

1. Answer following questions briefly: (65%)

(a) Why is it important or helpful to classify materials into different groups as we have done in chapter 1?

Classification of materials allows the engineer to associate certain general characteristics with a specific material¹. For instance, one you realized that material X is classified as a ceramic¹, without actually knowing the exact properties¹, you will immediately know that it will be brittle, low density, chemically stable, low friction etc¹. You will also know the nature of its atomic structure¹. In general, it gives you the ability to seek candidates for your materials selection applications¹.

(b) A 100-gram alloy of Fe and C consists of 95.7 wt% Fe and 4.3 wt% C. What are the atomic percentages of Fe and C in this alloy? (atomic mass: Fe 55.85 g/mol, C 12.01 g/mol)

$$\text{C: } (4.3/12.01)/[(95.7/55.85)+(4.3/12.01)] \times 100\% \quad \mathbf{1.5} = 17.3 \text{ at\% } \mathbf{1}$$

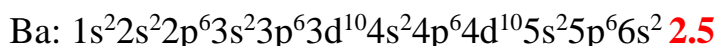
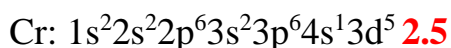
$$\text{Fe: } (95.7/55.85)/[(95.7/55.85)+(4.3/12.01)] \times 100\% \quad \mathbf{1.5} = 82.7 \text{ at\% } \mathbf{1}$$

(c) A hydrogen atom exists with its electron in the $n = 3$ state. The electron undergoes a transition to $n = 1$ state. Calculate the wavelength of the corresponding photo. ($h = 6.63 \times 10^{-34}$ J·s, $c = 3.00 \times 10^8$ m/s, $1 \text{ eV} = 1.60 \times 10^{-19}$ J).

$$\Delta E = E_3 - E_2 = (-13.6 \text{ eV}/3^2) - (-13.6 \text{ eV}/1^2) \quad \mathbf{1} = 12.09 \text{ eV} = 12.09 \text{ eV} \times 1.60 \times 10^{-19} \text{ J/eV} \quad \mathbf{1} = 19.3 \times 10^{-19} \text{ J } \mathbf{1}$$

$$\lambda = hc/\Delta E = (6.63 \times 10^{-34} \text{ J}\cdot\text{s} \times 3.00 \times 10^8 \text{ m/s})/(3.02 \times 10^{-19} \text{ J}) \quad \mathbf{1} = 1.028 \times 10^{-7} \text{ m} = 102.8 \text{ nm} \mathbf{1}$$

(d) List the electronic configurations of Cr ($Z = 24$) and Ba ($Z = 56$).



(e) Describe the trends of atomic radius and electron affinity in the periodic table..

One moves from top to bottom in a group, the size of the atom, generally, increases.

1.5

One moves across a period from left to right, the size of the atom, generally, decreases. **1.5**

Electron affinity increases as we move to right across a period **1** and decreases as we move down in a group. **1**

- (f) Calculate the density of FCC copper metal. (atomic radius = 0.128 nm, atomic mass = 63.55 g/mol)

$$a: \text{lattice parameter, } r: \text{atomic radius} \Rightarrow \sqrt{2}a = 4r \Rightarrow a = \left(\frac{4}{\sqrt{2}}\right)r$$

$$\rho = m/V = \left\{ \frac{(4 \text{ atoms})(63.55 \text{ g/mol})}{6.02 \times 10^{23} \text{ atoms/mol}} \left(\frac{10^{-6} \text{ Mg}}{\text{g}} \right) \right\} / \left((4/\sqrt{2}) \times 0.128 \times 10^{-9} \text{ m} \right)^3$$

$$= 8.90 \frac{\text{Mg}}{\text{m}^3}$$

1 1 1

- (g) Calculate the atomic packing factor (APF) for the BCC unit cell, assuming the atoms to be hard spheres.

$$\text{FCC: } \sqrt{3}a = 4r \Rightarrow a = \left(\frac{4}{\sqrt{3}}\right)r$$

$$\text{APF} = \frac{2 \times \frac{4\pi}{3}r^3}{(4r/\sqrt{3})^3} = \frac{\frac{8\pi}{3}}{64/(\sqrt{3})^3} = \frac{\pi\sqrt{3}}{8} = 0.6802$$

- (h) Define the seven crystal systems.

Cubic: $a = b = c$, $\alpha = \beta = \gamma = 90^\circ$

Tetragonal: $a = b \neq c$, $\alpha = \beta = \gamma = 90^\circ$

Orthorhombic: $a \neq b \neq c$, $\alpha = \beta = \gamma = 90^\circ$

Monoclinic: $a \neq b \neq c$, $\alpha = \gamma = 90^\circ \neq \beta$

Triclinic: $a \neq b \neq c$, $\alpha \neq \beta \neq \gamma \neq 90^\circ$

Rhombohedral: $a = b = c$, $\alpha = \beta = \gamma \neq 90^\circ$

Hexagonal: $a = b \neq c$, $\alpha = \beta = 90^\circ$, $\gamma = 120^\circ$

- (i) List the indices of two planes and three directions in Fig. 1.

Plane 1: (0001)

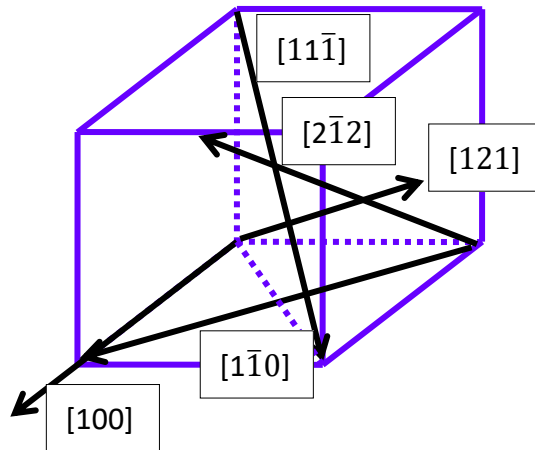
Plane 2: (1 $\bar{1}$ 00)

Direction 1: [01 $\bar{1}$ 0]

Direction 2: [$\bar{1}$ 2 $\bar{1}$ 3]

Direction 3: [$\bar{1}$ 2 $\bar{1}$ 6]

- (j) Draw the [100], [1 $\bar{1}$ 0], [11 $\bar{1}$], [121], and [2 $\bar{1}$ 2] directions in the cubic unit cells.



(k) List the earlier five diffraction peaks of FCC and BCC crystals.

Simple cubic: 100, 110, 111, 200, 210, 211, 220, 221, 310, 311, 222

FCC: **2.5** 111, 200, 220, 311, 222

BCC: **2.5** 110, 200, 211, 220, 310,

(l) Compare the differences between homogeneous and heterogeneous nucleation of solid particles in liquid metal.

	Homogeneous nucleation	Heterogeneous nucleation
Nucleation site: 2	Metal itself	Surfaces of other agents e.g.: Container surface, Insoluble impurities.
Activation energy: 1	Higher	Lower
Critical size: 1	Larger	Smaller
Undercooling: 1	Larger	Smaller

(m) Calculate the average grain size diameter d (at least involves 50 grains) in Fig. 2.

$$\text{Average grain size diameter} = d = C/(n_L M) \mathbf{1} = (1.5/200)[(8 \times 7)/(9+11+9+8+11+9+8)] \mathbf{3} \text{ cm} = 6.46 \times 10^{-3} \text{ cm} = 64.6 \mu\text{m} \mathbf{1}$$

2. Define smart materials and nanomaterials and describe their advantages. (10%)

Smart materials: They react to environment stimuli **1** (temperature, stress, light, humidity, gas, and EM fields) and change their properties by sensing external stimulus **1**. Sensors or actuators made by smart materials are usually used to detect the change in the environment **1** or perform a specific function or a response **1**. These devices can give a unique performance or simplify the design **1**.

Nanomaterials: They have a characteristic length scale **1** (that is, particle size, grain size, filament diameter, layer thickness, **1** etc.) smaller than 100 nm **1**. Nanomaterials, such as nanostructural pure copper, nano-zirconia implants, carbon nanofiber reinforced plastic, can be harder **1**, stronger, tougher **1**, or more reactive **1** than traditional materials.

3. Discuss the differences of the bonding-origins and material properties between the (a) ionic, (b) covalent, and (c) metallic bonds. (15%)

Bonding-origins

Ionic: Electrons are transferred **1** from electropositive to electronegative atoms and cations and anions are formed **1**. Ionic bonding is due to electrostatic force of attraction **1** between cations and anions.

