

10420PME 300600 材料科學導論 Introduction to Material Science

期中考一 Midterm Exam I

AM 10:10-12:00, April 11, 2016

1. Answer following questions briefly: (65%)

(a) Define “materials science” and “materials engineering”.

Materials science is primarily concerned with the research for basic knowledge **1** about the internal structure, properties**1**, and processing **1** of materials.

Materials engineering is mainly concerned with the use**1** of fundamental and applied **1** knowledge of materials so that the materials can be converted into products **1** needed or desired by society.

(b) A 100-gram alloy of Fe and C consists of 99.2 wt% Fe and 0.8 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)

$$\text{C: } (0.8/12.01)/[(99.2/55.85)+(0.8/12.01)] \times 100\% \quad \mathbf{1.5} = 3.61 \text{ at\% } \mathbf{1}$$

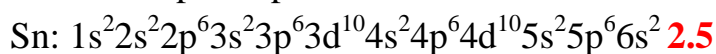
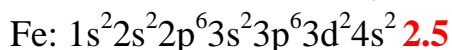
$$\text{Fe: } (99.2/55.85)/[(99.2/55.85)+(0.8/12.01)] \times 100\% \quad \mathbf{1.5} = 96.39 \text{ at\% } \mathbf{1}$$

(c) A hydrogen atom exists with its electron in the $n = 3$ state. The electron undergoes a transition to $n = 2$ 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).

$$\Delta E = E_3 - E_2 = (-13.6 \text{ eV}/3^2) - (-13.6 \text{ eV}/2^2) \quad \mathbf{1} = 1.89 \text{ eV} = 1.89 \text{ eV} \times 1.60 \times 10^{-19} \text{ J/eV} \quad \mathbf{1} = 3.02 \times 10^{-19} \text{ J} \quad \mathbf{1}$$

$$\lambda = hc/\Delta E = (6.63 \times 10^{-34} \text{ J}\cdot\text{s} \times 3.00 \times 10^8 \text{ m/s}) / (3.02 \times 10^{-19} \text{ J}) \quad \mathbf{1} = 6.59 \times 10^{-7} \text{ m} \\ = 659 \text{ nm} \quad \mathbf{1}$$

(d) List the electronic configurations of Ti ($Z = 22$) and Ba ($Z = 56$).



(e) Cartridge brass is an alloy of two metals: 70 wt% copper ($Z = 29$) and 30 wt% zinc ($Z = 30$). Discuss the nature of the bonds between copper and zinc in this alloy.

The electronic structure of Copper is $1s^2 2s^2 2p^6 3s^2 3d^{10}4s^1$ and that of Zn is $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}4s^2$. The 3d and 4s orbitals of Zinc are full. Thus, it has significantly less tendency for covalent bonding. When Cu is replaced by Zn, the overall percentage of covalent bonds is dropped. Thus, brass (70 wt % Cu – 30 wt % Zn) will have higher percentage metallic bonds when compared to Cu. Therefore, Brass will have a lower melt temperature than Cu and higher than Zn.

(f) Calculate the density of BCC tungsten metal. (atomic radius = 0.141 nm, atomic mass = 183.9 g/mol)

$$a: \text{lattice parameter, } r: \text{atomic radius} \Rightarrow \sqrt{3}a = 4r \Rightarrow a = \left(\frac{4}{\sqrt{3}}\right)r$$

$$\rho = m/V = \left\{ \frac{(2 \text{ atoms})(183.9 \text{ g/mol}) \left(\frac{10^{-6} \text{ Mg}}{\text{g}} \right)}{6.02 \times 10^{23} \text{ atoms/mol}} \right\} / \left((4/\sqrt{3}) \times 0.141 \times 10^{-9} \text{ m} \right)^3$$

$$= \frac{6.1096 \times 10^{-28} \text{ Mg}}{34.527 \times 10^{-30} \text{ m}^3} = 17.695 \frac{\text{Mg}}{\text{m}^3}$$

111

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

$$\text{FCC: } \sqrt{2}a = 4r \Rightarrow a = 2\sqrt{2}r$$

$$\text{APF} = \frac{4 \times \frac{4\pi}{3}r^3}{(2\sqrt{2}r)^3} = \frac{16\pi}{8(\sqrt{2})^3} = \frac{\pi}{3\sqrt{2}} = 0.740481$$

(h) List three elements for each BCC, FCC, and HCP crystal structures at room temperature.

BCC: Cr, Fe, Mo, K, Na, Ta, W, V.... **1.5**

FCC: Al, Cu, Au, Pb, Ni, Pt, Ag..... **1.5**

HCP: Cd, Zn, Mg, Co, Zr, Ti, Be..... **1.5**

+0.5

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

Plane 1: (0001) **1**

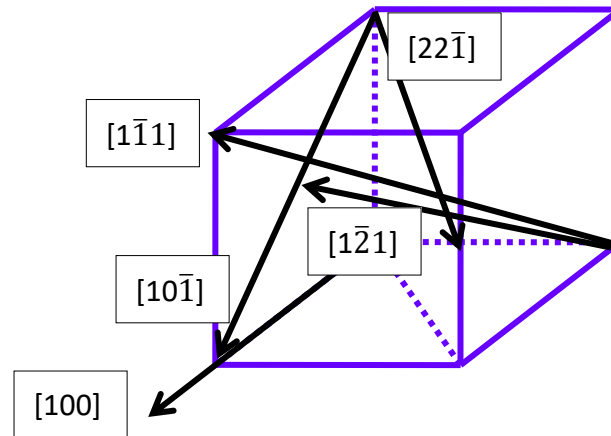
Plane 2: (1 $\bar{1}$ 00) **1**

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

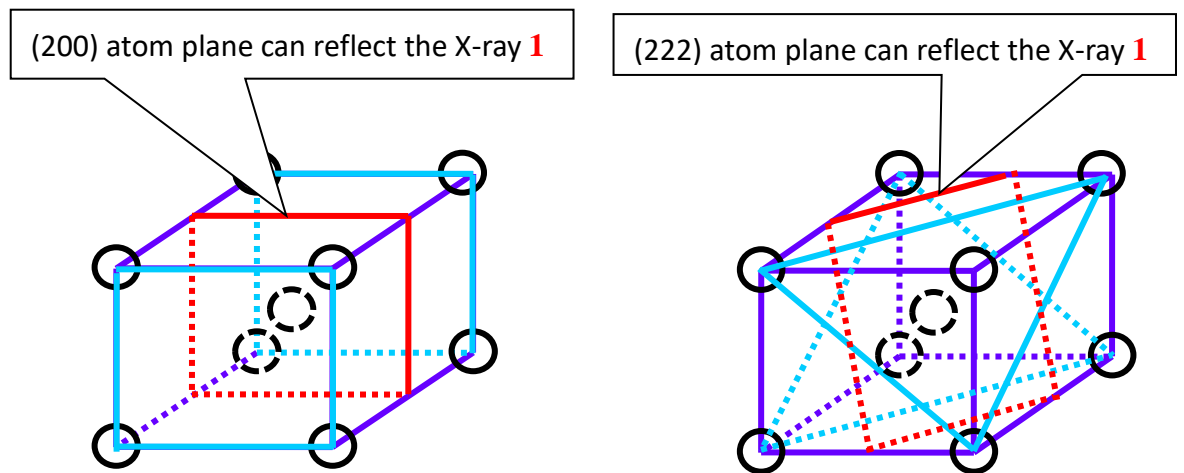
Direction 2: $[\bar{1}2\bar{1}1]$ **1**

Direction 3: $[1\bar{2}12]$ **1**

(j) Draw the $[100]$, $[10\bar{1}]$, $[1\bar{1}1]$, $[1\bar{2}1]$, and $[22\bar{1}]$ directions in the cubic unit cells.



