

## CHAPTER 11

## APPLICATIONS AND PROCESSING OF METAL ALLOYS

## PROBLEM SOLUTIONS

**Ferrous Alloys**

11.1 This question asks that we list four classifications of steels, and, for each, to describe properties and cite typical applications.

Low Carbon Steels

Properties: nonresponsive to heat treatments; relatively soft and weak; machinable and weldable.

Typical applications: automobile bodies, structural shapes, pipelines, buildings, bridges, and tin cans.

Medium Carbon Steels

Properties: heat treatable, relatively large combinations of mechanical characteristics.

Typical applications: railway wheels and tracks, gears, crankshafts, and machine parts.

High Carbon Steels

Properties: hard, strong, and relatively brittle.

Typical applications: chisels, hammers, knives, and hacksaw blades.

High Alloy Steels (Stainless and Tool)

Properties: hard and wear resistant; resistant to corrosion in a large variety of environments.

Typical applications: cutting tools, drills, cutlery, food processing, and surgical tools.

11.2 (a) Ferrous alloys are used extensively because:

- (1) Iron ores exist in abundant quantities.
- (2) Economical extraction, refining, and fabrication techniques are available.
- (3) The alloys may be tailored to have a wide range of properties.

(b) Disadvantages of ferrous alloys are:

- (1) They are susceptible to corrosion.
- (2) They have a relatively high density.
- (3) They have relatively low electrical conductivities.

11.3 The alloying elements in tool steels (e.g., Cr, V, W, and Mo) combine with the carbon to form very hard and wear-resistant carbide compounds.

11.4 We are asked to compute the volume percent graphite in a 2.5 wt% C cast iron. It first becomes necessary to compute mass fractions using the lever rule. From the iron-carbon phase diagram (Figure 11.2), the tie-line in the  $\alpha$  and graphite phase field extends from essentially 0 wt% C to 100 wt% C. Thus, for a 2.5 wt% C cast iron

$$W_{\alpha} = \frac{C_{\text{Gr}} - C_0}{C_{\text{Gr}} - C_{\alpha}} = \frac{100 - 2.5}{100 - 0} = 0.975$$

$$W_{\text{Gr}} = \frac{C_0 - C_{\alpha}}{C_{\text{Gr}} - C_{\alpha}} = \frac{2.5 - 0}{100 - 0} = 0.025$$

Conversion from weight fraction to volume fraction of graphite is possible using Equation 9.6a as

$$\begin{aligned} V_{\text{Gr}} &= \frac{\frac{W_{\text{Gr}}}{\rho_{\text{Gr}}}}{\frac{W_{\alpha}}{\rho_{\alpha}} + \frac{W_{\text{Gr}}}{\rho_{\text{Gr}}}} \\ &= \frac{\frac{0.025}{2.3 \text{ g/cm}^3}}{\frac{0.975}{7.9 \text{ g/cm}^3} + \frac{0.025}{2.3 \text{ g/cm}^3}} \\ &= 0.081 \text{ or } 8.1 \text{ vol\%} \end{aligned}$$

11.5 Gray iron is weak and brittle in tension because the tips of the graphite flakes act as points of stress concentration.

11.6 This question asks us to compare various aspects of gray and malleable cast irons.

(a) With respect to composition and heat treatment:

*Gray iron*--2.5 to 4.0 wt% C and 1.0 to 3.0 wt% Si. For most gray irons there is no heat treatment after solidification.

*Malleable iron*--2.5 to 4.0 wt% C and less than 1.0 wt% Si. White iron is heated in a nonoxidizing atmosphere and at a temperature between 800 and 900°C for an extended time period.

(b) With respect to microstructure:

*Gray iron*--Graphite flakes are embedded in a ferrite or pearlite matrix.

*Malleable iron*--Graphite clusters are embedded in a ferrite or pearlite matrix.

(c) With respect to mechanical characteristics:

*Gray iron*--Relatively weak and brittle in tension; good capacity for damping vibrations.

*Malleable iron*--Moderate strength and ductility.

11.7 This question asks us to compare white and nodular cast irons.

(a) With regard to composition and heat treatment:

*White iron*--2.5 to 4.0 wt% C and less than 1.0 wt% Si. No heat treatment; however, cooling is rapid during solidification.

*Nodular cast iron*--2.5 to 4.0 wt% C, 1.0 to 3.0 wt% Si, and a small amount of Mg or Ce. A heat treatment at about 700°C may be necessary to produce a ferritic matrix.

(b) With regard to microstructure:

*White iron*--There are regions of cementite interspersed within pearlite.

*Nodular cast iron*--Nodules of graphite are embedded in a ferrite or pearlite matrix.

(c) With respect to mechanical characteristics:

*White iron*--Extremely hard and brittle.

*Nodular cast iron*--Moderate strength and ductility.

11.8 It is *not possible* to produce malleable iron in pieces having large cross-sectional dimensions. White cast iron is the precursor of malleable iron, and a rapid cooling rate is necessary for the formation of white iron, which may not be accomplished at interior regions of thick cross-sections.

## Nonferrous Alloys

11.9 The principal difference between wrought and cast alloys is as follows: wrought alloys are ductile enough so as to be hot or cold worked during fabrication, whereas cast alloys are brittle to the degree that shaping by deformation is not possible and they must be fabricated by casting.

