

Production Engineering

Chapter-7 Casting Process

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Casting is one of the oldest manufacturing processes, and even today is the first step in manufacturing most products. In this process, the material is first liquefied by properly heating it in a suitable furnace. Then, the liquid is poured into a previously prepared mould cavity where it is allowed to solidify. Subsequently, the product is taken out of the mould cavity, trimmed, and cleaned to shape.

It is clear from the definition of the process that a successful casting operation needs a knowledge in the following areas:

1. Preparation of moulds and patterns (used to make the mould).
2. Melting and pouring of the liquefied metal.
3. Solidification and further cooling to room temperature.
4. Defects and inspection.

There are various types of casting processes depending, among others on the material, the type of patterns and moulds, and the pouring technique. Before going into the details of these processes, we shall discuss the basic common features among the various casting processes in the context of the four areas we have just mentioned.

The suitability of the casting operation for a given material depends on

1. the melting temperature of the job and the mould materials,
2. the solubility of and the chemical reaction between the job and the mould materials,
3. the solubility of the atmosphere in the material at different temperatures to be encountered in the casting operation,
4. the thermal properties such as conductivity and coefficient of linear expansion of both the mould and job materials.

7.1 PATTERN AND MOULD

A pattern is the replica of the part to be cast and is used to prepare the mould cavity. Patterns are made of either wood or metal. A mould is an assembly of two or more metal blocks, or bonded refractory particles (sand) consisting of a primary cavity. The mould cavity holds the liquid material and essentially acts as a negative of the desired product. The mould also contains secondary cavities for pouring and channeling the liquid material into the primary cavity and to act as a reservoir, if necessary.

A four-sided frame in which a sand mould is made is referred to as a *flask*. If the mould is made in more than one part, the top portion is called the *cope* and the bottom one is termed as the *drag*. For producing hollow sections, the entry of the liquid metal is prevented by having a *core* in the corresponding portion of the mould cavity. The projections on the pattern for locating the core in the mould are called *core prints*. There are diverse types of patterns and moulds depending on the material, the job, and the number of castings required.

Pattern Allowances

A pattern is always made somewhat larger than the final job to be produced. This excess in dimensions is referred to as the pattern allowance. There are two categories of pattern allowances, namely, the *shrinkage allowance* and the *machining allowance*.

The shrinkage allowance is provided to take care of the contractions of a casting. The total contraction of a casting takes place in three stages, and consists of

1. the contraction of the liquid from the pouring temperature to the] freezing temperature,

2. the contraction associated with the change of phase from liquid to; solid,
3. the contraction of the solid casting from the freezing temperature to the room temperature.

It must be noted, however, that it is only the last stage of the contraction which is taken care of by the shrinkage allowance. Obviously, the amount of shrinkage allowance depends on the linear coefficient of thermal expansion α_l , of the material. The higher the value of this coefficient, the more the value of shrinkage allowance. For a dimension l of a casting, the shrinkage allowance is given by the product $\alpha_l l (\theta_f - \theta_0)$, where θ_f is the freezing point of the material and θ_0 is the room temperature. This is normally expressed per unit length for a given material. Table 7.1 gives some quantitative idea about the shrinkage allowance for casting different materials.

Usually, a cast surface is too rough to be used in the same way as the surface of the final product. As a result, machining operations are required to produce the finished surface. The excess in the dimensions of the casting (and consequently in the dimensions of the pattern) over those of the final job to take care of the machining is called the machining allowance. The total machining allowance also depends on the material and the overall dimension of the job, though not linearly as the shrinkage allowance. Table 7.1 gives also an idea of the machining allowance for various materials. For internal surfaces, the allowances provided should obviously be negative, and normally the machining allowances are 1 mm more than those listed in the table.

Table 2.1 Machining allowance for various metals

Material	Shrinkage allowance	Machining allowance for dimensions	
		0-30 cm	30-60 cm
Cast iron	1/96	2.5 mm	4.0 mm
Cast steel (low carbon)	1/48	3 mm	4.5 mm
Aluminium	3/192	1.5 mm	3 mm
Bronze	3/192	1.5 mm	3 mm
Brass	1/48	1.5 mm	3 mm

There is another deviation from the original job dimensions and is, intentionally provided in the pattern; this is called *draft*. It refers to a taper put on the surface parallel to the direction of withdrawal of the pattern from the mould cavity. A draft facilitates easy withdrawal of the pattern. The average value of the draft is between $1/2^\circ$ and 2° .

Types of Patterns

The commonly-used patterns are classified as follows:

Loose pattern It is made in one piece, usually from wood, and is used for castings numbering up to 100.

Gated pattern This is simply one or more than one loose pattern with attached gates and runners and provides a channel through which the molten metal can flow from the pouring sprue to the mould cavity. This pattern is frequently set on a follow board conforming to the parting surface of the mould. The follow board helps in an easy removal of the pattern after the mould has been prepared.

Match plate pattern This pattern is made in two halves mounted on both sides of a *match plate* (of wood or metal) conforming to the contour of the parting surface. The match plate is accurately placed between the cope and the drag flasks by means of

locating pins. For small castings, several patterns can be mounted on the same match plate.

Cope and drag pattern Here, the cope and drag halves of a split pattern are separately mounted on two match plates. Thus, the cope and the drag flasks are made separately and brought together (with accurate relative location) to produce the complete mould.

Sweep pattern Normally made of wood, it is used to generate surfaces of revolution in large castings, and to prepare moulds out of a paste-like material. Here, "sweep" refers to the section that rotates about an edge to yield circular sections.

Skeleton pattern This consists of a simple wooden frame outlining the shape of the casting. It is used to guide the moulder for hand-shaping the mould and for large castings having simple geometrical shapes.