(k) Prove that the diffraction peaks of $\{100\}$ and $\{111\}$ planes are not found for a BCC crystal.



The extra distance of travel of ray 2 for (100) planes is λ means that the extra distance of travel of ray 2 for (200) planes is $\lambda/2$ **1**, so that destructive interference occurs **1** and no (100) diffraction peak can be seen.

The extra distance of travel of ray 2 for (110) planes is λ means that the extra distance of travel of ray 2 for (222) planes is $\lambda/2$, **1** so that destructive interference occurs **1** and no (110) diffraction peak can be seen.

(l) Derive the critical radius (r^*) of solid nucleus from liquid, $r^* = -2\gamma/\Delta G_v$, where γ is specific surface energy and ΔG_v is volume free energy.

$$\text{Total free-energy change: } \Delta G_T = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma$$

$$r = r^* \text{ when } d(\Delta G_T)/dr = 0 \rightarrow 4\pi r^{*2} \Delta G_v + 8\pi r^* \gamma = 0$$

$$\therefore r^* = -2\gamma/\Delta G_v$$

(m) Calculate the ASTM grain size number (n) in Fig. 2.

$$\text{Total grain number} = 4 \times 1/4 + ((10 + 9 + 9 + 8) \times 1/2 + 62 \times 1) = 81$$

$$\text{Area of this picture at } 200\times = 8 \times 8 \text{ cm}^2 = 64 \text{ cm}^2 \rightarrow \text{Area of this picture at } 100\times = 4 \times 4 \text{ cm}^2 = 16 \text{ cm}^2$$

$$= 16 \text{ cm}^2 [1 \text{ in}^2 / (2.54 \times 2.54 \text{ cm}^2)] = 2.48 \text{ in}^2$$

$$\rightarrow N = 81/2.48 = 32.7 = 2^{n-1} \rightarrow \ln(32.7) = (n-1) \ln 2 \rightarrow n = 6.03$$

2. Give two smart materials and illustrate how to use them. (10%)

Shape-memory alloys: once strained, revert back to their original shape upon an increase in temperature above T_c . Supporting weakened artery walls or expanding narrowed arteries: The deformed stent is first delivered in the appropriate position in the artery using a probe. The stent expands to its original shape and size after unfastening its bundle sheath and increasing its temperature to body temperature. Or other examples.

Piezoelectric ceramics: Produce an electric field when exposed to a mechanical force, and versa. Can used to sense, actuate, and reduce vibration.

Ultrasonic vibration cleaner and sonar are famous applications.

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

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

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.

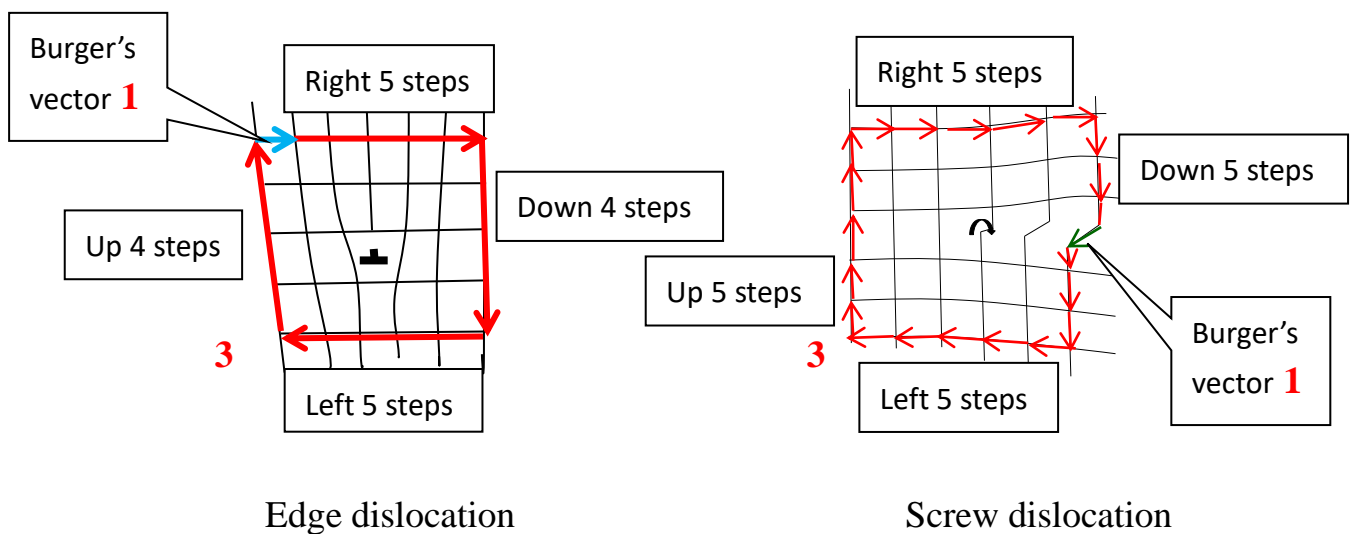
Material properties

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**.

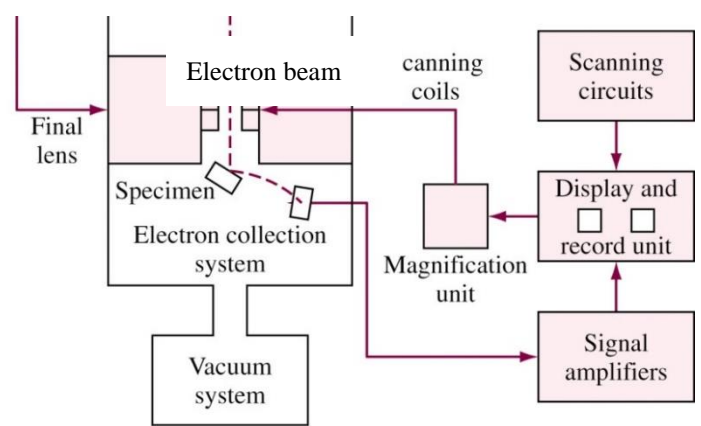
Metallic: Metals are significantly more malleable **1** than ionic or covalent networked materials. Metals are excellent conductors **1** of heat and electricity.

