Lecture 6

ME 361A

Also follow blackboard discussions

(C) Casting design

Control of the accompanied SOLIDIFICATION TRANPORT PHENOMENA - heat transfer, fluid flow and solidification - shrinkage, feeding, gating, filling

The Fluidity of Molten Metals

Objectives:

− To introduce the concept of fluidity of molten metal and its influence on the production of castings

− The student will understand the relevance of fluidity, the means by which this is measured and the effect of alloy type

Fluidity, in casting terminology, is the distance to which a metal, when cast at a given temperature, will flow in a given test mould before it is stopped by solidification. Fluidity is therefore a length, usually measured in millimetres or metres (It is not to be confused with the physicists' definition as the reciprocal of viscosity).

Fluidity is an important characteristic of molten metals and alloys, and it directly affects the casting soundness and solidified material quality.

Measurement of Fluidity

In a widely used test to characterize the fluidity of metals, called the spiral fluidity test. The total length (in inches) the metal travels in the spiral mold before solidifying is called its fluidity.

The rationale behind this is clearly the desire to compress the fluidity test into as small a mould as possible, and that the flow distance is sensitive to leveling errors, and that these are minimized by the spiral path of the liquid.

Measurement of Fluidity

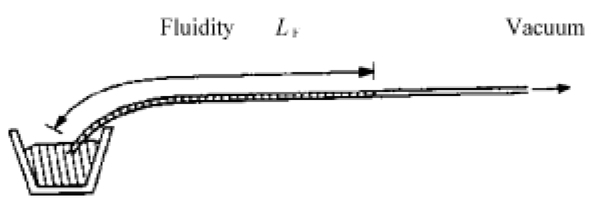
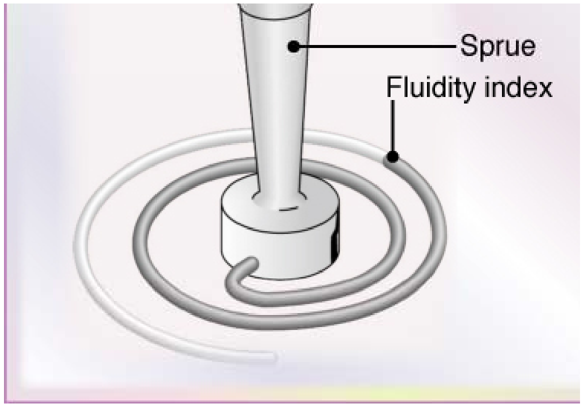


Figure 3.25 Equipment for measurement of maximum fluidity length in a laboratory. Reproduced with permission from Elsevier Science.



Alloy composition, pouring temperature, solid impurities (e.g., oxides), and density and viscosity all influence the fluidity.

A theoretical model that predicts the fluidity length of a metal in terms of the thermophysical properties of the metal and mold material

Consider a metal at its melting point, T_m, poured in a channel of radius, a, and flowing with an average velocity, V. The metal solidifies after a distance, L_f, in time t by losing latent heat to the mold. The rate of heat dissipation by solidifying metal equals the rate at which heat is transferred across the mold-metal interface. The thermal resistance at the interface is specified in terms of an interface heat transfer coefficient, h. Heat lost per unit time when a length, L_f, solidifies in time t is

$$\frac{\pi a^2 \rho_s L_f \cdot \Delta H}{t} = \pi a^2 \rho_s V \Delta H. \qquad (1)$$

Heat transferred across the mold–metal interface in time t is

$$2\pi a L_f h(T_m - T_0). \qquad (2)$$

Equate the two equations

$$L_f = \frac{\rho_s V \Delta H a}{2h(T_m - T_0)}.$$

If the metal is poured in a superheated state (i.e., $T > T_m$), then besides the latent heat of solidification, the superheat also must be dissipated. This is accounted for by modifying the latent heat term as ($\Delta H + c.\ \Delta T$), where $\Delta T = T_p - T_m$, and T_p is the pouring temperature, and c is the specific heat of the metal. Denominator will also be modified

Assumptions:

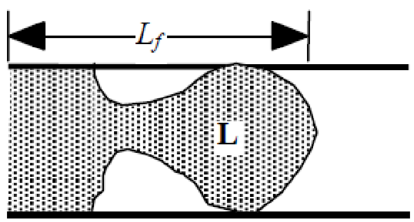
- Flow of liquid metal stops when an element of the melt solidifies due to heat extraction in the channel.
- All resistance to heat flow is at the mold-metal interface, that there is no significant effect of surface tension on flow velocity, that flow channel is filled with liquid metal (fully developed flow), and that there is no decrease in velocity from friction effect.

Despite these simplifications, the experimental measurements of fluidity of various metals are in good qualitative agreement with the preceding fluidity equation.

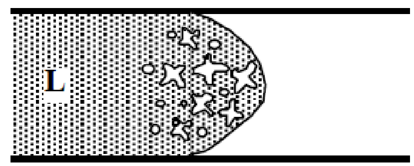
Fluidity of alloys when solid grains move

$$L_f = f_s^{cr} V \cdot t_s$$

V is the average velocity, t_s is the solidification time, f_s^{cr} is the critical fraction of solid at which flow stops. The critical fraction solid corresponds to dendrite coherency and is typically at 0.2 to 0.4.



Pure metal



Alloy where grain move

The influence of the solidification front morphology on fluidity:

Fluidity is maximum for the pure metal, short freezing range alloys (thin mushy zone) and the eutectic alloys that have very small solidification intervals, and decreases for long freezing range alloy that have large mushy zones.

The Filling of Castings

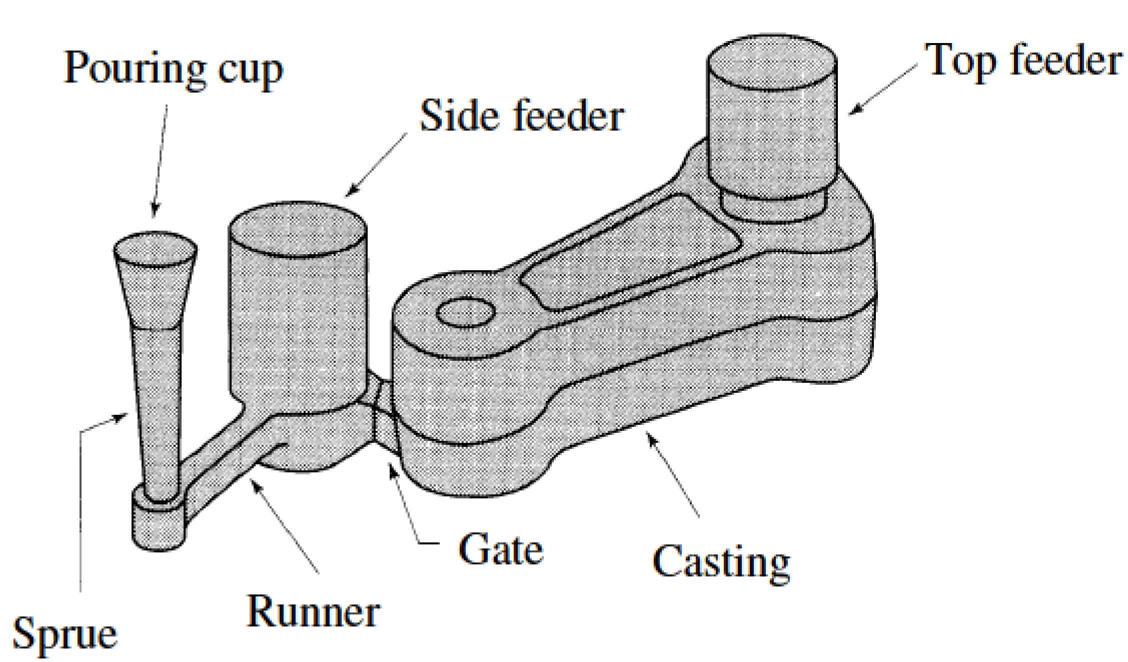
Objectives:

− To describe the function and design of all parts of the running and gating systems used in the production of castings