Types of Moulds

Moulds can be classified on the basis of either the material, i.e., green sand mould, plastic mould, metal mould, or on the method of making them, e.g., shell mould and investment mould. Metal moulds are permanent in the sense that a large number of castings can be made from a single mould; on the other hand, moulds of refractory materials can be used only once. Generally, the green sand moulds are used; in what follows, we shall consider some of their important characteristics.

Green Sand Mould

The material for a green sand mould is a mixture of sand, clay, water, and some organic additives, e.g., wood flour, dextrin, and sea coal. The percentage of these ingredients on weight basis is approximately 70-85% sand, 10-20% clay, 3-6% water, and 1-6% additives. This ratio may vary slightly depending on whether the casting is ferrous or nonferrous.

Sand is an inexpensive refractory material, but natural sand may not have all the desirable qualities of a moulding material. For example, it normally has higher clay content than desired. The sand used as a moulding material should have a specified clay, water, and additive content; in addition, it must have a specific grain size distribution. The importance of the grain size distribution would be clear from the discussion that follows.

Both the shape and the size of sand grains vary over a wide range. The grains may be smooth and round in shape or may have sharp angular corners. The bulk density of a sand-mix is very low if the grains are of almost equal size with smooth round shape. Such grains result in an increased void and a higher permeability. Higher permeability permits an easy outflow of the gases (produced during the casting operation) which may otherwise be entrapped within the casting. The situation gets reversed if the grains are of various sizes and have sharp corners. To study the grain size distribution, the screening test is performed. This is done by taking a fixed sample weight of sand and screening it through standard sieves. The screening is accomplished by shaking the sieves. The amount of sand that collects in the different sieves is then plotted. Finally, from this plot, the distribution of grain size and the average grain size are computed.

Clay, together with water, acts as a bonding agent and imparts tensile and shear strength to the moulding sand. The organic additives burn out at high temperatures and make room for the moulding sand to expand, and thus save the mould from crumbling.

The success of a casting process depends greatly on the properties of the moulding sand. These include (i) strength, (ii) permeability, (iii) deformation, (iv) flowability, and (v) refractoriness. (Standard specimens and tests are recommended for an evaluation of these properties.) Strength refers to the compressive strength and deformation indicates the change in length of a standard specimen at the point of failure. Permeability is (pressed as the gas flow rate through the specimen under a specified pressure difference across it. Flowability refers to the ability of the sand to flow around and over the pattern when the mould is rammed. Refractoriness measures the ability of the sand to remain solid as a function of temperature. For a given sand-clay ratio, the nature of variation of these properties with water content is as shown in Diagram 7.1. It is obvious, both from strength and permeability considerations, that there is an optimum water content. At a low water content, dry clay powder, being finer than sand grains, fills up the void between the sand particles, and thus reduces the permeability. With higher water content, moist clay forms a coating over the sand particles keeping them further away, thus enhancing the permeability. Beyond the optimum water content, water itself fills up the void and reduces the permeability.

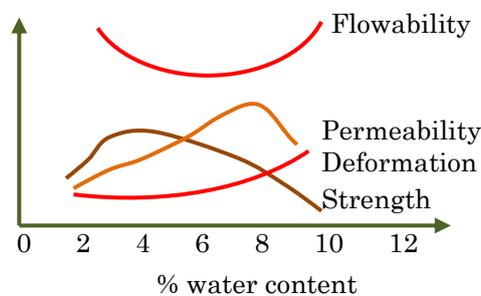


Diagram 7.1 Effect of water content on moulding sand properties.

7.2 MELTING

A proper care during melting is essential for a good, defect-free casting. The factors to be considered during melting include gases in metals, selection and control of scrap, flux, furnace, and temperature. We shall now give a short discussion on these.

Gases in Metals

The gases in metals normally lead to faulty castings. However, the presence of a controlled amount of specific gases can be beneficial in imparting certain desirable qualities to the castings. In metal castings, the gases

1. may be mechanically trapped (in such situations, proper venting arrangement in the mould prevent their occurrence),
2. may be generated due to the variation in their solubility at different temperatures and phases, and
3. may be produced due to chemical reactions.

The gases most commonly present are hydrogen and nitrogen. Metals are divided into two groups so far as the solubility of hydrogen is concerned. One group is called endothermic; this includes common metals such as aluminium, magnesium, copper, iron, and nickel. The other group, called exothermic, includes, amongst others, titanium and zirconium. Endothermic metals absorb less hydrogen than exothermic metals. Further, in endothermic metals, the solubility of hydrogen increases with temperature.

The reverse is true for exothermic metals. In both cases, the solubility (S) can be expressed as

$$S = C \exp [-E_s/(k\theta)], \quad [7.1]$$

where E_s (positive for endothermic) is the heat of solution of 1 mol of hydrogen and θ is the absolute temperature with C and k as constants: Equation (7.1) clearly shows that, gas precipitation during cooling cannot take place in exothermic metals for which E_s is negative.

Hydrogen is believed to dissolve interstitially in exothermic metals, thus causing lattice distortion. In endothermic metals, hydrogen dissolves at lattice defects and produces no distortion. Table 7.2 shows the solubility of hydrogen in the solid and liquid phases at solidus temperature for various metals. The difference in these solubilities is responsible for the evolution of the gases. It should be noted that hydrogen solubility is an acute problem in ferrous casting. Here, although the amount of hydrogen by weight appears negligible, the volume evolved during solidification is quite large. Sievert's law states that the amount of hydrogen dissolved in a melt varies as

$$\% \text{ hydrogen present} = K\sqrt{p_{H_2}}, \quad [7.2]$$

where p_{H_2} is the partial pressure of hydrogen in the atmosphere over the melt, and the constant K can be evaluated from Table 7.2.

Table 2.2 Solubility of hydrogen in various metals

Pressure = 1 atm		
Metal	Liquid solubility (cc/kg)	Solid solubility (cc/kg)
Iron	270	70
Magnesium	260	180
Copper	55	20
Aluminium	7	0.4

The primary sources of hydrogen in a melt are furnace dampness, air, oil and grease. There is no simple dehydrogenating addition to eliminate hydrogen in the form of slag. So, care should be taken to maintain the hydrogen level to a minimum.