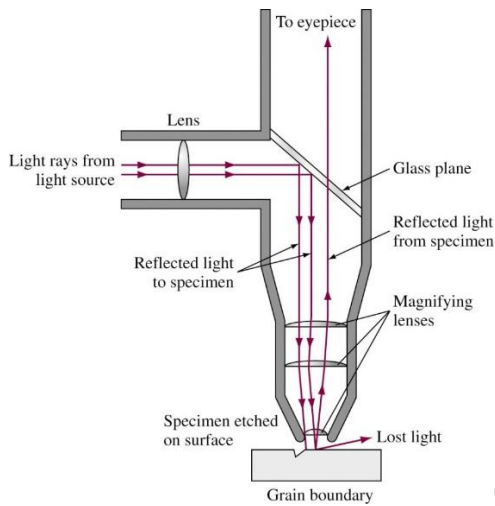
4. Draw the schematic diagrams of edge and screw dislocations and determine their Burger's vectors. (10%)



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 optical microscope (OM) and the scanning electron microscope (SEM). (10%)





OM 2

SEM 2

OM: A smooth, mirror-like surface **1** must be produced after ground and polished process of the sample. An etching process is applied to improve the contrast **1**. Optical microscope is using visible incident light to observe the reflect light from the sample surface **1**. The tint contrasts of different phases, groove lines **1**, internal defects construct the picture via various enlarge lens.

SEM: Electron gun generates electrons that is focused and hit the specimen surface and secondary electrons are produced **1**. The secondary electrons are collected to produce the signal. The signal is used to produce the image **1**. Scanning coils allow the electron beam to scan a small surface area **1** and get a high-magnification picture of this area **1**.

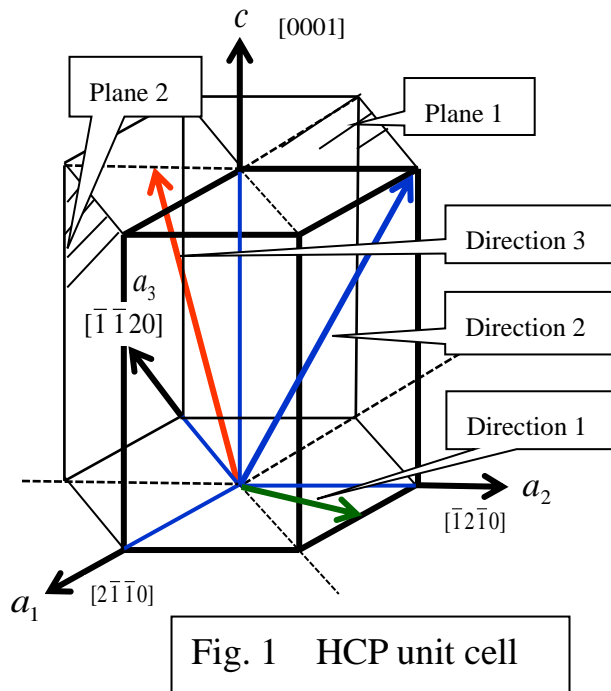


Fig. 1 HCP unit cell

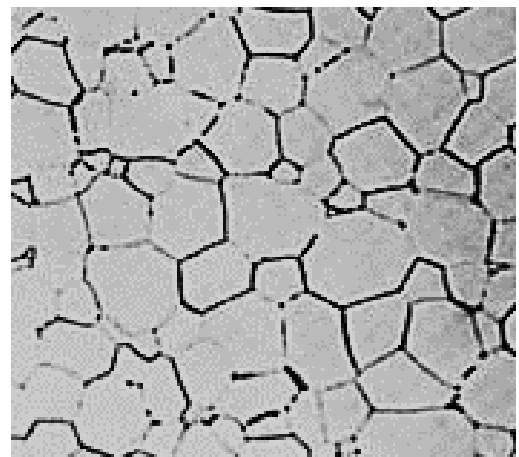


Fig. 2 Grain structure in the optical microscope. 200×
(The size of this photo is 8 × 8 cm.)

10420PME 300600 材料科學導論 Introduction to Material Science

期中考二 Midterm Exam II

10:10-12:00, May 16, 2016

1. Answer following questions briefly: (70%)

(a) Calculate the vacancy fraction at 650 °C in pure aluminum. Assume: $E_v = 0.74$ eV, $C = 1$ and $k = 8.62 \times 10^{-5}$ eV/K.

$$\frac{n}{N} \bullet = C e^{-E_v/kT} \bullet = e^{-0.74/[8.62 \times 10^{-5}(650+273)]} \bullet \bullet = 9.14 \times 10^{-5} \bullet$$

(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) List Fick's first law and Fick's second law and explain their physical meanings.

$$\text{Fick's first law: } J = -D \frac{dC}{dx} \bullet$$

The net flow of atoms by atomic diffusion (from rich to rare positions \bullet) is equal to diffusion coefficient (diffusivity) D times the concentration gradient dC/dx . \bullet

$$\text{Fick's second law: } \frac{dC}{dt} = \frac{d}{dx} \left(D \frac{dC}{dx} \right) \bullet$$

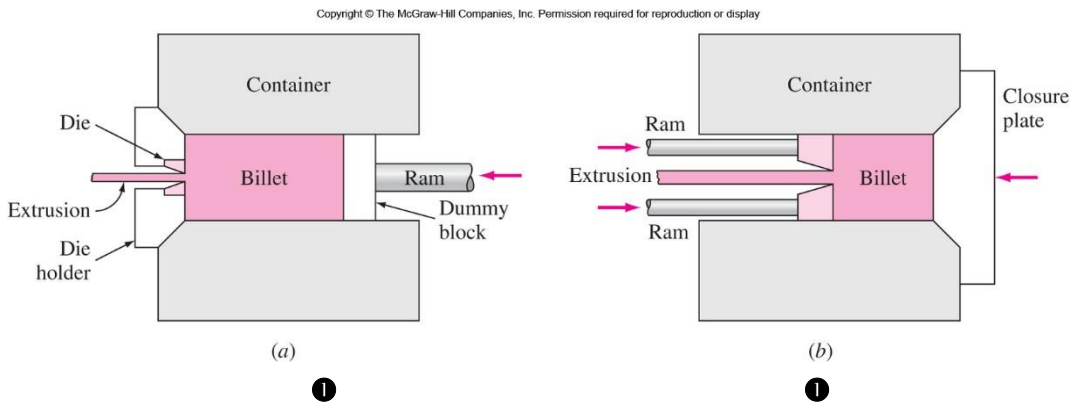
Rate of compositional change is equal to the rate of change \bullet of diffusivity times concentration gradient. \bullet

(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.