11.10 Rivets of a 2017 aluminum alloy must be refrigerated before they are used because, after being solution heat treated, they precipitation harden at room temperature. Once precipitation hardened, they are too strong and brittle to be driven.

11.11 The chief difference between heat-treatable and nonheat-treatable alloys is that heat-treatable alloys may be strengthened by a heat treatment wherein a precipitate phase is formed (precipitation hardening) or a martensitic transformation occurs. Nonheat-treatable alloys are not amenable to strengthening by such treatments.

11.12 This question asks us for the distinctive features, limitations, and applications of several alloy groups.

#### Titanium Alloys

Distinctive features: relatively low density, high melting temperatures, and high strengths are possible.

Limitation: because of chemical reactivity with other materials at elevated temperatures, these alloys are expensive to refine.

Applications: aircraft structures, space vehicles, and in chemical and petroleum industries.

#### Refractory Metals

Distinctive features: extremely high melting temperatures; large elastic moduli, hardnesses, and strengths.

Limitation: some experience rapid oxidation at elevated temperatures.

Applications: extrusion dies, structural parts in space vehicles, incandescent light filaments, x-ray tubes, and welding electrodes.

#### Superalloys

Distinctive features: able to withstand high temperatures and oxidizing atmospheres for long time periods.

Applications: aircraft turbines, nuclear reactors, and petrochemical equipment.

#### Noble Metals

Distinctive features: highly resistant to oxidation, especially at elevated temperatures; soft and ductile.

Limitation: expensive.

Applications: jewelry, dental restoration materials, coins, catalysts, and thermocouples.

## Forming Operations

11.13 The advantages of cold working are:

- (1) A high quality surface finish.
- (2) The mechanical properties may be varied.
- (3) Close dimensional tolerances.

The disadvantages of cold working are:

- (1) High deformation energy requirements.
- (2) Large deformations must be accomplished in steps, which may be expensive.
- (3) A loss of ductility.

The advantages of hot working are:

- (1) Large deformations are possible, which may be repeated.
- (2) Deformation energy requirements are relatively low.

The disadvantages of hot working are:

- (1) A poor surface finish.
- (2) A variety of mechanical properties is not possible.

11.14 (a) The advantages of extrusion as opposed to rolling are as follows:

- (1) Pieces having more complicated cross-sectional geometries may be formed.
- (2) Seamless tubing may be produced.

(b) The disadvantages of extrusion over rolling are as follows:

- (1) Nonuniform deformation over the cross-section.
- (2) A variation in properties may result over a cross-section of an extruded piece.

## **Casting**

11.15 Four situations in which casting is the preferred fabrication technique are:

- (1) For large pieces and/or complicated shapes.
- (2) When mechanical strength is not an important consideration.
- (3) For alloys having low ductilities.
- (4) When it is the most economical fabrication technique.

11.16 This question asks us to compare sand, die, investment, lost foam, and continuous casting techniques.

For *sand casting*, sand is the mold material, a two-piece mold is used, ordinarily the surface finish is not an important consideration, the sand may be reused (but the mold may not), casting rates are low, and large pieces are usually cast.

For *die casting*, a permanent mold is used, casting rates are high, the molten metal is forced into the mold under pressure, a two-piece mold is used, and small pieces are normally cast.

For *investment casting*, a single-piece mold is used, which is not reusable; it results in high dimensional accuracy, good reproduction of detail, and a fine surface finish; and casting rates are low.

For *lost foam casting*, the pattern is polystyrene foam, whereas the mold material is sand. Complex geometries and tight tolerances are possible. Casting rates are higher than for investment, and there are few environmental wastes.

For *continuous casting*, at the conclusion of the extraction process, the molten metal is cast into a continuous strand having either a rectangular or circular cross-section; these shapes are desirable for subsequent secondary metal-forming operations. The chemical composition and mechanical properties are relatively uniform throughout the cross-section.

### Miscellaneous Techniques

11.17 This problem asks that we specify and compare the microstructures and mechanical properties in the heat-affected weld zones for 1080 and 4340 alloys assuming that the average cooling rate is  $10^{\circ}\text{C}/\text{s}$ . Figure 10.27 shows the continuous cooling transformation diagram for an iron-carbon alloy of eutectoid composition (1080), and, in addition, cooling curves that delineate changes in microstructure. For a cooling rate of  $10^{\circ}\text{C}/\text{s}$  (which is less than  $35^{\circ}\text{C}/\text{s}$ ) the resulting microstructure will be totally pearlite--probably a reasonably fine pearlite. On the other hand, in Figure 10.28 is shown the CCT diagram for a 4340 steel. From this diagram it may be noted that a cooling rate of  $10^{\circ}\text{C}/\text{s}$  produces a totally martensitic structure. Pearlite is softer and more ductile than martensite, and, therefore, is most likely more desirable.

11.18 If a steel weld is cooled very rapidly, martensite may form, which is very brittle. In some situations, cracks may form in the weld region as it cools.

## Annealing Processes

11.19 Full annealing--Heat to about 50°C above the  $A_3$  line, Figure 11.10 (if the concentration of carbon is less than the eutectoid) or above the  $A_1$  line (if the concentration of carbon is greater than the eutectoid) until the alloy comes to equilibrium; then furnace cool to room temperature. The final microstructure is coarse pearlite.