Most hydrogen removal techniques are based on equation (7.2), i.e., reducing the partial pressure of hydrogen by bubbling some other dry insoluble gas through the melt. For nonferrous metals, chlorine, nitrogen, helium, or argon is used. Nitrogen cannot be used for ferrous and nickel based alloys since it is soluble in these, and also it may form nitrides which affect the grain size; therefore, in ferrous alloys in particular, an accurate control of the nitrogen is necessary. In such situations, carbon monoxide bubbles are used. This removes not only hydrogen but also nitrogen; the carbon content is controlled by subsequent oxidation and recarburization. For ferrous metals, a marked decrease in the solubility of nitrogen during the change of phase may give rise to porosity in the casting. The re-entry of nitrogen from the air is prevented by the impermeable slag at the top of the melt.

Currently, vacuum melting is increasingly being used for preventing the solution of gases in metals and the combination of reactive elements in the melt. Additions in the ladle, rather than in the melt, have been found to be more effective for controlling the gases and chemical compositions.

7.3 POURING (GATING DESIGN)

After melting, the metal is poured or injected into the mould cavity. We shall now discuss the difficulties faced in doing this and explain how these can be overcome by using an appropriate gating design. A good gating design ensures distribution of the metal in the mould cavity at a proper rate without excessive temperature loss, turbulence, and entrapping gases; and slags.

If the liquid metal is poured very slowly, then the time taken to fill up the mould is rather long and the solidification may start even before the mould has been completely filled up. This can be avoided by using too much superheat, but then gas solubility may cause a problem. On the other hand, if the liquid metal impinges on the mould cavity with too high a velocity, the mould surface may be eroded. Thus, a compromise has to be made in arriving at an optimum velocity.

The design of a gating system depends on both the metal and mould compositions. For example, an elaborate gating design is needed to avoid dross (e.g., oxides) in easily oxidized metals of low melting point such as aluminium. For cast iron, however, a short path for the liquid metal is selected to avoid a high pouring temperature. The gating design for a ceramic mould is quite different from that normally used for a permeable sand mould.

Broadly, gating designs can be classified into three categories, namely, (i) vertical gating, (ii) bottom gating, and (iii) horizontal gating. In vertical gating, the liquid metal is poured vertically to fill the mould with atmospheric pressure at the base. In bottom gating, on the other hand, the liquid metal is filled in the mould from bottom to top, thus avoiding the splashing and oxidation associated with vertical gating. Diagram 7.2 shows a simple vertical gating and a bottom gating design. In the horizontal gating system, additional horizontal portions are introduced for better distribution of the liquid metal with minimum turbulence.

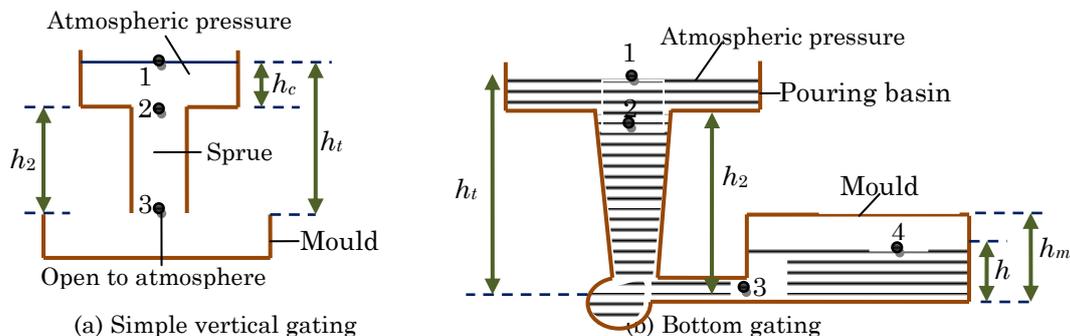


Diagram 7.2 Types of gatings.

Simple calculations based on principles of fluid flow can lead to an estimate of the time taken to fill up a mould. We shall illustrate this for the two designs in Diagram 7.2. The integrated energy balance equation on the basis of per unit mass flow, more commonly known as Bernoulli's equation, will be used. For example, in Diagram 7.2a, it is assumed that the pressure at points 1 and 3 is equal (i.e., $p_1 = p_3$) and that level 1 is maintained constant. Thus, the velocity at station 1 (v_1) is zero. Moreover, the frictional losses are neglected. Then, the energy balance equation between points 1 and 3 gives

$$gh_t = v_3^2/2$$

or

$$v_3 = \sqrt{2gh_t}, \quad [7.3]$$

where g is the acceleration due to gravity and v_3 is the velocity of the liquid metal at the gate, subsequently referred to as v_g . So, the time taken to fill up the mould (t_f) is obtained as

$$t_f = \frac{V}{A_g v_3} \quad [7.4]$$

where A_s and V are the cross-sectional area of the gate and the volume of the mould, respectively.