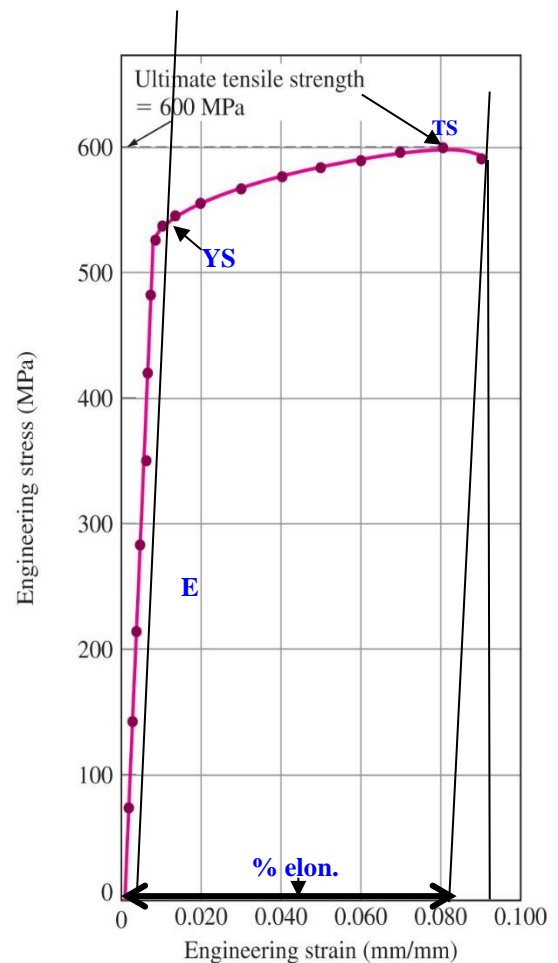
Elastic modulus: The slope of initial stress-strain curve (elastic deformation range). $E = \sigma/\epsilon$

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

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

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.

Toughness: The area below the stress-strain curve.



- (f) Compare the engineering stress and strain with the true stress and strain for the tensile test of a low-carbon steel. Load: 70,000 N, Instantaneous diameter (70,000 N): 1.20 cm, Initial diameter: 1.30 cm.

$$A_0 = \frac{\pi}{4} (0.0130 \text{ m})^2 = 0.0001327 \text{ m}^2 ; A_i = \frac{\pi}{4} (0.0120 \text{ m})^2 = 0.0001131 \text{ m}^2$$

$$\text{Assuming no volume change during extension, } l_0 A_0 = l_i A_i \Rightarrow \frac{l_i}{l_0} = \frac{A_0}{A_i}$$

$$\sigma = \frac{F}{A_0} = \frac{70,000 \text{ N}}{0.0001327 \text{ m}^2} = 527 \text{ MPa}; \sigma_t = \frac{F}{A_i} = \frac{70,000 \text{ N}}{0.0001131 \text{ m}^2} = 619 \text{ MPa}$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{l_i - l_0}{l_0} = \frac{A_0}{A_i} - 1 = \frac{0.0001327 \text{ m}^2}{0.0001131 \text{ m}^2} - 1 = 0.17$$

$$\varepsilon_t = \ln \frac{l_i}{l_0} = \ln \frac{A_0}{A_i} = \ln \frac{0.0001267 \text{ m}^2}{0.0001131 \text{ m}^2} = 0.160$$

- (g) List all the slip systems in FCC $\{111\}\langle 1\bar{1}0\rangle$ crystal structure.

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

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

- (h) A stress of 10 MPa is applied in the [100] direction of a unit cell of a BCC iron single crystal. Calculate the resolved shear stress for the following slip systems: (a) $(101)[\bar{1}11]$, (b) $(211)[\bar{1}11]$.

$$\tau = \sigma \times \cos \lambda \times \cos \phi \quad \bullet \Rightarrow$$

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

$$\tau = 10 \text{ MPa} \cdot \frac{2}{\sqrt{1} \times \sqrt{2^2 + 1^2 + 1^2}} \cdot \frac{-1}{\sqrt{1} \times \sqrt{1^2 + 1^2 + 1^2}} = 10 \text{ MPa} \cdot \frac{-2}{\sqrt{18}}$$

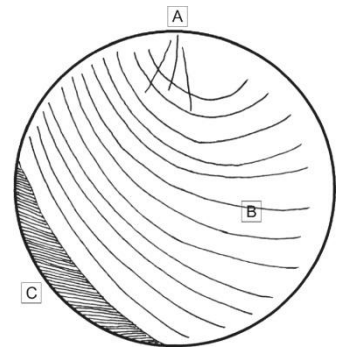
$$= -4.71 \text{ MPa} \quad \bullet \bullet$$

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

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



①①

①

(m) How to improve the fatigue strength of a metal?

(1) Stress concentration: Fatigue strength is reduced by stress concentration. ①

Avoided notches, keyways, or sharp changes in cross sections. ①

(2) Surface roughness: Smoother surface increases the fatigue strength ①.

Rough surfaces create stress raisers.

(3) Surface condition: Most fatigue failure originate at the surface. Surface hardening treatments like carburizing and nitriding increases fatigue life ①.

Compressive residual stress on the surface also increases fatigue life ①.

(n) 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.

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

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

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

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 $R = 8.314 \text{ J/(mol}\cdot\text{K)}$. (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 $10^{22} \text{ atoms/m}^3$ if the surface concentration is $10^{24} \text{ atoms/m}^3$? The solution of Fick's second law: $\frac{C_s - C_x}{C_s - C_0} =$

$\operatorname{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$. (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)

$$D = D_0 e^{-Q/RT} \text{ ①} = 2.0 \times 10^{-5} \text{ m}^2/\text{s} \left\{ \exp \frac{-142000 \text{ J/mol}}{[8.314 \text{ J/mol}\cdot\text{K}](927+273)\text{K}} \right\} \text{ ①①①}$$

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

(b)

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

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

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

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

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

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

(c)

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

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

$\operatorname{erf} 1.8 = 0.9891$, $\operatorname{erf} 1.9 = 0.9928$ \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 alloys❶.

3. Sketch and discuss (from the microstructure change) the annealing temperature effect on the tensile strength, elongation, and electrical conductivity of a heavily cold-worked 70Cu-30Zn alloy. (10%)

Low temperature recovery:

Vacancies are eliminated❶. Dislocations are moved into lower energy configuration and form subgrain structure (polygonization). ❶ The quantity of dislocation is not obvious decreased.

