10320PME 300600 材料科學導論 Introduction to Material Science

期中考一 Midterm Exam I   AM 10:10-12:00, April13, 2015

1. Answer following questions briefly: (55%)

    (a) List the five types of materials in this course.

    Metals, **1** Polymers, **1** Ceramics, **1** Composites, **1** and Electronic materials **1**.

    (b) What are shape-memory alloys? How to use these alloys for artery stents 心血管支架.

    Shape-memory alloys, once strained **1**, revert back to their original shape **1** upon an increase in temperature above T_c **1**.
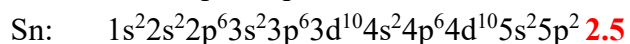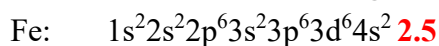
    Supporting weakened artery walls or expanding narrowed arteries **1**: The deformed stent is first delivered in the appropriate position in the artery using a probe **1**. The stent expands to its original shape and size after unfastening its bundle sheath and increasing its temperature to body temperature **1**.

    (c) A 100 gram alloy of Fe and C consists of 98wt% Fe and 2wt% C. What are the atomic percentages of Fe and C in this alloy? (atomic mass: Fe 55.85g/mol, C12.01g/mol)

    C: $(2/12.01)/[(98/55.85)+(2/12.01)] \times 100\%$ **1.5** = 8.67% **1**

    Fe: $(98/55.85)/[(98/55.85)+(2/12.01)] \times 100\%$ **1.5** = 91.33% **1**

    (d) List the electronic configurations of Fe (Z = 26) and Sn (Z= 50).

    Fe: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$ **2.5**

    Sn: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^2$ **2.5**

    (e) After ionization, why is the sodium ion smaller than the sodium atom? After ionization, why is the chloride ion larger than the chlorine atom?

    After ionization to the Na^+, the Na atom becomes smaller because the electron-to-proton ratio of the Na atom is decreased **1** when the Na^+ ion **1** forms.   Also, the outer third shell no longer exists once the $3s^1$ electron is lost by the Na atom **1**.

    After ionization, the Cl^- ion **1** is larger because the electron-to-proton ratio of the chlorine atom is decreased **1** by the ionization process.

    (f) Explain the differences (origin and strength) between the fluctuating and permanent secondary bonds.

The fluctuating secondary bonds: Dipoles are created due to temporary **1** asymmetrical distribution **1** of electron charges. Their strengths are very weak. **1**

The permanent secondary bonds: Dipoles are created due to permanent **1** asymmetrical **1** distribution of electron charges. Their strengths are stronger **1** than that of the fluctuating secondary bonds.

(g) Calculate the density of FCC aluminum metal. (atomic radius = 0.143 nm, atomic mass = 26.98 g/mol)

a: lattice parameter, r: atomic radius $\Rightarrow$ $\sqrt{2}a = 4r$ $\Rightarrow$ $a = 2\sqrt{2}\,r$ **1**

$$\rho = m/V = \left\{ \frac{(4\text{ atoms})(26.98\text{ g/mol})}{6.02 \times 10^{23}\text{atoms/mol}} \left(\frac{10^{-6}\text{Mg}}{\text{g}} \right) \right\} / \left(2\sqrt{2} \times 0.143 \times 10^{-9}\text{ m} \right)^3$$

$$= \frac{17.927 \times 10^{-29}}{66.167 \times 10^{-30}} \frac{\text{Mg}}{\text{m}^3} = 2.6911 \frac{\text{Mg}}{\text{m}^3}$$

2 + 1 + 1

(h) List the indices of two planes and three directions in Fig. 1.
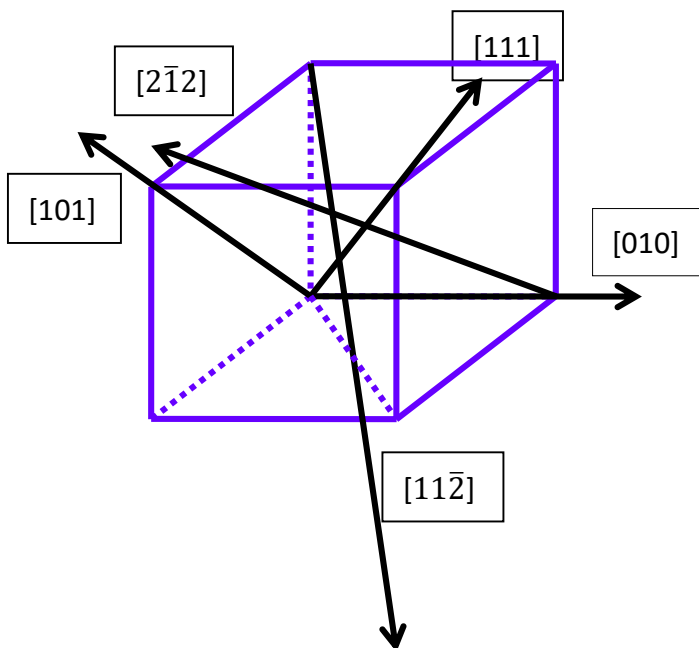
Plane 1: $(01\bar{1}0)$ **1**

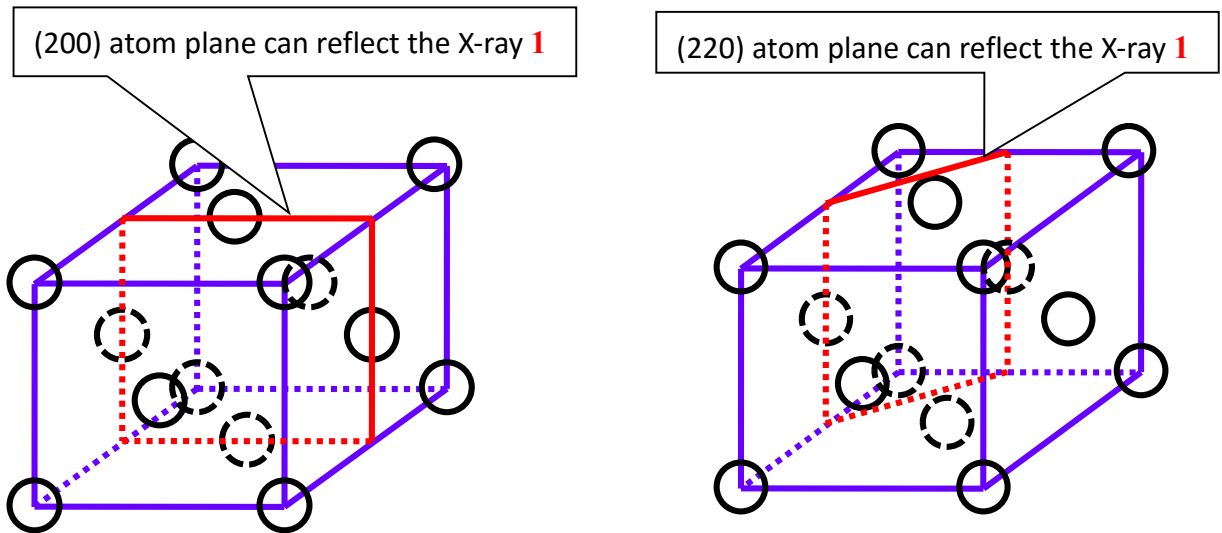Plane 2: $(1\bar{1}00)$ **1**

Direction 1: $[\bar{1}100]$ **1**

Direction 2: $[11\bar{2}1]$ **1**

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

(i) Draw the $[010]$, $[101]$, $[111]$, $[11\bar{2}]$, and $[2\bar{1}2]$ directions in the FCC unit cells.

