МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ

Національний аерокосмічний університет ім. М.Є. Жуковського
«Харківський авіаційний інститут»

M.K. Knyazyev, S.V. Sergeyev, O. V. Boguslayev

METAL-CASTING PROCESSES

Teaching aid

М.К. Князєв, С.В. Сергєєв, О. В. Богуслаєв

ПРОЦЕСИ ЛИТТЯ МЕТАЛЕВИХ СПЛАВІВ

Навчальний посібник

Харків «ХАІ» 2002

УДК 621.7/4 : 663 (075.8)

Metal-Casting Processes / M.K. Knyazyev, S.V. Sergeyev, O.V. Boguslayev. – Teaching aid. – Kharkiv: National Aerospace University "Kharkiv Aviation Institute", 2002. – 81 p.

Процеси лиття з металевих сплавів / М.К. Князєв, С.В. Сергєєв, О.В. Богуслаєв. – Навч. посібник. – Харків: Нац. аерокосмічний ун-т "Харк. авіац. ін-т", 2002. – 81 с.

The fundamentals of metal-casting processes are submitted. The main casting methods and corresponding equipment are described. The problems of casting design, casting alloys and economics of casting processes are discussed. Sand mold designing is considered in greater detail. The teaching aid was developed on the base of original sources.

It is destined to help the students of mechanical specialities in studying the discipline "Professional foreign language".

Подано основи ливарного виробництва з металевих сплавів. Описано основні ливарні методи та відповідне обладнання. Висвітлено питання конструкції відливок, сплавів для лиття та економічні питання ливарних процесів. Більш докладно розглянуто проектування земляних ливарних форм. Навчальний посібник розроблено на базі оригінальних джерел.

Для студентів механічних спеціальностей при вивченні дисципліни "Ділова іноземна мова".

Fig. 62. Tables 12. Bibliogr.: 3 titles

Рис. 62. Табл. 12. Бібліогр.: 3 назви

Рецензенти: канд. техн. наук, доц. М.Ф. Савченко
канд. філол. наук, доц. Н.Г. Доліна

CONTENT

Introduction

Casting is the fastest way to go from a raw material to a simple or complex shape that is hollow or nonuniform in cross section. More than 85 percent of all metal castings are poured into sand molds, the balance are made in ceramic shell or metal molds.

The casting process is basically accomplished by pouring a liquid material into a mold cavity of the shape of the desired item and allowing it to solidify. Castings are frequently hollow. The hole may be made by a core that the molten metal would surround, or one could allow a skin to freeze and the liquid center would then be poured out.

Bronze arrowheads were cast some 6000 years ago in open-faced clay molds; small statues and religious items were poured not much later. The art of founding is fundamental to the production of tools for all civilizations. Casting was practiced throughout the ancient world: in Europe, Central and South America, India, the Orient, and North Africa. The bronze age appeared at different times in each area, but it is not known whether the knowledge was transferred from people to people or whether it was, like language, discovered independently by the different civilizations. According to the Bible, Tubal Caine was the world's first historical foundryman.

Certainly the Church nurtured the art of founding and preserved much of the science of casting and practical metallurgy through the publication of Biringuccio's *Pirotechnia* in the 16th century. In that work he gave detailed instructions for casting large church bells using a pit mold build at the base of the steeple in order to minimize the handling of the large castings. Pit molding is still used today for castings such as a large turbine for a hydroelectric plant.

Now the casting processes are capable of producing intricate shapes in a single piece, including those with internal cavities. Typical cast products are engine blocks, crankshafts, pistons, valves, railroad wheels, and ornamental artifacts.

Although casting processes allow a great deal of versatility in part size and shape, they most often are selected over other manufacturing methods for the following reasons:

a) To produce complex shapes with internal cavities or hollow sections.
b) To produce very large parts.
c) To utilize workpiece materials which are difficult to process by other means.
d) Economic considerations.

Almost all metals can be cast in (or nearly in) the final shape desired, often with only minor finishing required. With appropriate control of material and process parameters, parts can be cast with uniform properties throughout. Although much progress has been made in improving quality, dimensional accuracy, and surface finish, major casting limitations remain.

Compared to parts made other shaping processes, castings have generally lower toughness and ductility and may contain defects, such as porosity.

Several casting processes have been developed to date (Fig. i.1). As in all manufacturing, each process has its own characteristics, applications, advantages, and limitations. Regardless of the method of casting used, we must understand and control certain fundamental aspects of the process in order to economically produce castings of good quality, dimensional accuracy, and surface finish. These aspects are solidification of metals, heat transfer, and flow of the molten metal into the mold cavities. They are influenced by mold material, casting design, and various other material and process variables. We present these fundamental aspects of casting in Chapter 1. You will then use this knowledge in studying Chapters 2 and 3 on casting processes and design.

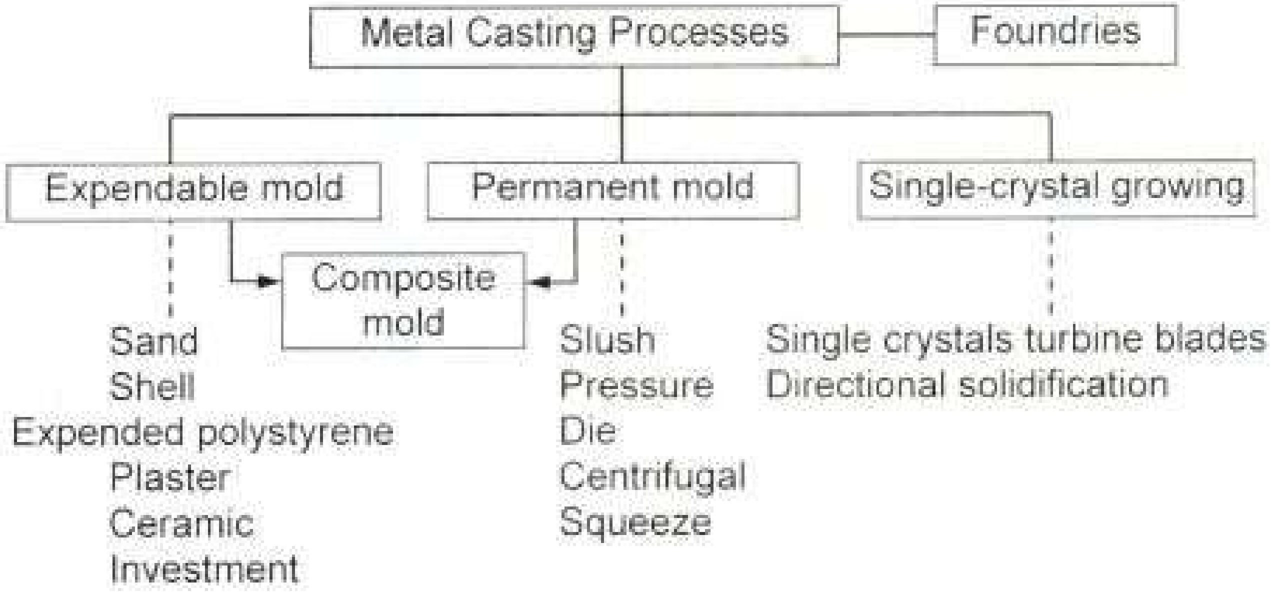


FIGURE i.1. An outline of metal casting processes

Two principal types of casting are expendable-mold and permanent-mold casting. In the former, the mold is made of nonmetallic materials, such as sand, plaster, and ceramics. It is broken to remove the casting – hence the word *expendable*. Engine blocks and heads, brake drums, machine bases pipe fittings, and valves are usually made by these processes. In permanent-mold casting, the mold is generally made of metallic materials and is used over and over again – hence the word *permanent*. Carburetors, pistons, toys, and outboard motor housings are made by these processes.

We explore the advantages and limitations of expendable-mold and permanent-mold processes in Chapter 2, together with process parameters typical applications. We also discuss casting processes in terms of the type of metals cast, minimum and maximum sizes and section thicknesses that can be cast, and surface finish, dimensional accuracy, and shape complexity that can be obtained. Because of their unique applications, we also describe crystal growing, a subject that is essential for components such as turbine blades, which must possess superior mechanical properties.

In Chapter 3 we are concerned with casting design considerations, alloy casting characteristics and casting economics. We present the fundamentals of casting design that are necessary to avoid defects and maintain part integrity, surface finish and dimensional accuracy. We also describe the characteristics and applications of major nonferrous and ferrous casting alloys, including cast irons and steels.

Regardless of the technological capabilities of various casting processes the economics of casting is important in selecting a method of manufacturing. We take a brief look at the factors that contribute to the cost of casting.

The knowledge gained in this part of the text will enable you to better evaluate the technical and economic feasibility of using casting to manufacture certain components. After studying other manufacturing processes, you will be able to decide whether a particular component should be produced by casting or by forming, machining, welding, or by a combination of manufacturing processes.

1. Fundamentals of Metal Casting

1.1. Introduction

The casting process basically involves pouring molten metal into a mold patterned after the part to be manufactured, allowing it to cool, and removing the metal from the mold. As with all other manufacturing processes, certain fundamental relationships are essential to the production of good quality and economical castings. Knowledge of these relationships helps us establish proper techniques for mold design and casting practice. Our objective is to produce castings that are free from defects and that meet requirements for strength, dimensional accuracy, and surface finish.

The important factors in casting operations are:

- the flow of the molten metal into the mold cavity;
- solidification of the metal from its molten state;
- heat transfer during solidification and cooling of the metal in the mold;
- influence of the type of mold material.

1.2. Solidification of Metals

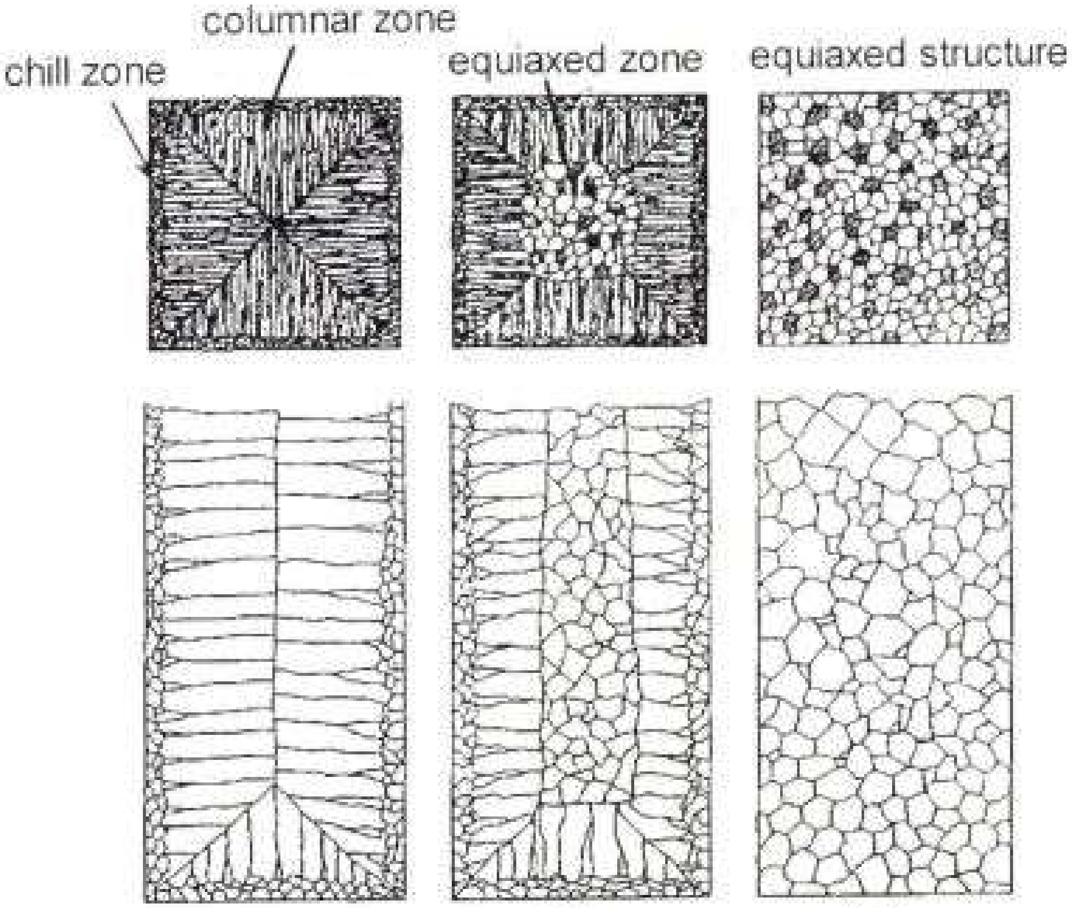
After molten metal is poured into a mold, a series of events takes place during solidification of the casting and its cooling to ambient temperature. These events greatly influence the size, shape, and uniformity of the grains formed throughout the casting, which in turn influence its overall properties. The significant factors affecting th events are the type of metal, thermal properties of both the metal and mold, the geometric relationship between volume and surface area of casting, and the shape of the mold.

1.2.1. Pure metals

Because a pure metal has a clearly defined melting or freezing p it solidifies at a constant temperature. Pure aluminum, for exam solidifies at 660 °C (1220 °F), iron at 1537 °C (2798 °F), and tungste 3410 °C (6170 °F).

When the temperature of the molten metal is reduced to its free point, its temperature remains constant while the latent heat of fusio given off. The solidification front (solid–liquid interface) moves through molten metal, solidifying from the mold walls in toward the center. O solidification has taken place at any point, cooling resumes. The solidi metal, which we now call the casting, is then taken out of the mold begins to cool to ambient temperature.

Grain structure. The grain structure of a pure metal cast in a sq mold is shown in Fig. 1.1(a).



(a) (b) (c)

FIGURE 1.1. Schematic illustration of three cast structures of me solidified in a square mold: (a) pure metals;(b) solid-solution alloys; an structure obtained in the absence of thermal gradients within the solidif metal, or using a catalyst to induce heterogeneous nucleation of grains

At the mold walls, the metal cools rapidly since the walls are at ambient temperature. Rapid cooling produces a solidified skin, or shell, of fine equiaxed grains. The grains grow in the direction opposite to the heat transfer out through the mold. Those grains that have favorable orientation will grow preferentially and are called columnar grains (Fig. 1.2). As the driving force of the heat transfer is reduced away from the mold walls, the grains become equiaxed and coarse. Those grains that have substantially different orientations are blocked from further growth.

The size and distribution of the overall grain structure throughout a casting depends on the rate and direction of heat flow. These are important considerations because grain size influences strength and ductility, and lack of uniform grain size and distribution results in castings with anisotropic properties.

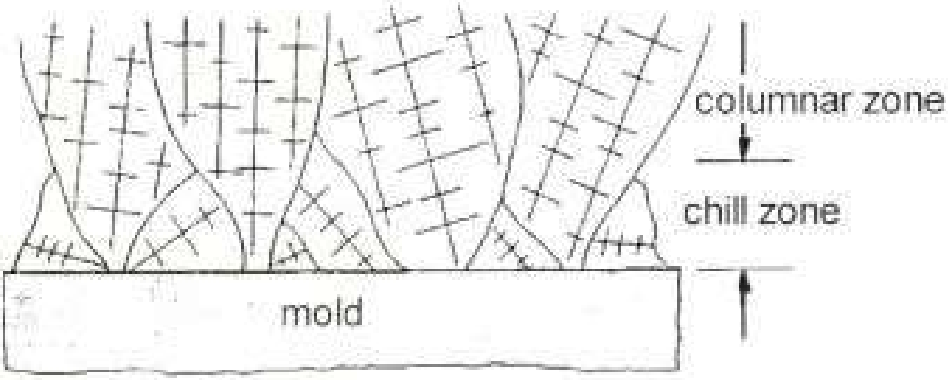


FIGURE 1.2. Development of a preferred texture at a cool mold wall. Note that only favorably oriented grains grow away from the surface of the mold

1.2.2. Alloys

Unlike pure metals, alloys solidify over a range of temperatures. Solidification begins when the temperature drops below the liquidus and is completed when it reaches the solidus (Fig. 1.3). Within this temperature range – the mushy zone – the alloy is in a mushy or pasty state with columnar or equiaxed dendrites (from the Greek *dendron* meaning akin to, and *drys* meaning tree). Note the presence of liquid metal between the dendrites.

Grain structure. A typical cast structure of a solid-solution alloy, with an inner zone of equiaxed grains, is shown in Fig. 1.1(b). The inner zone can be extended throughout the casting, as shown in Fig. 1.1(c), by the addition of a catalyst in the alloy. The catalyst, also called the inoculant, induces nucleation of grains throughout the molten metal, instead of the usual grain formation first at the cool mold walls, and progression toward the center of the casting (see Fig. 1.1a). Typical catalysts are sodium, bismuth, tellurium, and magnesium. Another method of obtaining the equiaxed structure shown in Fig. 1.1(c) is to reduce or eliminate thermal gradients, thus eliminating convection within the molten metal. Experiments are now being carried out in space, where the lack of gravity eliminates convection.

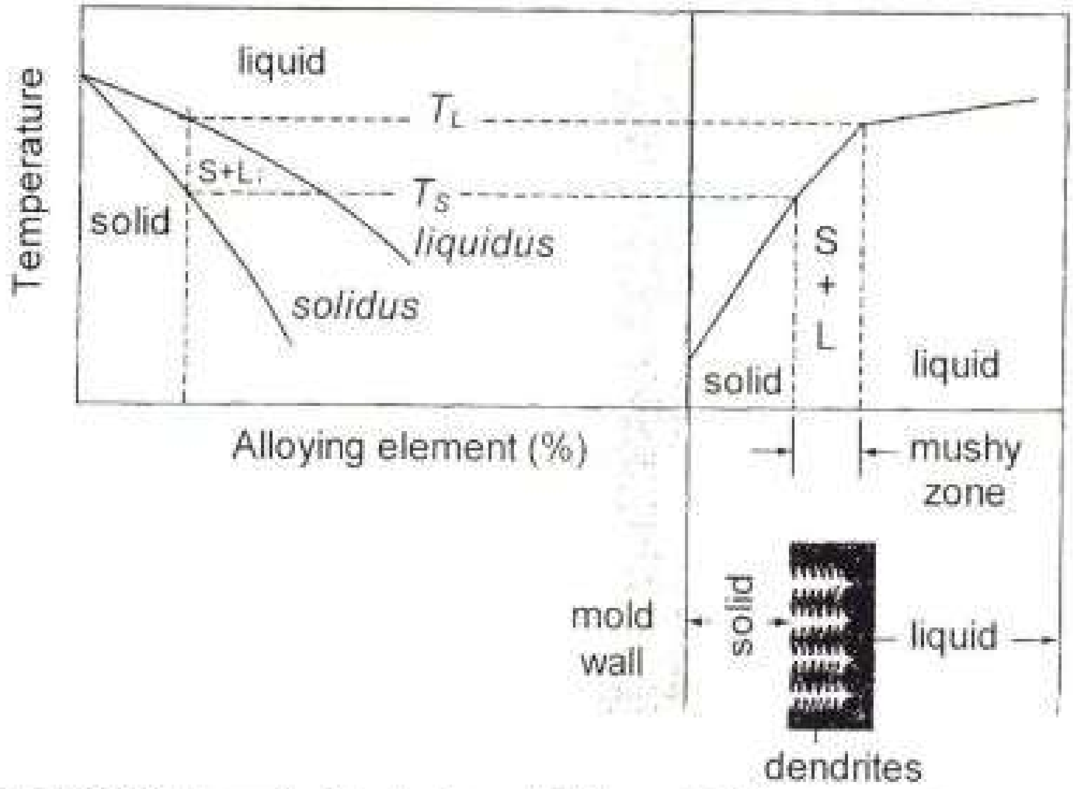


FIGURE 1.3. Schematic illustration of alloy solidification and temperatur distribution in the solidifying metal. Note the formation of dendrites in th mushy zone

As you can see in Fig. 1.4(a), dendrites have three-dimensional arm and branches, like the branches of a tree, and they eventually interlock.

When the alloy is cooled very slowly, each dendrite develops uniform composition. Normal cooling, however, forms cored dendrite which have a surface composition different from that at their centers. variety of dendritic structures can be obtained, depending on th composition of the alloy and cooling rate, which depends on the therma properties of the mold material. Sand molds have low thermal conductivity whereas metal molds (permanent molds) have much higher therma conductivity and the molten metal solidifies much faster.

With sand molds, steels containing lower percentages of carbo solidify with a marked skin formation, called *short freezing range* (Fig 1.4b). With higher carbon content, the molten metal develops extensiv mushy zones during solidification (*long freezing range*). Note how muc thicker the solidified skin is when chill molds are used, even though th elapsed time is much shorter. Freezing range is the difference between T and T_S, as shown in Fig. 1.3. The smaller the difference, the shorter is th freezing range. A list of various alloys and their freezing ranges ar presented in Table 1.1.

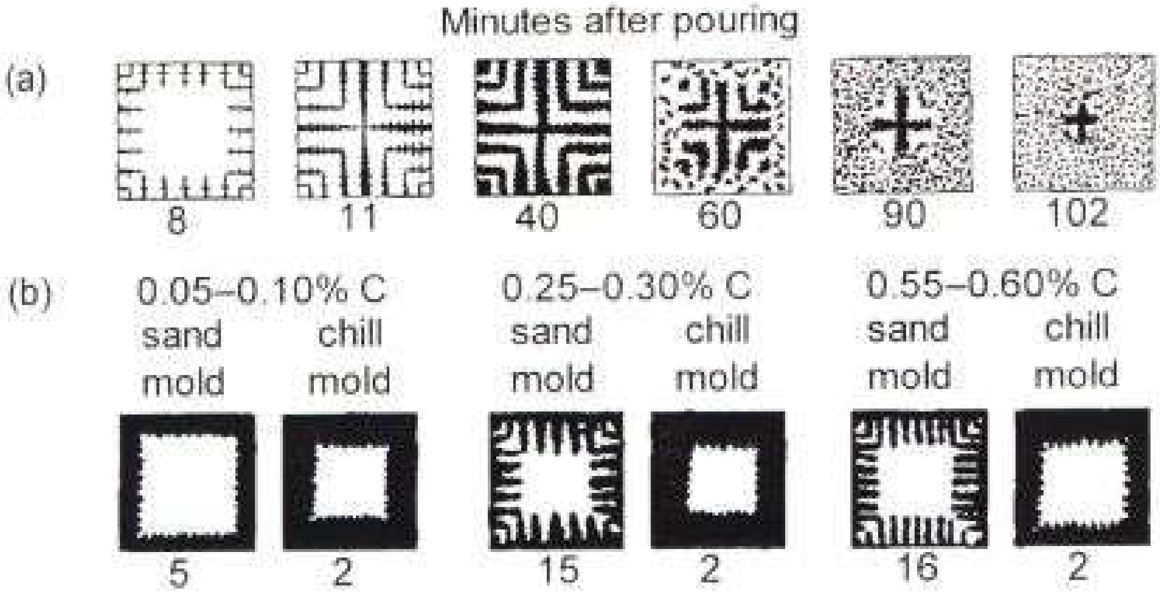


FIGURE 1.4. (a) Solidification patterns for gray cast iron in a 180-mm (7-in.) square casting. Note that after 11 min of cooling, dendrites reach each other, but the casting is still mushy throughout. It takes about two hours for this casting to solidify completely. (b) Solidification of carbon steels in sand and chill (metal) molds. Note the difference in solidification patterns as the carbon content increases.

TABLE 1.1. SOLIDIFICATION CHARACTERISTICS OF METALS AND ALLOYS IN CASTING

SHORT FREEZING RANGE (FREEZING WITH MARKED SKIN FORMATION)	LONG FREEZING RANGE (FREEZING WITH EXTENSIVE PASTY OR MUSHY ZONE)
Aluminum	Aluminum alloys
Aluminum bronzes	Bronzes
Brasses	Magnesium alloys
Copper	Nickel-base alloys
Low-carbon steels	Medium- and high-carbon steels

1.2.3. Solidification time

At the early stages of solidification, a thin solidified skin begins to form at the cool mold walls. As time passes, this skin thickness increases. With flat mold walls, this thickness is proportional to the square root of time. Thus doubling the time will make the skin $\sqrt{2} = 1.41$ times, or 41 percent, thicker.

The solidification time is a function of the volume of a casting and its surface area (Chvorinov's rule). We can express it as

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^2, \tag{1.1}$$

where C is a constant that depends on mold material, metal properties (including latent heat), and temperature. Thus a large sphere will solidify and cool to ambient temperature at a much slower rate than will a smaller diameter sphere. We can draw an analogy here with two freshly boiled potatoes having different diameters. We know from experience that the larger one cools more slowly than the smaller one. The reason is that the volume is proportional to the cube of the diameter of a sphere, and the surface area is proportional to the square of the diameter. Similarly, we can show that molten metal in a cube-shaped mold will solidify faster than in a spherical mold of the same volume.

The effects of mold geometry and elapsed time on skin thickness and its shape are shown in Fig. 1.5.

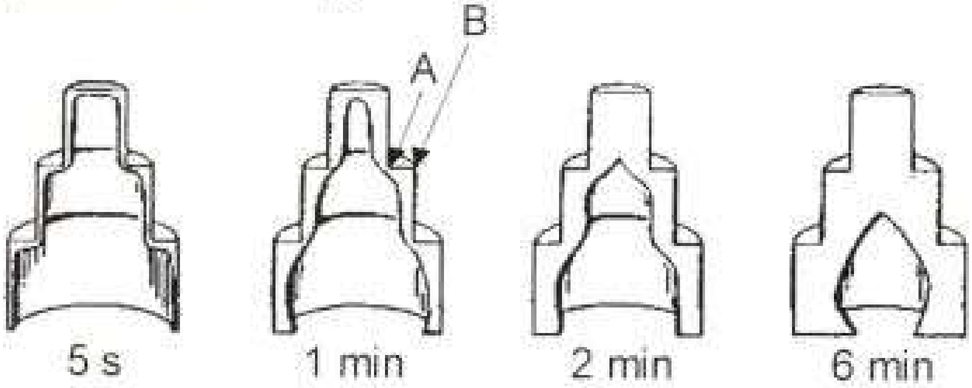


FIGURE 1.5. Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called slush casting, which is based on this principle

In these illustrations, the unsolidified molten metal has been poured from the mold at different time intervals, ranging from 5 s to 6 min. Note that the skin thickness increases with elapsed time but that the skin is thinner at internal angles (location A in the figure) than at external angles (location B). This latter condition is caused by slower cooling at internal angles than at external angles. Hollow ornamental and decorative objects are made by a process based on Fig. 1.5 called slush casting.

Example: Solidification times for various shapes.

Three pieces being cast have the same volume but different shapes. One is a sphere, one a cube, and the other a cylinder with height that is equal to the diameter. Which piece will solidify the fastest and which one the slowest?

Solution. Since the volumes are equal, we have from Eq. (1.1)

$$Solidification \quad time = C/(Surface\ area)^2 .$$

Assuming that the volume is unity (V = 1), we then determine the respective surface areas as follows:

$$\text{Sphere: } V = \frac{4}{3}\pi \cdot r^3, \text{ hence } r = \left(\frac{3}{4\pi}\right)^{1/3}.$$

$$A = 4\pi \cdot r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.48.$$

$$\text{Cube: } V = a^3, \text{ hence } a = 1.$$

$$A = 6a^2 = 6.$$

$$\text{Cylinder: } V = \pi \cdot r^2 h = 2\pi \cdot r^3, \text{ hence } r = \left(\frac{1}{2\pi}\right)^{1/3}.$$

$$A = 2\pi \cdot r^2 + 2\pi \cdot rh = 6\pi \cdot r^2 = 5.54.$$

Thus the solidification times t will be: t_{sphere} = 0.043C; t_{cube} = 0.028C; t_{cylinder} = 0.033C. Hence, the molten metal poured into the cube-shaped mold will solidify the fastest and that poured into the spherical mold will solidify the slowest.

1.2.4. Shrinkage and porosity

Because of their thermal expansion characteristics, metals shrink (contract) during solidification and cooling. This causes dimensional changes that can lead to centerline shrinkage, porosity, and, sometimes, cracking. Shrinkage results from the following three factors:

1. Contraction of the molten metal as it cools prior to its solidification.
2. Contraction of the solidifying metal caused by latent heat of fusion.
3. Contraction of the solidified metal (the casting) as its temperature drops to ambient temperature.

The largest amount of shrinkage occurs during cooling of the casting. The amount of contraction for various metals during solidification is shown in Table 1.2. (See also Table 3.1 for shrinkage allowance for castings.) Note that gray cast iron expands. This happens because graphite has a relatively high specific volume, and when it precipitates as graphite flakes during solidification, it causes a net expansion of the metal. Porosity in casting may be caused by shrinkage or gases, or both. Porosity is detrimental to the ductility of a casting (Fig. 1.6) and its surface finish, making it permeable and thus affecting pressure tightness of a cast pressure vessel.

TABLE 1.2. SOLIDIFICATION CONTRACTION FOR VARIOUS CAST METALS

METAL OR ALLOY	VOLUMETRIC SOLIDIFICATION CONTRACTION (%)	METAL OR ALLOY	VOLUMETRIC SOLIDIFICATION CONTRACTION (%)
Aluminum	6.6	70%Cu-30%Zn	4.5
Al– 4.5% Cu	6.3	90%Cu-10%Al	4
Al–12% Si	3.8	Gray iron	Expansion to 2.5
Carbon steel	2.5-3	Magnesium	4.2
1% carbon steel	4	White iron	4 – 5.5
Copper	4.9	Zinc	6.5

Porosity caused by shrinkage. Porous regions can develop in castings because of shrinkage of the solidified metal (Fig. 1.7). The thinner sections in a casting solidify sooner than thicker regions, and as a result, molten metal cannot be fed into the thicker regions that have not yet solidified. The surfaces of the thicker region begin to solidify, and because of contraction, a porous region develops at its center. Microporosity can also develop when the liquid metal solidifies and shrinks between dendrites and between dendrite branches (see Figs. 1.3 and 1.4).