The strength is reduced slightly and the ductility is increased slightly, but its electrical conductivity (green curve) is significantly increased. ❶

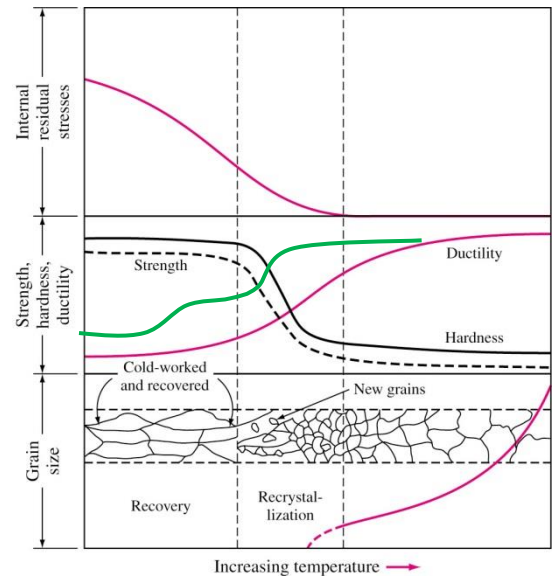
Intermediate temperature recrystallization:

The cold worked structure is completely replaced with recrystallized grain structure (new strain-free grain) ❶. The quantity of dislocation is obvious decreased and recover to the un-worked condition.

The strength is reduced obviously and the ductility is increased obviously❶, its electrical conductivity (green curve) is significantly increased again. ❶

High temperature grain growth:

The grain size becomes larger in order to reduce the area of grain boundary❶. The strength is reduced slightly and the ductility is increased slightly, its electrical conductivity (green curve) is slightly increased. ❶



❶❶❶

4. An alloy steel plate is subjected to a tensile stress of 120 MPa. The fracture toughness of the materials is given to be $50 \text{ MPa}\cdot\text{m}^{1/2}$. (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 120 MPa and 60 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)

$$K_{IC} = Y \sigma_f \sqrt{\pi a} \bullet \bullet \rightarrow 50 \text{ MPa} \cdot \text{m}^{1/2} = 1 \times 120 \text{ MPa} \sqrt{\pi a} \bullet \bullet \rightarrow a = 0.05526 \text{ m} \bullet$$

(b)

$$\sigma = 120 \text{ MPa}, a_f = a/2 = 0.02763 \text{ m}, N_f = 3 \times 10^6, m = 3, A = 2.0 \times 10^{-12}.$$

$$N_f = \frac{a_f^{-(\frac{m}{2})+1} - a_0^{-(\frac{m}{2})+1}}{A \sigma^m \pi^{m/2} Y^m [-(\frac{m}{2}) + 1]} \bullet \rightarrow 3 \times 10^6 = \frac{0.02763^{-0.5} - a_0^{-0.5}}{2.0 \times 10^{-12} 120^3 \pi^{3/2} 1^3 [-(\frac{3}{2}) + 1]} \bullet$$

$$-28.866 = 6.016 - a_0^{-0.5} \bullet$$

$$a_0^{-0.5} = 34.882 \bullet$$

$$a_0 = 8.2186 \times 10^{-4} \text{ m} \bullet$$

Copyright © The McGraw-Hill Companies, Inc. Permission required for reproduction or display

Table 5.3 Table of the error function

z	erf z	z	erf z	z	erf z	z	erf z
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

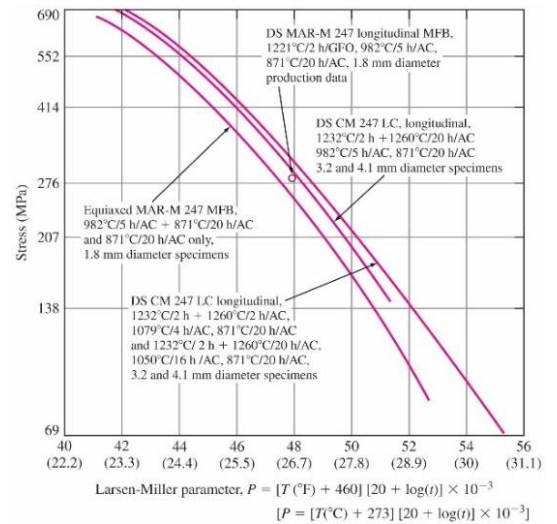


Fig. 7.31

1. Answer following questions briefly: (65%)

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

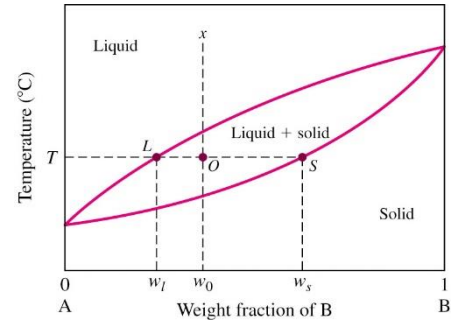
Alloy w_0 (B) at T: $X_l + X_s = 1$, $w_0 = X_l w_l + X_s w_s$ ①

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

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

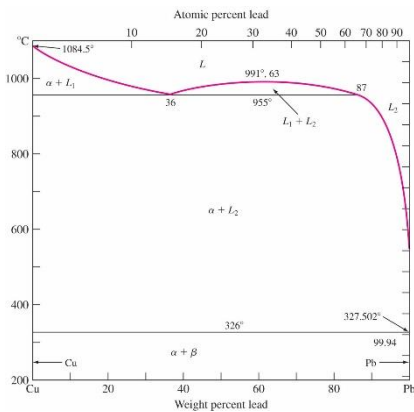
$w_0 = (1 - X_s) w_l + X_s w_s \rightarrow X_s (w_s - w_l) = w_0 - w_l$ ①

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



(b) Draw the monotectic invariant reaction in a phase diagram.

in a phase diagram.



①①①①

(c) Sketch and compare the single solid phase (such as Ni-30%Cu) microstructures between the equilibrium and non-equilibrium solidification conditions.

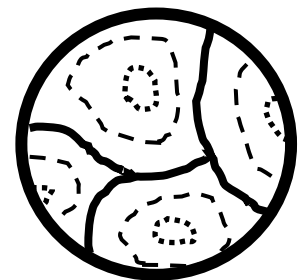
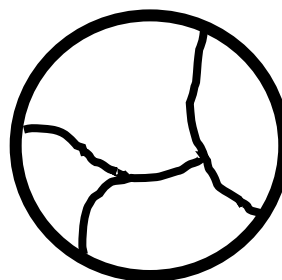
Equilibrium:

Composition uniform distribution in a polycrystalline structure. ①

Non-equilibrium:

Composition varying from lower Cu at grain-center to higher Cu near grain-boundary as the cored structure.

