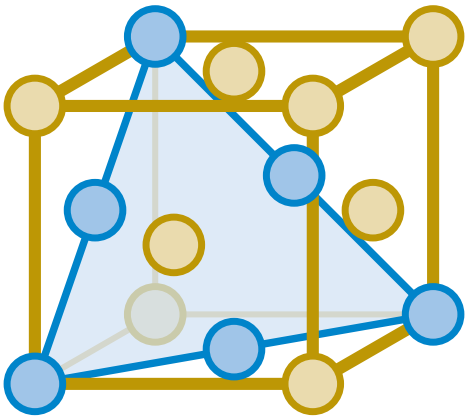
MATERIALS SCIENCE

PROBLEM BOOK

SAMPLE PAGES

13 chapters · 180 problems · step-by-step solutions



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How to use this book

- Each chapter opens with a reminder box summarizing the definitions and formulas the problems rely on.
- Difficulty: ★☆☆ basic ★★☆ intermediate ★★★ advanced. Each chapter has a few multiple-choice concept questions; its last problem is an exam-style mixed problem combining several topics.
- The dotted area below each problem is for your own work. Solve first; if stuck, go back to the reminder box and the lecture notes, and look at the solution last.
- All solutions are at the end of the book. The Solution → link next to a problem takes you to its solution, and ← Problem takes you back. Short answers are in the **ANSWER** box. Where needed, a solution begins with its assumptions and names the appendix tables it uses.
- **Appendix tables and diagrams:** Element data, mechanical and physical properties, diffusion data, the error function, phase diagrams, transformation (TTT, CCT) and Jominy curves, and electrode potentials are in the appendix at the end of the book. The problems are solved with this appendix and the data in the problem statement only; values between table entries are found by linear interpolation.
- **Advanced chapter: 13.** Physical properties (electrical, thermal, magnetic, and optical) are covered in only some of the courses; the chapter is marked ADVANCED in the contents. If your course does not cover these topics, you can skip this chapter.
- **Midterm and final:** Choose the chapters according to your own syllabus. All problems are in SI units.

Contents

Page numbers refer to the full book. Chapters in color are in this sample; click to go there.

1 Introduction, Atomic Structure, and Interatomic Bonding ..... 12 problems 4

2 Crystal Structures ..... 18 problems 12

3 Crystal Defects ..... 14 problems 22

4 Diffusion ..... 12 problems 30

5 Mechanical Properties ..... 18 problems 37

6 Dislocations and Strengthening Mechanisms ..... 12 problems 47

7 Failure ..... 14 problems 56

8 Phase Diagrams ..... 18 problems 66

9 The Iron–Carbon System and Phase Transformations ..... 14 problems 75

10 Heat Treatment and Metal Alloys ..... 14 problems 82

11 Ceramics, Polymers, and Composites ..... 14 problems 90

12 Corrosion and Degradation ..... 10 problems 98

13 Physical Properties ADVANCED ..... 10 problems 104

Solutions 110

Appendix: Tables and Diagrams 187

CHAPTER 2

CRYSTAL STRUCTURES

lattice parameter and atomic radius

SC: $a = 2R$, BCC: $a = \dfrac{4R}{\sqrt{3}}$, FCC: $a = 2\sqrt{2}R$

theoretical density $\rho = \dfrac{nA}{V_C N_A}$

atomic packing factor $\mathrm{APF} = \dfrac{n\frac{4}{3}\pi R^3}{V_C}$

HCP cell (6 atoms)

$V_C = \dfrac{3\sqrt{3}}{2}a^2 c, \quad \left(\dfrac{c}{a}\right)_{\text{ideal}} = 1.633$

radius ratio r_C/r_A and coordination number (CN)

$0.225\text{–}0.414 \rightarrow 4, \quad 0.414\text{–}0.732 \rightarrow 6, \quad \geq 0.732 \rightarrow 8$

linear and planar density

$\mathrm{LD} = \dfrac{N_{\text{line}}}{L}, \quad \mathrm{PD} = \dfrac{N_{\text{plane}}}{S_{\text{plane}}}$

interplanar spacing (cubic)

$d_{hkl} = \dfrac{a}{\sqrt{h^2 + k^2 + l^2}}$

Bragg's law $n\lambda = 2d_{hkl}\sin\theta$

reflecting planes in BCC $h + k + l$ even

reflecting planes in FCC h, k, l all odd or all even

Miller–Bravais plane $(hkil)$: $i = -(h + k)$

direction $[uvw] \rightarrow [UVTW]$

$U = \frac{2u - v}{3}, \; V = \frac{2v - u}{3}, \; T = -(U + V), \; W = w$

Atomic mass, crystal structure, lattice parameters (a, c), atomic radius, and density are read from Table M-1, and ionic radii from Table M-2; values not in the Appendix are given in the problem statement. Atoms are treated as hard spheres: in a metal the nearest neighbors touch one another, and in an ionic structure the cation and the anion touch. Avogadro's number is $N_A = 6.022 \times 10^{23}$ mol^{-1}, and the elementary charge $e = 1.602 \times 10^{-19}$ C. Lengths are written in nanometers; in density calculations 1 nm $= 10^{-7}$ cm, that is, 1 nm$^3 = 10^{-21}$ cm^3. The atomic packing factor (APF) is the fraction of the unit-cell volume occupied by the spheres. The coordination number (CN) is the number of nearest neighbors of an atom. In Miller indices a minus sign is written as a bar over the index: $(1\bar{1}0)$. In diffraction problems only first-order ($n = 1$) reflections are used. In the figures atoms are drawn as blue (the anion in ionic structures) and red (the cation) spheres, Miller planes in semitransparent green, and directions as red and blue arrows.

