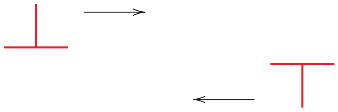
would this chain extend? Now suppose that the density is increased to 10^9 mm^{-2} by cold working. What would be the chain length of dislocations in 1000 mm^3 of material?

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 7.6*b*, 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 7.6*b*, 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:

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

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 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 $[1\bar{1}0]$, $[10\bar{1}]$, 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 $[1\bar{1}1]$ 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 7.17*b* and 7.18*b*, 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

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

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, 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:

	Circular (diameter, mm)	*Rectangular (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 7.21*c*.

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:

Time (min)	*Grain Diameter (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).

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.