Normalizing--Heat to at least 55°C above the  $A_3$  line Figure 11.10 (if the concentration of carbon is less than the eutectoid) or above the  $A_{cm}$  line (if the concentration of carbon is greater than the eutectoid) until the alloy completely transforms to austenite, then cool in air. The final microstructure is fine pearlite.

Quenching--Heat to a temperature within the austenite phase region and allow the specimen to fully austenitize, then quench to room temperature in oil or water. The final microstructure is martensite.

Tempering--Heat a quenched (martensitic) specimen, to a temperature between 450 and 650°C, for the time necessary to achieve the desired hardness. The final microstructure is tempered martensite.

11.20 Three sources of residual stresses in metal components are plastic deformation processes, nonuniform cooling of a piece that was cooled from an elevated temperature, and a phase transformation in which parent and product phases have different densities.

Two adverse consequences of these stresses are distortion (or warpage) and fracture.

11.21 This question asks that we cite the approximate minimum temperature at which it is desirable to austenitize several iron-carbon alloys during a normalizing heat treatment.

- (a) For 0.15 wt% C, heat to at least 915°C (1680°F) since the  $A_3$  temperature is 860°C (1580°F).
- (b) For 0.50 wt% C, heat to at least 825°C (1520°F) since the  $A_3$  temperature is 770°C (1420°F).
- (c) For 1.10 wt% C, heat to at least 900°C (1655°F) since the  $A_{cm}$  temperature is 845°C (1555°F).

11.22 We are asked for the approximate temperature at which several iron-carbon alloys should be austenitized during a full-anneal heat treatment.

- (a) For 0.20 wt% C, heat to about 890°C (1635°F) since the  $A_3$  temperature is 840°C (1545°F).
- (b) For 0.60 wt% C, heat to about 800°C (1470°F) since the  $A_3$  temperature is 750°C (1380°F).
- (c) For 0.76 wt% C, heat to about 777°C (1430°F) since the  $A_1$  temperature is 727°C (1340°F).
- (d) For 0.95 wt% C, heat to about 777°C (1430°F) since the  $A_1$  temperature is 727°C (1340°F).

11.23 The purpose of a spheroidizing heat treatment is to produce a very soft and ductile steel alloy having a spheroiditic microstructure. It is normally used on medium- and high-carbon steels, which, by virtue of carbon content, are relatively hard and strong.

## Heat Treatment of Steels

11.24 Hardness is a measure of a material's resistance to localized surface deformation, whereas hardenability is a measure of the depth to which a ferrous alloy may be hardened by the formation of martensite. Hardenability is determined from hardness tests.

11.25 The presence of alloying elements (other than carbon) causes a much more gradual decrease in hardness with position from the quenched end for a hardenability curve. The reason for this effect is that alloying elements retard the formation of pearlitic and bainitic structures which are not as hard as martensite.

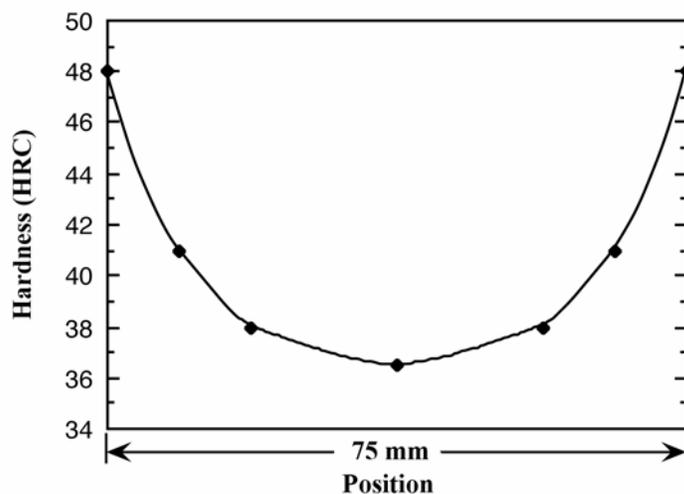
11.26 A decrease of austenite grain size will decrease the hardenability. Pearlite normally nucleates at grain boundaries, and the smaller the grain size, the greater the grain boundary area, and, consequently, the easier it is for pearlite to form.

11.27 The two thermal properties of a liquid medium that influence its quenching effectiveness are thermal conductivity and heat capacity.

11.28 (a) This part of the problem calls for us to construct a radial hardness profile for a 75 mm (3 in.) diameter cylindrical specimen of an 8640 steel that has been quenched in moderately agitated oil. In the manner of Example Problem 11.1, the equivalent distances and hardnesses tabulated below were determined from Figures 11.14 and 11.17(b).