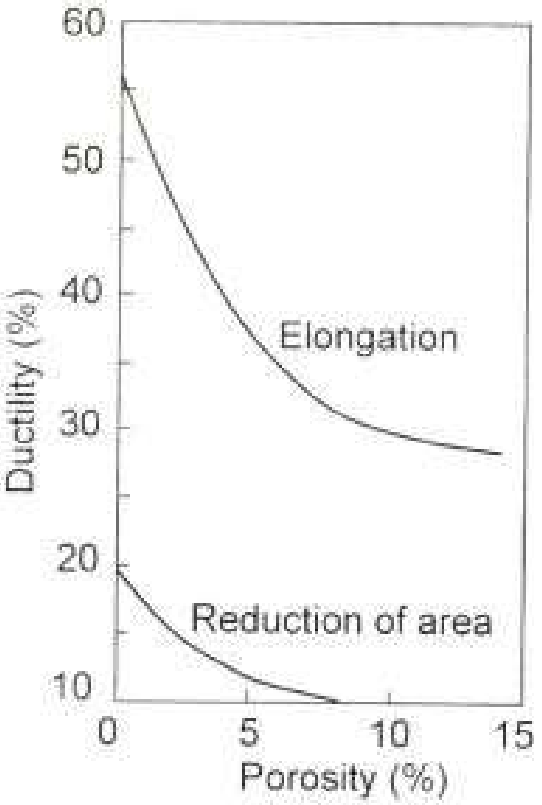


FIGURE 1.6. The effect of microporosity on the ductility of quenched and tempered 1% Cr – 0.25% Mo cast steel

Porosity caused by shrinkage can be reduced or eliminated by various means (Chapter 3). Basically, provision should be made for an adequate supply of liquid metal to avoid cavities caused by shrinkage. External or internal chills, used in sand casting (Fig. 1.8), are an effective means of reducing porosity. The function of the chills is to increase the rate of solidification in critical regions. Internal chills are usually made of the same material as the castings. External chills may be made of the same material or may be water-cooled copper or brass chills.

With alloys, porosity can be reduced or eliminated by methods that make the mushy zone in the casting (see Fig. 1.3) as narrow as possible. This can be done by making the temperature gradient steep by using mold materials that have high thermal conductivity or other methods. Subjecting the casting to hot isostatic pressing is another method of reducing porosity.

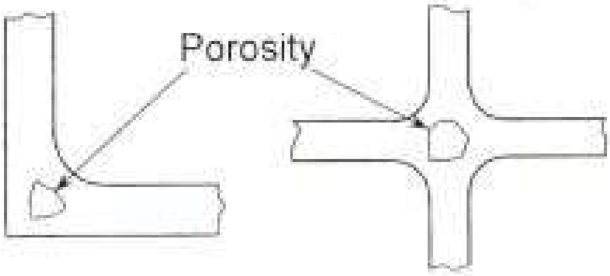


FIGURE 1.7. Examples of porosity in castings, due to shrinkage of the metal during cooling and solidification

Porosity caused by gases. Liquid metals have much greater solubility for gases than do solids. When a metal begins to solidify, the dissolved gases are expelled from the solution. They either accumulate in regions of existing porosity, such as in interdendritic areas, or they cause microporosity in the casting. Thus it is necessary to control or eliminate gases. Hydrogen and nitrogen are commonly present in castings, the former being soluble in all metals to various degrees.

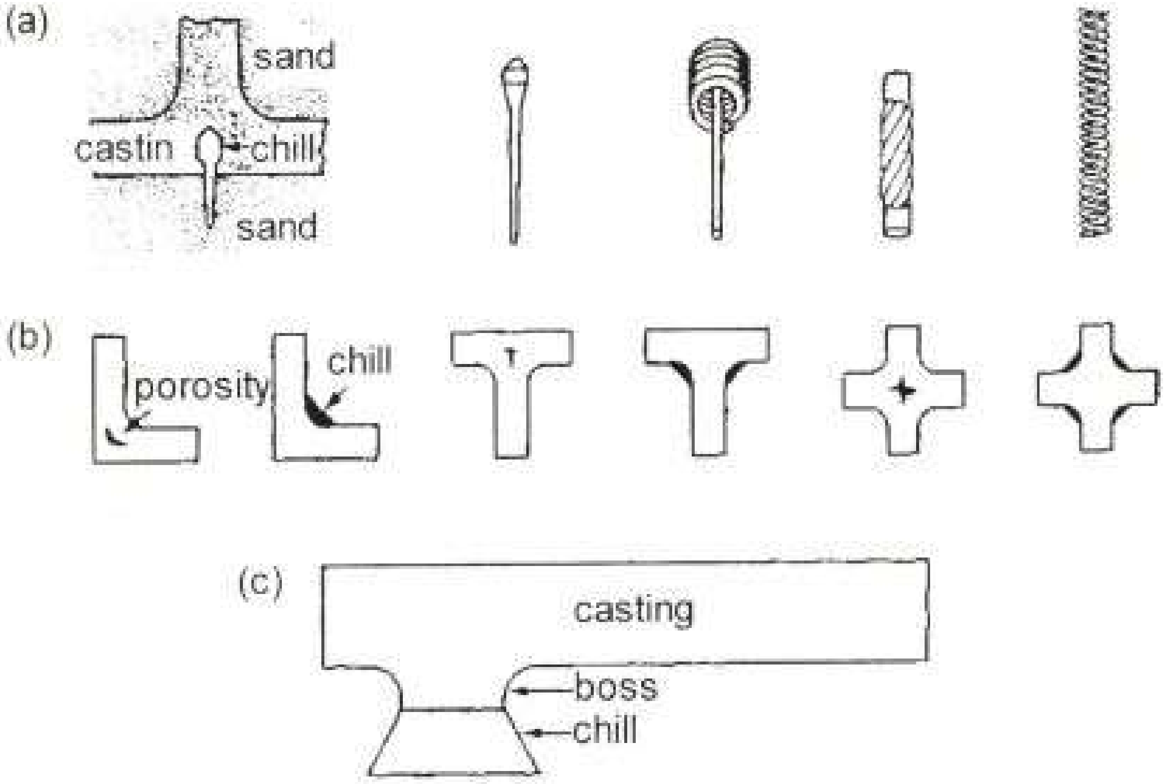


FIGURE 1.8. Various types of (a) internal and (b) external chills (dark areas in corners), used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metal, as shown in (c).

Dissolved gases may be removed from the molten metal by flushing or purging with an inert gas, or by melting and pouring the metal in a vacuum. If the dissolved gas is oxygen, the molten metal can be deoxidized. Steel is usually deoxidized with aluminum or silicon and copper-base alloys with phosphorus copper. High-quality steels are being produced by argon-oxygen deoxidation (AOD).

Whether microporosity is a result of shrinkage or is caused by gases may be difficult to determine. If the porosity is spherical and has smooth walls, much like the shiny surfaces of holes in Swiss cheese, it is generally from gases. If the walls are rough and angular, porosity is likely from shrinkage between dendrites. Gross porosity, such as that shown in Fig. 1.7, is from shrinkage and is usually called shrinkage cavities.

Porosity may be determined by metallographic examination under a microscope or by volumetric measurement. The latter method is used to determine the density of a casting, with a porous casting having a lower density.

1.3. Flow of Molten Metal in Molds

One of the most important aspects of the casting process is the flow of the molten metal as it is poured into the mold cavity. In order to appreciate its importance, let's first review a basic casting system (Fig. 1.9). The molten metal is poured through a pouring basin or cup, and then flows through the sprue and runners into the mold cavity. The purpose of risers is to ensure a reservoir of molten metal to supply the metal necessary to avoid shrinkage cavities. Although such a gating system appears to be relatively simple, successful casting practice requires careful design and control of the solidification process to ensure adequate metal flow into the mold.

The manner in which metal should flow through the passages of the mold and how it solidifies as a function of time require knowledge of fluid flow, heat transfer, and the influence of thermal gradients (temperature drop). Even before it reaches the mold cavity, the molten metal must be handled carefully in order to avoid (1) trapping gas, (2) formation of oxides on molten metal surfaces from exposure to the environment, or (3) introduction of impurities into the molten metal.

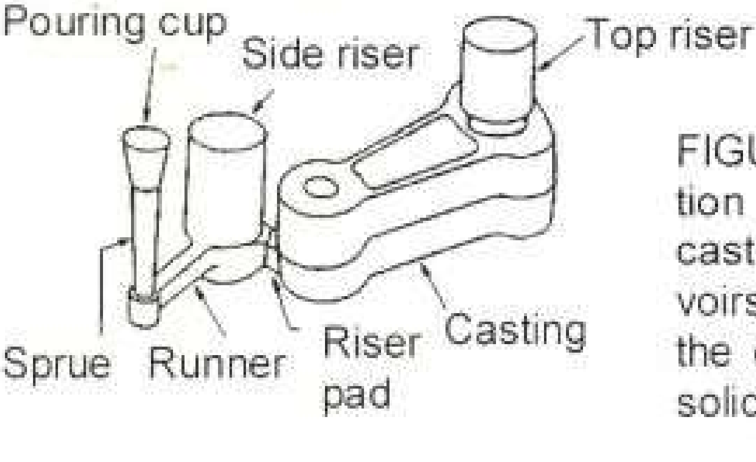


FIGURE 1.9. Schematic illustration of a typical riser gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification

1.3.1. Fluid flow

The molten metal must be introduced into the gating system in such a way that turbulence is minimized or eliminated; otherwise, the mold may be eroded and gas pickup may occur. Aspiration, which is entrapment of air resulting from a pressure differential at the bottom of the sprue or to turbulent flow, is another problem. This condition occurs particularly at the sprue but can be reduced substantially by tapering the sprue. Making the cross-section of the sprue smaller toward the bottom compensates for the velocity increase of the molten metal flowing downward by gravitational force.

The runners, which are channels to the mold cavity, should be streamlined and free from sharp corners or abrupt changes in cross-section in order to avoid further turbulence. Although it is difficult to eliminate turbulent flow during the casting process, turbulence can be minimized with proper design of the gating system.

The elimination of slag or dross is another consideration. They are usually formed as a result of impurities rising to the surface of the molten metal, or they may be caused by oxidation of the metal. Several techniques may be used to clean the molten metal before it enters the mold (Fig. 1.10). The slag or dross can be skimmed, using skim bobs and properly designed gating or pouring basins. Filters and screens may also be used, usually for nonferrous alloys. Filters are made of sheet metal, ceramics, graphite, mica, or fiberglass. The proper location and placement of these screens is important for filtering the slag or dross properly.

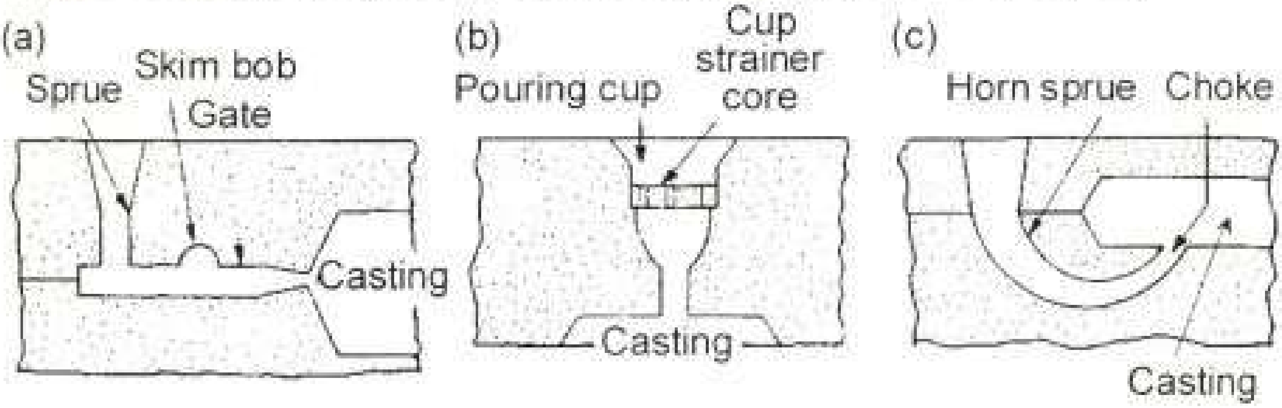


FIGURE 1.10. Types of sprues used to clean molten metal entering the mold: (a) parting gate with skim bob to trap slag; (b) top gate with strainer; and (c) bottom gate with horn sprue

1.3.2. Heat flow

In addition to the basic fluid-flow considerations that we have described, another important consideration is heat flow during the complete cycle from pouring of the molten metal to its solidification and cooling to ambient temperature. The heat flow at various regions in the system is complex and is influenced by many factors.

The liquid metal's flow rate must be sufficiently high to avoid premature chilling and solidification. The flow rate is particularly important for thin sections with high surface area-to-volume or surface area-to-thickness ratios. On the other hand, the flow rate must not be high enough to cause excessive turbulence.

1.3.3. Fluidity

A term commonly used to describe combined fluid flow and heat flow characteristics is fluidity. This term indicates the capability of the molten metal to flow into the cavities of the system before freezing. Thus we can regard fluidity as a characteristic related to viscosity, which is a fluid's internal resistance to flow. For example, oil flows readily at high temperatures, but less so at room temperature because of higher viscosity. In one test developed to quantify fluidity (Fig. 1.11), the molten metal is poured into the sprue and flows along a spiral channel that is at room temperature. The length of the solidified metal along the circular path is a measure of fluidity. The greater the length, the greater is the fluidity.

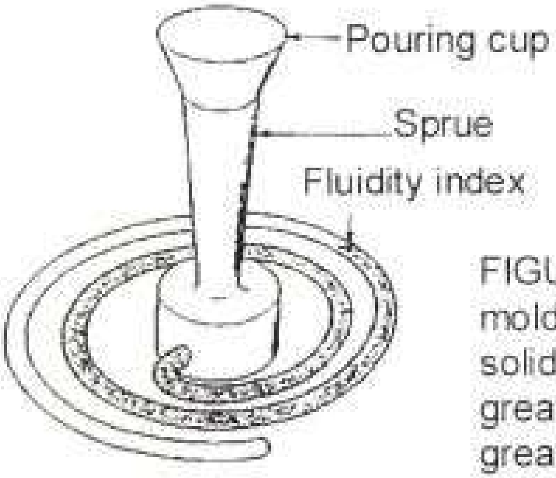


FIGURE 1.11. A test for fluidity using a spiral mold. The fluidity index is the length of the solidified metal in the spiral passage. the greater the length of the solidified metal, the greater is its fluidity

1.4. Furnaces and Melting Practices

Furnace selection and melting practices require careful consideration of a number of factors. These factors can have significant influence on the quality of castings, as well as on the economics of casting operations.

Let's consider briefly the types of furnaces commonly used in foundries to melt metals and alloys and the melting practices commonly employed.

1.4.1. Furnaces

A variety of furnaces that meet various requirements for melting and casting metals and alloys are available in foundries. The proper selection of a furnace generally depends on the following factors:

a) The composition and melting point of the alloy to be cast.
b) Control of the atmosphere to avoid contamination of the metal.
c) Capacity and the rate of melting required.
d) Environmental considerations, such as air pollution and noise.
e) Power supply and its availability and cost of fuels.
f) Economic considerations, such as initial cost and operating and maintenance costs.

The most commonly used furnaces in foundries today are cupolas and electric-arc and induction furnaces. Cupolas are basically refractory-lined vertical steel vessels that are charged with alternating layers of metal, coke, and flux (Fig. 1.12). Although they require major investments, cupolas produce large amounts of molten metal (as much as 40 tons per hour). They operate continuously and have high melting rates. Whereas cupolas are used for primary melting of metals to form pigs, these metals are remelted in electric-arc and induction furnaces to form composition-controlled smaller melts for casting shapes.

Different types of furnaces are used for batch melting and continuous melting. In a batch melting operation, a crucible of a certain capacity is used. In continuous operations, melting and tapping can be done continuously in a cupola.

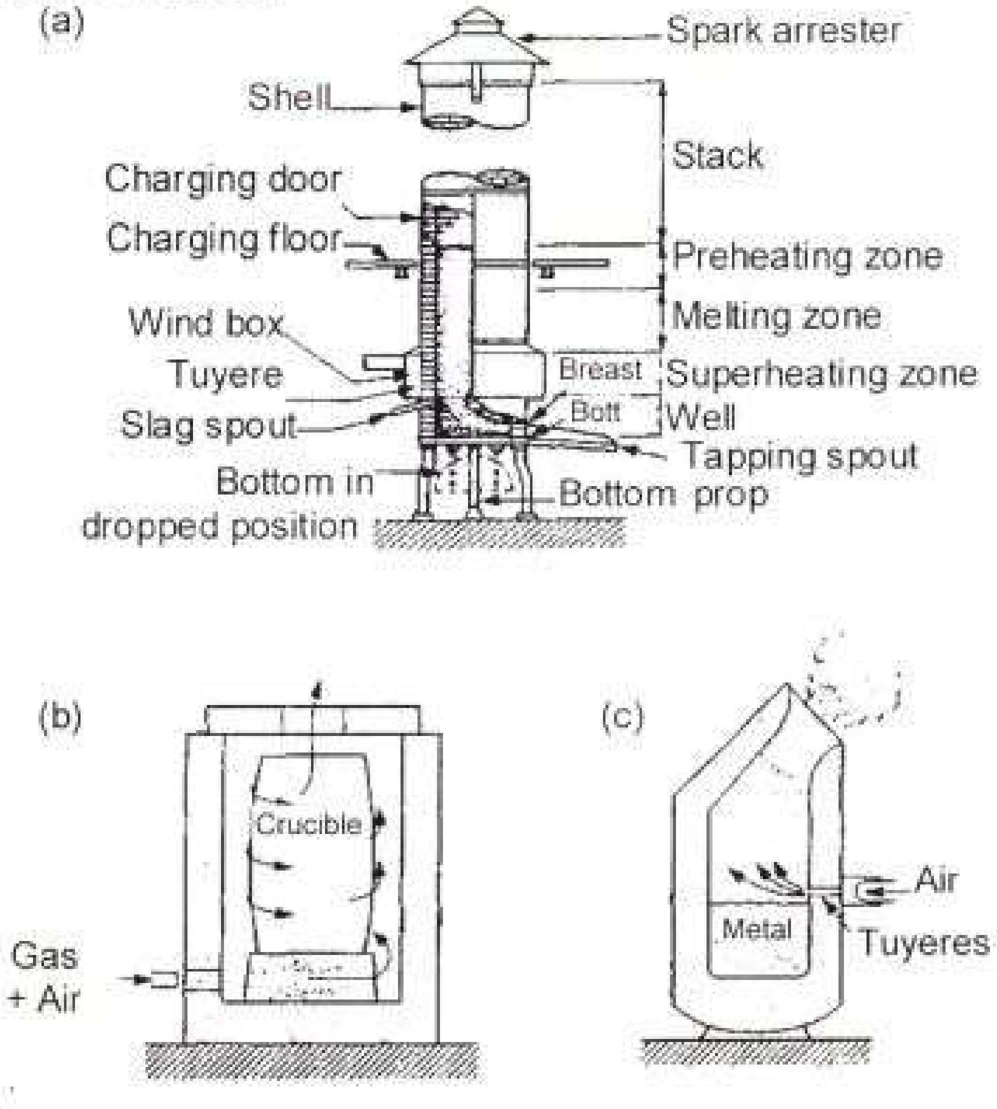


FIGURE 1.12. Types of melting furnaces used in foundries: (a) cupola; (b) crucible; (c) converter. The selection of a furnace for a particular application depends on many technical and economic factors

1.4.2. Melting practice

Melting practice is an important aspect of casting operations because it has a direct bearing on the quality of castings. Furnaces are charged with melting stock consisting of metal, alloying elements, and various other materials (such as flux and slag). Fluxes are inorganic compounds, such as limestone and dolomite, and may include secondary fluxes, such as sodium carbonate and calcium fluoride (for cast iron) and borax-silica mixtures (for copper alloys). These compounds refine the molten metal by removing dissolved gases and various impurities. The metal charge may be composed of commercially pure primary metals and secondary metals, which are remelted scrap. Clean scrapped castings, gates, and risers may also be included in the charge.

If the melting points of the alloying elements are sufficiently low, pure alloying elements are added to obtain the desired composition in the melt. If the melting points are too high, the alloying elements do not mix readily with the low-melting-point metals. In this case, master alloys, or hardeners, are used. They usually consist of lower melting-point alloys with higher concentrations of one or two of the needed alloying elements. Master alloys should not have a tendency to segregate in the melt because of differences in specific gravity.

In order to protect the surface of the molten metal against atmospheric reaction and contamination, and to refine the melt, it must be insulated against heat loss. This is usually done by covering the surface or mixing the melt with compounds that form a slag. In casting steels, the composition of the slag includes CaO, SiO_2, MnO, and FeO. A small quantity of liquid metal is usually tapped and its composition analyzed. Necessary additions or inoculations are then made prior to pouring the metal into the molds.

The tapping and pouring of the molten metal require careful handling in order to reduce contamination by gases and nonmetallic impurities. Ladles must be clean and free of moisture; otherwise explosions caused by water being trapped and converted into steam at a rapid rate may occur.

1.5. Casting Defects

Several types of defects in castings can be caused by the type of flow of the liquid metal into the mold cavity, shrinkage of the metal during solidification, and other conditions. If metal is constrained from shrinking freely during solidification, cracking (hot tearing) occurs (Fig. 1.13). Although many factors are involved, coarse grain size and low-melting segregates increase the tendency for hot tearing, a phenomenon similar to hot shortness. The design of the casting and the molds must therefore provide for contraction of the solidifying metal, such as by the use of collapsible sand cores. Several other types of defects occur in castings because of the way the liquid metal flows, trapped gases, and the presence of oxides and contaminants. The types of defects that generally relate to sand casting are (Fig. 1.14):

a) Blows, scars, blisters, and scabs (Fig. 1.14a-d), which are cavities on the surface of the casting.

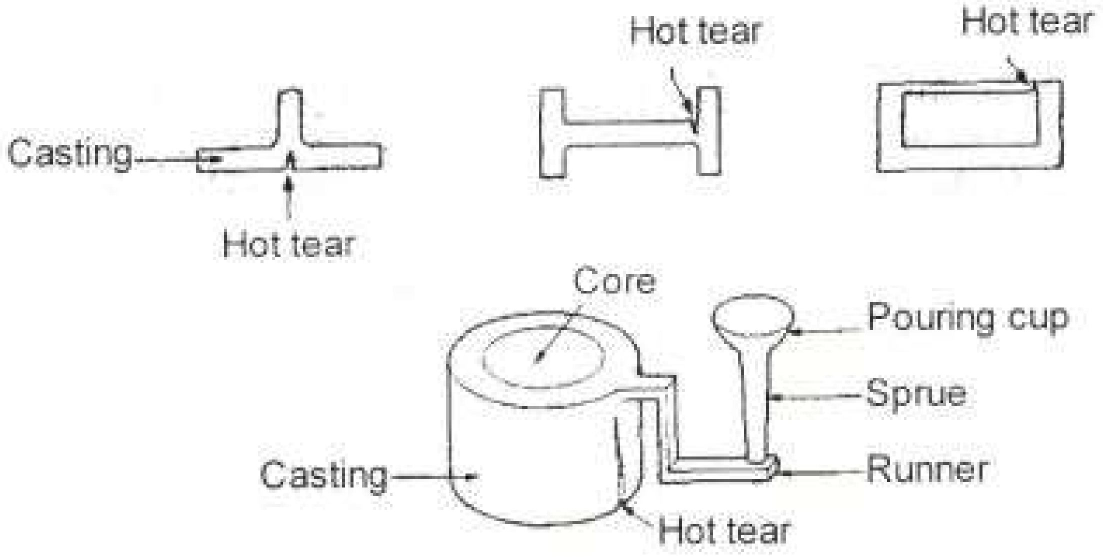


FIGURE 1.13. Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat producing) compounds may be used (exothermic padding) to control cooling at critical sections to avoid hot tears.

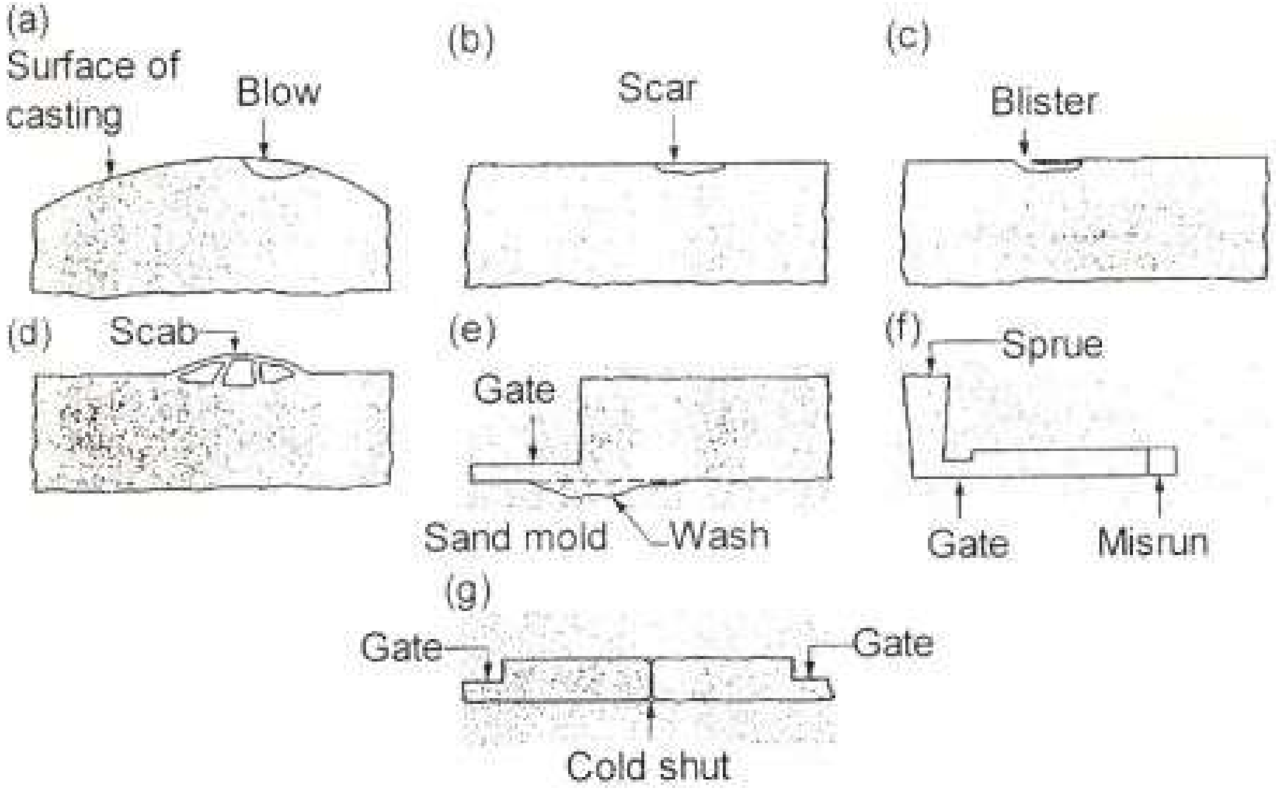


FIGURE 1.14. Examples of common defects in casting. These defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedure.

b) Wash or cut, which is a projection on the lower surface of the casting caused by erosion of the sand mold's surface (Fig. 1.14e) by the liquid metal flow.

c) Misruns (Fig. 1.14f), which are incomplete castings.

d) Cold shut, which is an interface in a casting that lacks complete fusion because of the meeting of two streams of liquid metal from different gates (Fig. 1.14g). This may also occur in die casting.

REVIEW QUESTIONS

1.1. Why is casting an important manufacturing process?

1.2. What is the difference between the solidification of pure metals and metal alloys?

1.3. What are dendrites?

1.4. State the difference between short and long freezing ranges. How is range determined ?

1.5. Describe the parameters on which solidification time depends.

1.6. Define shrinkage and porosity. How can you tell whether cavities in a casting are due to porosity or to shrinkage ?

1.7. What is the function of chills?

1.8. How are dissolved gases removed from molten metal?

1.9. Describe the features of a gating system.

1.10. How is fluidity defined? Why is it important?

1.11. Name the factors involved in the selection of furnaces.

1.12. What are master alloys?

1.13. Explain the reasons for hot tearing in castings.

1.14. Name various defects in castings.

1.15. Why is it important to remove dross or slag during the pouring of molten metal into the mold? What methods are used to remove them?

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

1.17. Describe the stages involved in the contraction of metals during casting.

1.18. Explain the reasons why heat transfer and fluid flow are so important in metal casting.

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

1.20. Describe the events depicted in Fig. 1.4.

1.21. Would you be concerned about the fact that parts of internal chills are left within the casting? What materials do you think chills should be made of, and why?

1.22. Can you think of fluidity tests other than that shown in Fig. 1.11? Explain your tests.

1.23. What practical illustrations can you offer to indicate the relationship of solidification time to volume and surface area ?

1.24. Do you think early formation of dendrites in a mold can impede the free flow of molten metal into the mold? Give an illustration.

1.25. Explain why you may want to subject a casting to various heat treatments.

1.26. Casting is one of the earliest manufacturing processes, dating back to about 4000 B.C. Why do you think this is so?

1.27. Why does porosity have detrimental effects on the mechanical properties of castings? Would physical properties such as thermal and electrical conductivity also be affected by porosity? Explain.

1.28. Assume that the Summary for this chapter is missing. Write a two-page summary.

1.29. Explain the use of risers. Why can blind risers be smaller than open-top risers?

1.30. A spoked handwheel 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.

1.31. Which of the following considerations are important for a riser to function properly? (a) Have a surface area larger than the part being cast, (b) Be kept open to atmospheric pressure, (c) Solidify first. Why?

1.32. A round casting is 0.1 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 2, 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?

1.33. Explain why the constant C in Eq. (1.1) depends on mold material, metal properties, and temperature.

1.34. Are external chills as effective as internal chills? Explain.

1.35. Explain why gray cast iron undergoes expansion, rather than contraction, during solidification, as shown in Table 1.2.