The unit cell and the crystal structures of metals

2.1 ★☆☆ Solution →

Which of the following statements about the cubic and hexagonal crystal structures of metals is true?

A) In the body-centered cubic (BCC) structure each atom has 12 nearest neighbors.

B) The number of atoms per face-centered cubic (FCC) unit cell is 2.

C) In the simple cubic (SC) structure the atoms touch one another along the face diagonal.

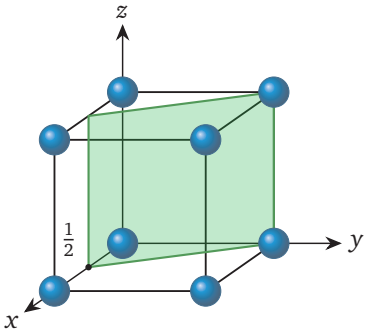
D) The ideal APF of the hexagonal close-packed (HCP) structure is clearly smaller than that of FCC.

E) In the FCC structure the coordination number of each atom is 12, and the atoms touch one another along the face diagonal.

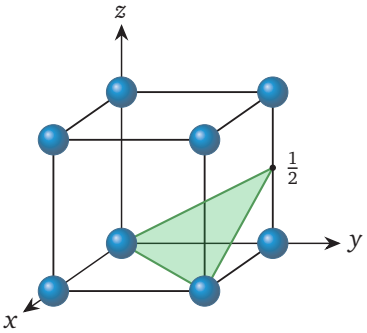
Miller indices

2.10 ★☆☆ Solution →

Two planes are shown in the cubic unit cells in the figure. Plane 2 passes through the origin. Find the Miller indices of the two planes.



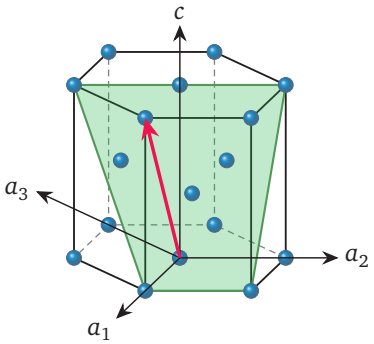
Plane 1



Plane 2

2.11 ★★☆ Solution →

Basal, prismatic, and pyramidal planes play a role in the deformation of titanium (HCP). In the HCP cell in the figure the a_1, a_2, a_3, and c axes are drawn from the center of the basal hexagon. The green plane passes through the front edge of the base and through the long diagonal of the top base, which runs through its center parallel to a_2. The red arrow extends from the origin to the top corner directly above the base corner at the tip of a_1.



a. Find the Miller–Bravais indices $(hkil)$ of the green plane.

b. Write the red direction in three-index $[uvw]$ and four-index $[UVTW]$ notation.

CHAPTER 5

MECHANICAL PROPERTIES

engineering stress and strain $\sigma = \dfrac{F}{A_0}, \quad \varepsilon = \dfrac{\Delta L}{L_0}$

Hooke's law, Poisson's ratio $\sigma = E\varepsilon, \quad \nu = -\dfrac{\varepsilon_{\text{lat}}}{\varepsilon_{\text{ax}}}$

shear modulus (isotropic) $G = \dfrac{E}{2(1+\nu)}$

ductility $\%\text{EL} = 100\,\dfrac{L_f - L_0}{L_0}, \quad \%\text{RA} = 100\,\dfrac{A_0 - A_f}{A_0}$

working stress $\sigma_{\text{w}} = \dfrac{\sigma_{\text{y}}}{N}$

modulus of resilience $U_r = \dfrac{\sigma_{\text{y}}^2}{2E}$

toughness, ductile material (approx.)

$U_T \approx \dfrac{\sigma_{\text{y}} + \sigma_{\text{TS}}}{2}\,\varepsilon_f$

true stress and strain (before necking)

$\sigma_T = \sigma(1+\varepsilon), \quad \varepsilon_T = \ln(1+\varepsilon)$

strain hardening, onset of necking

$\sigma_T = K\varepsilon_T^{\,n}, \quad \varepsilon_{T,u} = n$

Brinell (P in kilograms-force; D, d in millimeters)

$\text{HB} = \dfrac{2P}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}$

for steel (approx.) $\sigma_{\text{TS}}\ (\text{MPa}) \approx 3.45\,\text{HB}$

The modulus of elasticity E, Poisson's ratio ν, yield strength σ_{y} (0.2% offset), tensile strength σ_{TS}, percent elongation, and density are read from Table M-5; measured forces, lengths, and specification limits are given in the problem statement. Unless stated otherwise, stress and strain are engineering values (σ, ε); true values are denoted by σ_T, ε_T. Tensile stress and elongation are positive, compressive stress and contraction negative. Materials are assumed to be isotropic. Ceramics and composites do not yield: linear elastic behavior up to fracture is assumed and σ_{TS} is used. Energy per unit volume (modulus of resilience, toughness) is written in megajoules per cubic meter; numerically, 1 MJ/m^3 equals 1 MPa.

Stress, strain, and elastic behavior

5.2 ★☆☆ Solution →

One of the Ti-6Al-4V fixation rods used in spinal surgery has a diameter of 5.5 mm and a length of 120 mm. The rod is tested in the laboratory under an axial tensile force of 6.0 kN.

a. Find the stress in the rod; show that the rod remains in the elastic region.

b. Calculate the changes in the length and diameter of the rod.

c. At what force does yielding begin in the rod?

5.4 ★★☆ Solution →

In a student laboratory, a tensile specimen of Al 6061-T6 with a diameter of 10.0 mm is tested. The parallel length of the specimen is 80.0 mm; no extensometer is attached, and the elongation is read from the crosshead displacement. At a force of 15.0 kN the crosshead has moved 0.380 mm.

a. Calculate the (apparent) modulus of elasticity obtained from the crosshead reading and compare it with the value in Table M-5.

