Design and Optimization of gating and feeding system through simulation technique of Steel Impeller to avoid existing casting defects

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MASTERS THESIS WORK

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Acknowledgements

I am very much thankful to Allah for guiding me throughout this whole project and at every step and for every new thought which You put in my mind to improve my work. And it is for sure that I would not have achieved this mile stone without Your help.

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Danish khan

Dedicated to my mother who led me to this wonderful accomplishment.

Abstract

Casting is a manufacturing process to make complex shapes of metal materials; during mass production, we may experience many defects, such as gas porosity, pin holes, blow holes, shrinkages and incomplete filling that may occur in sand casting. Porosity is one of the defects most frequently encountered in Steel casting. Porosity impacts cost by scrap loss and limits the use of cast parts in critical high strength applications. The amount of porosity is closely related to the parameter of sand casting process. The gating/riser system design plays a very important role for improving casting quality. The main objectives were to study the existing design of gating and feeding system using ESI Pro-CAST casting simulation software, to prepare the sand mold and cast the part, to compare the simulated result and experimental results, and to reduce rejection rate and to enable the company to again start the mass production.

Using L9 array method certain experimental parameters were define and casting has been done. Each experiment was repeated thrice to get the parameters accurate. After getting all these results we have finalized the ideal parameters to get impeller without any Shrinkage porosity, Misrun and minute blowhole. The results that were received by simulation software precisely matches with the results at hand.

Most problematic issue was the rejection of casted part and the reduction of foundry production. The problem was highlighted because neither a single part would comply for the machining without any rework that includes welding, grinding etc. The rejection percentage of this part was around 60%. Effort has been made and we have successfully identified the basic and precise amount of attribute that were considered during the experimentation process.

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

My research is based on the two parts. First I have used Taguchi method to create an L9 array of four contributing variables and then done the casting trials on each of the experiments. The samples with best and worst results were further evaluated by doing confirmatory tests. In the second part of my thesis I have also confirmed those results using ESI ProCAST and showed results indicating hotspots and temperature distribution which perfectly back my earlier results.

1.1 Background

Casting is one of the oldest method of manufacturing process, it dates back to 3000B.C. After that this industry has been evolved and become the back bone of many world economies today. China is leading the charts of casting production worldwide by 47.2%. While India (11.35%) and US (10.39%) are on 2nd and 3rd position according to the latest figures.

Casting processes involves pouring molten metal into the mold cavity, as a result the metal after solidification takes the shape of mold cavity. Within a foundry the functions i.e. mixing of sand and binder, preparation of mold cavity, melting of metal in a furnace, casting, Rework on casting for cleaning, and if required surface treatment and thermal treatment has also been done. All these foundry function plays an important role in foundry finish product. Any deviation in these functions will significantly alter the results depending upon the alterations made in process. That is why foundry is called an ART.

Quality system is very integral for an organization to flourish and achieve his goals in shortest possible time. Also it can improve organizational efficiency. By implying similar concept in foundry we can only evolve by reducing our current casting defects.

Casting defects has a very negative impact on the base of foundry. It increases the rework on a particular casted part and in worse condition can increase the scrap cost. Rework includes welding in case of cold shuts and misrun defects. Some of the casting defects also get surfaced during machining process e.g. blow holes or shrinkage cavities. Internal cracks can only be known by doing the Ultrasonic testing of the casted part. These abnormalities also known as deviations and it generates additional cost and sometimes results in customer notifications / complaints. These issues are normally overcome by doing hit and trial method by a foundry personnel. As he does not have time to run a casting defect analysis, to find the root cause and to finally enforce amended or corrective techniques or methods in order to avoid these issues in future.

Foundries produce casted part in two major categories i.e. ferrous and non-ferrous.

Ferrous parts: Ferrous parts are those castings that are consists of iron and steel.

Non-ferrous parts: These castings are produced by utilizing Aluminum, Zinc, Copper, Lead, Tin, Magnesium and titanium.

1.1.1 Melting of Solid metal

Pure liquid metal may exist in some liquid metals. Some of these pure liquids may include pure gold, carbon manganese steel, but these however are rare during melting a molten metal.