1.36. Referring to Fig. 1.5, explain why internal corners (as A) develop a thinner skin than external corners (as B) during solidification.

1.37. Note the shape of the two risers in Fig. 1.9, and discuss your observations with respect to Eq. (1.1).

1.38. Is there any difference in the tendency for shrinkage void formation for metals with short freezing and long freezing ranges, respectively? Explain.

1.39. What is the influence of the cross-sectional area of the spiral channel in Fig. 1.11 on fluidity test results? What is the effect of sprue height? If this test is run with the test setup heated to elevated temperatures, would the test results be useful? Explain.

1.40. In Section 1.4 we have outlined the factors involved in furnace selection for melting metals and alloys. Explain why the type of furnace selected depends on these factors.

1.41. Make a list of safety considerations and precautions that should be taken concerning all aspects of melting and casting of metals, including the equipment involved.

2. Metal-Casting Processes

2.1. Introduction

In Chapter 1 we presented the fundamentals that underlie all casting processes. In this chapter we move to consideration of the major metal-casting processes and their principles, advantages, and limitations. Many parts and components are made by casting, including carburetors, frying pans, engine blocks, crankshafts, railroad-car wheels, plumbing fixtures, power tools, gun barrels, and machine bases. Various casting processes have been developed over a long period of time, each with its own characteristics and applications, to meet specific engineering and service requirements. In fact, the first castings were made during the period of 4000-3000 B.C., using stone and metal molds for casting copper.

Two trends currently are having a large impact on the casting industry. The first is continuing mechanization and automation of the casting process, which has led to significant changes in the use of equipment and labor. Advanced machinery and automated process-control systems have replaced traditional methods of casting. Moreover, casting processes that especially lend themselves to advances in technology are developing significant economic advantages over other processes (Table 2.1).

Table 2.1. GENERAL CHARACTERISTICS OF CASTING PROCESSES

PROCESS	TYPICAL MATERIALS CAST	WEIGHT (kg)		TYPICAL SURFACE FINISH (µm, R_a)	POROSITY*	SHAPE COMPLEXITY*	DIMENSIONAL ACCURACY*	SECTION THICKNESS (mm)	
		MINIMUM	MAXIMUM					MINIMUM	MAXIMUM
Sand	All	0.05	No limit	5-25	5	1-2	5	3	No limit
Shell	All	0.05	100+	1-3	5	2-3	2	2	—
Plaster	Nonferrous (Al, Mg, Zn, Cu)	0.05	50 +	1-2	3	1-2	2	1	—
Investment	All (High-melting pt.)	0.1	100+	1-3	5	1	1	1	75
Permanent mold	All	0.5	300	2-3	2-3	3-4	2	2	50
Die	Nonferrous (Al, Mg, Zn, Cu)	<0.05	50	1-2	1-2	3-4	1	0.5	12
Centrifugal	All	—	5000 +	2-10	1-2	3-4	3	2	100

* Relative rating: 1 – best; 5 – worst.

The second major trend affecting the casting industry is the increasing demand for high-quality castings with close tolerances. This demand is spurring the further development of casting processes that produce high-quality castings (see Table 2.1). We emphasize the significance of these trends as we discuss the major casting processes.

This chapter is organized around the major classifications of casting practices (see Fig. i.1 in the Introduction). These classifications are related to mold materials, molding processes, and methods of feeding the mold with the molten metal. The two major categories are expendable-mold and permanent-mold casting.

Expendable molds are made of sand, plaster, ceramics, and similar materials, which are generally mixed with various binders, or bonding agents. These materials are refractories, that is, they have the capability to withstand the high temperatures of molten metals. After the casting has solidified, the molds in these processes are broken up to remove the casting.

Permanent molds, as the name implies, are used repeatedly and are designed in such a way that the casting can be easily removed and the mold used for the next casting. These molds are made of metals that maintain their strength at high temperatures and thus can be used repeatedly. Because metal molds are better heat conductors than expendable molds, the solidifying casting is subjected to a higher rate of cooling, which in turn affects the microstructure and grain size within the casting.

2.2. Sand Casting

The traditional method of casting metals is in sand molds and has been used for millenia. Simply stated, sand casting consists of placing a pattern whose contour is the shape of the desired casting in sand to make an imprint, incorporating a gating system, filling the resulting cavity with molten metal, allowing the metal to cool until it solidifies, breaking away the sand mold, and removing the casting. While the origins of sand casting date to ancient times, it is still the most prevalent form of casting. In the United States alone, about 15 million tons of metal are cast by this method each year. Typical parts made by sand casting are machine-tool bases, engine blocks, cylinder heads, and pump housings (Fig. 2.1).

FIGURE 2.1. Typical gray iron castings used in automobiles, including transmission valve body (left); hub rotor with disk-brake cylinder (front)

In this section we describe the steps involved in sand casting (Fig. 2.2), the types of sand and patterns used, how the sand is molded around the patterns, and how the patterns are removed, as well as the principles of the casting operation and typical applications. We discuss this process in some detail to help you become familiar with some of the basic terms and concepts used throughout the remainder of this chapter.

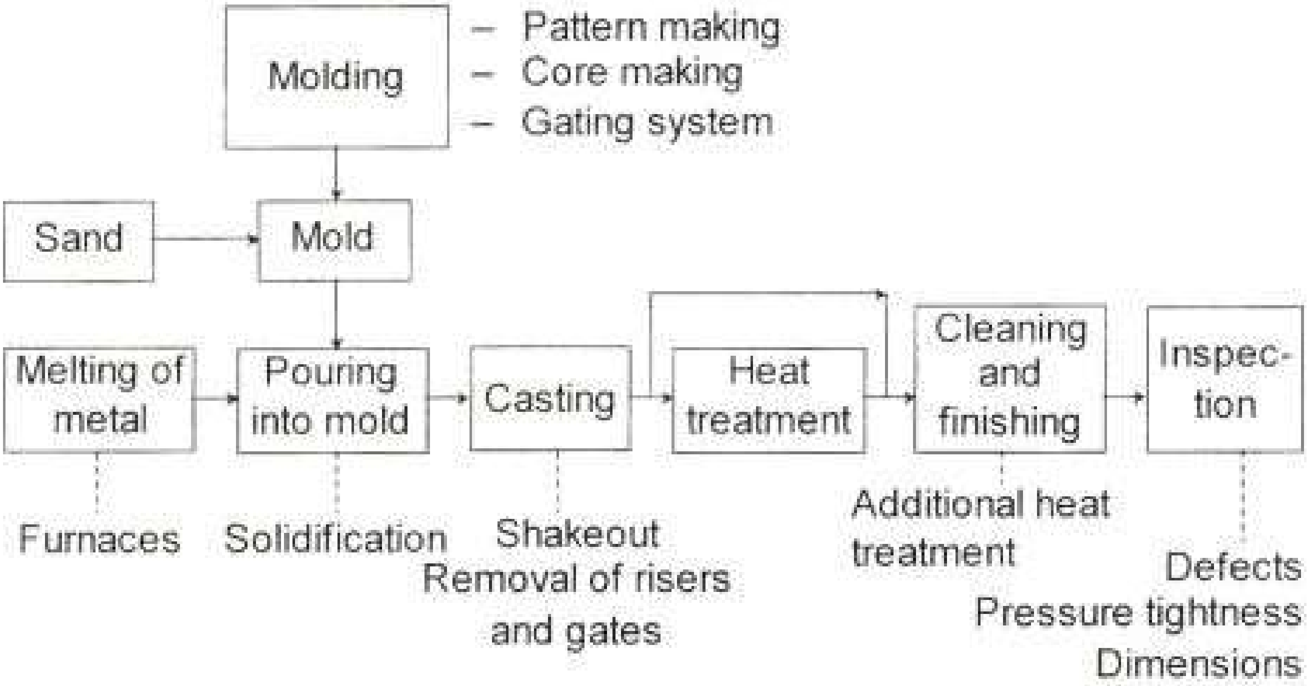


FIGURE 2.2. Outline of production steps in a typical sand-casting operation

2.2.1. Sands

Most sand casting operations use silica sand (SiO_2). Sand is the product of the disintegration of rocks over extremely long periods of time. It is inexpensive and is suitable as mold material because of its resistance to high temperature. There are two general types of sand: *naturally bonded* (*bank* sands) and *synthetic* (*lake* or *sharp* sands). Naturally bonded sands usually contain up to about 20 percent clay-base contaminants. Because its composition can be controlled more accurately, synthetic sand is preferred by most foundries for high-temperature casting.

Sand selection. Several factors are important in the selection of sand for molds. Sand having fine, round grains can be closely packed and form a smooth mold surface. Good permeability of molds and cores allows gases and steam evolved during casting to escape easily. Moisture content of the sand must be carefully controlled, so that its strength is not adversely affected. The mold should have good collapsibility as the casting shrinks while cooling to avoid defects in the casting, such as hot tearing and cracking (see Section 1.5). The selection of sand involves certain tradeoffs with respect to properties. For example, fine-grained sands enhance mold strength, but the fine grains also lower mold permeability.

Sand is typically conditioned before use. Mulling machines are used to uniformly mix sand with additives. Clay is often used in molds as a cohesive agent to bond sand particles, giving the sand greater strength. Cereals are also used to diffuse moisture and thus increase collapsibility. Mulling also serves to distribute moisture evenly. Sand must be aerated to eliminate packing.

Small variations in sand properties can significantly affect the quality of castings. As a result, many tests for measuring important properties of sand have been developed. These tests determine permeability, grain size, strength, surface hardness, moisture, and other properties.

2.2.2. Types of sand molds

Sand molds are characterized by the types of sand that comprise them and by the methods used to produce them. There are four basic types of sand molds: green-sand, skin-dried, dry-sand, and cold-cure molds.

Green-sand molds. The most common mold material is green molding sand. The term green refers to the fact that the sand in the mold is moist or damp while the metal is being poured into it. Green molding sand is actually a mixture of sand, clay, and water. Other materials can also be added to this mixture to impart various properties, such as improved strength at elevated temperatures, improved thermal stability, and improved surface finish of the casting. Green-sand molding is the least expensive method of making molds. Less time is required to reuse the sand mixture, and the mold exhibits good collapsibility, thus reducing defects.

Skin-dried molds. In the skin-dried method the mold surfaces are dried, either by storing the mold in air or drying it with torches to a depth greater than 12 mm (0.5 in.). If dried to a lesser depth, the mold is classified as a green-sand mold. Skin-dried molds are generally used for large castings because of their high strength.

Dry-sand molds. Oven dried (baked) prior to receiving the molten metal, dry-sand molds are stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, distortion of the mold is greater, the castings are more susceptible to hot tearing because of the lower collapsibility of the mold, and the production rate is slower because of the drying time required. Dry-sand molds are used for medium to large castings.

Cold-cure molds. To make cold-cure molds, various organic and inorganic binders are blended into the sand to chemically bond the grains for greater strength. These molds are dimensionally more accurate than green-sand molds but are more expensive and are generally used for larger castings.

2.2.3. Components of sand molds

Before we take a detailed look at the steps and equipment involved in making sand molds, let's consider their major components, which are depicted in Fig. 2.3.

- The mold itself is supported by a flask. Two-piece molds consist of a *cope* on top and a *drag* on the bottom. The seam between them is the *parting line*. When more than two pieces are used, the additional parts are called *cheeks*.
- The molten metal is poured into a *pouring cup* or *pouring basin*.
- The molten metal flows downward through a *sprue*.
- At the base of the sprue is a *gate*. Molds typically contain a system of gates constructed to minimize turbulence in the molten metal and control flow, so that metal is supplied at a rate appropriately related to the rate of solidification. Gating systems often include passageways, called *runners*.
- *Risers* supply additional material to the casting as it shrinks during solidification. Figure 2.3 shows two different types of risers: a *blind riser* and an *open riser*.
- *Cores* are inserts made from sand. They are placed in the mold to form hollow regions or otherwise define the interior surface of the casting.
- *Vents* are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the molds and the core.

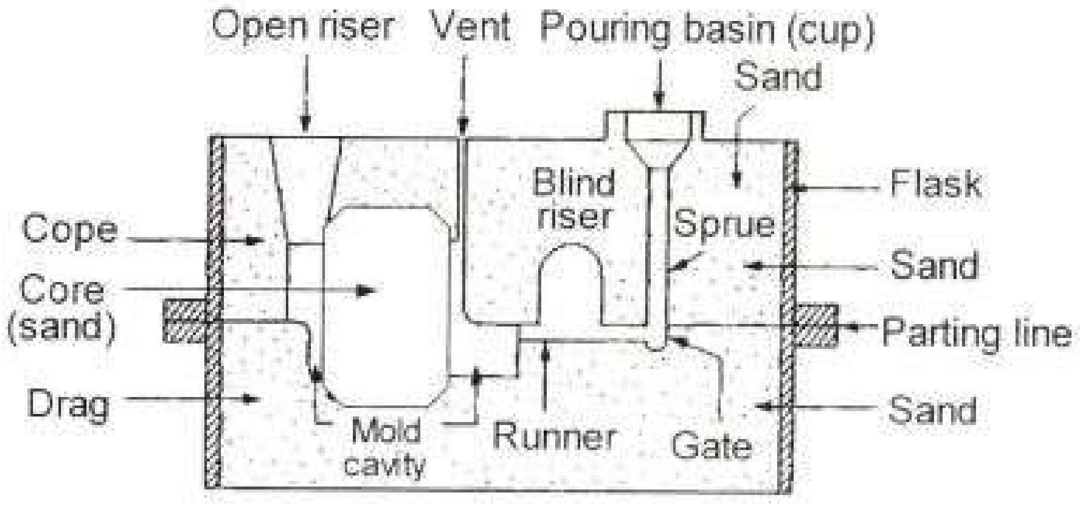


FIGURE 2.3. Schematic illustration of a sand mold showing various features

2.2.4. Patterns

Patterns are used to mold the sand mixture into the shape of the casting. They may be made of wood, plaster, plastic, or metal (Table 2.2). The selection of a pattern material depends on the size and shape of the casting, the dimensional accuracy and the quantity of castings required, and the molding process to be used. Because patterns are used repeatedly to make molds, the strength and durability of the material selected for patterns must be directly related to the number of castings the mold will produce. Wood patterns are used for small, aluminum for intermediate, and ferrous alloys for large production runs. Patterns may be made of a combination of materials to reduce wear in critical regions of the patterns. Patterns are usually coated with a *parting agent* to facilitate their removal from the molds.

TABLE 2.2. CHARACTERISTICS OF PATTERN MATERIALS

	RATING[a]				
CHARACTERISTIC	*WOOD*	*ALUMINUM*	*STEEL*	*PLASTIC*	*CAST IRON*
Machinability	E	G	F	G	G
Wear resistance	P	G	E	F	E
Strength	F	G	E	G	G
Weight[b]	E	G	P	G	P
Repairability	E	P	G	F	G
Resistance to:					
Corrosion[c]	E	E	P	E	P
Swelling[c]	P	E	E	E	E

[a] E, excellent; G, good; F, fair; P, poor.

[b] As a factor in operator fatigue.

[c] By water.

Types of patterns. Patterns can be designed with a variety of features to fit application and economic requirements. The major categories are one-piece, split, and match-plate patterns.

One-piece patterns are generally used for simpler shapes and low quantity production. They are generally made of wood and are inexpensive.

Split patterns are two-piece patterns made so that each part forms a portion of the cavity for the casting. In this way castings having complicated shapes can be produced.

Match-plate patterns are a popular type of mounted pattern in which two-piece patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate (Fig. 2.4). In such constructions, the gating system can be mounted on the drag side of the pattern. This type of pattern is most often used in conjunction with molding machines and large production runs.

Pattern design is a crucial aspect of the total casting operation. The design should provide for metal shrinkage, ease of removal from the sand mold by means of a *taper* or *draft* (Fig. 2.5), and proper metal flow in the mold cavity. We discuss these topics in greater detail in Chapter 3.

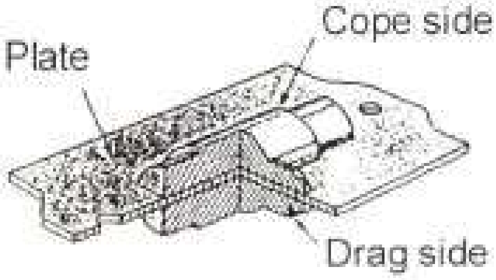


FIGURE 2.4. A typical metal match-plate pattern used in sand casting

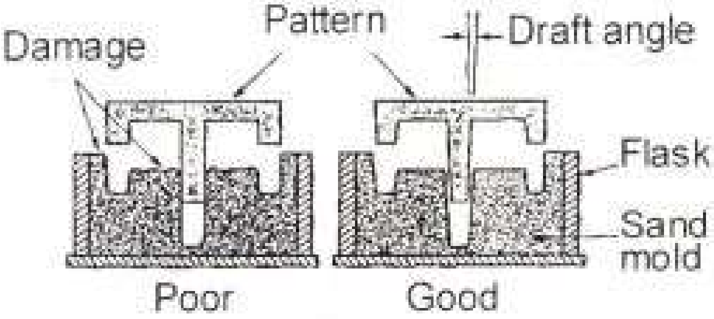


FIGURE 2.5. Taper on patterns for ease of removal from the sand mold

2.2.5. Cores

For castings with internal cavities or passages, such as in an automotive engine block or a valve body, cores are utilized (see Fig. 2.3). Cores are placed in the mold cavity before casting to form the interior surfaces of the casting, and are removed from the finished part during shakeout and further processing.

Like molds, cores must possess strength, permeability, the ability to withstand heat, and collapsibility. Therefore it is not surprising that cores are made of sand aggregates, although coarser sands are preferred for cores because of their higher permeability. Green-sand cores are made from mixtures similar to those for green-sand molds and are often strengthened with binders. They may also be strengthened mechanically with wires or rods for small cores, or by frames made of iron or steel (*core arbors*) for large cores. They are inexpensive but cannot be used for applications requiring high strength.

Dry-sand cores are made from silica sand and binders and are baked to improve their strength. Although dry-sand cores are more expensive than green-sand cores, they can better withstand impact from the molten metal, and they produce better dimensional accuracy and surface finish. After they are molded, dry-sand cores must be heated in an oven. This process hardens the cores, removes unwanted moisture, and activates the binders for improved strength.

Examples of cores are shown in Fig. 2.6. In the horizontally placed core (Fig. 2.6a), the core is anchored by *core prints*. These recesses are added to the pattern to support the core and to provide vents for the escape of gases. A common problem with cores is that for certain casting requirements, as in the case where a recess is required, they may lack sufficient structural support in the cavity. To keep the core from shifting, metal supports, known as *chaplets*, may be used to anchor the core in place (Fig. 2.6b).

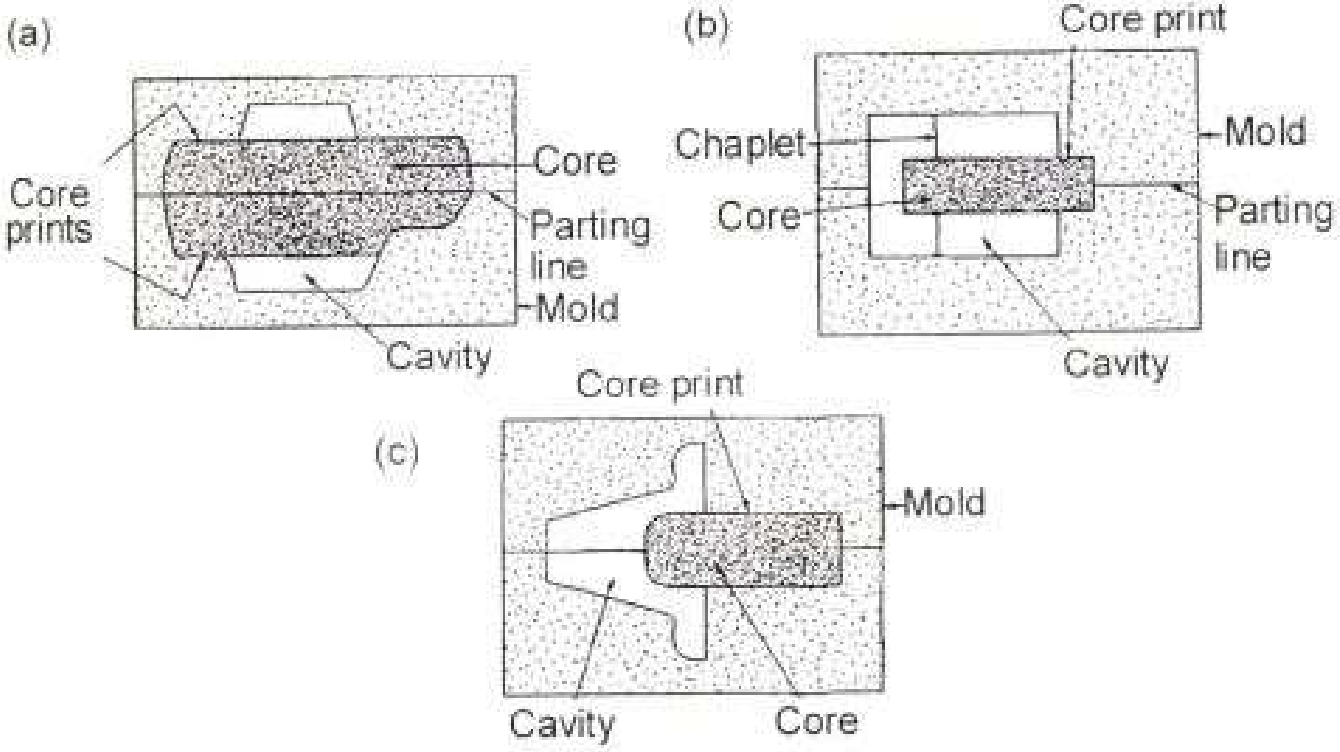


FIGURE 2.6. Examples of sand cores supported by core prints

Making cores. Cores are generally made in a manner similar to that used in making molds. They are also made by the carbon dioxide process described in Section 2.4. Cores are formed in *core boxes*, which are used much like patterns are used to form sand molds. The sand can be packed into the boxes with *sweeps* or blown into the box by compressed air from *core blowers*. Core blowers have the advantages of producing uniform cores and operating at a very high production rate. They can be used to form small- and medium-sized cores.

Cores may also be made using a variety of other methods, such as some of the molding techniques described in this chapter, or by using core extrusion machines that force the sand through a die and then cut the cores to appropriate lengths.

2.2.6. Sand-molding machines

The oldest known method of molding, which is still used for simple castings, is to compact the sand by *hand hammering* or *ramming* it around the pattern. For most operations, however, the sand mixture is compacted around the pattern by molding machines. These machines eliminate arduous labor, offer a higher quality casting by improving the application and distribution of forces, manipulate the mold in a carefully controlled fashion, and increase the rate of production.

Several methods of mold making are shown in Fig. 2.7. In the simplest operation, the sand is molded around the pattern by the squeezing action of a plate, a squeezing head (Fig. 2.7a). This operation, however, does not produce a uniform squeezing action. In another method (Fig. 2.7b) a squeezing head with a profile that matches the mold is used. In a better method, the squeezing action is equalized by individual pneumatic blocks or pistons (Fig. 2.7c). In the process illustrated in Fig. 2.7(d), sand is compacted around a pattern by applying pressure through a diaphragm.

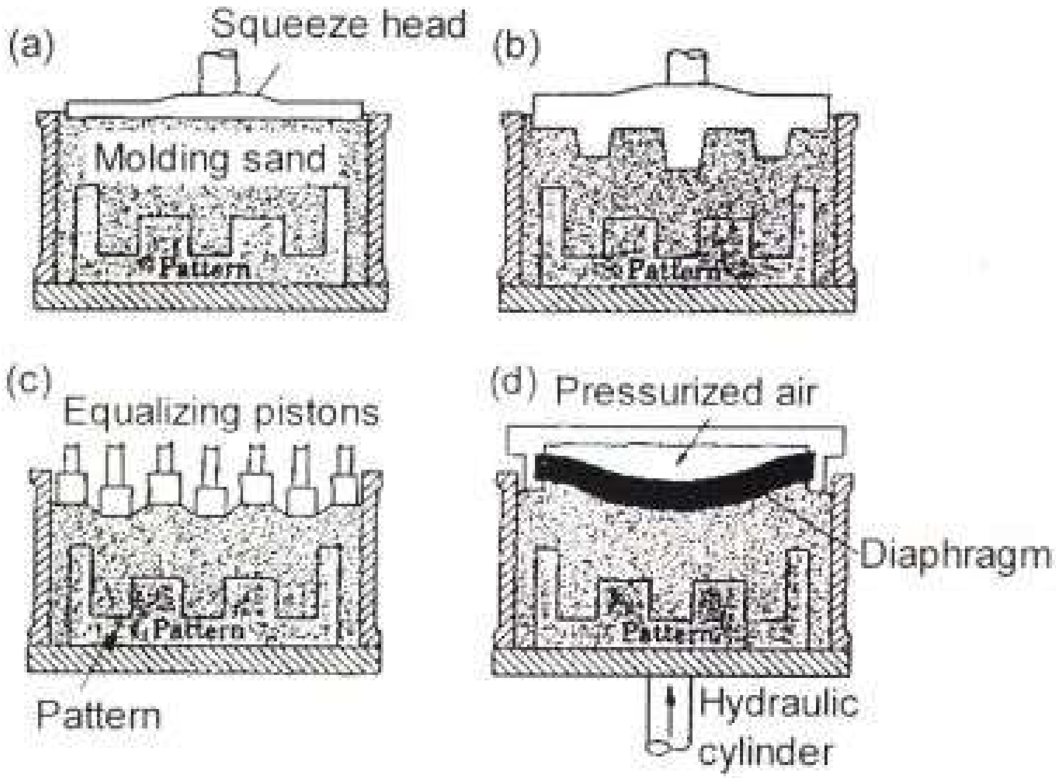


FIGURE 2.7. Various designs of squeeze heads for mold making: (a) conventional flat head; (b) profile head; (c) equalizing squeeze pistons; and (d) flexible diaphragm

Jolt machines. The mechanization of the molding process can be further assisted by jolting the assembly. The flask, molding sand, and pattern are placed on a pattern plate mounted on an anvil, and jolted upward by air pressure at rapid intervals. The inertial forces compact the sand around the pattern. Two types of jolt machines are illustrated in Fig. 2.8.

Vertical flaskless molding. The halves of the pattern form a vertical chamber wall against which sand is blown and compacted (Fig. 2.9a). Then the mold halves are packed horizontally, as shown in Fig. 2.9(b), with the parting line oriented vertically, and moved along a pouring conveyor. This operation is simple and eliminates the need to handle flasks, making potential production rates very high, particularly when other aspects of the operation, such as coring and pouring, are automated.

Sandthrowers. The flask is filled uniformly with sand under a stream of high pressure. Sandthrowers are used to fill large flasks and are typically operated by placing the flasks on a conveyor and moving them one by one in front of the machine. An impeller in the machine throws sand from its blades or cups at such high speeds that the machine accomplishes not only the placement of the sand but also the appropriate ramming.

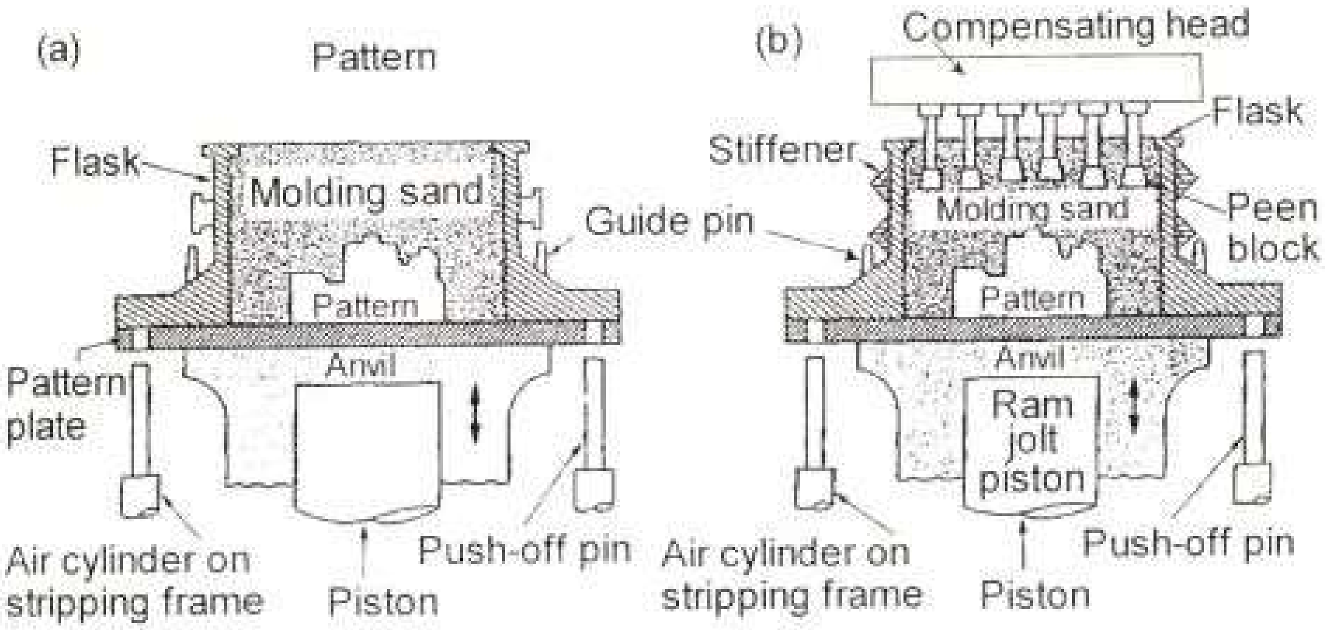


FIGURE 2.8. (a) Schematic illustration of a jolt-type mold-making machine. (b) Schematic illustration of a mold-making machine which combines jolting and squeezing

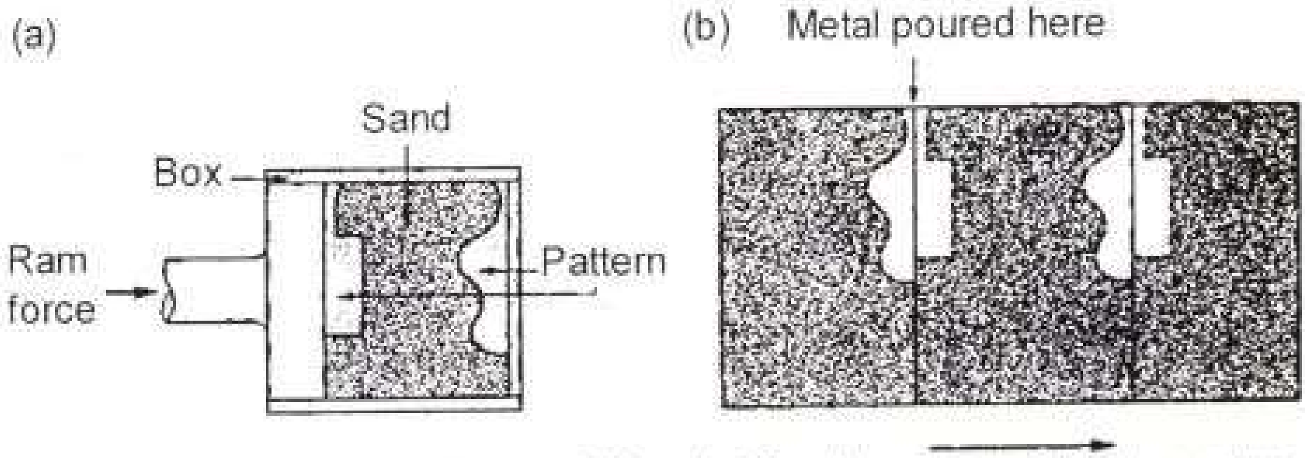


FIGURE 2.9. Vertical flaskless molding. (a) Sand is squeezed between two halves of the pattern. (b) Assembled molds pass along an assembly line for pouring

Impact molding. The sand is compacted by controlled explosion or instantaneous release of compressed gases. This method produces molds with uniform strength and good permeability.