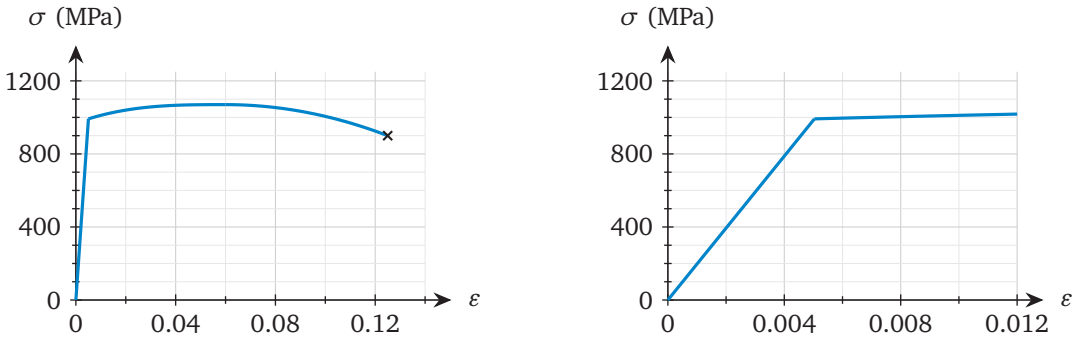
b. Assuming that the difference comes from the elastic deflection of the machine and the grips, find the stiffness of the machine (in N/mm).

c. If a 1040 steel specimen of the same dimensions is pulled with 15.0 kN on the same machine, how far does the crosshead move, and what apparent modulus of elasticity is obtained?

The tensile test: yielding, tensile strength, and ductility

5.5 ★★☆ Solution →

In a workshop, a tensile specimen is taken from a bar whose label has been lost. The engineering stress–strain curve measured with an extensometer is shown in full on the left and with its initial region enlarged on the right; × marks the fracture point.



a. Read the modulus of elasticity, the 0.2% offset yield strength and the tensile strength from the curves.

b. Find the percent elongation that would be measured after fracture.

c. Identify the material with the help of Table M-5.

CHAPTER 8

PHASE DIAGRAMS

lever rule ($\alpha + \mathrm{L}$; tie-line ends C_L, C_α)

$$W_\mathrm{L} = \frac{C_\alpha - C_0}{C_\alpha - C_\mathrm{L}}, \quad W_\alpha = \frac{C_0 - C_\mathrm{L}}{C_\alpha - C_\mathrm{L}}$$

Gibbs phase rule (constant pressure)

$$F = C - P + 1$$

eutectic and eutectoid (on cooling)

$$\mathrm{L} \to \alpha + \beta, \quad \gamma \to \alpha + \beta$$

peritectic (on cooling) $\alpha + \mathrm{L} \to \beta$

hypoeutectic: primary α' and eutectic structure

$$W_\mathrm{e} = \frac{C_0 - C_\alpha}{C_E - C_\alpha}, \quad W_{\alpha'} = \frac{C_E - C_0}{C_E - C_\alpha}$$

hypereutectic: primary β' $\quad W_{\beta'} = \dfrac{C_0 - C_E}{C_\beta - C_E}$

atom percent (w: weight percent)

$$a_\mathrm{B} = \frac{w_\mathrm{B}/A_\mathrm{B}}{w_\mathrm{B}/A_\mathrm{B} + w_\mathrm{A}/A_\mathrm{A}} \times 100$$

The Cu–Ni, Pb–Sn, and Al–Cu phase diagrams are in Tables M-6, M-7, and M-9; atomic mass, atomic radius, and density are read from Table M-1. Data for systems not in the Appendix are given in the problem statement. Compositions are in weight percent: "Pb–30 wt% Sn" is a Pb–Sn alloy containing 30 wt% Sn; C_0 is the composition of the alloy, and C_L, C_α, C_β are the compositions of the phases. The symbol W denotes a mass fraction; a primary (proeutectic) phase is marked with a prime (α', β'), and the eutectic structure is denoted by W_e. Unless stated otherwise, cooling and heating are slow enough to maintain equilibrium. Compositions and temperatures read from a diagram are written with "≈" to the reading precision (0.5–1 percentage point in composition, about 5 K in temperature); values printed as numbers in the Appendix, such as the eutectic and eutectoid points, are not read from the diagram but used directly. "Just below the eutectic temperature" refers to the state in which the reaction is complete but the change along the solvus has not yet taken effect.

Development of microstructure

8.12 ★☆☆ Solution →

A Pb–14 wt% Sn alloy is cooled slowly from 350 °C to 25 °C (Table M-7).

a. State the temperatures of the phase boundaries that the alloy crosses and the phases present between them.

b. Find the mass fraction of the β phase at 25 °C.

Mixed problems

8.15 ★★★ Solution →

A circuit board manufacturer will select a Pb–Sn solder for a wave soldering line. The bath operates at 250 °C, and the liquidus temperature of the solder must be at least 30 K below the bath temperature. So that the joint is not disturbed by vibration while it solidifies, the solidification range (between the liquidus and the eutectic temperature, the "pasty range") must be at most 15 K. Tin is more expensive than lead. Use Table M-7.

a. Find the Sn range that satisfies the bath condition alone.

b. Find the Sn range that satisfies both conditions together.

c. State the composition to be chosen on the basis of cost, and calculate the mass fraction of the primary phase in this alloy just below the eutectic temperature.

d. Explain why, conversely, a wide pasty range is desired for solders shaped by hand wiping at plumbing joints.