Covalent: Takes place between elements with small electronegativity differences **1**. Outer s and p electrons are shared **1** between two atoms to obtain noble gas configuration. Covalent bonds are directional. **1**

Metallic: Loosely bounded valence electrons **1** are attracted towards nucleus **1** of other atoms, shared by many atoms, form electron clouds **1**, and overall energy of individual atoms are lowered.

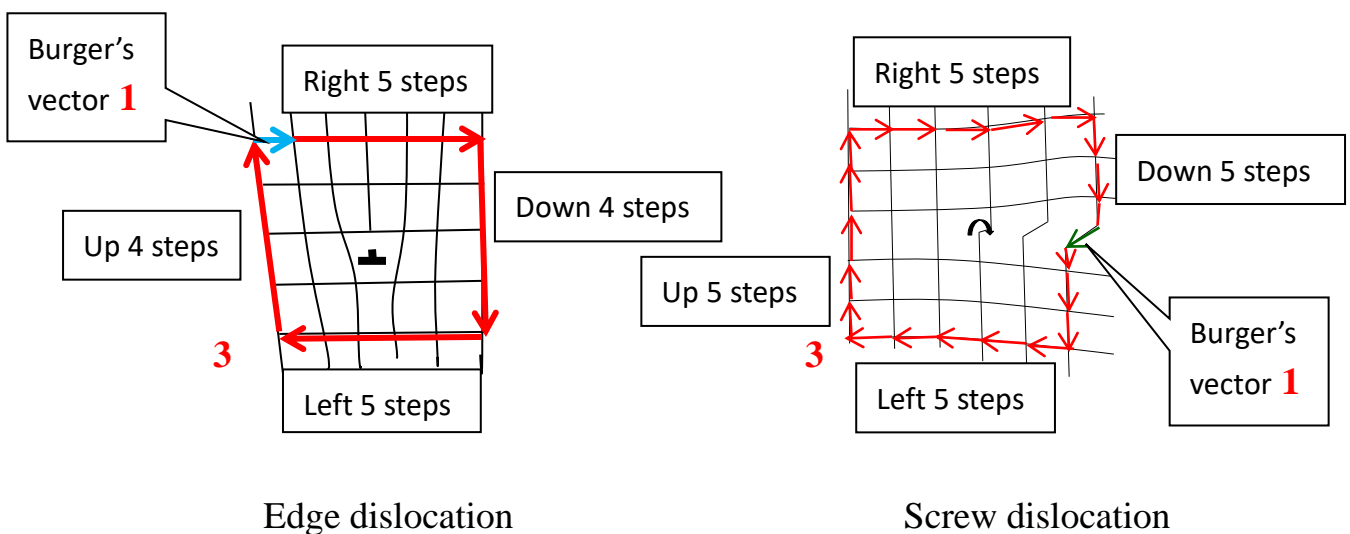
Material properties

Ionic: Ionic solids are hard, rigid, strong **1**, and brittle **1**. Ionic solids are excellent insulators **1**.

Covalent: Covalent solids are hard, rigid, strong and brittle **1**. Covalent materials are poor conductors of electricity **1** not only in a network solid form but also in a liquid or molten form **1**.

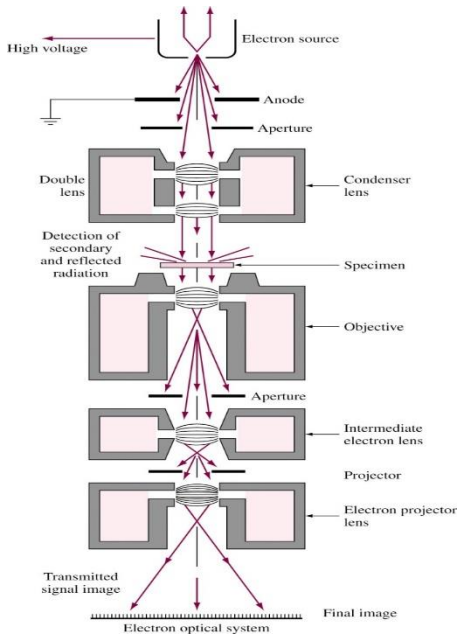
Metallic: Metals are significantly more malleable **1** than ionic or covalent networked materials. Metals are excellent conductors **1** of heat and electricity.

4. Draw the schematic diagrams of edge and screw dislocations and determine their Burger's vectors. (10%)



The dislocation lines of edge and screw dislocations are perpendicular to paper **1**. The Burger's vector of edge dislocation is perpendicular to the dislocation line **1** and the Burger's vector of screw dislocation is parallel to the dislocation line **1**.

5. Sketch and explain the principles for transmission electron microscope (TEM) and atomic force microscope (AFM). (10%)

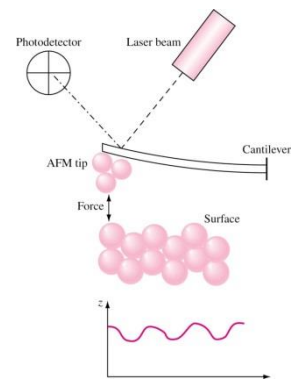


TEM: Electron gun generates electrons that are accelerated (75-300 kV), focused, and passes through very thin specimen¹. Difference in atomic arrangement change directions of electrons¹. Electron beam is enlarged and focused on fluorescent screen. The contrasts between matrix and defects or other phases can be displayed¹. The electron diffraction pattern liked XRD also can be gotten and analyzed¹.

2

AFM:

Similar to STM but tip attached to cantilever beam ¹. When tip interacts with surface, van der Waals forces deflect the beam. Deflection detected by laser and photodetector ¹. Short-range repulsive force (contact mode) or long-range attractive force (non-contact mode) can be detected ¹. Non-conductive materials can be scanned ¹.



2

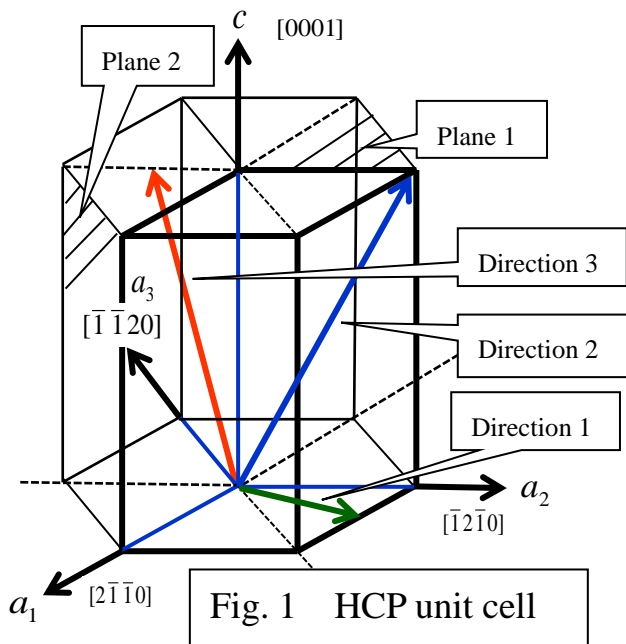


Fig. 1 HCP unit cell

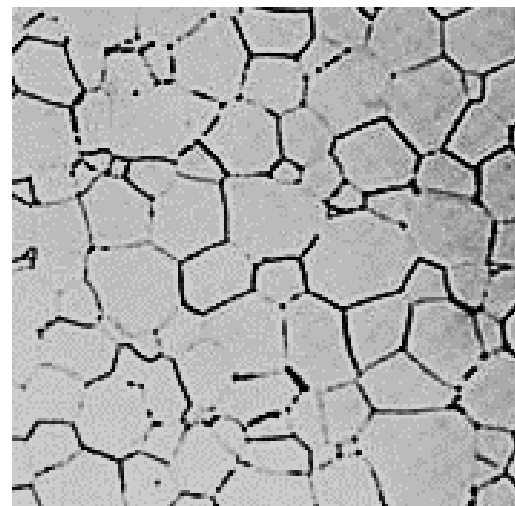


Fig. 2 Grain structure in the optical microscope. 200×
(The size of this photo is 8 × 8 cm.)

