Manufacturing Process II

Casting-3

Casting Processes

Metal casting processes divide into two categories, based on mold type: (1) expendable mold and (2) permanent mold. In expendable mold casting operations, the mold is sacrificed in order to remove the cast part. Since a new mold is required for each new casting, production rates in expendable-mold processes are often limited by the time required to make the mold rather than the time to make the casting itself. In permanent-mold casting processes, the mold is fabricated out of metal (or other durable material) and can be used many times to make many castings. Accordingly, these processes possess an advantage of higher production rates.

1- Expendable Mold Casting

1.1 Sand Casting

Sand casting is the most widely used casting process, accounting for a significant majority of the total tonnage cast. Nearly all casting alloys can be sand cast; indeed, it is one of the few processes that can be used for metals with high melting temperatures, such as steels, nickels, and titaniums. Its versatility permits the casting of parts ranging in size from small to very large.

Sand casting, also known as sand-mold casting, consists of pouring molten metal into a sand mold, allowing the metal to solidify, and then breaking up the mold to remove the casting. The casting must then be cleaned and inspected, and heat treatment is sometimes required to improve metallurgical properties. The cavity in the sand mold is formed by packing sand around a pattern (an approximate
duplicate of the part to be cast), and then removing the pattern by separating the mold into two halves. The mold also contains the gating and riser system. In addition, if the casting is to have internal surfaces (e.g., hollow parts or parts with holes), a core must be included in the mold. Since the mold is sacrificed to remove the casting, a new sand mold must be made for each part that is produced. Sand casting is seen to include not only the casting operation itself, but also the fabrication of the pattern and the making of the mold. The production sequence is outlined in Figure 1.

![Diagram of sand casting production sequence]

Figure 1. Steps in the production sequence in sand casting. The steps include not only the casting operation but also pattern making and mold making.

1.1.1 Patterns and Cores

Sand casting requires a pattern; a full-sized model of the part, enlarged to account for shrinkage and machining allowances in the final casting. Materials used to make patterns include wood, plastics, and metals. Wood is a common pattern material because it is easily shaped. Its disadvantages are that it tends to warp, and it is abraded by the sand being compacted around it, thus limiting the number of times it can be reused. Metal patterns are more expensive to make, but they last much longer. Plastics represent a compromise between wood and metal. Selection
of the appropriate pattern material depends to a large extent on the total quantity of castings to be made.

Patterns define the external shape of the cast part. If the casting is to have internal surfaces, a core is required. A core is a full-scale model of the interior surfaces of the part. It is inserted into the mold cavity prior to pouring, so that the molten metal will flow and solidify between the mold cavity and the core to form the casting’s external and internal surfaces. The core is usually made of sand, compacted into the desired shape. As with the pattern, the actual size of the core must include allowances for shrinkage and machining. Depending on the geometry of the part, the core may or may not require supports to hold it in position in the mold cavity during pouring. These supports, called chaplets, are made of a metal with a higher melting temperature than the casting metal. For example, steel chaplets would be used for cast iron castings. On pouring and solidification, the chaplets become bonded into the casting. A possible arrangement of a core in a mold using chaplets is sketched in Figure 2. The portion of the chaplet protruding from the casting is subsequently cut off.

Figure 2. (a) Core held in place in the mold cavity by chaplets, (b) possible chaplet design, and (c) casting with internal cavity.
1.1.2 Molds and Mold Making

Foundry sands are silica (SiO$_2$) or silica mixed with other minerals. The sand should possess good refractory properties; capacity to stand up under high temperatures without melting or otherwise degrading. Other important features of the sand include grain size, distribution of grain size in the mixture, and shape of the individual grains. Small grain size provides a better surface finish on the cast part, but large grain size is more permeable (to allow escape of gases during pouring). Molds made from grains of irregular shape tend to be stronger than molds of round grains because of interlocking, yet interlocking tends to restrict permeability.

In making the mold, the grains of sand are held together by a mixture of water and bonding clay. A typical mixture (by volume) is 90% sand, 3% water, and 7% clay. Other bonding agents can be used in place of clay, including organic resins (e.g., phenolic resins) and inorganic binders (e.g., sodium silicate and phosphate). Besides sand and binder, additives are sometimes combined with the mixture to enhance properties such as strength and/or permeability of the mold.

To form the mold cavity, the traditional method is to compact the molding sand around the pattern for both cope and drag in a container called a flask. The packing process is performed by various methods. The simplest is hand ramming, accomplished manually by a foundry worker. In addition, various machines have been developed to mechanize the packing procedure.