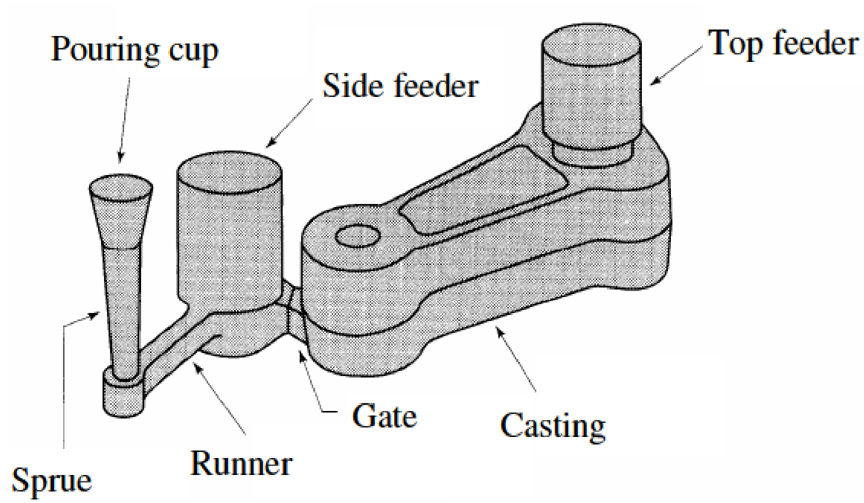
− The student will be able to tackle the design of a simple running system in a systematic manner

Filling system

− pouring basin
− downsprue
− sprue base or well
− runner which lead the molten metal towards the casting
− ingates, which introduce the metal into the mould cavity



Fluid Flow during Mold Filling, Shrinkage and Feeding

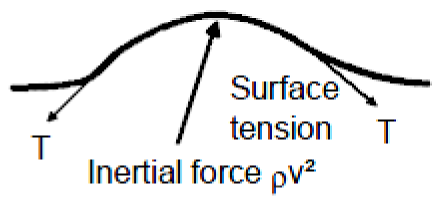


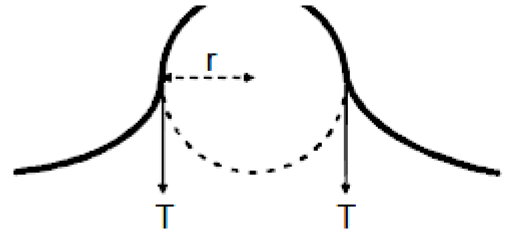
• It can be clearly seen that the filling and feeding systems are separate, which is appropriate since they perform completely different functions in the production of a casting.

• It might take ~ 10 seconds to fill the mould, whereas the feeding system would typically be operating for ~10 minutes as the casting solidifies.

• In this example of an aluminum casting, it should be appreciated that the metal has been carefully introduced into the cavity through gates in the bottom of the casting. This is in contrast to many iron castings in which the metal is poured directly into the top of the casting cavity with very little thought being given to providing a proper filling system. It is instructive to consider why this might be so.

Turbulent Flow in Metals





$$\rho V^2 = \frac{2T}{r}$$

Limiting condition is when a drop is about to form

Therefore $V_{crit} = \sqrt{\frac{2*T}{r*\rho}}$

Critical Velocity

$$V_{crit} = \sqrt{\frac{2*T}{r*\rho}}$$

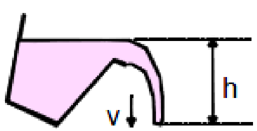
For aluminium T ~ 1N/m

ρ ~ 2500kg/m^3

Assume r ~ 5mm = 0.005m

$$\Rightarrow V_{crit} = 0.4 m/s$$

Generally find that v_{crit} ~ 0.5m/s for most metals



$$V = \sqrt{2 \cdot g \cdot h}$$

The critical velocity is reached after a drop of:

$$h_{crit} = \frac{V^2_{crit}}{2 \cdot g} \approx 12.7mm$$

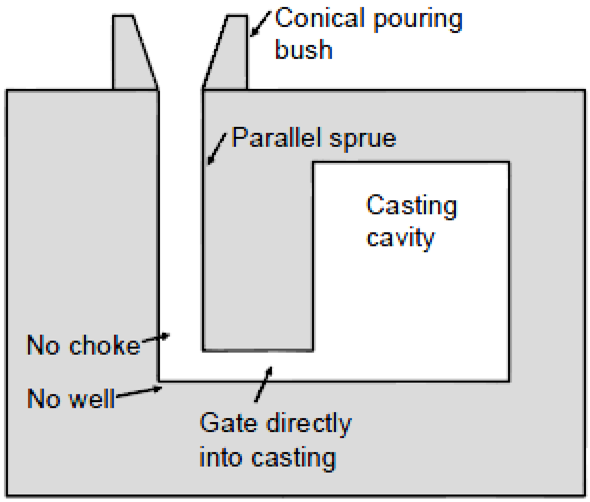
- Once these values are exceeded, the surface of the metal will behave in a turbulent fashion, i.e. there is a real risk that the surface will break up into waves and droplets, causing the oxide film defects seen earlier.

- This shows that once the metal has fallen by *only* **12.7 mm**, it is already at a critical velocity, i.e. it has sufficient energy to break its surface in a turbulent manner, and is therefore likely to cause defects. This implies that it is *never* possible to fill an Al casting from the top and therefore the only solution is to fill it from the bottom.

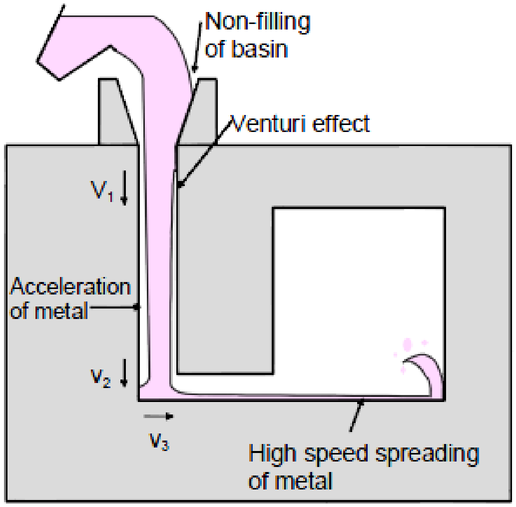
Let us examine a deliberately bad running system.

Unfortunately, it is one that is seen all too often in industries

Deliberately Bad Running System



Problems Resulting from Deliberately Bad Running System

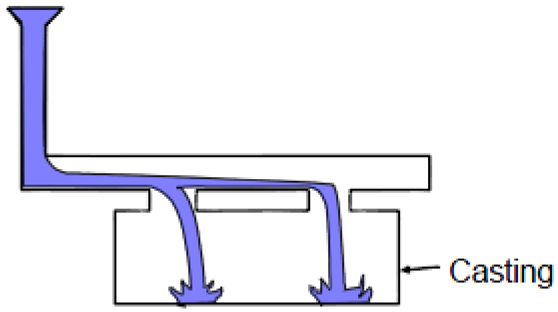


• As the metal is poured directly from the ladle into the conical pouring bush, it is already moving quite quickly as it enters the top of the sprue. Its velocity V_1 will be determined through the height through which it has fallen. Thus, this basin design is bad because it has no decelerating effect on the metal.

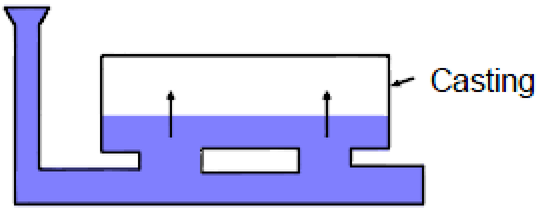
• As the metal runs down the sprue, it accelerates due to gravity and so the stream gets thinner, reaching a velocity V_2 at the bottom. Neither the sprue nor the pouring basin ever fill up completely. As a result, air being sucked into the metal stream through both the sand walls of the sprue and the incompletely filled pouring basin, thereby creating conditions for air entrapment and to form oxides.