1. Answer following questions briefly: (70%)

(a) The concentration of carbon on the surface of a 1018 steel gear is 0.8 wt% at 1000°C. Determine the flux of carbon atoms from the surface to a plane 25 μm below the surface where carbon concentration is unaffected by the surface concentration. (atomic mass: C = 12.01 g/6.02×10²³, Fe = 55.85 g/6.02×10²³; lattice parameter: $a_{\text{Fe}} = 0.351$ nm; $D_{1000^\circ\text{C}} = 3 \times 10^{-11}$ m²/s)

Convert wt % to atoms/m³. (assume 100 grams)

$$0.8 \text{ g carbon: } \frac{0.8}{12.01} \times 6.02 \times 10^{23} = 4.01 \times 10^{22} \text{ carbon atoms}$$

$$99.2 \text{ g iron: } \frac{99.2}{55.85} \times 6.02 \times 10^{23} \bullet = 1.07 \times 10^{24} \text{ iron atoms}$$

$$\text{atom \% carbon: } \frac{4.01 \times 10^{22}}{4.01 \times 10^{22} + 1.07 \times 10^{24}} = 3.61 \text{ at\%}; \text{ atom \% iron} = 96.39 \text{ at\%}$$

$$0.18 \text{ g carbon: } \frac{0.18}{12.01} \times 6.02 \times 10^{23} = 9.02 \times 10^{21} \text{ carbon atoms}$$

$$99.82 \text{ g iron: } \frac{99.82}{55.85} \times 6.02 \times 10^{23} \bullet = 1.076 \times 10^{24} \text{ iron atoms}$$

$$\text{atom \% carbon: } \frac{9.02 \times 10^{21}}{9.02 \times 10^{21} + 1.076 \times 10^{24}} = 0.83 \text{ at\%}; \text{ atom \% iron} = 99.17 \text{ at\%}$$

$$\text{For FCC iron, } \frac{4 \text{ atoms}}{(3.51 \times 10^{-9} \text{ m})^3} = 9.25 \times 10^{28} \frac{\text{atoms}}{\text{m}^3} \bullet$$

$$C_s = 0.0361 \times 9.25 \times 10^{28} / 0.9639 \left(\frac{\text{atoms}}{\text{m}^3} \right) = 3.464 \times 10^{27} \left(\frac{\text{atoms}}{\text{m}^3} \right) \bullet$$

$$C_{25\mu\text{m}} = 0.0083 \times 9.25 \times \frac{10^{28}}{0.9917} \left(\frac{\text{atoms}}{\text{m}^3} \right) = 7.742 \times 10^{26} \left(\frac{\text{atoms}}{\text{m}^3} \right) \bullet$$

$$J = -D_{1000^\circ\text{C}} \times \frac{C_{25\mu\text{m}} - C_s}{\Delta x} = -3 \times 10^{-11} \times \frac{7.742 \times 10^{26} - 3.464 \times 10^{27}}{25 \times 10^{-6}} \\ = 3.23 \times 10^{21} (\text{atoms/m} \cdot \text{s}) \bullet$$

(b) The diffusivity of copper atoms in solid copper is 10⁻¹⁸ cm²/s at 500 °C and 2 × 10⁻¹³ cm²/s at 1000 °C. Calculate the activation energy (J/mol) for the diffusion of Cu in Cu in the temperature range 500 °C to 1000 °C. [$R = 8.314$ J/(mol·K)]

$$\frac{D_{1000}}{D_{500}} = \frac{\exp(-Q/RT_2)}{\exp(-Q/RT_1)} = \exp\left(\frac{-Q}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right)$$

$$\frac{2 \times 10^{-13}}{1 \times 10^{-18}} = \exp\left(-\frac{Q}{R}\left(\frac{1}{1273} - \frac{1}{773}\right)\right)$$

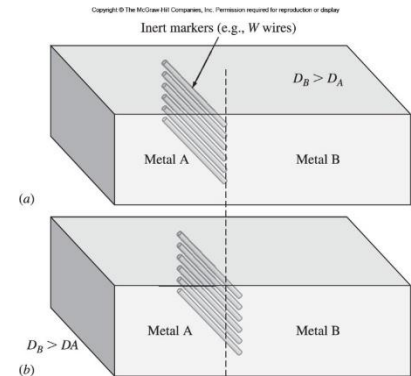
$$\ln(2.0 \times 10^5) = -\frac{Q}{R}(7.855 \times 10^{-4} - 12.94 \times 10^{-4}) = \frac{Q}{8.314}(5.08 \times 10^{-4})$$

$$12.21 = Q(6.11 \times 10^{-5}) \Rightarrow Q = 199,770 \text{ J/mol} = 200 \text{ kJ/mol}$$

(c) Sketch and explain the “Kirkendall effect”.

The inert markers (e.g. W or Mo wires) are welded at the interface between metal A and metal B of a binary diffusion couple.

After high temperature diffusion, the markers at the diffusion interface moved slightly in the opposite direction to the faster diffusing species of this binary diffusion couple.

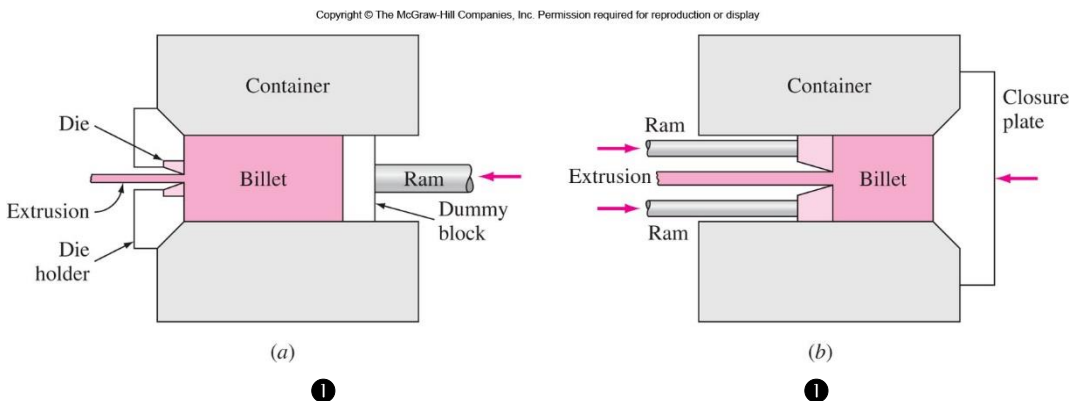


● ● ●

(d) Sketch to compare the advantages and disadvantages of indirect extrusion with that of direct extrusion.

Advantages: The friction forces and power requirements for indirect extrusion (Fig. b) are lower than those for direct extrusion (Fig. a).

Disadvantages: The loads that can be applied by using a hollow ram in the indirect extrusion (Fig. b) are more limited than those that can be used for direct extrusion (Fig. a).



●

●

- (e) Sketch to explain how to define the elastic modulus, yield strength, tensile strength, elongation, and toughness in the engineering stress-engineering strain curve.

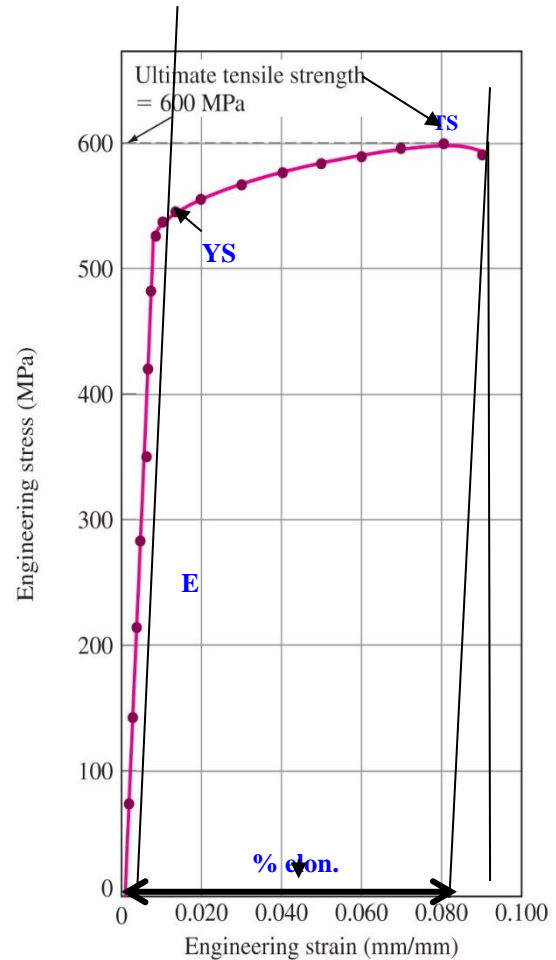
Elastic modulus: The slope of initial stress-strain curve (elastic deformation range). $E = \sigma/\epsilon$ ①

