Section 4-5 Schmid's Law

4-22 A single crystal of an FCC metal is oriented so that the [001] direction is parallel to an applied stress of 5000 psi. Calculate the resolved shear stress acting on the (111) slip plane in the $[\bar{1}10]$, $[0\bar{1}1]$, and $[10\bar{1}]$ slip directions. Which slip system(s) will become active first?

4-23 A single crystal of a BCC metal is oriented so that the [001] direction is parallel to the applied stress. If the critical resolved shear stress required for slip is 12,000 psi, calculate the magnitude of the applied stress required to cause slip to begin in the $[1\bar{1}1]$ direction on the (110), (011), and $(10\bar{1})$ slip planes.

Section 4-6 Influence of Crystal Structure

4-24 Why is it that single crystal and polycrystalline copper are both ductile, however, single crystal, but not polycrystalline, zinc can exhibit considerable ductility?

4-25 Why is it that cross slip in BCC and FCC metals is easier than that in HCP metals? How does this influence the ductility of BCC, FCC, and HCP metals?

Section 4-7 Surface Defects

4-26 The strength of titanium is found to be 65,000 psi when the grain size is 17×10^{-6} m and 82,000 psi when the grain size is 0.8×10^{-6} m. Determine

(a) the constants in the Hall-Petch equation; and
(b) the strength of the titanium when the grain size is reduced to 0.2×10^{-6} m.

4-27 A copper-zinc alloy has the following properties

Grain Diameter (mm)	Strength (MPa)
0.015	170 MPa
0.025	158 MPa
0.035	151 MPa
0.050	145 MPa

Determine

(a) the constants in the Hall-Petch equation; and
(b) the grain size required to obtain a strength of 200 MPa.

4-28 For an ASTM grain size number of 8, calculate the number of grains per square inch

(a) at a magnification of 100 and
(b) with no magnification.

4-29 Determine the ASTM grain size number if 20 grains/square inch are observed at a magnification of 400.

4-30 Determine the ASTM grain size number if 25 grains/square inch are observed at a magnification of 50.

4-31 Determine the ASTM grain size number for the materials in: Figure 4-15 and Figure 4-18.

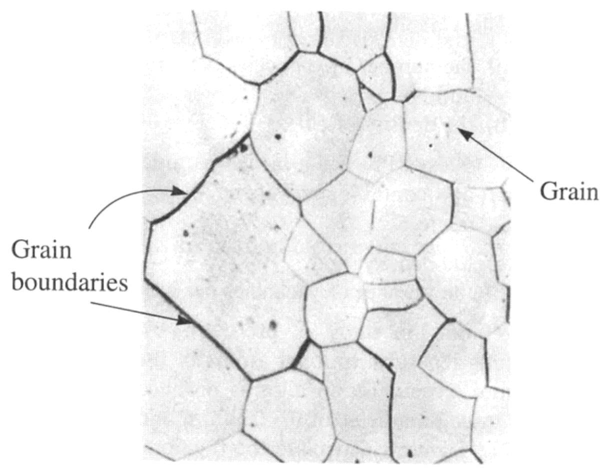

Figure 4-15 (Repeated for Problem 4-31) Microstructure of palladium (×100). (*From* ASM Handbook, *Vol. 9, Metallography and Microstructure (1985), ASM International, Materials Park, OH 44073.*)

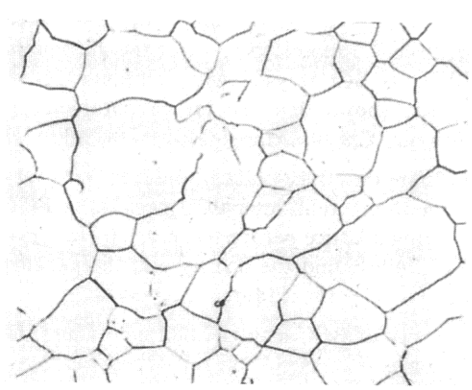

Figure 4-18 Microstructure of iron, for Problem 4-31 (×500). (*From* ASM Handbook, *Vol. 9, Metallography and Microstructure (1985), ASM International, Materials Park, OH 44073.*)

4-32 The yield stress of several samples of a steel containing 0.12% carbon with different grain sizes was measured. The data are shown here.