①



Equilibrium ① Non-equilibrium ①①

(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

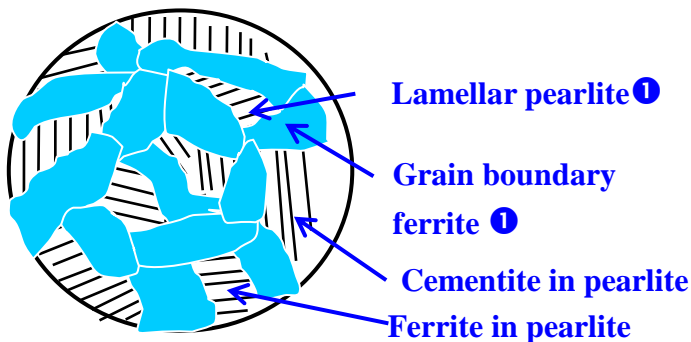
Eutectic: 942°C , $\text{L}(27.9\%\text{Ni}) \rightarrow \beta\text{Ti}(11.5\%\text{Ni}) + \text{Ti}_2\text{Ni}(37\%\text{Ni})$ ①

Peritectic: 984°C , $\text{L}(27.9\%\text{Ni}) + \text{TiNi}(54.4\%\text{Ni}) \rightarrow \text{Ti}_2\text{Ni}(38.5\%\text{Ni})$ 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

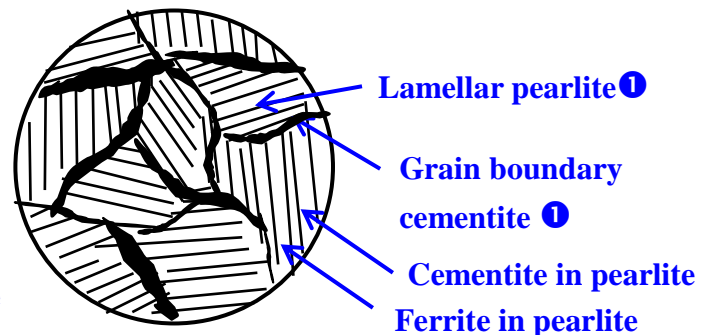
(e) Sketch and compare the slow-cooling microstructures of the Fe-0.4%C and Fe-1.2%C plain carbon steels.



Microstructure of Fe-0.4%C

Grain boundary ferrite ≈ 50 wt% ①

Lamellar pearlite ≈ 50 wt%



Microstructure of Fe-1.2%C

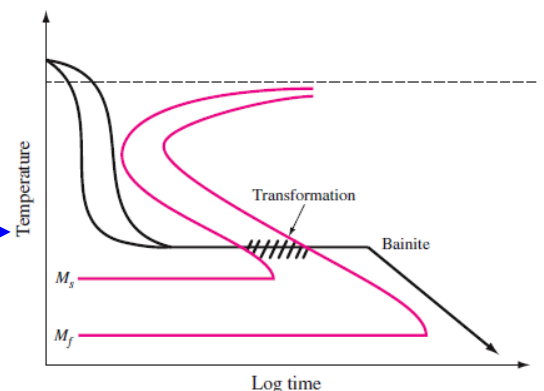
Grain boundary cementite ≈ 7 wt% ①

Lamellar pearlite ≈ 93 wt%

(f) Draw a cooling curve of austempering 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 austenite to Bainite transformation. ① ① ①

Advantages: (1) improves ductility and impact resistance. ① (2) decreased distortion of the quenched material. ①

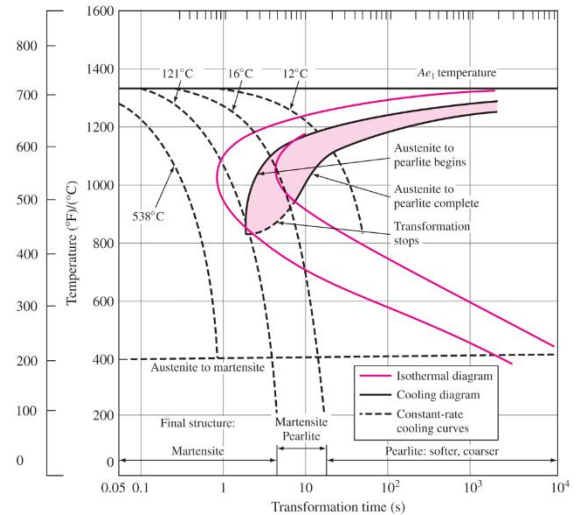


(g) Sketch and compare the CCT and TTT curves for a eutectoid plain-carbon steel.

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

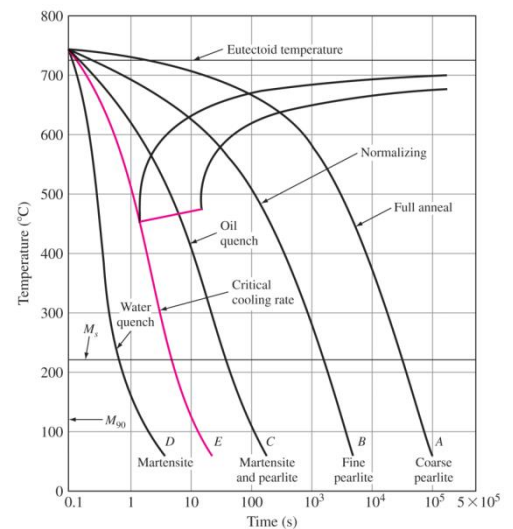


(h) List the limitations of the plain carbon steels compare with that of alloy steels.

1. Cannot be strengthened beyond 690 MPa without losing ductility and impact strength. ①
2. Not deep hardenable. ①
3. Low corrosion resistance. ①
4. Rapid quenching leads to crack and distortion. ①
5. Poor impact resistance at low temperature. ①

(i) 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



(j) Compare the differences (composition, treatment, application) between the 5xxx (e.g. 5052Al) and 7xxx (e.g. 7075Al) series of aluminum alloys.

5052Al: Al + 2.5% Mg ① + 0.2% Cr.

It cannot be precipitation-strengthened but can only be cold-worked to increase its strength. ①

Used in bus, truck and marine sheet metals. ①

7075Al: Al + 5.6% Zn ① + 2.5% Mg + 1.6% Cu + 0.25% Cr.

It can be precipitation-strengthened but also can be cold-worked to increase its strength. ①

Used for aircraft structures. ①

(k) Compare the differences (composition, corrosion resistance) between the ferritic (e.g. 430), martensitic (e.g. 440A), and austenitic (e.g. 304) stainless steels.

SS 430: Fe + 17% Cr ① + 0.012% C. Good corrosion resistance. ①

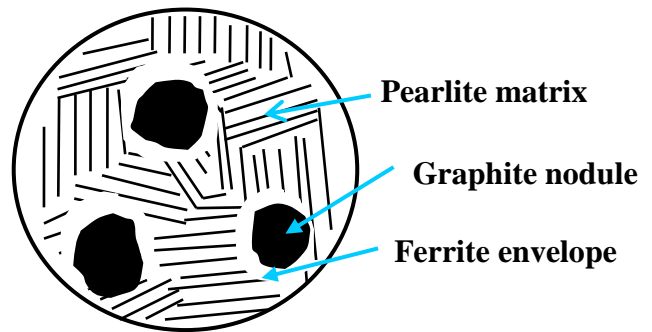
SS 440A: Fe + 17% Cr + 0.7% C. ① Poor or fair corrosion resistance. ①