8.16 ★★★ Solution →

One of the lead-free solders that became widespread in electronics after restrictions on lead is the Sn–Ag eutectic. The eutectic on the Sn side occurs at 221 °C and 3.5 wt% Ag: $\mathrm{L} \rightarrow \mathrm{Sn} + \mathrm{Ag_3Sn}$. The Ag dissolved in the Sn phase is neglected.

a. Using the atomic masses in Table M-1, find the weight percent of Ag in $\mathrm{Ag_3Sn}$.

b. Find the mass fraction of $\mathrm{Ag_3Sn}$ in the Sn–Ag eutectic, and compare it with the α and β fractions in the Pb–Sn eutectic (Table M-7).

c. For a Sn–3.0 wt% Ag solder, find the mass fractions of primary Sn and of total $\mathrm{Ag_3Sn}$ just below the eutectic temperature.

d. If the bath is held a fixed amount above the eutectic, by how much does the bath temperature increase in switching from the Pb–Sn eutectic to the Sn–Ag eutectic, and what is the drawback of this for the components on the board?

SOLUTIONS

2 CRYSTAL STRUCTURES

2.1

← Problem

In the FCC cell a corner atom touches the atoms at the centers of the three faces that share that corner; the face diagonal has a length of $4R$ ($a\sqrt{2} = 4R$). Each atom is surrounded by 12 neighbors. **E** is true.

- (A): In BCC an atom touches only the eight corner atoms, along the body diagonal: CN 8.
- (B): The FCC cell contains $8\times\frac{1}{8}+6\times\frac{1}{2} = 4$ atoms; 2 atoms is the number for BCC.
- (C): In SC the atoms touch along the cube edge ($a = 2R$); since the face diagonal is $2\sqrt{2}R$, the atoms on the diagonal do not touch one another.
- (D): Ideal HCP ($c/a = 1.633$) and FCC consist of the same close-packed planes stacked in different sequences (ABAB, ABCABC); both have an APF of 0.74.

ANSWER E

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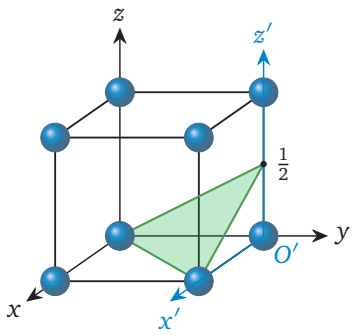
2.10

← Problem

The intercepts with the axes (in units of the cell edge) are found, their reciprocals are taken, and fractions are cleared.

Plane 1: $x = \frac{1}{2}$, $y = 1$, and it does not intersect the z axis (∞). The reciprocals are $2, 1, 0$: (210).

Since plane 2 passes through the origin, the origin is moved to an adjacent corner. If the new origin is taken at $(0, 1, 0)$, the plane intersects the x axis at 1, the y axis at -1 (the old origin, point $(0, 0, 0)$), and the z axis at $\frac{1}{2}$. The reciprocals are $1, -1, 2$: $(1\bar{1}2)$.



Check: The $(1\bar{1}2)$ plane has the form $x - y + 2z = 0$; the points $(0, 0, 0)$, $(1, 1, 0)$, and $(0, 1, \frac{1}{2})$ satisfy this equation.

ANSWER Plane 1 (210), plane 2 $(1\bar{1}2)$

2.11

← Problem

a. The plane intersects a_1 at the front corner of the base ($a_1 = 1$) and c at the center of the top base ($c = 1$); the front edge of the base and the top diagonal are parallel to a_2 ($a_2 = \infty$). The extension of the a_3 axis in the negative direction reaches the corner at the other end of the front edge: $a_3 = -1$.

$$(hkil) = \left(\tfrac{1}{1}, \tfrac{1}{\infty}, \tfrac{1}{-1}, \tfrac{1}{1}\right) = (10\bar{1}1).$$

Check: $i = -(h + k) = -(1 + 0) = -1$.

b. The arrow goes from the origin to the point $a_1 + c$: $[uvw] = [101]$. Conversion:

$$U = \tfrac{2u-v}{3} = \tfrac{2}{3}, \quad V = \tfrac{2v-u}{3} = -\tfrac{1}{3},$$
$$T = -(U + V) = -\tfrac{1}{3}, \quad W = w = 1.$$

Multiplying by 3 gives $[2\bar{1}\bar{1}3]$.

ANSWER a. $(10\bar{1}1)$ b. $[101]$, $[2\bar{1}\bar{1}3]$

5 MECHANICAL PROPERTIES

5.2

← Problem

From Table M-5, Ti-6Al-4V (annealed): $E = 114$ GPa, $\nu = 0.34$, $\sigma_y = 880$ MPa.

a. Cross-sectional area $A_0 = \pi(5.5)^2/4 = 23.758$ mm^2:

$$\sigma = \frac{F}{A_0} = \frac{6000}{23.758} = 252.5 \text{ MPa}.$$

Since $\sigma < \sigma_y = 880$ MPa, the rod is in the elastic region (29% of the yield strength).

b. Axial and lateral strains:

$$\varepsilon = \frac{\sigma}{E} = \frac{252.5}{114\,000} = 2.215 \times 10^{-3},$$
$$\Delta L = \varepsilon L_0 = 2.215 \times 10^{-3}\,(120) = 0.266 \text{ mm},$$
$$\Delta d = -\nu\varepsilon d_0 = -0.34\,(2.215 \times 10^{-3})(5.5)$$
$$= -4.14 \times 10^{-3} \text{ mm}.$$

The rod elongates by 0.266 mm, and its diameter decreases by about 4 μm.

