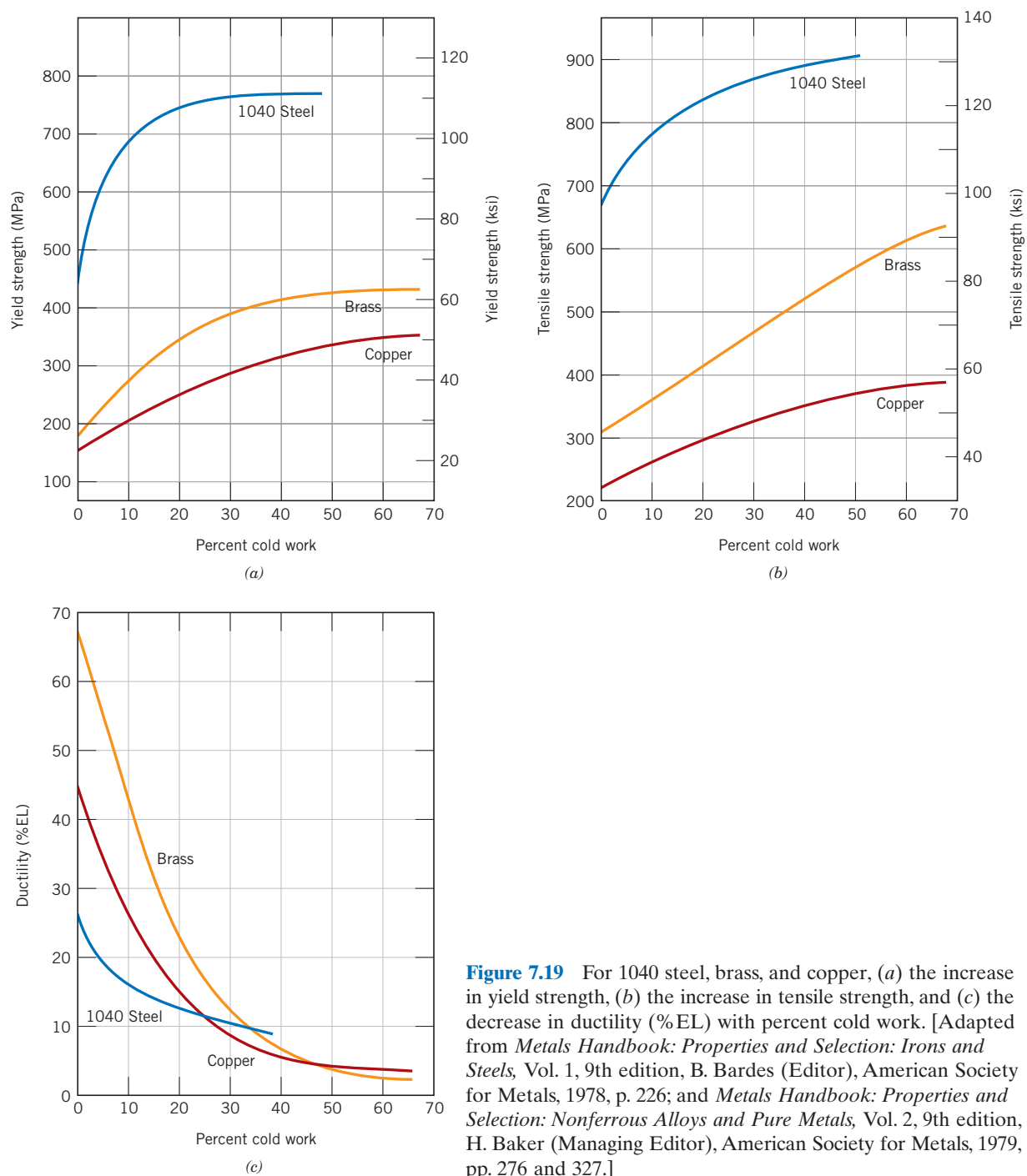


Figure 7.19 For 1040 steel, brass, and copper, (a) the increase in yield strength, (b) the increase in tensile strength, and (c) the decrease in ductility (%EL) with percent cold work. [Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), American Society for Metals, 1978, p. 226; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), American Society for Metals, 1979, pp. 276 and 327.]

Figures 7.19a and 7.19b demonstrate how steel, brass, and copper increase in yield and tensile strength with increasing cold work. The price for this enhancement of hardness and strength is in the ductility of the metal. This is shown in Figure 7.19c, in which the ductility, in percent elongation, experiences a reduction with increasing percent cold work for the same three alloys. The influence of cold work on the

7.10 Strain Hardening • 193

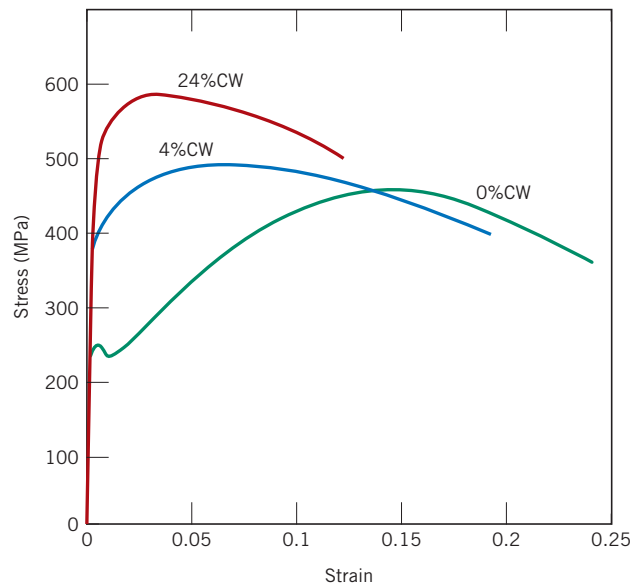


Figure 7.20 The influence of cold work on the stress–strain behavior of a low-carbon steel; curves are shown for 0% CW, 4% CW, and 24% CW.

stress–strain behavior of a low-carbon steel is shown in Figure 7.20; here stress–strain curves are plotted at 0% CW, 4% CW, and 24% CW.