(j) Prove that the diffraction peaks of {100} and {110} planes are not found for a FCC crystal.

(200) atom plane can reflect the X-ray **1**

(220) atom plane can reflect the X-ray **1**

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 λ/2 **1**, so that deconstructive 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 (220) planes is λ/2, **1** so that deconstructive interference occurs **1** and no (110) diffraction peak can be seen.

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

[(8 + 8 + 10 + 10) cm] **1**/[(16 + 17 +18 +21) grain] **1**= 0.5 cm/grain **1**

average grain diameter = 0.5 × 10^{-2} m/250 **1** = 2 × 10^{-5} m = 20 μm **1**

2. 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.
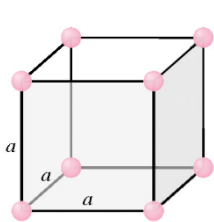
Material properties

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.
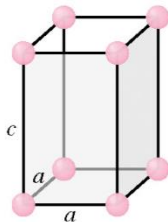
3. Sketch and explain the characteristics of the seven crystal systems.　　(10%)

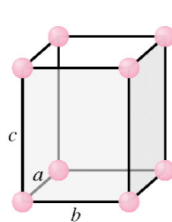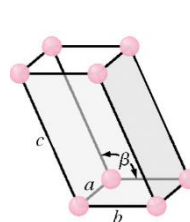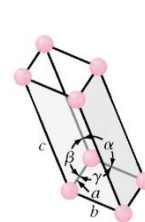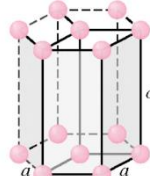| Cubic	Tetragonal	Orthorhombic	Monoclinic	Triclinic
$a = b = c$	$a = b \neq c$	$a \neq b \neq c$	$a \neq b \neq c$	$a \neq b \neq c$
$\alpha = \beta = \gamma = 90°$	$\alpha = \beta = \gamma = 90°$	$\alpha = \beta = \gamma = 90°$	$\alpha = \gamma = 90° \neq \beta$	$\alpha \neq \beta \neq \gamma \neq 90°$
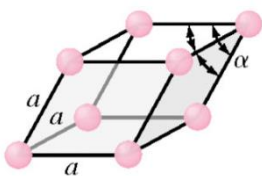
Rhombohedral
$a = b = c$
$\alpha = \beta = \gamma \neq 90°$ **1.5**

Hexagonal
$a = b \neq c$
$\alpha = \beta = 90°, \quad \gamma = 120°$ **1.5**

4. Calculate the maximum interstitial atomic radius of the interstitial (at the edge-center of a unit cell) in FCC and BCC of Fe. (atomic radius of Fe = 0.126 nm). Use these results to explain that it is easier for the iron lattice to house carbon atoms at temperatures higher than 912°C than slightly lower temperatures.　(10%)

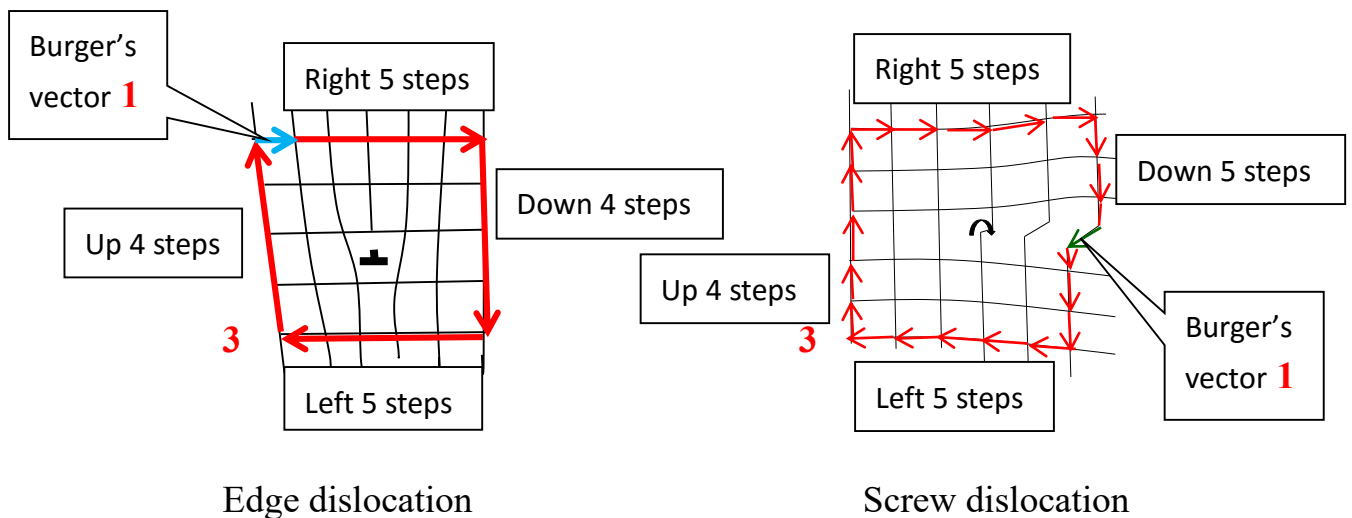*a*: lattice parameter, R: atomic radius of Fe (0.126 nm),

r: maximum atomic radius of interstitial.

FCC: $\sqrt{2}a = 4R \Rightarrow a = 2\sqrt{2} \ R = 2R + 2r$ **1** $\Rightarrow r = (\sqrt{2}-1) \ R$ **1** $= 0.0522$ nm **1**

BCC: $\sqrt{3}a = 4R \Rightarrow a = (4/\sqrt{3})R = 2R + 2r$ **1** $\Rightarrow r = [(2/\sqrt{3})-1] \ R$ **1** $= 0.0195$ nm **1**

Fe is a FCC lattice at temperatures higher than 912°C **1** and has a larger interstitial size to house carbon atoms. However, Fe transforms to a BCC lattice **1** at temperatures below than 912°C. The maximum interstitial atomic radius changes from a large one of 0.0522 nm to an obvious smaller one of 0.0195 nm. Hence, it is not easier to house carbon atoms for the iron lattice at temperatures below than 912°C.

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

Burger's vector **1**	Right 5 steps
	Down 4 steps
Up 4 steps	
3	
Left 5 steps	

Right 5 steps	
	Down 5 steps
Up 4 steps	
3	Burger's vector **1**
Left 5 steps	

Edge dislocation   Screw dislocation

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**.