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	13	48
3/4 R	18	41
Midradius	22	38
Center	26	36

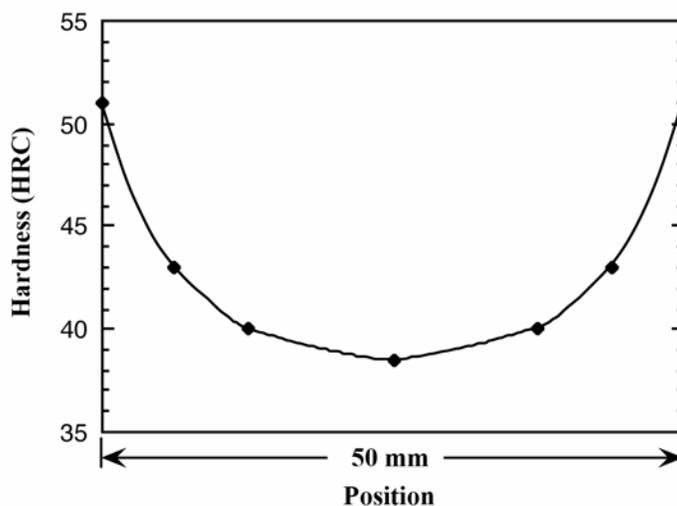
The resulting hardness profile is plotted below.



(b) The radial hardness profile for a 50 mm (2 in.) diameter specimen of a 5140 steel that has been quenched in moderately agitated oil is desired. The equivalent distances and hardnesses tabulated below were determined using Figures 11.14 and 11.17(b).

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	7	51
3/4 R	12	43
Midradius	14	40
Center	16	38.5

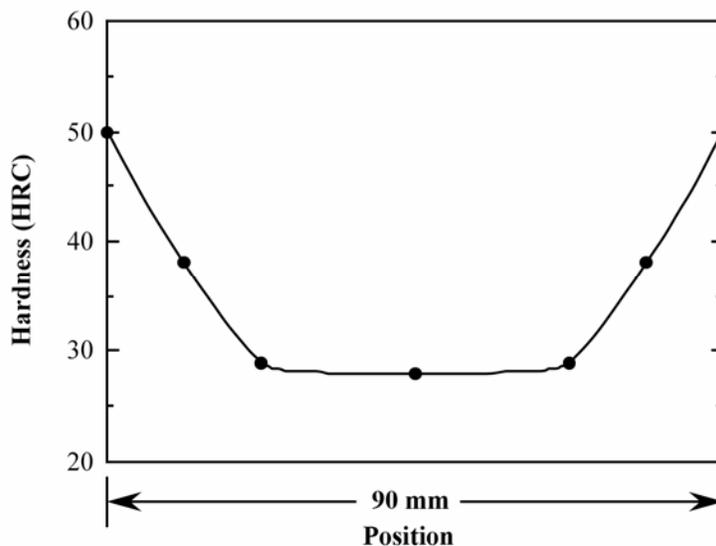
The resulting hardness profile is plotted below.



(c) The radial hardness profile for a 90-mm (3-1/2 in.) diameter specimen of an 8630 steel that has been quenched in moderately agitated water is desired. The equivalent distances and hardnesses for the various radial positions, as determined using Figures 11.15 and 11.17(a) are tabulated below.

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	3	50
3/4 R	10	38
Midradius	17	29
Center	22	27

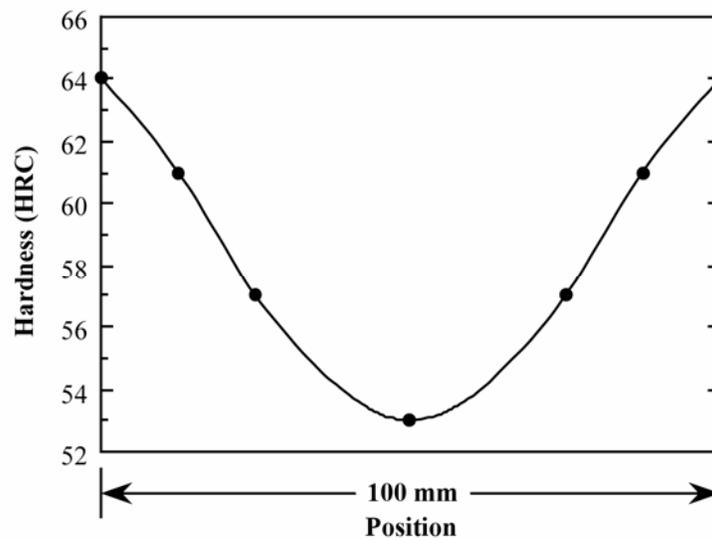
The resulting hardness profile is plotted here.



(d) The radial hardness profile for a 100-mm (4-in.) diameter specimen of a 8660 steel that has been quenched in moderately agitated water is desired. The equivalent distances and hardnesses for the various radial positions, as determined using Figures 11.15 and 11.17(a), are tabulated below.

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	3	64
3/4 R	11	61
Midradius	20	57
Center	26	53

The resulting hardness profile is plotted here.



11.29 We are asked to compare the effectiveness of quenching in moderately agitated water and oil by graphing, on a single plot, the hardness profiles for 75-mm (3-in.) diameter cylindrical specimens of an 8640 steel that had been quenched in both media.