Yield strength: The corresponding stress of a small certain plastic deformation (such as 0.2%). ①

Tensile strength: The maximum stress for a stress-strain curve. ①

Elongation: Draw a line that is parallel to elastic range from the end point of the stress-strain curve and intercept with abscissa at a specific strain. This specific strain is elongation. ①

Toughness: The area below the stress-strain curve. ①

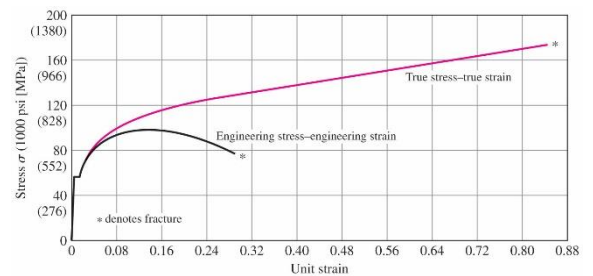


- (f) Define the true stress and true strain and compare the true stress-strain curve with engineering stress-strain curve for the same test specimen.

$$\text{True Stress} = \sigma_t = \frac{\text{Force}}{\text{instantaneous area}} = \frac{F}{A_i} \text{ ①}$$

$$\text{True Strain} = \epsilon_t = \int_{l_0}^{l_i} \frac{dl}{l} = \ln \frac{l_i}{l_0} = \ln \frac{A_0}{A_i} \text{ ①}$$

True stress is always greater than engineering stress. ①



① ①

- (g) List all the $\{110\}\langle\bar{1}11\rangle$ slip systems in BCC crystal structure.

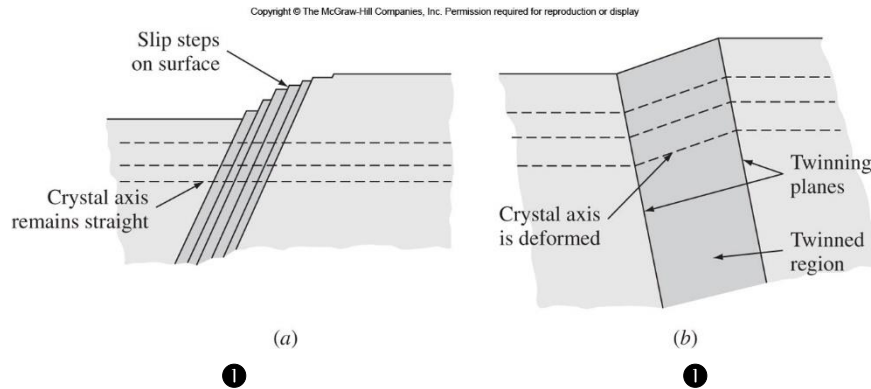
$(110)[\bar{1}\bar{1}1]$, $(1\bar{1}0)[111]$, $(101)[11\bar{1}]$, $(10\bar{1})[111]$, $(011)[11\bar{1}]$, $(01\bar{1})[111]$,
 $(110)[\bar{1}11]$, $(1\bar{1}0)[11\bar{1}]$, $(101)[\bar{1}11]$, $(10\bar{1})[1\bar{1}1]$, $(011)[1\bar{1}1]$, $(01\bar{1})[\bar{1}11]$.

- (h) A stress of 10 MPa is applied in the $[001]$ direction of a unit cell of an FCC nickel single crystal. Calculate the resolved shear stress for the $(111)[0\bar{1}1]$ slip system.

$$\tau = \sigma \times \cos \lambda \times \cos \phi \text{ ① ①} \Rightarrow$$

$$\tau = 10 \text{ MPa} \cdot \frac{1}{\sqrt{1^2 + 1^2 + 1^2} \times \sqrt{1}} \cdot \frac{1}{\sqrt{1} \times \sqrt{(-1)^2 + 1^2}} = 10 \text{ MPa} \cdot \frac{1}{\sqrt{6}} = 4.08 \text{ MPa} \quad \text{①①①}$$

- (i) Sketch and compare the differences between slip and twinning deformation in (a) atomic move distance, (b) lattice orientation.



(a) In slip the atoms on one side of the slip plane all move equal distances ①, whereas in twinning the atoms move distances proportional to their distance from twinning plane. ①

(b) Slip does not reorient lattice. However, twinning reorients lattice and may place new slip systems. ①

- (j) Explain superplasticity and describe superplasticity conditions.

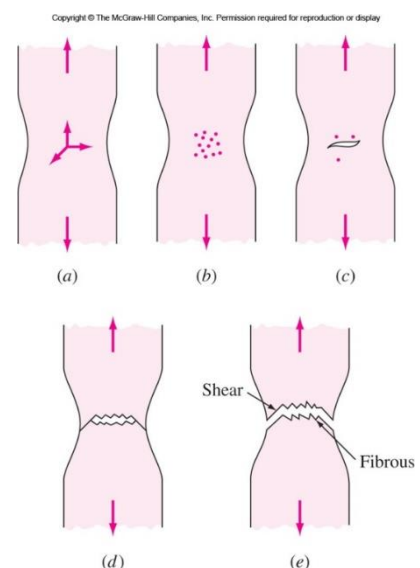
1. At elevated temperature and slow loading, some alloys can be deformed 2000% ① because this alloy can uniformly spread its deformation and delay the necking. ①
2. Superplasticity conditions:
 - Very fine grain size (5-10 microns) ①,
 - Highly strain-rate sensitive ①,
 - Temperature above $0.5 T_m$ ①,
 - Slow strain rate (0.01-0.0001/s) ①.

- (k) Sketch and describe how to form a cup-and-cone ductile fracture.

(a, b): Specimen forms neck and cavities within neck. ①

(c): Cavities form crack and crack propagates towards surface, perpendicular to stress. ①

(d, e): When the crack nears the surface, direction of crack changes to 45° resulting in cup-and-cone fracture. ①



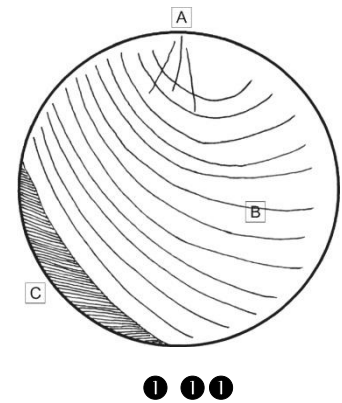
①①

(l) Sketch and explain the characteristics of the fatigue fracture surface.

A: Crack nucleates at region of stress concentration near surface (sharp corner, notch inclusion or flaw) and propagates due to cyclic loading. ①

B: Clamshell or “beach” markers are created with cyclic loading. (smooth region). ①

C: Failure occurs when cross sectional area of the metal too small to withstand applied load. (rough surface area) ①



(m) Equiaxed MAR-M 247 MFB alloy is to support a stress of 138 MPa (Fig. 7.31).

Determine the time to stress rupture at 900 °C.

From Fig. 7.31: $P(\text{L.M.}) = [27.8 + (28.9 - 27.8)4/10] \times 10^3$ ① = 28240 ①

$P(\text{L.M.}) = 28240 = [T(^{\circ}\text{C}) + 273](20 + \log t_r)$ ① = (900 + 273) (20 + log t_r)

$20 + \log t_r = 24.075$ ① $\Rightarrow t_r = 10^{4.075} = 1543.1 \cong 11885$ (h) ①

(n) How to get a structure of 25% micrometer-sized grains in a matrix of nano-meter and ultrafine grains in pure copper?

This structure can be produced by cold rolling at liquid nitrogen temperature ① (additional cooling after each pass ①). A large density of dislocations is formed and cannot to recovery ①. This severely deformed sample has a mixture of nanocrystalline and ultrafine grain structure ①. The following controlled annealing results in some grains allows recrystallization ① and abnormal grain growth to 1-3 μm ①. Then, a structure of 25% micrometer-sized grains in a matrix of nano-meter and ultrafine grains in pure copper.