6. Sketch and explain the principles for the scanning tunneling microscope (STM) and atomic force microscope (AFM).   (10%)

STM:

Very sharp tip placed one atom diameter from surface **1**. Voltage applied across tip and surface **1**. Electrons tunnel the gap and produce current **1**. Current produced is proportional to change in gap. Detect the variation of current (constant height mode) or adjust the Z coordinate of the tip (constant current mode) to reflect the surface morphology **1**.   **2**
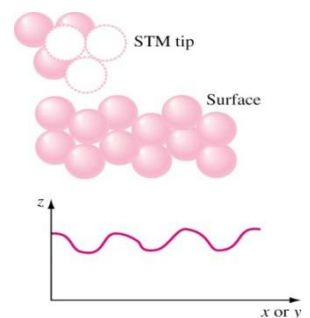
AFM:

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**.
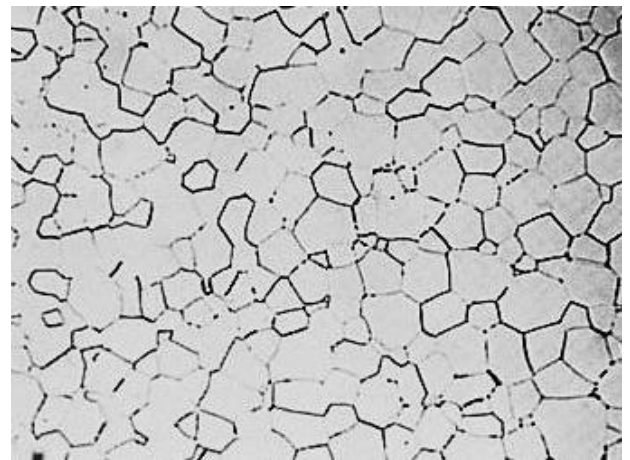

2
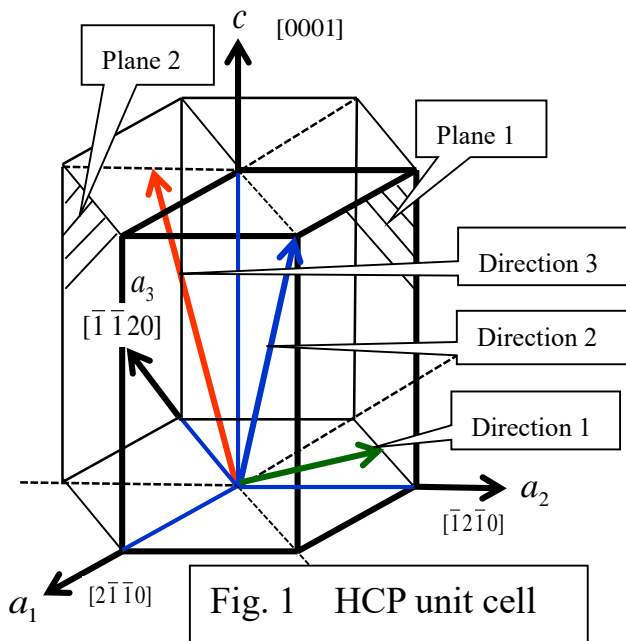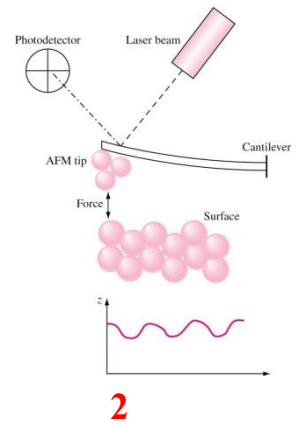

Fig. 1   HCP unit cell

Fig. 2   Grainstructure in the optical
microscope. 250×
(diagonal length of this photo is 10 cm,
width of this photo is 8 cm)

1. Answer following questions briefly: (60%)

   (a) Calculate the vacancy fraction at 1080 °C in pure copper. Assume: $E_v = 0.90$ eV, $C = 1$ and $k = 8.62 \times 10^{-5}$ eV/K.

   $$\frac{n}{N} ❶ = Ce^{-E_v/kT} ❶ = e^{-0.90/[8.62 \times 10^{-5}(1080+273)]} ❶❶ = 4.45 \times 10^{-4} ❶$$

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

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

   The net flow of atoms by atomic diffusion (from rich to rare positions ❶) is equal to diffusion coefficient (diffusivity) D times the concentration gradient dC/dx. ❶
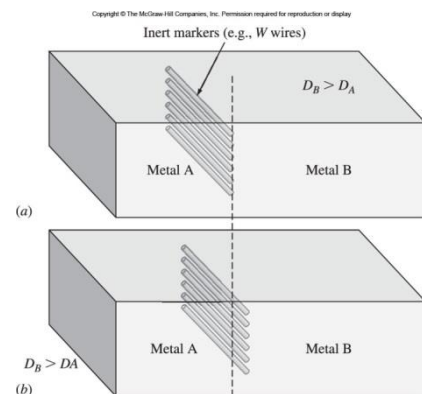
   Fick's first law: $\frac{dC}{dt} = \frac{d}{dx}\left(D\frac{dC}{dx}\right)$ ❶

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

   (c) Sketch and explain the experiment of Kirkendall effect.

   Insert markers (W or Mo wire) at the interface between metal A and metal B ❶. After high temperature treatment for a long time, the markers at the diffusion interface moved slight ❶ in the opposite direction to the faster diffusing species ❶.

   ❶ ❶ ❶

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   Inert markers (e.g., W wires)

   $D_B > D_A$

   Metal A   Metal B

   (a)

   Metal A   Metal B

   $D_B > DA$

   (b)

   (d) A sheet of a 70% Cu-30%Zn alloy is cold-rolled 30 percent to a thickness of 2.80 mm. The sheet is then further cold-rolled to 1.50 mm. What is the total percent cold work?

   $$\frac{t_0 - t_f}{t_0} \times 100\% = \% \text{ roll reduction } ❶ \rightarrow \frac{t_0 - 2.80 \text{ mm}}{t_0} \times 100\% = 30 \text{ \%}❶$$

   $$t_0 = 4.00 \text{ mm } ❶ \rightarrow \frac{t_0 - t_f}{t_0} \times 100\% = \frac{4.00 - 1.50}{4.00} \times 100\%❶ = 62.5\%❶$$

(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). $E = \sigma/\varepsilon$ ❶