Several indicators are used to determine the quality of the sand mold: (1) strength; the mold’s ability to maintain its shape and resist erosion caused by the flow of molten metal; it depends on grain shape, adhesive qualities of the binder, and other factors; (2) permeability; capacity of the mold to allow hot air and gases from the
casting operation to pass through the voids in the sand; (3) thermal stability; ability of the sand at the surface of the mold cavity to resist cracking and buckling upon contact with the molten metal; (4) collapsibility; ability of the mold to give way and allow the casting to shrink without cracking the casting; it also refers to the ability to remove the sand from the casting during cleaning; and (5) reusability; can the sand from the broken mold be reused to make other molds? These measures are sometimes incompatible; for example, a mold with greater strength is less collapsible.

1.1.3 The Casting Operation

After the core is positioned (if one is used) and the two halves of the mold are clamped together, then casting is performed. Casting consists of pouring, solidification, and cooling of the cast part. The gating and riser system in the mold must be designed to deliver liquid metal into the cavity and provide for a sufficient reservoir of molten metal during solidification shrinkage. Air and gases must be allowed to escape.

One of the hazards during pouring is that the buoyancy of the molten metal will displace the core. Buoyancy results from the weight of molten metal being displaced by the core, according to Archimedes’ principle. The force tending to lift the core is equal to the weight of the displaced liquid less the weight of the core itself. Expressing the situation in equation form,

\[ F_b = W_m - W_c \]

Where \( F_b \) = buoyancy force, N; \( W_m \) = weight of molten metal displaced, N; and \( W_c \) = weight of the core, N. Weights are determined as the volume of the core multiplied by the respective densities of the core material (typically sand) and the metal being cast. The density of a sand core is approximately 1.6 g/cm\(^3\).
Example: A sand core has a volume \( = 1875 \text{ cm}^3 \) and is located inside a sand mold cavity. Determine the buoyancy force tending to lift the core during pouring of molten lead into the mold. Density of the sand core is 1.6 \( \text{g/cm}^3 \), and density of lead is 11.3 \( \text{g/cm}^3 \).

1.2 Shell-Mold Casting

Shell molding is a casting process in which the mold is a thin shell (typically 9mm) made of sand held together by a thermosetting resin binder. Developed in Germany during the early 1940s, the process is described and illustrated in Figure 3.

There are many advantages to the shell-molding process. The surface of the shell mold cavity is smoother than a conventional green-sand mold, and this smoothness permits easier flow of molten metal during pouring and better surface finish on the final casting. Good dimensional accuracy is also achieved, with tolerances of \( \pm 0.25 \) mm. The good finish and accuracy often precludes the need for further machining. Collapsibility of the mold is generally sufficient to avoid tearing and cracking of the casting.

Disadvantages of shell molding include a more expensive metal pattern than the corresponding pattern for green-sand molding. This makes shell molding difficult to justify for small quantities of parts. Shell molding can be mechanized for mass production and is very economical for large quantities. It seems particularly suited to steel castings of less than 8 kg. Examples of parts made using shell molding include gears, valve bodies, bushings, and camshafts.
Figure 3. Steps in shell molding: (1) a match-plate or cope-and-drag metal pattern is heated and placed over a box containing sand mixed with thermosetting resin; (2) box is inverted so that sand and resin fall onto the hot pattern, causing a layer of the mixture to partially cure on the surface to form a hard shell; (3) box is repositioned so that loose, uncured particles drop away; (4) sand shell is heated in oven for several minutes to complete curing; (5) shell mold is stripped from the pattern; (6) two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is accomplished. The finished casting with sprue removed is shown in (7).

1.3 Expanded Polystyrene Process

The expanded polystyrene casting process uses a mold of sand packed around a polystyrene foam pattern that vaporizes when the molten metal is poured into the mold. The process and variations of it are known by other names, including lost-foam process, lost pattern process, evaporative-foam process, and full-mold process (the last being a trade name). The foam pattern includes the sprue, risers,
and gating system, and it may also contain internal cores (if needed), thus eliminating the need for a separate core in the mold. Also, since the foam pattern itself becomes the cavity in the mold, considerations of draft and parting lines can be ignored. The mold does not have to be opened into cope and drag sections. The sequence in this casting process is illustrated and described in Figure 4.

The pattern is normally coated with a refractory compound to provide a smoother surface on the pattern and to improve its high temperature resistance. Molding sands usually include bonding agents.

![Figure 4. Expanded polystyrene casting process: (1) pattern of polystyrene is coated with refractory compound; (2) foam pattern is placed in mold box, and sand is compacted around the pattern; and (3) molten metal is poured into the portion of the pattern that forms the pouring cup and sprue. As the metal enters the mold, the polystyrene foam is vaporized ahead of the advancing liquid, thus allowing the resulting mold cavity to be filled.]

A significant advantage for this process is that the pattern need not be removed from the mold. This simplifies and expedites mold making. In a conventional green-sand mold, two halves are required with proper parting lines, draft allowances must be provided in the mold design, cores must be inserted, and the
gating and riser system must be added. With the expanded polystyrene process, these steps are built into the pattern itself. A new pattern is needed for every casting, so the economics of the expanded polystyrene casting process depend largely on the cost of producing the patterns. The process has been applied to mass produce castings for automobiles engines.

