Chapter 5

Metal-Casting Processes and Equipment; Heat Treatment

Questions

5.1 Describe the characteristics of (1) an alloy, (2) pearlite, (3) austenite, (4) martensite, and (5) cementite.

(a) Alloy: composed of two or more elements, at least one element is a metal. The alloy may be a solid solution or it may form intermetallic compounds.

(b) Pearlite: a two-phase aggregate consisting of alternating lamellae of ferrite and cementite; the closer the pearlite spacing of lamellae, the harder the steel.

(c) Austenite: also called gamma iron, it has a fcc crystal structure which allows for a greater solubility of carbon in the crystal lattice. This structure also possesses a high ductility, which increases the steel's formability.

(d) Martensite: forms by quenching austenite. It has a bct (body-centered tetragonal) structure, and the carbon atoms in interstitial positions impart high strength. It is hard and very brittle.

(e) Cementite: also known as iron-carbide (Fe_3C), it is a hard and brittle intermetallic phase.

5.2 What are the effects of mold materials on fluid flow and heat transfer?

The most important factor is the thermal conductivity of the mold material; the higher the conductivity, the higher the heat transfer and the greater the tendency for the fluid to solidify, hence possibly impeding the free flow of the molten metal. Also, the higher the cooling rate of the surfaces of the casting in contact with the mold, the smaller the grain size and hence the higher the strength. The type of surfaces developed in the preparation of mold materials may also be different. For example, sand-mold surfaces are likely be rougher than those of metal molds whose surfaces can be prepared to varying degrees of roughness, including the directions of roughness (lay).

5.3 How does the shape of graphite in cast iron affect its properties?

The shape of graphite in cast irons has the following basic forms:

(a) Flakes. Graphite flakes have sharp edges which act as stress raisers in tension. This shape makes cast iron low in tensile strength and ductility, but it still has high compressive strength. On the other hand, the flakes also act as vibration dampers, a characteristic important in damping of machine-tool bases and other structures.

(b) Nodules. Graphite can form nodules or spheroids when magnesium or cerium is added to the melt. This form has increased ductility, strength, and shock resistance compared to flakes, but the damping ability is reduced.

(c) Clusters. Graphite clusters are much like nodules, except that they form from the breakdown of white cast iron upon annealing. Clusters have properties that are basically similar to flakes.

(d) Compacted flakes. These are short and thick flakes with rounded edges. This form has properties that are between nodular and flake graphite.

5.4 Explain the difference between short and long freezing ranges. How are they determined? Why are they important?

Freezing range is defined by Eq. (5.3) on p. 196 in terms of temperature difference. Referring to Fig. 5.6 on p. 197, note that once the phase diagram and the composition is known, we can determine the freezing range, $T_L - T_S$. As described in Section 5.3.2 on p. 196, the freezing range has an important influence on the formation and size of the mushy zone, and, consequently, affects structure-property relationships of the casting.

5.5 We know that pouring molten metal at a high rate into a mold has certain disadvantages. Are there any disadvantages to pouring it very slowly? Explain.

There are disadvantages to pouring metal slowly. Besides the additional time needed for mold filling, the liquid metal may solidify or partially solidify while still in the gating system or before completely filling the mold, resulting in an incomplete or partial casting. This can have extremely detrimental effects in a tree of parts, as in investment casting.

5.6 Why does porosity have detrimental effects on the mechanical properties of castings? Which physical properties are also affected adversely by porosity?

Pores are, in effect, internal discontinuities that are prone to cracking and crack propagation. Thus, the toughness of a material will decrease as a result of porosity. Furthermore, the presence of pores in a piece of metal under tension indicates that the material around the pores has to support a greater load than if no pores were present; thus, the strength is also lowered. Considering thermal and electrical conductivity, an internal defect such as a pore decreases both the thermal and electrical conductivity, nting that air is a very poor conductor.

5.7 A spoked hand wheel is to be cast in gray iron. In order to prevent hot tearing of the spokes, would you insulate the spokes or chill them? Explain.

Referring to Table 5.1 on p. 206, we note that, during solidification, gray iron undergoes an expansion of 2.5%. Although this fact may suggest that hot tearing cannot occur, consideration must also be given to significant contraction of the spokes during cooling. Since the hot-tearing tendency will be reduced as the strength increases, it would thus be advisable to chill the spokes to develop this strength.

5.8 Which of the following considerations are important for a riser to function properly? (1) Have a surface area larger than that of the part being cast. (2) Be kept open to atmospheric pressure. (3) Solidify first. Explain.