Strain hardening is demonstrated in a stress–strain diagram presented earlier (Figure 6.17). Initially, the metal with yield strength σ_{y_0} is plastically deformed to point *D*. The stress is released, then reapplied with a resultant new yield strength, σ_{y_i} . The metal has thus become stronger during the process because σ_{y_i} is greater than σ_{y_0} .

The strain-hardening phenomenon is explained on the basis of dislocation–dislocation strain field interactions similar to those discussed in Section 7.3. The dislocation density in a metal increases with deformation or cold work, due to dislocation multiplication or the formation of new dislocations, as noted previously. Consequently, the average distance of separation between dislocations decreases—the dislocations are positioned closer together. On the average, dislocation–dislocation strain interactions are repulsive. The net result is that the motion of a dislocation is hindered by the presence of other dislocations. As the dislocation density increases, this resistance to dislocation motion by other dislocations becomes more pronounced. Thus, the imposed stress necessary to deform a metal increases with increasing cold work.

Strain hardening is often utilized commercially to enhance the mechanical properties of metals during fabrication procedures. The effects of strain hardening may be removed by an annealing heat treatment, as discussed in Section 11.7.

In passing, for the mathematical expression relating true stress and strain, Equation 6.19, the parameter n is called the *strain-hardening exponent*, which is a measure of the ability of a metal to strain harden; the larger its magnitude, the greater the strain hardening for a given amount of plastic strain.

Concept Check 7.3

When making hardness measurements, what will be the effect of making an indentation very close to a preexisting indentation? Why?

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

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**Concept Check 7.4**

Would you expect a crystalline ceramic material to strain harden at room temperature? Why or why not?

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

EXAMPLE PROBLEM 7.2**Tensile Strength and Ductility Determinations for Cold-Worked Copper**

Compute the tensile strength and ductility (%EL) of a cylindrical copper rod if it is cold worked such that the diameter is reduced from 15.2 mm to 12.2 mm (0.60 in. to 0.48 in.).

Solution

It is first necessary to determine the percent cold work resulting from the deformation. This is possible using Equation 7.8:

$$\% \text{CW} = \frac{\left(\frac{15.2 \text{ mm}}{2}\right)^2 \pi - \left(\frac{12.2 \text{ mm}}{2}\right)^2 \pi}{\left(\frac{15.2 \text{ mm}}{2}\right)^2 \pi} \times 100 = 35.6\%$$

The tensile strength is read directly from the curve for copper (Figure 7.19b) as 340 MPa (50,000 psi). From Figure 7.19c, the ductility at 35.6% CW is about 7% EL.

In summary, we have just discussed the three mechanisms that may be used to strengthen and harden single-phase metal alloys: strengthening by grain size reduction, solid-solution strengthening, and strain hardening. Of course they may be used in conjunction with one another; for example, a solid-solution strengthened alloy may also be strain hardened.

It should also be noted that the strengthening effects due to grain size reduction and strain hardening can be eliminated or at least reduced by an elevated-temperature heat treatment (Sections 7.12 and 7.13). Conversely, solid-solution strengthening is unaffected by heat treatment.

Recovery, Recrystallization, and Grain Growth

As outlined in the preceding paragraphs of this chapter, plastically deforming a polycrystalline metal specimen at temperatures that are low relative to its absolute melting temperature produces microstructural and property changes that include (1) a change in grain shape (Section 7.6), (2) strain hardening (Section 7.10), and (3) an increase in dislocation density (Section 7.3). Some fraction of the energy expended in deformation is stored in the metal as strain energy, which is associated with tensile, compressive, and shear zones around the newly created dislocations (Section 7.3).

7.12 Recrystallization • 195

Furthermore, other properties such as electrical conductivity (Section 18.8) and corrosion resistance may be modified as a consequence of plastic deformation.

These properties and structures may revert back to the precold-worked states by appropriate heat treatment (sometimes termed an annealing treatment). Such restoration results from two different processes that occur at elevated temperatures: *recovery* and *recrystallization*, which may be followed by *grain growth*.

7.11 RECOVERY

recovery

During **recovery**, some of the stored internal strain energy is relieved by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature. There is some reduction in the number of dislocations, and dislocation configurations (similar to that shown in Figure 4.8) are produced having low strain energies. In addition, physical properties such as electrical and thermal conductivities and the like are recovered to their precold-worked states.