• The metal stream then hits the bottom of the sprue. Here it can form a splash => air entrapment. Also the stream spreads out in a relatively thin film along the horizontal surface of the gate with a velocity of V_3 which can be significantly greater than V_2. It therefore enters the casting at speed, hitting the far wall where it rebounds in an uncontrolled manner, forming again some splash and creating conditions for further air entrapment/oxidation.

Top versus Bottom Gating



Top gating - causes turbulence



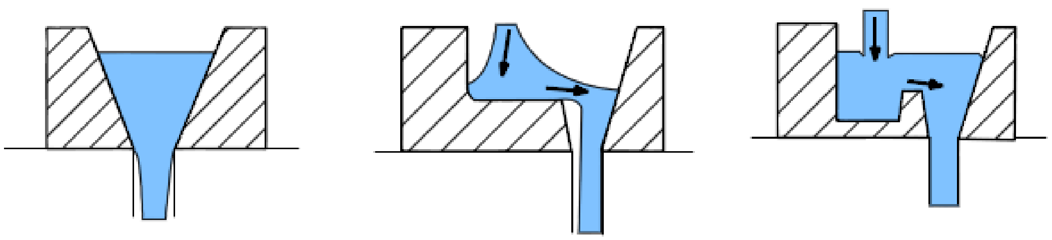
Bottom gating - prevents turbulence

The critical velocity is readily exceeded and the resulting turbulence and splashing cause oxidation of the molten metal.

The preferred technique is to use bottom gating, i.e. to introduce the metal uphill into the casting although, as we will see, it is still important to limit the velocity with which the metal enters the mould.

We will now look at the proper way to design a running system, starting from the pouring basin and working our way through in order.

Good Design 1: Pouring Basin



BAD
conical basin

BETTER
offset basin

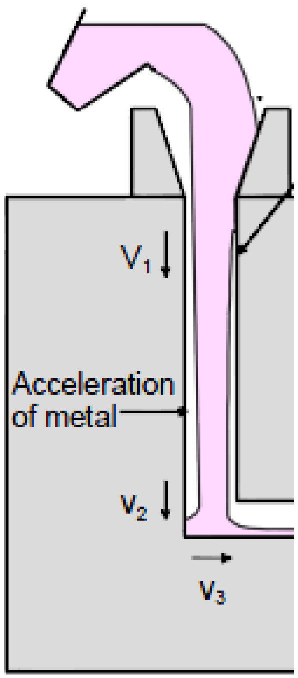
BEST
offset stepped basin

• As we have already seen, it is important to avoid the use of a conical pouring basin since this does not decelerate the metal and also acts as a venturi and causes air ingress.

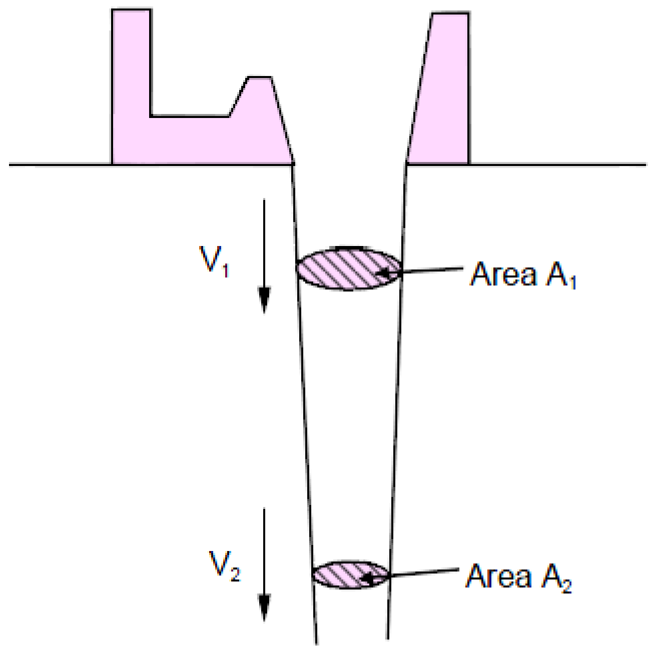
• One improvement would be to use an offset pouring basin which helps to decelerate the metal stream before it enters the sprue. However, a jet of metal still travels at high velocity across the top of the sprue, hitting the far side, and there is a tendency for the metal to flow down only one side of the sprue.

• The best design is to introduce a step into the basin to give an *offset stepped basin.* The step acts to stop the rapid motion of the metal over the top of the sprue and helps to ensure that the latter is completely filled.

Good Design 2: Tapered Sprue



Straight sprue



Tapered sprue

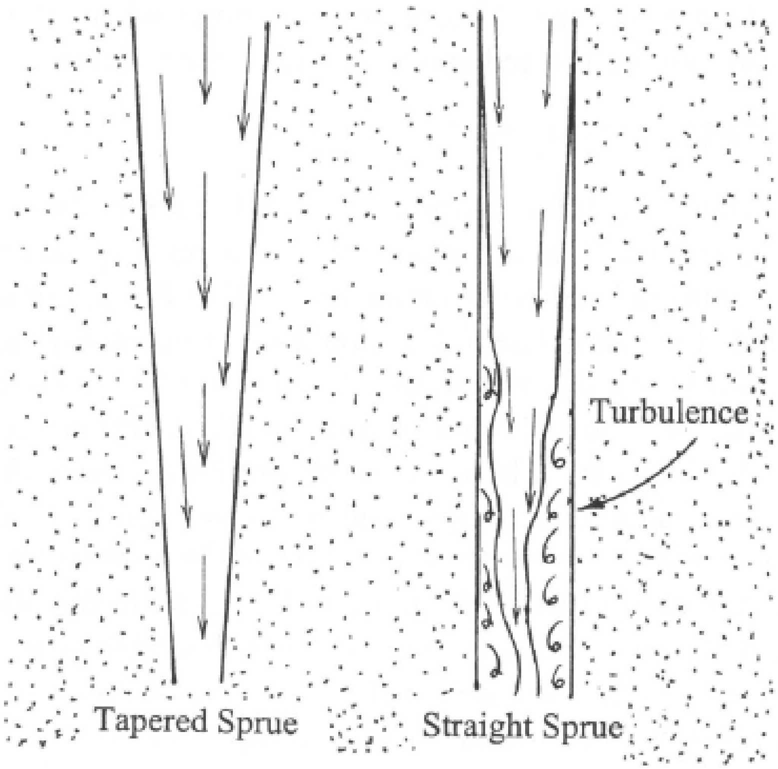
Metal accelerates from V_1 to V_2 due to gravity.

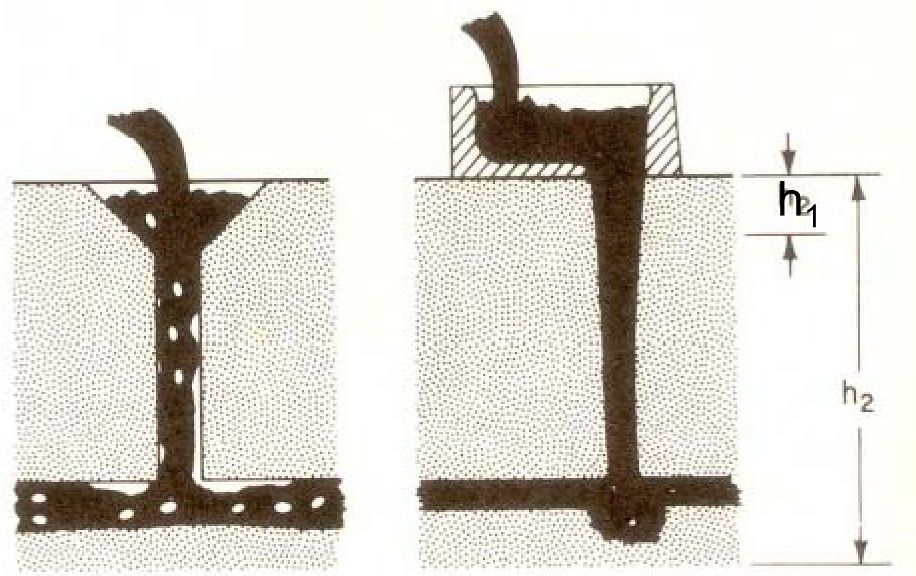
Sprue will remain full of metal if the sprue is tapered so that

$$A_1 \cdot V_1 = A_2 \cdot V_2$$

SPRUES:

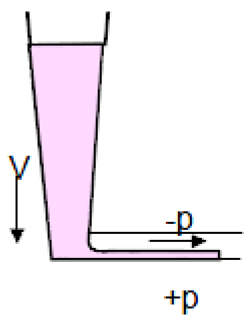
Sprues should be tapered with the small end being down.