Both (1) and (3) would result in a situation contrary to a riser's purpose. That is, if a riser solidifies first, it cannot feed the mold cavity. However, concerning (2), an open riser has some advantages over closed risers. Recognizing that open risers have the danger of solidifying first, they must be sized properly for proper function. But if the riser is correctly sized so that it remains a reservoir of molten metal to accommodate part shrinkage during solidification, an open riser helps exhaust gases from the mold during pouring, and can thereby eliminate some associated defects. A so-called blind riser that is not open to the atmosphere may cause pockets of air to be trapped, or increased dissolution of air into the metal, leading to defects in the cast part. For these reasons, the size and placement of risers is one of the most difficult challenges in designing molds.

5.9 Explain why the constant C in Eq. (5.9) depends on mold material, metal properties, and temperature.

The low ductility of some cast alloys should certainly be taken into consideration in the engineering application of the casting. The low ductility will:

(a) affect properties, such as toughness and fatigue,

(b) have a significant influence on further processing and finishing of the casting, i.e., machining processes, such as milling, drilling, and tapping, and

(c) possibly affect tribological behavior.

It should be noted that many engineering applications do not require high ductility; for example, when stresses are sufficiently small to ensure the material remains elastic and where impact loads do not occur.

5.24 The modulus of elasticity of gray iron varies significantly with its type, such as the ASTM class. Explain why.

Because the shape, size, and distribution of the second-phase (i.e., the graphite flakes) vary greatly for gray cast irons, there is a large corresponding variation of properties attainable. The elastic modulus, for example, is one property which is affected by this factor.

5.25 List and explain the considerations involved in selecting pattern materials.

Pattern materials have a number of important material requirements. Often, they are machined, thus good machinability is a requirement. The material should be sufficiently stiff to allow good shape development. The material must have sufficient wear and corrosion resistance so that the pattern has a reasonable life. The economics of the operation is affected also by material cost.

5.26 Why is the investment-casting process capable of producing fine surface detail on castings?

The surface detail of the casting depends on the quality of the pattern surface. In investment casting, for example, the pattern is made of wax or a thermoplastic poured or injected into a metal die with good surface finish. Consequently, surface detail of the casting is very good and can be controlled. Furthermore, the coating on the pattern (which then becomes the mold) consists of very fine silica, thus contributing to the fine surface detail of the cast product.

5.27 Explain why a casting may have a slightly different shape than the pattern used to make the mold.

After solidification, shrinkage continues until the casting cools to room temperature. Also, due to surface tension, the solidifying metal will, when surface tension is high enough, not fully conform to sharp corners and other intricate surface features. Thus, the cast shape will generally be slightly different from that of the pattern used.

5.28 Explain why squeeze casting produces parts with better mechanical properties, dimensional accuracy, and surface finish than expendable-mold processes.

The squeeze-casting process consists of a combination of casting and forging. The pressure applied to the molten metal by the punch, or upper die, keeps the entrapped gases in solution, and thus porosity is generally not found in these products. Also, the rapid heat transfer results in a fine microstructure with good mechanical properties. Due to the applied pressure and the type of die used, i.e., metal, good dimensional accuracy and surface finish are typically found in squeeze-cast parts.

5.29 Why are steels more difficult to cast than cast irons?

The primary reason steels are more difficult to cast than cast irons is that they melt at a higher temperature. The high temperatures complicate mold material selection, preparation, and techniques involved for heating and pouring of the metal.

5.30 What would you recommend to improve the surface finish in expendable-mold casting processes?

One method of improving the surface finish of castings is to use what is known as a facing sand, such as Zircon. This is a sand having better properties (such as permeability and surface finish) than bulk sand, but is generally more expensive. Thus, facing sand is used as a first layer against the pattern, with the rest of the mold being made of less expensive (silica) sand.

5.31 You have seen that even though die casting produces thin parts, there is a limit to the minimum thickness. Why can't even thinner parts be made by this process?

Because of the high thermal conductivity that metal dies exhibit, there is a limiting thickness below which the molten metal will solidify prematurely before filling the mold cavity. Also, the finite viscosities of the molten metal (which increases as it begins to cool) will require higher pressures to force the metal into the narrow passages of the die cavities.

5.32 What differences, if any, would you expect in the properties of castings made by permanent-mold vs. sand-casting methods?