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

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

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. ❶

Toughness: The area below the stress-strain curve. ❶   ❶ ❶
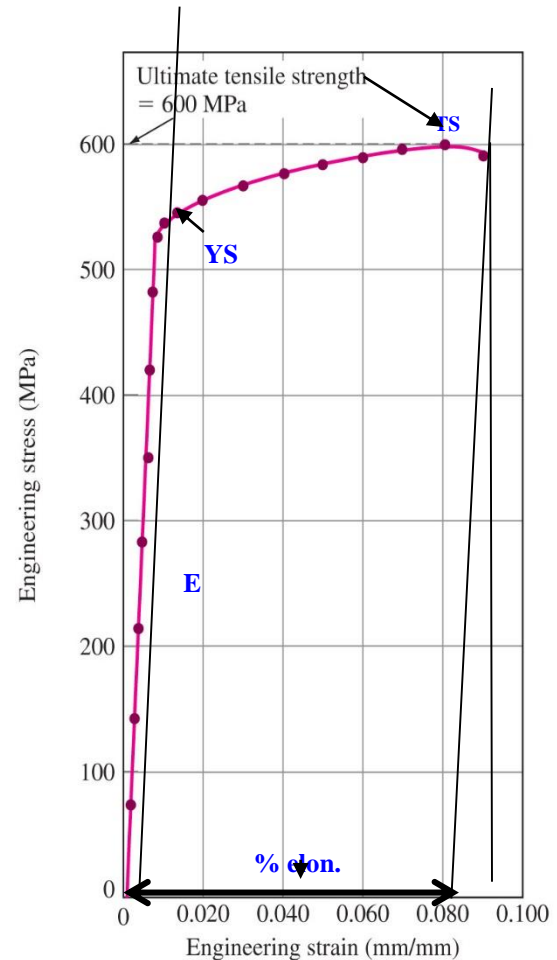
(f) List all the slip systems in BCC {110}<1$\bar{1}$1> crystal structure.

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

(g) Determine the tensile stress that must be applied to the [100] axis of a high-purity copper single crystal to cause slip on the $(111)[1\bar{1}0]$ system. The resolved shear stress for the crystal is 0.85 MPa.

$\tau = \sigma \times \cos \lambda \times \cos \phi$ ❶ $\Rightarrow$ 0.85 MPa $= \sigma \cdot \dfrac{1}{\sqrt{1} \times \sqrt{1^2 + 1^2}} \cdot \dfrac{1}{\sqrt{1} \times \sqrt{1^2 + 1^2 + 1^2}} = \sigma \cdot \dfrac{1}{\sqrt{6}}$ ❶❶

$\sigma = \sqrt{6} \cdot 0.85$ MPa ❶ $= 2.08$ MPa ❶

(h) Explain "superplasticity" and give the certain conditions to get superplasticity.
Superplasticity: Some alloys can be deformed very large strain ❶, such as 2000%, far beyond normal deformation ❶, about dozens %.

・ Superplasticity conditions:
   * Very fine grain size (5-10 microns), ❶
   * Highly strain-rate sensitive, ❶
   * Temperature above 0.5 T_m, ❶
   * Slow strain rate (0.01-0.0001/s). ❶

(i) Indicate the different characteristics between ductile fracture surface and brittle fracture surface.

Ductile fracture surface has significant plastic deformation ❶ before fracture and conical dimples ❶ in the fracture surface.

Brittle fracture surface has no significant plastic deformation ❶ before fracture and along specific transgranular cleavage planes ❶, intergranular facet grain boundaries ❶, or chevron pattern ❶ in the fracture surface.

(j) 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. ❶

B. Clamshell or "beach" markers are created with cyclic loading. (smooth region). ❶

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

❶ ❶❶
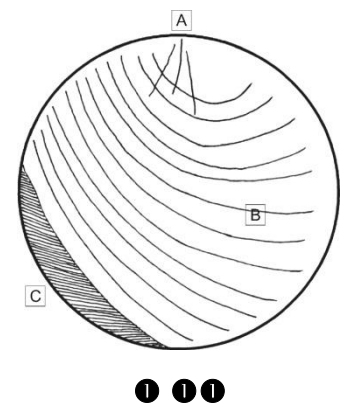
(k) Sketch and discuss the creep curve under a constant load.

Primary creep: The metals strain-hardens to support the applied load ❶ and the creep rate ($d\varepsilon/dt$) decreases gradually.

Secondary creep: Creep rate is constant (and minimum) due simultaneous strain hardening ❶ and recovery process. ❶

Tertiary creep: Creep rate rapidly increases with time leading to necking and fracture. ❶

❶ ❶
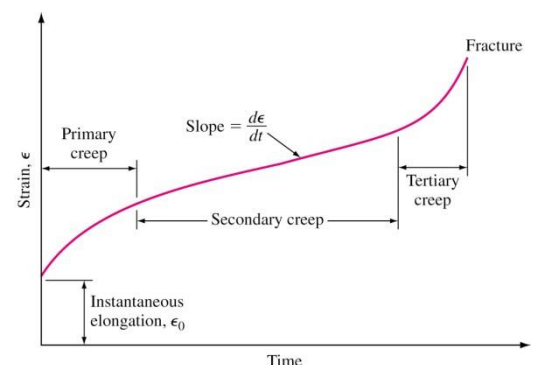
(l) Equiaxed MAR-M 247 alloy is to support a stress of 207 MPa (Fig. 7.31). Determine the time to stress rupture at 900 °C.

From Fig. 7.31: P(L.M.) = [26.7 + (27.8–26.7)5/11] × 10³ ● = 27200 ●

P(L.M.) = 27200 = [T(°C) + 273](20 + log t_r) ●= (900 + 273) (20 + log t_r)

20 + log t_r = 23.188 ●   ⇒ t_r = 10³·¹⁸⁸⁴ = 1543.1 ≅ 1543 (h) ●

2. The diffusivity values depend on 5 variables. Discuss how to affect?   (10%)

Diffusivity depends upon

Type of diffusion: Whether the diffusion is interstitial or substitutional. Small interstitial atoms are easy to move ● and interstitial diffusion rates are always faster than that of substitutional diffusion. ●

Temperature: As the temperature increases diffusivity increases. ● Melting point ↑ ⇒   Diffusivity ↓. ●

Type of crystal structure: BCC crystal has lower APF ● than FCC and hence has higher diffusivity. ●

Type of crystal imperfection: More open structures (such as grain boundaries) increases diffusion ●. Grain boundary diffusion rates are far faster than that of lattice diffusion. ●

The concentration of diffusing species: Higher concentrations ● of diffusing solute atoms will affect diffusivity. ●

3. (a) Calculate the value of the diffusivity D for the diffusion of carbon in γ iron at 950 °C. Use values of D_0 = 2.0 × 10⁻⁵ m²/s, Q = 142 kJ/mol, and R = 8.314 J/mol·K. (b) Consider the gas carburizing of a gear of 1025 steel at 950 °C. Calculate the time in minutes necessary to increase the carbon content to 0.45 % at 0.50 mm below the surface. C_s = 0.90% C. The solution of Fick's second law: $\frac{C_s - C_x}{C_s - C_0} = \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$ (10%)

$D = D_0 e^{-Q/RT}$ ● $= 2.0 \times 10^{-5} \ \mathrm{m^2/s}\left\{\exp\dfrac{-142000 \ \mathrm{J/mol}}{[8.314 \ \mathrm{J/mol\cdot K}](950+273)\mathrm{K}}\right\}$ ●●

$D = 1.72 \times 10^{-11}$ m²/s   (at 950 °C) ●

$\dfrac{C_s - C_x}{C_s - C_0} = \mathrm{erf}\left(\dfrac{x}{2\sqrt{Dt}}\right) \rightarrow \dfrac{0.90 - 0.45}{0.90 - 0.25} = \mathrm{erf}\left(\dfrac{0.50 \ \mathrm{mm}}{2\sqrt{1.72 \times 10^{-11} \ \mathrm{m^2/s} \ \times t}}\right)$ ●●

$$\frac{0.90 - 0.45}{0.90 - 0.25} = 0.692 = \text{erf}\left(\frac{0.50 \text{ mm}}{2\sqrt{1.72 \times 10^{-11} \text{ m}^2/\text{s} \times t}}\right) ❶$$