1.4 Investment Casting

In investment casting, a pattern made of wax is coated with a refractory material to make the mold, after which the wax is melted away prior to pouring the molten metal. It is a precision casting process, because it is capable of making castings of high accuracy and intricate detail. The process is also known as the lost-wax process, because the wax pattern is lost from the mold prior to casting.

Steps in investment casting are described in Figure 5. Since the wax pattern is melted off after the refractory mold is made, a separate pattern must be made for every casting. Pattern production is usually accomplished by a molding operation; pouring or injecting the hot wax into a master die that has been designed with proper allowances for shrinkage of both wax and subsequent metal casting. In cases where the part geometry is complicated, several separate wax pieces must be joined to make the pattern. In high production operations, several patterns are attached to a sprue, also made of wax, to form a pattern tree; this is the geometry that will be cast out of metal.

Coating with refractory (step 3) is usually accomplished by dipping the pattern tree into a slurry of very fine grained silica or other refractory (almost in powder form) mixed with plaster to bond the mold into shape. The small grain size of the refractory material provides a smooth surface and captures the intricate details of
the wax pattern. The final mold (step 4) is accomplished by repeatedly dipping the tree into the refractory slurry or by gently packing the refractory around the tree in a container. The mold is allowed to air dry for about 8 hours to harden the binder.

Figure 5. Steps in investment casting: (1) wax patterns are produced; (2) several patterns are attached to a sprue to form a pattern tree; (3) the pattern tree is coated with a thin layer of refractory material; (4) the full mold is formed by covering the coated tree with sufficient refractory material to make it rigid; (5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity; (6) the mold is preheated to a high temperature, which ensures that all contaminants are eliminated from the mold; it also permits the liquid metal to flow more easily into the detailed cavity; the molten metal is poured; it solidifies; and (7) the mold is broken away from the finished casting. Parts are separated from the sprue.
Advantages of investment casting include: (1) parts of great complexity and intricacy can be cast; (2) close dimensional control; tolerances of ± 0.075 mm are possible; (3) good surface finish is possible; (4) the wax can usually be recovered for reuse; and (5) additional machining is not normally required; this is a net shape process.

Because many steps are involved in this casting operation, it is a relatively expensive process. Investment castings are normally small in size, although parts with complex geometries weighing up to 30 kg have been successfully cast. All types of metals, including steels, stainless steels, and other high temperature alloys, can be investment cast. Examples of parts include complex machinery parts, blades, and other components for turbine engines, jewelry, and dental fixtures.

1.5 Plaster-Mold and Ceramic-Mold Casting

**Plaster-Mold** casting is similar to sand casting except that the mold is made of plaster of Paris (gypsum, CaSO₄–2H₂O) instead of sand. Additives such as talc and silica flour are mixed with the plaster to control contraction and setting time, reduce cracking, and increase strength. To make the mold, the plaster mixture combined with water is poured over a plastic or metal pattern in a flask and allowed to set. Wood patterns are generally unsatisfactory due to the extended contact with water in the plaster.

Curing of the plaster mold is one of the disadvantages of this process, at least in high production. The mold must set for about 20 minutes before the pattern is stripped. The mold is then baked for several hours to remove moisture.

Plaster molds cannot withstand the same high temperatures as sand molds. They are therefore limited to the casting of lower-melting-point alloys, such as
aluminum, magnesium, and some copper-base alloys. Casting sizes range from about 20 g to more than 100 kg. Advantages of plaster molding are good surface finish and dimensional accuracy and the capability to make thin cross-sections in the casting.

Ceramic-mold casting is similar to plaster-mold casting, except that the mold is made of refractory ceramic materials that can withstand higher temperatures than plaster. Thus, ceramic molding can be used to cast steels, cast irons, and other high temperature alloys. Its applications (relatively intricate parts) are similar to those of plaster-mold casting except for the metals cast. Its advantages (good accuracy and finish) are also similar.

2- Permanent Mold Casting
The economic disadvantage of any of the expendable-mold processes is that a new mold is required for every casting. In permanent-mold casting, the mold is reused many times.

2.1 Basic Permanent-Mold Process
Permanent-mold casting uses a metal mold constructed of two sections that are designed for easy, precise opening and closing. These molds are commonly made of steel or cast iron. The cavity, with gating system included, is machined into the two halves to provide accurate dimensions and good surface finish. Metals commonly cast in permanent molds include aluminum, magnesium, copper-base alloys, and cast iron. Cores can be used in permanent molds to form interior surfaces in the cast product. The cores can be made of metal, but if withdrawal of a metal core would be difficult or impossible, sand cores can be used.
Steps in the basic permanent-mold casting process are described in Figure 6. In preparation for casting, the mold is first preheated and one or more coatings are sprayed on the cavity. Preheating facilitates metal flow through the gating system and into the cavity. The coatings aid heat dissipation and lubricate the mold surfaces for easier separation of the cast product. After pouring, as soon as the metal solidifies, the mold is opened and the casting is removed. Unlike expendable molds, permanent molds do not collapse, so the mold must be opened before appreciable cooling contraction occurs in order to prevent cracks from developing in the casting.