c. Yielding begins when $\sigma = \sigma_y$:

$$F_y = \sigma_y A_0 = 880\,(23.758) = 20\,910 \text{ N} \approx 20.9 \text{ kN}.$$

ANSWER a. $\sigma = 252.5$ MPa < 880 MPa, elastic
b. $\Delta L = 0.266$ mm; $\Delta d = -4.14 \times 10^{-3}$ mm
c. 20.9 kN

5.4

← Problem

a. $A_0 = \pi(10.0)^2/4 = 78.54$ mm^2,
$\sigma = 15\,000/78.54 = 190.99$ MPa:

$$E_{app} = \frac{\sigma L_0}{\Delta L} = \frac{190.99\,(80.0)}{0.380}$$
$$= 40\,208 \text{ MPa} \approx 40.2 \text{ GPa}.$$

Table M-5 gives $E = 69$ GPa for Al 6061-T6: the apparent value is 42% smaller.

b. Actual elongation of the specimen and the share of the machine:

$$\Delta L_{sp} = \frac{\sigma L_0}{E} = \frac{190.99\,(80.0)}{69\,000} = 0.2214 \text{ mm},$$
$$\Delta_{mach} = 0.380 - 0.2214 = 0.1586 \text{ mm},$$
$$k = \frac{F}{\Delta_{mach}} = \frac{15\,000}{0.1586} = 9.46 \times 10^4 \text{ N/mm}.$$

c. From Table M-5, 1040 steel: $E = 207$ GPa. The

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stress is the same:

$$\Delta L_{sp} = \frac{190.99\,(80.0)}{207\,000} = 0.0738 \text{ mm},$$
$$\Delta_{tot} = 0.0738 + 0.1586 = 0.2324 \text{ mm},$$
$$E_{app} = \frac{190.99\,(80.0)}{0.2324} = 65\,750 \text{ MPa} \approx 65.8 \text{ GPa}.$$

With a stiff specimen the share of the machine is larger: for steel the apparent modulus is not even one third of the true value. The modulus of elasticity is therefore measured with an extensometer attached to the specimen.

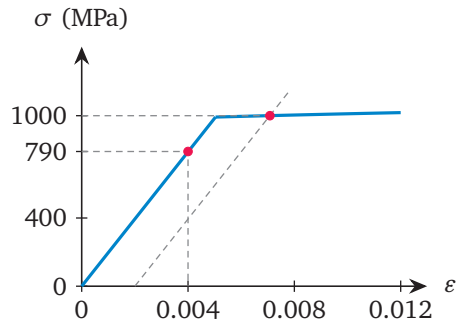
ANSWER a. $E_{app} \approx 40.2$ GPa (Table M-5: 69 GPa) b. 9.46×10^4 N/mm c. 0.2324 mm; $E_{app} \approx 65.8$ GPa

5.5 ← Problem

a. On the enlarged curve the straight line passes through $\sigma \approx 790$ MPa at $\varepsilon = 0.004$:

$$E \approx \frac{790}{0.004} = 1.975 \times 10^5 \text{ MPa} \approx 2.0 \times 10^2 \text{ GPa}.$$

The line drawn from $\varepsilon = 0.002$ parallel to the elastic line intersects the curve at $\sigma \approx 1000$ MPa: $\sigma_y \approx 1000$ MPa. The highest point of the full curve gives $\sigma_{TS} \approx 1070$ MPa.



b. At fracture the total strain is $\varepsilon_f \approx 0.125$ and the stress ≈ 900 MPa. After fracture the elastic part is recovered:

$$\%\text{EL} \approx 100\left(0.125 - \frac{900}{197\,000}\right) = 12.0.$$

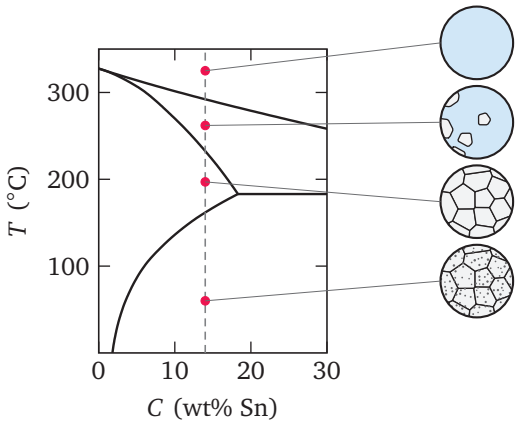
c. Since $E \approx 200$ GPa, the material is a steel or a Ni alloy. Materials in Table M-5 with a yield strength of about 1000 MPa: 17-4 PH stainless (H1025) 1000/1070 MPa, 12%; 4140 1080/1180 MPa, 15%; Ni 718 1100/1340 MPa, 18%. The tensile strength and the elongation match only 17-4 PH.

ANSWER a. $E \approx 2.0 \times 10^2$ GPa, $\sigma_y \approx 1000$ MPa, $\sigma_{TS} \approx 1070$ MPa b. 12.0% c. 17-4 PH stainless steel (H1025)

8 PHASE DIAGRAMS

8.12 ← Problem

a. The 14 wt% Sn composition line intersects the liquidus at ≈ 292 °C, the solidus at ≈ 232 °C, and the α solvus at ≈ 162 °C. In order: L; $\alpha + \text{L}$ (between the liquidus and the solidus); α only (between 232 and 162 °C); $\alpha + \beta$ (below 162 °C; β precipitates as small particles within the α grains and at their boundaries). Since $14 < 18.3$, the eutectic isotherm is not encountered, and no eutectic structure forms.