In Diagram 7.2b, applying Bernoulli's equation between points 1 and 3, we get

$$gh_t = \frac{p_3}{\rho_m} + \frac{v_3^2}{2} \quad [7.5]$$

where ρ_m is the density of the liquid metal. p_3 is the gauge pressure at station 3, and h_t is again assumed to be constant. Further, applying Bernoulli's equation between points 3 and 4, with the assumptions that v_4 is very small and all the kinetic energy at station 3 is lost after the liquid metal enters the mould, we can write

$$p_3 / \rho_m = gh. \quad [7.6]$$

From equations (7.5) and (7.6), the velocity of the liquid metal at the gate we obtain is

$$v_3 = v_g = \sqrt{2g(h_t - h)}. \quad [7.7]$$

Equation (7.7) gives the velocity of a jet discharging against a static head h , making the effective head as $(h_t - h)$. Now, for the instant shown, let the metal level in the mould move up through a height dh in a time interval dt ; A_m and A_g are the cross-sectional areas of the mould and the gate, respectively. Then,

$$A_m dh = A_g v_g dt, \quad [7.8]$$

Using equations (7.7) and (7.8), we get

$$\frac{1}{\sqrt{2g}} \int_0^{h_m} \frac{dh}{\sqrt{(h_t - h)}} = \frac{A_g}{A_m} dt \quad [7.9]$$

At $t = 0$, $h = 0$ and at $t = t_f$ (filling time), $h = h_m$. Integrating equation (7.9) between these limits, we have

$$\begin{aligned} \frac{1}{\sqrt{2g}} \int_0^{h_m} \frac{dh}{\sqrt{(h_t - h)}} &= \frac{A_g}{A_m} \int_0^{t_f} dt \\ t_f &= \frac{A_g}{A_m} \frac{1}{\sqrt{2g}} 2 \left(\sqrt{h_t} - \sqrt{(h_t - h_m)} \right) \end{aligned} \quad [7.10]$$

If a riser (reservoir to take care of the shrinkage from the pouring temperature) is used, then the pouring time t_f should also include the time needed to fill up the riser. Normally, open risers are filled up to the level of the pouring sprue; thus, the time taken to fill up the riser is calculated with A_m replaced by A_r (riser cross-section) and h_m by h_t in equation (7.10).

$$t_f = \frac{A_r}{A_g} \sqrt{\frac{2h_t}{g}}$$

Application 7.1: Two gating designs for a mould of 50 cm × 25 cm × 15 cm are shown in Diagram 7.3. The cross-sectional area of the gate is 5 cm². Determine the filling time for both the designs.

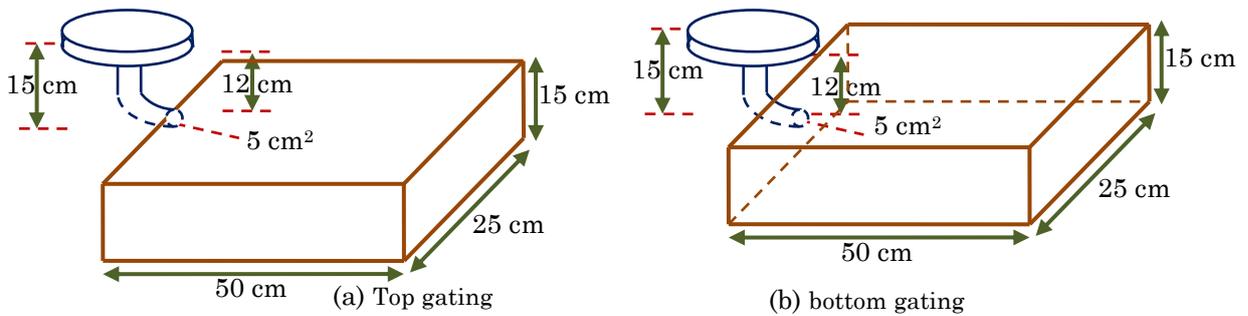


Diagram 7.3 Top and bottom gating design.

Solution: Diagram 7.3a. Since $h_t = 15$ cm, from equation (7.3), we have

$$v_2 = \sqrt{2 \times 981 \times 15} \text{ cm/sec} = 171.6 \text{ cm/sec.}$$

The volume of the mould is $V = 50 \times 25 \times 15 \text{ cm}^3$ and the cross-sectional area of the gate is $A_g = 5 \text{ cm}^2$. So, from equation (7.4), we get

$$t_f = \frac{50 \times 25 \times 15}{5 \times 171.6} = 21.86 \text{ sec.}$$

Diagram 7.3b, here, $h_t = 15$ cm, $h_m = 15$ cm, $A_m = 50 \times 25 \text{ cm}^2$, and $A_g = 5 \text{ cm}^2$. Using equation (7.10), we have

$$t_f = \frac{50 \times 25}{5} \sqrt{\frac{2}{981} \times 15} = 43.71 \text{ sec.}$$

It should be noted that in Diagram 7.3b the time taken is double of that in Diagram 7.3a. We can easily verify that this will always be so if $h_m = h_t$.

Aspiration Effect

For a mould made of a permeable material (e.g., sand), care should be taken to ensure that the pressure anywhere in the liquid metal stream does not fall below the atmospheric pressure. Otherwise, the gases originating from baking of the organic compounds in the mould will enter the mol-ten metal stream, producing porous castings. This is known as the *aspiration effect*.

Referring to Diagram 7.2a and applying Bernoulli's equation between points 2 and 3, we obtain

$$gh_2 + \frac{p_2}{\rho_m} + \frac{v_2^2}{2} = \frac{p_3}{\rho_m} + \frac{v_3^2}{2} \quad [7.11]$$

where p and v refer to the pressure and velocity, respectively, of the liquid metal at stations 2 and 3. If the pressure at point 3 is atmospheric, i.e., $p_3 = 0$, then $p_2 = -\rho_m gh_2$ as $v_2 = v_3$. Hence, the design in Diagram 7.2a is not acceptable. To avoid negative pressure at point 2 (to ensure positive pressure anywhere in the liquid column), the sprue should be tapered, the ideal shape of which can be determined as follows.