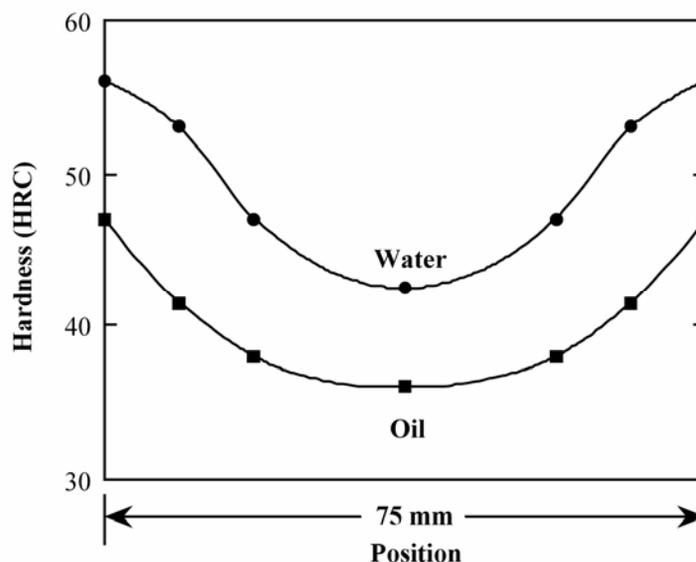
For moderately agitated water, the equivalent distances and hardnesses for the several radial positions [Figures 11.17(a) and 11.15] are tabulated below.

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	3	56
3/4 R	8	53
Midradius	13	47
Center	17	42.5

While for moderately agitated oil, the equivalent distances and hardnesses for the several radial positions [Figures 11.17(b) and 11.15] are tabulated below.

<u>Radial Position</u>	<u>Equivalent Distance, mm</u>	<u>HRC Hardness</u>
Surface	13	47
3/4 R	19	41.5
Midradius	22	38
Center	25	36

These data are plotted here.



## Precipitation Hardening

11.30 This problem asks us to compare various aspects of precipitation hardening, and the quenching and tempering of steel.

(a) With regard to the total heat treatment procedure, the steps for the *hardening of steel* are as follows:

- (1) Austenitize above the upper critical temperature.
- (2) Quench to a relatively low temperature.
- (3) Temper at a temperature below the eutectoid.
- (4) Cool to room temperature.

With regard to *precipitation hardening*, the steps are as follows:

- (1) Solution heat treat by heating into the solid solution phase region.
- (2) Quench to a relatively low temperature.
- (3) Precipitation harden by heating to a temperature that is within the solid two-phase region.
- (4) Cool to room temperature.

(b) For the *hardening of steel*, the microstructures that form at the various heat treating stages in part (a) are:

- (1) Austenite
- (2) Martensite
- (3) Tempered martensite
- (4) Tempered martensite

For *precipitation hardening*, the microstructures that form at the various heat treating stages in part (a) are:

- (1) Single phase
- (2) Single phase--supersaturated
- (3) Small plate-like particles of a new phase within a matrix of the original phase.
- (4) Same as (3)

(c) For the *hardening of steel*, the mechanical characteristics for the various steps in part (a) are as follows:

- (1) Not important
- (2) The steel becomes hard and brittle upon quenching.
- (3) During tempering, the alloy softens slightly and becomes more ductile.
- (4) No significant changes upon cooling to or maintaining at room temperature.

For *precipitation hardening*, the mechanical characteristics for the various steps in part (a) are as follows:

- (1) Not important
- (2) The alloy is relatively soft.
- (3) The alloy hardens with increasing time (initially), and becomes more brittle; it may soften

with overaging.

- (4) The alloy may continue to harden or overage at room temperature.

11.31 For precipitation hardening, natural aging is allowing the precipitation process to occur at the ambient temperature; artificial aging is carried out at an elevated temperature.

## DESIGN PROBLEMS

### **Ferrous Alloys**

### **Nonferrous Alloys**

11.D1 This problem calls for us to select, from a list of alloys, the best alloy for each of several applications and then to justify each choice.

(a) Gray cast iron would be the best choice for an engine block because it is relatively easy to cast, is wear resistant, has good vibration damping characteristics, and is relatively inexpensive.

(b) Stainless steel would be the best choice for a heat exchanger to condense steam because it is corrosion resistant to the steam and condensate.

(c) Titanium alloys are the best choice for high-speed aircraft jet engine turbofan blades because they are light weight, strong, and easily fabricated very resistant to corrosion. However, one drawback is their cost.

(d) A tool steel would be the best choice for a drill bit because it is very hard retains its hardness at high temperature and is wear resistant, and, thus, will retain a sharp cutting edge.

(e) For a cryogenic (low-temperature) container, an aluminum alloy would be the best choice; aluminum alloys have an FCC crystal structure, and therefore, are ductile at very low temperatures.

(f) As a pyrotechnic in flares and fireworks, magnesium is the best choice because it ignites easily and burns readily in air with a very bright flame.

(g) Platinum is the best choice for high-temperature furnace elements to be used in oxidizing atmospheres because it is very ductile, has a relatively very high melting temperature, and is highly resistant to oxidation.

11.D2 (a) Compositionally, the metallic glass materials are rather complex; several compositions are as follows:  $\text{Fe}_{80}\text{B}_{20}$ ,  $\text{Fe}_{72}\text{Cr}_8\text{P}_{13}\text{C}_7$ ,  $\text{Fe}_{67}\text{Co}_{18}\text{B}_{14}\text{Si}$ ,  $\text{Pd}_{77.5}\text{Cu}_{6.0}\text{Si}_{16.5}$ , and  $\text{Fe}_{40}\text{Ni}_{38}\text{Mo}_4\text{B}_{18}$ .