SS 304: Fe + 19% Cr + 10% Ni. ① Excellent corrosion resistance. ①

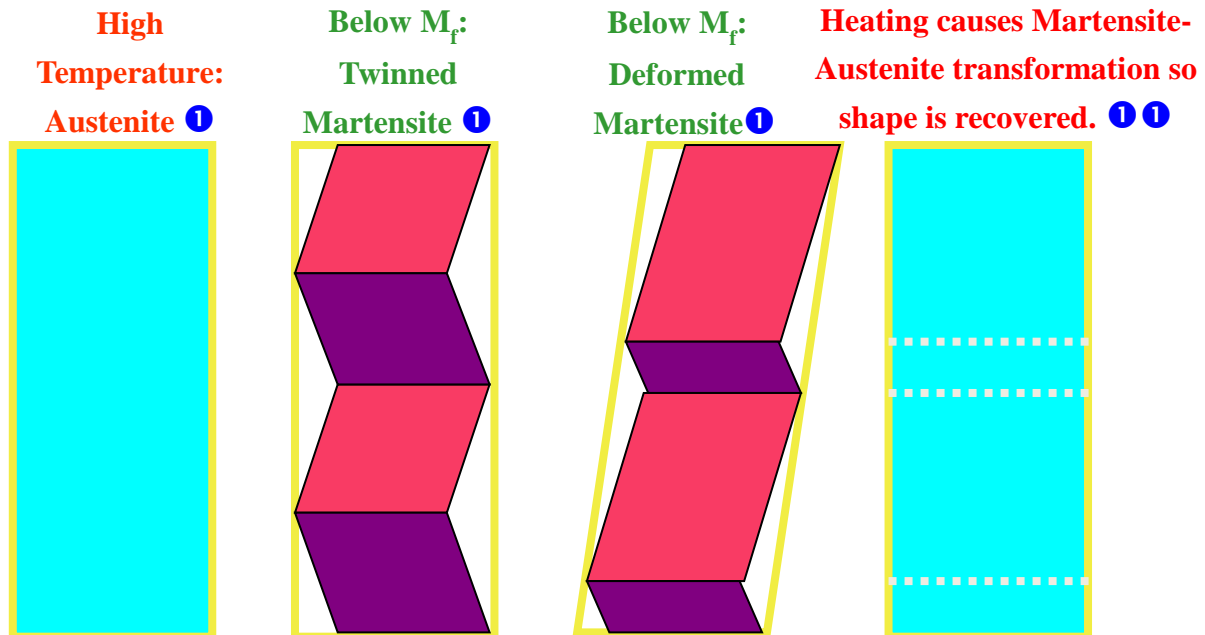
(l) Sketch and explain the microstructure of Grade 80-55-06 as-cast ductile iron.

Spherical nodules of graphite ① in envelopes of free ferrite (bull's-eye structure) ① in a pearlite matrix. ①

① ① ①



(m) Show the shape-memory effect by using the crystal deformation schematic



diagrams.

2. Calculate the relative amount of each phase at 184, 182, 60 °C of a Pb-30wt%Sn

alloy from the Pb-Sn phase diagram. Sketch the microstructures of this alloy at 184 °C and 182 °C. (15%)

From Lever rule:

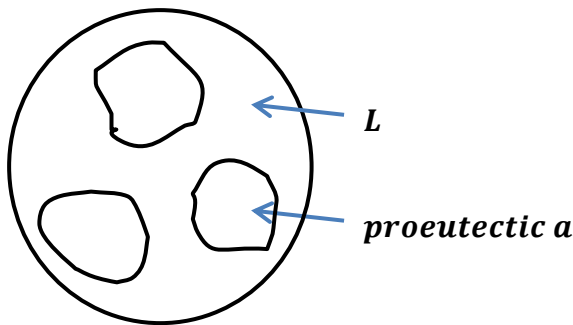
$$184\text{ }^\circ\text{C}: W_\alpha = (61.9 - 30) / (61.9 - 18.3); W_L = (30 - 18.3) / (61.9 - 18.3) \text{ ①}$$

$$\Rightarrow W_\alpha = 73.2\%; W_L = 26.8\% \text{ ①}$$

$$182\text{ }^\circ\text{C}: W_\alpha = (97.8 - 30) / (97.8 - 18.3); W_\beta = (30 - 18.3) / (97.8 - 18.3) \text{ ①}$$

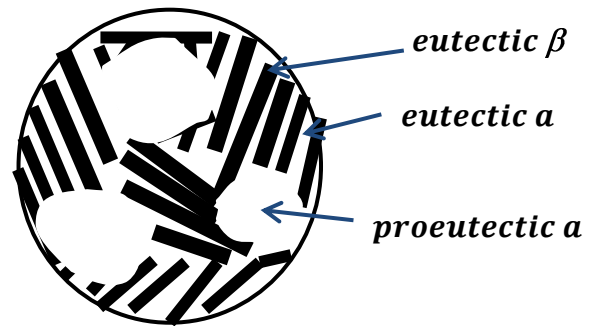
$$\Rightarrow W_\alpha = 85.3\%; W_\beta = 14.7\% \text{ ①}$$

$$60\text{ }^\circ\text{C}: W_\alpha = (98.7 - 30) / (98.7 - 2.6); W_\beta = (30 - 2.6) / (98.7 - 2.6) \text{ ①}$$



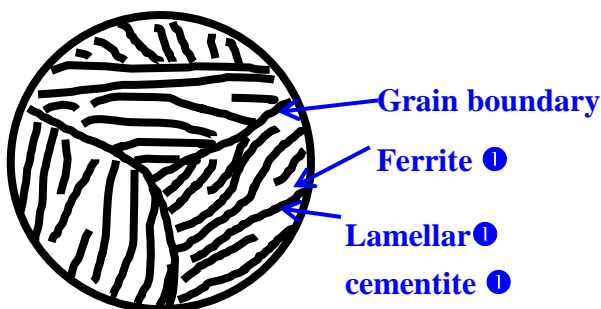
$$\Rightarrow W_\alpha = 71.5\%; W_\beta = 28.5\% \text{ ①}$$

Microstructure at 184 °C ①①

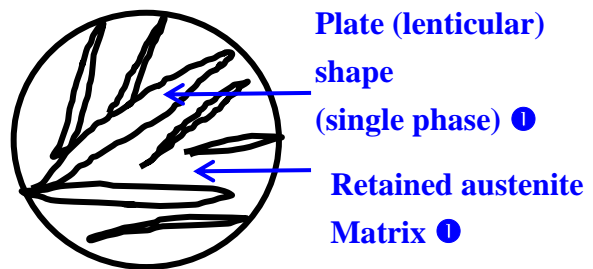


Microstructure at 182 °C ①①

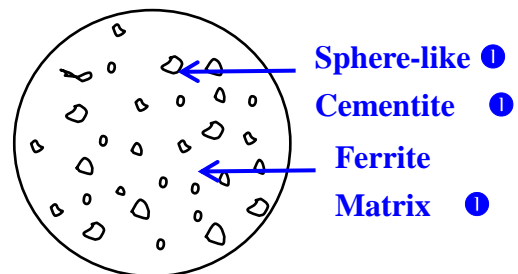
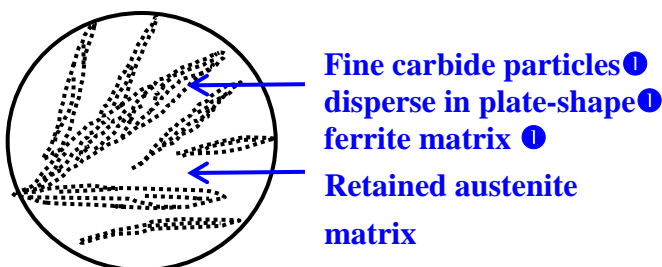
3. Sketch and explain the microstructure characteristics of pearlite, martensite, bainite, and tempered martensite for a eutectoid carbon steel.(10%)