Let, in the limiting case, p_2 be equal to zero, when, from equation (7.11),

$$gh_2 + \frac{v_2^2}{2} = \frac{v_3^2}{2} \quad [7.12]$$

From the principle of continuity of flow, $A_2 v_2 = A_3 v_3$, where A is the cross-sectional area. Thus,

$$v_2 = \frac{A_3}{A_2} v_3 = R v_3 \quad [7.13]$$

where $R = A_3/A_2$. Using equations (7.12) and (7.13), we obtain

$$\frac{v_3^2}{2g} = h_2 + R^2 \frac{v_3^2}{2g}$$

or

$$R^2 = 1 - \frac{2gh_2}{v_3^2} \quad [7.14]$$

Again, $v_3^2 = 2gh_t$, (applying Bernoulli's equation between points 1 and 3 with $p_1 = p_3 = 0$ and $v_1 = 0$). Substituting this in equation (7.14), we have

$$R^2 = 1 - \frac{h_2}{h_t} = \frac{h_c}{h_t}$$

or

$$R = \frac{A_3}{A_2} = \sqrt{\frac{h_c}{h_t}} \quad [7.15]$$

This can easily be seen to be the shape of a freely falling stream when $v_2 = [2gh_c]^{1/2}$ and $v_3 = [2gh_t]^{1/2}$. Thus, ideally, the sprue profile should be as shown by the solid lines in Diagram 7.4 when the pressure throughout the stream is just atmospheric. However, a straight tapered sprue (shown by the dashed lines) is safer (pressure everywhere, except at points 2 and 3, is above atmospheric) and easier to construct. The sprue design in Diagram 7.2b is better than that in Diagram 7.2a.

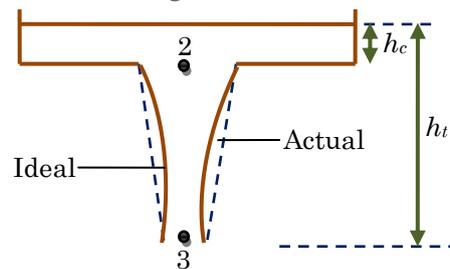


Diagram 7.4 Ideal and actual shapes of sprue.

The sprue should be tapered down to take in to account the gain velocity of the metal as it flows reducing the air aspiration.

The exact tapering can be obtained by the equation of continuity and Bernoulli's.

Assuming that the pressure at the top of the sprue to equal to the pressure at the bottom and there is no frictional losses at any point in the sprue the relationship between height and cross-sectional area is given by the following relation

$$\frac{A_3}{A_2} = \sqrt{\frac{h_c}{h_t}}$$

Another situation where aspiration effect comes into the picture is associated with a sudden change in the flow direction. As shown in Diagram 7.5a, the liquid metal stream contracts around a sharp corner due to the momentum effect. In vertical gating, this has got nothing to do with acceleration due to gravity. The constricted region shown at station 2 in Diagram 7.5a is known as *vena contracta*. To avoid the creation of vacuum around station 2, the mould is made to fit the vena contracta, as done in Diagram 7.5b. In other words, a sharp change in the flow direction is avoided. If the runner diameter is d and the diameter at the entrance is d' , then, normally, d'/d is maintained at a value approximately equal to 1.3. This means $r \approx 0.15d$.

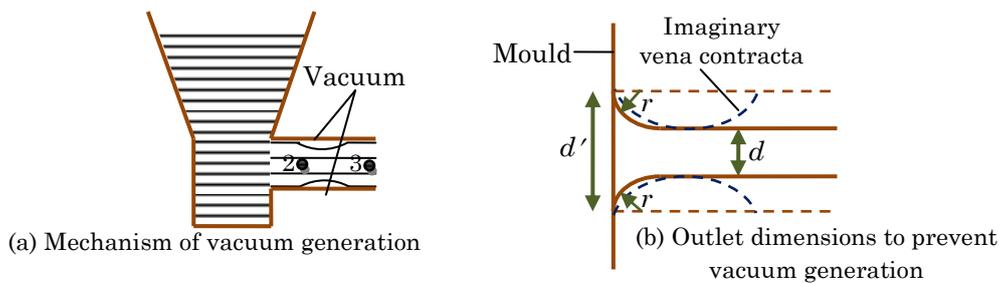


Diagram 7.5 Principle of avoiding vacuum generation.

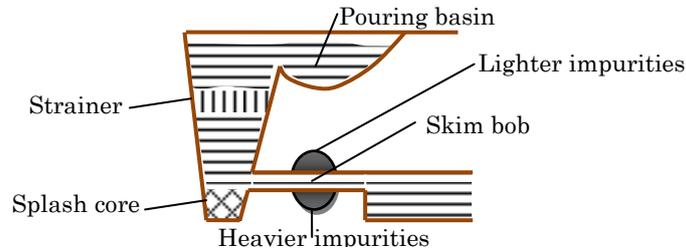


Diagram 7.6 Gating design to prevent impurities.

The common items employed in a gating design to prevent impurities in the casting are as follows (see also- Diagram 7.6).

Pouring basin This reduces the eroding force of the liquid metal stream coming directly from the furnace. A constant pouring head can also be maintained by using a pouring basin.

Strainer A ceramic strainer in the sprue removes dross.

Splash core A ceramic splash core placed at the end of the sprue also reduces the eroding force of the liquid metal stream.

Skim bob It is a trap placed in a horizontal gate to prevent heavier and lighter impurities from entering the mould.

7.4 RISER DESIGN AND PLACEMENT

The solidification time depends primarily on the ratio V/A , where V is the volume of the casting and A is the surface area of heat dissipation (i.e., of the casting). This is also to be expected intuitively since the amount of heat content is proportional to volume and the rate of heat dissipation depends on the surface area. This information is utilized when designing a riser to ensure that the riser solidifies after the casting. However, the information on the amount of liquid metal needed from the riser is used only to compensate for the shrinkage that takes place from the pouring temperature till solidification. Depending on the metal, the percentage of this shrinkage varies from 2.5 to 7.5. Thus, the use of a large riser volume (to ensure large solidification time) is uneconomical. So, a riser should be designed with the minimum possible volume while maintaining a cooling rate slower than that of the casting.

It may be noted that a casting with a high surface area/volume ratio is a riser larger than that determined by considering only the cooling rate. This is shown clearly by the example that follows.