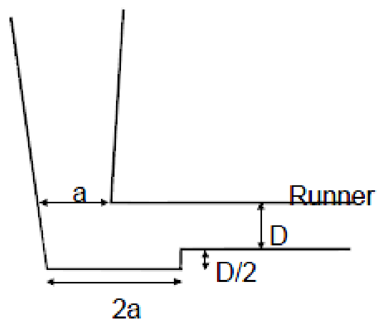




$$\frac{A_1}{A_2} \geq \sqrt{\frac{h_2}{h_1}}$$

Good Design 3: Sprue Well



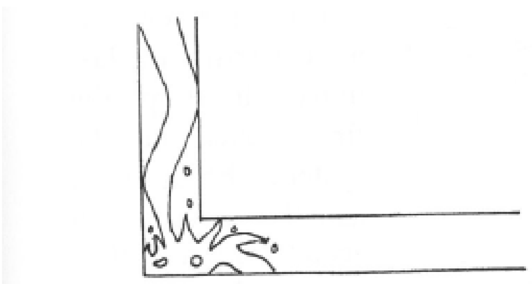


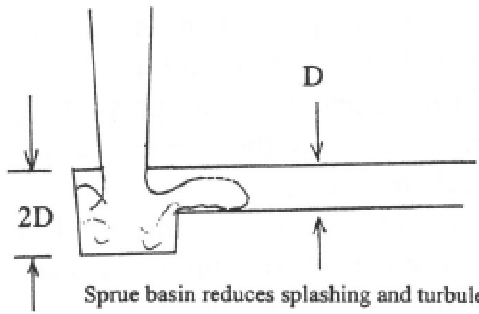
The sprue well helps to: (i) Declarate metal
(ii) Stop first splash
(iii) Fill runner

If there is no well, the falling metal stream hits the bottom surface of the runner bar at a velocity *V* and spreads along the bottom surface of the runner. In doing so, it creates a pressure, +p, which is balanced by a negative pressure, *-p*, on the top surface of the runner bar. This tends to draw in air through the permeable sand mould, leading to oxidation of the metal.

Therefore, some sprue well is needed.

Sprue basin or sprue well

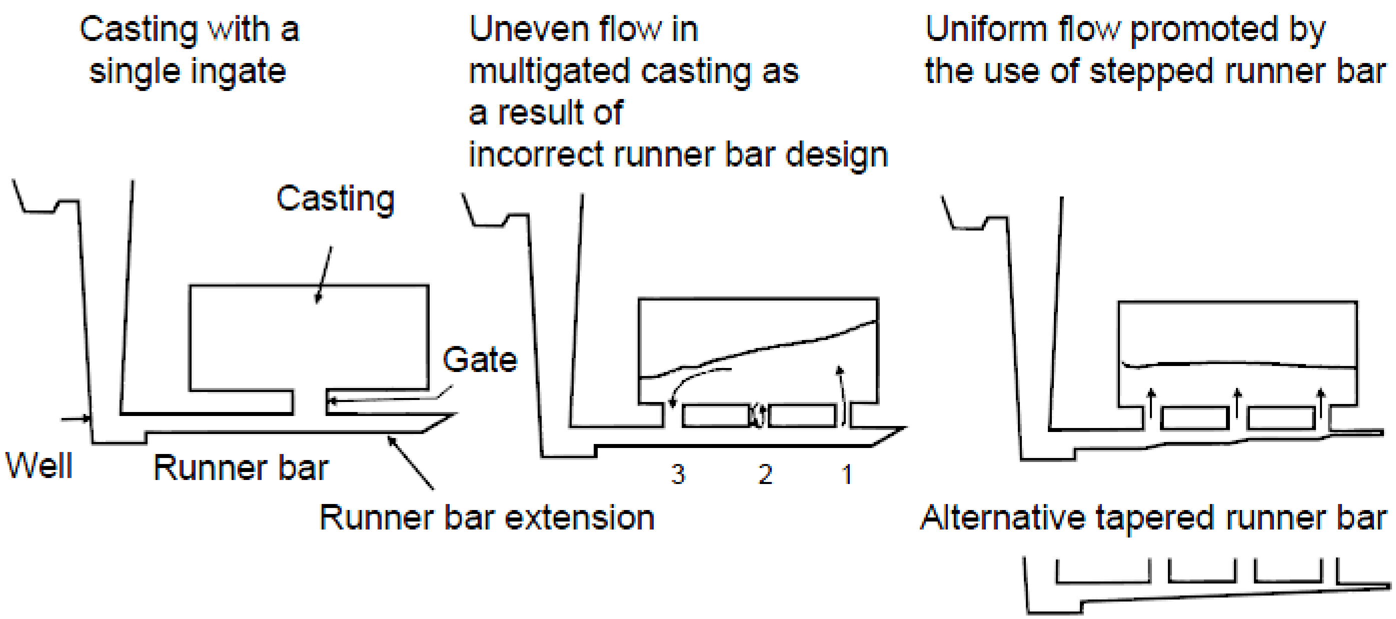




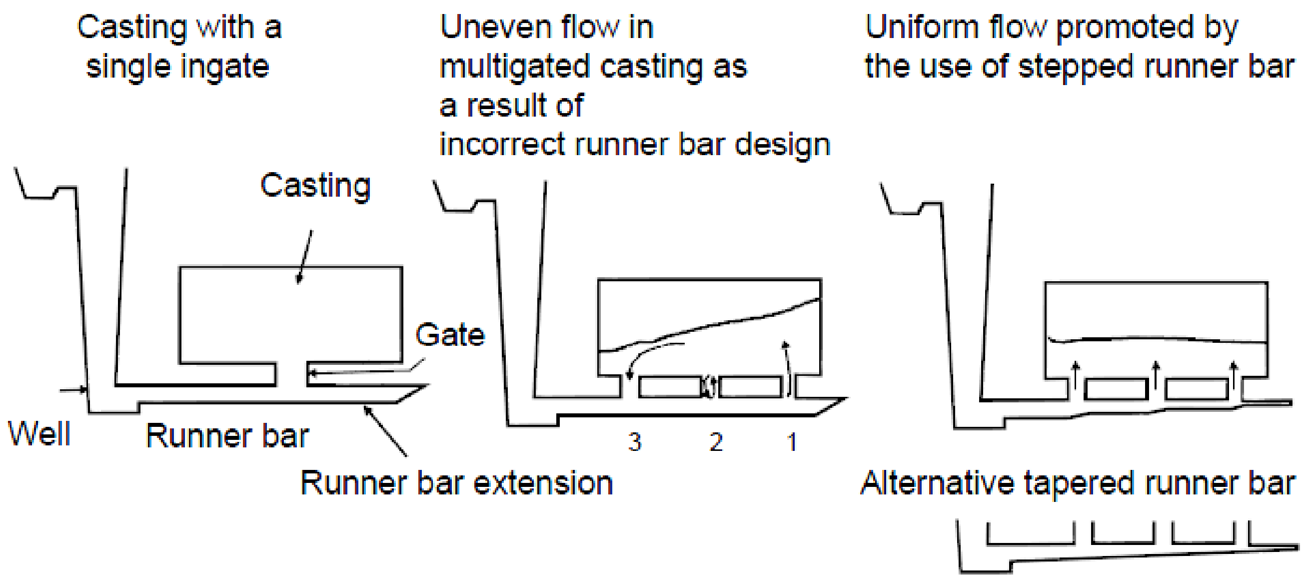
Sprue basin reduces splashing and turbulence

Good Design 4: Runner Bar and Gates

AIMS: (i) to distribute metal to lowest point(s) on a casting
(ii) to reduce metal velocity.