(b) These materials are exceptionally strong and tough, extremely corrosion resistant, and are easily magnetized.

(c) Principal drawbacks for these materials are 1) complicated and exotic fabrication techniques are required; and 2) inasmuch as very rapid cooling rates are required, at least one dimension of the material must be small--i.e., they are normally produced in ribbon form.

(d) Potential uses include transformer cores, magnetic amplifiers, heads for magnetic tape players, reinforcements for pressure vessels and tires, shields for electromagnetic interference, security tapes for library books.

(e) Production techniques include centrifuge melt spinning, planar-flow casting, rapid pressure application, arc melt spinning.

11.D3 This question provides us with a list of several metal alloys, and then asks us to pick those that may be strengthened by heat treatment, by cold work, or both. Those alloys that may be heat treated are either those noted as "heat treatable" (Tables 11.6 through 11.9), or as martensitic stainless steels (Table 11.4). Alloys that may be strengthened by cold working must not be exceptionally brittle (which may be the case for cast irons, Table 11.5), and, furthermore, must have recrystallization temperatures above room temperature (which immediately eliminates zinc). The alloys that fall within the three classifications are as follows:

<u>Heat Treatable</u>	<u>Cold Workable</u>	<u>Both</u>
410 stainless steel	410 stainless steel	410 stainless steel
4340 steel	4340 steel	4340 steel
ZK60A magnesium	ZK60A magnesium	ZK60A magnesium
356.0 aluminum	C26000 cartridge brass	
	R56400 Ti	
	1100 aluminum	

11.D4 This problem asks us to rank four alloys (brass, steel, titanium, and aluminum), from least to greatest weight for a structural member to support a 44,400 N (10,000 lb<sub>f</sub>) load without experiencing plastic deformation. From Equation 6.1, the cross-sectional area ( $A_0$ ) must necessarily carry the load ( $F$ ) without exceeding the yield strength ( $\sigma_y$ ), as

$$A_0 = \frac{F}{\sigma_y}$$

Now, given the length  $l$ , the volume of material required ( $V$ ) is just

$$V = lA_0 = \frac{lF}{\sigma_y}$$

Finally, the mass of the member ( $m$ ) is

$$m = V\rho = \frac{\rho lF}{\sigma_y}$$

Here  $\rho$  is the density. Using the values given for these alloys

$$m(\text{brass}) = \frac{(8.5 \text{ g/cm}^3)(25 \text{ cm})(44,400 \text{ N})}{(345 \times 10^6 \text{ N/m}^2)\left(\frac{1 \text{ m}}{10^2 \text{ cm}}\right)^2} = 273 \text{ g}$$

$$m(\text{steel}) = \frac{(7.9 \text{ g/cm}^3)(25 \text{ cm})(44,400 \text{ N})}{(690 \times 10^6 \text{ N/m}^2)\left(\frac{1 \text{ m}}{10^2 \text{ cm}}\right)^2} = 127 \text{ g}$$

$$m(\text{aluminum}) = \frac{(2.7 \text{ g/cm}^3)(25 \text{ cm})(44,400 \text{ N})}{(275 \times 10^6 \text{ N/m}^2)\left(\frac{1 \text{ m}}{10^2 \text{ cm}}\right)^2} = 109 \text{ g}$$

$$m(\text{titanium}) = \frac{(4.5 \text{ g/cm}^3)(25 \text{ cm})(44,400 \text{ N})}{(480 \times 10^6 \text{ N/m}^2)\left(\frac{1 \text{ m}}{10^2 \text{ cm}}\right)^2} = 104 \text{ g}$$

Thus, titanium would have the minimum weight (or mass), followed by aluminum, steel, and brass.



11.D5 This question asks for us to decide whether or not it would be advisable to hot-work or cold-work several metals and alloys.

Platinum is one of the noble metals. Even though it has a high melting temperature and good resistance to oxidation, at room temperature it is relatively soft and ductile, and is amenable to cold working.

Molybdenum, one of the refractory metals, is hard and strong at room temperature, has a high recrystallization temperature, and experiences oxidation at elevated temperatures. Cold-working is difficult because of its strength, and hot-working is not practical because of oxidation problems. Most molybdenum articles are fabricated by powder metallurgy, or by using cold-working followed by annealing cycles.

Lead would almost always be hot-worked. Even deformation at room temperature would be considered hot-working inasmuch as its recrystallization temperature is below room temperature (Table 7.2).

304 stainless steel is relatively resistant to oxidation. However, it is very ductile and has a moderate yield strength (Table 11.4), therefore, it may be cold-worked, but hot-working is also a possibility.

Copper is relatively soft and very ductile and ductile at room temperature (see, for example, C11000 copper in Table 11.6); therefore, it may be cold-worked.

## Heat Treatment of Steels

11.D6 A 38-mm (1-1/2 in.) diameter steel specimen is to be quenched in moderately agitated oil. We are to decide which of five different steels will have surface and center hardnesses of at least 50 and 40 HRC, respectively.

In moderately agitated oil, the equivalent distances from the quenched end for a 38 mm diameter bar for surface and center positions are 5 mm (3/16 in.) and 12 mm (15/32 in.), respectively [Figure 11.17(b)]. The hardnesses at these two positions for the alloys cited (as determined using Figure 11.14) are given below.