Let us consider a steel plate of dimensions $25 \text{ cm} \times 25 \text{ cm} \times 0.25 \text{ cm}$. The casting then has the A/V ratio as

$$\left(\frac{A}{V}\right)_c = \frac{2 \times 625 \times 4(25 \times 0.25)}{25 \times 25 \times 0.25} = 8.16 \text{ cm}^{-1}$$

A cubical riser with sides 1.25 cm has the A/V ratio as

$$\left(\frac{A}{V}\right)_r = \frac{6 \times 1.25 \times 1.25}{1.25 \times 1.25 \times 1.25} = 4.8 \text{ cm}^{-1}$$

Thus, the riser is assured to have a much slower cooling rate (more solidification time) than that of the casting. The volume shrinkage of steel during solidification is 3%. So, the minimum volume of the riser necessary is

$$0.03 \times \frac{625}{4} = 4.69 \text{ cm}^3$$

The riser we have considered has the volume 1.95 cm³ only. Therefore, a much larger riser is required.

For a given shape of the riser, the dimensions of the riser should, however, be chosen so as to give a minimum A/V ratio, and the minimum volume should be ensured from the shrinkage consideration. It must be remembered that a liquid metal flows from the riser into the mould only during the early part of the solidification process. This necessitates the minimum volume of the riser to be approximately three times that dictated by the shrinkage consideration alone.

Application 7.2: Determine the dimensions of a cylindrical riser to be used for casting as aluminium cube of sides 15 cm. The volume shrinkage of aluminium during solidification is 6.5%.

Solution: First of all, let us determine the diameter/height ratio of the most compact cylinder so that, for a given volume, the surface area is minimum. With the diameter and the height of the cylinder as d and h respectively, the surface area of the cylinder is

$$A = \pi dh + 2 \frac{\pi}{4} d^2$$

and the volume of the cylinder is

$$V = \frac{\pi}{4} d^2 h$$

or

$$h = 4V/\pi d^2.$$

Hence,

$$A = \pi d \frac{4V}{\pi d^2} + 2 \frac{\pi}{4} d^2 = \frac{4V}{d} + \frac{\pi}{2} d^2$$

For A to be minimum, $\partial A/\partial d = 0$.

$$-\frac{4V}{d^2} + \pi d$$

or

$$d^3 = 4V/\pi.$$

Again

$$d^3 = 4V/\pi = d^2 h.$$

or

$$h = d \quad \{\text{when } A/V = 6/d\}$$

[This optimum ratio $h/d = 1$ for a cylindrical riser is true only if the riser is attached to the side of the casting. For a riser attached to the top of a casting, the surface area $A = \pi dh + (\pi/4)d^2$ when the optimum ratio h/d turns out to be equal to 1/2. Sometimes, the dimensions to yield the minimum value of A for a given value of V are determined using the Lagrange multiplier technique for constrained optimization.]

Now, the minimum volume necessary for the riser is $V_r = 3 \times 0.065 V_c$, where V_c is the volume of the casting and is equal to 3375 cm^3 . So, $V_r = 658.2 \text{ cm}^3$. Thus, the diameter of the riser (d), which is also equal to the height of the riser, can be written as

$$h = (4V_r/\pi)^{1/3} = 9.43 \text{ cm.}$$

Now,

$$\left(\frac{A}{V}\right)_r = \frac{6}{d} = \frac{6}{h} = \frac{6}{9.43} = 0.636 \text{ cm}^{-1}$$

$$\left(\frac{A}{V}\right)_c = \frac{6 \times 15 \times 15}{15^3} = 0.4 \text{ cm}^{-1}$$

$(A/V)_c$ this is less than $(A/V)_r$.

So, the riser will not have a longer solidification time. The dimensions of the riser can be recalculated as follows. For

$$(A/V)_r \leq (A/V)_c,$$

we need

$$6/d \leq 0.4 \text{ cm}^{-1} \quad \text{or} \quad d \geq 15 \text{ cm.}$$

With the minimum value of d , $V_r = (\pi/4)d^2h = (\pi/4)d^3 = 2650 \text{ cm}^3$. This volume is much more, than the minimum V_r necessary. Let us now consider the top riser when the optimum cylindrical shape is obtained with $h = d/2$ and again $(A/V)_r = 6/d$. However, with a large top riser, the cube loses its top surface for the purpose of heat dissipation. Hence,

$$\left(\frac{A}{V}\right)_c = \frac{5 \times 15 \times 15}{15^3} = \frac{1}{3} \text{ cm}^{-1}$$

To have

$$(A/V)_r \leq (A/V)_c,$$

or

$$6/d \leq 1/3 \text{ cm}^{-1}.$$

d should be greater than or equal to 18 cm. So, the riser volume with minimum diameter is given as

$$V_r = \frac{\pi}{4}d^2h = \frac{\pi}{4}18^2 \times 9 = 2289 \text{ cm}^3$$

which is greater than the minimum V_r necessary. Though we see that with a top riser there is a little saving of material as compared with the side riser, we have to use, however, a deeper mould with the top riser. Thus, in this case, the side riser may be chosen.

Application 7.3: Prove that the volume/area ratio for most compact economical cylindrical side riser of height h and diameter d is $d/6$ and d/h ratio is 1.

Solution: h = height of cylindrical riser, d = dia. of cylindrical riser

For side riser

Surface area of riser

$$A = \pi dh + 2 \frac{\pi}{4} d^2 \quad [i]$$

Volume of cylinder

$$V = \frac{\pi}{4} d^2 h \quad [ii]$$

or

$$h = 4V/\pi d^2.$$

Put value of h in above equation, we get

$$A = \pi d \frac{4V}{\pi d^2} + 2 \frac{\pi}{4} d^2 = \frac{4V}{d} + \frac{\pi}{2} d^2$$

For A to be minimum, $\partial A / \partial d = 0$.

$$-\frac{4V}{d^2} + \pi d$$

or

$$d^3 = 4V / \pi$$

Again

$$d^3 = 4V / \pi = d^2 h$$

or

$$h = d$$

Putting $h = d$ in equation (i) and (ii), we get

$$V/A = d/6$$

To check the adequacy of the riser size for a steel casting, Caine's relationship is normally used. Now, the solidification time is proportional to the square of the ratio volume/surface area. Caine's relationship, however, is based on the assumption that the cooling rate is linearly proportional to the ratio surface area/volume. A typical risering curve is depicted in Diagram 7.8.