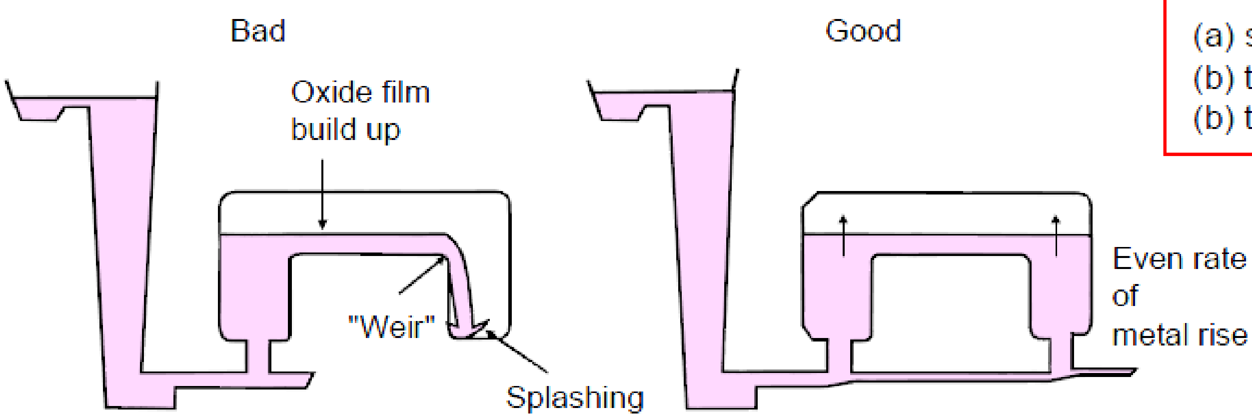
The well should be the lowest point of the casting and filling system and the metal should always progress uphill thereafter. In doing so, it firstly passes through the runner bar which distributes it through gates to the lowest point or points on the casting. Careful thought has to be given to how the metal will flow through the runner and casting, bearing in mind the need to keep the speed low in order to avoid surface turbulence.



In some castings, only one gate will be required. In such cases, the runner bar will be a simple parallel sided channel, arranged so that the metal rises uphill from the sprue base, through the runner and gate and into the casting. It is good practice to have a runner bar extension which can be used to receive the first metal poured into the mould and which often contains air bubbles and slag particles.

In other castings, it may be necessary to use two or more gates, in which case the runner bar must be stepped to promote equal flow through both gates. If this is not done, in the case of three gates for instance, the furthest gate (gate1) tends to fill first and so becomes super-heated, whereas metal tends to flow out of gate 3 and the latter becomes cold. Gate 2 takes on a neutral character. Uneven flow leads to an uneven temperature distribution and an increased risk of turbulence-induced defects. The runner bar should therefore have a gentle tapered step at each gate to promote even metal flow.
In extreme cases, where there are many gates or a single gate along the length of the casting, the runner bar can be tapered along its length.

Good Design 4 (Continued): Runner Bar and Gates



Waterfall effects must be avoided so that:

(a) splashing is prevented
(b) the critical velocity is not exceeded
(b) the metal meniscus is never stationary

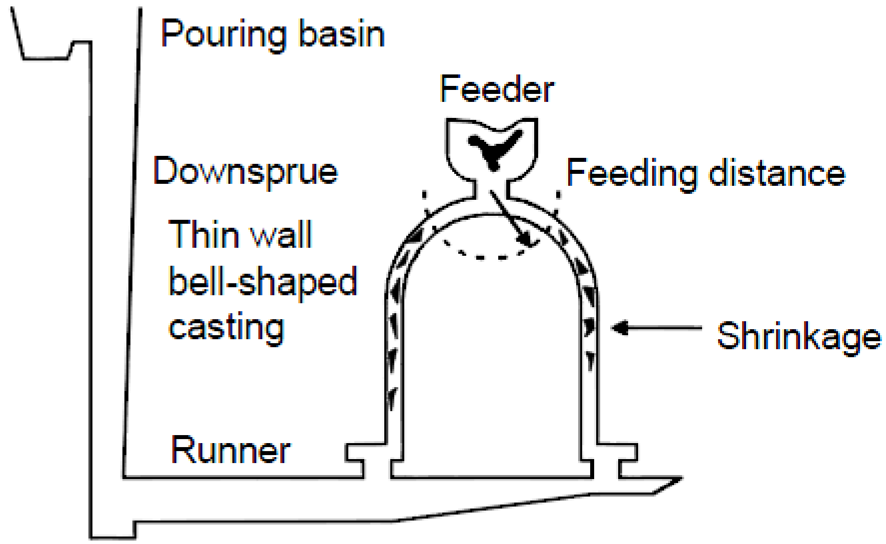
Another important feature is that the gating arrangement must avoid waterfall effects.

In the first example shown here, metal is introduced into only one leg of an inverted 'U' casting. As one leg fills up, the point is reached where the metal splashes over the 'weir'. The splashing leads to unwanted oxidation of the metal and is of course particularly bad if the fall exceeds the critical height defined earlier (12.5 mm in aluminium) since the critical velocity condition will then be reached. At the same time, whilst the metal is filling the non-gated leg, the top meniscus is static. As a result, its oxide surface layer will be rapidly growing in thickness and will become increasingly difficult to move once the waterfall effect has finished. The molten metal will then tend to flow over the top of the thick oxide skin, leading to an entrapped defect which is known as an **oxide lap.**

The solution is to use more than one gate, so that metal rises in both legs at the same time. This avoids both the waterfall effect and the development of thick oxide films. For castings with multiple isolated low points, a separate ingate is required for each low point.

Filling
vs.
feeding

Beware!!
Filling distance may exceed feeding distance

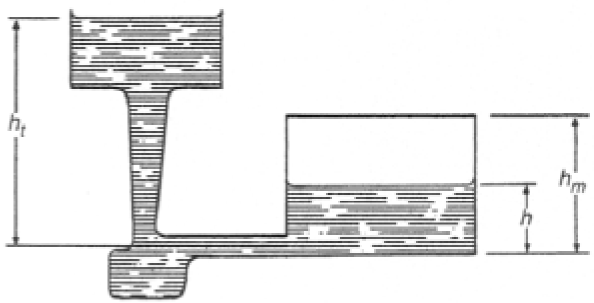


Lecture 7

ME 361A

Also follow blackboard discussions

Mold-Filling Time



$$\text{The velocity of the metal at the gate} = V_3 = \sqrt{2g(h_t - h)},$$

where h is the instantaneous metal level in the mold, and h_t is total height of the metal in the sprue. This is the velocity of a jet discharging against a static head h, making the effective head as (h_t - h).

when instantaneous height is h - let the metal level in mold move up through an infinitesimal height, dh, in a time interval dt. If A_m and A_g denote the cross-sectional areas of the mold and gate

$A_m dh = A_g V_3 dt$. On substituting $\sqrt{2g(h_t - h)}$ for V_3, yields

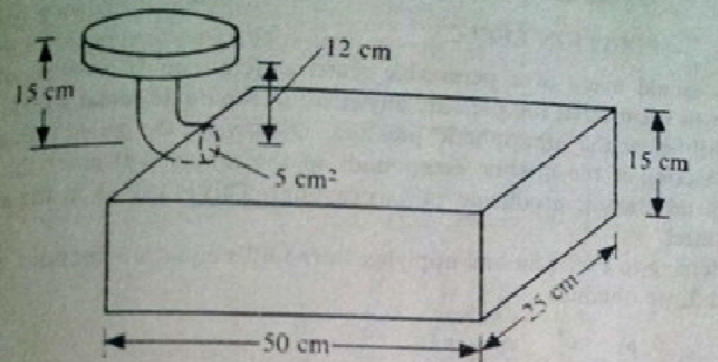
$$\frac{A_g}{A_m}\int_0^{t_f} dt = \frac{1}{\sqrt{2g}}\int_0^{h_m}\frac{dh}{\sqrt{h_t - h}}$$

$$\boxed{t_f = \frac{A_g}{A_m}\frac{1}{\sqrt{2g}}\left(2\sqrt{h_t} - \sqrt{h_t - h_m}\right).}$$

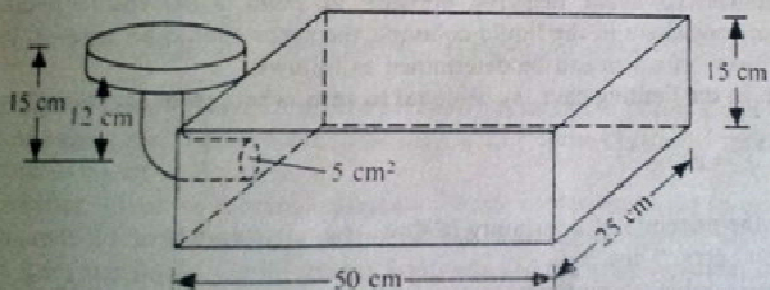
Because of a constantly increasing back-pressure on the incoming metal in a bottom-gated mold, the metal velocity progressively decreases in proportion to the instantaneous metal head (h_t-h), and the time to fill the mold becomes greater than that for a top-gated mold.

equation (2.10).