From error function Table: $z = 0.70 \rightarrow \text{erf } z = 0.6778$ and $z = 0.75 \rightarrow \text{erf } z = 0.7112$ ❶

$\therefore \quad \text{erf} \quad z \quad = \quad 0.692 \quad \rightarrow \quad \frac{0.7112 - 0.6778}{0.75 - 0.70} = \frac{0.692 - 0.6778}{z - 0.70} ❶ \rightarrow z = 0.72$

$$= \frac{0.50 \text{ mm}}{2\sqrt{1.72 \times 10^{-11} \text{ m}^2/\text{s} \times t}} ❶$$

$t = 7009 \text{ s} = 117 \text{ min } ❶$

4. Define the engineering stress σ, engineering strain ε, true stress σ_t, true strain ε_t, and prove $\sigma_t = \sigma(1 + \varepsilon)$; $\varepsilon_t = \ln(1 + \varepsilon)$ for the uniform deformation stage. (10%)

Engineering stress $\sigma: = \dfrac{F(\text{Tensile force})}{A_0(\text{Original cross-sectional area})} ❶$

Engineering strain $\varepsilon: = \dfrac{\Delta l(\text{Change in length})}{l_0(\text{Original length})} ❶$

True stress $\sigma_t: = \dfrac{F(\text{Tensile force})}{A_i(\text{Instantaneous area})} ❶$

True strain $\varepsilon: = \int_{l_0}^{l_i} \dfrac{dl}{l} = \ln \dfrac{l_i(\text{Instataneous length})}{l_0(\text{Original length})} ❶$

For the uniform deformation stage: $l_0 A_0 = l_i A_i \rightarrow \dfrac{l_i}{l_0} = \dfrac{A_0}{A_i} ❶$

$\sigma_t = \dfrac{F}{A_i} = \dfrac{F}{A_0} \times \dfrac{A_0}{A_i} ❶ = \sigma \times \dfrac{l_i}{l_0} = \sigma \times \dfrac{l_0 + \Delta l}{l_0} ❶ = \sigma \times (1 + \dfrac{\Delta l}{l_0}) = \sigma \times (1 + \varepsilon) ❶$

$\varepsilon_t = \ln \dfrac{l_i}{l_0} = \ln \dfrac{l_0 + \Delta l}{l_0} = \ln(1 + \dfrac{\Delta l}{l_0}) = \ln(1 + \varepsilon) ❶$

5. 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
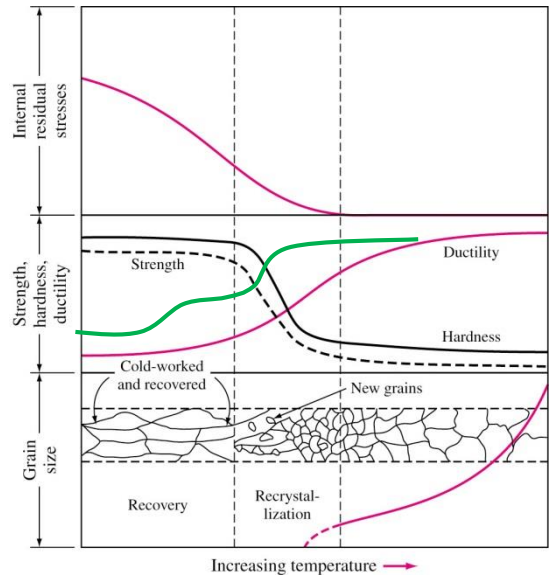
Intermediate temperature recrystallization:

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

6. An alloy steel plate is subjected to a tensile stress of 150 MPa. The fracture toughness of the materials is given to be 60 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 50 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 : $N_f = \dfrac{a_f^{-(m/2)+1} - a_0^{-(m/2)+1}}{AY^m \sigma^m \pi^{m/2}[-(m/2)+1]}$ (Where $m = 3,\ A = 2.0 \times 10^{-12}$)

(*a*)

$K_{IC} = Y\ \sigma_f\ \sqrt{\pi a}$❶ → 60 MPa·m$^{1/2}$ = 1 × 150 MPa $\sqrt{\pi a}$❶ → a

                = 0.05093 m❶

(*b*)

$\sigma = 150$ MPa, $a_f = a/2 = 0.02547$ m, ❶ $N_f = 3 \times 10^6$, $m = 3$, $A = 2.0 \times 10^{-12}$. ❶

$$N_f = \frac{a_f^{-\left(\frac{m}{2}\right)+1} - a_0^{-\left(\frac{m}{2}\right)+1}}{A\sigma^m \pi^{m/2} Y^m \left[-\left(\frac{m}{2}\right)+1\right]} \quad \text{❶} \rightarrow \quad 3 \times 10^6 = \frac{0.02547^{-0.5} - a_0^{-0.5}}{2.0 \times 10^{-12} 150^3 \pi^{3/2} 1^3 \left[-\left(\frac{3}{2}\right)+1\right]} \quad \text{❶}$$

$-56.379 = 19.815 - a_0^{-0.5}$ ❶

$a_0^{-0.5} = 76.194$ ❶

$a_0 = 0.00017225$ m ❶

Table 5.3 Table of the error function

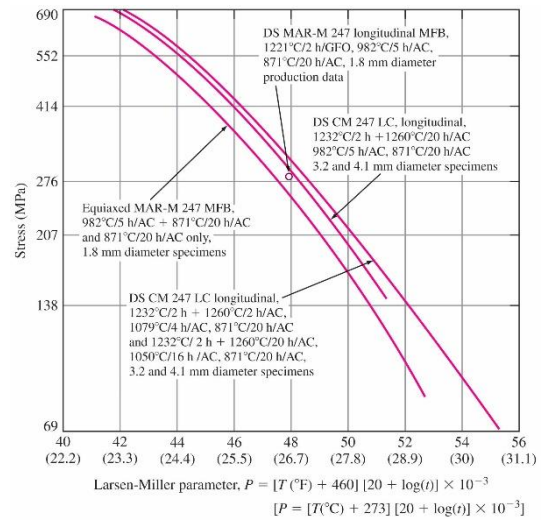| z	erf z	z	erf z	z	erf z	z	erf z
0	0	0.40	0.4284	0.85	0.7707	1.6	0.9763
0.025	0.0282	0.45	0.4755	0.90	0.7970	1.7	0.9838
0.05	0.0564	0.50	0.5205	0.95	0.8209	1.8	0.9891
0.10	0.1125	0.55	0.5633	1.0	0.8427	1.9	0.9928
0.15	0.1680	0.60	0.6039	1.1	0.8802	2.0	0.9953
0.20	0.2227	0.65	0.6420	1.2	0.9103	2.2	0.9981
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

10320PME 300600 材料科學導論 Introduction to Material Science

期末考 Final Exam   10:10-12:00, June 22, 2015

1. Answer following questions briefly: (55%)

(a) List Gibbs phase rule and explain the degree of freedom of single-, two-, and three-phase regions in a binary phase diagram under 1 atm pressure.