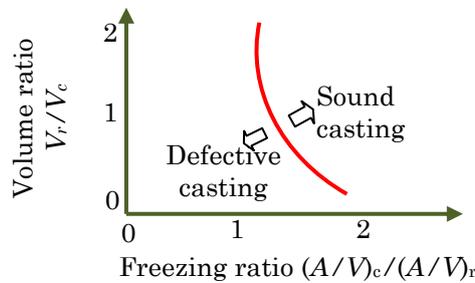


Diagram 7.8 Proper combinations of volume and freezing ratios.

Here, the ordinate of a point on the curve shows the volume ratio and the abscissa the freezing ratio; also, the subscripts c and r refer to the casting and the riser, respectively. For a given casting-riser combination, if the point in Diagram 7.8 falls to the right of the curve, the adequacy of the riser is ensured. The equation for a risering curve is of the form

$$x = \frac{a}{y - b} + c \tag{7.16}$$

where a is the freezing constant for the metal, b is the contraction ratio from liquid to solid, and c is a constant depending on the different media around the riser and the casting. The value of c is unity if the mould material around the casting and the riser is the same. For steel, the typical values are $a = 0.1$ and $b = 0.03$.

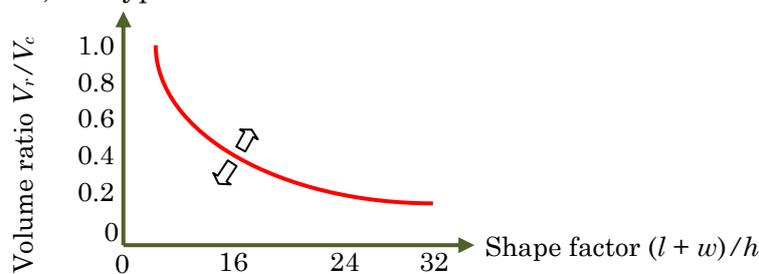


Diagram 7.9 Proper combinations of volume ratio and shape factor.

The tedious calculation of $(A/V)_c$ for a complex casting has given rise to another method where a risering curve of the type shown in Diagram 7.9 is used. In this method, the

shape factor $(l + w)/h$, instead of $(A/V)_c$, is plotted along the x -axis, where l , w , and h denote, respectively, the maximum length, the maximum width, and the maximum thickness of the casting. This method and Caine's relationship give almost identical results for a casting of simple shape.

If the appendages to the main body (of a simple, regular shape) of a casting are thin, then the solidification time does not alter significantly. As a result, a marginal increase in the calculated volume (on the basis of the main body) of the riser performs the job satisfactorily. As the appendages become heavier, the riser volume required is calculated on the basis of a modified total volume of the casting. The total volume of the casting is taken as the volume of the main section plus the effective percentage of the appendage volume, called the parasitic volume. The effective percentage is estimated from curves of the type shown in Diagram 7.10.

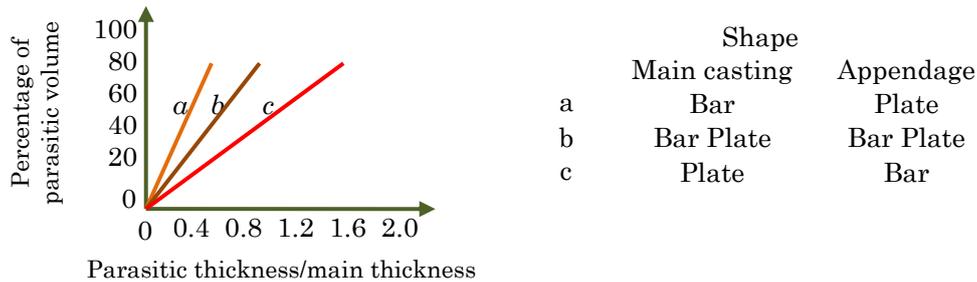


Diagram 7.10 Effective parasitic volume.

A shape is called *plate-like* or *bar-like* depending on whether the width of the cross-section is more or less than three times the depth.

Application 7.4: Calculate the size of cylindrical riser ($h = d$) necessary to feed a steel slab casting $25 \times 25 \times 5$ cm with a side riser, casting poured horizontal into the mould.

Solution: $V = 35 \times 25 \times 5 = 4375 \text{ cm}^3$.
 Surface area of casting = $2 \times 35 \times 25 + 4 \times 25 \times 5 = 2250 \text{ cm}^2$.
 Volume of riser = $\pi D^3/4$.
 Surface area of riser

$$= \pi D^2 + \frac{\pi}{4} D^2 = 1.25\pi D^2$$

$$x = (\text{Surface area of casting}/\text{volume of casting})/(\text{Surface area of riser}/\text{volume of riser})$$

Freezing ratio

$$x = \frac{2250/4375}{1.25\pi D^2/0.25\pi D^3} = 0.1028D$$

Now,

$$y = \text{Volume of riser}/\text{Volume of casting}$$

$$y = 0.25\pi D^3/4375 = 0.00018D^3$$

Caine's equation for steel

$$x = \frac{a}{y - b} + c$$

for steel $a = 0.1$, $b = 0.03$ and $c = 1.0$, then

$$0.103D = \frac{0.10}{0.000251D^3 - 0.03} + 1.0$$

On solving we get

$$D^4 - 8.9286 D^3 - 119.52D = 2490$$

by errors and Trial method we get

$$D = 11.44 \approx 12 \text{ cm}$$

7.5 DEFECTS IN CASTINGS

In this section, we shall discuss the different types of defects in castings and their origin and remedies. The treatment is restricted essentially to the sand mould castings. The defects in a casting may arise due to the defect: in one or more of the following:

1. Design of casting and pattern.
2. Moulding sand and design of mould and core.
3. Metal composition.
4. Melting and pouring.
5. Gating and risering.