As described in the text, permanent-mold castings generally possess better surface finish, closer tolerances, more uniform mechanical properties, and more sound thin-walled sections than sand castings. However, sand castings generally can have more intricate shapes, larger overall size, and lower in cost (depending upon the alloy) than permanent-mold castings.

5.33 Which of the casting processes would be suitable for making small toys in large numbers? Explain.

This is an open-ended problem, and the students should give a rationale for their choice. Refer also to Table 5.2 and note that die casting is one of the best processes for this application. The student should refer to the application requiring large production runs, so that tooling cost per casting can be low, the sizes possible in die casting are suitable for such toys, and the dimensional tolerances and surface finish are acceptable.

5.34 Why are allowances provided for in making patterns? What do they depend on?

Shrinkage allowances on patterns are corrections for the shrinkage that occurs upon solidification of the casting and its subsequent contraction while cooling to room temperature. The allowance will therefore depend on the amount of contraction an alloy undergoes.

5.35 Explain the difference in the importance of drafts in green-sand casting vs. permanent-mold casting.

Draft is provided to allow the removal of the pattern without damaging the mold. If the mold material is sand and has no draft, the mold cavity is likely to be damaged upon pattern removal, due to the low strength of the sand mold. However, a die made of high-strength steel, which is typical for permanent-mold castings, is not at all likely to be damaged during the removal of the part; thus smaller draft angles can be employed.

5.36 Make a list of the mold and die materials used in the casting processes described in this chapter. Under each type of material, list the casting processes that are used, and explain why these processes are suitable for that particular mold or die material.

This is an open-ended problem, and students should be encouraged to develop an answer based on the contents of this chapter. An example of an acceptable answer would, in a brief form, be:

- Sand: Used because of its ability to resist very high temperatures, availability, and low cost. Used for sand, shell, expanded-pattern, investment, and ceramic-mold casting processes.
- Metal: Such as steel or iron. Results in excellent surface finish and good dimensional accuracy. Used for die, slush, pressure, centrifugal, and squeeze-casting processes.
- Graphite: Used for conditions similar to those for metal molds; however, lower pressures should be employed for this material. Used mainly in pressure- and centrifugal-casting.
- Plaster of paris: Used in plaster-mold casting for the production of relatively small components, such as fittings and valves.

5.37 Explain why carbon is so effective in imparting strength to iron in the form of steel.

Carbon has an atomic radius that is about 57% of the iron atom, thus it occupies an interstitial position in the iron unit cell (see Figs. 3.2 on

p. 84 and 3.9 on p. 90). However, because its radius is greater than that of the largest hole between the Fe atoms, it strains the lattice, thus interfering with dislocation movement and leading to strain hardening. Also, the size of the carbon atom allows it to have a high solubility in the fcc high-temperature phase of iron (austenite). At low temperatures, the structure is bcc and has a very low solubility of carbon atoms. On quenching, the austenitic structure transforms to body-centered tetragonal (bct) martensite, which produces high distortion in the crystal lattice. Because it is higher, the strength increase is more than by other element additions.

5.38 Describe the engineering significance of the existence of a eutectic point in phase diagrams.

The eutectic point corresponds to a composition of an alloy that has a lowest melting temperature for that alloy system. The low melting temperature associated with a eutectic point can, for example, help in controlling thermal damage to parts during joining, as is done in soldering. (See Section 12.13.3 starting on p. 776).

5.39 Explain the difference between hardness and hardenability.

Hardness represents the material's resistance to plastic deformation when indented (see Section 2.6 starting on p. 51), while hardenability is the material's capability to be hardened by heat treatment. (See also Section 5.11.1 starting on p. 236).

5.40 Explain why it may be desirable or necessary for castings to be subjected to various heat treatments.

The morphology of grains in an as-cast structure may not be desirable for commercial applications. Thus, heat treatments, such as quenching and tempering (among others), are carried out to optimize the grain structure of castings. In this manner, the mechanical properties can be controlled and enhanced.

5.41 Describe the differences between case hardening and through hardening insofar as engineering applications are concerned.

Case hardening is a treatment that hardens only the surface layer of the part (see Table 5.7 on p. 242). The bulk retains its toughness, which allows for blunting of surface cracks as they propagate inward. Case hardening generally induces compressive residual stresses on the surface, thus retarding fatigue failure. Through hardened parts have a high hardness across the whole part; consequently, a crack could propagate easily through the cross section of the part, causing major failure.

5.42 *Type metal* is a bismuth alloy used to cast type for printing. Explain why bismuth is ideal for this process.