Gibbs phase rule: $F = C - P + 1$ ❶   F: Degrees of freedom, ❶

C: Number of components

P: Number of phases that coexist in a system

Single-phase region: $C = 2, P = 1 \therefore F = 2 - 1 + 1 = 2$ ❶

Two-phase region: $C = 2, P = 2 \therefore F = 2 - 2 + 1 = 1$ ❶

Three-phase region: $C = 2, P = 3 \therefore F = 2 - 3 + 1 = 0$ ❶
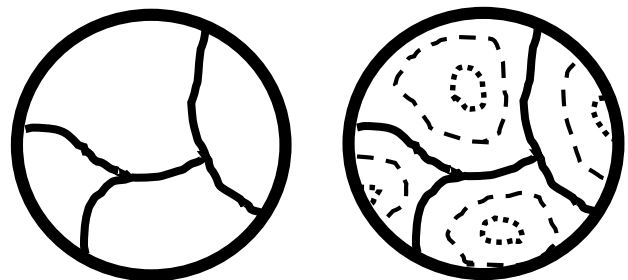
(b) Sketch and compare the single solid phase (such as Ni-30%Cu) microstructures between the equilibrium and non-equilibrium solidification conditions.

Equilibrium:

Composition uniform distribution in a polycrystalline structure. ❶

Non-equilibrium:

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

Equilibrium ❶   Non-equilibrium ❶ ❶

(c) List five possible invariant reactions in the binary phase diagrams.

L, L_1, L_2: Liquid phases，α, β, γ: Solid phases

Eutectic: $L \rightarrow \alpha + \beta$ ❶

Peritectic: $L + \alpha \rightarrow \beta$ ❶

Monotectic: $L_1 \rightarrow L_2 + \alpha$ ❶

Eutectoid: $\gamma \rightarrow \alpha + \beta$ ❶

Peritectoid: $\alpha + \beta \rightarrow \gamma$ ❶

(d) List the equilibrium phase(s) for 30(wt%)Fe-30Cr-40Ni, 30Fe-50Cr-20Ni, 70Fe-

20Cr-10Ni, 74Fe-18Cr-8Ni, 74Fe-22Cr-4Ni alloys at 650 °C.

30Fe-30Cr-40Ni: γ;   30Fe-50Cr-20Ni: α + γ + σ;   70Fe-20Cr-10Ni: γ + σ;

74Fe-18Cr-8Ni: γ;   74Fe-22Cr-4Ni: α + γ + σ.

(e) Describe the typical experimental procedures to get an isothermal transformation diagram for a eutectoid plain carbon steel.

Several small samples ❶are first austenitized above eutectoid temperature (723 °C) in a salt bath ❶and rapidly cooled to desired temperature in another salt bath (below 723 °C) ❶ and then quenched in cold water at various time intervals❶. The microstructure can be examined to show how much pearlite has been formed❶. By repeating the same procedure at progressively lower temperatures❶, an isothermal transformation diagram can be constructed.


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

Austinitizing, quenching at around M$_s$, holding in quenching media until temperature is uniform❶, removing before bainite forms and cooling at a moderate rate❶, and then tempering. The martensite transformation temperatures of surface and center of the steel are the same and quenching crack can be avoided❶. This steel has higher impact energy values❶ than that of convention quenching and tempering condition.

❶❶
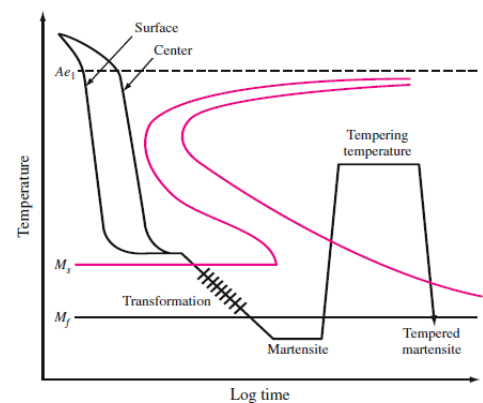
(g) Draw the cooling curves of full anneal, normalizing, oil quench, water quench and critical cooling rate in the continuous-cooling diagram of eutectoid plain-carbon steels.
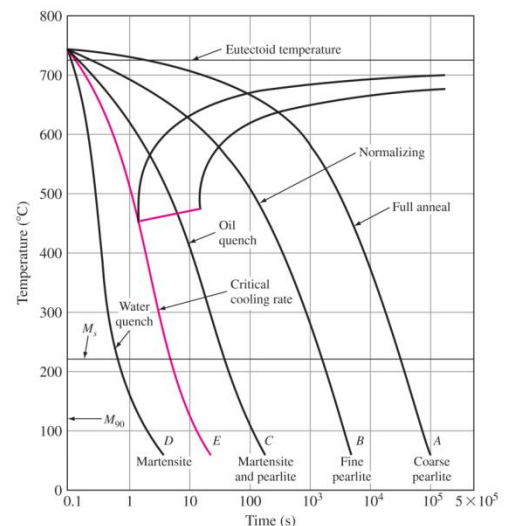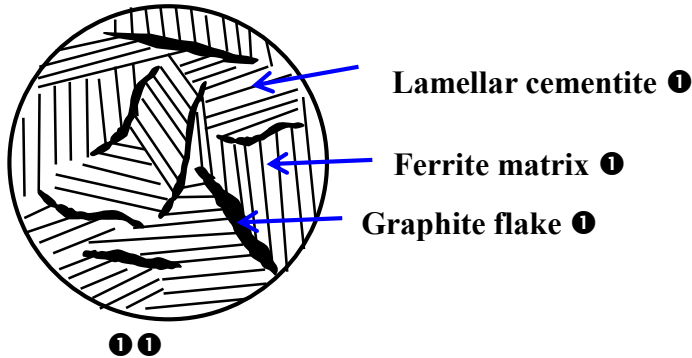
(h) List the major alloy elements for the seven types of 1xxx-7xxx aluminum alloys.
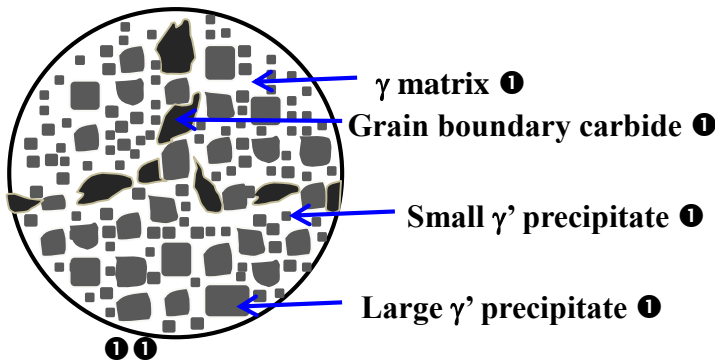
1xxx: pure aluminum, > 99%;   2xxx: Al-Cu;   3xxx: Al-Mn;

4xxx: Al-Si;   5xxx: Al-Mg;   6xxx: Al-Mg-Si;   7xxx: Al-Zn(-Mg-Cu).