2. (a) Calculate the value of the diffusivity D for the diffusion of carbon in γ iron at 927 °C. Use values of $D_0 = 2.0 \times 10^{-5} \text{ m}^2/\text{s}$, $Q = 142 \text{ kJ/mol}$, and $R = 8.314 \text{ J}/(\text{mol}\cdot\text{K})$. (b) Consider the gas carburizing of a gear of 1020 steel at 927 °C. Calculate the time in minutes necessary to increase the carbon content to 0.60% at 0.40 mm below the surface. $C_s = 1.20\% \text{ C}$. (c) Consider the impurity diffusion of gallium into a silicon wafer. If gallium is diffused into a silicon wafer with no previous gallium in it at 1100 °C ($D_{1100^{\circ}\text{C}} = 7.0 \times 10^{-17} \text{ m}^2/\text{s}$) for 5 h, what is the depth below the surface at which the concentration is $10^{22} \text{ atoms}/\text{m}^3$ if the surface concentration is $10^{24} \text{ atoms}/\text{m}^3$?

The solution of Fick's second law: $\frac{C_s - C_x}{C_s - C_0} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$. (d) The activation energy of hydrogen in steel is 15 kJ/mol. Should we worry about hydrogen embrittlement of steels (is it very likely to occur)? Explain. (20%)

(a)

$$D = D_0 e^{-Q/RT} \text{ ①} = 2.0 \times 10^{-5} \text{ m}^2/\text{s} \left\{ \exp \frac{-142000 \text{ J/mol}}{[8.314 \text{ J/mol}\cdot\text{K}](927+273)\text{K}} \right\} \text{ ① ① ①}$$

$$D = 1.3174 \times 10^{-11} \text{ m}^2/\text{s} \quad (\text{at } 927 \text{ }^\circ\text{C}) \text{ ①}$$

(b)

$$\frac{C_s - C_x}{C_s - C_0} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \rightarrow \frac{1.20 - 0.60}{1.20 - 0.20} = \text{erf}\left(\frac{0.40 \text{ mm}}{2\sqrt{1.3174 \times 10^{-11} \text{ m}^2/\text{s} \times t}}\right) \text{ ①}$$

$$0.60 = \text{erf}\left(\frac{0.40 \text{ mm}}{2\sqrt{1.72 \times 10^{-11} \text{ m}^2/\text{s} \times t}}\right) \text{ ①}$$

From error function Table: $z = 0.55 \rightarrow \text{erf } z = 0.5633$ and $= 0.60 \rightarrow \text{erf } z = 0.6039$ ①

$$\therefore \text{erf } z = 0.60 \rightarrow \frac{0.6039 - 0.5633}{0.60 - 0.55} = \frac{0.60 - 0.5633}{z - 0.55}$$

$$\rightarrow z = 0.5952 = \frac{0.40 \text{ mm}}{2\sqrt{1.3174 \times 10^{-11} \text{ m}^2/\text{s} \times t}} \text{ ①}$$

$$t = 8571 \text{ s} = 143 \text{ min} \text{ ①}$$

(c)

$$\frac{10^{24} - 10^{22}}{10^{24} - 0} = \text{erf}\left(\frac{x \text{ m}}{2\sqrt{(7.0 \times 10^{-17} \text{ m}^2/\text{s})(3600 \times 5 \text{ s})}}\right)$$

$$1 - 0.01 = \text{erf}\left(\frac{x \text{ m}}{2.245 \times 10^{-6} \text{ m}}\right) = \text{erf } Z = 0.99$$

$\text{erf } 1.8 = 0.9891$, $\text{erf } 1.9 = 0.9928$ \therefore

$$\frac{0.9928 - 0.9891}{1.9 - 1.8} = \frac{0.99 - 0.9891}{Z - 1.8} \Rightarrow Z = 1.82$$

$$x = (1.82)(2.245 \times 10^{-6} \text{ m}) = 4.0859 \times 10^{-6} \text{ m} = 4.1 \mu\text{m}$$

(d)

Compare the activation energy of hydrogen in iron (15 kJ/mol) ① to that of carbon in iron (142 kJ/mol) ①. It is clear that $Q_{\text{H-Fe}}$ is 10 times smaller than $Q_{\text{C-Fe}}$ ①. Now, consider the equation for diffusivity:

$D = D_0 e^{-Q/RT}$. As Q is decreased by a factor of 10, $-Q/RT$ also decreases resulting in a large increase in $e^{-\frac{Q}{RT}}$ ①. We should be concerned with diffusion of hydrogen in ferrous alloys ①.

3. Describe the strain hardening and solid solution strengthening and discuss their

mechanisms. (10%)

- **Strain hardening:** The hardness, YS, and UTS of a metal increase with increased cold deformation. Dislocation movements are hindered by other dislocations and number of dislocations are increased by cold work. It becomes more and more difficult for the dislocations to move through the existing “forest of dislocations,” and thus the metal work or strain hardens with increased cold deformation.
- **Solid solution strengthening:** Addition of one or more metals can increase the strength of metals. The size of solute atom usually differs from that of solvent atom and the solute atom distorts the lattice of solvent atom. So, solute atoms (substitutional or interstitial) create stress fields around themselves. These stress fields interact with stress fields of dislocations and hinder the dislocation movement and thus the solid solution become stronger than the pure metal.

4. An alloy steel plate is subjected to a tensile stress of 150 MPa. The fracture toughness of the materials is given to be 50 MPa·m^{1/2}. (a) Determine the critical crack length to assure the plate will not fail under the static loading conditions (assume $Y = 1$). (b) Consider the same plate under the action of cyclic tensile/compressive stresses of 150 MPa and 70 MPa respectively. Under the cyclic conditions, a crack length reaching 50% of the critical crack length under static conditions (part a) would be considered unacceptable. If the component is to remain safe for 3 million cycles, what is largest allowable initial crack length? (10%)

Hint :
$$N_f = \frac{a_f^{-(m/2)+1} - a_0^{-(m/2)+1}}{AY^m \sigma^m \pi^{m/2} [-(m/2) + 1]} \quad (\text{Where } m = 3, Y = 1, A = 2.0 \times 10^{-12})$$

(a)

$$K_{IC} = Y \sigma_f \sqrt{\pi a} \rightarrow 50 \text{ MPa} \cdot \text{m}^{1/2} = 1 \times 150 \text{ MPa} \sqrt{\pi a} \rightarrow a = 0.035368 \text{ m}$$

(b)

$$\sigma = 150 \text{ MPa}, a_f = a/2 = 0.017684 \text{ m}, N_f = 3 \times 10^6, m = 3, A = 2.0 \times 10^{-12}.$$

$$N_f = \frac{a_f^{-(\frac{m}{2})+1} - a_0^{-(\frac{m}{2})+1}}{A \sigma^m \pi^{m/2} Y^m [-(\frac{m}{2}) + 1]} \rightarrow 3 \times 10^6 = \frac{0.017684^{-0.5} - a_0^{-0.5}}{2.0 \times 10^{-12} 150^3 \pi^{3/2} 1^3 [-(\frac{3}{2}) + 1]}$$

$$-56.379 = 7.52 - a_0^{-0.5}$$

$$a_0^{-0.5} = 63.899$$

$$a_0 = 2.449 \times 10^{-4} \text{ m}$$

Table 5.3 Table of the error function

<i>z</i>	erf <i>z</i>	<i>z</i>	erf <i>z</i>	<i>z</i>	erf <i>z</i>	<i>z</i>	erf <i>z</i>
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.50	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.60	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
0.25	0.2763	0.70	0.6778	1.3	0.9340	2.4	0.9993
0.30	0.3286	0.75	0.7112	1.4	0.9523	2.6	0.9998
0.35	0.3794	0.80	0.7421	1.5	0.9661	2.8	0.9999

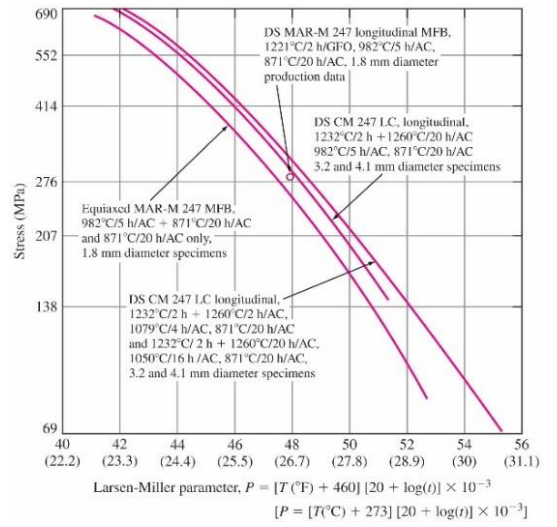


Fig. 7.31

1. Answer following questions briefly: (65%)

(a) Prove the lever-rule equation of two-phase region in a phase diagram.