Vacuum molding. In vacuum molding, also known as the "V" process, the pattern is covered tightly by a thin sheet of plastic. A flask is placed over the coated pattern and is filled with sand. A second sheet of plastic is placed on top of the sand, and a vacuum action hardens the sand so that the pattern can be withdrawn. Both halves of the mold are made in this fashion and then assembled. During pouring the mold remains under a vacuum but the casting cavity does not. Once the metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting. Vacuum molding produces castings having very good detail and accuracy. It is especially well suited for large, relatively flat castings.

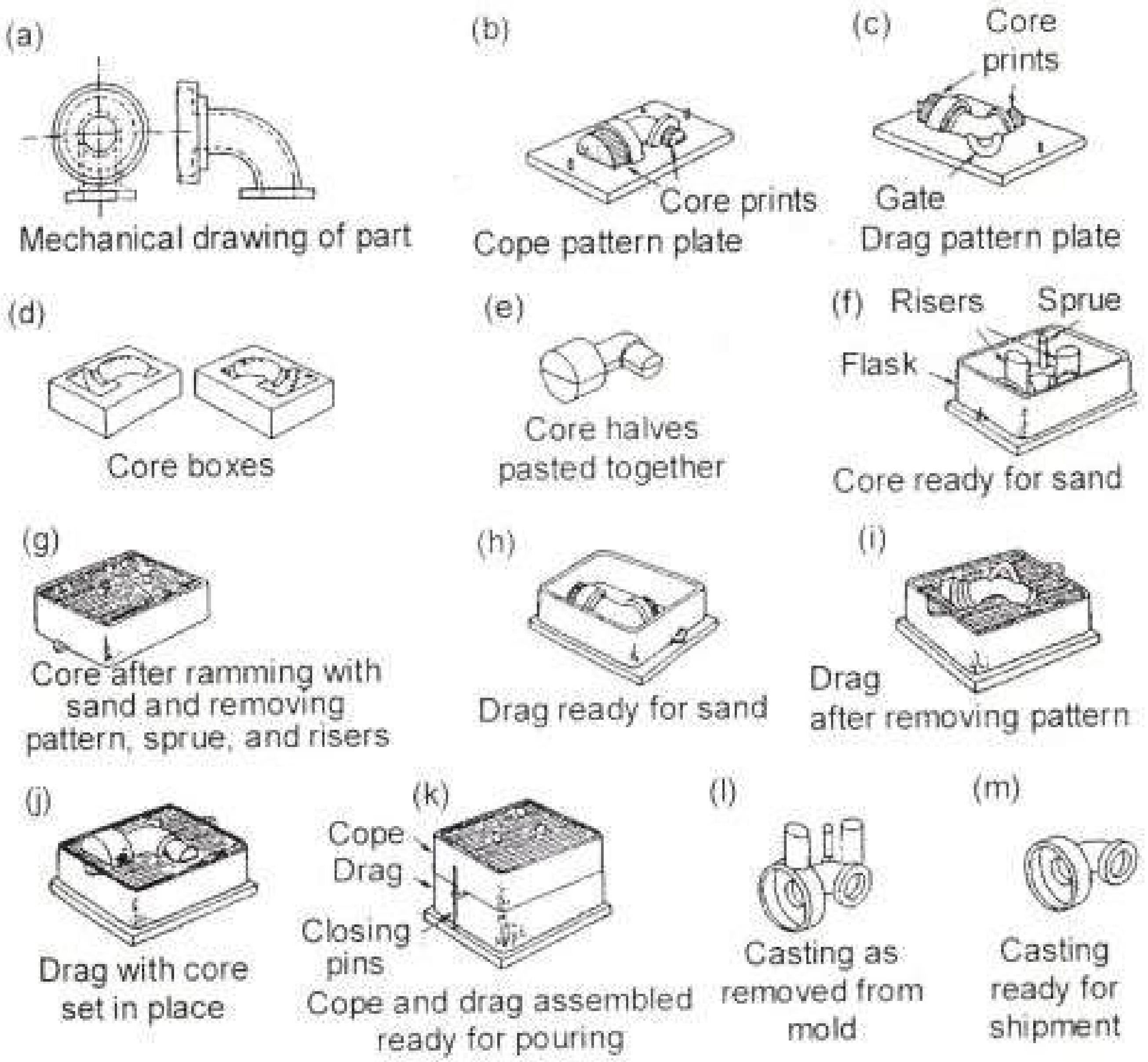
2.2.7. The sand-casting operation

After the mold has been shaped and the cores have been placed in position, the two halves (cope and drag) are closed, clamped, and weighted down. They are weighted to prevent the separation of the mold sections under the pressure exerted when the molten metal is poured into the mold cavity.

The design of the gating system is important for proper delivery of the molten metal into the mold cavity. As we described in Section 1.3, turbulence must be minimized, air and gases must be allowed to escape by such means as vents, and proper temperature gradients must be established and maintained to minimize shrinkage and porosity. The design of risers is also important in order to supply the necessary molten metal during solidification of the casting. The pouring basin may also serve as a riser. A complete sequence of operations in sand casting is shown in Fig. 2.10.

A mechanical drawing of the part is used to generate a design for the pattern (a). Considerations such as part shrinkage and draft must be built into the drawing. Patterns have been mounted on plates equipped with pins for alignment (b-c). Note the presence of core prints designed to hold the core in place. Core boxes produce core halves, which are pasted together (d-e). The cores will be used to produce the hollow area of the part shown in (a). The cope half of the mold is assembled by taking the cope pattern plate, securing it to the flask through aligning pins, and attaching inserts to form the sprue and risers (f). The flask is rammed with sand and the plate and inserts are removed (g). The drag half is produced in a similar manner, with the pattern inserted (h). A bottom board is placed below the drag and aligned with pins. The pattern, flask, and bottom board are inverted, and the pattern is withdrawn, leaving the appropriate imprint (i). The core is set in place within the drag cavity (j). The mold is closed by placing the cope on top of the drag and securing the assembly with pins (k). The flasks are then subjected to pressure to counteract buoyant forces in the liquid, which might lift the cope. After the metal solidifies, the casting is removed from the mold (l). The sprue and risers are cut off and recycled, and the casting is cleaned and inspected before shipment (m).

After solidification, the casting is shaken out of its mold, and the sand and oxide layers adhering to the casting are removed by vibration (using a shaker) or by sand blasting. The risers and gates are cut off by oxyfuel-gas cutting, sawing, shearing, and abrasive wheels, or they are trimmed in dies. Castings may be cleaned by electrochemical means or by pickling with chemicals to remove surface oxides.



(a) Mechanical drawing of part

(b) Cope pattern plate

(c) Drag pattern plate

(d) Core boxes

(e) Core halves pasted together

(f) Core ready for sand

(g) Core after ramming with sand and removing pattern, sprue, and risers

(h) Drag ready for sand

(i) Drag after removing pattern

(j) Drag with core set in place

(k) Cope and drag assembled ready for pouring

(l) Casting as removed from mold

(m) Casting ready for shipment

FIGURE 2.10. Schematic illustration of the sequence of operations for sand casting

The surface of castings is important in subsequent machining operations, because machinability can be adversely affected if the castings are not cleaned properly and sand particles remain on the surface. If regions of the casting have not formed properly or have formed incompletely, the defects may be repaired by welding by filling them with weld metal. Sand-mold castings generally have rough, grainy surfaces, although that depends on the quality of the mold and the materials used.

Depending on the metal used, the casting may subsequently be heat treated or annealed to improve certain properties needed for its intended service use; these processes are particularly important for steel castings. Finishing operations may involve straightening or forging with dies to obtain final dimensions, and machining. Inspection is an important final step and is carried out to ensure that the casting meets all design and quality-control requirements.

2.2.8. Applications

Almost all metals can be sand cast. The surface finish obtained is largely a function of the materials used in making the mold. Dimensional accuracy is not as good as that of other casting processes. However, intricate shapes can be cast by this process, such as cast-iron engine blocks and very large propellers for ocean liners and impellers (Fig. 2.11). Sand casting can be economical for relatively small production runs, and equipment costs are generally low. The characteristics of sand casting and other casting processes are given in Table 2.1 (see also Chapter 3).

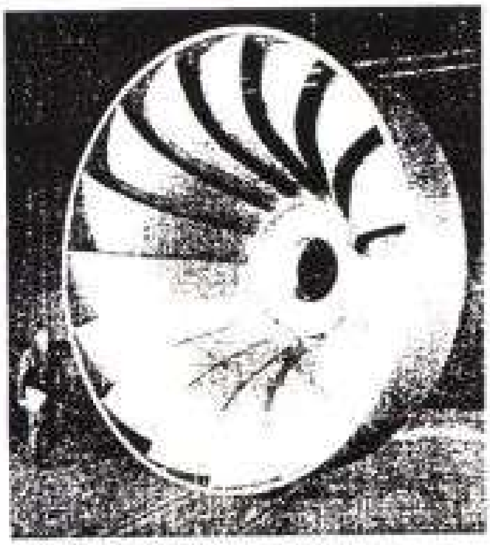


FIGURE 2.11. A cast-steel runner (buckets and shrouds) for a Francis-type hydraulic turbine. This casting weighs 50,000 kg (110,000 lb) and has a diameter of 4.6 m (180 in.)

2.3. Shell Molding

Shell molding was first developed in the 1940s and has grown significantly because it can produce many types of castings with close tolerances and good surface finishes at a low cost. In this process, a mounted pattern, made of a ferrous metal or aluminum, is heated to 175-370 °C (350-700 °F), coated with a parting agent such as silicone, and clamped to a box or chamber containing a fine sand containing 2.5-4.0 percent thermosetting resin binder, such as phenol-formaldehyde, which coats the sand particles. The sand mixture is blown over the heated pattern, coating it evenly.

The assembly is then placed in an oven for a short period of time to complete the curing of the resin. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins. Two half-shells are made in this manner and are bonded or clamped together in preparation for pouring.

The thickness of the shell can be accurately determined by controlling the time that the pattern is in contact with the mold. In this way the shell can be formed with the required strength and rigidity to hold the weight of the molten liquid. The shells are light and thin, usually 5-10 mm (0.2-0.4 in.), and consequently their thermal characteristics are different from those for thicker molds. The thin shells allow the escape of gases during solidification of the metal.

The mold is generally used vertically and is supported by surrounding it with steel shot in a cart. The walls of the mold are relatively smooth, offering low resistance to flow of the molten metal and producing castings with sharper corners, thinner sections, and smaller projections than are possible in green-sand molds. With the use of multiple gating systems, several castings can be made in a single mold. Nearly any metal suited for sand casting may be cast by the shell-molding process. The size of parts produced is somewhat limited: Weights can be as much as 100 kg (220 lb) but are most often under 10 kg. The accuracy produced is comparable to other high-precision casting methods.

Shell molding may be more economical than other casting processes, depending on various production factors. The cost of the resin binders is offset somewhat by the fact that only 5 percent as much sand is used, compared to sand casting. The relatively high cost of metal patterns becomes a smaller factor as the size of production runs increases. The high quality of the finished casting can significantly reduce cleaning, machining, and other finishing costs. The operation involves less specialized machinery than do other casting processes, thus reducing capital investment. Complex shapes can be produced with less labor, and the process can be automated fairly easily.

Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, and connecting rods. Shell molding is also widely used in producing high-precision molding cores.

2.3.1. Composite molds

Composite molds are made of two or more different materials and are used in shell molding and other casting processes. They are generally employed in casting complex shapes, such as impellers for turbines. Examples of composite molds are shown in Figs. 2.12 and 2.13. Molding materials commonly used are shells (made as previously described), plaster, sand with binder, metal, and graphite. Composite molds may also include cores and chills to control the rate of solidification in critical areas of castings. Composite molds increase the strength of the mold, improve the dimensional accuracy and surface finish of castings, and may help reduce overall costs and processing time.

2.4. Silicate-Bonded Sand Process (Carbon-Dioxide Process)

The mold material in the carbon-dioxide process is a mixture of sand and 1.5-6 percent sodium silicate (waterglass) as the binder for sand. This mixture is packed around the pattern and hardened by blowing carbon dioxide (CO_2) gas through it.

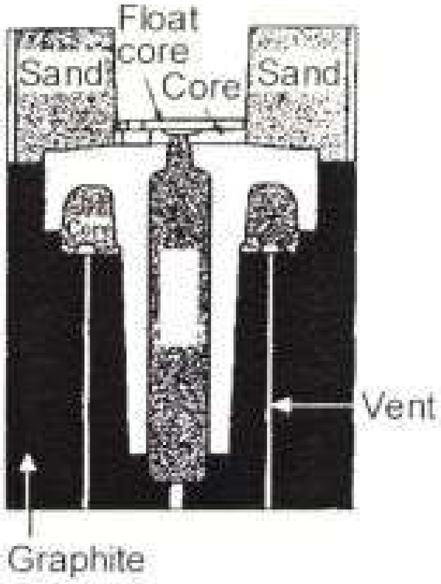


FIGURE 2.12. Schematic illustration of semipermanent composite mold

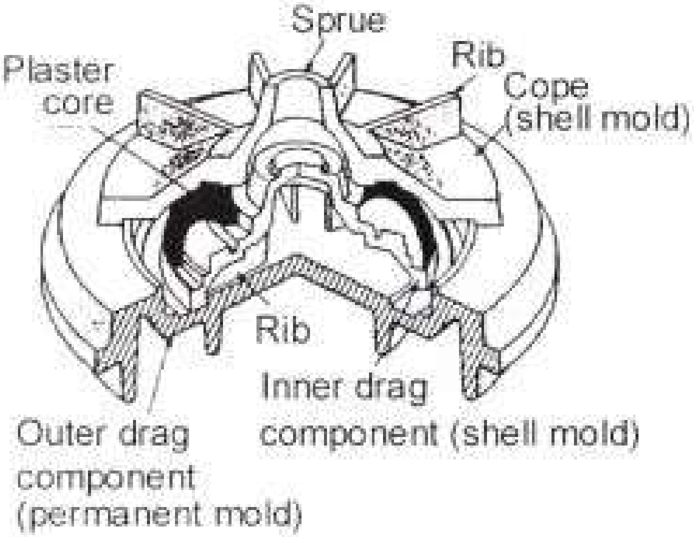


FIGURE 2.13. A composite mold used in casting an aluminum-alloy torque converter. This part was previously cast in an all-plaster mold

This process was first used in the 1950s and has been developed further, such as by using various other chemicals for binders. Cores made by this process reduce the tendency to tear because of their compliance at elevated temperatures.

2.5. Evaporative Pattern Process

Also developed in the 1950s, the evaporative-pattern process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting. The process is also known as *lost-foam* or *lost-pattern* casting, and under the trade name *Full-Mold* process.

The basic steps of this process are the following. First, raw polystyrene "beads, containing 5–8 percent pentane (a volatile hydrocarbon) are placed in a preheated die, usually made of aluminum. The polystyrene expands and takes the shape of the die cavity. Additional heat is applied to fuse and bond the beads together. The die is then cooled, opened, and the polystyrene pattern is removed. Complex patterns may be made in this way.

The pattern is then coated with a refractory slurry (a watery mixture), dried, and placed in a flask. The flask is filled with sand, which surrounds and supports the pattern. The sand may be dried or mixed with bonding agents to give it additional strength. Then, without removing the polystyrene pattern, the molten metal is poured into the mold. This action immediately vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene pattern.

This process is relatively simple because there are no parting lines or cores. Inexpensive flasks are sufficient for the process, and the need for cleaning and machining are relatively low. Polystyrene is inexpensive, can be easily processed into a wide variety of shapes, and thus can be used to make complex castings of various sizes economically. Typical applications are cylinder heads, crankshafts, brake components and manifolds for automobiles, and machine bases.

2.6. Plaster-Mold Casting

In the plaster-mold casting process the mold is made of plaster of paris (gypsum, or calcium sulfate), with the addition of talc and silica flour to improve strength and control the time required for the plaster to set. These components are mixed with water, and the resulting slurry is poured over the pattern. After the plaster sets, usually within 15 minutes, the pattern is removed and the mold is dried at 120-260 °C (250-500 °F) to remove the moisture. Higher drying temperatures may be used depending on the type of plaster. The mold halves are then assembled to form the mold cavity and preheated to about 120 °C (250 °F). The molten metal is then poured into the mold.

Because plaster molds have very low permeability, gases evolved during solidification of the metal cannot escape. Consequently, the molten metal is poured either in a vacuum or under pressure. Plaster-mold permeability can be increased substantially by the *Antioch* process: The molds are dehydrated in an autoclave (pressurized oven) for 6-12 hours, then dehydrated in air for 14 hours. Another method of increasing permeability is to use foamed plaster, containing trapped air bubbles.

Patterns for plaster molding are generally made of aluminum alloys, thermosetting plastics, brass, or zinc alloys. Wood patterns are not suitable for making a large number of molds, because the patterns are repeatedly subjected to the water-based plaster slurry. Since there is a limit to the maximum temperature that the plaster mold can withstand, generally about 1200 °C (2200 °F), plaster-mold casting is used only for aluminum, magnesium, zinc, and some copper-base alloys. The castings have fine details with good surface finish. Because plaster molds have lower thermal conductivity than others, the castings cool slowly, and more uniform grain structure is obtained with less warpage. Wall thickness of parts can be 1-2.5 mm (0.04-0.1 in.).

This process and the ceramic-mold and investment casting processes (described below) are known as precision casting because of the high dimensional accuracy and good surface finish obtained. Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments. Castings usually weigh less than 10 kg (22 lb) and are typically in the range of 125-250 g (1/4-1/2 lb), although parts as light as 1 g (0.035 oz) have been made.

2.7. Ceramic-Mold Casting

The ceramic-mold casting process is similar to the plaster-mold process, with the exception that it uses refractory mold materials suitable for high-temperature applications. The process is also called cope-and-drag investment casting. The slurry is a mixture of fine-grained zircon ($ZrSiO_4$), aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern (Fig. 2.14), which has been placed in a flask.

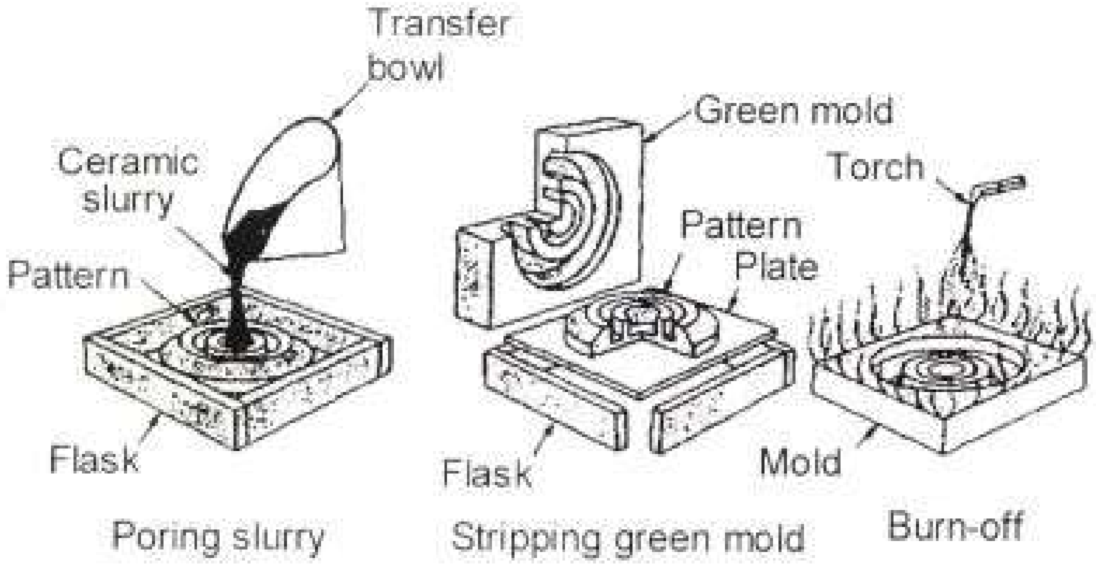


FIGURE 2.14. Sequence of operations in making a ceramic mold

The pattern may be made of wood or metal. After setting, the molds (ceramic facings) are removed, dried, burned off to remove volatile matter, and baked. The molds are clamped firmly and used as all-ceramic molds. In the Shaw process, the ceramic facings are backed by fireclay (clay used in making firebricks that resist high temperatures) to give strength to the mold. The facings are then assembled into a complete mold, ready to be poured.

The high-temperature resistance of the refractory molding materials allows these molds to be used in casting ferrous and other high-temperature alloys, stainless steels, and tool steels. The castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes, but the process is somewhat expensive. Typical parts made are impellers, cutters for machining, dies for metalworking, and molds for making plastic or rubber components. Parts weighing as much as 700 kg (1500 lb) have been cast by this process.

2.8. Investment Casting

The investment-casting process, also called the lost-wax process, was first used during the period 4000-3000 B.C. The pattern is made of wax or a plastic such as polystyrene. The sequences involved in investment casting are shown in Fig. 2.15.

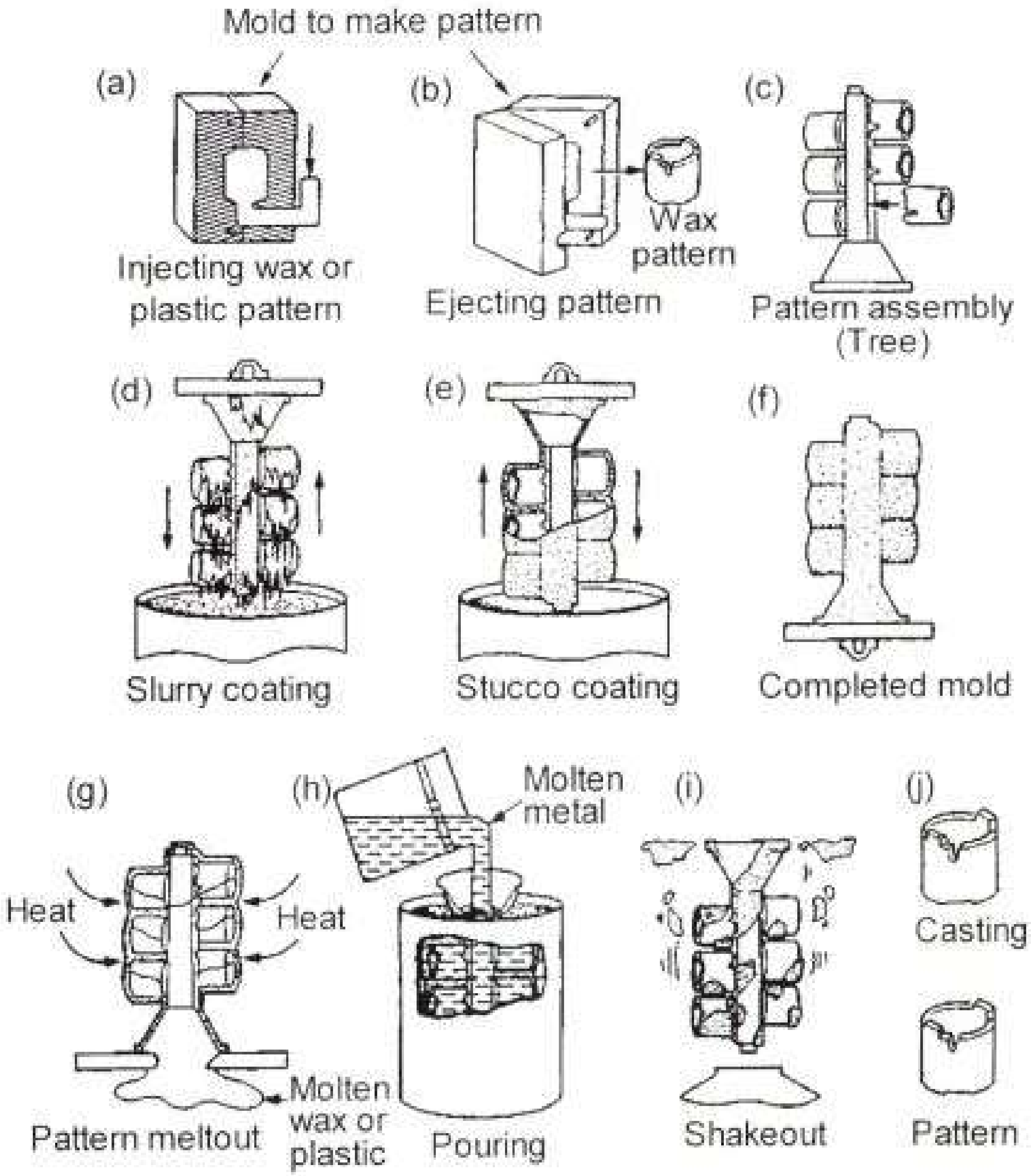


FIGURE 2.15. Schematic illustration of investment casting (lost-wax process). Castings by this method can be made with very fine detail and from variety of metals

The pattern is made by injecting molten wax or plastic into a metal die in the shape of the pattern. The pattern is then dipped into a slurry of refractory material, such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly to increase its thickness. The term investment comes from the fact that the pattern is invested with the refractory material. Wax patterns require careful handling because they are not strong enough to withstand the forces involved during mold making.

The one-piece mold is dried in air and heated to a temperature of 90-175 °C (200-375 °F) – in an inverted position to melt out the wax – for about 12 hours. The mold is then fired to 650-1050 °C (1200-1900 °F) for about 4 hours, depending on the metal to be cast, to drive off the water of crystallization (chemically combined water). After the mold has been poured and the metal has solidified, the mold is broken up and the casting is removed. A number of patterns can be joined to make one mold, called a tree (Fig. 2.15c), thus increasing the production rate.

Although the labor and materials involved make the lost-wax process costly, it is suitable for casting high-melting-point alloys with good surface finish and close tolerances. Thus little or no finishing operations are required, which would otherwise add significantly to the total cost of the casting. This process is capable of producing intricate shapes, with parts weighing from 1 g to 35 kg (0.035 oz to 75 lb), from a wide variety of ferrous and nonferrous metals and alloys. Typical parts made are components for office equipment and mechanical components such as gears, cams, valves, and ratchets.

Example: Eliminating porosity.

In investment casting of an aluminum-alloy valve body, porosity developed at the core-casting interface. The mold was originally heated to 200 °C (400 °F), which was too high for the metal around the core to solidify at a sufficiently high rate. Thus the casting began to solidify from the outside wall toward the core, and the gas (hydrogen) expelled during freezing of the metal accumulated at the area near the core-metal interface, thus producing porosity. By lowering the mold temperature to around 90 °C (200 °F), the metal around the core solidified at a high enough rate to prevent expulsion of gases around the core area, thus eliminating porosity.

2.8.1. Ceramic-shell investment casting

A variation of the investment-casting process is ceramic-shell casting. It uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and then into a fluidized bed of fine-grained fused silica or zircon flour. The pattern is then dipped into coarser grain silica to build up additional coatings and thickness to withstand the thermal shock of pouring. The rest of the procedure is similar to investment casting. This process is economical and is used extensively for precision casting of steels and high-temperature alloys.

The sequence of operations involved in making a turbine disk by this method is shown in Fig. 2.16. Another complex part – an exhaust duct of a gas turbine – made by this process is shown in Fig. 2.17. If ceramic cores are used in the casting, they are removed by leaching with caustic solutions under high pressure and temperature. The molten metal may be poured in a vacuum to extract evolved gases and reduce oxidation, thus improving the quality of the casting. To further reduce microporosity, the castings made by this and other processes are subjected to hot isostatic pressing. Aluminum castings, for example, are subjected to a gas pressure up to 100 MPa (15 ksi) at 500 °C (900 °F).

