MF9254 ADVANCES IN CASTING AND WELDING PROCESSES

UNIT I CASTING DESIGN

Heat transfer between metal and mould –– Design considerations in casting – Designing for directional solidification and minimum stresses - principles and design of gating and risering

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Design Considerations in Metal Casting

Mold and Gating System Design, Directional Solidification, and Troubleshooting

In the previous sections we discussed the fundamental aspects of manufacturing parts by metal casting. We covered the creation of patterns, and the setup of the mold and gating system. Also we discussed the casting operation itself including the pouring of the molten material into the mold, the elements and functions of the different parts of the mold during the manufacture of the cast part, and the problems and possible defects encountered during the employment of the manufacturing process of casting. In this section we will examine the specifics of good mold and gating system design in order to manufacture higher quality castings and minimize defects that may occur during the casting process. This section will be useful to those designing a system to manufacture a part by metal casting, or to help as a troubleshooting guide for improvement upon an existing system.

Gating System and Mold Design:

When selecting to manufacture a part by casting one must consider the material properties and possible defects that this manufacturing process produces. The primary way to control casting defects is through good mold design considerations in the creation of the casting's mold and gating system. The key is to design a system that promotes *directional solidification*. Directional solidification, in casting manufacture, means that the material will solidify in a manner that we plan, usually as uniformly as possible with the areas farthest away from the supply of molten metal solidifying first and then progressing towards the risers. The solidification of the casting must be such that there is never any solid areas that will cut off the flow of liquid material to unsolidified areas creating isolated regions that result in vacancies within the casting's material, as discussed in the Metal Casting Operation section and shown in Figure 14.

In the development of an effective manufacturing process. Gating system design is crucial in controlling the rate and turbulence in the molten metal being poured, the flow of liquid metal through the casting's system, and the temperature gradient within the metalcasting. Hence a good gating system will create directional solidification throughout the casting, since the flow of molten material and temperature gradient will determine how the casting solidifies.

When designing a mold for a casting or trying to fix or improve upon and existing design you may want to consider the following areas.

Insure that you have adequate material:

This may seem very obvious, but in the manufacturing of parts many incomplete castings have been a result of insufficient material. Make sure that that you calculate for the volume of all the areas of your casting accounting for shrinkage.

Consider the Superheat:

Increasing the superheat, (temperature difference between the metal at pouring and freezing), as mentioned previously can increase fluidity of the material for the casting, which can assist with its flow into the mold. There is a compromise involved to the manufacturing process. Increasing the superheat has problems associated with it, such as increased gas porosity, increased oxide formation, and mold penetration.

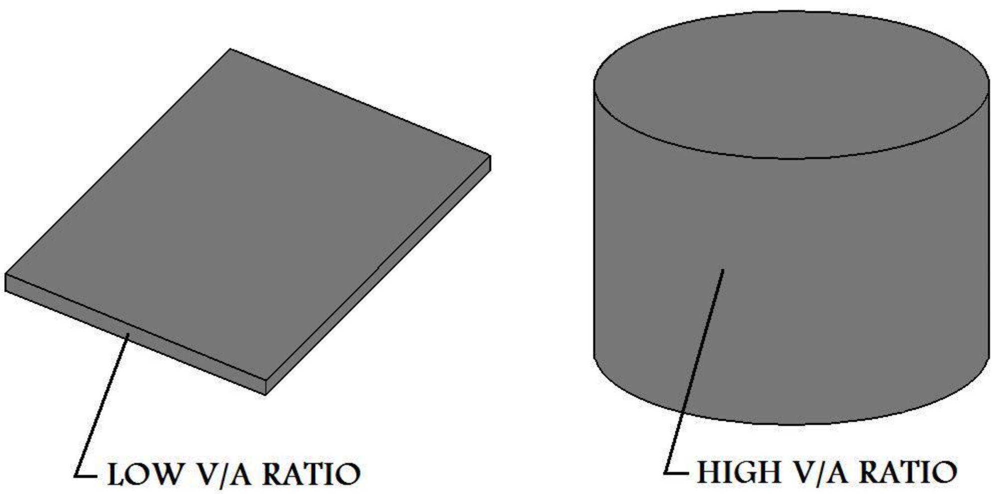
Insulate Risers:

Since the riser is the reservoir of molten material for the casting it should be last to solidify. Insulating the top as mentioned earlier, shown in figure 13, will greatly reduce cooling in the risers from the steep temperature gradient between the liquid metal of the casting, and the the room temperature air.

Consider V/A Ratios:

In casting manufacture, V/A ratio stands for volume to surface area or mathematically (volume/surface area). When solidification of a casting begins a thin skin of solid metal is first formed on the surface between the casting and the mold wall. As solidification continues the thickness of this skin increases towards the center of the liquid mass. Sections in the casting with low volume to surface area will solidify faster than sections with higher volume to surface area. When manufacturing a part by metalcasting consideration of the of V/A ratios is critical in avoiding premature solidification of the casting and the formation of vacancies.

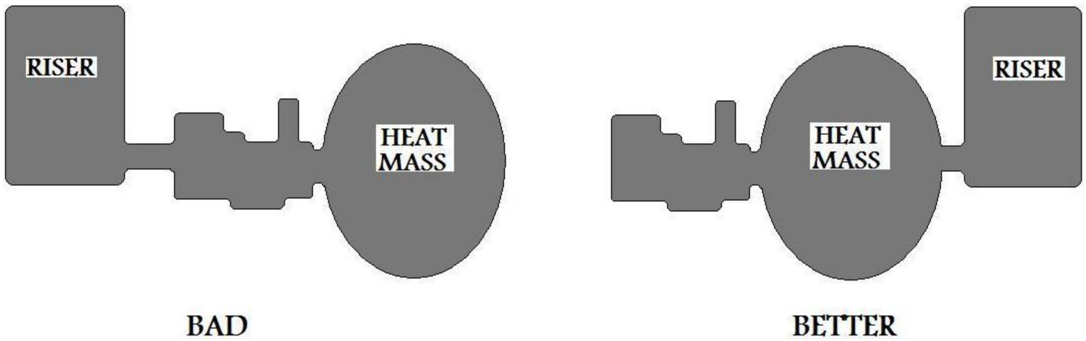
Figure:15



Heat Masses:

Avoid large heat masses in locations distant to risers. Instead locating sections of the casting with low V/A ratios further away from the risers will insure a smooth solidification of the casting.

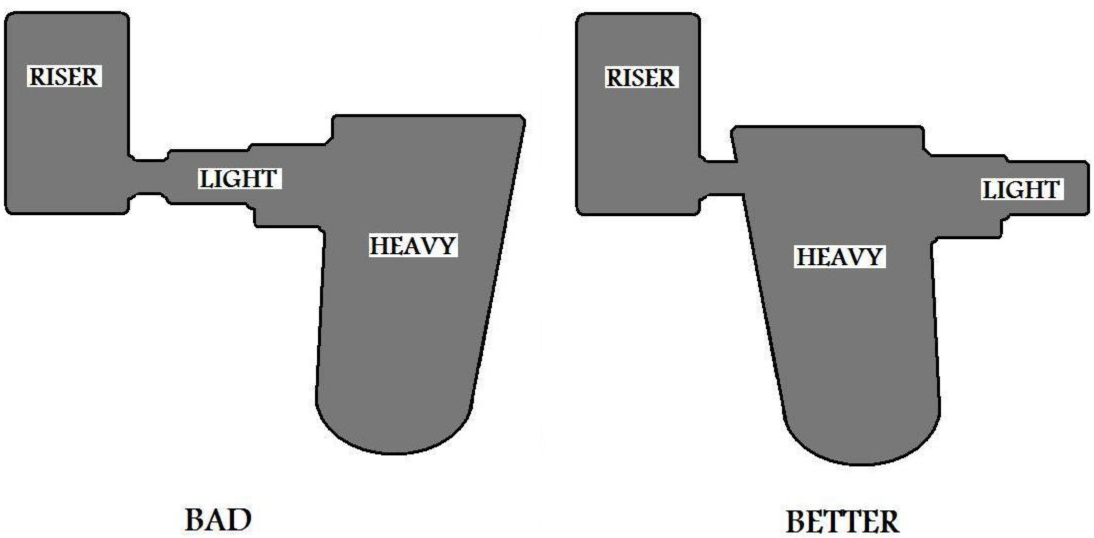
Figure:16



Sections of the Casting:

The flow of material is very important to the manufacturing process. Do not feed a heavy section through a lighter one.