Advantages of permanent-mold casting include good surface finish and close dimensional control, as previously indicated. In addition, more rapid solidification caused by the metal mold results in a finer grain structure, so stronger castings are produced.

The process is generally limited to metals of lower melting points. Other limitations include simple part geometries compared to sand casting (because of the need to open the mold), and the expense of the mold. Because mold cost is substantial, the process is best suited to high-volume production and can be automated accordingly. Typical parts include automotive pistons, pump bodies, and certain castings for aircraft and missiles.

### 2.2 Slush Casting

Slush casting is a permanent-mold process in which a hollow casting is formed by inverting the mold after partial freezing at the surface to drain out the liquid metal in the center. Solidification begins at the mold walls because they are relatively cool, and it progresses over time toward the middle of the casting. Thickness of the
shell is controlled by the length of time allowed before draining. Slush casting is used to make statues, lamp pedestals, and toys out of low-melting-point metals such as zinc and tin. In these items, the exterior appearance is important, but the strength and interior geometry of the casting are minor considerations.

Figure 6. Steps in permanent-mold casting: (1) mold is preheated and coated; (2) cores (if used) are inserted, and mold is closed; (3) molten metal is poured into the mold; and (4) mold is opened. Finished part is shown in (5).

2.3 Low-Pressure Casting

In the basic permanent-mold casting process and in slush casting, the flow of metal into the mold cavity is caused by gravity. In low-pressure casting, the liquid metal
is forced into the cavity under low pressure (approximately 0.1 MPa) from beneath so that the flow is upward, as illustrated in Figure 7. The advantage of this approach over traditional pouring is that clean molten metal from the center of the ladle is introduced into the mold, rather than metal that has been exposed to air. Gas porosity and oxidation defects are thereby minimized, and mechanical properties are improved.

2.4 Vacuum Permanent-Mold Casting

This process is a variation of low-pressure casting in which a vacuum is used to draw the molten metal into the mold cavity. The general configuration of the vacuum permanent mold casting process is similar to the low-pressure casting operation. The difference is that reduced air pressure from the vacuum in the mold is used to draw the liquid metal into the cavity, rather than forcing it by positive air pressure from below. There are several benefits of the vacuum technique relative to low-pressure casting: air porosity and related defects are reduced, and greater strength is given to the cast product.

2.5 Die Casting

Die casting is a permanent-mold casting process in which the molten metal is injected into the mold cavity under high pressure. The pressure is maintained during solidification, after which the mold is opened and the part is removed. The use of high pressure to force the metal into the die cavity is the most notable feature that distinguishes this process from others in the permanent-mold category.

Molds in this casting operation are called dies; hence the name “die casting”. Die casting operations are carried out in special die casting machines. The general configuration is shown in Figure 8.
Figure 7. Low-pressure casting. The diagram shows how air pressure is used to force the molten metal in the ladle upward into the mold cavity. Pressure is maintained until the casting has solidified.

Figure 8. General configuration of a (cold-chamber) die casting machine.
There are two main types of die casting machines: (1) hot-chamber and (2) cold-chamber, differentiated by how the molten metal is injected into the cavity.

In **hot-chamber** machines, the metal is melted in a container attached to the machine, and a piston is used to inject the liquid metal under high pressure into the die. Typical injection pressures are 7 to 35 MPa. The casting cycle is summarized in Figure 9. Production rates up to 500 parts per hour are not uncommon. The process is limited in its applications to low melting-point metals. The metals include zinc, tin, lead, and sometimes magnesium.

In **cold-chamber** die casting machines, molten metal is poured into an unheated chamber from an external melting container, and a piston is used to inject the metal under high pressure into the die cavity. Injection pressures used in these machines are typically 14 to 140 MPa. The production cycle is explained in Figure 10. Compared to hot-chamber machines, cycle rates are not usually as fast because of the need to ladle the liquid metal into the chamber from an external source. Nevertheless, this casting process is a high production operation. Cold-chamber machines are typically used for casting aluminum, brass, and magnesium alloys. Low-melting-point alloys (zinc, tin, lead) can also be cast on cold-chamber machines, but the advantages of the hot-chamber process usually favor its use on these metals.
Figure 9. Cycle in hot-chamber casting: (1) with die closed and plunger withdrawn, molten metal flows into the chamber; (2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification; and (3) plunger is withdrawn, die is opened, and solidified part is ejected. Finished part is shown in (4).
Advantages of die casting include (1) high production rates possible; (2) economical for large production quantities; (3) close tolerances possible, on the order of $\pm 0.076\text{mm}$ for small parts; (4) good surface finish; (5) thin sections are possible, down to about $0.5\text{mm}$; and (6) rapid cooling provides small grain size and good strength to the casting. The limitation of this process, in addition to the metals cast, is the shape restriction. The part geometry must allow for removal from the die cavity.