<u>Alloy</u>	<u>Surface Hardness (HRC)</u>	<u>Center Hardness (HRC)</u>
1040	40	24
5140	53	42
4340	57	55
4140	56	53
8640	55	48

Thus, alloys 4340, 4140, 8640, and 5140 will satisfy the criteria for both surface and center hardnesses.

11.D7 (a) This problem calls for us to decide which of 8660, 8640, 8630, and 8620 alloys may be fabricated into a cylindrical piece 57 mm (2-1/4 in.) in diameter which, when quenched in mildly agitated water, will produce a minimum hardness of 45 HRC throughout the entire piece.

The center of the steel cylinder will cool the slowest and therefore will be the softest. In moderately agitated water the equivalent distance from the quenched end for a 57 mm diameter bar for the center position is about 11 mm (7/16 in.) [Figure 11.17(a)]. The hardnesses at this position for the alloys cited (Figure 11.15) are given below.

<u>Alloy</u>	<u>Center Hardness (HRC)</u>
8660	61
8640	49
8630	36
8620	25

Therefore, only 8660 and 8640 alloys will have a minimum of 45 HRC at the center, and therefore, throughout the entire cylinder.

(b) This part of the problem asks us to do the same thing for moderately agitated oil. In moderately agitated oil the equivalent distance from the quenched end for a 57 mm diameter bar at the center position is about 17.5 mm (11.16 in.) [Figure 11.17(b)]. The hardnesses at this position for the alloys cited (Figure 11.15) are given below.

<u>Alloy</u>	<u>Center Hardness (HRC)</u>
8660	59
8640	42
8630	30
8620	21

Therefore, only the 8660 alloy will have a minimum of 45 HRC at the center, and therefore, throughout the entire cylinder.

11.D8 A forty-four millimeter (one and three-quarter inch) diameter cylindrical steel specimen is to be heat treated such that the microstructure throughout will be at least 50% martensite. We are to decide which of several alloys will satisfy this criterion if the quenching medium is moderately agitated (a) oil, and (b) water.

(a) Since the cooling rate is lowest at the center, we want a minimum of 50% martensite at the center position. From Figure 11.17(b), the cooling rate is equal to an equivalent distance from the quenched end of 13 mm (9/16 in.). According to Figure 11.14, the hardness corresponding to 50% martensite for these alloys is 42 HRC. Thus, all we need do is to determine which of the alloys have a 42 HRC hardness at an equivalent distance from the quenched end of 13 mm (9/16 in.). At an equivalent distance of 13 mm, the following hardnesses are determined from Figure 11.14 for the various alloys.

<u>Alloy</u>	<u>Hardness (HRC)</u>
4340	55
4140	52
8640	47
5140	41
1040	23

Thus, only alloys 4340, 4140 and 8640 will qualify.

(b) For moderately agitated water, the cooling rate at the center of a 44 mm (1-3/4 in.) diameter specimen is 9 mm (11/32 in.) equivalent distance from the quenched end [Figure 11.17(a)]. At this position, the following hardnesses are determined from Figure 11.14 for the several alloys.

<u>Alloy</u>	<u>Hardness (HRC)</u>
4340	57
4140	55
8640	53
5140	48
1040	30

It is still necessary to have a hardness of 42 HRC or greater at the center; thus, alloys 4340, 4140, 8640, and 5140 qualify.

11.D9 A fifty-millimeter (two-inch) diameter cylindrical steel specimen is to be quenched in moderately agitated water. We are to decide which of eight different steels will have surface and center hardnesses of at least 50 and 40 HRC, respectively.

In moderately agitated water, the equivalent distances from the quenched end for a 50-mm diameter bar for surface and center positions are 2 mm (1/16 in.) and 10 mm (3/8 in.), respectively [Figure 11.17(a)]. The hardnesses at these two positions for the alloys cited are given below (as determined from Figures 11.14 and 11.15).

<u>Alloy</u>	<u>Surface Hardness (HRC)</u>	<u>Center Hardness (HRC)</u>
1040	50	27
5140	56	45
4340	57	56
4140	57	54
8620	42	27
8630	51	38
8640	57	51
8660	64	64

Thus, alloys 5140, 4340, 4140, 8640, and 8660 will satisfy the criteria for both surface hardness (minimum 50 HRC) and center hardness (minimum 40 HRC).

11.D10 We are asked to determine the maximum diameter possible for a cylindrical piece of 4140 steel that is to be quenched in moderately agitated oil such that the microstructure will consist of at least 80% martensite throughout the entire piece. From Figure 11.14, the equivalent distance from the quenched end of a 4140 steel to give 80% martensite (or a 50 HRC hardness) is 16 mm (5/8 in.). Thus, the quenching rate at the center of the specimen should correspond to this equivalent distance. Using Figure 11.17(b), the center specimen curve takes on a value of 16 mm (5/8 in.) equivalent distance at a diameter of about 50 mm (2 in.).

11.D11 We are to determine, for a cylindrical piece of 8660 steel, the maximum allowable diameter possible in order yield a surface hardness of 58 HRC, when the quenching is carried out in moderately agitated oil.