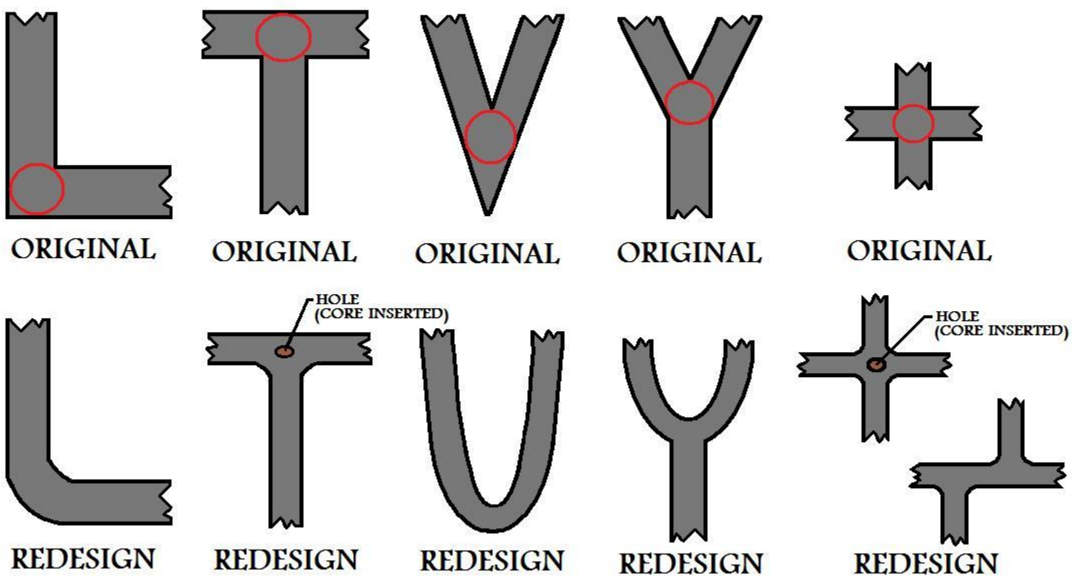
Figure:17



Be Careful With Consideration To L,T,V,Y and + junctions:

Due to the nature of the geometry of these sections it is likely that they will contain an area where the casting's solidification is slower than the rest of the junction. These *hot spots* are circled in red in Figure 18. They are located such that the material around them, which will undergo solidification first, will cut of the hot spots from the flow of molten material. The flow of casting material must be carefully considered when manufacturing such junctions. If there is some flexibility in the design of the casting and it is possible you may want to think about redesigning the junction. Some possible design alternatives are shown in Figure 18. These should reduced the likelihood of the formation of hot spots.

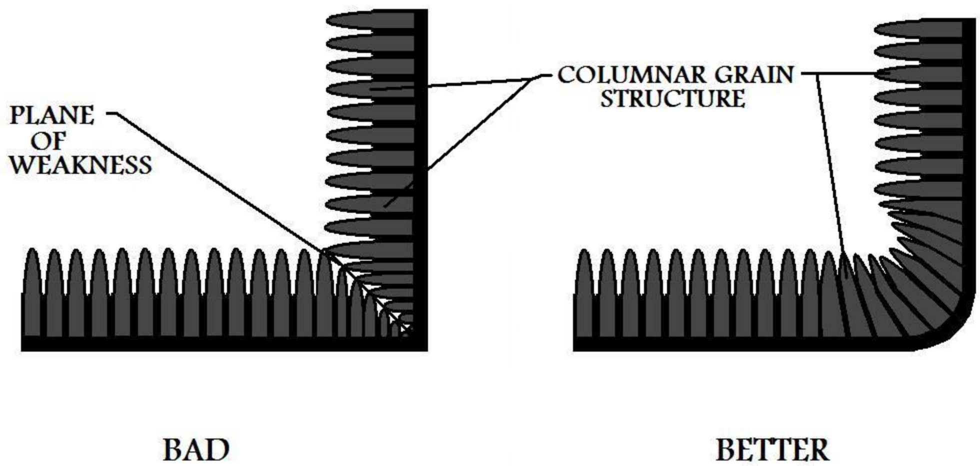
Figure:18



Prevent Planes of Weakness:

When castings solidify, columnar grain structures tend to develop, in the material, pointing towards the center. Due to this nature, sharp corners in the casting may develop a plane of weakness. By rounding the edges of sharp corners this can be prevented.

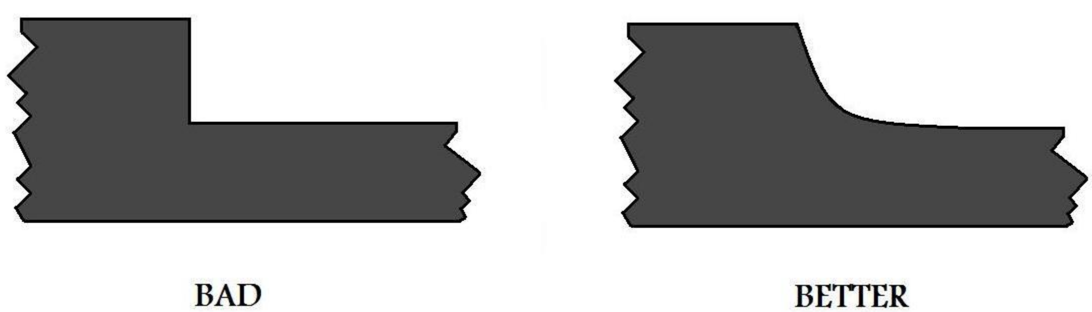
Figure:19



Reduce Turbulence:

When manufacturing a casting, turbulence is always a factor in our flow of molten metal. Turbulence, as covered earlier in the pouring section, is bad because it can trap gases in the casting material and cause mold erosion. Although not altogether preventable in the manufacturing process, turbulence can be reduced by the design of a gating system that promotes a more laminar flow of the liquid metal. Sharp corners and abrupt changes in sections within the casting can be a leading cause of turbulence. Their affect can be mitigated by the employment of radii.

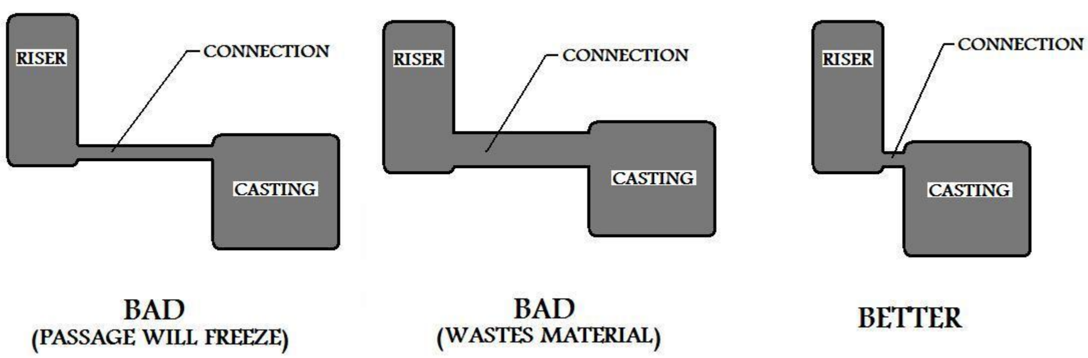
Figure:20



Connection Between Riser and Casting Must Stay Open:

Riser design is very important in metalcasting manufacture. If the passage linking the riser to the casting solidifies before the casting, the flow of molten metal to the casting will be blocked and the riser will cease to serve its function. If the connection has a larger cross sectional area it will decrease its time to freeze. Good manufacturing design, however, dictates that that we minimize this cross section as much as possible to reduce the waste of material in the casting process. By making the passageway short we can keep the metal in its liquid state longer since it will be receiving more heat transfer from both the riser and the casting.