### 2.6 Semi-Solid Metal Casting

Semi-solid metal casting is a family of net-shape and near net-shape processes performed on metal alloys at temperatures between the liquidus and solidus. Thus
the alloy is a mixture of solid and molten metals during casting, like a slurry; it is in the mushy state. In order to flow properly, the mixture must consist of solid metal globules in a liquid rather than the more typical dendritic solid shapes that form during freezing of a molten metal. This is achieved by forcefully stirring the slurry to prevent dendrite formation and instead encourage the spherical shapes, which in turn reduces the viscosity of the work metal. Advantages of semisolid metal casting include the following: (1) complex part geometries, (2) thin walls in parts, (3) close tolerances, (4) zero or low porosity, resulting in high strength of the casting.

2.7 Centrifugal Casting

Centrifugal casting refers to several casting methods in which the mold is rotated at high speed so that centrifugal force distributes the molten metal to the outer regions of the die cavity. The group includes (1) true centrifugal casting, (2) semicentrifugal casting, and (3) centrifuge casting.

2.7.1- True Centrifugal Casting: In true centrifugal casting, molten metal is poured into a rotating mold to produce a tubular part. Examples of parts made by this process include pipes, tubes, bushings, and rings. One possible setup is illustrated in Figure 11. Molten metal is poured into a horizontal rotating mold at one end. In some operations, mold rotation commences after pouring has occurred rather than beforehand. The high-speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. Thus, the outside shape of the casting can be round, octagonal, hexagonal, and so on. However, the inside shape of the casting is (theoretically) perfectly round, due to the radially symmetric forces at work. Orientation of the axis of mold rotation can be either horizontal or vertical, the former being more common.
In *horizontal centrifugal casting* for the process to work successfully, the rotational speed \((N)\) should be enough to prevent dropping of molten metal. Centrifugal force is defined by this physics equation:

\[
F = \frac{mv^2}{R}
\]

Where \(F\) = force, \(N\); \(m\) = mass, kg; \(v\) = velocity, m/s; and \(R\) = inside radius of the mold, m.

The minimum required rotational speed \((N)\) as revolution per minute is given below:

\[
N = \frac{30}{\pi} \sqrt{\frac{2gGF}{D}}
\]

Where \(N\) = rotational speed, revolution per minute. \(GF\) = G-Factor. \(D\) = inside diameter of the mold, m. If the G-factor is too low in centrifugal casting, the liquid metal will not remain forced against the mold wall during the upper half of the circular path but will “rain” inside the cavity. Slipping occurs between the molten metal and the mold wall, which means that the rotational speed of the metal is less

*Figure 11. Setup for true centrifugal casting.*
than that of the mold. On an empirical basis, values of $GF = 60$ to $80$ are found to be appropriate for horizontal centrifugal casting, although this depends to some extent on the metal being cast.

In *vertical centrifugal casting*, the effect of gravity acting on the liquid metal causes the casting wall to be thicker at the base than at the top. The inside profile of the casting wall takes on a parabolic shape. The difference in inside radius between top and bottom is related to speed of rotation as follows:

$$ N = \frac{30}{\pi} \sqrt{\frac{2 g L}{R_t^2 - R_b^2}} $$

Where $L =$ vertical length of the casting, m; $R_t =$ inside radius at the top of the casting, m; and $R_b =$ inside radius at the bottom of the casting, m. This equation can be used to determine the required rotational speed for vertical centrifugal casting, given specifications on the inside radii at top and bottom. One can see from the formula that for $R_t$ to equal $R_b$, the speed of rotation $N$ would have to be infinite, which is impossible of course. As a practical matter, part lengths made by vertical centrifugal casting are usually no more than about twice their diameters. This is quite satisfactory for bushings and other parts that have large diameters relatively to their lengths, especially if machining will be used to accurately size the inside diameter.

Castings made by true centrifugal casting are characterized by high density, especially in the outer regions of the part where centrifugal force is greatest. Solidification shrinkage at the exterior of the cast tube is not a factor, because the centrifugal force continually reallocates molten metal toward the mold wall during freezing. Any impurities in the casting tend to be on the inner wall and can be removed by machining if necessary.
### 2.7.2 Semicentrifugal Casting

In this method, centrifugal force is used to produce solid castings, as in Figure 12, rather than tubular parts. The rotation speed \((N)\) in semicentrifugal casting is usually set so that G-factors of around 15 are obtained, and the molds are designed with risers at the center to supply feed metal. Density of metal in the final casting is greater in the outer sections than at the center of rotation. The process is often used on parts in which the center of the casting is machined away, thus eliminating the portion of the casting where the quality is lowest. Wheels and pulleys are examples of castings that can be made by this process. Expendable molds are often used in semicentrifugal casting.