Most of the liquid metal consists of several type of other solid phases that are floating and they look like slurries on top. This type of slurry liquid metal can be seen more often while pouring from furnace. This slurry type metal can create defects and are normally neglected during the process of defects investigation in castings. This slurry type solidified liquid layer is mostly remove during melting.

The liquid metal is highly reactive and can react with both gases above and also with flux that will be floating above the liquid surface. Also molten metal react with the furnace linings and can cause major accidents in foundry premises.

1.1.2 Entrainment and its defects

1.1.2.1 Bifilms

When an Aluminum or Steel in liquid form enters a mold cavity with a specific velocity that is greater than the critical value, it will cause the outer surface (skin) of the liquid metal to fold itself with entrapped air and submerge itself in a bulk liquid. This phenomenon is called bifilm defect. In case if the entrained surface is a solid layer (Film) then crack will appear as a defect in this case as shown in Fig. That crack will be of few nanometers in thickness and will not visible easily to most of our usual inspection techniques and methods.

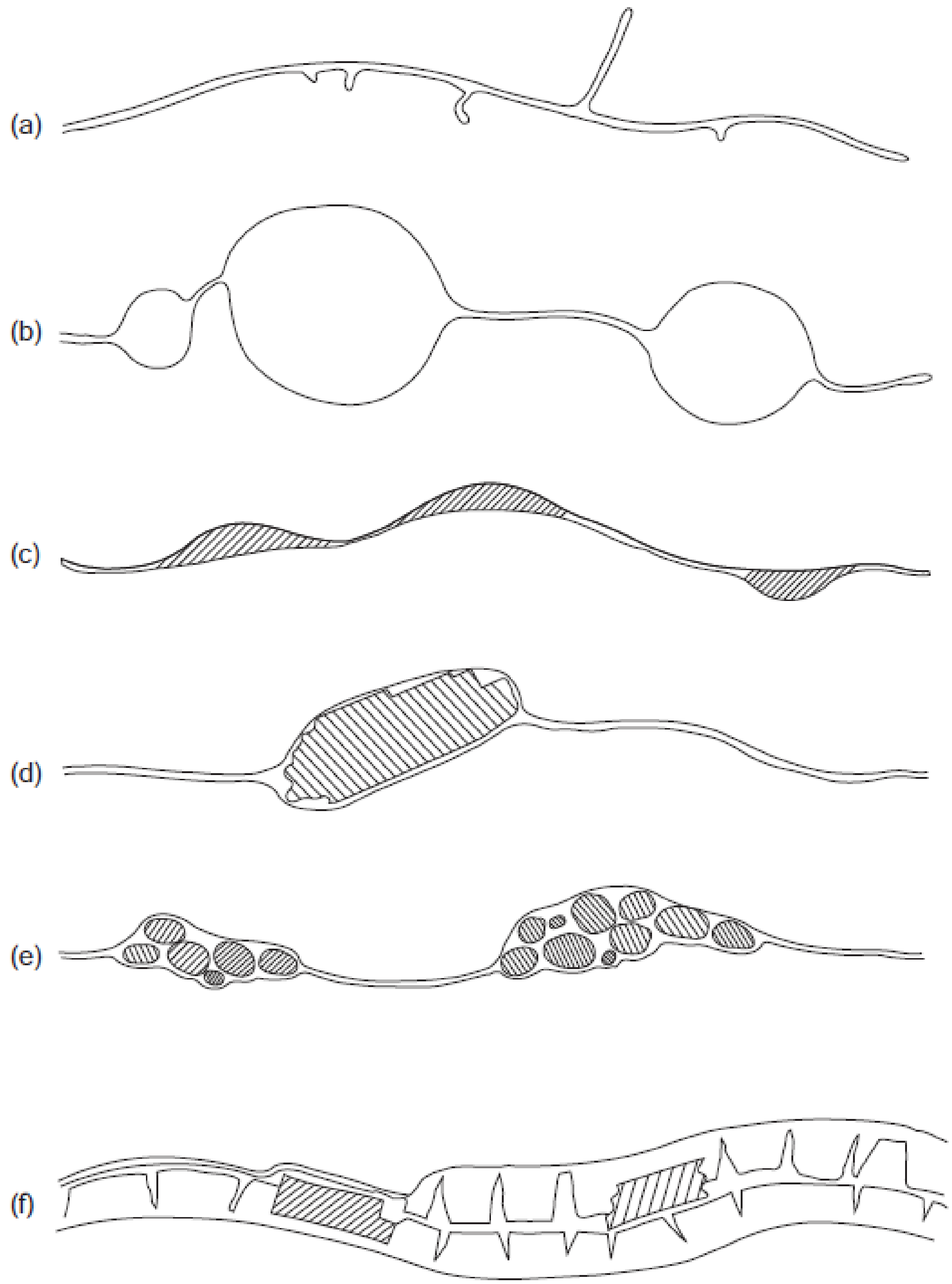


Figure 1. 1 Cracks in a solid layer (film) [4]

In Figure-b the entaintment of suface oxides can be seen. It occurs after entraintment of air bubbles due to which the the two films are not together. In Figure-2c it occurs doe to suface liquid flux entraintment. Figure-2d represents accomulation of solid debries. Figure-2e The mold sand has been fallen and has been entrapped between the layers. Figure-2f shows old oxides that has been fallen from time to time on the surface.

Entrainment of solids into liquid metals: (a) the introduction of melt charge materials; (b)