Figure:21



Tapered Down Sprue:

Flow considerations for our casting manufacture begin as soon as the molten metal enters the mold. The liquid metal for the casting travels from the pouring basin through the down sprue, (Refer to Figure 7 in the Metal Casting Basics section). As it goes downward it will pick up speed, and thus it will have a tendency to separate from the walls of the mold. The down sprue must be tapered such that continuity of the fluid flow is maintained. Remember the fluid mechanics equation for continuity $A_1V_1 = A_2V_2$

Where V is the velocity of the liquid and A is the cross sectional area that it is traveling through. If you are casting for a hobby and/or just can not make these measurements, just remember it would be better to err on the side of making A_2 smaller, provided your pouring rate does not become too slow. In other words taper a little more and just adjust your pouring of the casting so that you keep a consistent flow of liquid metal.

Ingate Design:

Another aspect of manufacturing design which relates to the flow of metal through the casting's system. The ingate, (Figure 7) is basically where the casting material enters the actual mold cavity. It is a crucial element, and all other factors of the casting's mold design are dependent on it. In the location next to the sprue base the cross sectional area of the ingate is reduced (choke area). The cross sectional reduction must be carefully calculated. The flow rate of casting material into the mold can be controlled accurately in this way. The flow rate of the casting metal must be high enough to avoid any premature solidification. However, you want to be certain that the flow of molten material into the mold does not exceed the rate of delivery into the pouring basin and thus ensure that the casting's gating system stays full of metal throughout the manufacturing process.

Other Flow Considerations:

In the manufacturing design phase, when planning the metalcasting process, the analysis of the path of flow of liquid metal within the mold must be carefully calculated. At no point in the filling of the casting cavity should two separate streams of liquid metal meet. The result could be an incomplete fusion of the casting material (cold shut), as covered in the defects section under discontinuities.

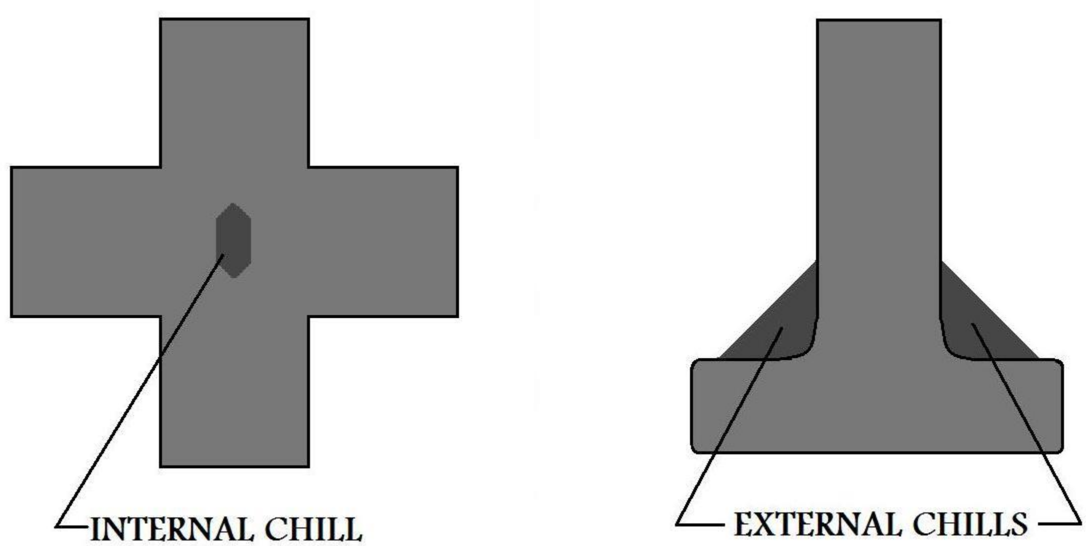
Use of Chills:

As mentioned earlier directional solidification is very important to the manufacture of a part during the metalcasting process, in order to ensure that no area of the casting is cut off from the flow of liquid material before it solidifies. To achieve directional solidification within the casting, it is important to control the flow of fluid material and the solidification rate of the *different areas of the casting*. With respect to the solidification of the metalcasting's different sections, **regulation of thermal gradients** is the key.

Sometimes we may have an area of the metalcasting that will need to solidify at a faster rate in order to ensure that directional solidification occurs properly. Manufacture planning, and design of flow and section locations within the mold may not be sufficient. To accelerate the solidification of a section like this in our casting, we may employ the use of chills. Chills act as heat sinks, increasing the cooling rate in the vicinity were they are placed.

Chills are solid geometric shapes of material, manufactured for this purpose. They are placed inside the mold cavity before pouring. Chills are of two basic types. Internal chills are located inside the mold cavity and are usually made of the same material of the casting. When the metal solidifies the internal chills are fused into the casting itself. External chills are located just outside of the casting. External chills are made of a material that can remove heat from the casting faster than the surrounding mold material. Possible materials for external chills include iron, copper, and graphite. Figure 22 demonstrates the use of the two types of chills to solve the hot spot problem in a + and T junction.

Figure:22



Directional solidification

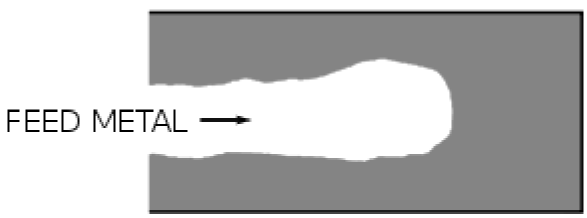
"Directional solidification" is a metal casting term. It refers to the process of controlled feeding of the molten metal into a temperature-controlled mold to produce a part that is free of hollow spots, called shrink defects. Directional solidification is also used to refine the metal during the casting process because the impurities found in the molten metal will continue to rise to the surface of the pool, following the path of least resistance as they are pushed up by the solid materials below.

In the directional solidification process, the molten metal at the far end of the mold begins to cool and solidify before the rest of the mold does. As the metal on the bottom of the mold cools, this line of solidification moves steadily upward toward the molten metal feed. By controlling the rate of flow for the molten metal feed and introducing thermal variations in the mold, shrink defects can be eliminated, because the liquid metal will naturally run into these dips and vacant areas.

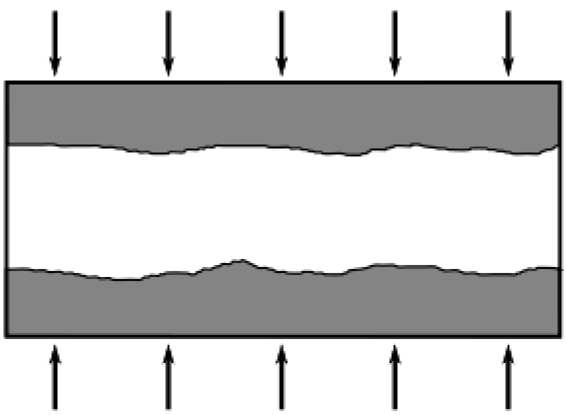
The process of directional solidification is not to be confused with progressive solidification, also called parallel solidification. Although these processes share some similar traits, in progressive solidification, the cooling and solidifying process begins at the walls of the casting and works its way inward. With directional solidification, the process of solidification begins at the bottom of the casting and works its way to the top.