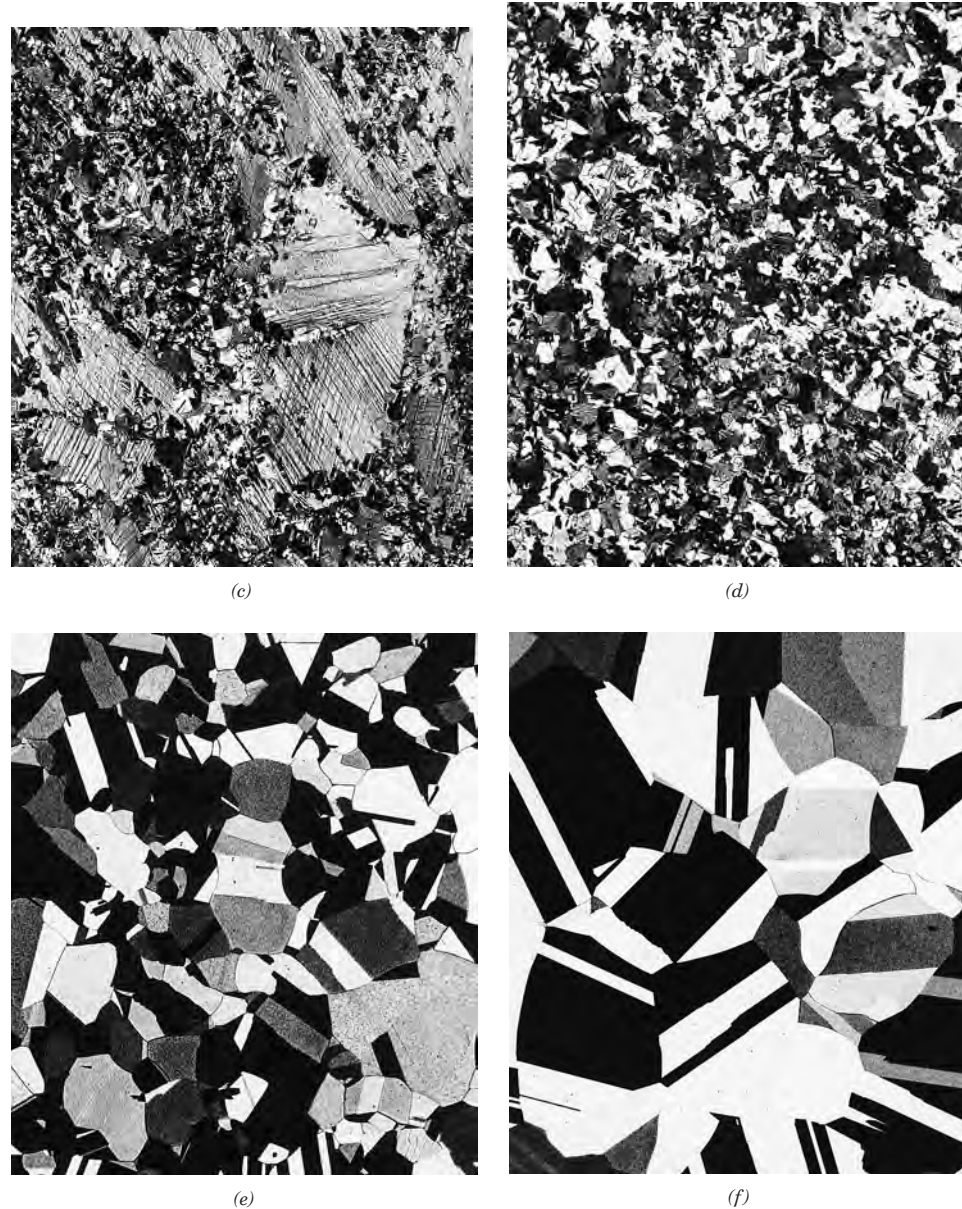
7.12 RECRYSTALLIZATION

recrystallization

Even after recovery is complete, the grains are still in a relatively high strain energy state. **Recrystallization** is the formation of a new set of strain-free and equiaxed grains (i.e., having approximately equal dimensions in all directions) that have low dislocation densities and are characteristic of the precold-worked condition. The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material. The new grains form as very small nuclei and grow until they completely consume the parent material, processes that involve short-range diffusion. Several stages in the recrystallization process are represented in Figures 7.21a to 7.21f; in these photomicrographs, the small



Figure 7.21 Photomicrographs showing several stages of the recrystallization and grain growth of brass. (a) Cold-worked (33% CW) grain structure. (b) Initial stage of recrystallization after heating 3 s at 580°C (1075°F); the very small grains are those that have recrystallized. (c) Partial replacement of cold-worked grains by recrystallized ones (4 s at 580°C). (d) Complete recrystallization (8 s at 580°C). (e) Grain growth after 15 min at 580°C. (f) Grain growth after 10 min at 700°C (1290°F). All photomicrographs 75×. (Photomicrographs courtesy of J. E. Burke, General Electric Company.)

196 • Chapter 7 / Dislocations and Strengthening Mechanisms**Figure 7.21** (continued)

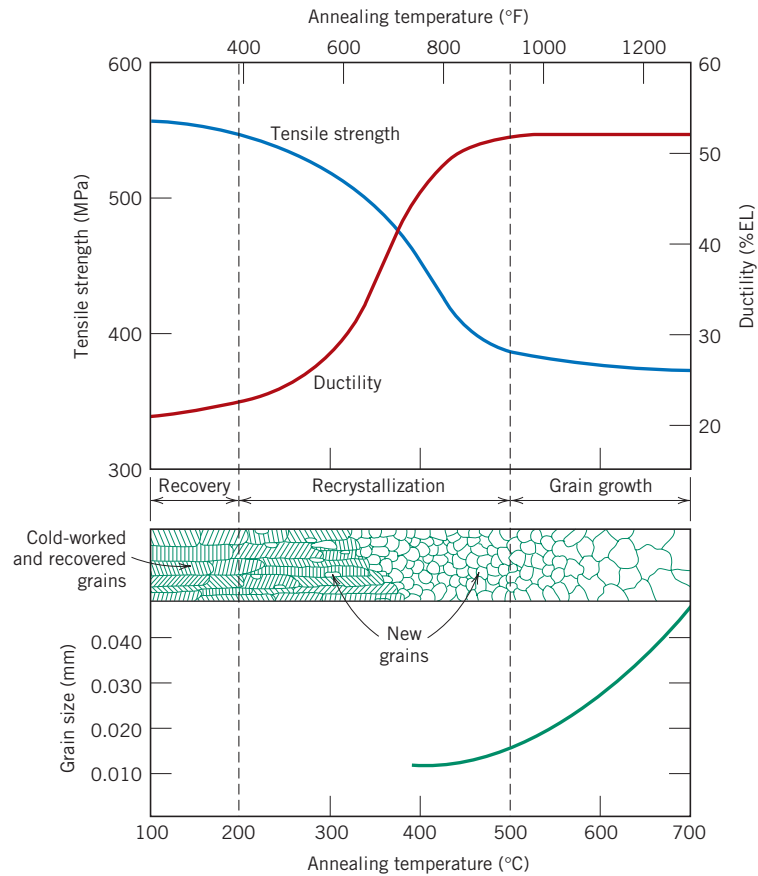
speckled grains are those that have recrystallized. Thus, recrystallization of cold-worked metals may be used to refine the grain structure.