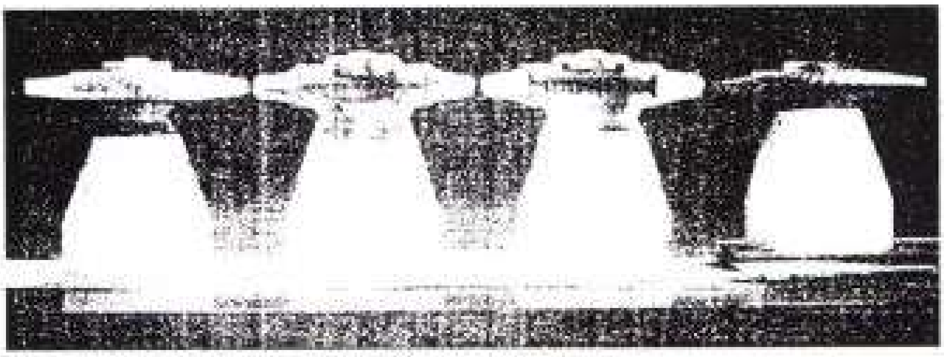


FIGURE 2.16. Investment casting of an integrally cast rotor for a gas turbine, (a) Wax pattern assembly, (b) Ceramic shell around wax pattern, (c) Wax is melted out and mold is filled, under a vacuum, with molten superalloy. (d) The cast rotor, produced to net or near-net shape

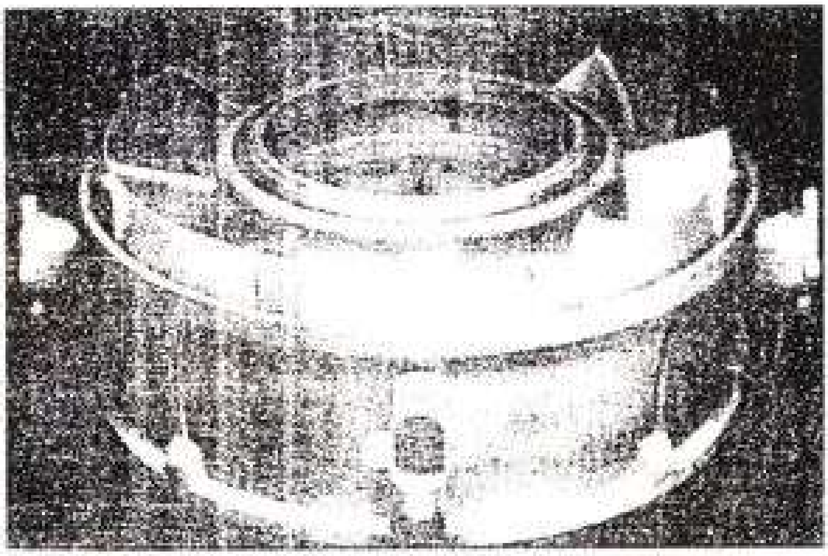


FIGURE 2.17. Integrally cast exhaust duct for the General Electric T700 gas turbine, made by investment casting

2.9. Permanent-Mold Casting

In the permanent-mold casting process, also called *hard mold casting*, two halves of a mold are made from materials such as cast iron, steel, bronze, graphite, or refractory metal alloys. The mold cavity and gating system are machined into the mold and thus become an integral part of it. To produce castings with internal cavities, cores made of metal or sand aggregate are placed in the mold prior to casting. Typical core materials are oil-bonded or resin-bonded sand, plaster, graphite, gray iron, low-carbon steel, and hot-work die steel. Gray iron is the most commonly used, particularly for large molds for aluminum and magnesium castings. Inserts are also used for various parts of the mold.

In order to increase the life of permanent molds, the surfaces of the mold cavity are usually coated with a refractory slurry, such as sodium silicate and clay, or sprayed with graphite every few castings. These coatings also serve as parting agents and as thermal barriers, controlling the rate of cooling of the casting. Mechanical ejectors, such as pins located in various parts of the mold, may be needed for removal of complex castings. Ejectors usually leave small round impressions on castings.

The molds are clamped together by mechanical means (Fig. 2.18) and heated to about 150-200°C (300-400°F) to facilitate metal flow and reduce thermal damage to the dies. The molten metal is then poured through the gating system. After solidification, the molds are opened and the casting is removed. Special means employed to cool the mold include water or the use of fins, similar to those found on motorcycle or lawnmower engines that cool the engine block.

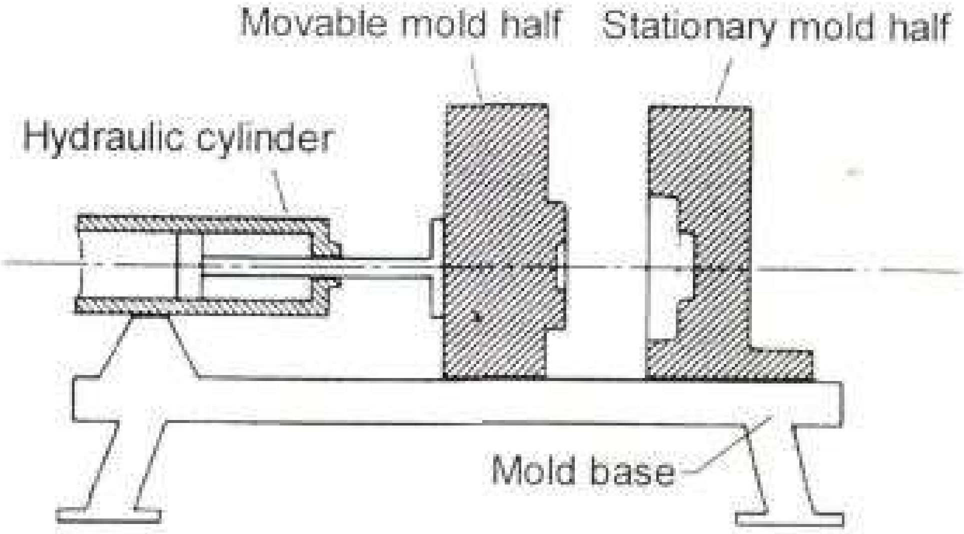


FIGURE 2.18. Schematic drawing of straight-line permanent-mold machine equipped with two-piece deep-cavity die

Although the permanent-mold casting operation can be performed manually, the process can be automated for large production runs. This process is used mostly for aluminum, magnesium, and copper alloys and gray iron because of their generally lower melting points. Steels can also be cast using graphite or heat-resistant metal molds.

This process produces castings with good surface finish, close tolerances, uniform and good mechanical properties, and at high production rates. Typical parts made by permanent-mold casting are automobile pistons (Fig. 2.19), cylinder heads, connecting rods, gear blanks for appliances, and kitchenware. Parts that can be made economically generally weigh less than 25 kg (55 lb), although special castings weighing a few hundred kilograms have been made by this process.

Although equipment costs can be high because of die costs, the process can be mechanized, thus keeping labor costs low. Permanent-mold casting is not economical for small production runs. Furthermore, because of the difficulty in removing the casting from the mold, intricate shapes cannot be cast by this process. However, easily collapsed sand cores can be used and removed from castings to leave intricate internal cavities. The process is then called semipermanent-mold casting.

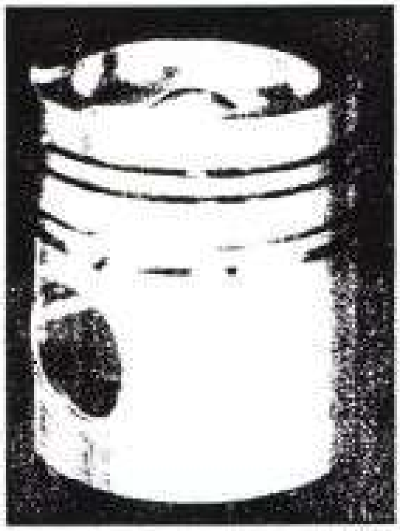


FIGURE 2.19. An automotive piston made by permanent-mold casting

2.10. Slush Casting

We noted in Fig. 1.5 that a solidified skin first develops in a casting and that this skin becomes thicker with time. Hollow castings with thin walls can be made by permanent-mold casting using this principle. This process is called *slush casting*. The molten metal is poured into the metal mold, and after the desired thickness of solidified skin is obtained, the mold is inverted or slung, and the remaining liquid metal is poured out. The mold halves are then opened and the casting is removed. The process is suitable for small production runs and is generally used for making ornamental and decorative objects and toys from low-melting-point metals, such as zinc, tin, and lead alloys.

2.11. Pressure Casting

In the two permanent-mold processes that we have just described, the molten metal flows into the mold cavity by gravity. In the pressure casting process, also called *pressure pouring* or *low-pressure casting* (Fig. 2.20a), the molten metal is forced upward by gas pressure into a graphite or metal mold. The pressure is maintained until the metal has completely solidified in the mold. The molten metal may also be forced upward by a vacuum, which also removes dissolved gases and gives the casting lower porosity.

Pressure casting is generally used for high-quality castings. An example of this process is steel railroad-car wheels. These wheels may also be cast in sand molds or semipermanent molds made of graphite and sand (Fig. 2.20b).

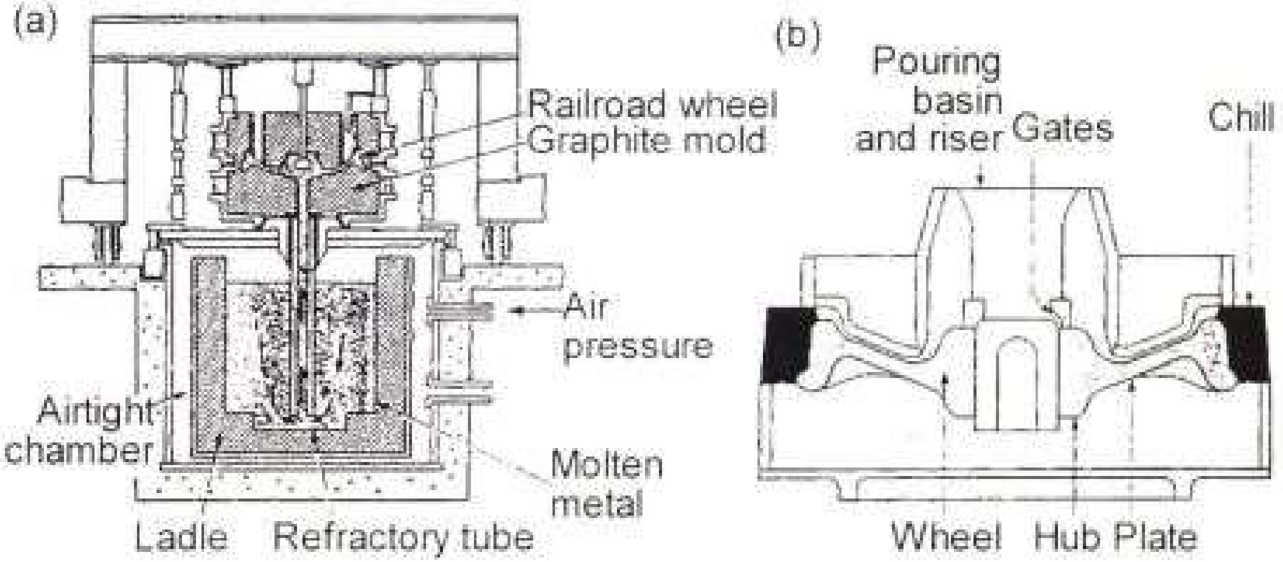


FIGURE 2.20. (a) Bottom-pressure casting process utilizes graphite molds for the production of steel railroad wheels. (b) Gravity-pouring method of casting a railroad wheel

2.12. Die Casting

The **die-casting process**, developed in the early 1900s, is a further example of permanent-mold casting. The molten metal is forced into the die cavity at pressures ranging from 0.7-700 MPa (0.1-100 ksi). The European term *pressure die casting*, or simply *die casting*, that we describe in this section, is not to be confused with the term *pressure casting* that we described in Section 2.11. Typical parts made by die casting are carburetors, motors, business-machine and appliance components, hand tools, and toys. The weight of most castings ranges from less than 90 g (3 oz) to about 25 kg (55 lb). There are two basic types of die-casting machines: hot-chamber and cold-chamber.

2.12.1. Hot-chamber process

The hot-chamber process (Fig. 2.21) involves the use of a piston, which traps a certain volume of molten metal and forces it into the die cavity through a gooseneck and nozzle. The pressures range up to 35 MPa (5000 psi), with an average of about 15 MPa (2000 psi). The metal is held under pressure until it solidifies in the die. To improve die life and to aid in rapid metal cooling – thus reducing cycle time – dies are usually cooled by circulating water or oil through various passageways in the die block. Cycle times usually range up to 900 shots (individual injections) per hour for zinc, although very small components such as zipper teeth can be cast at 18,000 shots per hour. Low-melting-point alloys such as zinc, tin, and lead are commonly cast by this process.

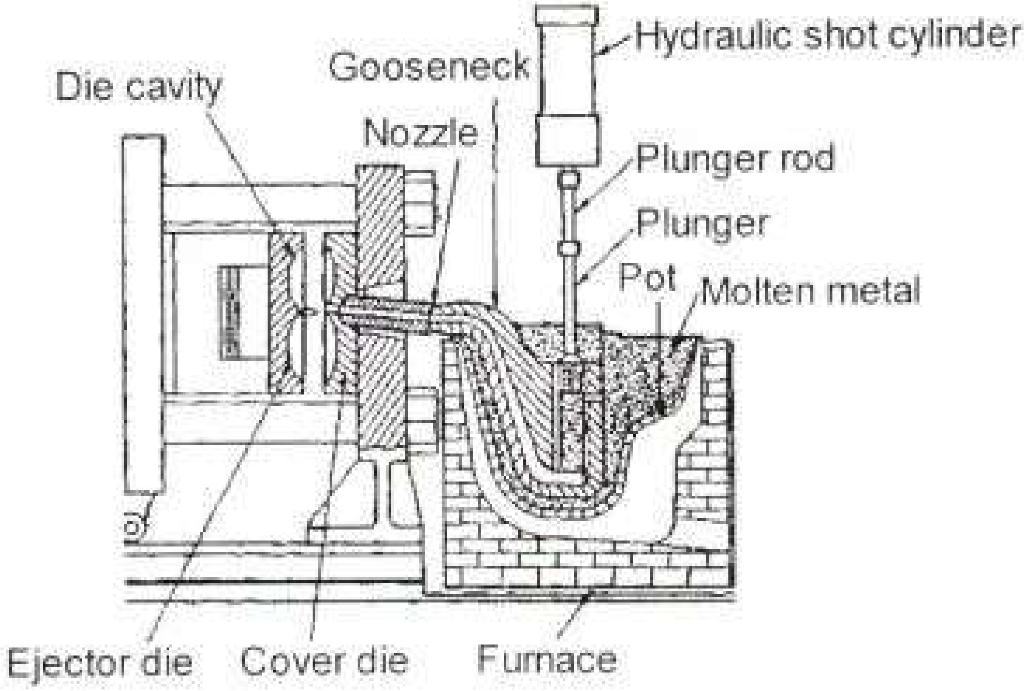


FIGURE 2.21. Sequence of steps in die casting of a part in the hot-chamber process

2.12.2. Cold-chamber process

In the cold-chamber process (Fig. 2.22) molten metal is poured into the injection cylinder (*shot chamber*) with a ladle. The shot chamber is not heated – hence the term cold chamber. The metal is forced into the die cavity at pressures usually ranging from 20 MPa to 70 MPa (3 ksi to 10 ksi), although they may be as high as 150 MPa (20 ksi).

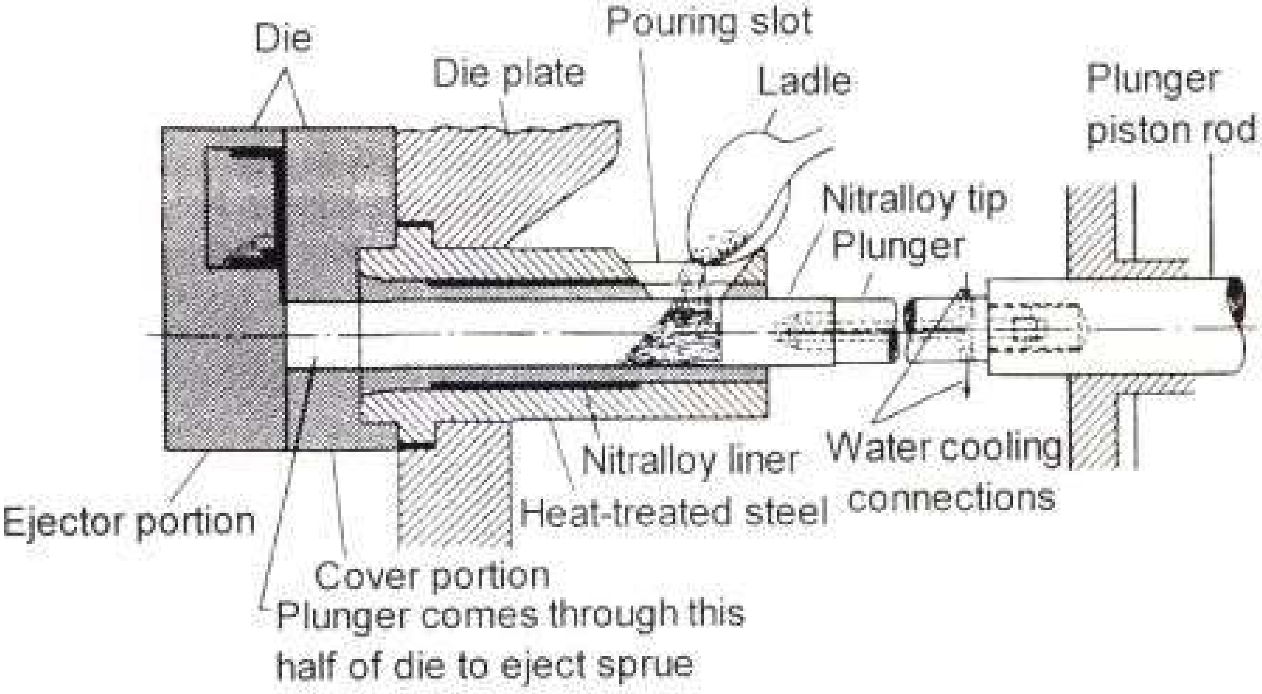


FIGURE 2.22. Schematic view of the cold-chamber die-casting process

The machines may be horizontal (Fig. 2.23) or vertical, in which the shot chamber is vertical and the machine is similar to a vertical press. These machines are large compared to the size of the casting because large forces are required to keep the two halves of the dies closed. Otherwise, the pressure of the molten metal in the die cavities may force the dies apart.

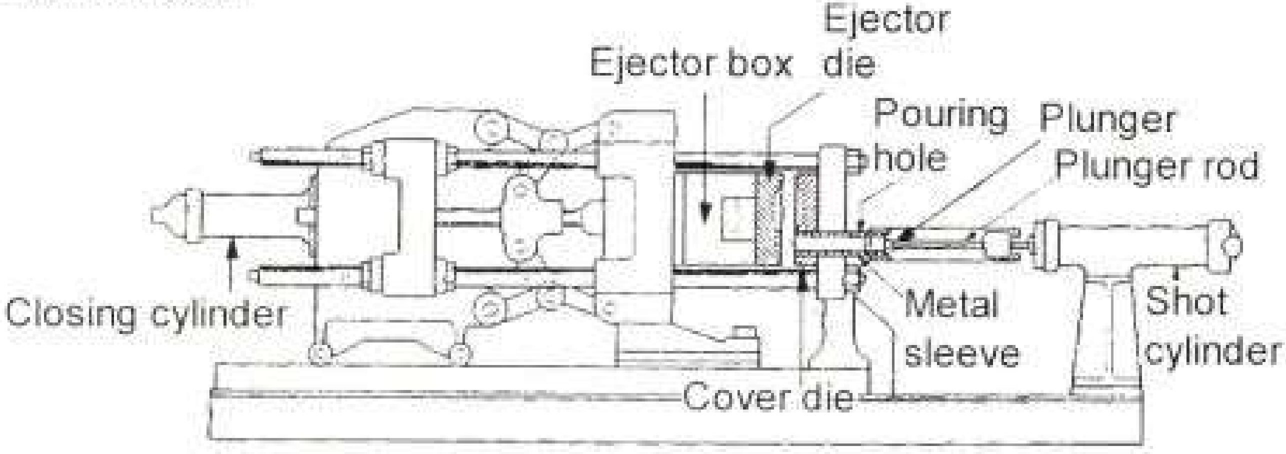


FIGURE 2.23. Schematic illustration of a die-casting machine

High-melting-point alloys of aluminum, magnesium, and copper are normally cast by this method, although other metals (including ferrous metals) can also be cast in this manner. Molten-metal temperatures start at about 600°C (1150°F) for aluminum and magnesium alloys and increase considerably for copper-base and iron-base alloys.

2.12.3. Process capabilities and machine selection

Because of the high pressures involved, the dies have a tendency to part unless clamped together tightly. Die-casting machines are rated according to the clamping force that can be exerted to keep the dies closed. The capacities of commercially available machines range from about 25 tons to 3000 tons. Other factors involved in the selection of die-casting machines are die size, piston stroke, shot pressure, and cost.

Die-casting dies (Fig. 2.24) may be made single cavity, multiple cavity (several identical cavities), combination cavity (several different cavities), or unit dies (simple small dies that can be combined in two or more units in a master holding die). Dies are usually made of hot-work die steels or mold steels. Die wear increases with the temperature of the molten metal. *Heat cracking* of dies (surface cracking from repeated heating and cooling of the die) can be a problem. When die materials are selected and maintained properly, dies may last more than half a million shots before any significant die wear takes place.

Die design includes taper (draft) to allow the removal of the casting. The sprues and runners may be removed either manually or by using trim dies in a press. The entire die casting and finishing process can be highly automated. Lubricants (parting agents) are usually applied as thin coatings on die surfaces. Alloys, except magnesium alloys, generally require lubricants. These are usually water-base lubricants with graphite or other compounds in suspension. Because of the high cooling capacity of water, these fluids are also effective in keeping die temperatures low.

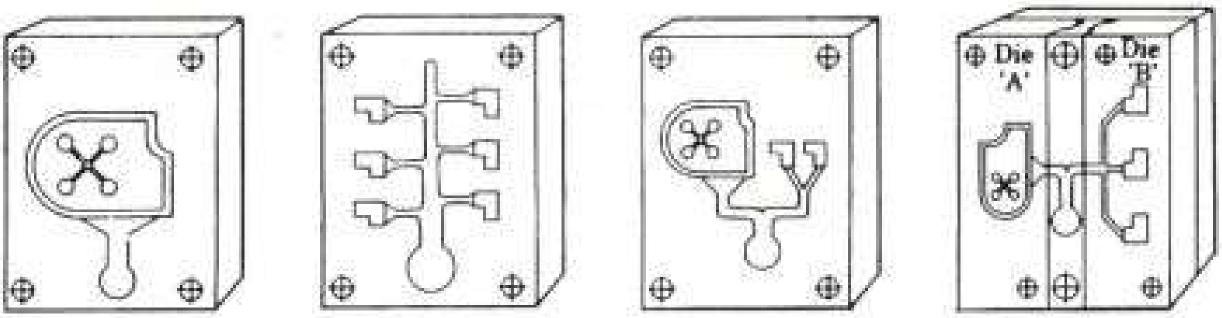


FIGURE 2.24. Various types of cavities in die-casting dies

Die casting has the capability for high production rates with good strength, high-quality parts with complex shapes, good dimensional accuracy and surface details, thus requiring little or no subsequent machining or finishing operations. Because of the high pressures involved, wall thicknesses as small as 0.5 mm (0.02 in.) are produced and are smaller than those obtained by other casting methods. Components such as pins, shafts, and fasteners can be cast integrally (*insert molding*). This process is similar to putting wooden sticks (the pin) in popsicles (the casting). Ejector marks remain, as do small amounts of flash (thin material squeezed out between the dies) at the die parting line.

Typical part made by die casting is shown in Fig. 2.25. Note the intricate shape and fine surface detail. In the fabrication of certain parts, die casting can compete favorably with other manufacturing methods, such as sheet-metal stamping and forging, or other casting processes. Additionally, because the molten metal chills rapidly at the die walls, the casting has a fine-grain, hard skin with higher strength. Consequently, the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness. With good surface finish and dimensional accuracy, die casting can produce bearing surfaces that are normally machined.

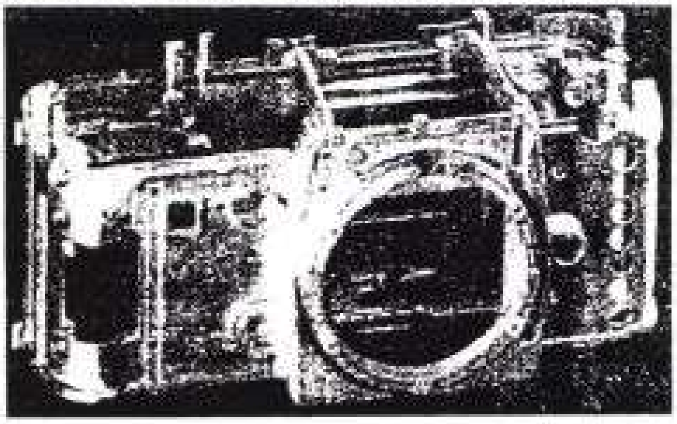


FIGURE 2.25. Die-cast body for a 35-mm camera, made of copper-aluminum alloy

Equipment costs, particularly the cost of dies, are somewhat high, but labor costs are generally low because the process is semi- or fully automated. Die casting is economical for large production runs. The properties and typical applications of common die-casting alloys are given in Table 2.3.

TABLE 2.3. PROPERTIES AND TYPICAL APPLICATIONS OF COMMON DIE CASTING ALLOYS

ALLOY	ULTIMATE TENSILE STRENGTH (MPa)	YIELD STRENGTH (MPa)	ELONGATION IN 50mm (%)	APPLICATIONS
Aluminum 380 (3.5 Cu–8.5 Si)	320	160	2.5	Appliances, automotive components, electrical motor frames and housings
Aluminum 13 (12 Si)	300	150	2.5	Complex shapes with thin walls; parts requiring strength at elevated temperatures
Brass 858 (60 Cu)	380	200	15	Plumbing fixtures, lock hardware, bushings, ornamental castings
Magnesium AZ91B (9 Al-0.7 Zn)	230	160	3	Power tools, automotive parts, sporting goods
Zinc No. 3 (4 Al)	280	—	10	Automotive parts, office equipment, household utensils, building hardware, toys
Zinc No. 5 (4 Al -1 Cu)	320	—	7	Appliances, automotive parts, building hardware, business equipment

Source: Data from American Die Casting Institute.

2.13. Centrifugal Casting

As its name implies, the centrifugal casting process utilizes the inertial forces caused by rotation to distribute the molten metal into the mold cavities. This method was first suggested in the early 1800s. There are three types of centrifugal casting: true centrifugal casting, semicentrifugal casting, and centrifuging.

2.13.1. True centrifugal casting

In *true centrifugal casting*, hollow cylindrical parts, such as pipes, gun barrels, and streetlamp posts, are produced by the technique shown in Fig.

2.26, in which molten metal is poured into a rotating mold. The axis of rotation is usually horizontal but can be vertical for short workpieces. Molds are made of steel, iron, or graphite and may be coated with a refractory lining to increase mold life. The mold surfaces can be shaped so that pipes with various outer shapes, including square or polygonal, can be cast. The inner surface of the casting remains cylindrical because the molten metal is uniformly distributed by centrifugal forces. However, because of density differences, lighter elements such as dross, impurities, and pieces of the refractory lining tend to collect on the inner surface of the casting. Cylindrical parts ranging from 13 mm (0.5 in.) to 3 m (10 ft) in diameter and 16 m (50 ft) long can be cast centrifugally, with wall thicknesses ranging from 6 mm to 125 mm (0.25 in. to 5 in.). The pressure generated by the centrifugal force is high, as much as 150 g's, and are necessary for casting thick-walled parts. Castings of good quality, dimensional accuracy, and external surface detail are obtained by this process. In addition to pipes, typical parts made are bushings, engine-cylinder liners, and bearing rings with or without flanges.

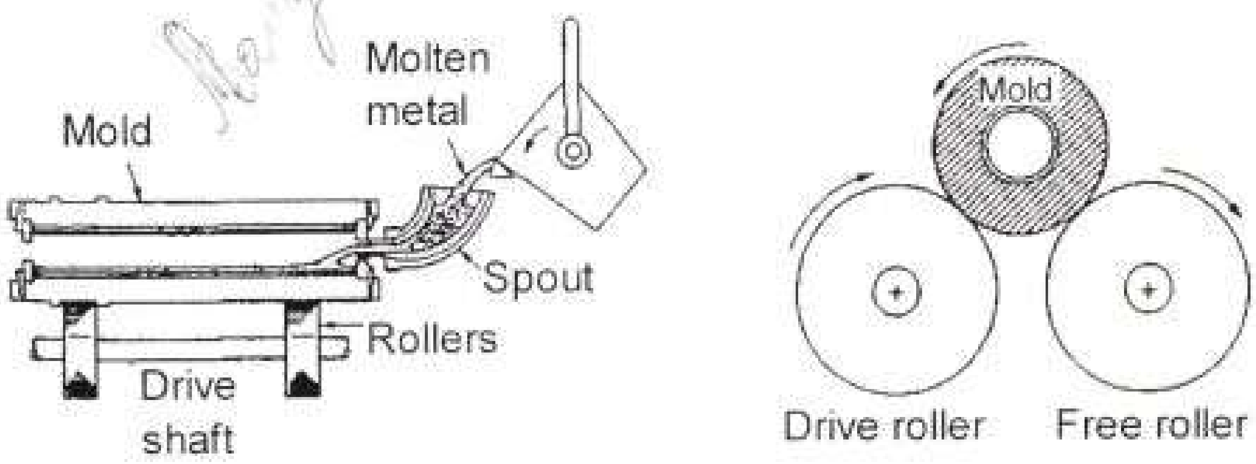


FIGURE 2.26. Schematic illustration of the centrifugal casting process. Pipes, cylinder liners, and similarly shaped parts can be cast by this process.

2.13.2. Semicentrifugal casting

An example of *semicentrifugal casting* is shown in Fig. 2.27(a). This method is used to cast parts with rotational symmetry, such as a wheel with spokes.