Parallel solidification in a casting is the underlying cause of defects. As the molten metal cools too quickly in some areas or remains heated for too long in other areas, it creates defects as a result of solidification, thermal expansion and contraction. For example, if molten metal is poured into an L-shaped mold, the metal at the corner of the mold might cool too quickly, causing a bottleneck and trapping an air pocket in the lower leg of the mold. This air pocket creates a hollow spot in the finished metal part, thus weakening the overall structure.

To control parallel solidification and encourage directional solidification in the casting process, several techniques are employed. Thermal variations are introduced into the mold by using risers or chills to control hot or cold spots that might create problems with the cast part. Insulated sleeves also are used to ensure a steady, controlled temperature for the mold. Finally, the rate of flow and temperature of the molten metal feed are carefully controlled to ensure directional solidification.



Directional solidification



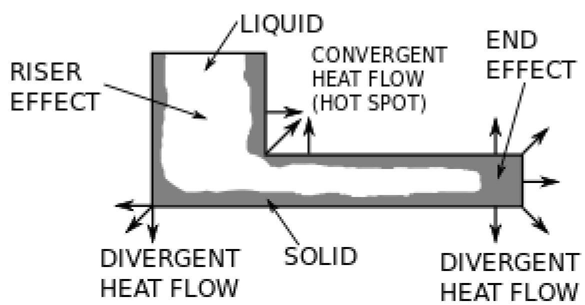
Progressive solidification

Directional solidification and **progressive solidification** describe types of solidification within castings. Directional solidification describes solidification that occurs from farthest end of the casting and works its way towards the sprue. Progressive solidification, also known as **parallel**

solidification,[1] is solidification that starts at the walls of the casting and progresses perpendicularly from that surface.[2]

Theory

Most metals and alloys shrink as the material changes from a liquid state to a solid state. Therefore, if liquid material is not available to compensate for this shrinkage a *shrinkage defect* forms.[3] When progressive solidification dominates over directional solidification a shrinkage defect will form.[2]



The geometrical shape of the mold cavity has direct effect on progressive and directional solidification. At the end of tunnel type geometries divergent heat flow occurs, which causes that area of the casting to cool faster than surrounding areas; this is called an *end effect*. Large cavities do not cool as quickly as surrounding areas because there is less heat flow; this is called a *riser effect*. Also note that corners can create divergent or convergent (also known as *hot spots*) heat flow areas.[4]

In order to induce directional solidification chills, risers, insulating sleeves, control of pouring rate, and pouring temperature can be utilized.[5]

Directional solidification can be used as a purification process. Since most impurities will be more soluble in the liquid than in the solid phase during solidification, impurities will be "pushed" by the solidification front, causing much of the finished casting to have a lower concentration of impurities than the feedstock material, while the last solidified metal will be enriched with impurities. This last part of the metal can be scrapped or recycled. The suitability of directional solidification in removing a specific impurity from a certain metal depends on the partition coefficient of the impurity in the metal in question, as described by the Scheil equation. Directional solidification is frequently employed as a purification step in the production of multicrystalline silicon for solar cells.[*citation needed*]

Gating and Risering

Gates and risers are part of the system to provide molten metal to the part you're casting. This page will provide a starting point for you, it is certainly not the definitive collection on the subject. There are whole books devoted to this subject. On my LINKS page there are some book titles for those who may want more information. That being said, it is possible to make good castings without following, or even knowing these rules. When I first started casting I just cut my gates and runners with an old kitchen spoon so that they looked right to me. If you remember to gate to the largest part of your casting and round all the corners in the system you will likely have good luck with your castings, particularly simple ones. If you have a casting that is giving you problems with shrinkage defects, misruns, etc. you may want to have a look at the information below to see if you can try any of it to help solve the problem. If your pattern is on a matchplate, once you find a gating system that works well you can build that onto the matchplate as well so it is molded at the same time as your mold cavity.

First some definitions will make it easier to understand this page.

Choke

A restriction in the gating system that limits the flow rate of the molten metal.

Cope

The top part of the mold.

Drag

The lower part of the mold.

Gate

A short passageway that connects the runner to the mold.

Match Plate

A type of pattern that is used for making a run of the same part, it is possible to make it so that it includes the gates, runners and sprue bases.

Pouring Basin

An enlarged portion at the top of the sprue.

Riser

A vertical passageway which provides a source of hot metal to prevent shrinkage in the casting.

Runner

The passageway the metal flows through to get to the gates from the sprue.

Runner Extension

A short extension of the runner which goes beyond the last gate

Sprue

A vertical passageway through which the molten metal gets to the runner.

The goals for the gating system are;

- To minimize turbulence to avoid trapping gases and breaking up the sand mold.
- To get enough metal into the mold cavity before the metal starts to solidify.
- To avoid shrinkage.

Sprue design

The design of the pouring basin and sprue can affect turbulence. For best results you want to design your pouring basin and sprue so that you can keep the sprue full of molten metal throughout your pour. A sprue tapered to a smaller size at its bottom will create a choke which will help keep the sprue full of molten metal. If you don't use a tapered sprue you can put a choke in when you are making the runners, you will want to have the choke as close to the bottom of the sprue as possible. The choke will also increase the speed of the molten metal, which is undesirable. To address this problem you can create an enlarged area at the bottom of the sprue, called a sprue base. This decreases the speed of the molten metal. There are two basic types of sprue bases, enlargement and well.

The general rules of thumb for enlargement bases are;

- Diameter is roughly 2.5 times the width of the runner.
- Depth is equal to the depth of the runner.

The general rules of thumb for well bases are;

- Depth of a well base is twice that of the runners.
- Cross sectional area of the base is 5 times the cross sectional area of the sprue exit (a 1/2 sq. in. sprue exit would mean you need a base with an area of 2.5 sq. in. which would be a 1.5 inch diameter).

The bottom of the sprue base should be flat, not rounded like a bowl. If it's it will cause turbulence in the metal.

Runner Design

One of the most important things to remember in your runners and gates is to avoid sharp corners. Any changes in direction or cross sectional area should make use of rounded corners. Also make sure the runners and gates are well rammed and smooth. This will help avoid sand erosion and turbulence.

To ensure that the metal is not flowing too fast in the runners the rule of thumb is that the cross sectional area of the runners should be greater than the area of the choke. The walls of the runners should be as smooth as possible to avoid causing turbulence. The runners should be filled with metal before the gates are, one way to ensure this happens is to put the runners in the drag and the gates in the cope. If you need to have a choke in the runner to restrict flow it should be at least 6" from the first gate.

The cross sectional area of the runners should decrease as the gates come off them to keep the the same gating ratio. A good gating ration for aluminum is 1:4:4. The 1 is for the cross sectional area of the choke. The first 4 is the **total** cross sectional area of the runners (measured after the choke but before the first gate) and the final 4 is **total** cross sectional area of the gates. For example, say you have a tapered sprue with an exit area of 0.5 sq. in., two runners with 2 gates off of each runner. The total runner area should be 2 sq. in so each runner would be 1 sq. in. The total gate area should be 2 sq. in., there are 4 gates so each gate would have an area of 0.5 sq. in. The gate calculation only works this way if there are an equal number of gates on each runner. If that is not the case divide the area of the runner by the number of gates on that runner to get the area of each gate.

The area of the runners should be reduced just after a gate by an amount equal to the area of that gate. This will insure that each gate in the system will have the same flow of metal, even if it's farther from the sprue. The first bit of metal poured is most likely to be contaminated by air and sand entrapment. To prevent this metal from going into the mold cavity you use a runner extension. That first bit of metal will flow to the end of this dead end and be trapped there, where it can't harm the piece you're trying to cast.The runner extension will have the same area as that of the last gate on that runner.