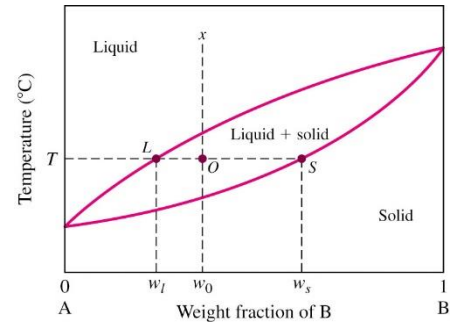
Alloy w_0 (B) at T: $X_l + X_s = 1$, $w_0 = X_l w_l + X_s w_s$ ①

$w_0 = X_l w_l + (1 - X_l) w_s \rightarrow X_l (w_s - w_l) = w_s - w_0$ ①

$\rightarrow X_l = \frac{w_s - w_0}{w_s - w_l} = \frac{OS}{LS}$ ①

$w_0 = (1 - X_s) w_l + X_s w_s \rightarrow X_s (w_s - w_l) = w_0 - w_l$ ①

$\rightarrow X_s = \frac{w_0 - w_l}{w_s - w_l} = \frac{LO}{LS}$ ①



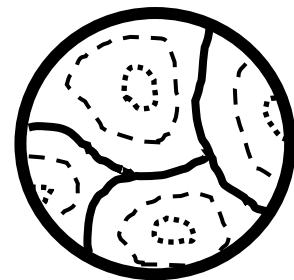
(b) List the Gibbs phase rule and explain how to construct a ternary phase diagram.

$P + F = C + 2$ ① (P = number of phases that coexist in a system, C = Number of components, F = Degrees of freedom) ①. Generally, the pressure is set at 1 atm, then Gibbs phase rule becomes to $P + F = C + 1$. ①

Ternary phase diagrams (C = 3 and P = 1, $\rightarrow F = 3 + 1 - 1 = 3$) can be constructed by using an equilateral triangle ① as a base with temperature on a vertical axis ①. Pure components are at each end of triangle and any composition can locate in this triangle ①.

(c) Explain the cored structure in an alloy casting. How to eliminate cored structure?.

The cored structure in an alloy casting means the composition varying from lower solute element at grain-center ① to higher solute element near grain-boundary ①. Homogenization treatment ①: cast ingots heated to elevated temperature to eliminate cored structure ①. Temperature of homogenization must be lower than lowest melting point of any of the alloy components ①.



①

(d) List the name, temperature, and composition of the all invariant reactions in the Ti-Ni phase diagram.

Eutectoid: 765°C , $\beta\text{Ti}(5.5\%\text{Ni}) \rightarrow \alpha\text{Ti}(0.5\%\text{Ni}) + \text{Ti}_2\text{Ni}(37\%\text{Ni})$ ①

Eutectic: 942°C , $L(27.9\%\text{Ni}) \rightarrow \beta\text{Ti}(11.5\%\text{Ni}) + \text{Ti}_2\text{Ni}(37\%\text{Ni})$ ①

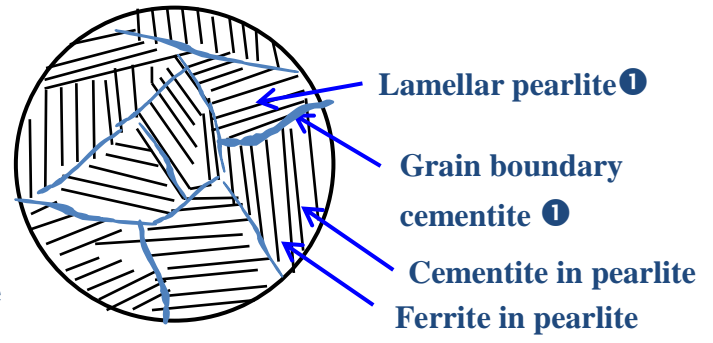
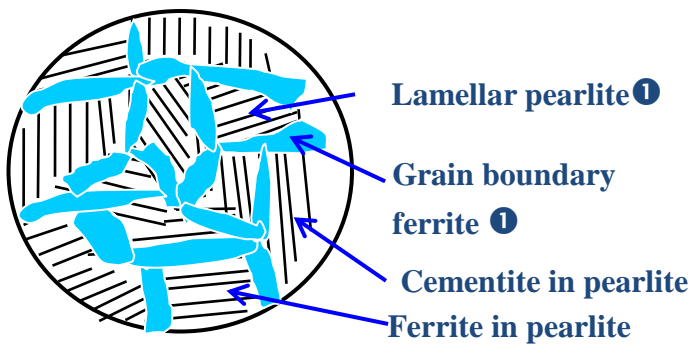
Peritectic: 984°C , $\text{L}(37.5\% \text{Ni}) + \text{TiNi}(54.4\% \text{Ni}) \rightarrow \text{Ti}_2\text{Ni}(37.8\% \text{Ni})$ ①

Eutectic: 1118°C , $\text{L}(65.7\% \text{Ni}) \rightarrow \text{TiNi}(61.8\% \text{Ni}) + \text{TiNi}_3(78.3\% \text{Ni})$ ①

Eutectic: 1304°C , $\text{L}(86.1\% \text{Ni}) \rightarrow \text{TiNi}_3(78.3\% \text{Ni}) + \text{Ni}(88.6\%)$ ①

Eutectoid: 630°C , $\text{TiNi}(54.5\% \text{Ni}) \rightarrow \text{Ti}_2\text{Ni}(38.3\% \text{Ni}) + \text{TiNi}_3(78.3\% \text{Ni})$ ①

(e) Sketch and compare the slow-cooling microstructures of the Fe-0.2%C and Fe-1.0%C plain carbon steels.



Microstructure of Fe-0.2%C

Grain boundary ferrite $\approx 25 \text{ wt\%}$ ①

Lamellar pearlite $\approx 75 \text{ wt\%}$

Microstructure of Fe-1.2%C

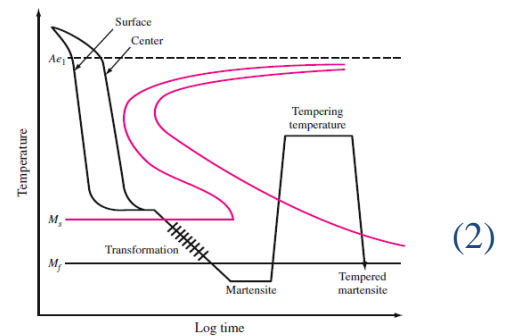
Grain boundary cementite $\approx 3.5 \text{ wt\%}$ ①

Lamellar pearlite $\approx 96.5 \text{ wt\%}$

(f) Draw a cooling curve of martempering treatment in a eutectoid plain-carbon steel IT diagram (TTT curve) and explain the advantages of this treatment.

Austinitizing, quenching at around M_s , holding in quenching media until temperature is uniform ①, removing before Bainite forms and cooling at a moderate rate. Subsequently tempered ①. ① ①

Advantages: (1) improves impact resistance. ① decreased distortion of the quenched material. ①

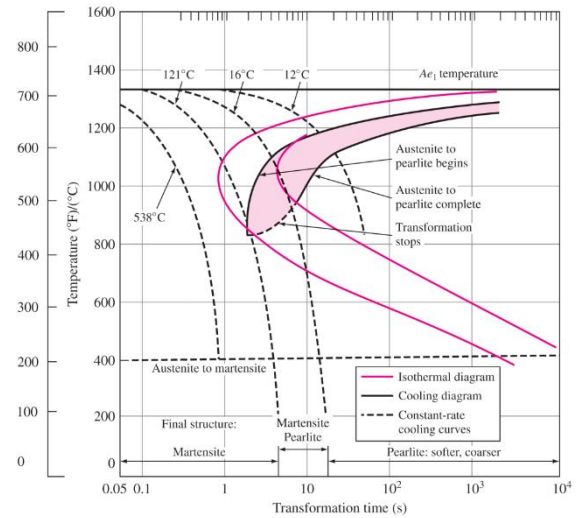


(g) Sketch and compare the CCT and TTT curves for a eutectoid plain-carbon steel.