b. At 25 °C the tie line intersects the solvus lines at $C_\alpha \approx 2$ and $C_\beta \approx 100$ (practically pure Sn):

$$W_\beta = \frac{14 - 2}{100 - 2} = 0.122 \approx 0.12.$$

ANSWER a. liquidus ≈ 292 °C, solidus ≈ 232 °C, solvus ≈ 162 °C; $\text{L} \to \alpha + \text{L} \to \alpha \to \alpha + \beta$ b. $W_\beta \approx 0.12$

8.15 ← Problem

a. The liquidus is at most $250 - 30 = 220$ °C. The 220 °C isotherm intersects the liquidus on the α side at ≈ 48 wt% Sn and that on the β side at ≈ 91

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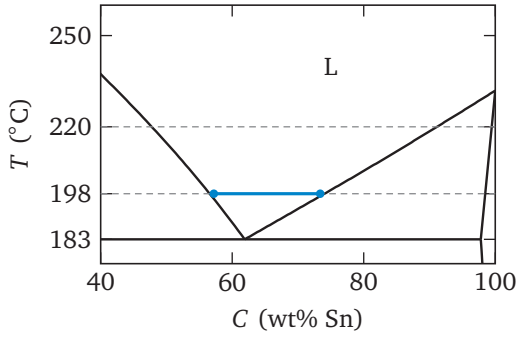
wt% Sn. The alloys in between have lower liquidus temperatures: ≈ 48–91 wt% Sn.

b. Alloys in this range finish solidifying at 183 °C; for a pasty range ≤ 15 K the liquidus must be at most 198 °C. The 198 °C isotherm intersects the liquidus lines at ≈ 57 and ≈ 74 wt% Sn: ≈ 57–74 wt% Sn.



c. The least Sn is at the lower end of the range: ≈ 57 wt% Sn (close to the common 60/40 solder). The alloy is hypoeutectic, and the primary phase is α:

$$W_{\alpha'} = \frac{61.9 - 57}{61.9 - 18.3} = \frac{4.9}{43.6} = 0.112 \approx 0.11.$$

For example, if 48 wt% Sn were chosen, the pasty range would be ≈ 37 K.

d. A wiped solder must remain for a long time in the pasty state, in which solid and liquid coexist; during this time the plumber wipes and shapes the solder with a cloth. A wide liquidus–solidus range (Pb-rich alloys around 30–40 wt% Sn) provides this; a eutectic solder, by contrast, solidifies all at once.

ANSWER a. ≈ 48–91 wt% Sn b. ≈ 57–74 wt% Sn c. ≈ 57 wt% Sn; $W_{\alpha'} \approx 0.11$ d. shaping requires a long time in the pasty state

8.16

← Problem

Assumptions: equilibrium cooling; Ag_3Sn is stoichiometric with a single composition; the solubility of Ag in Sn is zero.

a. From Table M-1, $A_{Ag} = 107.87$, $A_{Sn} = 118.71$ g/mol:

$$M = 3(107.87) + 118.71 = 442.32 \text{ g/mol},$$
$$w_{Ag} = \frac{323.61}{442.32} \times 100 = 73.16.$$

b. The ends of the eutectic isotherm are Sn (0 Ag) and Ag_3Sn (73.16 Ag):

$$W_{Ag_3Sn} = \frac{3.5 - 0}{73.16 - 0} = 0.0478, \quad W_{Sn} = 0.952.$$

In the Pb–Sn eutectic (61.9; between 18.3 and 97.8):

$$W_{\alpha} = \frac{97.8 - 61.9}{97.8 - 18.3} = 0.4516 \approx 0.452, \quad W_{\beta} = 0.548.$$

The Pb–Sn eutectic is a roughly equal mixture of two phases, whereas the Sn–Ag eutectic consists of a small fraction (4.8%) of hard intermediate-phase particles in an almost pure Sn matrix.

c. Since 3.0 < 3.5 wt% Ag, the alloy is hypoeutectic and the primary phase is Sn:

$$W_{Sn'} = \frac{3.5 - 3.0}{3.5 - 0} = 0.143,$$

$$W_{Ag_3Sn} = \frac{3.0 - 0}{73.16 - 0} = 0.0410.$$

d. The increase is $221 - 183 = 38$ K. The components (plastic-packaged chips, capacitors) and the board material are exposed to a higher temperature: the risks of thermal stress, package cracking due to moisture vaporization, and board warpage increase.

ANSWER a. 73.16 wt% Ag b. 0.0478; in Pb–Sn $W_{\alpha} = 0.452$, $W_{\beta} = 0.548$ c. $W_{Sn'} = 0.143$, $W_{Ag_3Sn} = 0.0410$ d. 38 K; risk of thermal damage to components and board

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APPENDIX: TABLES AND DIAGRAMS

The tables and diagrams in this appendix are used to solve the problems; units are SI. The values are rounded from compiled reference data (element and ion data, diffusion coefficients, electrode potentials); mechanical and physical properties are typical values. The phase and transformation diagrams are drawn through the characteristic points given in the literature; intermediate values are read from the grid. Values not in a table are found by **linear interpolation**: if $x_1 < x < x_2$, then $y = y_1 + (y_2 - y_1)(x - x_1)/(x_2 - x_1)$. The numerical answers of the problems are computed with the values in this appendix.

This sample includes only the Appendix tables used by the selected problems (M-1, M-5, M-7). The Appendix of the full book has 16 tables on 11 pages: element and ion data, diffusion and the error function, mechanical properties, phase diagrams, TTT, CCT, and Jominy curves, the electrochemical and galvanic series, and electrical and thermal properties.