Risers

Risers are important to ensure a flow of molten metal to the part being cast as it's starting to solidify. Without a riser heavier parts of the casting will have shrinkage defects, either on the surface or internally.

As molten metal solidifies it shrinks. If it does not have a source of more molten metal to feed it as it shrinks you will get defects in your casting. A risers purpose is to provide that extra molten metal. Basically a riser is a vertical portion of the gating system, similar to a straight sprue, that stores the molten metal until it is needed by the casting. This means the metal in the riser must stay liquid longer than the metal in the part being cast.

A riser may be required for every hot spot in your cast part. In other words the part of the casting that solidifies last, usually an are with a larger volume of metal. The risers can either be attached to the top or the side of a part. They may also be blind risers. A blind riser is completely contained in the mold, not exposed to the air. Since it's not open to the air this type of riser cools slower and thus will stay liquid longer. It's important that no matter where it's located the gate that connects the riser to the casting is not too small and as short as possible or else the gate will solidify too soon and prevent the metal in the riser from reaching the casting, try and keep the length to 1/2 the diameter of the riser.

Risers may be upstream from the casting in the runner/gate system. In this case the metal must flow through the riser prior to reaching the casting and after the pour is completed the metal in the riser will be hotter than the metal in the casting. They may also be placed downstream, after the casting. This means the metal flows through the casting to get to the riser so the metal in the riser will be cooler than the metal in the casting. This could cause the metal in the casting to feed the riser as it cools, definitely not desired.

You want the metal in the riser to solidify last, after the part being cast. Since the more surface area something has the faster it cools you want to minimize the surface area of the riser for a given volume. Because of this the optimum shape for a riser would be a sphere, however that is not an easy shape to mold. The next best alternative is a cylinder, which is easy to make. Ideally the cylinders height should be some where between 1/2 and 1 1/2 times the diameter. If possible the bottom, and top if it's a blind riser, should be spherical, or bowl shaped. This will also help the metal stay molten longer.

Gating Design and Analysis

On the timeline of a cast product, mould filling is a mere dot. Yet, it has the greatest influence on casting quality, both internal and external. The flow of molten metal after being poured is a transient phenomenon which is accompanied by turbulence, splashing, separation of streams near change of sections, branching off and rejoining of streams, changes in melt properties such as density, viscosity and surface tension and the onset of solidification. In this chapter, we describe the objectives and types of gating systems, followed by a systematic procedure for their location, design, analysis, optimization and validation.

5.1 Mould Filling Phenomenon

Let us review two major characteristics of molten metal related to mould filling – fluidity and turbulence, and see how they are related to flow related defects.

Fluidity is not a physical property. It is a technological characteristic. It indicates the ability of liquid metal to flow through a given mould passage – even as it is solidifying – and fill the cavity to reproduce the design details. It is quantified in terms of the solidified length of a standard spiral casting.

The fluidity as defined by the foundry community is different that defined by physicists (as the reciprocal of viscosity). The casting fluidity is driven by metallostatic pressure and hindered by: viscosity and surface tension of molten metal, heat diffusivity of mould, back pressure of air in mould cavity and friction between the metal-mould pair.

Metallostatic head: The metallostatic pressure is given by $\rho g h$ where ρ is the metal density and h is the height of liquid metal column above the filling point. A higher metallostatic pressure gives higher velocity of molten metal, and thereby higher fluidity.

Viscosity: Viscosity depends on the metal family, composition and the instantaneous temperature. For most metals, the viscosity at the pouring temperature is close to that of water (1 centistoke); aluminum: 1.2 and iron: 0.9 centistokes. In comparison, the viscosity of typical mineral oils is about 600.

Surface tension: For a flat plate of thickness t, the relation between head, thickness and surface tension is given by: $\rho g h = \gamma / t$, where γ is the surface tension. At the pouring

temperature, the surface tension of aluminum and iron is 0.5 and 0.9 N/m respectively; similar to mercury at room temperature (0.46 N/m), but higher than water (0.07 N/m).
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Heat diffusivity: Moulds with high heat diffusivity transfer heat faster from the molten metal, causing it to freeze earlier and stop flowing. It is given by $\sqrt{(K_m \rho_m C_m)}$, where K_m is thermal conductivity, ρ_m is density and C_m is specific heat of the mould material.
Back Pressure: As molten metal advances in the mould, the back pressure of air that is being compressed in the cavity ahead effectively reduces the metallostatic pressure, and thus hinders filling. The back pressure depends on the cavity volume, mould permeability and the velocity of the advancing front. Venting helps.
Friction: The rough surface of sand mould hinders metal flow. Thus mould coating (usually water based, containing silica flour and graphite) reduces the friction between the metal and mould, contributing to higher fluidity.
In general, fluidity of pure metals is higher than alloys. Within alloys, eutectics have higher fluidity than non-eutectics. The fluidity of grey iron ranges between 0.5-1.0 m, and can be estimated by the empirical equation:

$$Fluidity = 14.9\ CE + 0.05\ T_p - 155\ inch$$

Where CE is the carbon equivalent given by $CE = \%C + 0.25\ \%Si + 0.5\ \%P$ and T_p is the pouring temperature in Fahrenheit.
Turbulence implies irregular, fluctuating flow with disturbances. It is observed when: (1) inertia forces (which make the fluid continue in the same direction), are much higher than the drag forces (which tend to stop the fluid motion), and (2) there are obstructions in the path of flow, such as a sharp corner or a change of section thickness.
The drag forces include those caused by viscosity and surface tension. The viscous forces mainly operate in the bulk of the liquid metal, whereas surface tension forces operate near the mould wall. Thus we have two types of turbulence: bulk and surface.
Bulk turbulence is quantified by Reynolds number R_e, which is the ratio of inertia to viscous pressure in a fluid. It is given by $\rho\ V\ d\ /\ \mu$ where ρ is the density, μ is the viscosity
and V is the velocity of the liquid; d is a characteristic dimension of the flow path. If R_e is more than 2000, then the flow is usually turbulent.
Surface turbulence is quantified by the Weber number W_e, which is the ratio of inertia to surface tension pressure in a fluid. It is given by $\rho\ V^2\ r\ /\ \gamma$ where r is the radius of curvature of the free liquid surface. For W_e is less than 1, surface turbulence is absent. When it is 100 or more, surface turbulence is prominent, leading to violent mixing of surface layers with the bulk of the molten metal.
The path of molten metal during casting process comprises mainly four parts:
1. Pouring of molten metal from ladle to the cup in the mould
2. Flow within the gating channels, from pouring basin to ingate
3
3. Jet of molten metal emerging from ingate and entering the mould cavity
4. Filling of mould cavity by liquid movements in the bulk as well as near the surface.
In general, the entire path of molten metal, within the gating system as well as the mould cavity, is turbulent in most castings. This can be readily ascertained by calculating the value of Reynolds number for a typical casting. A major purpose of the gating system

(instead of pouring metal directly into the mould cavity) is to reduce the turbulence, though it cannot be completely eliminated.

There are mainly three major classes of casting defects related to mould filling: incomplete filling, solid inclusions and gaseous entrapments (Fig.4.1).

Fig.4.1: Filling related defects. Top left - cold shut, right - misrun. Bottom left - blow hole, right - sand and slag inclusions.
[Source: Atlas of Casting Defects, Institute of British Foundrymen]

Incomplete filling: This is primarily caused by poor fluidity of molten metal, and manifests in the form of a *cold shut* or *misrun*. A cold shut occurs when two streams of molten metal coming from opposite directions meet, but do not fuse completely. A misrun occurs when the molten metal does not completely fill a section of the mould cavity (usually an end section far from the entry point). The presence of surface oxides and impurities on the advancing front of liquid metal aggravates such defects.