EXAMPLE 2.1 Two gating designs for a mould of 50 cm × 25 cm × 15 cm are shown in Fig. 2.7. The cross-sectional area of the gate is 5 cm². Determine the filling time for both the designs.



(a) Top gating



(b) Bottom gating

Fig. 2.7 Top and bottom gating designs.

SOLUTION Figure 2.7a. Since $h_t = 15$ cm, from equation (2.3), we have

$$v_3 = \sqrt{2 \times 981 \times 15} \text{ cm/sec} = 171.6 \text{ cm/sec.}$$

The volume of the mould is $V = 50 \times 25 \times 15$ cm³ and the cross-sectional area of the gate is $A_g = 5$ cm². So, from equation (2.4), we get

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

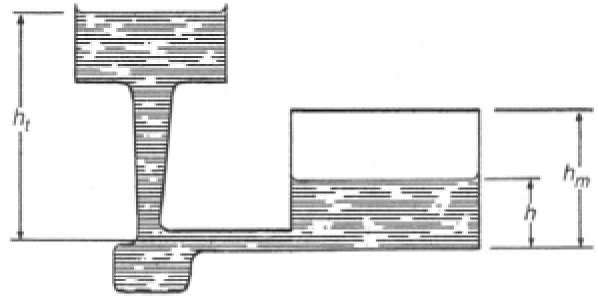
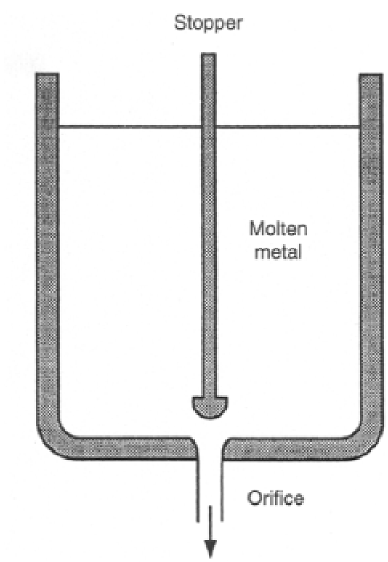


Figure 2.7b. Here, $h_t = 15$ cm, $h_m = 15$ cm, $A_m = 50 \times 25$ cm², and $A_g = 5$ cm². Using equation (2.10), we have

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

It should be noted that in Fig. 2.7b the time taken is double of that in Fig. 2.7a. We can easily verify that this will always be so if $h_m = h_t$.

Emptying the ladle



Ladle discharge through an orifice at base of the ladle

Molds are poured with the help of a ladle, so it is of interest to determine the time to discharge the ladle. Let A_1 and A_n denote the ladle and nozzle cross-sectional areas, respectively, and let h be the instantaneous metal level at some time t after pouring was initiated through the orifice. The average metal velocity in the nozzle (assuming no friction) is

$$V_n = \sqrt{2gh}$$

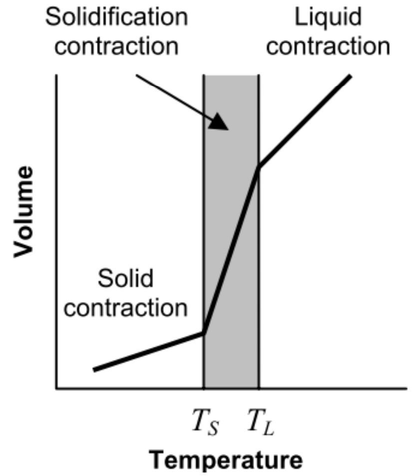
$$m = -\rho_m A_l \frac{dh}{dt} = \rho_m A_n V_n = \rho_m A_n \sqrt{2gh}$$

$$-\int_{h_i}^{h_f} \frac{dh}{\sqrt{h}} = \frac{A_n}{A_l}\sqrt{2g}\int_0^{t_f} dt$$

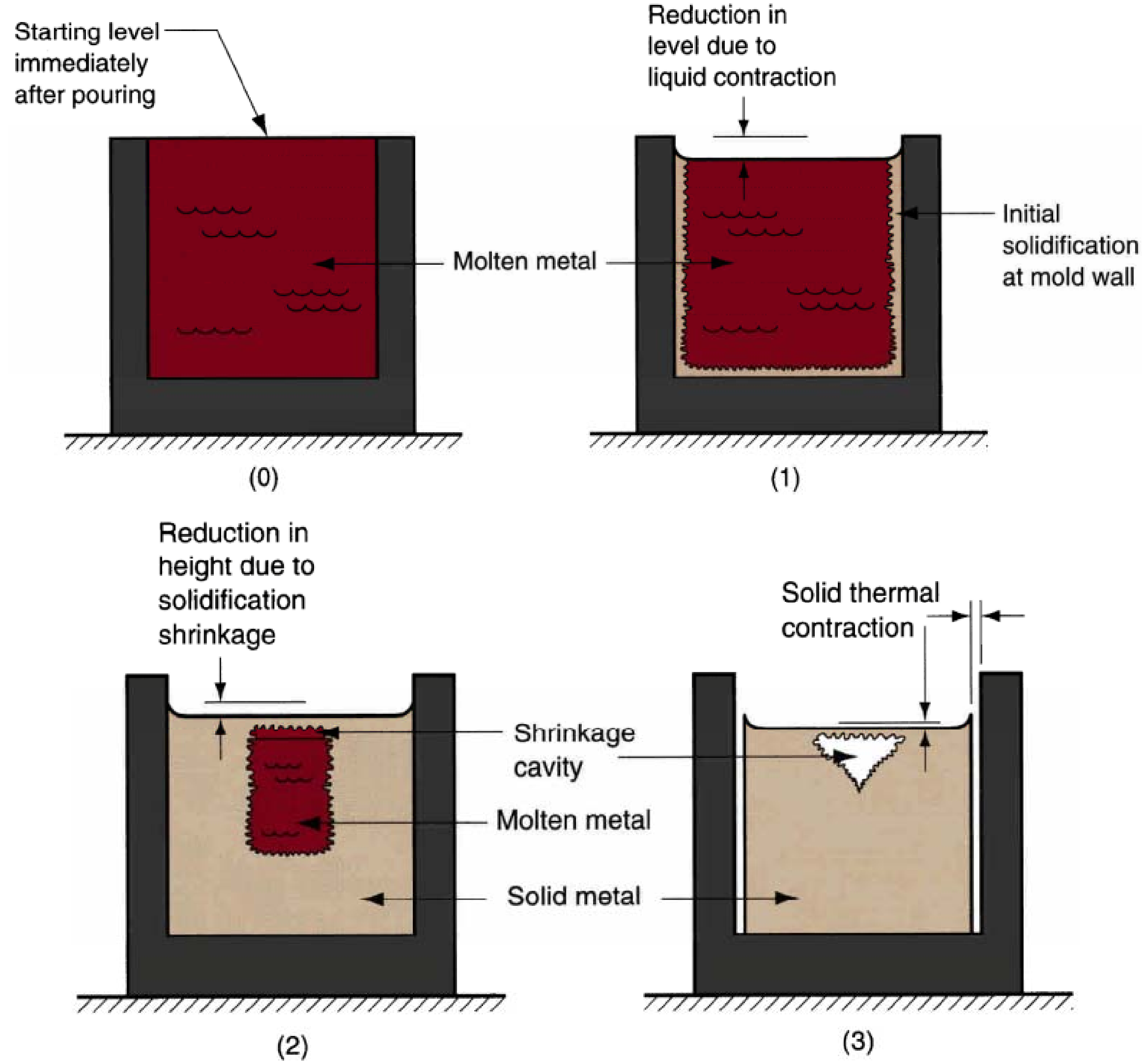
$$t_f = \frac{\sqrt{2}}{\sqrt{g}}\frac{A_l}{A_n}\left(\sqrt{h_i} - \sqrt{h_f}\right).$$