The following defects are most commonly encountered in the sand mould castings (Diagram 7.11):

Blow It is a fairly large, well-rounded cavity produced by the gases which displace the molten metal at the cope surface of a casting. Blows usually occur on a convex casting surface and can be avoided by having a proper venting and an adequate permeability. A controlled content of moisture and volatile constituents in the sand-mix also helps in avoiding the blow holes.

Scar A shallow blow, usually found on a flat casting surface, is referred to as a scar.

Blister This is a scar covered by the thin layers of a metal.

Gas holes These refer to the entrapped gas bubbles having a nearly spherical shape, and occur when an excessive amount of gases is dissolved in the liquid metal.

Pin holes These are nothing but tiny blow holes, and occur either at or just below the casting surface. Normally, these are found in large numbers and are almost uniformly distributed in the entire casting surface.

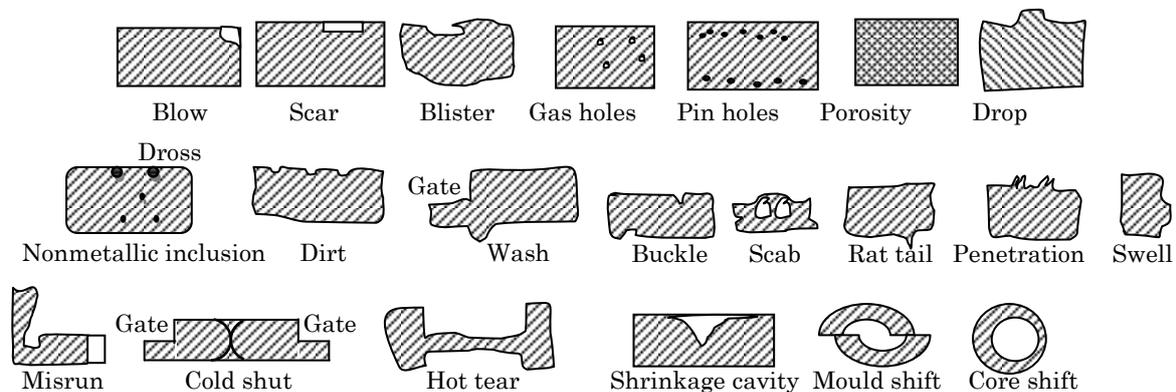


Diagram 7.11 Common casting defects.

Porosity This indicates very small holes uniformly dispersed throughout a casting. It arises when there is a decrease in gas solubility during solidification.

Drop An irregularly-shaped projection on the cope surface of a casting is called a drop. This is caused by dropping of sand from the cope or other overhanging projections into the mould. An adequate strength of the sand and the use of gagers can help in avoiding the drops.

Inclusion It refers to a nonmetallic particle in the metal matrix. It becomes highly undesirable when segregated.

Dross Lighter impurities appearing on the top surface of a casting are called dross. It can be taken care of at the pouring stage by using items such as a strainer and a skim bob.

Dirt Sometimes sand particles dropping out of the cope get embedded on the top surface of a casting. When removed, these leave small, angular holes, known as dirt. Defects such as drop and dirt suggest that a well-designed pattern should have as little a part as possible in the cope. Also, the most critical surface should be placed in the drag.

Wash A low projection on the drag surface of a casting commencing near the gate is called a wash. This is caused by the erosion of sand due to the high velocity jet of liquid metal in bottom gating.

Buckle This refers to a long, fairly shallow, broad, vee-shaped depression occurring in the surface of a flat casting of a high temperature metal. At this high temperature, an expansion of the thin layer of sand at the mould face takes place before the liquid metal at the mould face solidifies. As this expansion is obstructed by the flask, the mould face tends to bulge out, forming the vee shape. A proper amount of volatile additives in the sand-mix is therefore essential to make room for this expansion and to avoid the buckles.

Scab This refers to the rough, thin layer of a metal, protruding above the casting surface, on top of a thin layer of sand. The layer is held on to the casting by a metal stringer through the sand. A scab results when the upheaved sand is separated from the mould surface and the liquid metal flows into the space between the mould and the displaced sand.

Rat tail It is a long, shallow, angular depression normally found in a thin casting. The reason for its formation is the same as that for a buckle. Here, instead of the expanding sand upheaving, the compressed* layer fails by one layer, gliding over the other.

Penetration If the mould surface is too soft and porous, the liquid metal may flow between the sand particles up to a distance, into the mould. This causes rough, porous projections and this defect is called penetration. The fusion of sand on a casting surface produces a rough, glossy appearance.

Swell This defect is found on the vertical surfaces of a casting if the moulding sand is deformed by the hydrostatic pressure caused by the high moisture content in the sand.

Misrun Many a time, the liquid metal may, due to insufficient superheat, start freezing before reaching the farthest point of the mould cavity. The defect that thus results is termed as a misrun.

Cold shut For a casting with gates at its two sides, the misrun may show up at the centre of the casting. When this happens, the defect is called a cold shut.

Hot tear A crack that develops in a casting due to high residual stresses is called a hot tear.

Shrinkage cavity An improper riser may give rise to a defect called shrinkage cavity, as already detailed.

Shift A misalignment between two halves of a mould or of a core may give rise to a defective casting, as shown in Diagram 7.11. Accordingly, this defect is called a mould shift or a core shift.