2.13.3. Centrifuging

In *centrifuging*, also called *centrifuge casting*, mold cavities of any shape are placed at a certain distance from the axis of rotation. The molten metal is poured from the center and is forced into the mold by centrifugal forces (Fig. 2.27b). The properties of castings vary by distance from the axis of rotation.

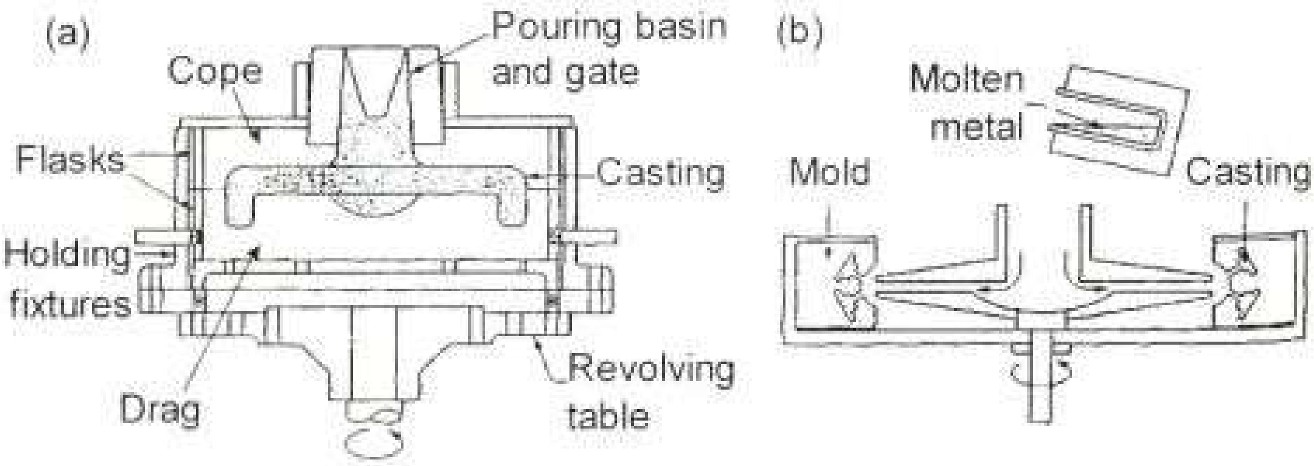
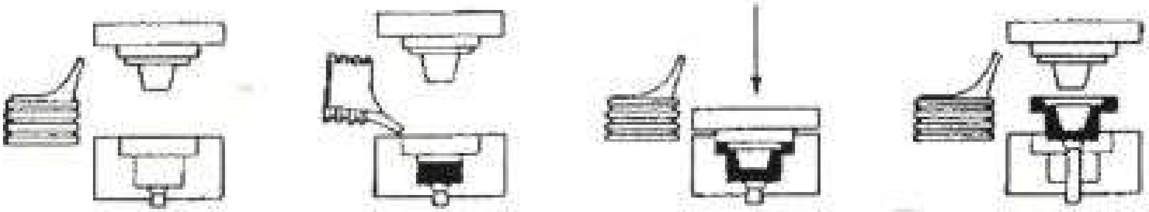


FIGURE 2.27. (a) Schematic illustration of the semicentrifugal casting process. (a) Schematic illustration of casting by centrifuging

2.14. Squeeze Casting

The squeeze-casting process, developed in the 1960s, involves solidification of the molten metal under high pressure. Thus it is a combination of casting and forging (Fig. 2.28). The machinery includes a die, punch, and ejector pin. The pressure applied by the punch keeps the entrapped gases in solution, and the contact under high pressure at the die-metal interface promotes rapid heat transfer, resulting in a fine microstructure with good mechanical properties.

Parts can be made to near-net shape, with complex shapes and fine surface detail, from both nonferrous and ferrous alloys. Typical products made are automotive wheels and mortar bodies (a short-barreled cannon). The pressures required in squeeze casting are lower than those for hot or cold forging.



Melt metal

Pour molten metal into die

Close die and apply pressure

Eject squeeze casting and charge melt stock and repeat cycle

FIGURE 2.28. Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging

2.15. Casting Techniques for Single-Crystal Components

Now we'll consider techniques for producing single-crystal (*mono-crystal*) components. We'll illustrate these techniques by describing the casting of gas turbine blades, which are generally made of nickel-base superalloys. The procedures involved can also be used for other alloys and components.

2.15.1. Conventional casting of turbine blades

The *conventional casting process* using a ceramic mold is shown in Fig. 2.29(a). The molten metal is poured into the mold and begins to solidify at the ceramic walls. The grain structure developed is polycrystalline and is similar to that shown in Fig. 1.1(c). The presence of grain boundaries makes this structure susceptible to creep and cracking along those boundaries under the centrifugal forces at elevated temperatures.

2.15.2. Directionally solidified blades

In the *directional solidification process* (Fig. 2.29b), first developed in 1960, the ceramic mold is preheated by radiant heating. The mold is supported by a water-cooled chill plate. After the metal is poured into the mold, the assembly is lowered slowly. Crystals begin to grow at the chill-plate surface and upward, like the columnar grains shown in Fig. 1.2. The blade is thus directionally solidified, with longitudinal but no transverse grain boundaries. Consequently, the blade is stronger in the direction of centrifugal forces developed in the gas turbine.

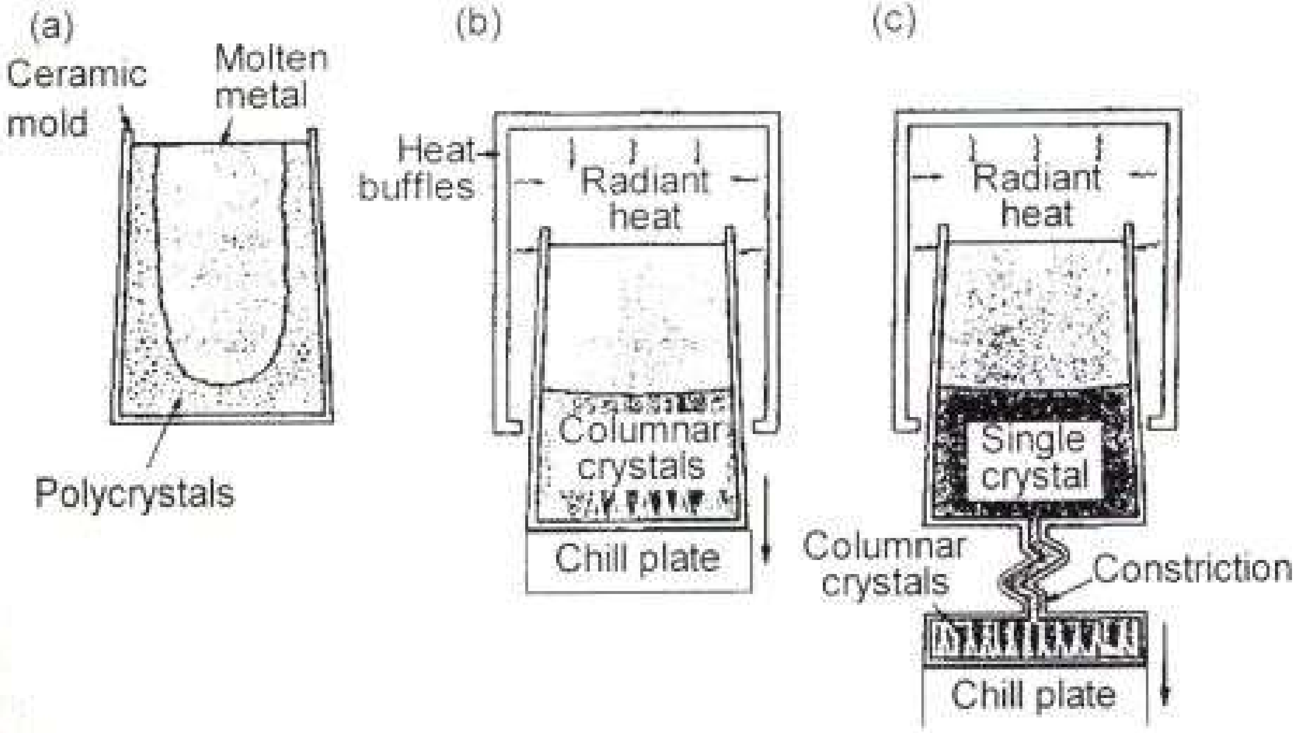


FIGURE 2.29. Three methods of casting turbine blades: (a) conventional casting with ceramic mold; (b) directional solidification; (c) method to produce single-crystal blade

2.15.3. Single-crystal blades

In *crystal growing*, developed in 1967, the mold has a constriction in the shape of a corkscrew (Fig. 2.29c), the cross-section of which allows only one crystal to fit through. As the assembly is lowered slowly, a single crystal grows upward through the constriction and begins to grow in the mold. Strict control of the rate of movement is necessary. The solidified mass in the mold is a single-crystal blade. Although more expensive than other blades, the lack of grain boundaries makes these blades resistant to creep and thermal shock. Thus they have a longer and more reliable service life.

2.16. Inspection of Castings

Several methods are available for inspection of castings to determine quality and the presence of any defects. Castings can be inspected visually or optically for surface defects. Subsurface and internal defects are investigated using various nondestructive techniques.

In destructive testing, test specimens are removed from various sections of a casting and tested for strength, ductility, and other mechanical properties, and to determine the presence and location of any defects.

Pressure tightness of cast components (valves, pumps, pipes) is usually determined by sealing the openings in the casting and pressurizing it with water, oil, or air. The casting is then inspected for leaks while the pressure is maintained. Because air is compressible, its use is dangerous in such tests because of the possibility of a sudden explosion if there is a major flaw in the casting.

Unacceptable or defective castings are remelted for reprocessing. Because of the major economic impact, the types of defects present in castings and their causes must be investigated. Control of all stages during casting, from mold preparation to the removal of castings from molds or dies, is important in maintaining good quality.

2.17. Foundries

The casting operations are usually carried out in *foundries* (from the Latin *fundere*, meaning melting and pouring). Although casting operations have traditionally involved much manual labor, modern foundries have automated and computer-integrated facilities for all aspects of their operations. They produce a wide variety and sizes of castings at high production rates, at low cost, and with good quality control.

As outlined in Fig. 2.2, foundry operations initially involve two separate activities. The first is pattern and mold making, which now utilize computer-aided design and manufacturing techniques, minimizing trial and error and improving efficiency. A variety of automated machinery is used to minimize labor costs, which can be significant in the production of castings. The second activity is melting the metals, controlling their composition and impurities, and pouring them into appropriate molds.

The rest of the operations, such as pouring into molds carried along conveyors, shakeout, cleaning, heat treatment, and inspection, are also automated. Automation minimizes labor, reduces the possibility of human error, increases the production rate, and attains higher quality levels.

The main advantages and limitations of various metal-casting processes are submitted in the Table 2.4.

TABLE 2.4. SUMMARY OF CASTING PROCESSES, THEIR ADVANTAGES AND LIMITATIONS

PROCESS	ADVANTAGES	LIMITATIONS
Sand	Almost any metal is cast; no limit to size, shape or weight; low tooling cost.	Some finishing required; somewhat coarse finish; wide tolerances.
Shell mold	Good dimensional accuracy and surface finish; high production rate.	Part size limited; expensive patterns and equipment required.
Expended polystyrene	Most metals cast with no limit to size; complex shapes.	Patterns have low strength and can be costly for low quantities.
Plaster mold	Intricate shapes; good dimensional accuracy and finish; low porosity.	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long.
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish.	Limited size.
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast.	Part size limited; expensive patterns, molds, and labor.
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate.	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals.
Die	Excellent dimensional accuracy and surface finish; high production rate.	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time.
Centrifugal	Large cylindrical parts with good quality; high production rate.	Equipment is expensive; part shape limited.

REVIEW QUESTIONS

2.1. Describe the differences between expendable and permanent molds.
2.2. Name the important factors in selecting sand for molds.
2.3. What are the major types of sand molds? What are their characteristics?
2.4. List the considerations for selecting pattern materials.
2.5. What is the function of a core? What are core prints?
2.6. Name and describe the characteristics of the types of sand-molding machines.
2.7. What is the difference between sand and shell molding?
2.8. What are composite molds? Why are they used?
2.9. Describe the features of plaster-mold casting.
2.10. Why is the investment-casting process capable of producing fine surface detail on castings ?

2.11. Name the type of materials used for permanent-mold casting processes.

2.12. What are the advantages of pressure casting?

2.13. List the advantages and limitations of die casting.

2.14. What are parting agents?

2.15. Describe the methods used for producing single-crystal parts.

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

2.17. What are the reasons for the large variety of casting processes that have been developed over the years? Explain your answer with specific examples.

2.18. If you need only five units of a casting, which process(es) would you use? Why?

2.19. Describe the advantages and limitations of hot-chamber and cold-chamber die casting processes, respectively.

2.20. Explain why processes such as sand, shell, plaster, and investment casting can produce parts with greater shape complexity than others, such as permanent-mold, die, and centrifugal casting.

2.21. Why is it that die casting can produce the smallest parts?

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

2.23. Would you recommend preheating the molds in permanent-mold casting? Also, would you remove the casting soon after it has solidified? Explain your reasons.

2.24. Describe the advantages of composite molds. Where would you use them?

2.25. Referring to Fig. 2.3, do you think it is necessary to weigh down or clamp the two halves of the mold? Explain your reasons. Do you think the kind of metal cast, such as gray cast iron versus aluminum, should make a difference on the clamping force?

2.26. Give a step-by-step procedure for the (a) investment-casting process and (b) die-casting process.

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

2.28. In a sand-casting operation, what factors determine the time at which you would remove the casting from the mold ?

2.29. Which of the casting processes would be suitable for making small toys? Why?

2.30. What would you do to improve the surface finish in expendable-mold casting processes ?

2.31. How would you attach the individual wax patterns on a "tree" in investment casting?

2.32. Describe the measures that you would take to reduce core shifting in sand casting.

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

2.34. What is the function of a blind riser?

2.35. Describe the procedures that would be involved in making a bronze statue. Which casting processes would be suitable? Why?

2.36. Write a brief report on the permeability of molds and the techniques that are used to determine permeability.

2.37. Describe the characteristics of chaplet materials. Should they melt while molten metal is being poured and solidified in the mold? Explain.

2.38. Estimate the clamping force for a die casting machine in which the casting is rectangular with projected dimensions of 100 mm x 200 mm (4 in. x 8 in.). Would your answer depend on whether or not it is a hot-chamber or cold-chamber process? Explain.

2.39. Make a list of the mold and die materials used in the casting process 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.

2.40. How are hollow parts with various cavities made by die casting? Are cores used? If so, how? Explain.

2.41. Explain why the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness.

3. Casting Design. Casting Alloys. Economics of Casting

3.1. Introduction

In the preceding two chapters we saw that successful casting practice requires careful control of a large number of variables. These variables pertain to the particular characteristics of the metals and alloys cast, method of casting, mold and die materials, mold design, and various process parameters. The flow of the molten metal in the mold cavities, gating systems, the rate of cooling, and the gases evolved all influence the quality of a casting.

In this chapter we discuss general design considerations and guidelines for metal casting. As we pointed out in Section 1.5, poor casting practices and lack of control of process variables can lead to defective castings. We present suggestions for avoiding defects. We also describe the alloys that are commonly cast, together with their characteristics and typical applications.

As we have stated before, the economics of manufacturing processes are just as important as the technical considerations that we have been describing in detail. In this chapter we outline the basic economic factors relevant to casting operations and make some economic comparisons between different casting processes.

3.2. Design Considerations

As in all engineering practice and manufacturing operations, certain guidelines and **design principles** pertaining to casting have been developed over many years. Although these principles were established primarily through practical experience, analytical methods and computer-aided design and manufacturing techniques are now coming into wider use, improving productivity and the quality of castings. Moreover, careful design can result in significant cost savings.

3.2.1. Designing for expendable-mold casting

The following guidelines generally apply to all types of castings. The most significant design considerations are identified and addressed.

Corners, angles, and section thickness. Sharp corners, angles, and fillets should be avoided (Fig. 3.1), as they may cause cracking and tearing during solidification of the metal. Fillet radii should be selected to reduce stress concentrations and to ensure proper liquid-metal flow during the pouring process. Fillet radii usually range from 3 mm to 25 mm (1/8 in. to 1 in.), although smaller radii may be permissible in small castings and in limited applications. On the other hand, if the fillet radii are too large, the volume of the material in those regions is also large and, consequently, the rate of cooling is less.

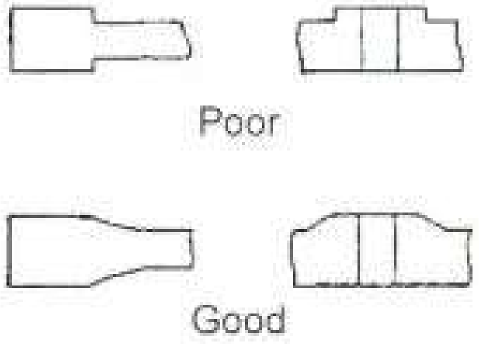


FIGURE 3.1. Suggested design modifications to avoid defects in casting Note that sharp corners are avoided to reduce stress concentrations

Section changes in castings should smoothly blend into each other. The location of the largest circle that can be inscribed in a particular region is critical as far as shrinkage cavities are concerned (Fig. 3.2a and b). Because the cooling rate in regions with the larger circles is less, they are called **hot spots**. These regions could develop *shrinkage cavities* and *porosity* (Fig. 3.2c and d). Cavities at hot spots can be eliminated with small cores. Although they produce cored holes in the casting (Fig. 3.2e), these holes do not affect the strength of the casting significantly.

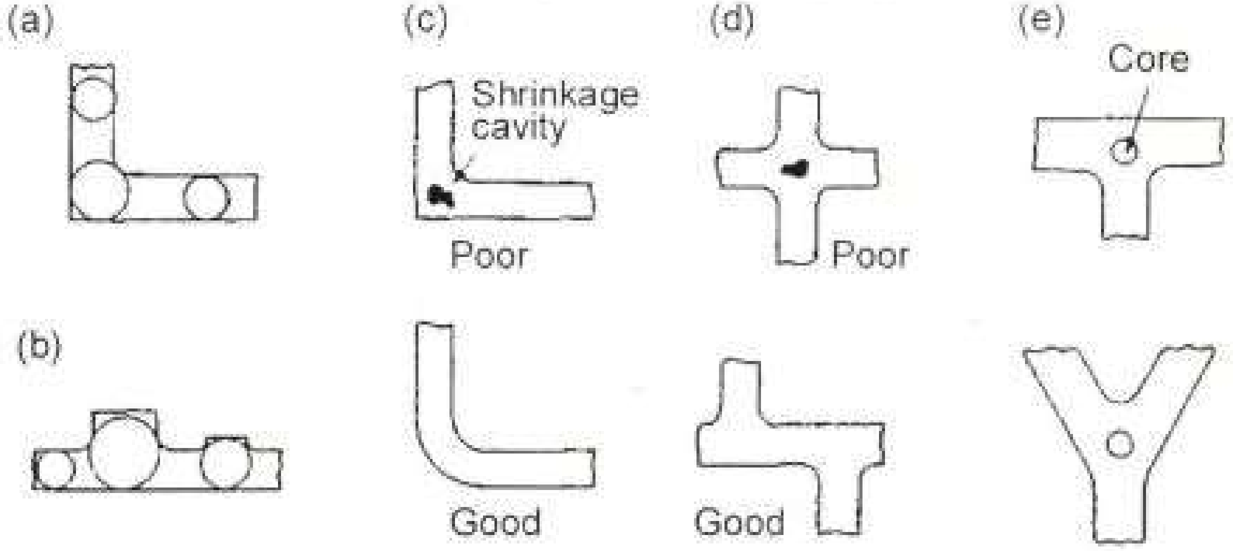


FIGURE 3.2. Examples of designs showing the importance of maintaining uniform cross-sections in castings to avoid hot spots and shrinkage cavities

Other examples of design principles that can be used to avoid shrinkage cavities are shown in Fig. 3.3. Although they increase the cost of production, metal paddings in the mold can eliminate or minimize hot spots. These paddings act as external chills, such as that shown for casting of a hollow cylindrical part with internal ribs in Fig. 3.4. From these illustrations you can see the importance of maintaining, insofar as possible, uniform cross-sections and wall thicknesses throughout the casting to avoid shrinkage cavities.

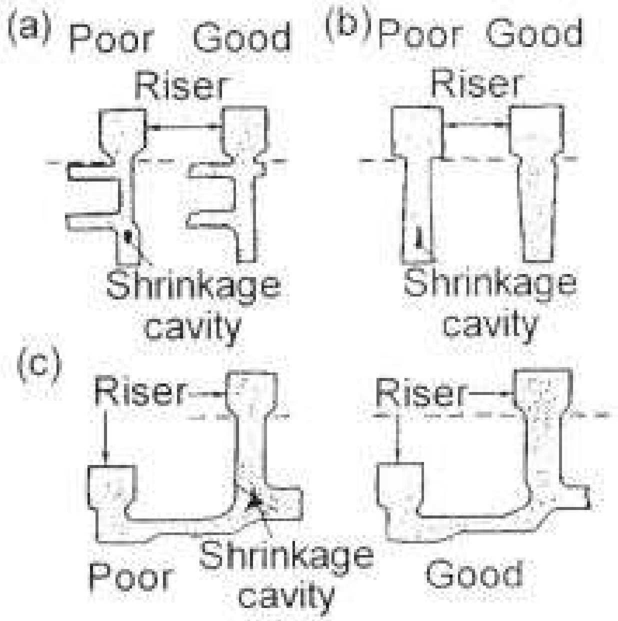


FIGURE 3.3. Examples of design modifications to avoid shrinkage cavities in castings

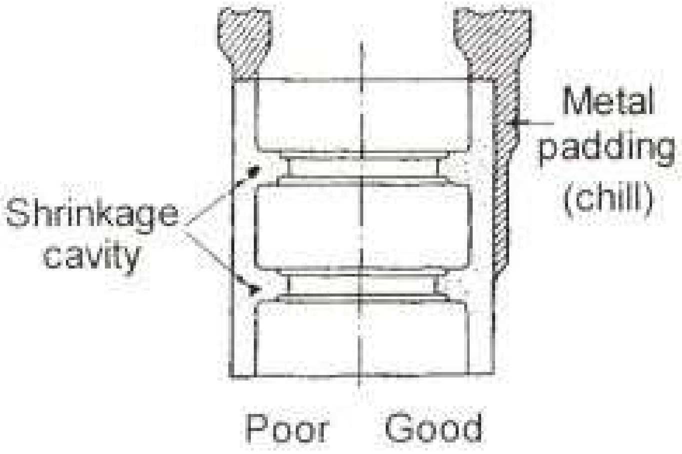


FIGURE 3.4. The use of metal padding (chills) to increase the rate of cooling in thick regions in a casting to avoid shrinkage cavities

Flat areas. Large flat areas (plain surfaces) should be avoided, as they may warp because of temperature gradients during cooling or develop poor surface finish because of uneven flow of metal during pouring. Flat surfaces can be broken up with ribs and serrations.

Shrinkage. Allowances for shrinkage during solidification should be provided for, so as to avoid cracking of the casting. Figure 3.5(a) depicts a wheel with spokes. If the spokes are curved, the tensile stress in them resulting from contraction during solidification – and hence the tendency for cracking – is reduced. Another example is shown in Fig. 3.5(b), in which the original design has been altered slightly. In castings with intersecting ribs (Fig. 3.6), the tensile stresses can be reduced by staggering the ribs, as shown in Fig. 3.2(d), or by changing the intersection geometry from an X configuration to a Y configuration.

Pattern dimensions should also provide for shrinkage of the metal during solidification and cooling. Allowances for shrinkage, also known as patternmaker's shrinkage allowances, usually range from about 10 mm/m to 20 mm/m (1/8 in./ft to 1/4 in./ft). Table 3.1 gives the normal shrinkage allowance for metals commonly sand cast.

TABLE 3.1. NORMAL SHRINKAGE ALLOWANCE FOR METALS CAST IN SAND MOLDS

METAL	PERCENT
Gray cast iron	0.83 -1.3
White cast iron	2.1
Malleable cast iron	0.78 -1.0
Aluminum alloys	1.3
Magnesium alloys	1.3
Yellow brass	1.3 -1.6
Phosphor bronze	1.0 -1.6
Aluminum bronze	2.1
High-manganese steel	2.6

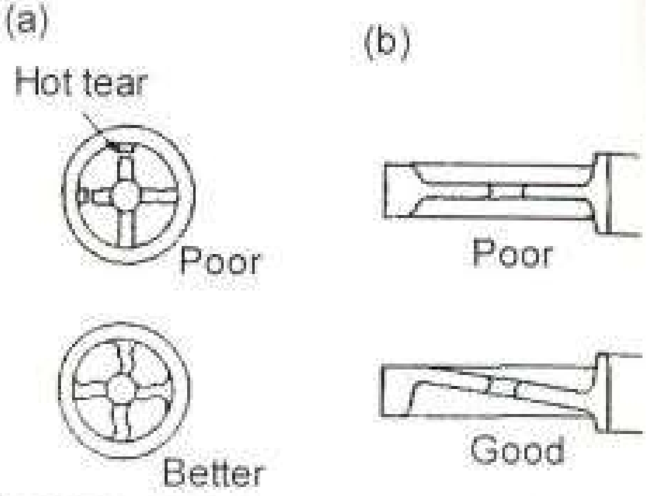


FIGURE 3.5. Two examples of poor and good casting design practice to avoid tears caused by contraction during cooling

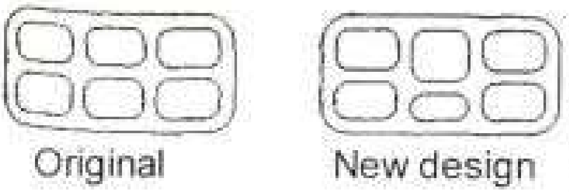


FIGURE 3.6. Modification of a design to avoid shrinkage cavities in castings. Note the staggering of intersecting regions in the improved design

Parting line. Recall that the parting line is the line, or plane, separating the upper (cope) and lower (drag) halves of molds (see Figs. 2.3 and 3.7). In general, it is desirable for the parting line to be along a flat plane, rather than contoured. Whenever possible, the parting line should be at the corners or edges of castings, rather than on flat surfaces in the middle of the casting. In this way, the flash at the parting line (material squeezing out between the two halves of the mold) will not be as visible.

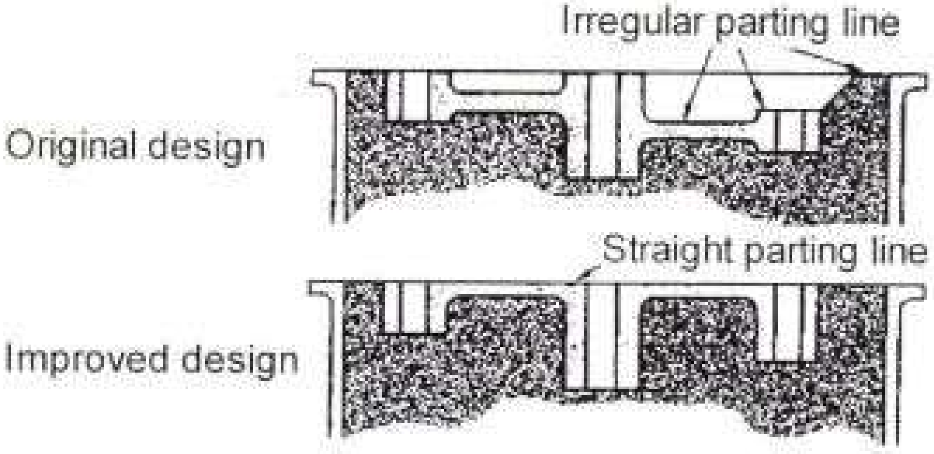


FIGURE 3.7. Redesign of a casting by making the parting line straight to avoid defects

The location of the parting line is important because it influences mold design, ease of molding, number and shape of cores, method of support, and the gating system. Since preparation of dry-sand cores requires additional time and cost, you should minimize or eliminate their use. This can usually be accomplished by reviewing the design of castings and simplifying them. Three examples of casting design modifications are shown in Fig. 3.8.

Draft. As we saw in Fig. 2.5, a small draft (taper) is provided in sand-mold patterns to enable removal of the pattern without damaging the mold. Typical drafts range from 5 mm/m to 15 mm/m (1/16 in./ft to 3/16 in./ft). Depending on the quality of the pattern, draft angles usually range from 0.5° to 2°. The angles on inside surfaces are typically twice this range. They have to be higher than those for outer surfaces because the casting shrinks inward toward the core.

Tolerances. Tolerances – the permissible variations in the dimensions of a part – depend on the particular casting process, size of the casting, and type of pattern used. Tolerances are smallest within one part of the mold and, because they are cumulative, increase between different parts of the mold. Tolerances should be as wide as possible, within the limits of good part performance; otherwise the cost of the casting increases. In commercial practice, tolerances usually are in the rang of ±0.8 mm (1/32 in.) for small castings and increase with the size of castings, say, to 6 mm (1/4 in.) for large castings.

Machining allowance. Because most expendable-mold castings require some additional finishing operations, such as machining, allowances should be made in casting design for these operations.