Solid inclusions: This is primarily caused by the turbulence in molten metal, and manifests in the form of *sand inclusion* or *slag inclusion*. Sand inclusions are mainly caused by bulk turbulence in gating channels or mould cavity, which dislodges sand

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particles from the mould wall. Slag inclusions can be caused by surface turbulence anywhere along the path of molten metal, leading to mixing of surface oxide layers with the rest of molten metal.

Gaseous entrapments: This class of casting defects includes air and gas entrapment, usually in form of *blow hole* and *gas porosity*, respectively. They occur when the air or gas inside the mould cavity cannot escape through the mould. The major source of gases includes dissolved gases in the molten metal, vaporization of mould sand moisture and combustion of binders in core or mould sand. The occurrence of these defects increases when the amount of air entrapped or gas generated is high, filling and solidification of molten metal are fast, the venting of the mould is poor.

5.2 Gating System and Types

A mould cavity must be filled with clean metal in a controlled manner to ensure smooth, uniform and complete filling, for the casting to be free of discontinuities, solid inclusions and voids. This can be achieved by a well-designed gating system. The first step involves selecting the type of gating system and the layout of gating channels: the orientation and position of sprue, runner and ingate(s). The most critical design decision is the ideal filling time, based on which the gating channels are designed.

The main objective of a gating system is to lead *clean molten metal* poured from ladle to the casting cavity, ensuring *smooth*, *uniform* and *complete* filling. Clean metal implies preventing the entry of slag and inclusions into the mould cavity, and minimizing surface turbulence. Smooth filling implies minimizing bulk turbulence. Uniform filling implies that all portions of the casting fill in a controlled manner, usually at the same time. Complete filling implies leading molten metal to thin and end sections with minimum resistance.

Fig.4.2: Major elements of a gating system

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The major elements of a gating system include pouring basin, sprue, well, runner and ingate, in the sequence of flow of molten metal from the ladle to the mould cavity

(Fig.4.2). The pouring basin or bush or cup is a circular or rectangular pocket that accepts the molten metal from the ladle. The sprue or downsprue, usually circular in crosssection, leads molten metal from the pouring basin to the sprue well. The sprue well or base changes the direction of molten metal by right-angle and sends it to the runner. The runner takes the metal from the sprue to close to the casting. Finally, the ingate leads the metal to the mould cavity. Another major element is filter or slag trap, usually placed in the runner or between the runner and ingate, meant for filtering out slag and other inclusions.

The sprue is always vertical. The well, runner and ingate are usually located in the parting plane. Depending on the orientation of the parting plane, the gating systems can be classified as horizontal and vertical gating systems. Thus in horizontal gating systems, the sprue is perpendicular to the parting plane, whereas in vertical gating systems, the sprue is parallel to the parting plane.

Gating systems can be classified depending on the orientation of the parting plane (which contains the sprue, runner and ingates), as horizontal or vertical. Depending on the position of the ingate(s), gating systems can be classified as top, parting and bottom.

Horizontal gating systems are suitable for flat castings filled under gravity. They are widely used in sand casting of ferrous metals, as well as gravity diecasting of non-ferrous metals.

Vertical gating systems are suitable for tall castings. They are employed in high-pressure sand mould, shell mould and diecasting processes, where the parting plane is vertical.

Fig.4.3: Layout of vertical gating system with top, side and bottom ingates

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Top gating systems, in which hot molten metal enters at the top of the casting, promote directional solidification from bottom to top of the casting. These are however, suitable only for flat castings to limit the damage to metal as well as the mould by free fall of the molten metal during initial filling.

Bottom gating systems have the opposite characteristics: the metal enters at the bottom of the casting and gradually fills up the mould with minimal disturbances. It is recommended for tall castings, where free fall of molten metal (from top or parting gates) has to be avoided.

Middle or side or parting gating systems combine the characteristics of top and bottom gating systems. If the gating channels are at the parting plane, they are also easier to produce and modify if necessary, during trial runs.

The most widely used system is the horizontal gating with ingates at the parting plane. In vertical gating systems, ingates may be positioned at top, bottom *and* side.

5.3 Gating Channel Layout

The most important decision here is the number and location of ingate(s). Let us consider horizontal gating systems with side ingates. Their location is governed by the following considerations (Fig.4.4).

Fig.4.4 Heuristics for ingate location

1. Side feeders: If side feeders are employed, then their efficiency can be improved by filling with the first stream of hot molten metal through ingates. It also reduces the fettling effort and the resulting marks on the casting, since the ingates do not have to be removed separately.

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2. Thick sections: The next best position after a side feeder is a thick section, which will allow molten metal to flow to other sections with minimal cooling. It will also reduce occasional breakage during fettling of ingates.
3. Clear path: In sand casting, the molten metal should be allowed to flow with minimal obstructions and change of direction (particularly at sharp corners) to avoid turbulencerelated problems. Ingates should never be placed directly opposite a core.
4. Low free fall: The ingate should be located where the free fall of molten metal inside the mould cavity is low. This minimizes oxidation during fall and erosion at the point of impact of molten metal.
The number of ingates must be sufficient enough, so that the distance of flow from any ingate to the farthest point filled by that ingate is less than the fluidity distance.
The sprue conducts the molten metal from the pouring basin at its top to the plane in which the runners and ingates are located. Its location is governed by the following considerations:
1. Flow distance: The sprue location must minimize the total flow distance within the gating channels, to reduce heat loss as well as maximize yield.
2. Heat concentration: Since the hottest metal flows through the sprue, it must be away from hot spots (essentially thick sections) in the casting.
3. Mould layout: The sprue must be located to minimize the size of the bounding box enclosing the entire casting (including the gating channels), so that a smaller mould is required. This also applies to multi cavity layout, where the sprue and runner(s) are shared by multiple cavities.
The runner layout is simply given by the shortest path to connect the ingates with sprue.

5.4 Optimal Filling Time

A casting that fills too slow can have discontinuities such as cold shuts and misruns. Too fast filling can lead to solid and gaseous inclusions.
The higher limit of filling time (slowest filling) is governed by the need to avoid premature freezing in thin sections before complete filling. The lower limit of the filling time (fastest filling) is governed by the onset of surface turbulence. The correct filling time lies somewhere in between, and is a function of cast metal, weight, minimum section thickness and pouring temperature.
Several empirical equations for determining the correct filling time for major metals have been developed by casting researchers, based on experimental investigations. The filling

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time τ_f is expressed as a function of casting weight W in kg, section thickness t in mm and fluidity length L_f in mm. A generalized equation for filling time can be written as:

$$\tau_f = K_0 \left(K_f L_f / 1000\right) \left(K_s + K_t\, t / 20\right) \left(K_w W\right)^P$$

There are five coefficients: K_0 is an overall coefficient, and K_f, K_s, K_t, K_w are the coefficients for fluidity, size, thickness and weight, respectively. For grey iron the following values may be used: $K_0 = 1.0$, $K_f = 1.0$, $K_s = 1.1$ (for castings of size 100-1000 mm), $K_t = 1.4$ (for wall thickness up to 10 mm), $K_w = 1$ and $P = 0.4$. Based on individual experience, an expert casting engineer can set the values of the coefficients for each metal-process combination. These form a valuable part of the knowledge base of a foundry specializing in specific castings.

Metal velocity: The optimal filling time is determined such that gating channels can be designed to avoid surface turbulence and minimize bulk turbulence within the gating channels as well as the mould cavity. This mainly depends on the velocity of the molten metal, which varies widely within the gating channels as well as inside the mould cavity. For a given location in the casting, the velocity also changes with time, from the start to end of filling. The most important event is that of molten metal emerging from the ingate, just after the filling of gating channels and before the filling of mould cavity. The metal is both hot and fast at this location and instant, and can lead to considerable damage if not controlled properly. The velocity of molten metal at the ingate depends on mainly two parameters: (1) the metallostatic head and (2) the ratio of cross-sections of sprue exit, runner(s) and ingates(s), referred to as the gating ratio. In general, the velocity of molten metal must be kept lower than 1 m/s for ferrous metals and 0.5 m/s for aluminum alloys.