Sample ID	Grain-Size Inverse Square Root ($d^{-1/2}$)	Yield Stress (MPa)
A	24	500
B	19	420
C	12	320
D	10	250
E	6	190

(a) Calculate the grain size of each steel sample in micrometers.
(b) Which sample has the grain size of 27.7 μm?
(c) Fit these data to a straight line and calculate the constants σ_0 and K for the Hall-Petch equation.
(d) What is the grain size of the sample that has the highest yield strength?
(e) A sample of this steel with 15 μm grain size is produced. What will be the yield stress of this sample?

4-33 A researcher working in the nano-science area develops a sample of 0.12% carbon steel such that the value of $d^{-1/2}$ is 110. What will be the grain size of this steel? Can she use the Hall-Petch relationship developed for this steel in the previous problem to predict the yield stress of this sample?

Section 4-8 Importance of Defects

4-34 What is meant by the term strain hardening?

4-35 Which mechanism of strengthening is the Hall-Petch equation related to?

4-36 Pure copper is strengthened by addition of small concentration of Be. What mechanism of strengthening is this related to?

Design Problems

4-37 The density of pure aluminum calculated from crystallographic data is expected to be 2.69955 g/cm^3.

(a) Design an aluminum alloy that has a density of 2.6450 g/cm^3.
(b) Design an aluminum alloy that has a density of 2.7450 g/cm^3.

4-38 You would like to use a metal plate with good weldability. During the welding process, the metal next to the weld is heated almost to the melting temperature and, depending on the welding parameters, may remain hot for some period of time. Design an alloy that will minimize the loss of strength in this "heat-affected zone" during the welding process.

Grain boundary diffusion Diffusion of atoms along grain boundaries. This is faster than volume diffusion, because the atoms are less closely packed in grain boundaries.

Grain growth Movement of grain boundaries by diffusion in order to reduce the amount of grain boundary area. As a result, small grains shrink and disappear and other grains become larger, similar to how some bubbles in soap froth become larger at the expense of smaller bubbles. In many situations, grain growth is not desirable.

Interstitial diffusion Diffusion of small atoms from one interstitial position to another in the crystal structure.

Permeability A relative measure of the diffusion rate in materials, often applied to plastics and coatings. It is often used as an engineering design parameter that describes the effectiveness of a particular material to serve as a barrier against diffusion.

Self-diffusion The random movement of atoms within an essentially pure material. No net change in composition results.

Sintering A high-temperature treatment used to join small particles. Diffusion of atoms to points of contact causes bridges to form between the particles. Further diffusion eventually fills in any remaining voids. The driving force for sintering is a reduction in total surface area of the powder particles.

Surface diffusion Diffusion of atoms along surfaces.

Vacancy diffusion Diffusion of atoms when an atom leaves a regular lattice position to fill a vacancy in the crystal. This process creates a new vacancy and the process continues.

Volume diffusion Diffusion of atoms through the interior of grains.

PROBLEMS

Section 5-1 Applications of Diffusion

5-1 What is the driving force for diffusion?

5-2 In the carburization treatment of steels, what are the diffusing species?

5-3 Why do we use PET plastic to make carbonated beverage bottles?

Section 5-2 Stability of Atoms and Ions

5-4 Atoms are found to move from one lattice position to another at the rate of $5 \times 10^5 \frac{\text{jumps}}{\text{s}}$ at 400°C when the activation energy for their movement is 30,000 cal/mol. Calculate the jump rate at 750°C.

5-5 The number of vacancies in a material is related to temperature by an Arrhenius equation. If the fraction of lattice points containing vacancies is 8×10^{-5} at 600°C, determine the fraction of lattice points at 1000°C.

Section 5-3 Mechanisms for Diffusion

Section 5-4 Activation Energy for Diffusion

5-6 The diffusion coefficient for Cr^{+3} in Cr_2O_3 is 6×10^{-15} cm²/s at 727°C and is 1×10^{-9} cm²/s at 1400°C. Calculate

(a) the activation energy; and
(b) the constant D_0.

5-7 The diffusion coefficient for O^{-2} in Cr_2O_3 is 4×10^{-15} cm²/s at 1150°C, and 6×10^{-11} cm²/s at 1715°C. Calculate

(a) the activation energy; and
(b) the constant D_0.

5-8 Without referring to the actual data, can you predict whether the activation energy for diffusion of carbon in FCC iron will be higher or lower than that in BCC iron? Explain.

Section 5-5 Rate of Diffusion (Fick's First Law)

5-9 Write down Fick's first law of diffusion. Clearly explain what each term means.

Section 5-6 Factors Affecting Diffusion

5-10 Write down the equation that describes the dependence of D on temperature.