(i) Sketch and explain the microstructure of an as-cast pearlitic grey iron.
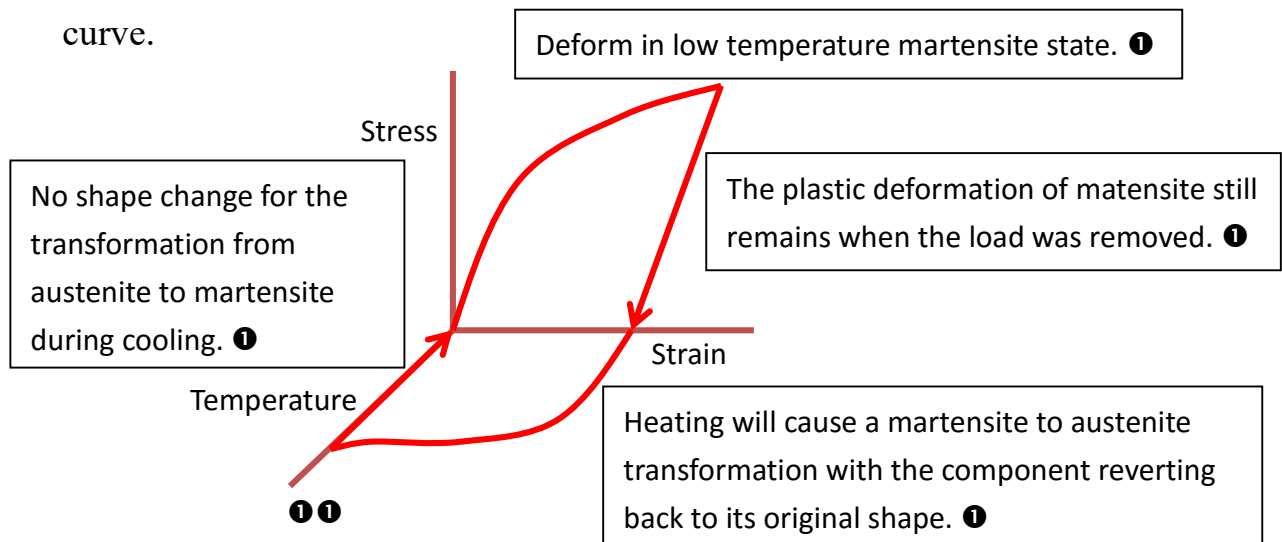
Graphite flakes disperse in pearlite (lamellar cementite in ferrite) matrix.

Lamellar cementite ❶

Ferrite matrix ❶

Graphite flake ❶

❶❶

(j) Sketch the typical microstructure ($\gamma + \gamma' +$ carbides) of a nickel-based superalloy.

γ matrix ❶

Grain boundary carbide ❶

Small γ' precipitate ❶

Large γ' precipitate ❶

❶❶

(k) Explain shape-memory effect of the shape-memory alloys by using a stress-strain curve.

Deform in low temperature martensite state. ❶

Stress

No shape change for the transformation from austenite to martensite during cooling. ❶

The plastic deformation of matensite still remains when the load was removed. ❶

Strain

Temperature

Heating will cause a martensite to austenite transformation with the component reverting back to its original shape. ❶

❶❶

2. Calculate the relative amount of each phase at 184, 182, 60 °C of a Pb-80wt%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 °C: W_β = (80 – 61.9) / (97.8 – 61.9) ; W_L = (97.8 –80) / (97.8 – 61.9) ❶

$\Rightarrow$ W_β = 50.4% ❶; W_L = 49.6% ❶

Microstructure at 184 °C ❶   Microstructure at 182 °C
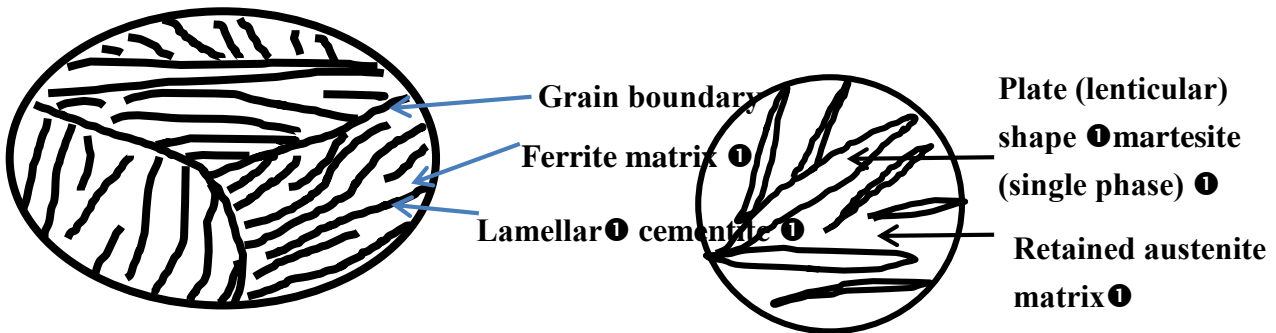
182 °C: W_β = (80 – 18.3) / (97.8 – 18.3) ; W_α = (97.8 – 80) / (97.8 – 18.3) ❶

$\Rightarrow$ W_β = 77.6% ❶; W_α = 22.4% ❶

60 °C: W_β = (80 – 2.5) / (98.9 – 2.5) ; W_L = (98.9 –80) / (98.9 – 2.5) ❶

$\Rightarrow$ W_β = 81.1% ❶; W_L = 18.9% ❶

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

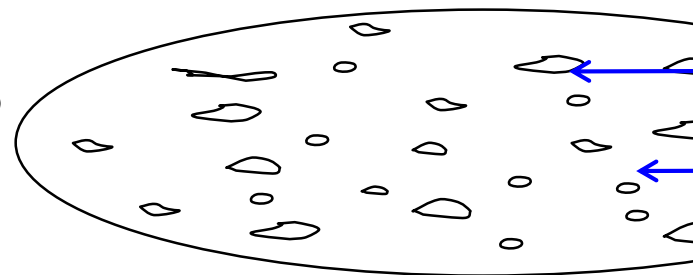
Microstructure of pearlite   Microstructure of martensite
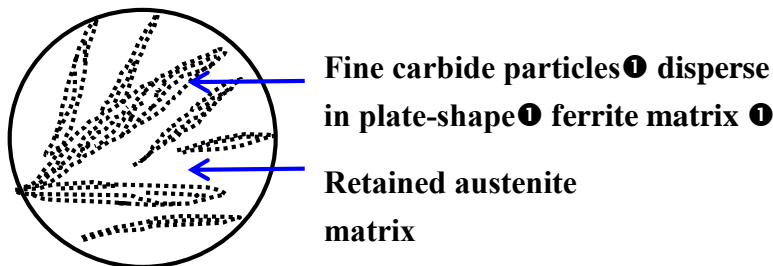
Microstructure of bainite   Microstructure of tempered martensite