![Figure 12. Semicentrifugal casting.](image)

### 2.7.3 Centrifuge Casting

In centrifuge casting, Figure 13, the mold is designed with part cavities located away from the axis of rotation, so that the molten metal poured into the mold is
distributed to these cavities by centrifugal force. The process is used for smaller parts, and radial symmetry of the part is not a requirement as it is for the other two centrifugal casting methods.

Figure 13. (a) Centrifuge casting: centrifugal force causes metal to flow to the mold cavities away from the axis of rotation; and (b) the casting.
Questions and Problems- Casting

A- Review Questions

1- What is the difference between a pattern and a core in sand molding?
2- What is meant by the term superheat?
3- Why should turbulent flow of molten metal into the mold be avoided?
4- What are some of the factors that affect the fluidity of a molten metal during pouring into a mold cavity?
5- What does heat of fusion mean in casting?
6- How does solidification of alloys differ from solidification of pure metals?
7- What is the Chvorinov’s rule in casting?
8- Identify the three sources of contraction in a metal casting after pouring.
9- What is a chill in casting?
10- What properties determine the quality of a sand mold for sand casting?
11- What are the most common metals used in die casting?
12- Which die casting machines usually have a higher production rate, cold-chamber or hot-chamber, and why?
13- What is flash in die casting?
14- What is the difference between true centrifugal casting and semicentrifugal casting?
B- Multiple Choice Quizzes

1- Sand casting is which of the following types: (a) expendable mold or (b) permanent mold?

2- The upper half of a sand-casting mold is called which of the following: (a) cope or (b) drag?

3- In casting, a flask is which one of the following: (a) water bottle for foundrymen, (b) box which holds the cope and drag, (c) container for holding liquid metal, or (d) metal which extrudes between the mold halves?

4- In foundry work, a runner is which one of the following: (a) channel in the mold leading from the downsprue to the main mold cavity, (b) foundryman who moves the molten metal to the mold, or (c) vertical channel into which molten metal is poured into the mold?

5- Turbulence during pouring of the molten metal is undesirable for which of the following reasons (two best answers): (a) it causes discoloration of the mold surfaces, (b) it dissolves the binder used to hold together the sand mold, (c) it increases erosion of the mold surfaces, (d) it increases the formation of metallic oxides that can become entrapped during solidification, (e) it increases the mold filling time, and (f) it increases total solidification time?

6- Total solidification time is defined as which one of the following: (a) time between pouring and complete solidification, (b) time between pouring and cooling to room temperature, (c) time between solidification and cooling to room temperature, or (d) time to give up the heat of fusion?

7- During solidification of an alloy when a mixture of solid and liquid metals is present, the solid-liquid mixture is referred to as which one of the following:
(a) eutectic composition, (b) ingot segregation, (c) liquidus, (d) mushy zone, or (e) solidus?

8- Chvorinov’s rule states that total solidification time is proportional to which one of the following quantities: (a) \((A/V)^n\), (b) \(H_f\), (c) \(T_m\), (d) \(V\), (e) \(V/A\), or (f) \((V/A)^2\); where \(A\) = surface area of casting, \(H_f\) = heat of fusion, \(T_m\) = melting temperature, and \(V\) = volume of casting?

9- A riser in casting is described by which of the following (three correct answers): (a) an insert in the casting that inhibits buoyancy of the core, (b) gating system in which the sprue feeds directly into the cavity, (c) metal that is not part of the casting, (d) source of molten metal to feed the casting and compensate for shrinkage during solidification, and (e) waste metal that is usually recycled?

10- In a sand-casting mold, the \(V/A\) ratio of the riser should be (a) equal to, (b) greater than, or (c) smaller than the \(V/A\) ratio of the casting itself?

11- Which of the following riser types are completely enclosed within the sand mold and connected to the main cavity by a channel to feed the molten metal (two correct answers): (a) blind riser, (b) open riser, (c) side riser, and (d) top riser?

12- Which one of the following casting processes is the most widely used: (a) centrifugal casting, (b) die casting, (c) investment casting, (d) sand casting, or (e) shell casting?

13- In sand casting, the volumetric size of the pattern is (a) bigger than, (b) same size as, or (c) smaller than the cast part?

14- Silica sand has which one of the following compositions: (a) \(\text{Al}_2\text{O}_3\), (b) \(\text{SiO}\), (c) \(\text{SiO}_2\), or (d) \(\text{SiSO}_4\)?

15- Which of the following casting processes are expendable-mold operations (three correct answers): (a) centrifugal casting, (b) die casting, (c)
investment casting, (d) low pressure casting, (e) sand casting, (f) shell molding, (g) slush casting.

16- Shell molding is best described by which one of the following: (a) casting operation in which the molten metal has been poured out after a thin shell has been solidified in the mold, (b) casting process in which the mold is a thin shell of sand bonded by a thermosetting resin, (c) sand casting operation in which the pattern is a shell rather than a solid form, or (d) casting operation used to make artificial sea shells?