Microstructure of pearlite



Microstructure of martensite



Microstructure of bainite

Microstructure of tempered martensite

4. Two austenite 70 mm diameter 5140 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 5140 alloy to 4340 alloy and predict RC hardness again. (10%)

From Fig. 9.40:

Water quenched: $D_{\text{surface}} = 2.8 \text{ mm}$ ① ; $D_{\text{center}} = 15.8 \text{ mm}$ ①

Oil quenched: $D_{\text{surface}} = 10.8 \text{ mm}$ ① ; $D_{\text{center}} = 22.4 \text{ mm}$ ①

From Fig. 9.38:

5140 steel ($\pm 0.5 \text{ RC}$):

$S_{\text{water}} = 52.5 \text{ RC}$ ①

$C_{\text{water}} = 29.4 \text{ RC}$ ①

$S_{\text{oil}} = 35.6 \text{ RC}$ ①

$C_{\text{oil}} = 25.6 \text{ RC}$ ①

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

$S_{\text{water}} = 53.5 \text{ RC}$ ①

$C_{\text{water}} = 50.6 \text{ RC}$ ①

$S_{\text{oil}} = 51.9 \text{ RC}$ ①

$C_{\text{oil}} = 49.0 \text{ RC}$ ①

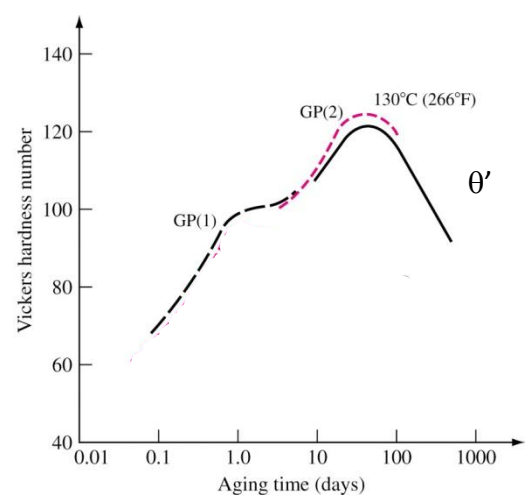
5. Describe the precipitation sequence (phase name, composition, crystal structure) for an Al-4%Cu alloy aged at 130 °C after solution treatment. Draw its hardness-aging curves and indicate the approximate sites of these precipitates. (10%)

(1) GP1 zone: Cu-rich phase, FCC(Al). ①①

(2) θ'' (GP2): CuAl_2 , Tetragonal. ①①

(3) θ' : CuAl_2 , Tetragonal. ①

(4) θ : CuAl_2 , Tetragonal. ①



①①①①

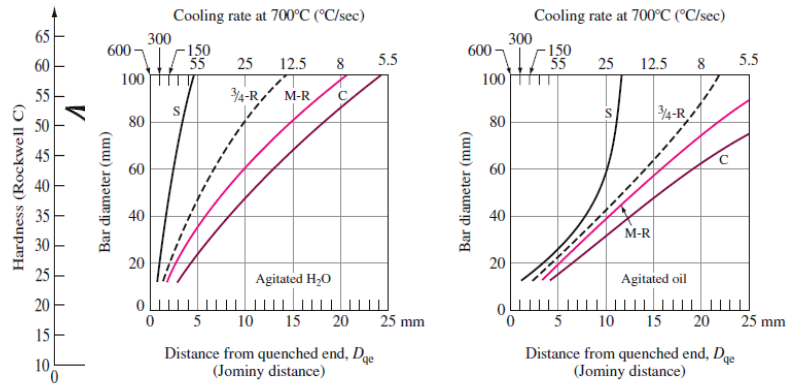
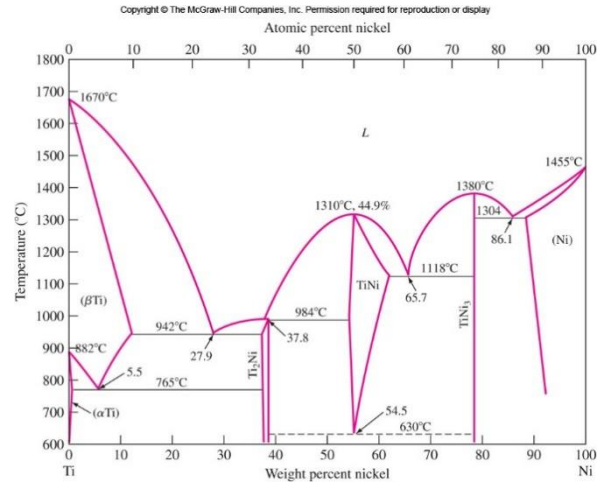
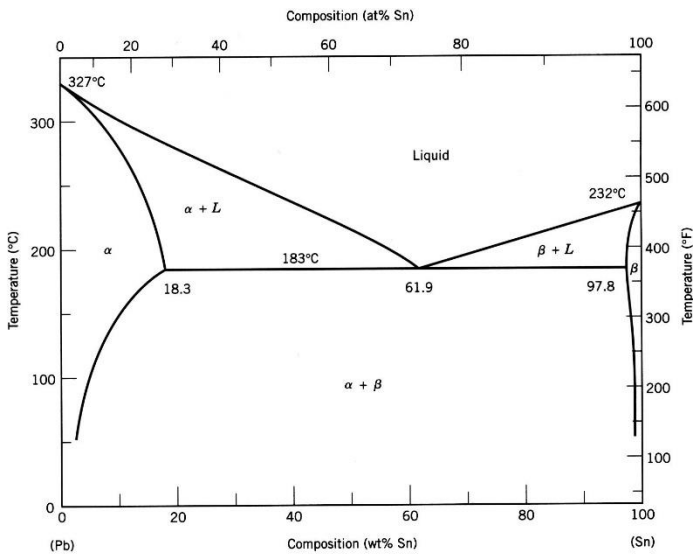


Figure 9.40

Figure 9. 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 $\frac{3}{4}$ -radius positions on the cross section of bars.)
 [From H.E.]
 9th ed., Unit
 Corporation. reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.]