Table M-1 Atomic and crystal data of the elements

Element	Symbol	Z	Atomic mass g/mol	Crystal structure (20 °C)	a nm	c nm	R nm	ρ g/cm^3	T_m °C
Hydrogen	H	1	1.0080	—	—	—	—	—	−259.2
Carbon (graphite)	C	6	12.011	Hexagonal	0.2464	0.6711	0.0711	2.26	—
Nitrogen	N	7	14.007	—	—	—	—	—	−210
Oxygen	O	8	15.999	—	—	—	—	—	−218.8
Sodium	Na	11	22.990	BCC	0.4291	—	0.1858	0.968	97.8
Magnesium	Mg	12	24.305	HCP	0.3209	0.5211	0.1599	1.74	650
Aluminum	Al	13	26.982	FCC	0.4050	—	0.1432	2.70	660.3
Silicon	Si	14	28.085	DC	0.5431	—	0.1176	2.33	1414
Sulfur	S	16	32.06	Orthorhombic	—	—	—	2.07	115.2
Chlorine	Cl	17	35.45	—	—	—	—	—	−101.5
Potassium	K	19	39.098	BCC	0.5328	—	0.2307	0.862	63.5
Titanium	Ti	22	47.867	HCP	0.2951	0.4684	0.1448	4.51	1668
Vanadium	V	23	50.942	BCC	0.3024	—	0.1309	6.11	1910
Chromium	Cr	24	51.996	BCC	0.2885	—	0.1249	7.19	1907
Manganese	Mn	25	54.938	Cubic (complex)	—	—	—	7.30	1246
Iron (α)	Fe	26	55.845	BCC	0.2867	—	0.1241	7.87	1538
Cobalt	Co	27	58.933	HCP	0.2507	0.4070	0.1249	8.86	1495
Nickel	Ni	28	58.693	FCC	0.3524	—	0.1246	8.91	1455
Copper	Cu	29	63.546	FCC	0.3615	—	0.1278	8.96	1085
Zinc	Zn	30	65.38	HCP	0.2665	0.4947	0.1332	7.13	419.5
Germanium	Ge	32	72.630	DC	0.5658	—	0.1225	5.32	938.3
Zirconium	Zr	40	91.224	HCP	0.3232	0.5148	0.1589	6.51	1855
Niobium	Nb	41	92.906	BCC	0.3300	—	0.1429	8.57	2477
Molybdenum	Mo	42	95.95	BCC	0.3147	—	0.1363	10.2	2623
Silver	Ag	47	107.87	FCC	0.4086	—	0.1445	10.5	961.8
Cadmium	Cd	48	112.41	HCP	0.2979	0.5619	0.1490	8.65	321.1
Tin (β)	Sn	50	118.71	Tetragonal	0.5832	0.3182	0.1508	7.29	231.9
Tantalum	Ta	73	180.95	BCC	0.3301	—	0.1430	16.7	3017
Tungsten	W	74	183.84	BCC	0.3165	—	0.1371	19.3	3422
Platinum	Pt	78	195.08	FCC	0.3924	—	0.1387	21.5	1768
Gold	Au	79	196.97	FCC	0.4078	—	0.1442	19.3	1064
Lead	Pb	82	207.2	FCC	0.4950	—	0.1750	11.3	327.5

FCC: face-centered cubic, BCC: body-centered cubic, HCP: hexagonal close-packed, DC: diamond cubic. a, c: lattice parameters at room temperature. R: atomic radius, half the nearest-neighbor distance (FCC $a\sqrt{2}/4$, BCC $a\sqrt{3}/4$, DC $a\sqrt{3}/8$; for HCP from the nearest-neighbor distance). ρ: density at 20–25 °C (— for gases). T_m: melting point at 1 atm; carbon does not melt at 1 atm, it sublimes at about 3825 °C. The unit cell of β-Sn and that of graphite contain 4 atoms.

Table M-5 Mechanical properties of engineering materials (room temperature)

Material	Condition	ρ g/cm^3	E GPa	ν	σ_y MPa	σ_{TS} MPa	Elong. %	K_{Ic} MPa$\sqrt{m}$
Metals and alloys								
Mg alloy AZ31B	H24 sheet	1.77	45	0.35	220	290	15	28
Al casting alloy A356	T6	2.68	72	0.33	190	265	5	18
Al 1100 (commercially pure)	annealed	2.71	69	0.33	34	90	35	—
Al alloy 6061	T6	2.70	69	0.33	275	310	12	29
Al alloy 2024	T3	2.78	73	0.33	345	485	18	37
Al alloy 7075	T6	2.81	72	0.33	505	570	11	26
Ti-6Al-4V	annealed	4.43	114	0.34	880	950	14	70
Ti, Grade 2 (commercially pure)	annealed	4.51	105	0.37	275	345	20	—
Gray cast iron EN-GJL-250	as cast	7.20	110	0.26	—	250	0.5	18
Ductile iron EN-GJS-500-7	as cast	7.10	169	0.28	320	500	7	50
Stainless steel 17-4 PH	H1025	7.80	197	0.27	1000	1070	12	110
Steel 1020	hot rolled	7.87	207	0.29	210	380	25	—
Steel 1040	cold drawn	7.85	207	0.29	490	590	12	—
Steel 1080	normalized	7.85	207	0.29	520	965	11	—
Steel 4140	tempered, 540 °C	7.85	205	0.29	1080	1180	15	80
Steel 4340	tempered, 315 °C	7.85	205	0.29	1500	1720	11	55
Stainless steel 304	annealed	8.00	193	0.29	215	505	50	—
Ni superalloy 718	aged	8.19	200	0.29	1100	1340	18	95
Beryllium copper C17200	aged	8.25	128	0.30	1000	1200	5	—
Brass C26000 (70Cu-30Zn)	annealed	8.53	110	0.35	100	340	60	—
Copper C11000	annealed	8.89	115	0.34	70	220	45	—
Ceramics and glasses								
Fused silica glass		2.20	73	0.17	—	100†	—	0.8
Soda-lime glass		2.50	70	0.23	—	70†	—	0.8
Silicon carbide (SiC)	sintered	3.15	410	0.14	—	450†	—	3.5
Silicon nitride (Si_3N_4)	hot pressed	3.25	310	0.27	—	800†	—	6.0
Alumina (Al_2O_3, 99.5%)	sintered	3.89	375	0.22	—	350†	—	4.0
Zirconia (ZrO_2, Y_2O_3-doped)	sintered	6.05	205	0.31	—	1000†	—	8.0
Polymers								
Polypropylene (PP)		0.905	1.4	0.43	32	35	150	3.0
High-density polyethylene (HDPE)		0.950	1	0.46	25	30	500	2.0
Polystyrene (PS)		1.05	3.2	0.34	—	45	2	0.9
Nylon 6,6 (dry)		1.14	2.9	0.39	80	82	60	3.0
PMMA		1.19	3.1	0.37	—	72	4	1.2
Polycarbonate (PC)		1.20	2.4	0.37	62	66	110	2.5
Epoxy	cured	1.20	2.8	0.35	—	60	3	0.6
PVC (rigid)		1.40	3	0.38	45	50	40	2.5
PTFE		2.17	0.5	0.46	12	25	300	—
Composites								
Carbon fiber/epoxy, unidirectional, $V_f = 0.60$	fiber direction	1.60	140	0.28	—	2000	1.4	—
Glass fiber/epoxy, unidirectional, $V_f = 0.60$	fiber direction	2.10	45	0.28	—	1000	2.5	—