Gating Ratio: It is given by $A_s : A_r : A_g$ where A_s, A_r, A_g are the cross-sectional areas of sprue exit, runner(s) and ingate(s). If multiple runners and ingates are present, the total area (of all runners, or all ingates, respectively) must be considered. A convergingdiverging system, where the ingate area is more than the sprue exit area, is to be preferred. This ensures that the metal slows down (thereby reducing turbulence-related problems). Examples of such gating ratios include: 1:2:1.5 for ferrous and 1:4:4 for nonferrous metals. Higher values of ingate area may be used (such as 1:4:8) to further reduce the velocity of molten metal through the ingates to within the recommended range, as long as flow separation (and thereby air aspiration) is avoided.

5.5 Gating Element Design

The gating system can be designed to fill a given casting in a predetermined time, by keeping a constant level of liquid metal in the pouring basin during pouring, to achieve a controlled rate of flow through the *choke*. The choke is the smallest cross-section in the gating system that controls the flow rate of molten metal. The element (sprue exit, runners or ingates) with the smallest value in the gating ratio is considered the choke. The choke area A_c is given by:

$$A_c = W / (\rho_c \tau_f V_c)$$

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Where, W is the total casting weight (including feeders and gating channels), ρ_c is the metal density, τ_f is the total filling time and V_c is the choke velocity.

The choke velocity is given by: $V_c = V_p + c_f \sqrt{(2 g H)}$

where H is the metallostatic pressure head, given by the vertical distance between the liquid level in pouring cup and the centerline of the choke. The value of pouring velocity V_p is non-zero, if poured from a height or if bottom pouring ladles are used. The friction factor c_f within the gating system depends on its geometry and surface finish, and ranges between 0.6-0.9.

Note that the weight of the gating system is unknown at the time of calculating the mould filling time and choke area. This can be overcome by determining the total casting weight *after* gating design and repeating the calculations.

During actual filling, the metallostatic pressure head gradually decreases after the molten metal starts rising above the level of choke. Thus the average value of actual choke velocity is less than the one used above, leading to slower filling. This can be compensated by estimating the actual filling time (as described in a later section), and then correcting the choke area.

Fig. 4. 5: Flow chart of gating element design

The cross-sectional area of sprue exit, runners and ingates, is initially determined based on the choke area, gating ratio and the number of individual elements. Then the sectional area of individual elements, as well as their shape and dimensions are determined as follows.

Sprue: It usually has a circular cross-section, which minimizes turbulence and heat loss. The cross-sectional area at the sprue exit or bottom is calculated from the choke area and

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gating ratio. The area of the sprue top should be calculated using mass and energy balance equations, to prevent flow separation in the sprue. Essentially,

$$A_1 \sqrt{H_1} = A_2 \sqrt{H_2}$$

Where, H_1 and H_2 are the metallostatic pressure head at the top and bottom of the sprue, respectively; A_1 and A_2 being the respective cross-sectional areas. The ideal sprue must be larger at the top and smaller at the bottom. Since this leads to an undercut, such a sprue can not be created by the pattern during moulding operations, and must be formed by a core. If this is not economical, then the choke can be created in the beginning of runner.

Sprue well: It arrests the free fall of molten metal through the sprue and turns it by a right angle towards the runner. It must be designed to minimize turbulence and air aspiration. The recommended shape of a sprue well is cylindrical, with diameter twice that of sprue exit and depth twice that of runner. A fillet between the well and runner will facilitate smooth transfer of molten metal.

Runner: The main function of the runner is to slow down the molten metal, which speeds up during its free fall through the sprue, and take it to all the ingates. This implies that the total cross-sectional area of runner(s) must be greater than the sprue exit. In general, a ratio of 1:2 is recommended. A much higher ratio (such as 1:4) may lead to flow separation in the runner. The second implication is that the runner must fill completely before letting the molten metal enter the ingates. Finally, in casting where more than one ingate is present, the runner cross-section area must be reduced after each ingate connection (by an amount equal to the area of that ingate), to ensure uniform flow.

Ingate: The ingate leads the molten metal from the gating system to the mould cavity. A number of conflicting requirements apply to the design of ingates, as listed below.

1. Ingate section must be designed to reduce the metal velocity below the critical limit. This implies that in general, the ingate area must be more than the sprue exit (choke).
2. Ingate must be easy to fettle. This implies a smaller cross-section, preferably a flat section (against a square one), is preferred.
3. Ingate must not lead to a local hot spot. This implies that the ingate modulus (ratio of volume to cooling surface area) must be smaller than that of the connected section.
4. Flow of molten metal through an ingate (and therefore its cross-sectional area) must be proportional to the volume of the connected casting region.

The number, shape (aspect ratio) and dimensions of ingates must be carefully designed to optimize the above requirements.

5.6 Mould Filling Analysis

The flow of molten metal during casting process is a transient event, accompanied by

splashing, flow through contracting or expanding sections and bends, stream separation
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and rejoining, flow against the forces of viscosity, surface tension, friction and gravity, air aspiration and entrapment, mould erosion, metal oxidation and the onset of solidification. We will focus on two major issues: instantaneous metal velocity and total filling time. To facilitate mathematical analysis of mould filling, it is divided into three phases – gating channel filling, melt stream impinging on the mould wall, and mould cavity filling. As we will see, determination of molten metal velocity (including its direction) becomes gradually difficult as we move from the first phase to the last.

Fig. 4.6: Gating parameters for filling analysis

Assuming that the gating channels have been designed correctly to avoid flow separation and surface turbulence, the velocities in different sections of the gating channels are given by the following equations. The subscripts 1 and 2 refer to entry and exit crosssections, respectively, of any gating element.

$$V_{basin2} = V_{sprue1} = c_f \sqrt{(2 g (h_{pour} + h_{basin}))}$$

$$V_{sprue2} = c_f \sqrt{(2 g (h_{pour} + h_{basin} + h_{sprue}))}$$

$$V_{ingate} = V_{sprue2} A_{sprue2} / A_{ingate}$$

$$= c_f \sqrt{(2 g (h_{pour} + h_{cope}))} G_{sprue} / G_{ingate}$$

Where, G_{sprue} and G_{ingate} are the sprue and ingate terms of the gating ratio.
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The above equation for ingate velocity is valid only in the case of top gating. If the ingates are located at the bottom or side of the casting, then the ingate velocity gradually starts decreasing after the metal starts rising above the level of ingates. The instantaneous velocity of molten metal through the ingates in such a case is given by:

$$V_{ingate} = c_f \sqrt{(2 g (h_{pour} + h_{cope} - h_i))} G_{sprue} / G_{ingate}$$

Where, h_i is the instantaneous vertical distance of molten metal level above the plane of ingates. The filling time of the entire gating system can be calculated based on the velocity of molten metal in each element (basin, sprue, runners, ingates, etc.).
The first stream of molten metal emerging from the ingate(s) is both hot and fast, and can erode the mould wall at the point of impingement, leading to sand inclusions. The occurrence and severity of mould erosion is governed by the velocity of molten metal at the point of impingement: its speed as well as direction. The instantaneous velocity V_i of molten metal at an instant $\Delta\tau$ after emerging from the ingate is given by:

$$V_i = V_{ingate} + g \Delta\tau = c_f \sqrt{(2 g (h_{pour} + h_{cope} - h_i))} G_{sprue} / G_{ingate} + g \Delta\tau$$

The initial direction of the molten metal stream is assumed to be along the axis of the ingate. The vertical and horizontal distance traveled by the stream can be computed by taking small increments of time, finally giving the location and direction of impingement when the stream touches the mould wall. At the point of impingement, mould damage (erosion) may be caused if:
1. The velocity of impingement is more than the critical velocity for the mould material.
2. The angle between the direction n_{im} of molten metal and normal n_f to that face is less than a critical value.