When one considers the use of type or for precision castings such as mechanical typewriter impressions, one realizes that the type tool must have extremely high precision and smooth surfaces. A die casting using most metals would have shrinkage that would result in the distortion of the type, or even the metal shrinking away from the mold wall. Since bismuth expands during solidification, the molten metal can actually expand to fill molds fully, thereby ensuring accurate casting and repeatable typefaces.

5.43 Do you expect to see larger solidification shrinkage for a material with a bcc crystal structure or fcc? Explain.

The greater shrinkage would be expected from the material with the greater packing efficiency or atomic packing factor (APF) in a solid state. Since the APF for fcc is 0.74 and for bcc it is 0.68, one would expect a larger shrinkage for a material with a fcc structure. This can also been seen from Fig. 3.2 on p. 84. Note, however, that for an alloy, the answer is not as simple, since it must be determined if the alloying element can fit into interstitial positions or serves as a substitutional element.

5.44 Describe the drawbacks to having a riser that is (a) too large, or (b) too small.

The main drawbacks to having a riser too large are: the material in the riser is eventually scrapped and has to be recycled; the riser hass to be cut off, and a larger riser will cost more

5.55 Rank the casting processes described in this chapter in terms of their solidification rate. For example, which processes extract heat the fastest from a given volume of metal and which is the slowest?

There is, as expected, some overlap between the various processes, and the rate of heat transfer can be modified whenever desired. However, a general ranking in terms of rate of heat extraction is as follows: Die casting (cold chamber), squeeze casting, centrifugal casting, slush casting, die casting (hot chamber), permanent mold casting, shell mold casting, investment casting, sand casting, lost foam, ceramic-mold casting, and plaster-mold casting.

5.56 The heavy regions of parts typically are placed in the drag in sand casting and not in the cope. Explain why.

A simple explanation is that if they were to be placed in the cope, they would develop a high buoyancy force that would tend to separate the mold and thus develop flashes on the casting.

Problems

5.57 Referring to Fig. 5.3, estimate the following quantities for a 20% Cu-80% Ni alloy: (1) liquidus temperature, (2) solidus temperature, (3) percentage of nickel in the liquid at 1400°C (2550°F), (4) the major phase at 1400°C, and (5) the ratio of solid to liquid at 1400°C.

We estimate the following quantities from Fig. 5.3 on p. 192: (1) The liquidus temperature is 1400°C (2550°F). (2) The solidus temperature is 1372°C (2500°F). (3) At 2550°F, the alloy is still all liquid, thus the nickel concentration is 80%. (4) The major phase at 1400°C is liquid, with no solids present since the alloy is not below the liquidus temperature. (5) The ratio is zero, since no solid is present.

5.58 Determine the amount of gamma and alpha phases (see Fig. 5.4b) in a 10-kg, AISI 1060 steel casting as it is being cooled to the following temperatures: (1) 750°C, (2) 728°C, and (3) 726°C.

We determine the following quantities from Fig. 5.6 on p. 197: (a) At 750°C, the alloy is just in the single-phase austenite (gamma) region, thus the percent gamma is 100% (10 kg), and alpha is 0%. (b) At 728°C, the alloy is in the two-phase gamma-alpha field, and the weight percentages of each is found by the lever rule (see Example 5.1):

$$\begin{aligned}\%\alpha &= \left(\frac{x_\gamma - x_o}{x_\gamma - x_\alpha}\right) \times 100\% \\ &= \left(\frac{0.77-0.60}{0.77-0.022}\right) \times 100\% \\ &= 23\% \text{ or } 2.3 \text{ kg}\end{aligned}$$

$$\begin{aligned}\%\gamma &= \left(\frac{x_o - x_\alpha}{x_\gamma - x_\alpha}\right) \times 100\% \\ &= \left(\frac{0.60-0.022}{0.77-0.022}\right) \times 100\% \\ &= 77\% \text{ or } 7.7 \text{ kg}\end{aligned}$$

OR 100% - %α

(c) At 726°C, the alloy is in the two-phase alpha and Fe_3C field. No gamma phase is present. Again the lever rule is used to find the amount of alpha present:

$$\%\alpha = \left(\frac{6.67-0.60}{6.67-0.022}\right) \times 100\% = 91\% \text{ or } 9.1 \text{ kg}$$

5.59 A round casting is 0.3 m in diameter and 0.5 m in length. Another casting of the same metal is elliptical in cross section, with a major-to-minor axis ratio of 3, and has the same length and cross sectional area as the round casting. Both pieces are cast under the same conditions. What is the difference in the solidification times of the two castings?