Also, during recrystallization, the mechanical properties that were changed as a result of cold working are restored to their precold-worked values; that is, the metal becomes softer, weaker, yet more ductile. Some heat treatments are designed to allow recrystallization to occur with these modifications in the mechanical characteristics (Section 11.7).

Recrystallization is a process the extent of which depends on both time and temperature. The degree (or fraction) of recrystallization increases with time, as may be noted in the photomicrographs shown in Figures 7.21a–d. The explicit

7.12 Recrystallization • 197

Figure 7.22 The influence of annealing temperature (for an annealing time of 1 h) on the tensile strength and ductility of a brass alloy. Grain size as a function of annealing temperature is indicated. Grain structures during recovery, recrystallization, and grain growth stages are shown schematically. (Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, American Society for Metals, 1940, p. 139.)



time dependence of recrystallization is addressed in more detail near the end of Section 10.3.

The influence of temperature is demonstrated in Figure 7.22, which plots tensile strength and ductility (at room temperature) of a brass alloy as a function of the temperature and for a constant heat treatment time of 1 h. The grain structures found at the various stages of the process are also presented schematically.

recrystallization temperature

The recrystallization behavior of a particular metal alloy is sometimes specified in terms of a **recrystallization temperature**, the temperature at which recrystallization just reaches completion in 1 h. Thus, the recrystallization temperature for the brass alloy of Figure 7.22 is about 450°C (850°F). Typically, it is between one-third and one-half of the absolute melting temperature of a metal or alloy and depends on several factors, including the amount of prior cold work and the purity of the alloy. Increasing the percentage of cold work enhances the rate of recrystallization, with the result that the recrystallization temperature is lowered, and approaches a constant or limiting value at high deformations; this effect is shown in Figure 7.23. Furthermore, it is this limiting or minimum recrystallization temperature that is normally specified in the literature. There exists some critical degree of cold work below which recrystallization cannot be made to occur, as shown in the figure; normally, this is between 2% and 20% cold work.

Recrystallization proceeds more rapidly in pure metals than in alloys. During recrystallization, grain-boundary motion occurs as the new grain nuclei form and then grow. It is believed that impurity atoms preferentially segregate at and interact

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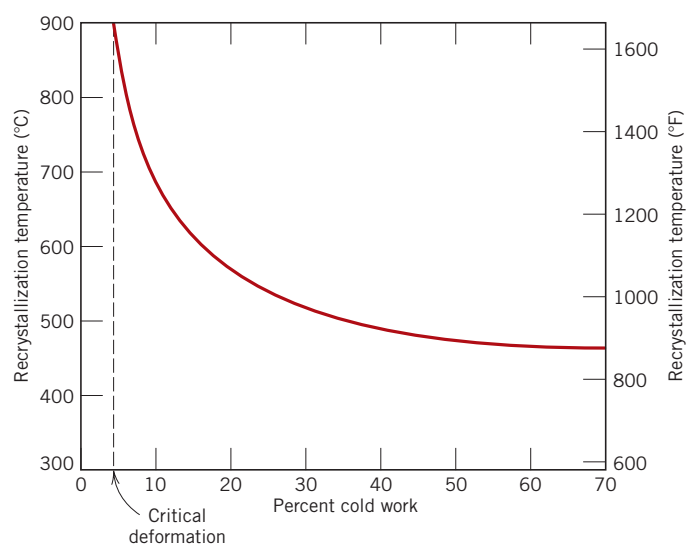


Figure 7.23 The variation of recrystallization temperature with percent cold work for iron. For deformations less than the critical (about 5% CW), recrystallization will not occur.

with these recrystallized grain boundaries so as to diminish their (i.e., grain boundary) mobilities; this results in a decrease of the recrystallization rate and raises the recrystallization temperature, sometimes quite substantially. For pure metals, the recrystallization temperature is normally $0.3T_m$, where T_m is the absolute melting temperature; for some commercial alloys it may run as high as $0.7T_m$. Recrystallization and melting temperatures for a number of metals and alloys are listed in Table 7.2.

Plastic deformation operations are often carried out at temperatures above the recrystallization temperature in a process termed *hot working*, described in Section 11.4. The material remains relatively soft and ductile during deformation because it does not strain harden, and thus large deformations are possible.



Concept Check 7.5

Briefly explain why some metals (i.e., lead and tin) do not strain harden when deformed at room temperature.

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

Table 7.2 Recrystallization and Melting Temperatures for Various Metals and Alloys

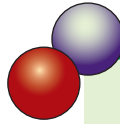
Metal	Recrystallization Temperature		Melting Temperature	
	°C	°F	°C	°F
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

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**Concept Check 7.6**

Would you expect it to be possible for ceramic materials to experience recrystallization? Why or why not?

[The answer may be found at www.wiley.com/college/callister (Student Companion Site).]

**DESIGN EXAMPLE 7.1****Description of Diameter Reduction Procedure**

A cylindrical rod of noncold-worked brass having an initial diameter of 6.4 mm (0.25 in.) is to be cold worked by drawing such that the cross-sectional area is reduced. It is required to have a cold-worked yield strength of at least 345 MPa (50,000 psi) and a ductility in excess of 20% EL; in addition, a final diameter of 5.1 mm (0.20 in.) is necessary. Describe the manner in which this procedure may be carried out.