From Figure 11.15, the equivalent distance from the quenched end of an 8660 steel to give a hardness of 58 HRC is about 18 mm (3/4 in.). Thus, the quenching rate at the surface of the specimen should correspond to this equivalent distance. Using Figure 11.17(b), the surface specimen curve takes on a value of 18 mm equivalent distance at a diameter of about 95 mm (3.75 in.).

11.D12 This problem asks if it is possible to temper an oil-quenched 4140 steel cylindrical shaft 25 mm (1 in.) in diameter so as to give a minimum yield strength of 950 MPa (140,000 psi) and a minimum ductility of 17%EL. In order to solve this problem it is necessary to use Figures 11.20(b) and 11.20(c), which plot, respectively, yield strength and ductility versus tempering temperature. For the 25 mm diameter line of Figure 11.20(b), tempering temperatures less than about 575°C are required to give a yield strength of at least 950 MPa. Furthermore, from Figure 11.20(c), for the 25 mm diameter line, tempering temperatures greater than about 550°C will give ductilities greater than 17%EL. Hence, it *is possible* to temper this alloy to produce the stipulated minimum yield strength and ductility; the tempering temperature will lie between 550°C and 575°C.

11.D13 This problem asks if it is possible to temper an oil-quenched 4140 steel cylindrical shaft 50 mm (2 in.) in diameter so as to give a minimum tensile strength of 900 MPa (130,000 psi) and a minimum ductility of 20%EL. In order to solve this problem it is necessary to use Figures 11.20(a) and 11.20(c), which plot, respectively, tensile strength and ductility versus tempering temperature. For the 50 mm diameter line of Figure 11.20(a), tempering temperatures less than about 590°C are required to give a tensile strength of at least 900 MPa. Furthermore, from Figure 11.20(c), for the 50 mm diameter line, tempering temperatures greater than about 600°C will give ductilities greater than 20%EL. Hence, it *is not possible* to temper this alloy to produce the stipulated minimum tensile strength and ductility. To meet the tensile strength minimum,  $T(\text{tempering}) < 590^\circ\text{C}$ , whereas for ductility minimum,  $T(\text{tempering}) > 600^\circ\text{C}$ ; thus, there is no overlap of these tempering temperature ranges.

## Precipitation Hardening

11.D14 This problem is concerned with the precipitation-hardening of copper-rich Cu-Be alloys. It is necessary for us to use the Cu-Be phase diagram (Figure 11.28).

(a) The range of compositions over which these alloys may be precipitation hardened is between approximately 0.2 wt% Be (the maximum solubility of Be in Cu at about 300°C) and 2.7 wt% Be (the maximum solubility of Be in Cu at 866°C).

(b) The heat treatment procedure, of course, will depend on the composition chosen. First of all, the solution heat treatment must be carried out at a temperature within the  $\alpha$  phase region, after which, the specimen is quenched to room temperature. Finally, the precipitation heat treatment is conducted at a temperature within the  $\alpha + \gamma_2$  phase region.

For example, for a 1.5 wt% Be-98.5 wt% Cu alloy, the solution heat treating temperature must be between about 600°C (1110°F) and 900°C (1650°F), while the precipitation heat treatment would be below 600°C (1110°F), and probably above 300°C (570°F). Below 300°C, diffusion rates are low, and heat treatment times would be relatively long.

11.D15 We are asked to specify a practical heat treatment for a 2014 aluminum alloy that will produce a minimum yield strength of 345 MPa (50,000 psi), and a minimum ductility of 12%EL. From Figure 11.27(a), the following heat treating temperatures and time ranges are possible to give the required yield strength.

<u>Temperature (°C)</u>	<u>Time Range (h)</u>
260	not possible
204	0.3-15
149	10-700
121	300-?

With regard to temperatures and times to give the desired ductility [Figure 11.27(b)]:

<u>Temperature (°C)</u>	<u>Time Range (h)</u>
260	<0.02, >10
204	<0.4, >350
149	<20
121	<1000

From these tabulations, the following may be concluded:

It is not possible to heat treat this alloy at 260°C so as to produce the desired set of properties—attainment of a yield strength of 345 MPa is not possible at this temperature.

At 204°C, the heat treating time would need to be about 0.4 h, which is practical.

At 149°C, the time range is between 10 and 20 h, which is a little on the long side.

Finally, at 121°C, the time range is unpractically long (300 to 1000 h).

11.D16 This problem inquires as to the possibility of producing a precipitation-hardened 2014 aluminum alloy having a minimum yield strength of 380 MPa (55,000 psi) and a ductility of at least 15%EL. In order to solve this problem it is necessary to consult Figures 11.27(a) and 11.27(b). Below are tabulated the times required at the various temperatures to achieve the stipulated yield strength.

<u>Temperature (°C)</u>	<u>Time Range (h)</u>
260	not possible
204	0.5-7
149	10-250
121	500-2500

With regard to temperatures and times to give the desired ductility:

<u>Temperature (°C)</u>	<u>Time Range (h)</u>
260	<0.005
204	<0.13
149	<10
121	<500

Therefore, an alloy having this combination of yield strength and ductility is marginally possible. A heat treatment at 149°C for 10 h would probably just achieve the stipulated ductility and yield strength.