In continuous cooling transformation: ①

- (1) Start and finish lines of pearlite transformation shifted to longer time. ①
- (2) No transformation for austenite-to-bainite transformation below 450 °C. ①

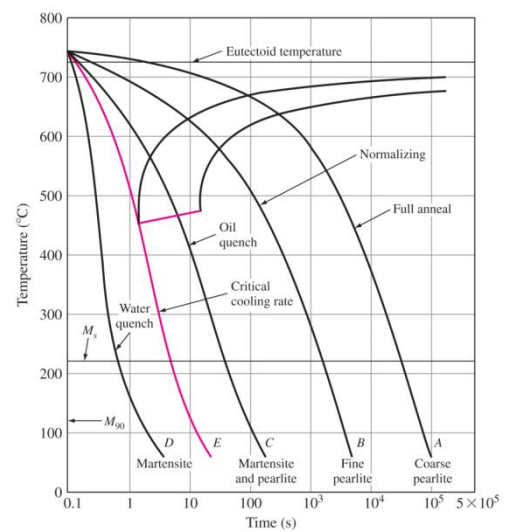
① ① ①



(h) Draw the cooling curves of full anneal, normalizing, oil quench, water quench and critical cooling rate in the continuous-cooling diagram of eutectoid plain-carbon steel.

① ① ① ① ①

- (i) List the major alloy elements for the 2xxx, 3xxx, 5xxx, 6xxx, and 7xxx aluminum alloys.
- 2xxx: Cu-Mg, 3xxx: Mn, 5xxx: Mg,
6xxx: Mg-Si, 7xxx: Zn-Mg-Cu



(j) Describe and explain the effect of aging temperature on the aging curves. As aging temperature increases the time to reach peakaging is shorter ① and the peakaging hardness ① is lower ① than that of lower aging temperature. These phenomena result from the fast diffusion ① and coarse precipitates ① for higher aging temperature.

(k) Give the Cr, Ni, C quantities in a 304 stainless steel. How to prevent the intergranular corrosion of 304 stainless steel?

Composition of 304 stainless steels: 18-20 wt% Cr ①, 8-10.5 wt% Ni ①, < 0.08 wt% C ①.

Prevent the intergranular corrosion: Decreasing carbon content to below 0.03% ①, Adding Nb or Ti element ①, Fast cooling between 870 °C and 600 °C ①.

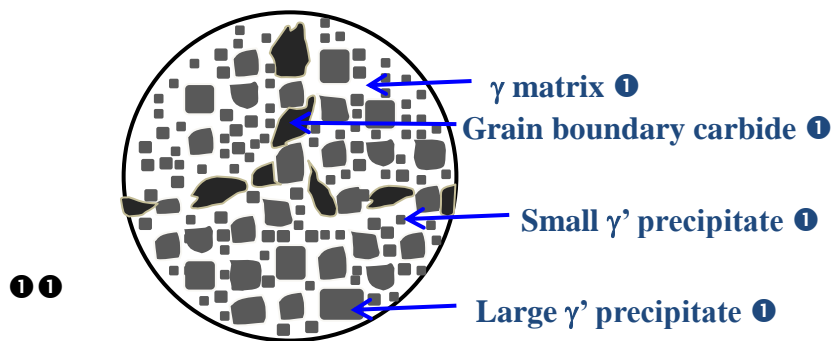
(l) Explain the number meanings in the 32510 malleable cast iron and 80-55-06 ductile

cast iron.

32510 malleable cast iron: Yield Strength = 32.5 ksi ①, Elongation = 10% ①

80-55-06 ductile cast iron: Tensile Strength = 80 ksi ①, Yield Strength = 55 ksi ①, Elongation = 6% ①.

(m) Sketch the typical microstructure ($\gamma + \gamma' + \text{carbides}$) of a nickel-based superalloy.



2. Calculate the relative amount of each phase at 184, 182, 60 °C of a Pb-50wt%Sn alloy from the Pb-Sn phase diagram. Sketch the microstructures of this alloy at 184 °C and 182 °C. (15%)

From Lever rule:

$$184\text{ }^\circ\text{C}: W_\alpha = (61.9 - 50) / (61.9 - 18.3); W_L = (50 - 18.3) / (61.9 - 18.3) \text{ ①}$$

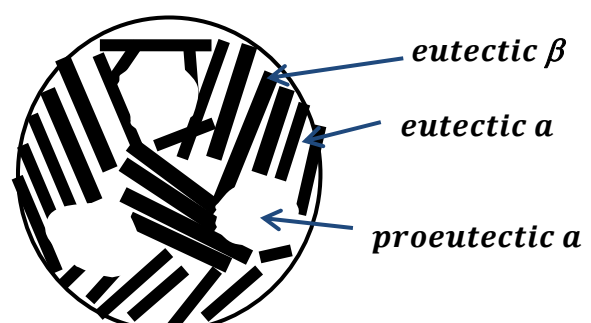
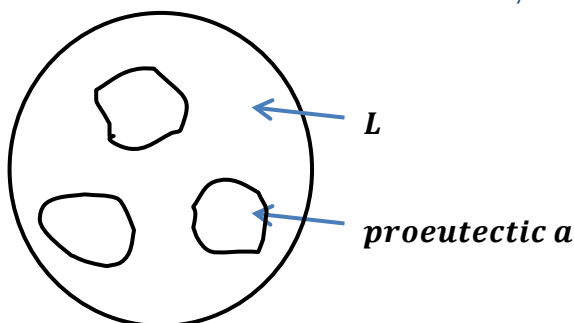
$$\Rightarrow W_\alpha = 27.3\% \text{ ①}; W_L = 72.7\% \text{ ①}$$

$$182\text{ }^\circ\text{C}: W_\alpha = (97.8 - 50) / (97.8 - 18.3); W_\beta = (50 - 18.3) / (97.8 - 18.3) \text{ ①}$$

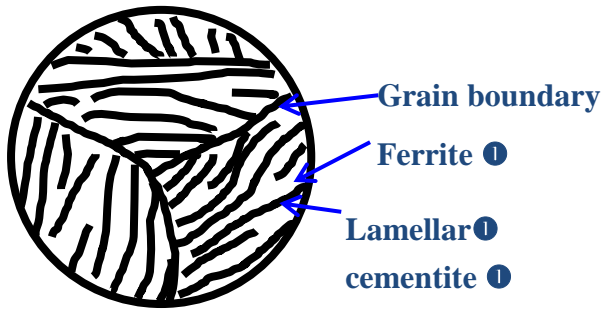
$$\Rightarrow W_\alpha = 60.1\% \text{ ①}; W_\beta = 39.9\% \text{ ①}$$

$$60\text{ }^\circ\text{C}: W_\alpha = (98.7 - 50) / (98.7 - 2.6); W_\beta = (50 - 2.6) / (98.7 - 2.6) \text{ ①}$$

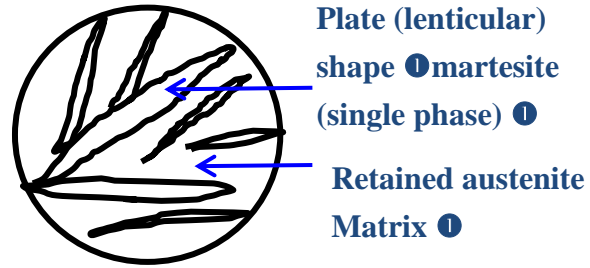
$$\Rightarrow W_\alpha = 50.7\% \text{ ①}; W_\beta = 49.3\% \text{ ①}$$



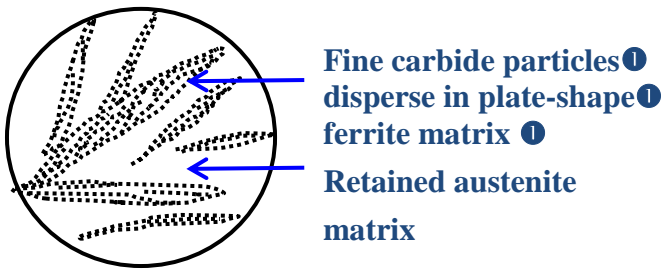
3. Sketch and explain the microstructure characteristics of pearlite, martensite, bainite, and tempered martensite for a eutectoid carbon steel. (10%)