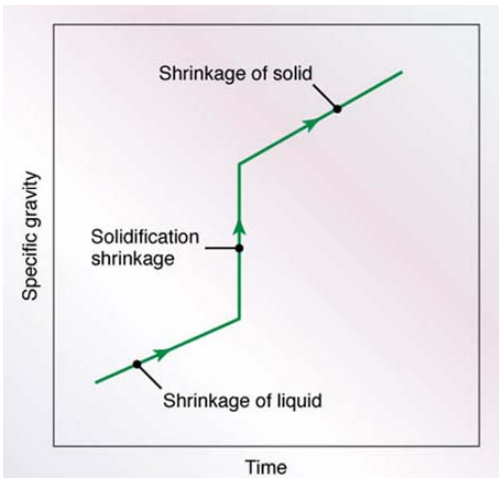
More rigorous fluid dynamic calculations can be made to account for non-steady flow with fluid friction effects and calculate the mold filling times for the purpose of mold design

Shrinkage and feeding



Solidification shrinkage = $$\alpha = \frac{V_l - V_s}{V_l} = \frac{\rho_s - \rho_l}{\rho_s}$$





Shrinkage regimes.

Solid shrinkage = patternmaking shrinkage

Shrinkage for various materials

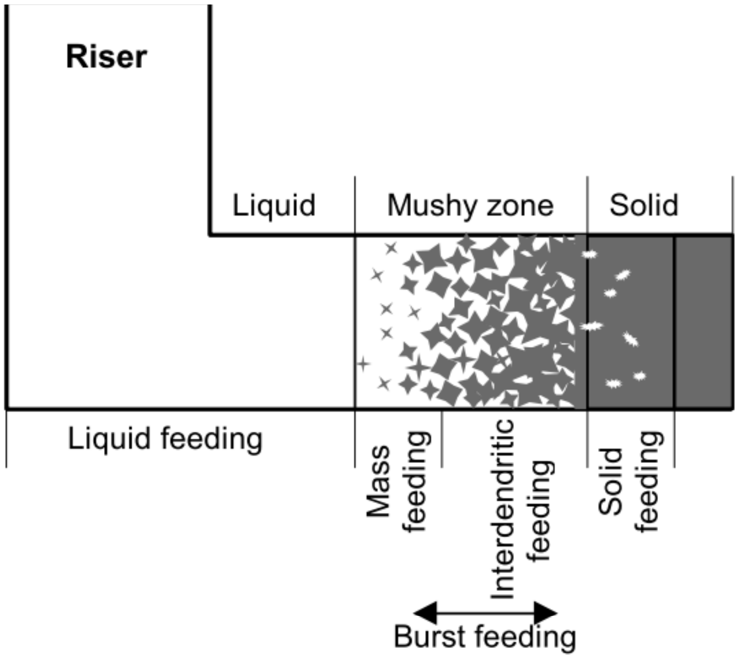
Solidification contraction of various metals and alloys

Material	Volumetric solidification contraction, %	Material	Volumetric solidification contraction, %
carbon steel	2.5 to 3	Cu-30%Zn	4.5
1% carbon steel	4	Cu-10%Al	4
white iron	4 to5.5	aluminum	6.6
gray iron	-2.5 (expansion) to 1.6	Al-4.5%Cu	6.3
ductile iron	-4.5 (expansion) to 2.7	Al-12%Si	3.8
copper	4.9	magnesium	4.2
		zinc	6.5

Feeding

For effective feeding to occur during solidification four main requirements must be satisfied:

- a feeding source (riser) that solidifies after the region to be fed;
- sufficient liquid must be available to feed the shrinkage;
- unrestricted feeding channels (path of flow from the feeder to the shrinkage);
- sufficient pressure on the liquid to make it flow toward the shrinkage region.

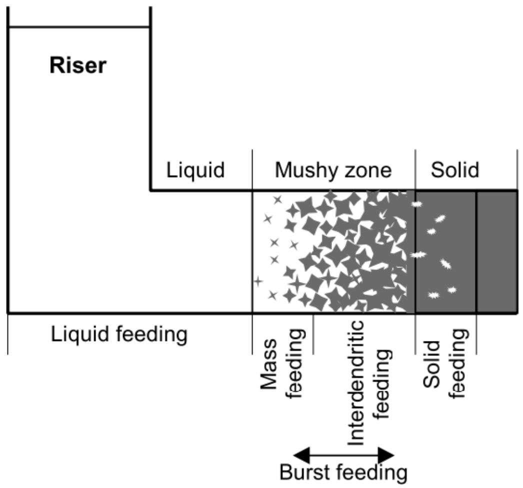


Mechanisms of feeding.

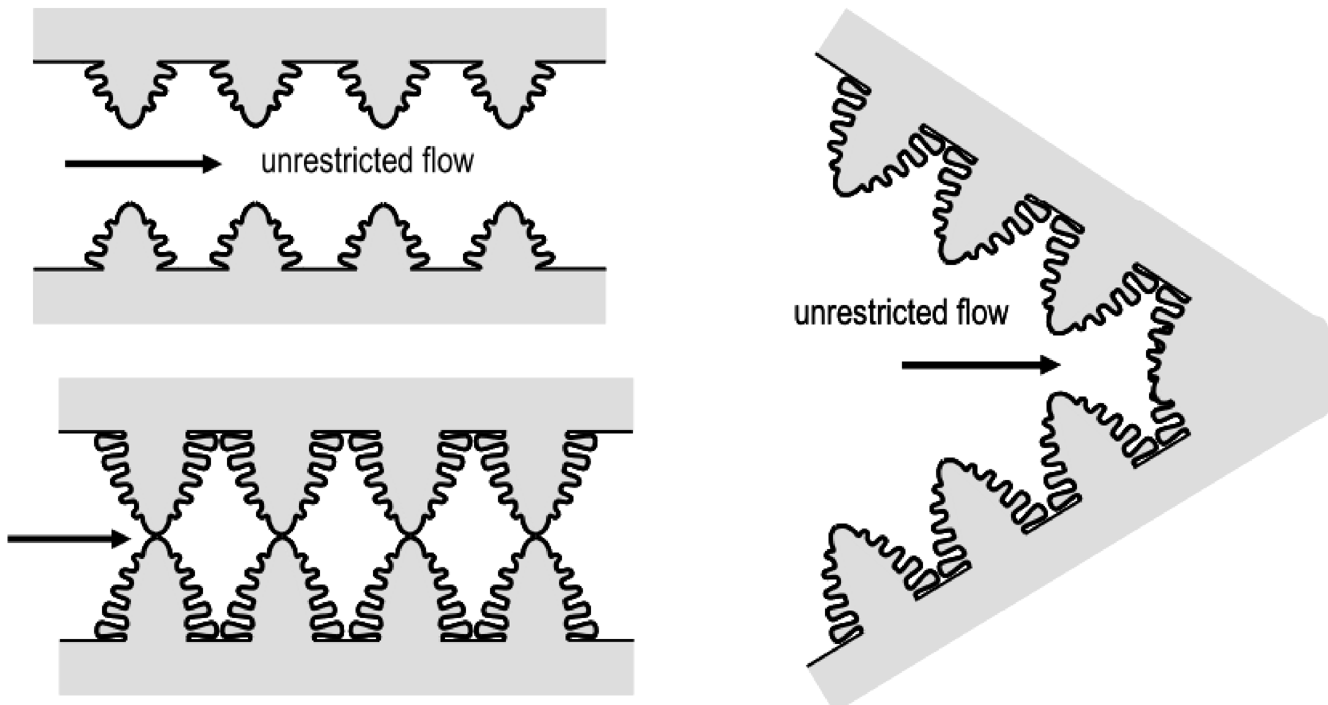
Let us try to evaluate the feeding velocity, V_f, which is the average velocity of the mass moving to fill the mass deficit. As explained earlier (see Eq. (3.7) it can be expressed as $V_f = f_L V_L + f_S V_S$, where V_S and V_L are the velocity of the solid and liquid, respectively.