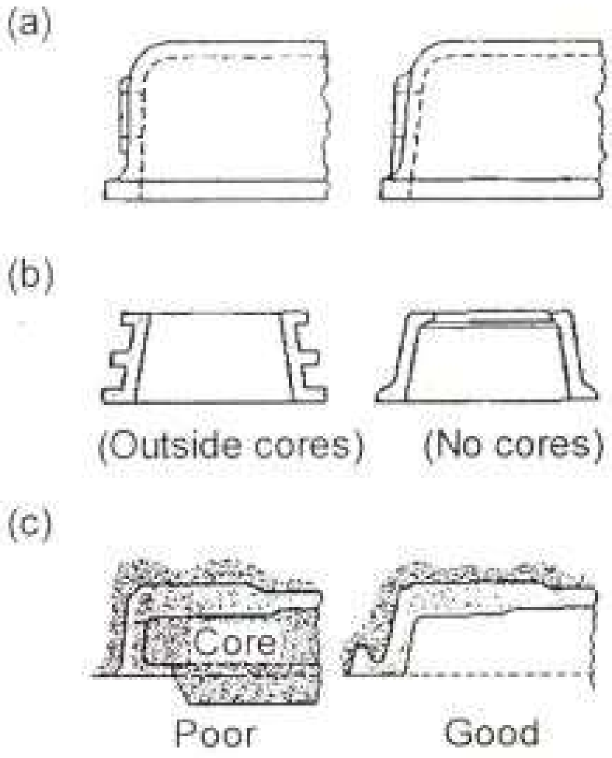


FIGURE 3.8. Examples of casting design modifications

Machining allowances, which are included in pattern dimensions, depend on the type of casting and increase with the size and section thickness of castings. Allowances usually range from about 2 mm to 5 mm (0.1 in. to 0.2 in.) for small castings, to more than 25 mm (1 in.) for large castings.

Residual stresses. The different cooling rates within the body of a casting cause residual stresses. Stress relieving may thus be necessary to avoid distortions in critical applications.

3.2.2. Designing for permanent-mold casting

The design principles for permanent-mold casting are similar to those for expendable-mold casting. Typical design guidelines and examples for permanent-mold casting are shown schematically in Fig. 3.9 for die casting. Note that the cross-sections have been reduced in order to decrease the time for solidification and save material.

Special considerations are involved in designing and tooling for die casting, where sharp edges rather than smooth transitions at the intersection of two members may be desirable for longer mold life. Furthermore, designs may be modified to eliminate the draft for better dimensional accuracy.

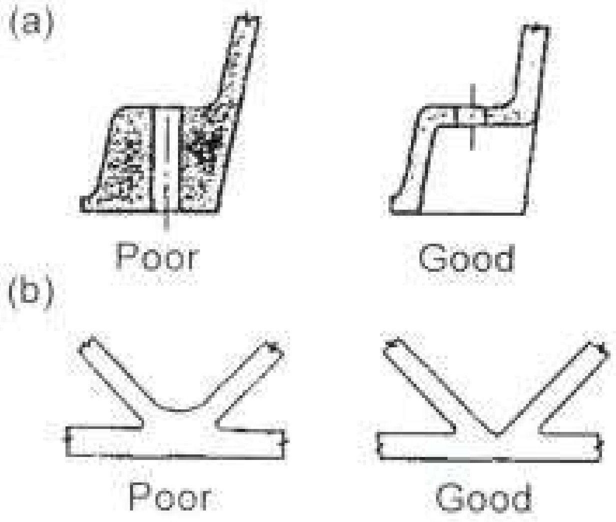


FIGURE 3.9. Examples of undesirable and desirable design practices for die-cast parts. Note that section-thickness uniformity is maintained throughout the part.

3.3. Casting Alloys

We classify casting alloys as ferrous and nonferrous. Parts made of aluminum-base and magnesium-base alloys are known as light-metal castings. We describe the basic properties and characteristics of various casting alloys in this section. We summarize the mechanical properties of cast metals in Tables 3.2–3.5.

TABLE 3.2. TYPICAL APPLICATIONS FOR CASTINGS AND CASTING CHARACTERISTICS

TYPE OF ALLOY	APPLICATION	CAST-ABILITY*	WELD-ABILITY*	MACHIN ABILITY*
Aluminum	Pistons, clutch housings, exhaust manifolds	E	F	G-E
Copper	Pumps, valves, gear blanks, marine propellers	F-G	F	F-G
Gray iron	Engine blocks, gears, brake disks and drums, machine bases	E	D	G
Magnesium	Crankcase, transmission housings	G-E	G	E
Malleable iron	Farm and construction machinery, heavy-duty bearings, railroad rolling stock	G	D	G
Nickel	Gas turbine blades, pump and valve components for chemical plants	F	F	F
Nodular iron	Crankshafts, heavy-duty gears	G	D	G
Steel (carbon and low alloy)	Die blocks, heavy-duty gear blanks, aircraft undercarriage members, railroad wheels	F	E	F
Steel (high alloy)	Gas turbine housings, pump and valve components, rock crusher jaws	F	E	F
White iron	Mill liners, shot blasting nozzles, railroad brake shoes, crushers and pulverizers	G	VP	VP
Zinc	Door handles, radiator grills, carburetor bodies	E	D	E

* E, excellent; G, good; F, fair; VP, very poor; D, difficult.

TABLE 3.3. PROPERTIES AND TYPICAL APPLICATIONS OF CAST IRONS

CAST IRON	TYPE	ULTIMATE TENSILE STRENGTH (MPa)	YIELD STRENGTH (MPa)	ELONGATION IN 50 mm (%)	TYPICAL APPLICATIONS
Gray	Ferritic	170	140	0.4	Pipe, sanitary ware
	Pearlitic	275	240	0.4	Engine blocks, machine tools
	Martensitic	550	550	0	Wearing surfaces
Nodular (Ductile)	Ferritic	415	275	18	Pipe, general service
	Pearlitic	550	380	6	Crankshafts, highly stressed parts
	Tempered martensite	825	620	2	High-strength machine parts, wear resistance
Malleable	Ferritic	365	240	18	Hardware, pipe fittings, general engineering service
	Pearlitic	450	310	10	Railroad equipment, couplings
	Tempered martensite	700	550	2	Railroad equipment, gears, connecting rods
White	Pearlitic	275	275	0	Wear-resistance, mill rolls

TABLE 3.4. MECHANICAL PROPERTIES OF GRAY CAST IRONS

ASTM CLASS	ULTIMATE TENSILE STRENGTH (MPa)	COMPRESSIVE STRENGTH (MPa)	ELASTIC MODULUS (GPa)	HARDNESS (HB)
20	152	572	66 to 97	156
25	179	669	79 to 102	174
30	214	752	90 to 113	210
35	252	855	100 to 119	212
40	293	965	110 to 138	235
50	362	1130	130 to 157	262
60	431	1293	141 to 162	302

TABLE 3.5. PROPERTIES AND TYPICAL APPLICATIONS OF CAST NONFERROUS ALLOYS

ALLOYS (*UNS*)	CONDITION	ULTIMATE TENSILE STRENGTH (MPa)	YIELD STRENGTH (MPa)	ELONGATION IN 50 mm (%)	TYPICAL APPLICATIONS
ALUMINUM ALLOYS					
195 (A01950)	Heat treated	220-280	110-220	8.5-2	Sand castings
319 (A03190)	Heat treated	185-250	125-180	2-1.5	Sand castings
356 (A03560)	Heat treated	260	185	5	Permanent mold castings
COPPER ALLOYS					
Red brass (C83600)	Annealed	235	115	25	Pipe fittings, gears
Yellow brass (C86400)	Annealed	275	95	25	Hardware, ornamental
Manganese bronze (C86100)	Annealed	480	195	30	Propeller hubs, blades
Leaded tin bronze (C92500)	Annealed	260	105	35	Gears, bearings, valves
Gun metal (C90500)	Annealed	275	105	30	Pump parts, fittings
Nickel silver (C97600)	Annealed	275	175	15	Marine parts, valves
MAGNESIUM ALLOYS					
AZ91A	F	230	150	3	Die castings
AZ63A	T4	275	95	12	Sand and permanent mold castings
AZ91C	T6	275	130	5	High strength
EZ33A	T5	160	110	3	Elevated temperatur
HK31A	T6	210	105	8	Elevated temperatur
QE22A	T6	275	205	4	Highest strength

3.3.1. Nonferrous casting alloys

Aluminum-base alloys. Alloys with an aluminum base have a wide range of mechanical properties, mainly because of various hardening mechanisms and heat treatments that can be used with them. Their fluidity depends on oxides and alloying elements in the metal. These alloys have high electrical conductivity and generally good corrosion resistance to most elements (except alkali). They are nontoxic and lightweight and have good machinability. However, except for alloys with silicon, they generally have low resistance to wear and abrasion. Aluminum-base alloys have many applications, including architectural and decorative use. Engine blocks of some automobiles are made of aluminum-alloy castings.

Magnesium-base alloys. The lowest density of all commercial casting alloys are those in the magnesium-base group. They have good corrosion resistance and moderate strength, depending on the particular heat treatment used.

Copper-base alloys. Although somewhat expensive, copper-base alloys have the advantages of good electrical and thermal conductivity, corrosion resistance, nontoxicity, and wear properties suitable for bearing materials. Mechanical properties and fluidity are influenced by the alloying elements.

Zinc-base alloys. A low-melting-point alloy group, zinc-base alloys have good fluidity and sufficient strength for structural applications. These alloys are commonly used in die casting.

High-temperature alloys. High-temperature alloys have a wide range of properties and typically require temperatures of up to 1650 °C (3000 °F) for casting titanium and superalloys—and higher for refractory alloys. Special techniques are used to cast these alloys into parts for jet and rocket engine components. Some of these alloys are more suitable and economical for casting than for shaping by other manufacturing methods, such as forging.

3.3.2. Ferrous casting alloys

Cast irons. Cast irons represent the largest amount of all metals cast. They generally possess several desirable properties, such as wear resistance, hardness, and good machinability. These alloys can easily be cast into intricate shapes.

The term **cast iron** refers to a family of alloys. They are classified as gray cast iron (gray iron), nodular (ductile or spheroidal) iron, white cast iron, malleable iron, and compacted graphite iron. We discuss the characteristics of each of these cast irons in this section. We show their general properties and typical applications in Tables 3.3 and 3.4.

Gray cast iron. Castings of gray cast iron have relatively few shrinkage cavities and little porosity. Recall that various forms of gray cast iron are termed ferritic, pearlitic, and martensitic. Because of differences in their structures, each type has different properties.

Typical uses of gray cast iron are for engine blocks, machine bases, electric-motor housings, pipes, and wear surfaces for machines. Gray cast irons are specified by a two-digit ASTM designation. Class 20, for example, specifies that the material must have a minimum tensile strength of 20 ksi (140 MPa). We show the mechanical properties for several classes of gray cast iron in Table 3.4.

Nodular (ductile) iron. Typically used for machine parts, pipe, and crankshafts, nodular cast irons are specified by a set of two-digit numbers. Thus, class or grade 80-55-06, for example, indicates that the material has a minimum tensile strength of 80 ksi (550 MPa), a minimum yield strength of 55 ksi (380 MPa), and 6 percent elongation in 2 in. (50 mm).

White cast iron. Because of its extreme hardness and wear resistance, white cast iron is used mainly for liners for machinery to process abrasive materials, rolls for rolling mills, and railroad-car brake shoes.

Malleable iron. The principal use of malleable iron is for railroad equipment and various types of hardware. Malleable irons are specified by a five-digit designation. Thus 35018, for example, indicates that the yield strength of the material is 35 ksi (240 MPa), and its elongation is 18 percent in 2 in.

Compacted graphite iron. First produced commercially in 1976, compacted graphite iron has properties that fall between those of gray and nodular irons. Its machinability is better than nodular iron. Typical applications are automotive engine blocks and heads.

Cast steels. Because of the high temperatures required to melt cast steels, up to about 1500°C (2700°F), their casting requires considerable knowledge and experience. The high temperatures involved present difficulties in the selection of mold materials – particularly in view of the high reactivity of steels with oxygen – in melting and pouring the metal. Steel castings possess properties that are more uniform (isotropic) than those made by mechanical working processes. Cast steels can be welded without the loss of any properties from the heat of welding. Cast weldments have gained importance where complex configurations, or the size of the casting, may prevent casting the part economically in one place.

Cast stainless steels. Casting of stainless steels involves considerations similar to those for steels in general. Stainless steels generally have a long freezing range and high melting temperatures. They develop various structures, depending on their composition and the process parameters. Cast stainless steels are available in various compositions and can be heat treated and welded.

3.4. Economics of Casting

When looking at various casting processes, we noted that some require more labor than others, some require expensive dies and machinery, and some take a great deal of time to complete. These important characteristics are outlined in Table 3.6. Each of the individual factors listed affects to varying degrees the overall cost of a casting operation.

TABLE 3.6. GENERAL COST CHARACTERISTICS OF CASTING PROCESSES

PROCESS	COST*			PRODUCTION RATE (Pc/hr)
	DIE	EQUIPMENT	LABOR	
Sand	L	L	L-M	< 20
Shell	L-M	M-H	L-M	< 50
Plaster	L-M	M	M-H	< 10
Investment	M-H	L-M	H	< 1000
Permanent mold	M	M	L-M	< 60
Die	H	H	L-M	< 200
Centrifugal	M	H	L-M	< 50

* L, low; M, medium; H, high.

The cost of a product involves the costs of materials, labor, tooling, and equipment. Preparations for casting a product include making molds and dies that require raw materials, time, and effort, which we can translate into costs. As you can see in Table 3.6, relatively little cost is involved in molds for sand casting. On the other hand, die-casting dies require expensive materials and a great deal of machining and preparation. In addition to molds and dies, facilities are required for melting and pouring the molten metal into the molds or dies. These facilities include furnaces and related machinery; their costs depend on the level of automation desired. Finally, costs are involved in cleaning and inspecting castings.

The amount of labor required for these operations can vary considerably, depending on the particular process and level of automation. Investment casting, for example, requires a great deal of labor because of the large number of steps involved in this operation. On the other hand, operations such as highly automated die casting can maintain high production rates with little labor required.

We should note, however, that the cost of equipment per casting (unit cost) will decrease as the number of parts cast increases (Fig. 3.11). Thus sustained high production rates can justify the high cost of dies and machinery. However, if demand is relatively small, the cost per casting increases rapidly. It then becomes more economical to manufacture the parts by sand casting – or by other manufacturing processes. Note that

Fig. 3.10 can be expanded to include other casting processes suitable for making the same part.

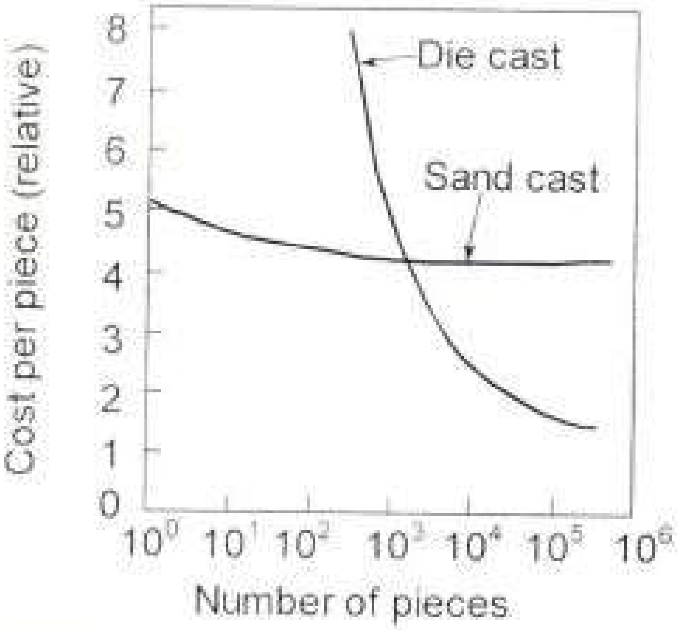


FIGURE 3.10. Economic comparison of making a part by two different casting processes. Note that because of the high cost of equipment, die casting is economical for large production runs.

The two processes (sand and die casting) we compared produce castings with significantly different dimensional and surface-finish characteristics (see Table 2.1). Thus not all manufacturing decisions are based purely on economic considerations. In fact, parts can usually be made by more than one or two processes. The final decision rests on both economic and technical considerations.

REVIEW QUESTIONS

3.1. List the general design considerations in casting.
3.2. What are hot spots?
3.3. What is shrinkage allowance? Machining allowance?
3.4. Why are drafts necessary in some molds?
3.5. What are light-metal castings?
3.6. Name the types of cast irons and list their major characteristics.
3.7. Why are steels more difficult to cast than cast irons?
3.8. Name the important factors involved in the economics of casting operations.
3.9. Describe your observations concerning Figs. 3.2, 3.3, and 3.4.
3.10. Describe the procedure you would follow to determine whether a defect in a casting is a shrinkage cavity or porosity caused by gases.
3.11. Explain how you would go about avoiding hot tearing.
3.12. If you need only a few castings of the same design, which three processes would be the most expensive per piece?
3.13. Do you generally agree with the cost ratings in Table 3.6? If so, why?
3.14. Explain how ribs and serrations are helpful in casting flat surfaces that otherwise may warp. Give an illustration.

3.15. Describe the nature of the design changes made in Fig. 3.8. What general principles do you observe?

3.16. Assume that the Introduction to this chapter is missing. Write a brief introduction to highlight the importance of the topics covered in this chapter.

3.17. Do you think there will be fewer or more defects in a casting made by gravity pouring or made by pouring under pressure?

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

3.19. Explain the difference in importance in draft in green-sand casting versus permanent-mold casting.

3.20. What type of cast iron would be suitable for a stationary heavy machine base? Why?

3.21. Explain the advantages and limitations of sharp and rounded fillets, respectively, in casting design.

3.21. Referring to Tables 1.2 and 3.1, do you think that there is a contradiction regarding the behavior of gray cast iron? Explain.

3.22. Explain why the elastic modulus of gray cast iron varies so much, as shown in Table 3.4.

4. Designing Sand Molds

4.1.Gating systems For Sand Molds

4.1.1. Designs

The gating system for a casting is a series of channels that lead molten metal into the mold cavity. It may include any or all of the following: pouring basin, sprue, sprue base, runners, and ingates. A well-designed gating system should:

1. Minimize turbulence within the molten metal as it flows through the gating system. The use of tapered sprues and proper streamlining will reduce excessive erosion and gas entrainment.
2. Reduce the velocity of the molten metal in order to attain minimum turbulence.
3. Deliver the molten metal at the best location to achieve proper directional solidification and optimum feeding of shrinkage cavities.
4. Provide a build-in metering device to permit uniform, standardized pouring times regardless of variations in pouring techniques.

Figure 4.1 is a typical nonpressurized gating system for an aluminum alloy. Note that each gate has a riser.

4.1.2. Turbulence within a gating system

Extensive research has shown that molten metal and water flow similarly and that gating systems can be designed using the principles of fluid mechanics.

Several limitations are apparent. The high density of metals (up to 10 times that of water) makes it difficult to force molten alloys to turn a corner as from a runner to an ingate. But once Newton's law of inertia is applied to flowing metal, proper gating systems can readily be designed. The density of a metal does not affect its flow characteristics, because the rate

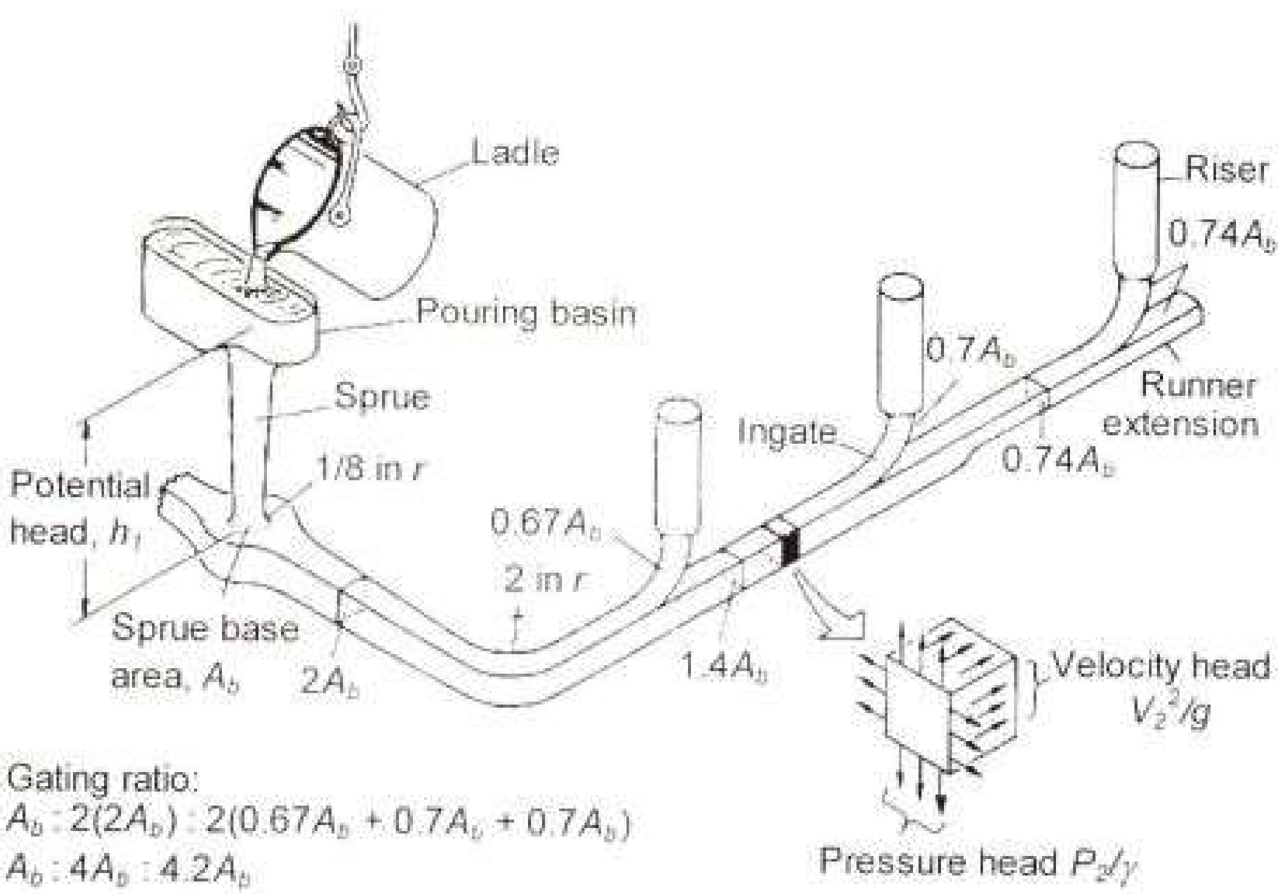


FIGURE 4.1. Design of a nonpressurized gating system using 1 : 4 : 4 gating ratio

and nature of fluid flow depend on the inertia of the fluid and the forces applied to it. Both factors depend on density in the same way, so it has no effect on the fluid flow. But impact depends upon density alone; hence mold erosion increases directly with density.

Although water has a surface tension approximately one-tenth that of molten metals, recent experiments have shown that Wood's metal and mercury have nearly equal to water surface tension and ability to entrain air. However, the greater surface tension and the natural oxide coating that envelopes a stream of molten metal seem to permit it to flow in a nondisruptive fashion at a greater velocity than that suitable for water in a given channel.

4.1.3. Velocities within a gating system

The flow of molten metal in a gating system is a function of a number of other variables. Bernoulli's theorem states that the sum of the potential, pressure, kinetic, and friction energies at any point in a flowing liquid is a constant:

$$W h_1 + \frac{W P_1}{\gamma} + \frac{W V_1^2}{2g} + W F_1 = W h_2 + \frac{W P_2}{\gamma} + \frac{W V_2^2}{2g} + W F_2 \qquad (4.1)$$

Dividing by W the total weight of liquid flow per unit time, one obtains the usual form:

$$h_1 + \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + F_1 = h_2 + \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + F_2 \qquad (4.2)$$

where h_1, h_2 are the respective heads at stations 1 and 2, in. P_1, P_2 are the respective pressures on liquid, lb/in.^{2} V_1, V_2 are the respective liquid velocities, in./s. γ is the specific weight of liquid, lb/in.^{3} g is the gravitational constant on Earth, 386 in./s^2 and F_1, F_2 are the respective head losses from fraction, in.

The velocity of the molten metal at any point in a gating system can be evaluated by the use of Bernoulli's theorem. Proper streamlining will permit a significant increase in the flow rate of a gating system (Fig. 4.2).

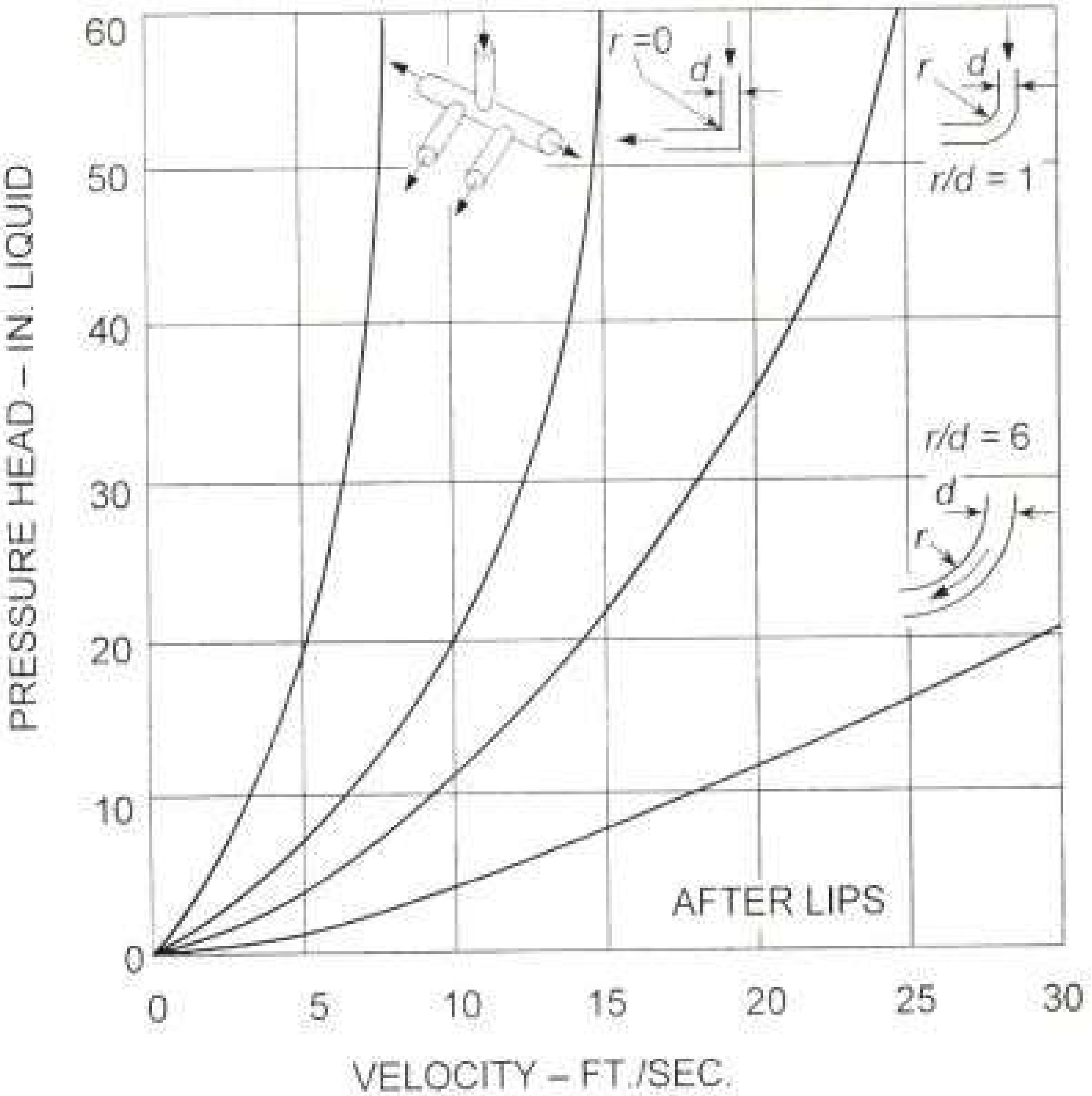


FIGURE 4.2. Effect of streamlining gating on velocity

4.1.4. Effect of streamlining a gating system

Gates of rounded cross section are more efficient than those of any other shape because they have the smallest surface-area-to-volume ratio and, consequently, can pass a greater volume of metal with the least heat loss. The gating system should be streamlined and of correct magnitude so as to control the velocity of the flowing metal. Too high a velocity will cause disruptive turbulent flow, resulting in sand inclusions and erosion of the mold cavity wall. Streamlining can effectively increase the volumetric capacity of a gating system and thereby allow smaller-size gates and runners that will consequently increase effective melt utilization. The effect of streamlining on metal velocity is shown in Fig. 4.2. A method of improving streamlining at the base of a T section from the sprue to runner is shown in Fig. 4.1.

4.1.5. The law of continuity

A second fundamental relationship in fluid flow is the *law of continuity*, which states that the flow rate of a fluid is a constant at any point in a continuous stream:

$$q = A_1 v_1 = A_2 v_2 \quad \text{or} \quad Q = A\,v\,t \tag{4.3}$$

where q is the flow rate, in.^{3}/s. Q is the volume of flow in a given time, in.^{3}. A_1, A_2 are the respective cross-sectional areas of the flow channels at points 1 and 2, in.^{2}. v_1, v_2 are the respective velocities of flow at points 1 and 2, in./s and t is the time, s.

4.1.6. The vertical elements of a gating system

The law of continuity requires that the same quantity (flow rate) of material must exit at all points in a flowing stream. In the vertical part of a gating system (sprue), the acceleration of gravity increases the velocity of flow. If a straight-sided sprue is used, the cross-sectional area of the flowing stream at the sprue base will be less than that of the sprue. Consequently, air will be aspirated from the surrounding mold until the sprue volume is completely filled. However, if a tapered sprue is designed to conform to the dimensions of the descending stream, such a condition can no longer exist and the metal quality will improve.