4. Two austenite 50 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: $D_{surface}$ = 2 mm ❶ ; D_{center} = 10.5 mm ❶

Oil quenched: $D_{surface}$ = 9 mm ❶ ; D_{center} = 15.5 mm ❶

From Fig. 9.38:

5140 steel (± 0.5 RC):

S_{water} = 53.5 RC ❶

C_{water} = 34 RC ❶

S_{oil} = 39.5 RC ❶

C_{oil} = 30 RC ❶

4340 steel (± 0.5 RC):

S_{water} = 53.5 RC ❶

C_{water} = 52.5 RC ❶

S_{oil} = 53 RC ❶

C_{oil} = 51.5 RC ❶

5. Sketch and explain the hardness versus aging time curve for an Al-4%Cu alloy aged at 130 °C. Describe and explain the effect of aging temperature on the aging curves. (10%)
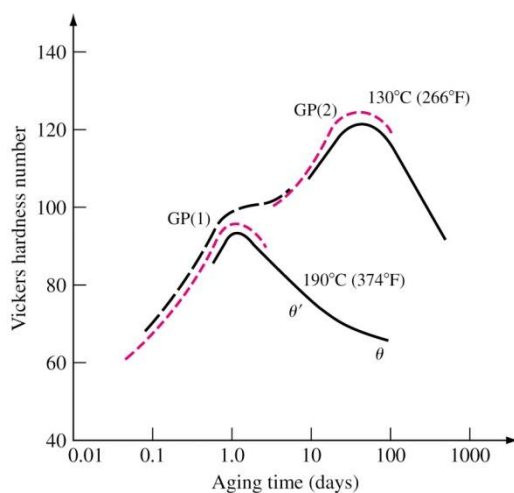
As aging time increases alloy becomes harder and reaches the peakaging ❶with highest hardness. Before peakaging condition, it is called underaging. After peakaging condition, ❶it becomes softer and is called overaging. The ability of precipitates to resist dislocation moving is not enough for underaging condition❶. The number of precipitates to resist dislocation moving is not enough for overaging condition❶. These phenomena result in the hardness of Al-4%Cu alloy for underaging or overaging condition is lower than that of peakaging condition❶.

As aging temperature increases the time to reach peakaging is shorter ❶and the peakaging hardness is lower ❶than that of lower aging temperature. These phenomena result from the fast diffusion ❶and coarse precipitates ❶for higher aging temperature.

6. What makes austenitic stainless steels that are cooled slowly through the 870 °C to 600 °C range become susceptible to intergranular corrosion? How can the intergranular susceptibility of slow-cooled austenite stainless steels be prevented? (10%)

If the cooling rate is slow through the 870 °C to 600 °C range, chromium carbides ❶form and precipitate at the grain boundary❶. As a result, the protective effect❶ of chromium at the grain boundary will be diminished ❶ (since chromium is locked in the carbides❶) and will be susceptible to corrosion.

This can be prevented by lowering the carbon content❶ in the alloy to less than 0.03 wt% ❶or by adding alloying elements that form carbides more readily❶ than chromium❶ (for instance, Nb or Ti❶).
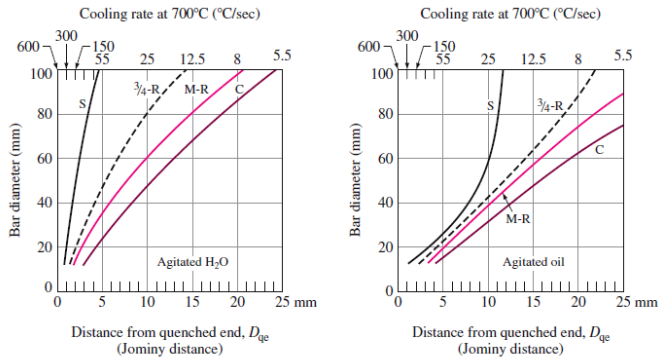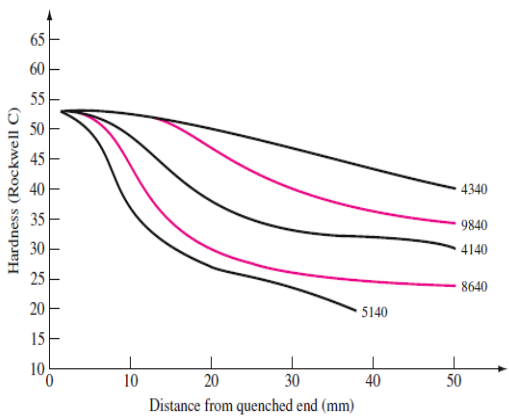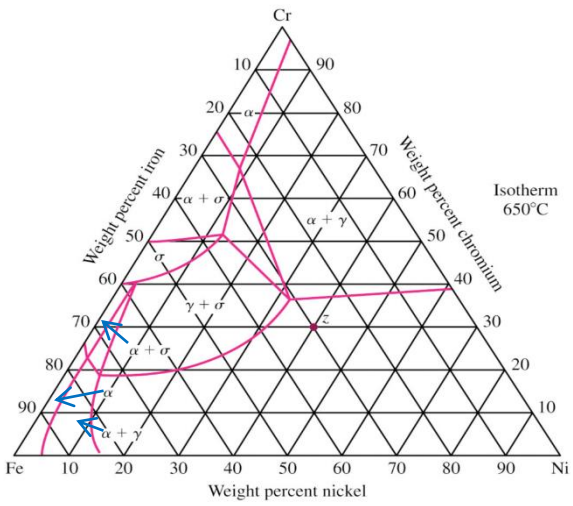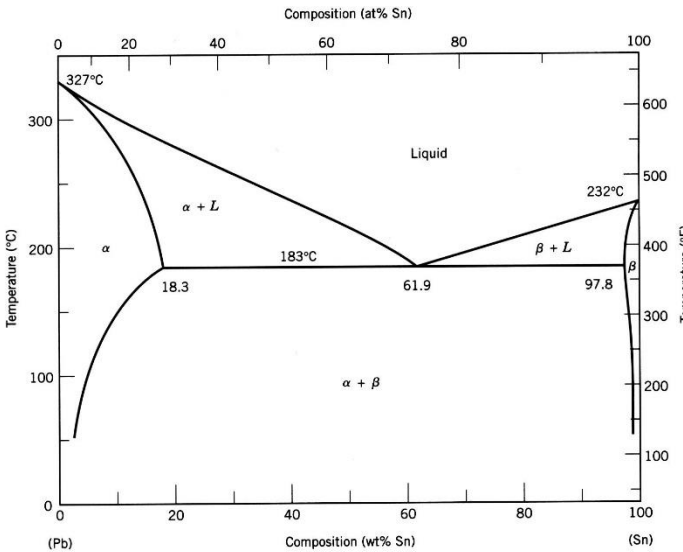

Figure 9.38
Comparative hardenability curves for 0.40 percent C alloy steel.
[*From H.E. McGannon (ed.), "The Making, Shaping, and Treating of Steel," 9th ed., United States Steel Corp., 1971, p. 1139. Courtesy of United States Steel Corporation.*]

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 ¾-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.*)