For the same length and cross sectional area (thus the same volume), and the same casting conditions, the same C value in Eq. (5.11) on p. 205 on p. 205 should be applicable. The surface area and volume of the round casting is

$$A_{\text{round}} = 2\pi rl + 2\pi r^2 = 0.613 \text{ m}^2$$

$$V_{\text{round}} = \pi r^2 l = 0.0353 \text{ in}^2$$

Since the cross-sectional area of the ellipse is the same as that for the cylinder, and it has a major and minor diameter of a and b, respectively, where $a = 3b$, then

$$\pi ab = \pi r^2$$

$$3b^2 = r^2 \quad \rightarrow \quad b = \sqrt{\frac{(0.15)^2}{3}}$$

or $b = 0.0866$ m, so that $a = 0.260$ m. The surface area of the ellipse-based part is (see a basic geometry text for the area equation derivations):

$$A_{\text{ellipse}} = 2\pi ab + 2\pi\sqrt{a^2 + b^2}l = 1.002 \text{ m}^2$$

The volume is still 0.0353 in^2. According to Eq. (5.11) on p. 205, we thus have

$$\frac{T_{\text{round}}}{T_{\text{ellipse}}} = \frac{(V/A_{\text{round}})^2}{(V/A_{\text{ellipse}})^2} = \left(\frac{A_{\text{ellipse}}}{A_{\text{round}}}\right)^2 = 2.67$$

5.60 Derive Eq. (5.7).

We note that Eq. (5.5) on p. 200 gives a relationship between height, h, and velocity, v, and Eq. (5.6) on p. 201 gives a relationship between height, h, and cross sectional area, A. With the reference plate at the top of the pouring basin (and denoted as subscript 0), the sprue top is denoted as 1, and the bottom as 2. Note that h_2 is numerically greater than h_1. At the top of the sprue we have $v_o = 0$ and $h_o = 0$. As a first approximation, assume that the pressures p_o, p_1 and p_2 are equal and that the frictional loss f is negligible. Thus, from Eq. (5.5) we have

$$h_o + \frac{p_o}{\rho g} + \frac{v_o^2}{2g} = h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + f$$

or, solving for v_1,

$$0 = h_1 + \frac{v_1^2}{2g} \quad \rightarrow \quad v_1 = \sqrt{2gh_1}$$

Similarly,

$$h_o + \frac{p_o}{\rho g} + \frac{v_o^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f$$

or

$$v_2 = \sqrt{2gh_2}$$

Substituting these results into the continuity equation given by Eq. (5.6), we have

$$A_1 v_1 = A_2 v_2$$

$$A_1\sqrt{2gh_1} = A_2\sqrt{2gh_2}$$

$$\frac{A_1}{A_2} = \frac{\sqrt{2gh_2}}{\sqrt{2gh_1}} = \sqrt{\frac{h_2}{h_1}}$$

which is the desired relationship.

5.61 Two halves of a mold (cope and drag) are weighted down to keep them from separating due to the pressure exerted by the molten metal (buoyancy). Consider a solid, spherical steel casting, 9 in. in diameter, that is being produced by sand casting. Each flask (see Fig. 5.10) is 20 in. by 20 in. and 15 in. deep. The parting line is at the middle of the part. Estimate the clamping force required. Assume that the molten metal has a density of 500 lb/ft^3 and that the sand has a density of 100 lb/ft^3,

The force exerted by the molten metal is the product of its cross-sectional area at the parting line and the pressure of the molten metal due to the height of the sprue. Assume that the sprue has the same height as the cope, namely, 15 in. The pressure of the molten metal is the product of height and density. Assuming a density for the molten metal of 500 lb/ft^3, the pressure at the parting line will be $(500)(15/12) = 625$ lb/ft^2, or 4.34 psi. The buoyancy force is the product of projected area and pressure, or $(625)(\pi)(9/12)^2 = 1100$ lb. The net volume of the sand in each flask is

$$V = (20)(20)(15) - (0.5)\left(\frac{4\pi}{3}\right)(9)^3$$

or $V = 4473$ in^3 $= 2.59$ ft^3. For a sand density of 100 lb/ft^3, the cope weighs 454 lb. Under these circumstances, a clamping force of $1100 - 259 \approx 850$ lb is required.