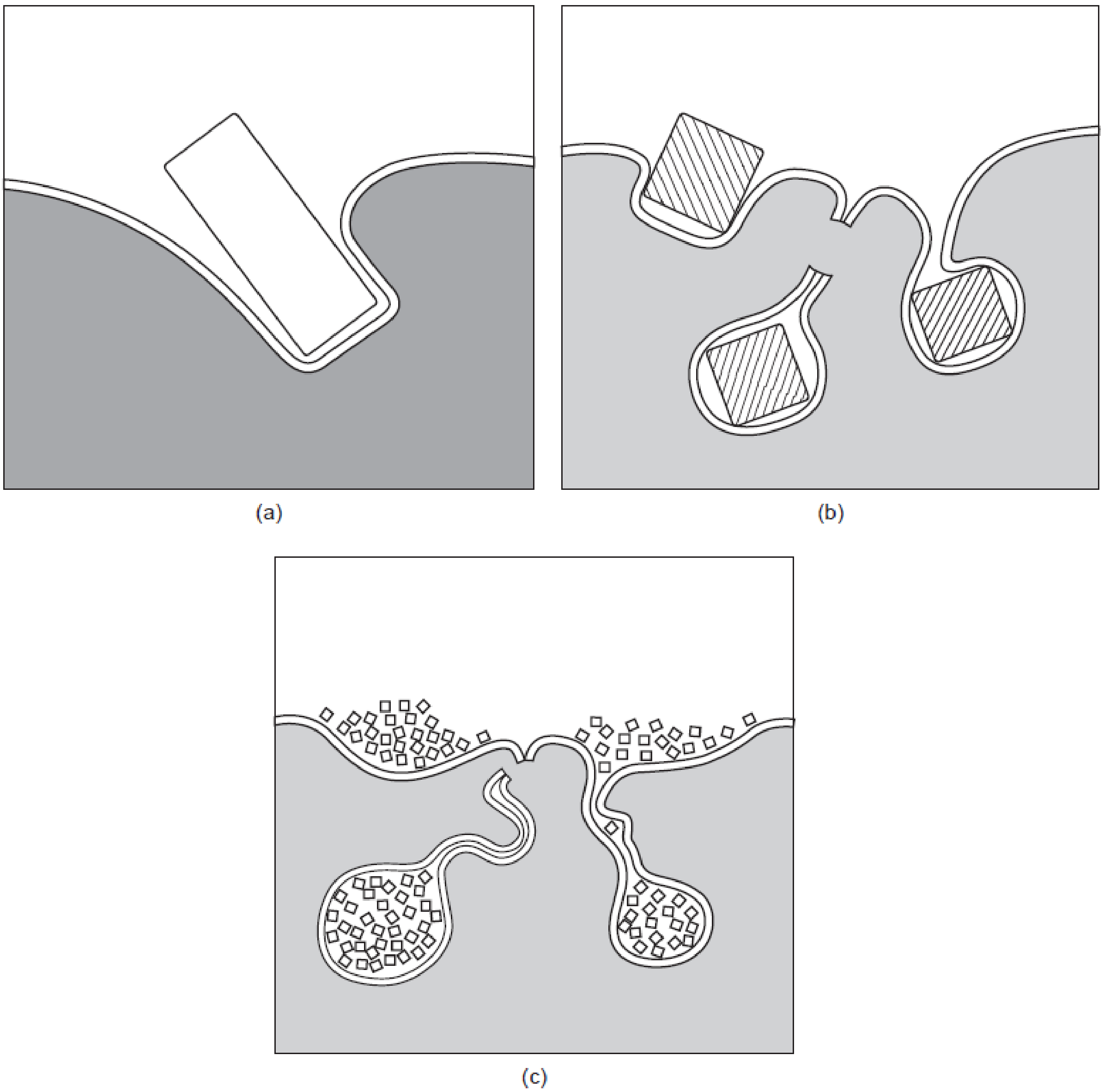


Figure 1. 2 (a) the introduction of melt charge materials; (b) optimum production of MMCs; (c) usual production of MMCs [4]

optimum production of MMCs; (c) usual production of MMCs.

1.1.2.2 Bubbles:

Small bubbles are normally formed due to the entrainment of air particles as shown in Figure-2b and these type of entrainment result in micro porosity in a particular casting. Large bubbles are also formed whenever a severe turbulence occurs during pouring in a liquid metal. The formation of large bubbles has been shown in Figure 4. The size of the bubble ranges up to 5mm in diameter. Due to the buoyancy effect these large bubbles are very rear to get entrapped in the casting as they get surfaced on the top layer and gets escapes mostly. But the bubbles that are arriving later will get trapped and causes the bubble defect. These bubble damages constitutes 80% of the casting defects and it cannot be even detected by today's computer simulation software's.