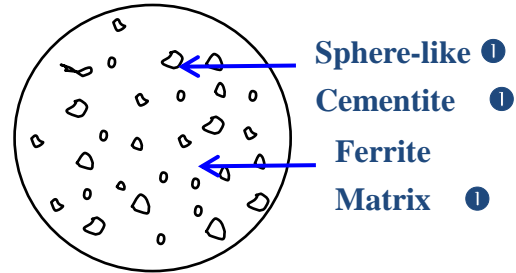
Microstructure of pearlite



Microstructure of martensite



Microstructure of bainite



Microstructure of tempered martensite

4. Two austenite 60 mm diameter 8640 alloy bars are quenched in agitated water and agitated oil, respectively. Predict what the Rockwell C (RC) hardness of the bars will be at (a) its surface and (b) its center. Change 8640 alloy to 4340 alloy and predict RC hardness again. (10%)

From Fig. 9.40:

Water quenched: $D_{\text{surface}} = 2.3 \text{ mm}$; $D_{\text{center}} = 12.7 \text{ mm}$

Oil quenched: $D_{\text{surface}} = 10 \text{ mm}$; $D_{\text{center}} = 19 \text{ mm}$

From Fig. 9.38:

8640 steel ($\pm 0.5 \text{ RC}$):

$S_{\text{water}} = 53 \text{ RC}$

$C_{\text{water}} = 38 \text{ RC}$

$S_{\text{oil}} = 44 \text{ RC}$

$C_{\text{oil}} = 30 \text{ RC}$

4340 steel ($\pm 0.5 \text{ RC}$):

$S_{\text{water}} = 53.5 \text{ RC}$

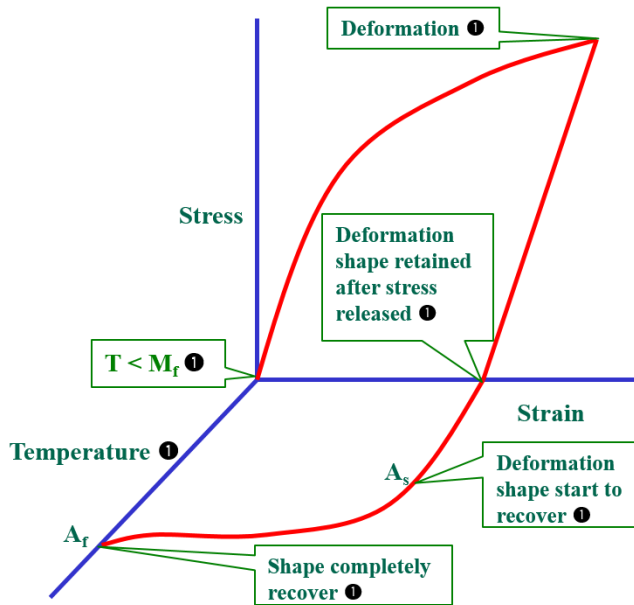
$C_{\text{water}} = 52 \text{ RC}$

$S_{\text{oil}} = 52.5 \text{ RC}$

$C_{\text{oil}} = 50 \text{ RC}$

5. Explain shape-memory effect and super-elasticity (stress-induced martensitic transformation) of the shape-memory alloys by using the stress-strain curves. (10%)

Shape-memory effect



Super-elasticity

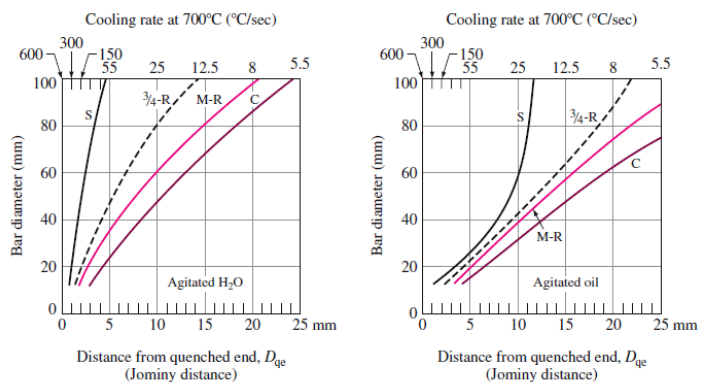
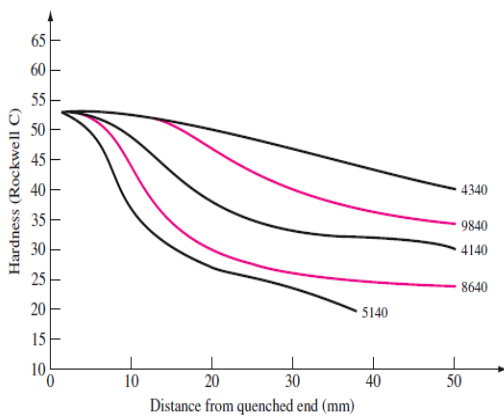
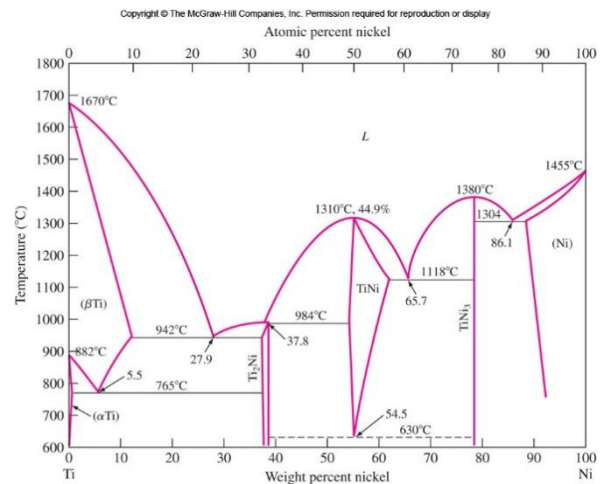
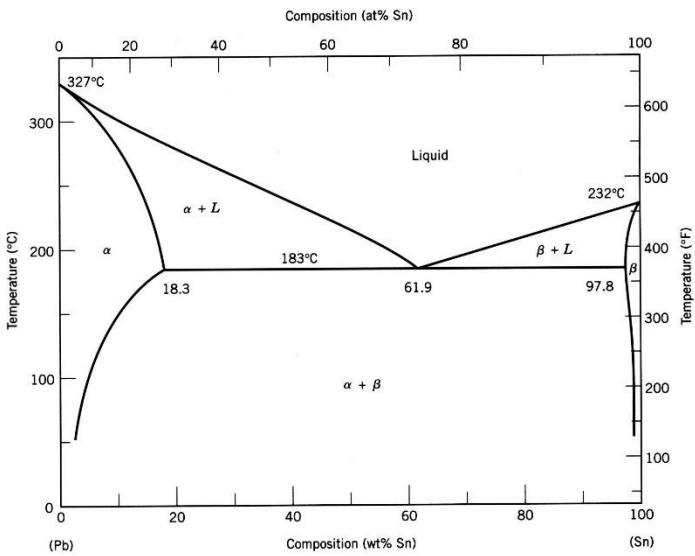
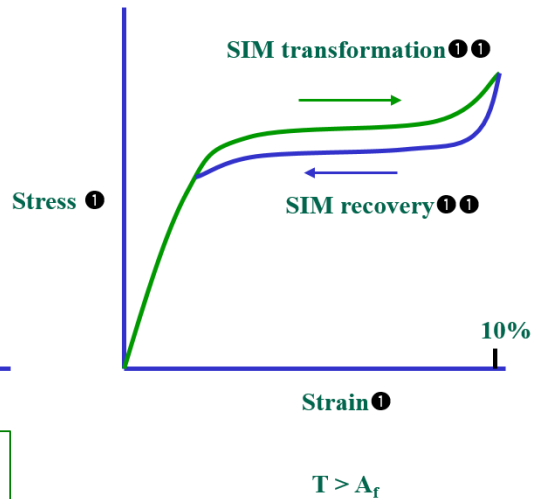


Figure 9.38
Comparative hardenability curves for 0.40 percent C alloy steel.
[From H.E. McGannon (ed.), "The Making, Shaping, and Treating of Steel,"
9th ed., United States Steel Corp., 1971, p. 1139. Courtesy of United States Steel
Corporation.]

Figure 9.40
Cooling rates in long round steel bars quenched in (i) agitated water and (ii) agitated
oil. Top abscissa, cooling rates at 700°C; bottom abscissa, equivalent positions on an
end-quenched test bar. (C = center, M-R = midradius, S = surface, dashed line =
approximate curve for 3/4-radius positions on the cross section of bars.)
(Van Vlack, L.H., "Materials for Engineering: Concepts and Applications," 1st ed., © 1982. Electronically
reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)