Solution

Let us first consider the consequences (in terms of yield strength and ductility) of cold working in which the brass specimen diameter is reduced from 6.4 mm (designated by d_0) to 5.1 mm (d_i). The %CW may be computed from Equation 7.8 as

$$\begin{aligned}\% \text{CW} &= \frac{\left(\frac{d_0}{2}\right)^2 \pi - \left(\frac{d_i}{2}\right)^2 \pi}{\left(\frac{d_0}{2}\right)^2 \pi} \times 100 \\ &= \frac{\left(\frac{6.4 \text{ mm}}{2}\right)^2 \pi - \left(\frac{5.1 \text{ mm}}{2}\right)^2 \pi}{\left(\frac{6.4 \text{ mm}}{2}\right)^2 \pi} \times 100 = 36.5\% \text{CW}\end{aligned}$$

From Figures 7.19a and 7.19c, a yield strength of 410 MPa (60,000 psi) and a ductility of 8% EL are attained from this deformation. According to the stipulated criteria, the yield strength is satisfactory; however, the ductility is too low.

Another processing alternative is a partial diameter reduction, followed by a recrystallization heat treatment in which the effects of the cold work are nullified. The required yield strength, ductility, and diameter are achieved through a second drawing step.

Again, reference to Figure 7.19a indicates that 20%CW is required to give a yield strength of 345 MPa. On the other hand, from Figure 7.19c, ductilities greater than 20% EL are possible only for deformations of 23%CW or less. Thus during the final drawing operation, deformation must be between 20%CW and 23%CW. Let's take the average of these extremes, 21.5%CW, and then calculate the final diameter for the first drawing d'_0 , which becomes the original diameter for the second drawing. Again, using Equation 7.8,

$$21.5\% \text{CW} = \frac{\left(\frac{d'_0}{2}\right)^2 \pi - \left(\frac{5.1 \text{ mm}}{2}\right)^2 \pi}{\left(\frac{d'_0}{2}\right)^2 \pi} \times 100$$

Now, solving for d'_0 from the expression above gives

$$d'_0 = 5.8 \text{ mm (0.226 in.)}$$



7.13 GRAIN GROWTH

grain growth

After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at the elevated temperature (Figures 7.21d–f); this phenomenon is called **grain growth**. Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials, metals and ceramics alike.

An energy is associated with grain boundaries, as explained in Section 4.6. As grains increase in size, the total boundary area decreases, yielding an attendant reduction in the total energy; this is the driving force for grain growth.

Grain growth occurs by the migration of grain boundaries. Obviously, not all grains can enlarge, but large ones grow at the expense of small ones that shrink. Thus, the average grain size increases with time, and at any particular instant there will exist a range of grain sizes. Boundary motion is just the short-range diffusion of atoms from one side of the boundary to the other. The directions of boundary movement and atomic motion are opposite to each other, as shown in Figure 7.24.

For many polycrystalline materials, the grain diameter d varies with time t according to the relationship

$$d^n - d_0^n = Kt \quad (7.9)$$

For grain growth,
dependence of grain
size on time

where d_0 is the initial grain diameter at $t = 0$, and K and n are time-independent constants; the value of n is generally equal to or greater than 2.

The dependence of grain size on time and temperature is demonstrated in Figure 7.25, a plot of the logarithm of grain size as a function of the logarithm of time for a brass alloy at several temperatures. At lower temperatures the curves are linear. Furthermore, grain growth proceeds more rapidly as temperature increases; that is, the curves are displaced upward to larger grain sizes. This is explained by the enhancement of diffusion rate with rising temperature.

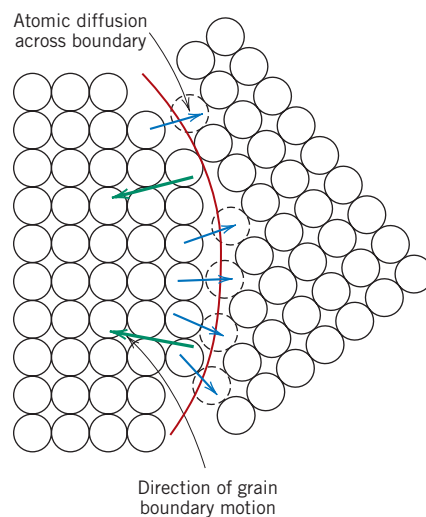
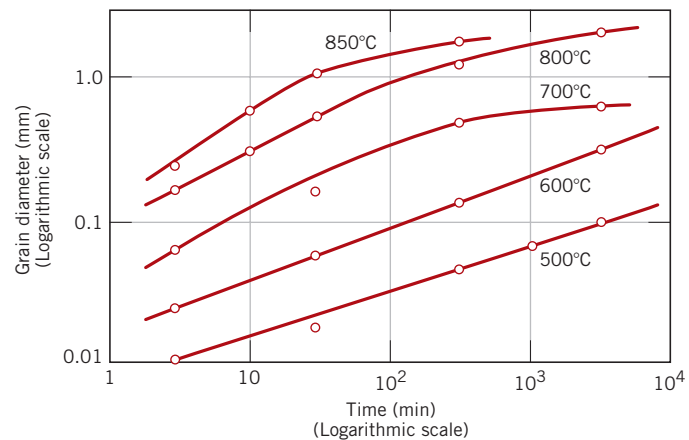


Figure 7.24 Schematic representation of grain growth via atomic diffusion. (From Van Vlack, Lawrence H., *Elements of Materials Science and Engineering*, © 1989, p. 221. Adapted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)

Figure 7.25 The logarithm of grain diameter versus the logarithm of time for grain growth in brass at several temperatures. (From J. E. Burke, "Some Factors Affecting the Rate of Grain Growth in Metals." Reprinted with permission from *Metallurgical Transactions*, Vol. 180, 1949, a publication of The Metallurgical Society of AIME, Warrendale, Pennsylvania.)