5-11 Explain briefly the dependence of D on the concentration of diffusing species.

Assume that these data are sufficient to make a straight line fit for the relationship between $\ln(D)$ and $1/T$ and calculate the values of the activation energy for diffusion of oxygen in $YBa_2Cu_3O_7$ containing no silver.

5-21 Diffusion of oxygen in $YBa_2Cu_3O_7$ doped with silver was measured. It was seen that the diffusion of oxygen was slowed down by silver doping, as shown in the data here.

Temperature (°C)	Diffusion Coefficient (D) (cm^2/s)
650	2.89×10^{-7}
700	8.03×10^{-7}
750	3.07×10^{-6}

(Source: D.K. Aswal, S.K. Gupta, P.K. Mishra, V.C. Sahni, Superconductor Science and Technology, *1998,* ***11****[7], pp. 631–6).*

Ideally, more data points would be better. However, assume that these data are sufficient to make a straight line fit for the relationship between $\ln(D)$ and $1/T$ and calculate the values of the activation energy for diffusion of oxygen in $YBa_2Cu_3O_7$ containing silver.

5-22 Zinc oxide (ZnO) ceramics are used in a variety of applications, such as surge-protection devices. The diffusion of oxygen in single crystals of ZnO was studied by Tomlins and co-workers. These data are shown in the table here.

Temperature (°C)	Diffusion Coefficient (D) (cm^2/s)
850	2.73×10^{-17}
925	8.20×10^{-17}
995	2.62×10^{-15}
1000	2.21×10^{-15}
1040	5.48×10^{-15}
1095	4.20×10^{-15}
1100	6.16×10^{-15}
1150	1.31×10^{-14}
1175	1.97×10^{-14}
1200	3.50×10^{-14}

(Source: G.W. Tomlins, J.L. Routbort, and T.O. Mason, Journal of the American Ceramic Society, *1998,* ***81****[4], pp. 869–76).*

Using these data, calculate the activation energy for the diffusion of oxygen in ZnO. What is the value of D_0 in cm^2/s?

Section 5-7 Permeability of Polymers

5-23 Amorphous PET is more permeable to CO_2 than PET that contains micro-crystallites. Explain why.

5-24 Explain why a rubber balloon filled with helium gas deflates over time.

Section 5-8 Composition Profile (Fick's Second Law)

5-25 Consider a 2-mm-thick silicon (Si) wafer to be doped using antimony (Sb). Assume that the dopant source (gas mixture of antimony chloride and other gases) provides a constant concentration of 10^{22} atoms/m^3. If we need a dopant profile such that the concentration of Sb at a depth of 1 micrometer is 5×10^{21} atoms/m^3. What will be the time for the diffusion heat treatment? Assume that the silicon wafer to begin with contains no impurities or dopants. Assume the activation energy for diffusion of Sb in silicon is 380 kJ/mole and D_0 for Sb diffusion in Si is 1.3×10^{-3} m^2/s.

5-26 Compare the diffusion coefficients of carbon in BCC and FCC iron at the allotropic transformation temperature of 912°C and explain the difference.

5-27 What is carburizing? Explain why this process is expected to cause an increase in the hardness of the surface of plain carbon steels?

5-28 A carburizing process is carried out on a 0.10% C steel by introducing 1.0% C at the surface at 980°C, where the iron is FCC. Calculate the carbon content at 0.01 cm, 0.05 cm, and 0.10 cm beneath the surface after 1 h.

5-29 Iron containing 0.05% C is heated to 912°C in an atmosphere that produces 1.20% C at the surface and is held for 24 h. Calculate the carbon content at 0.05 cm beneath the surface if

(a) the iron is BCC; and
(b) the iron is FCC. Explain the difference.

5-30 What temperature is required to obtain 0.50% C at a distance of 0.5 mm beneath the surface of a 0.20% C steel in 2 h, when 1.10% C is present at the surface? Assume that the iron is FCC.

5-31 A 0.15% C steel is to be carburized at 1100°C, giving 0.35% C at a distance of 1 mm beneath the surface. If the surface composition is maintained at 0.90% C, what time is required?

5-32 A 0.02% C steel is to be carburized at 1200°C in 4 h, with a point 0.6 mm beneath the surface reaching 0.45% C. Calculate the carbon content required at the surface of the steel.

5-33 A 1.2% C tool steel held at 1150°C is exposed to oxygen for 48 h. The carbon content at the steel surface is zero. To what depth will the steel be decarburized to less than 0.20% C?