During *liquid feeding*, which occurs before the beginning of solidification, $f_S = 0$ and thus $V_f = V_L$. When solidification starts, solid particles (grains) form in the liquid. As long as these particles are not in contact with one another, that is when $f_S < f_S^{cr}$, it may be assumed that the solid moves with the liquid ($V_S = V_L$), and the metal behaves like a slurry (semisolid). Its relative viscosity is increased (fluidity is decreased). Because of this increased viscosity, during *mass* (semisolid) *feeding* the flow velocity decreases to $V_f < V_L$.

As solidification proceeds, dendrite coherency (i.e. a rigid network of contiguous dendrites) will occur when $f_S < f_S^{cr}$, and a fixed solid network will form. Then, since $V_S = 0$, the feeding velocity becomes $V_f = f_L \cdot V_L$, meaning a further decrease in feeding. Only *interdendritic feeding* is possible at this point.



Mechanisms of feeding.



a) parallel solidification fronts

b) converging solidification fronts

Plate- and wedge-type solidification.

The Feeding of Castings

Objectives:

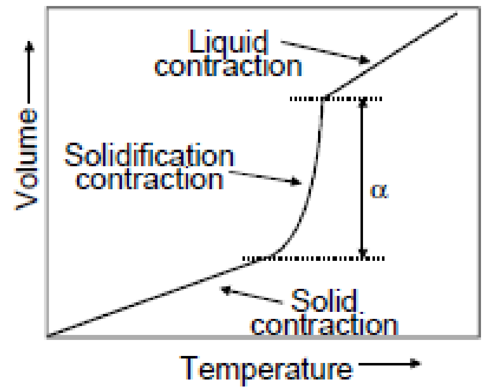
− To provide an introduction to the techniques used to compensate for the solidification shrinkage of castings.

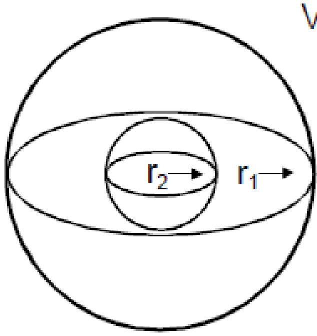
− The student will be able to understand the basic principles of how to design a feeder system to produce a shrinkage-free casting

Shrinkage

Solidification shrinkage = $$\alpha = \frac{V_l - V_s}{V_l} = \frac{\rho_s - \rho_l}{\rho_s}$$

volume change
as the liquid metal transforms to a solid due to the change in the arrangement of the atoms from the rather open, random close-packed manner in a liquid to a regular close-packed form in a solid





Volume of sphere $= \frac{4}{3}\pi r_1^3$ Volume of shrinkage $= \alpha \frac{4}{3}\pi r_1^3 = \frac{4}{3}\pi r_2^3$

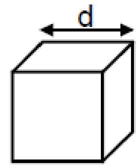
$$\therefore r_2 = r_1 \cdot \alpha^{\frac{1}{3}}$$

For example: for Al, α = 7%, ⇨ r_2= 0.41 r_1
i.e. 7% shrinkage creates a void having a radius of over 40% of the sphere.

Feeding rules for effective feeding

Rule No.1:
Heat Transfer Requirement (Chvorinov's Rule)

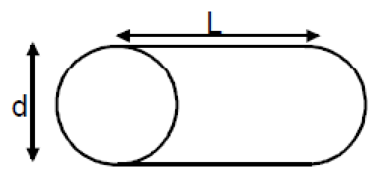
The feeder must solidify at the same time as, or later than, the casting.



$$M = \frac{d^3}{6 \cdot d^2} = \frac{d}{6}$$

i.e. Modulus of feeder $\geq$ Modulus of casting

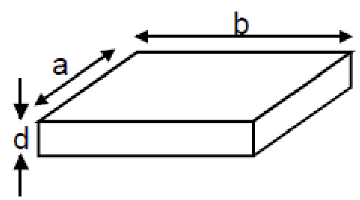
Normally $M_f = 1.2\ M_c$



$$M = \frac{\pi \cdot d^2 \cdot L}{4 \cdot \pi \cdot d \cdot L} = \frac{d}{4}$$

$$\text{Modulus} = \frac{\text{Volume of casting}}{\text{Cooling surface area}}$$

As M increases, solidification time increases



$$M = \frac{d \cdot a \cdot b}{2 \cdot a \cdot b} = \frac{d}{2}$$

"the freezing time of the feeder must be at least as long as the freezing time of the casting".

It can be re-stated in simple terms as:

"the modulus of the feeder must be equal to or greater than the modulus of the casting".

Rule No. 2: Volume Requirement

The feeder must contain sufficient liquid
to satisfy the volume contraction of the casting.

Volume needed $= \alpha \cdot (V_c + V_f)$ where V_c = volume of casting
and V_f = volume of feeder

Feed metal available $= \varepsilon \cdot V_f$ where ε = feeder efficiency

$\longrightarrow$ for sound castings, $\varepsilon \cdot V_f \geq \alpha \cdot (V_c + V_f)$

For aluminium, $\alpha \sim 7\%$ and for a sand mould, $\varepsilon \approx 14\%$

$\longrightarrow$ $0.14 \cdot V_f \geq 0.07 \cdot (V_c + V_f)$

Approximately, $2\ V_f \geq V_c + V_f$

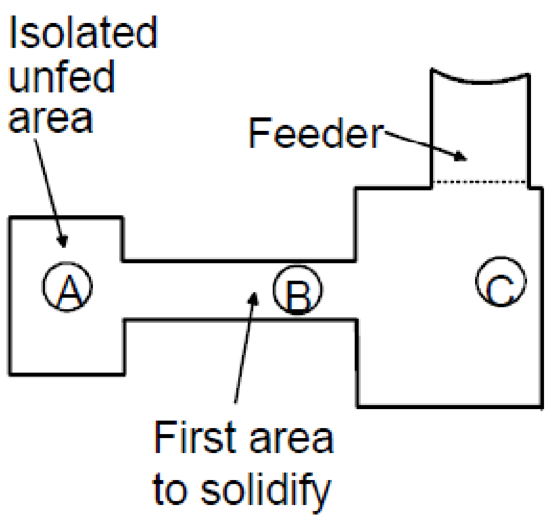
$\longrightarrow$ $V_f \geq V_c$

Therefore, yield is only about 50% for aluminium.

For steels, $\alpha \sim 3\%$ and yield rises to ~78%.

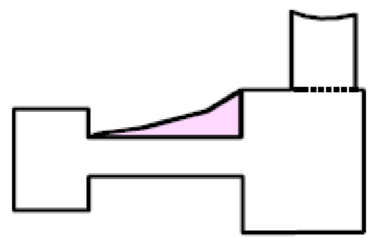
Rule No. 3 The Feed Path Requirement

There must be a path to allow feed metal to reach the regions that need it.

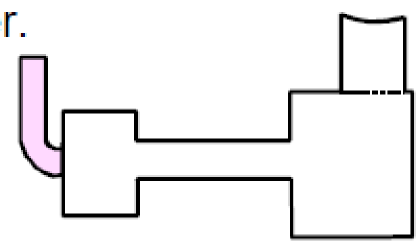


Possible solutions

1. Use padding



2. Use extra feeder.



3. Change design