The mechanical properties at room temperature of a fine-grained metal are usually superior (i.e., higher strength and toughness) to those of coarse-grained ones. If the grain structure of a single-phase alloy is coarser than that desired, refinement may be accomplished by plastically deforming the material, then subjecting it to a recrystallization heat treatment, as described above.

SUMMARY

Basic Concepts

Slip Systems

On a microscopic level, plastic deformation corresponds to the motion of dislocations in response to an externally applied shear stress, a process termed "slip." Slip occurs on specific crystallographic planes and within these planes only in certain directions. A slip system represents a slip plane-slip direction combination, and operable slip systems depend on the crystal structure of the material.

Slip in Single Crystals

The critical resolved shear stress is the minimum shear stress required to initiate dislocation motion; the yield strength of a single crystal depends on both the magnitude of the critical resolved shear stress and the orientation of slip components relative to the direction of the applied stress.

Plastic Deformation of Polycrystalline Materials

For polycrystalline materials, slip occurs within each grain along the slip systems that are most favorably oriented with the applied stress; furthermore, during deformation, grains change shape in such a manner that coherency at the grain boundaries is maintained.

Deformation by Twinning

Under some circumstances limited plastic deformation may occur in BCC and HCP metals by mechanical twinning. Normally, twinning is important to the degree that accompanying crystallographic reorientations make the slip process more favorable.

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Characteristics of Dislocations Strengthening by Grain Size Reduction Solid-Solution Strengthening Strain Hardening

Since the ease with which a material is capable of plastic deformation is a function of dislocation mobility, restricting dislocation motion increases hardness and strength. On the basis of this principle, three different strengthening mechanisms were discussed. Grain boundaries serve as barriers to dislocation motion; thus refining the grain size of a polycrystalline material renders it harder and stronger. Solid-solution strengthening results from lattice strain interactions between impurity atoms and dislocations. Finally, as a material is plastically deformed, the dislocation density increases, as does also the extent of repulsive dislocation–dislocation strain field interactions; strain hardening is just the enhancement of strength with increased plastic deformation.

Recovery Recrystallization Grain Growth

The microstructural and mechanical characteristics of a plastically deformed metal specimen may be restored to their predeformed states by an appropriate heat treatment, during which recovery, recrystallization, and grain growth processes are allowed to occur. During recovery there is a reduction in dislocation density and alterations in dislocation configurations. Recrystallization is the formation of a new set of grains that are strain free; in addition, the material becomes softer and more ductile. Grain growth is the increase in average grain size of polycrystalline materials, which proceeds by grain boundary motion.

IMPORTANT TERMS AND CONCEPTS

Cold working	Recovery	Slip system
Critical resolved shear stress	Recrystallization	Solid-solution strengthening
Dislocation density	Recrystallization temperature	Strain hardening
Grain growth	Resolved shear stress	
Lattice strain	Slip	

REFERENCES

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| <p>Hirth, J. P., and J. Lothe, <i>Theory of Dislocations</i>, 2nd edition, Wiley-Interscience, New York, 1982. Reprinted by Krieger, Melbourne, FL, 1992.</p> <p>Hull, D., <i>Introduction to Dislocations</i>, 3rd edition, Butterworth-Heinemann, Woburn, UK, 1984.</p> | <p>Read, W. T., Jr., <i>Dislocations in Crystals</i>, McGraw-Hill, New York, 1953.</p> <p>Weertman, J., and J. R. Weertman, <i>Elementary Dislocation Theory</i>, Macmillan, New York, 1964. Reprinted by Oxford University Press, New York, 1992.</p> |
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QUESTIONS AND PROBLEMS

Basic Concepts Characteristics of Dislocations

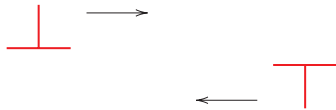
- 7.1** To provide some perspective on the dimensions of atomic defects, consider a metal spec-

imen that has a dislocation density of 10^5 mm^{-2} . Suppose that all the dislocations in 1000 mm^3 (1 cm^3) were somehow removed and linked end to end. How far (in miles)

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would this chain extend? Now suppose that the density is increased to 10^9 mm^{-2} by cold working. What would be the chain length of dislocations in 1000 mm^3 of material?

- 7.2** Consider two edge dislocations of opposite sign and having slip planes that are separated by several atomic distances as indicated in the diagram. Briefly describe the defect that results when these two dislocations become aligned with each other.



- 7.3** Is it possible for two screw dislocations of opposite sign to annihilate each other? Explain your answer.
- 7.4** For each of edge, screw, and mixed dislocations, cite the relationship between the direction of the applied shear stress and the direction of dislocation line motion.

Slip Systems

- 7.5 (a)** Define a slip system.
- (b)** Do all metals have the same slip system? Why or why not?
- 7.6 (a)** Compare planar densities (Section 3.11 and Problem 3.53) for the (100), (110), and (111) planes for FCC.
- (b)** Compare planar densities (Problem 3.54) for the (100), (110), and (111) planes for BCC.
- 7.7** One slip system for the BCC crystal structure is $\{110\}\langle 111 \rangle$. In a manner similar to Figure 7.6b, sketch a $\{110\}$ -type plane for the BCC structure, representing atom positions with circles. Now, using arrows, indicate two different $\langle 111 \rangle$ slip directions within this plane.
- 7.8** One slip system for the HCP crystal structure is $\{0001\}\langle 11\bar{2}0 \rangle$. In a manner similar to Figure 7.6b, sketch a $\{0001\}$ -type plane for the HCP structure and, using arrows, indicate three different $\langle 11\bar{2}0 \rangle$ slip directions within this plane. You might find Figure 3.8 helpful.
- 7.9** Equations 7.1a and 7.1b, expressions for Burgers vectors for FCC and BCC crystal structures, are of the form

$$\mathbf{b} = \frac{a}{2} \langle uvw \rangle$$

where a is the unit cell edge length. Also, since the magnitudes of these Burgers vectors may be determined from the following equation:

$$|\mathbf{b}| = \frac{a}{2} (u^2 + v^2 + w^2)^{1/2} \quad (7.10)$$

determine values of $|\mathbf{b}|$ for copper and iron. You may want to consult Table 3.1.