17- Which of the following metals would typically be used in die casting (three best answers): (a) aluminum, (b) cast iron, (c) steel, (d) tin, (e) tungsten, and (f) zinc?

C- Problems

1- A disk 40 cm in diameter and 5 cm thick is to be cast of pure aluminum in an open-mold casting operation. The melting temperature of aluminum = 660 °C, and the pouring temperature will be 800 °C. Assume that the amount of aluminum heated will be 5% more than what is needed to fill the mold cavity. Compute the amount of heat that must be added to the metal to heat it to the pouring temperature, starting from a room temperature of 25 °C. The heat of fusion of aluminum = 389.3 J/g, the density of aluminum is 2.7 g/cm³, assume that specific heat = 900 J Kg⁻¹°C⁻¹ in the solid state and 800 J Kg⁻¹°C⁻¹ in the liquid state.

2- The downsprue leading into the runner of a certain mold has a length =175 mm. The cross-sectional area at the base of the sprue is 400mm². The mold cavity has a volume = 0.001m³. Determine (a) the velocity of the molten
metal flowing through the base of the downsprue, (b) the volume rate of
flow, and (c) the time required to fill the mold cavity.

3- The flow rate of liquid metal into the downsprue of a mold = 1 L/s. The
cross-sectional area at the top of the sprue = 800 mm², and its length = 175
mm. What area should be used at the base of the sprue to avoid aspiration of
the molten metal?

4- Molten metal can be poured into the pouring cup of a sand mold at a steady
rate of 1000 cm³/s. The molten metal overflows the pouring cup and flows
into the downsprue. The cross-section of the sprue is round, with a diameter
at the top = 3.4 cm. If the sprue is 25cm long, determine the proper diameter
at its base so as to maintain the same volume flow rate.

5- During pouring into a sand mold, the molten metal can be poured into the
downsprue at a constant flow rate during the time it takes to fill the mold. At
the end of pouring the sprue is filled and there is negligible metal in the
pouring cup. The downsprue is 15 cm long. Its cross-sectional area at the top
= 5 cm² and at the base = 3.75 cm². The cross-sectional area of the runner
leading from the sprue also = 3.75 cm², and it is 20 cm long before leading
into the mold cavity, whose volume = 1000 cm³. The volume of the riser
located along the runner near the mold cavity = 390 cm³. It takes a total of
3.0 sec to fill the entire mold (including cavity, riser, runner, and sprue. This
is more than the theoretical time required, indicating a loss of velocity due to
friction in the sprue and runner. Find (a) the theoretical velocity and flow
rate at the base of the downsprue; (b) the total volume of the mold; (c) the
actual velocity and flow rate at the base of the sprue; and (d) the loss of head
in the gating system due to friction.

6- A flat plate is to be cast in an open mold whose bottom has a square shape
that is 200mm × 200mm. The mold is 40 mm deep. A total of 1,000,000mm³
of molten aluminum is poured into the mold. Solidification shrinkage is known to be 6.0%. The linear shrinkage due to thermal contraction after solidification is 1.3%. If the availability of molten metal in the mold allows the square shape of the cast plate to maintain its 200 mm × 200 mm dimensions until solidification is completed, determine the final dimensions of the plate.

7- In the casting of steel under certain mold conditions, the mold constant in Chvorinov’s rule is known to be 4.0 min/cm², based on previous experience. The casting is a flat plate whose length = 30 cm, width = 10 cm, and thickness = 20 mm. Determine how long it will take for the casting to solidify.

8- A disk-shaped part is to be cast out of aluminum. The diameter of the disk = 500 mm and its thickness = 20 mm. If the mold constant = 2.0 s/mm² in Chvorinov’s rule, how long will it take the casting to solidify?

9- In casting experiments performed using a certain alloy and type of sand mold; it took 155 s for a cube-shaped casting to solidify. The cube was 50 mm on a side. (a) Determine the value of the mold constant in Chvorinov’s rule. (b) If the same alloy and mold type were used, find the total solidification time for a cylindrical casting in which the diameter = 30 mm and length = 50 mm.

10- A steel casting has a cylindrical geometry with 10 cm diameter and weighs 8 kg. This casting takes 6.0 min to completely solidify. Another cylindrical shaped casting with the same diameter-to-length ratio weighs 4.8 kg. This casting is made of the same steel, and the same conditions of mold and pouring were used. Determine: (a) the mold constant in Chvorinov’s rule, (b) the dimensions, and (c) the total solidification time of the lighter casting. The density of steel is 7.9 g/cm³.
11- The total solidification times of three casting shapes are to be compared: (1) a sphere with diameter = 10 cm, (2) a cylinder with diameter and length both = 10 cm, and (3) a cube with each side = 10 cm. The same casting alloy is used in the three cases. (a) Determine the relative solidification times for each geometry. (b) Based on the results of part (a), which geometric element would make the best riser? (c) If the mold constant = 3.5 min/cm² in Chvorinov’s rule, compute the total solidification time for each casting.