If we neglect friction and take a horizontal plane through the ingate as a reference, Bernoulli's equation becomes

$$h_t + \frac{P_t}{\gamma} + \frac{v_t^2}{2g} = h_b + \frac{P_b}{\gamma} + \frac{v_b^2}{2g} \tag{4.4}$$

where t refers to the top and b to the base. Then $h_b = 0$ because it is on the reference plane, $v_t = 0$ because there is no velocity at the top, and P_t/γ and P_b/γ = 14.7 lb/in.^{2} because the system is at atmospheric pressure at both ends. Then we have

$$h_t = \frac{v_b^2}{2g} \quad \text{or} \quad v_b = \sqrt{2gh_t} = 27.8\sqrt{h_t} \tag{4.5}$$

To design a sprue of suitable proportions, let the area at the top of the sprue be A_t and the velocity there be at a flow rate q_t; then $q_t = A_t v_t$ from continuity. Similarly, at the sprue base $q_b = A_b v_b = q_t = A_t v_t$. Then $A_t = A_b(v_b / v_t)$. From Bernoulli's equation,

$$v_t = \sqrt{2gh_t} \qquad \text{and} \qquad v_b = \sqrt{2gh_b}$$

where h_t and h_b are the heads, in inches of metal, at the top and bottom of the sprue. Then

$$A_t = A_b \frac{\sqrt{2gh_b}}{\sqrt{2gh_t}} \qquad \text{or} \qquad A_t = A_b \sqrt{\frac{h_b}{h_t}} \tag{4.6}$$

Thus, once the area of the sprue base is known, the vertical gating system can be designed. Equation (4.6) indicates that the sprue should have parabolic sides, but experience shows that a straight-sided sprue having the calculated diameters at the top and bottom is satisfactory (when solved for a series of heights).

When the height h_t of the pouring basin above the sprue base is known, if a tapered sprue is used, and if the pouring basin is kept full throughout the pour, Bernoulli's equation can give an approximate answer, but much of the flow is transient and the cavity must be in the drag and nonpressurized.

To find the diameter of the sprue base, it is convenient to use the result from previous research in which it was found that for an unpressurized system, poured with aluminum alloy, an average of 5.75 lb of alloy per minute passed through each square inch of the sprue area. This is equivalent to 60 in.^{3}/minute per square inch of cross-sectional area.

In the case where $h_t = 9$, the following calculation may be made.

$$A_b = \frac{60 \text{ in.}^3/\left(\min/\text{in.}^2\right)}{27.8\sqrt{h_t}} = 0.72 \text{ in.}^2 \quad \text{or} \quad A_b = \pi r^2 = 0.72 \text{ in.}^2 \tag{4.7}$$

$$\therefore r = \sqrt{\frac{0.72}{\pi}} = \sqrt{0.229} = 0.479 \text{ in.} , \qquad \therefore d = 0.95 \text{ in.}$$

If a bottom gate is used, then the filling time is longer because the metal is subject to a decreasing head during filling. Therefore in an increment of time dt, the height will increase dh and the volume of the metal will increase by the area of the mold $A_m\, dh$, while the flow through the ingate in time dt will be $A_g v\, dh$ and the velocity of the metal through the gate will be $\sqrt{2g(h_t - h)}$ at any instant. If we equate the increase in casting volume in time dt to the flow through the ingate in that same time interval, we find

$$\frac{A_g}{A_m}dt = \frac{dh}{\sqrt{2g(h_t - h)}} \quad \text{or} \quad A_m dh = A_g\sqrt{2g(h_t - h)}dt \tag{4.8}$$

Let t_p be the time to fill the mold and h_m be the height of the mold cavity. Then

$$\frac{1}{\sqrt{2g}}\int_0^{h_m}\frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m}\int_0^{t_p}dt \tag{4.9}$$

$$\therefore t_p = \frac{2A_m}{A_g\sqrt{2g}}\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right) \tag{4.10}$$

It is found that bottom gating takes twice the pouring time of a top gating system; this is obvious. If parting-line gating is used, the calculation is made in two parts: (1) top gating until the drag is filled, and (2) bottom until the mold is filled. If a top riser is used, a third calculation is required. Of course, we have considered the simple case of a mold of constant cross section without a core. Appropriate corrections must be mad for the more complex shapes.

4.1.7. Gating ratio

There are two types of gating systems: *nonpressurized*, or free flowing like a sewer system (Fig. 4.1), and *pressurized*. The latter has less total cross-sectional area at the ingates to the mold cavity than at the sprue base. The gating ratio relates the cross-section areas of each component of the gating system taking the sprue base areas as unity, followed by the total runner area and finally the total ingate area. Thus a pressurized system would have a ratio of 1: 0.75 : 0.5, whereas a nonpressurized system might be 1: 1.5 : 2 or 1: 4 : 4 as in Fig. 4.1.

Unpressurized gating system reduce velocity, turbulence, and aspiration but must use tapered sprues, enlarged sprue base wells, and pouring basins to achieve proper flow control. In addition, they can deliver metal uniformly to each ingate only if the runners are in the drag with the ingates in the cope and if the runner area is reduced by the area of each ingate after the junction, in a manner similar to that used for ducts in a heating system (Fig. 4.1).

4.2. Risers for sand molds

Risers serve a dual function: they compensate for solidification shrinkage and they are also a heat source, so that they freeze last and promote directional solidification. Risers provide thermal gradients from a remote chilled area to the riser. Gating systems and risers are closely interrelated; in some cases the ingate is through a riser (Fig. 4.1).

Riser design includes supplying feed metal for shrinkage and any mold enlargement, riser location, spacing of risers for casting soundness, adequate sizing, proper connection to the casting, and the use of chills or insulation. Risers designed according to these concepts can result in improved casting quality and reduced cost.

4.2.1. Solidification shrinkage

Gray iron with a carbon equivalent of 4.3 percent actually expends up to 2.5 percent because of graphite precipitation, but other ferrous alloys contract 2.5 to 4 percent during freezing. Nonferrous metals contract even more: pure aluminum contracts 6.6 percent and copper 4.9 percent. Their alloys usually shrink somewhat less, with near eutectic compositions contracting least. Lead has 7.7 percent reduction in volume at its phase change.

When an alloy has a short solidification range, as in a eutectic, pure metal, or low-carbon steel, a solid skin freezes at the mold-metal interface. Solidification then proceeds slowly toward the thermal center of the casting. Alloys that solidify over a long freezing range, such as aluminum or bronzes, are subject to dispersed microporosity more or less uniformly distributed throughout the cast structure. Skin-forming alloys are likely to have centerline shrinkage. Eutectic alloys require the least feed metal and therefore most commercial alloys are of near-eutectic composition. The risering concepts given are for low-carbon steel.

4.2.2. Riser location

No matter how complex, any casting can be reduced to a series of geometrical shapes that consist of two heavier sections joined by a thinner one. Each heavier section needs its own riser. If the thinner section is not tapered to become larger toward the heavier sections, centerline shrinkage is probable. Chills at the thinner section may prevent such shrinkage and may promote directional solidification from the chill to the riser.

4.2.3. Feeding distance

Past research has shown that an adequate riser can provide soundness for a distance of $4.5t$ for a plate casting; $2t$ is the riser contribution and $2.5t$ is from the edge effect. The maximum distance between risers is $4t$ for plates but is only $1t$ to $4t$ for bars. Chills increase the feeding distance for plates to a total of $4.5t + 2$ in. for a plate and to $6\sqrt{t} + t$ for a bar. Thus, the maximum spacing between risers if chills are used midway between them is $9t + 4$ in. for plates and $12\sqrt{t} + 2t$ for bars. Note that the distances are from the outside edge, not the centerline, of the riser (Fig. 4.3).

4.2.4. Riser size

The riser size for a given application depends primarily on the alloy poured and the volume-to-surface-area ratio of riser relative to that of the

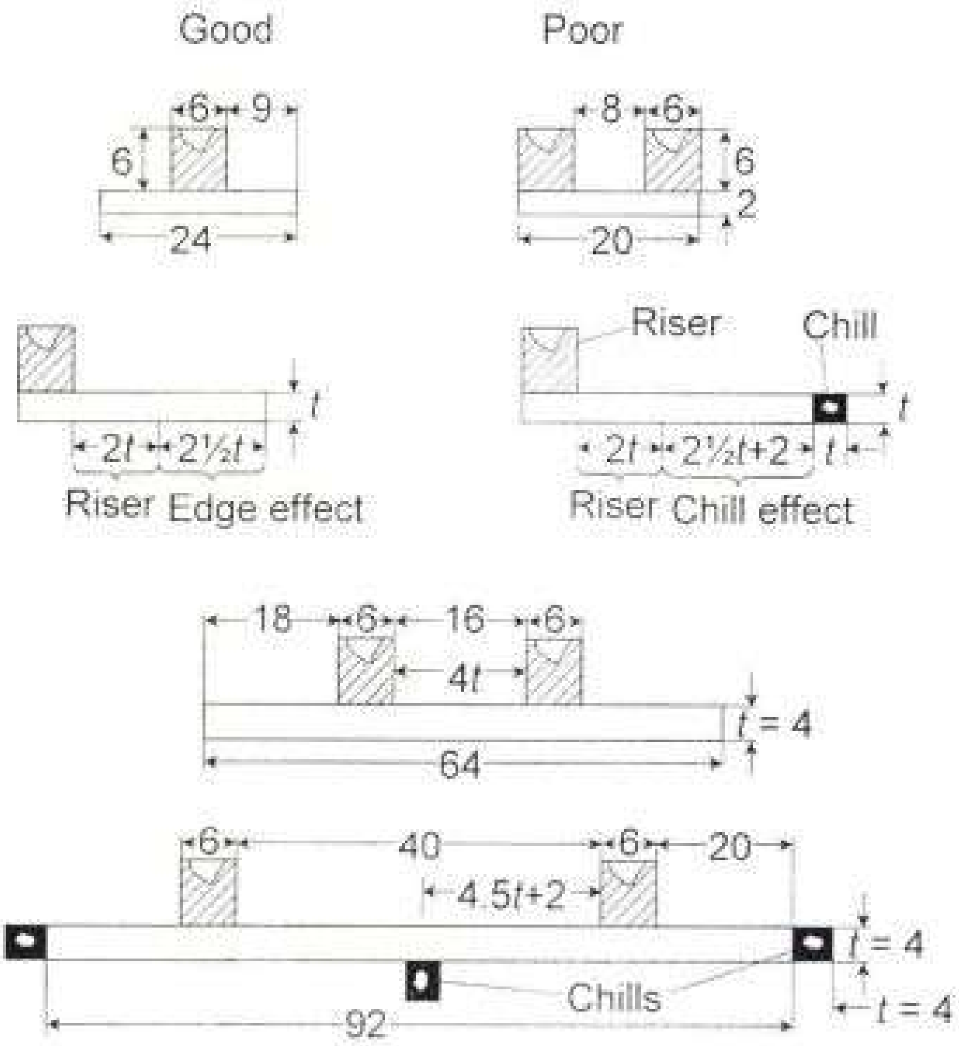


FIGURE 4.3. Feeding distance of risers for steel plates

casting section which is to be fed. Obviously, to be effective a riser must freeze more slowly than the casting.

Chvorinov's rule is the basis of most methods now used to calculate the proper size for short-freezing-range alloys such as steel or for pure metals. There is no satisfactory method for calculating the riser size for nonferrous alloys. Chvorinov's rule states that the solidification time for an alloy is

$$t = k\left(\frac{v}{sa}\right)^2$$

where t is solidification time, min. v is the volume of the casting section, in.^{3} sa is the cooling surface of the casting section, in.^{2}

There are two types of risers – top risers and side risers. Top risers are placed above the volume to be fed and extend to the top of the cope. Side or blind risers are located at the parting line to feed locally. There are several alternative procedures for determining an adequate riser size for an alloy that freezes in a skin-forming manner. All give approximately the same result. One of the most direct depends on the *shape factor*, which is defined as the sum of the length and width of the section in question divided by its average thickness. In the 1950s the Naval Research Laboratory devised the shape factor chart (Fig. 4.4) and riser height and volume chart (Fig. 4.5). With this chart the proper risers for steel castings

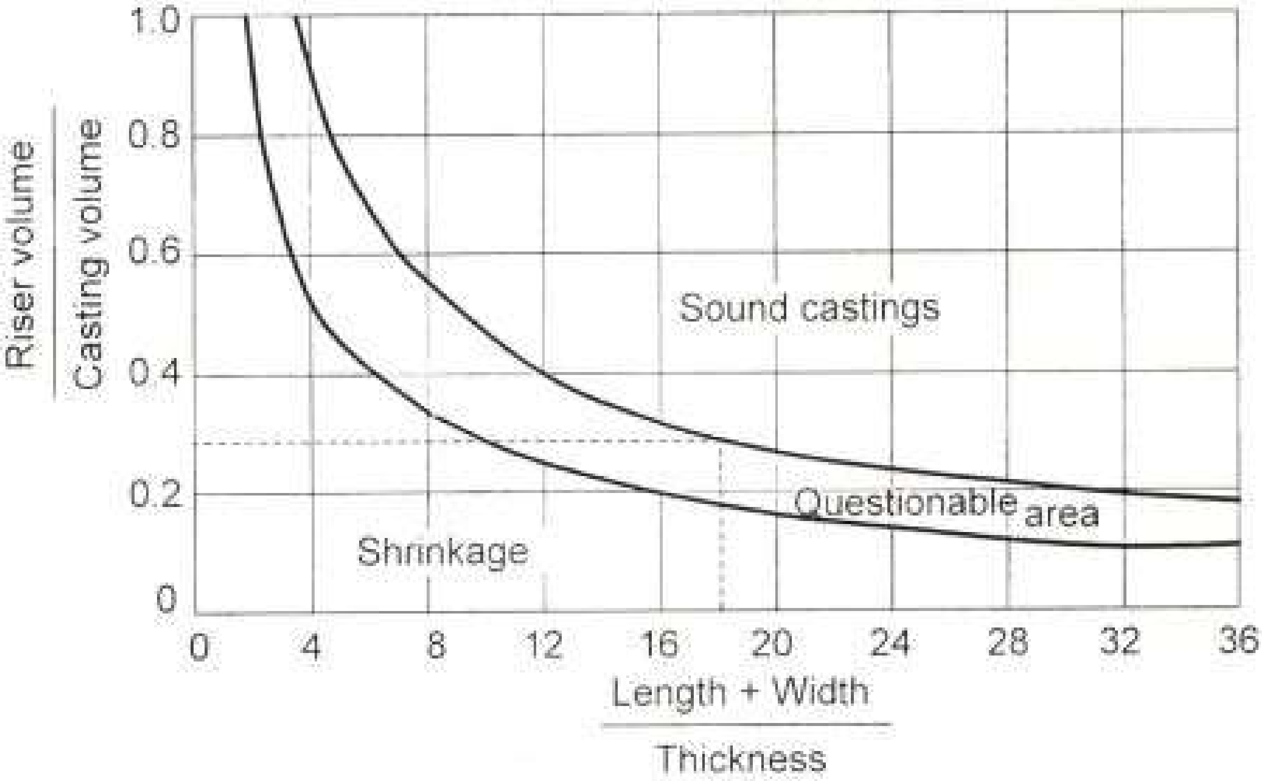


FIGURE 4.4. Riser volume to casting volume ratio as a function of the shape factor

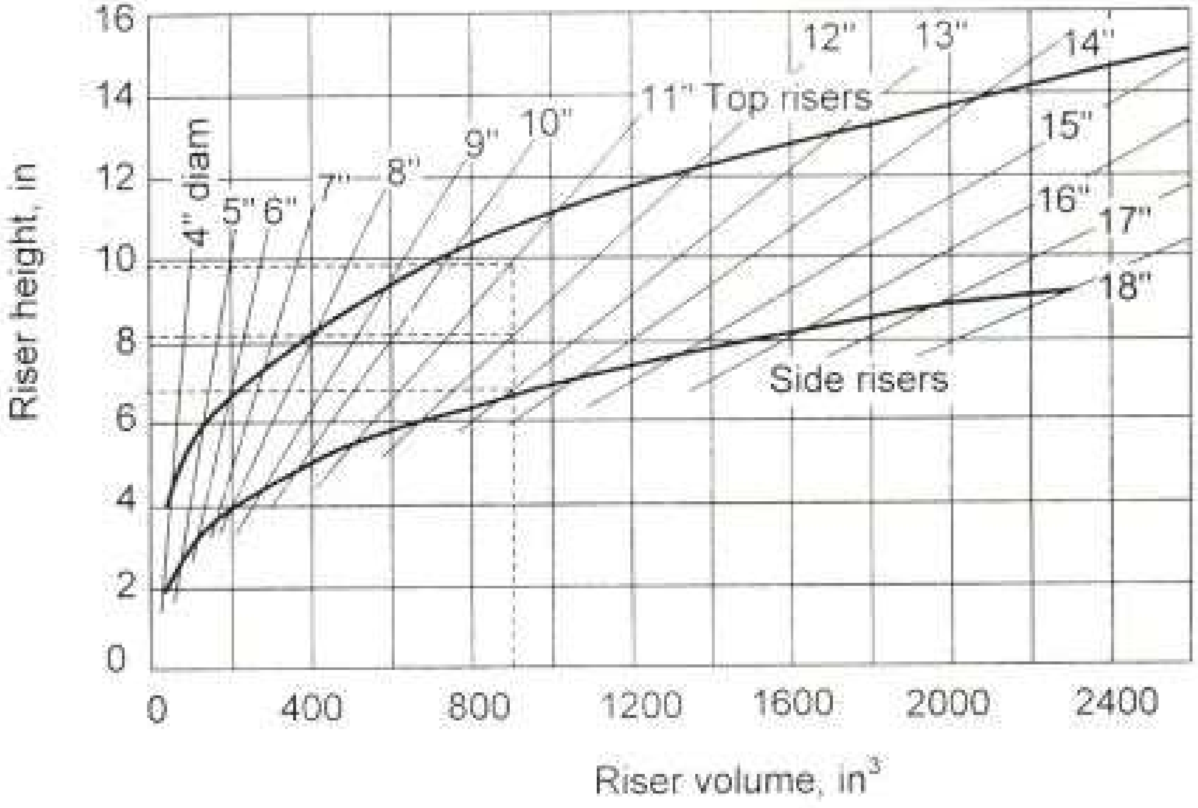


FIGURE 4.5. Chart for determining riser diameter

can easily be selected, once the casting has been divided into the proper sections. This method gives conservative answers, but that is good when only one casting is to be poured and it must be correct the first time. In high-volume production, some additional experiments would be in order before final pattern construction.

4.2.5. Riser connections

The riser connection to the casting requires considerable care because it determines how well the riser feeds and, secondly, how readily a riser can be removed. To aid in top riser removal, it is wise to consider placing an annular core similar to a large washer in the riser neck. The thin section of core sand soon becomes hot, so that little chilling occurs and feeding takes place through the center hole. The connection length for a riser should not exceed *D/3* to *D/2*, where *D* is the diameter of the riser and the inner hole should be about 1.2 times the connection length.

REVIEW QUESTIONS AND PROBLEMS

4.1. How can riser size be calculated in order to feed a given casting satisfactorily?
4.2. What is meant by directional solidification?
4.3. Give a sketch of the ideal shape of a casting to obtain directional solidification.
4.4. Why a steel difficult to cast?
4.5. A pattern is 42 in. long and is being used for the production of gray iron castings What shrinkage in inches should the pattern accommodate?
4.6. For what reasons are molds vented?
4.7. What is the purpose of core prints?
4.8. For what reason are clamps and/or weights placed on a mold?
4.9. What factors should be considered in pattern design?
4.10. What is the function of chaplets? Make a sketch of chaplet in use.
4.11. What information is the engineer expected to provide on the engineering drawing?
4.12. What precautions should be observed in the design of a steel casting so that internal stresses are as small as possible?
4.13. Why it is especially important no to have thin sections when designing steel castings?
4.14. What is meant by hot tears? How can they be eliminated?
4.15. What is misrun? How it is cased?
4.16. What are sand inclusions and how can they be minimized?
4.17. Explain how Bernoulli's theorem is utilized in the design of a gating system.
4.18. What is the function of the riser?
4.19. Explain why gray iron with a carbon equivalent of 4.3 may actually expand rather than shrink during freezing.
4.20. What would be the maximum distance between two risers on a plate casting that is 3 in. thick?
4.21. Explain the use of Chvorinov's rule in the design of risers.
4.22. From an economic standpoint, for a precision casting of 1 in.^{3} in volume and daily production requirements of 2000 pieces, would you recommend permanent molding or die casting? Explain your answer.
4.23. Sketch a match-plate layout for the gate valve casting shown in Fig. 4.6. Determine the parting line. The casting is a globe valve for domestic water

systems, so choose the alloy accordingly. Specify the alloy to be used and the casting process. Would you modify the design of the part to make better casting? If so, how? What gating ratio would you use? Show calculations on your drawing.

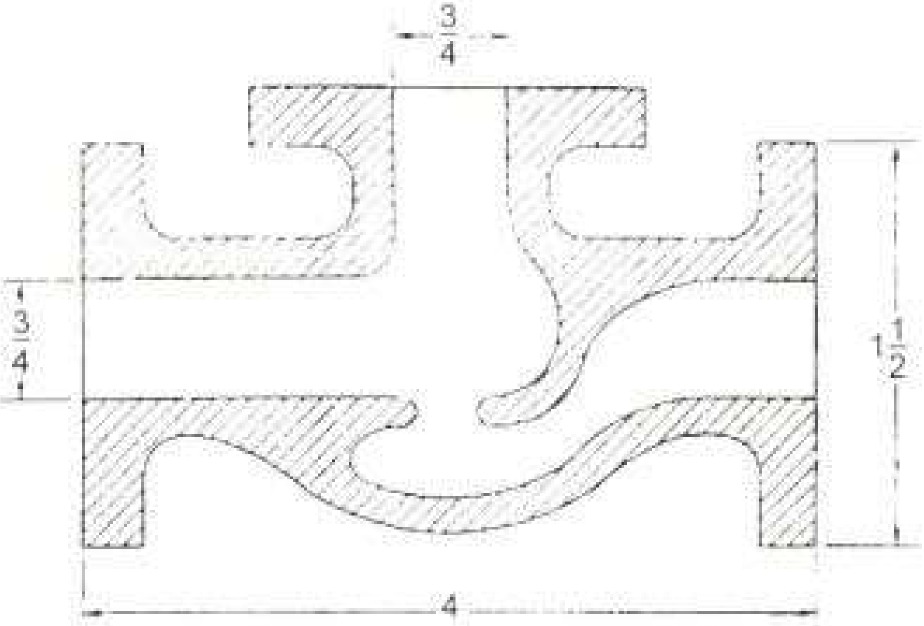


FIGURE 4.6. Sketch of valve casting

4.24. The part shown in Fig. 4.7 is to be made as a permanent-mold casting. Suggest what changes in design should be made and explain why. Make a careful sketch to scale to show the details of the part redesigned for permanent molding.

4.25. Explain the use of blind risers and the type of alloy that can be fed by them. Calculate the height in inches to which a blind riser can feed a casting that has a specific weight in the molten state of 0.246 lb/in.^{3} if it freezes like low-carbon steel.

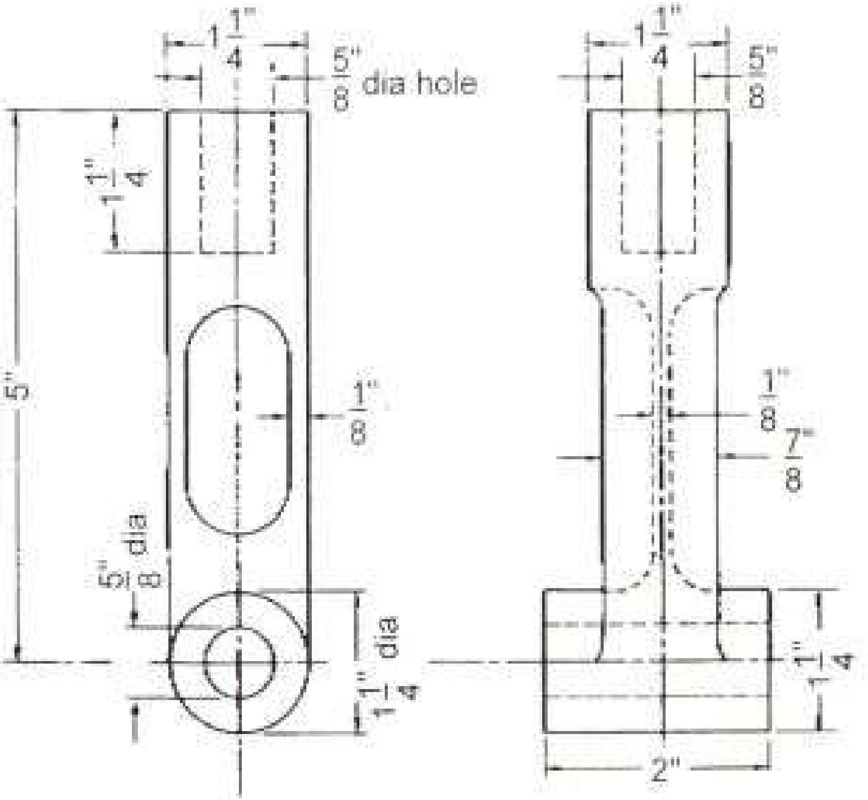


FIGURE 4.7. Sketch of the part to be cast

4.26. A casting as shown in Fig. 4.8 is produced in a green-sand mold that measures 30 × 30 in. with a 6-in. cope over an 8-in. drag. The casting is specified to be class 40 gray cast iron. Determine the total weight of metal required to fill the mold, the gating ratio, whether the gating system is pressurized or unpressurized, and the casting yield, i.e., the ratio of good casting to the total weight poured.

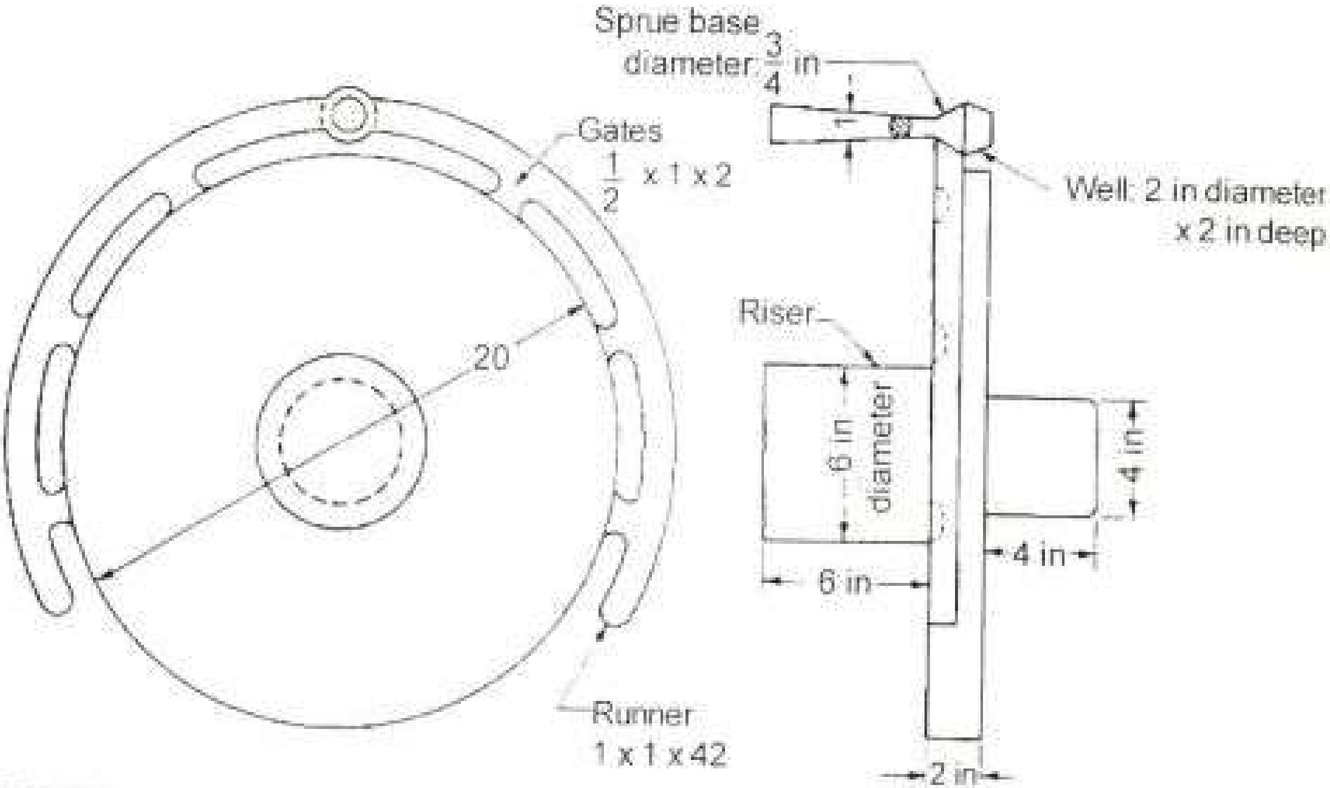


FIGURE 4.8. Casting produced in green-sand mold

4.27. Two casting are molded in green sand. They differ in weight by a factor of 3.8 but they are both cubes. An experiment has shown that the lighter casting solidifies in 8.7 min. How much time would you estimate that it would take for the larger casting to solidify?

REFERENCES

1. Manufacturing Engineering and Technology / Serope Kalpakjian. Illinois Institute of Technology: Addison-Wesley Publishing Company. 1990. – 1224 p.
2. Modern Manufacturing Process Engineering / Benjamin W. Neibel, Alan B. Draper, Richard A. Wysk. Copyright © 1989 by McGraw-Hill, Inc. – 896 p.
3. Metal Process Engineering / Under the editorship of prof. P. Polukhin. English translation, Mir Publishers. 1977. – 426 p.

Князєв Михайло Климович

Сергєєв Сергій Валерійович

Богуслаєв Олександр В'ячеславович

ПРОЦЕСИ ЛИТТЯ МЕТАЛЕВИХ СПЛАВІВ

Редактор Т. А. Ястремська

Зв. план, 2002
Підписано до друку 12.12.2002
Формат 60x84 1/16.Бум. офс. № 2 . Офс. друк.
Ум.-друк.арк.4,5.Обл.-вид.арк. 5,06. Т. 50 прим. Замовлення 4203. Ціна вільна.

Національний аерокосмічний університет ім. М. Є. Жуковського
«Харківський авіаційний інститут»
61070, Харків-70, вул. Чкалова, 17
http://www.khai.edu

Видавництво ВАТ «Мотор Січ»
69068, м. Запоріжжя, вул. 8 Березня, 15