- 7.10 (a)** In the manner of Equations 7.1a, 7.1b, and 7.1c, specify the Burgers vector for the simple cubic crystal structure. Its unit cell is shown in Figure 3.23. Also, simple cubic is the crystal structure for the edge dislocation of Figure 4.3, and for its motion as presented in Figure 7.1. You may also want to consult the answer to Concept Check 7.1.
- (b)** On the basis of Equation 7.10, formulate an expression for the magnitude of the Burgers vector, $|\mathbf{b}|$, for simple cubic.

Slip in Single Crystals

- 7.11** Sometimes $\cos \phi \cos \lambda$ in Equation 7.2 is termed the *Schmid factor*. Determine the magnitude of the Schmid factor for an FCC single crystal oriented with its $[120]$ direction parallel to the loading axis.
- 7.12** Consider a metal single crystal oriented such that the normal to the slip plane and the slip direction are at angles of 60° and 35° , respectively, with the tensile axis. If the critical resolved shear stress is 6.2 MPa (900 psi), will an applied stress of 12 MPa (1750 psi) cause the single crystal to yield? If not, what stress will be necessary?
- 7.13** A single crystal of zinc is oriented for a tensile test such that its slip plane normal makes an angle of 65° with the tensile axis. Three possible slip directions make angles of 30° , 48° , and 78° with the same tensile axis.
- (a)** Which of these three slip directions is most favored?
- (b)** If plastic deformation begins at a tensile stress of 2.5 MPa (355 psi), determine the critical resolved shear stress for zinc.
- 7.14** Consider a single crystal of nickel oriented such that a tensile stress is applied along a $[001]$ direction. If slip occurs on a (111) plane and in a $[\bar{1}01]$ direction, and is initiated at an

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applied tensile stress of 13.9 MPa (2020 psi), compute the critical resolved shear stress.

- 7.15** A single crystal of a metal that has the FCC crystal structure is oriented such that a tensile stress is applied parallel to the $[100]$ direction. If the critical resolved shear stress for this material is 0.5 MPa, calculate the magnitude(s) of applied stress(es) necessary to cause slip to occur on the (111) plane in each of the $[110]$, $[10\bar{1}]$, and $[0\bar{1}1]$ directions.

- 7.16 (a)** A single crystal of a metal that has the BCC crystal structure is oriented such that a tensile stress is applied in the $[100]$ direction. If the magnitude of this stress is 4.0 MPa, compute the resolved shear stress in the $[111]$ direction on each of the (110) , (011) , and $(10\bar{1})$ planes.

(b) On the basis of these resolved shear stress values, which slip system(s) is (are) most favorably oriented?

- 7.17** Consider a single crystal of some hypothetical metal that has the BCC crystal structure and is oriented such that a tensile stress is applied along a $[121]$ direction. If slip occurs on a (101) plane and in a $[\bar{1}11]$ direction, compute the stress at which the crystal yields if its critical resolved shear stress is 2.4 MPa.

- 7.18** The critical resolved shear stress for copper is 0.48 MPa (70 psi). Determine the maximum possible yield strength for a single crystal of Cu pulled in tension.

Deformation by Twinning

- 7.19** List four major differences between deformation by twinning and deformation by slip relative to mechanism, conditions of occurrence, and final result.

Strengthening by Grain Size Reduction

- 7.20** Briefly explain why small-angle grain boundaries are not as effective in interfering with the slip process as are high-angle grain boundaries.
- 7.21** Briefly explain why HCP metals are typically more brittle than FCC and BCC metals.
- 7.22** Describe in your own words the three strengthening mechanisms discussed in this chapter (i.e., grain size reduction, solid-solution

strengthening, and strain hardening). Be sure to explain how dislocations are involved in each of the strengthening techniques.

- 7.23 (a)** From the plot of yield strength versus (grain diameter) $^{-1/2}$ for a 70 Cu–30 Zn cartridge brass, Figure 7.15, determine values for the constants σ_0 and k_y in Equation 7.7.

(b) Now predict the yield strength of this alloy when the average grain diameter is 2.0×10^{-3} mm.

- 7.24** The lower yield point for an iron that has an average grain diameter of 1×10^{-2} mm is 230 MPa (33,000 psi). At a grain diameter of 6×10^{-3} mm, the yield point increases to 275 MPa (40,000 psi). At what grain diameter will the lower yield point be 310 MPa (45,000 psi)?

- 7.25** If it is assumed that the plot in Figure 7.15 is for noncold-worked brass, determine the grain size of the alloy in Figure 7.19; assume its composition is the same as the alloy in Figure 7.15.

Solid-Solution Strengthening

- 7.26** In the manner of Figures 7.17b and 7.18b, indicate the location in the vicinity of an edge dislocation at which an interstitial impurity atom would be expected to be situated. Now briefly explain in terms of lattice strains why it would be situated at this position.

Strain Hardening

- 7.27 (a)** Show, for a tensile test, that

$$\% \text{CW} = \left(\frac{\epsilon}{\epsilon + 1} \right) \times 100$$

if there is no change in specimen volume during the deformation process (i.e., $A_0 l_0 = A_d l_d$).

(b) Using the result of part (a), compute the percent cold work experienced by naval brass (for which the stress–strain behavior is shown in Figure 6.12) when a stress of 415 MPa (60,000 psi) is applied.