12- A riser in the shape of a sphere is to be designed for a sand casting mold. The casting is a rectangular plate, with length = 200 mm, width = 100mm, and thickness = 18 mm. If the total solidification time of the casting itself is known to be 3.5 min, determine the diameter of the riser so that it will take 25% longer for the riser to solidify.

13- A cylindrical riser is to be designed for a sand casting mold. The length of the cylinder is to be 1.25 times its diameter. The casting is a square plate, each side = 25 cm and thickness = 1.875 cm. If the metal is cast iron, and the mold constant = 2.5 min/cm² in Chvorinov’s rule, determine the dimensions of the riser so that it will take 30% longer for the riser to solidify.

14- A 92% aluminum-8% copper alloy casting with density of 2.81 g/cm³ is made in a sand mold using a sand core that weighs 20 kg. Determine the buoyancy force in Newtons tending to lift the core during pouring.

15- Chaplets are used to support a sand core inside a sand mold cavity. The design of the chaplets and the manner in which they are placed in the mold cavity surface allows each caplet to sustain a force of 4 kg. Several caplets are located beneath the core to support it before pouring; and several other caplets are placed above the core to resist the buoyancy force during pouring. If the volume of the core = 5000 cm³, and the metal poured is brass,
determine the minimum number of caplets that should be placed (a) beneath the core, and (b) above the core. Density of brass = 8 g/cm³.

16- A sand core used to form the internal surfaces of a steel casting experiences a buoyancy force of 23 kg. The volume of the mold cavity forming the outside surface of the casting = 5000 cm³. What is the weight of the final casting? Ignore considerations of shrinkage, density of steel = 7.9 g/cm³.

17- A horizontal true centrifugal casting operation will be used to make copper tubing. The lengths will be 1.5 m with outside diameter = 15.0 cm, and inside diameter = 12.5 cm. If the rotational speed of the pipe = 1000 rev/min, determine the G-factor.

18- A true centrifugal casting operation is to be performed in a horizontal configuration to make cast iron pipe sections. The sections will have a length = 105 cm, outside diameter = 20 cm, and wall thickness = 1.25 cm. If the rotational speed of the pipe = 500 rev/min, determine the G-factor. Is the operation likely to be successful?

19- A horizontal true centrifugal casting process is used to make brass bushings with the following dimensions: length = 10 cm, outside diameter = 15 cm, and inside diameter = 12 cm. (a) Determine the required rotational speed in order to obtain a G-factor of 70. (b) When operating at this speed, what is the centrifugal force per square meter (Pa) imposed by the molten metal on the inside wall of the mold?

20- True centrifugal casting is performed horizontally to make large diameter copper tube sections. The tubes have a length = 1.0 m, diameter = 0.25 m, and wall thickness = 15 mm. (a) If the rotational speed of the pipe = 700 rev/min, determine the G-factor on the molten metal. (b) Is the rotational speed sufficient to avoid “rain?” (c) What volume of molten metal must be poured into the mold to make the casting if solidification shrinkage and
contraction after solidification are considered? Solidification shrinkage for copper = 4.5%, and solid thermal contraction = 7.5%.

21- A horizontal true centrifugal casting process is used to make aluminum rings with the following dimensions: length = 5 cm, outside diameter = 65 cm, and inside diameter = 60 cm. (a) Determine the rotational speed that will provide a G-factor = 60. (b) Suppose that the ring were made out of steel instead of aluminum. If the rotational speed computed in part (a) were used in the steel casting operation, determine the G-factor and (c) centrifugal force per square meter (Pa) on the mold wall. (d) Would this rotational speed result in a successful operation?

22- For the steel ring of preceding Problem 21(b), determine the volume of molten metal that must be poured into the mold, given that the liquid shrinkage is 0.5%, solidification shrinkage = 3%, and solid contraction after freezing = 7.2%.

23- A vertical, true centrifugal casting process is used to make tube sections with length = 25 cm and outside diameter = 15 cm. The inside diameter of the tube = 13.75 cm at the top and 12.5 cm at the bottom. At what speed must the tube be rotated during the operation in order to achieve these specifications?

24- A vertical, true centrifugal casting process is used to produce bushings that are 200 mm long and 200 mm in outside diameter. If the rotational speed during solidification is 500 rev/min, determine the inside diameter at the top of the bushing if the inside diameter at the bottom is 150 mm.

25- A vertical, true centrifugal casting process is used to cast brass tubing that is 37.5 cm long and whose outside diameter = 20 cm. If the speed of rotation during solidification is 1000 rev/min, determine the inside diameters at the
top and bottom of the tubing if the total weight of the final casting = 30 kg,
brass density = 8 g/cm$^3$. 