A simplified approach to determining the total filling time is based on the assumption that the casting fills layer-by-layer. The time $\Delta\tau$ to fill a layer is given by

$\Delta \tau = A_i \Delta h / \Sigma_j V_{ingate-j} A_{ingate-j}$

where, A_i is the cross-sectional area of the casting layer being filled, Δh is the layer thickness; and $A_{ingate-j}$ and $V_{ingate-j}$ are the cross-sectional area and the instantaneous velocity respectively, of ingate j.

The total time to fill the mould cavity can be determined by integrating the incremental time of filling for all layers from the bottom to the top of the mould cavity:

$\tau_f = \int_{0-h} (A_i / \Sigma_j V_{ingate-j} A_{ingate-j}) \, dh$

The above approach cannot predict other phenomenon in mould filling (such as splashing, branching and rejoining of streams), which require determination of the

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velocity components along the three axes. This requires numerical simulation of mould filling.

5.7 Numerical Simulation

Numerical simulation of mould filling is based on three fundamental equations for mass, momentum and energy balance. These equations, expressed in a differential form are referred to as Navier-Stokes equations, given below. The first one is for continuity, the next three for momentum along x, y and z directions, respectively, and the last for energy.

The equations are solved using finite difference methods such as Marker and Cell (MAC), simplified MAC (SMAC) and Solution Algorithm-Volume of Fluid (SOLAVOF). All the methods divide the mould model into a number of rectangular cells, which are classified as *empty*, *full* or *surface* cells. The methods differ in the way they keep track of the location of free surface.

In MAC and SMAC a set of imaginary markers is introduced into the system to represent the location of fluid at any instant. A cell is empty if it contains no markers; full when it contains at least one marker and all the cells surrounding it also contain at least one marker; and surface when it contains at least one marker and at least one cell surrounding it contains no marker. The SOLA-VOF method uses fluid function values F to classify the cells. A cell is considered empty when $F=0$, full (or interior) when $F=1$, and surface when F has an intermediate value.

For an interior cell, the following principles are applied:

1. Continuity: mass of metal flowing into the cell equals mass flowing out of the cell.
2. Momentum: change of momentum equals momentum-in minus momentum-out.

For a surface cell, the following principles are applied:

3. Tangential stress on the free surface is zero

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4. Normal stress is equal to the sum of applied pressure and surface tension.

The equations are solved for pressure and velocity, and repeated for the time steps considered. Finally, the results are processed and displayed graphically, to visualize the flow front (sequence of filling) through the casting. This aids prediction of filling-related defects such as cold shuts and blow holes.

$\tau = 3.00$ s

$\tau = 5.25$ s

$\tau = 6.75$ s

$\tau = 7.14$ s

Fig. 4.7: Mould filling simulation of a grey iron textile machine casting by SOLA-VOF method

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5.8 Optimization and Validation

Several iterations of gating system design and mould filling analysis may be carried out until filling related problems are eliminated. In general, several different gating designs (essentially, the number, location and dimensions of gating channels) may lead to defectfree castings. We will therefore, develop a set of criteria to assess a given gating design, which can be used in an optimization exercise. Finally we describe different experimental techniques to observe mould filling for validating the gating design.

A given design of gating system can be assessed using the following criteria. All criteria have been normalized and are sought to be maximized.

Mould filling time: The actual filling time as determined by computer simulation or actual experiment must be close to the optimal filling time for which the gating system was designed. This criterion is expressed as follows:

$$C_{G1} = 1 - (| \tau_{f\text{-}actual} - \tau_{f\text{-}optimal} |) / \tau_{f\text{-}optimal}$$

Note that if a casting is found to have filling-related defects at the optimal filling time, but is defect-free at some other filling time, then the empirical equation for optimal filling time may be corrected for the particular combination of geometry, metal and process.

Ingate velocity: The velocity of molten metal emerging from the ingate must be as low as possible to minimize turbulence.

$$C_{G2} = 1 - (V_{ingate} / V_{critical})$$

Where, $V_{critical}$ is the recommended limit of velocity depending on the metal: about 1 m/s for iron, and 0.5 m/s for aluminum.

Impingement: The velocity and direction of the first stream of molten metal emerging from an ingate and striking a mould face affect mould erosion at that location. A fast stream striking in a direction perpendicular to the face of impingement should be avoided. This is expressed as follows:

$$C_{G3} = V_{imp\text{-}limit} / (V_{imp} (\mathbf{n}_{imp} . \mathbf{n}_f))$$

Where, $V_{imp\text{-}limit}$ is the limiting value of impingement velocity for the onset of mould erosion, V_{imp} is the velocity of impingement; $\mathbf{n}_{imp}$ and $\mathbf{n}_f$ are the unit vectors along the direction of impingement and normal to the casting face of impingement, respectively.

Gating yield: The volume of the gating system must be minimized to increase the yield. The criterion is given by:

$$C_{G4} = N_c\, v_c / (N_c\, v_c + v_g)$$

Where, N_c is number of casting cavities per mould, v_c is the volume of each cavity, and v_g is the volume of the common gating system for all the cavities in the mould.

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Fettling: The size of an ingate must be small compared to the connected portion of the casting to avoid casting breakage or cracks during fettling. When several ingates are present, one that is most likely to cause damage determines the criteria assessment value.

$$C_{G5} = min_i (1 - (t_{gi} / t_{ci})$$

Where, t_{gi} is the thickness of ingate i and t_{ci} is the thickness of the connected potion of casting.

The gating design can be validated by various techniques. Visualization of mould filling

– even if indirect (since the moulds are opaque) – provides a useful pointer to fillingrelated defects and their causes. Other techniques are briefly described here.

Shop floor trials: Sample castings are produced using the materials and processes that will be finally used for production castings. Then their surface, sub-surface and internal quality may be observed by visual, destructive and non-destructive testing. Destructive testing includes machining and cutting the sections through critical regions.

High-speed radiography: This involves recording the mould-filling phenomenon using a high-speed x-ray camera. This is most useful for observing all major phenomenon in mould filling, including initial filling of the gating system, the sequence of filling through different ingates, branching and rejoining of streams, etc. It is however, limited to low density metals and small castings (in terms of thickness along the direction of rays).

Partial filling: Several moulds are prepared; and say only 10% of metal is poured in the first mould, 20% in the second mould, and so on. The sequence of partially filled and solidified castings facilitates visualizing the mould filling. This is suitable for thin castings in which the mould filling time is comparable to the casting solidification time.

Open mould: This is suitable for castings that are primarily in the drag. A portion of cope directly above the casting cavity is cut away, leaving the gating system. A standard video camera is used to record the molten metal stream emerging from the ingate and the gradual filling of the mould. The video can later be played back in slow motion. The absence of back pressure of air in the mould may lead to some errors.

Contact wire sensing: Contact wires can be placed in different parts of the mould. The completion of circuit when the metal reaches a particular wire is recorded by a multichannel recorder. Based on the sequence of observations, the time taken for the metal to reach different parts of the mould can be assessed. This is however, useful only to record the initial flow of metal to different parts of the mould.

Water in transparent mould: Since the viscosity of water is close to that of most molten metals, the flow of water in a transparent mould (constructed by Perspex or other transparent polymers) provides a very useful indicator. A color marker (if turbulence is low), oil droplets or particles are introduced for better visualization and determination of velocity in different sections. This is however, not suitable for studying flow in thin castings in which the flow of molten metal is affected by the onset of solidification.