- 7.28** Two previously undeformed cylindrical specimens of an alloy are to be strain hardened by reducing their cross-sectional areas (while maintaining their circular cross sections). For one specimen, the initial and deformed radii are 15 mm and 12 mm, respectively. The second specimen, with an initial radius of 11 mm,

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must have the same deformed hardness as the first specimen; compute the second specimen's radius after deformation.

- 7.29** Two previously undeformed specimens of the same metal are to be plastically deformed by reducing their cross-sectional areas. One has a circular cross section, and the other is rectangular; during deformation the circular cross section is to remain circular, and the rectangular is to remain as such. Their original and deformed dimensions are as follows:

	<i>Circular</i> (diameter, mm)	<i>Rectangular</i> (mm)
Original dimensions	18.0	20×50
Deformed dimensions	15.9	13.7×55.1

Which of these specimens will be the hardest after plastic deformation, and why?

- 7.30** A cylindrical specimen of cold-worked copper has a ductility (%EL) of 15%. If its cold-worked radius is 6.4 mm (0.25 in.), what was its radius before deformation?
- 7.31 (a)** What is the approximate ductility (%EL) of a brass that has a yield strength of 345 MPa (50,000 psi)?
- (b)** What is the approximate Brinell hardness of a 1040 steel having a yield strength of 620 MPa (90,000 psi)?
- 7.32** Experimentally, it has been observed for single crystals of a number of metals that the critical resolved shear stress τ_{crss} is a function of the dislocation density ρ_D as

$$\tau_{\text{crss}} = \tau_0 + A\sqrt{\rho_D}$$

where τ_0 and A are constants. For copper, the critical resolved shear stress is 0.69 MPa (100 psi) at a dislocation density of 10^4 mm^{-2} . If it is known that the value of τ_0 for copper is 0.069 MPa (10 psi), compute the τ_{crss} at a dislocation density of 10^6 mm^{-2} .

Recovery Recrystallization Grain Growth

- 7.33** Briefly cite the differences between recovery and recrystallization processes.
- 7.34** Estimate the fraction of recrystallization from the photomicrograph in Figure 7.21c.

- 7.35** Explain the differences in grain structure for a metal that has been cold worked and one that has been cold worked and then recrystallized.

- 7.36 (a)** What is the driving force for recrystallization?
- (b)** For grain growth?

- 7.37 (a)** From Figure 7.25, compute the length of time required for the average grain diameter to increase from 0.03 to 0.3 mm at 600°C for this brass material.

- (b)** Repeat the calculation at 700°C.

- 7.38** The average grain diameter for a brass material was measured as a function of time at 650°C, which is tabulated below at two different times:

<i>Time</i> (min)	<i>Grain Diameter</i> (mm)
40	5.6×10^{-2}
100	8.0×10^{-2}

- (a)** What was the original grain diameter?

- (b)** What grain diameter would you predict after 200 min at 650°C?

- 7.39** An undeformed specimen of some alloy has an average grain diameter of 0.050 mm. You are asked to reduce its average grain diameter to 0.020 mm. Is this possible? If so, explain the procedures you would use and name the processes involved. If it is not possible, explain why.

- 7.40** Grain growth is strongly dependent on temperature (i.e., rate of grain growth increases with increasing temperature), yet temperature is not explicitly given as a part of Equation 7.9.

- (a)** Into which of the parameters in this expression would you expect temperature to be included?

- (b)** On the basis of your intuition, cite an explicit expression for this temperature dependence.

- 7.41** An uncold-worked brass specimen of average grain size 0.01 mm has a yield strength of 150 MPa (21,750 psi). Estimate the yield strength of this alloy after it has been heated to 500°C for 1000 s, if it is known that the value of σ_0 is 25 MPa (3625 psi).

206 • Chapter 7 / Dislocations and Strengthening Mechanisms**DESIGN PROBLEMS***Strain Hardening**Recrystallization*

- 7.D1** Determine whether or not it is possible to cold work steel so as to give a minimum Brinell hardness of 240, and at the same time have a ductility of at least 15%EL. Justify your decision.
- 7.D2** Determine whether or not it is possible to cold work brass so as to give a minimum Brinell hardness of 150, and at the same time have a ductility of at least 20%EL. Justify your decision.
- 7.D3** A cylindrical specimen of cold-worked steel has a Brinell hardness of 240.
- (a) Estimate its ductility in percent elongation.
 - (b) If the specimen remained cylindrical during deformation and its original radius was 10 mm (0.40 in.), determine its radius after deformation.
- 7.D4** It is necessary to select a metal alloy for an application that requires a yield strength of at least 310 MPa (45,000 psi) while maintaining a minimum ductility (%EL) of 27%. If the metal may be cold worked, decide which of the following are candidates: copper, brass, and a 1040 steel. Why?
- 7.D5** A cylindrical rod of 1040 steel originally 11.4 mm (0.45 in.) in diameter is to be cold worked by drawing; the circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 825 MPa (120,000 psi) and a ductility of at least 12%EL are desired. Furthermore, the final diameter must be 8.9 mm (0.35 in.). Explain how this may be accomplished.
- 7.D6** A cylindrical rod of brass originally 10.2 mm (0.40 in.) in diameter is to be cold worked by drawing; the circular cross section will be maintained during deformation. A cold-worked yield strength in excess of 380 MPa (55,000 psi) and a ductility of at least 15%EL are desired. Furthermore, the final diameter must be 7.6 mm (0.30 in.). Explain how this may be accomplished.
- 7.D7** A cylindrical brass rod having a minimum tensile strength of 450 MPa (65,000 psi), a ductility of at least 13%EL, and a final diameter of 12.7 mm (0.50 in.) is desired. Some 19.0 mm (0.75 in.) diameter brass stock that has been cold worked 35% is available. Describe the procedure you would follow to obtain this material. Assume that brass experiences cracking at 65%CW.