Typical, rounded values (the 17-4 PH row gives specification minimums); actual values depend on processing and heat treatment. σ_y: yield strength (0.2% offset), σ_{TS}: tensile strength, elongation: elongation at fracture over a 50 mm gauge length, K_{Ic}: plane-strain fracture toughness. —: not defined, or no valid K_{Ic} can be measured in a ductile material (very high toughness). †For ceramics and glasses, three-point flexural strength (modulus of rupture) instead of tensile strength; compressive strengths are 5–15 times larger. Polymer values are for 23 °C and a tensile rate of about 5 mm/min. Gray cast iron has no distinct yield point. Tempered steels are quenched first. For 2024-T3, K_{Ic} is for T351 plate, L-T orientation.

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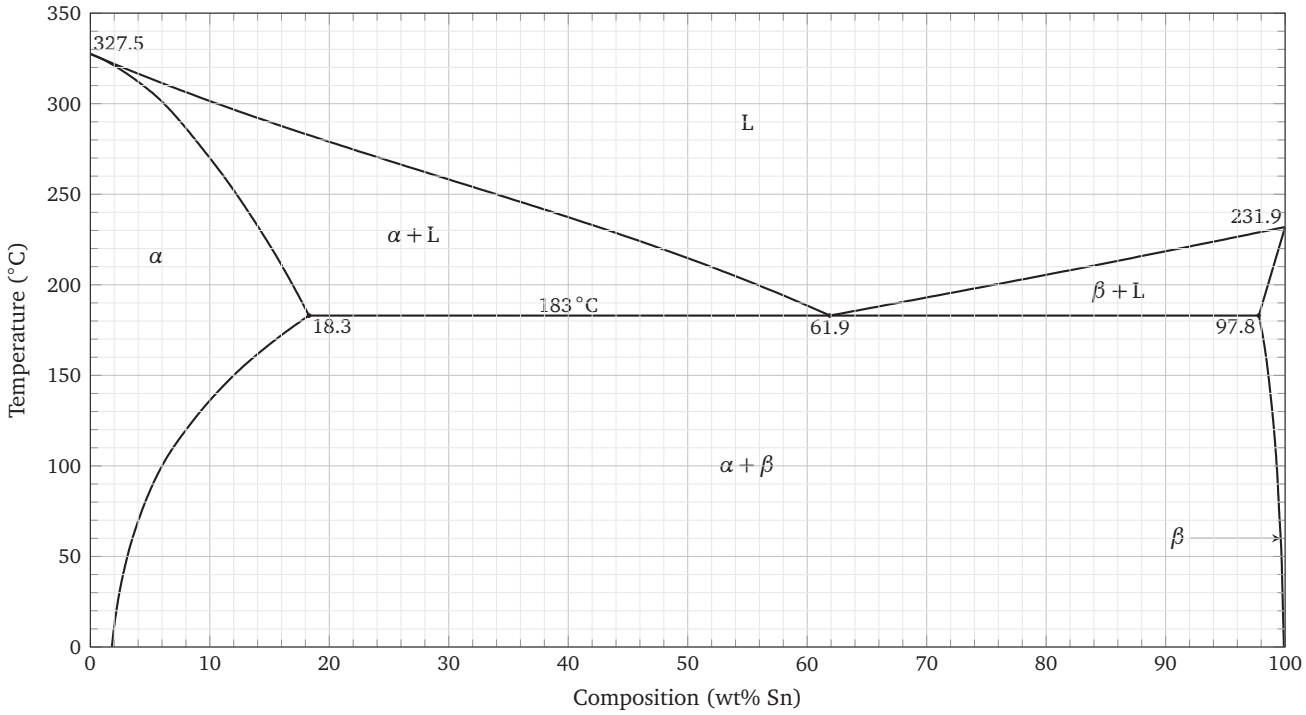
Table M-7 Pb–Sn phase diagram



α: Pb-rich, β: Sn-rich solid solution. Eutectic: 183 °C, 61.9 wt% Sn; L → α (18.3 wt% Sn) + β (97.8 wt% Sn).

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