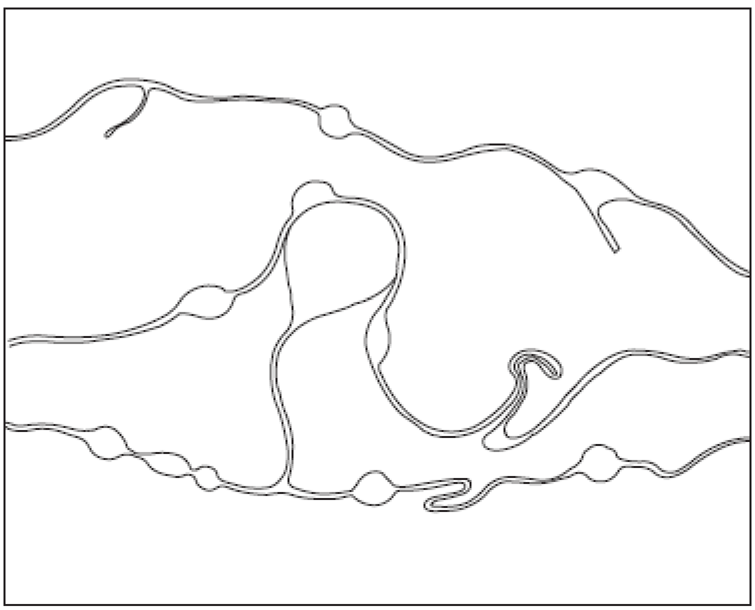


Figure 1. 3 Schematic illustration of bifilm with trapped micro bubbles [4]

1.1.2.3 External inclusions

External inclusion includes flux and sand inclusions etc. Fluxes are commonly found on the machined surfaces of light alloy surfaces of casted parts and is consists of the chlorides and fluorides. When these are exposed to the environment it absorbs water particles in air and results in formation of corrosion pockets. NaCl and KCl are the most commonly formed on the surfaces. In case of steel whenever a layer of liquid slag is present it is seen that it will be consisting of liquid throughout. In figure, the entrainment of gases and liquid can be seen along with the detrainment of the slag formation.

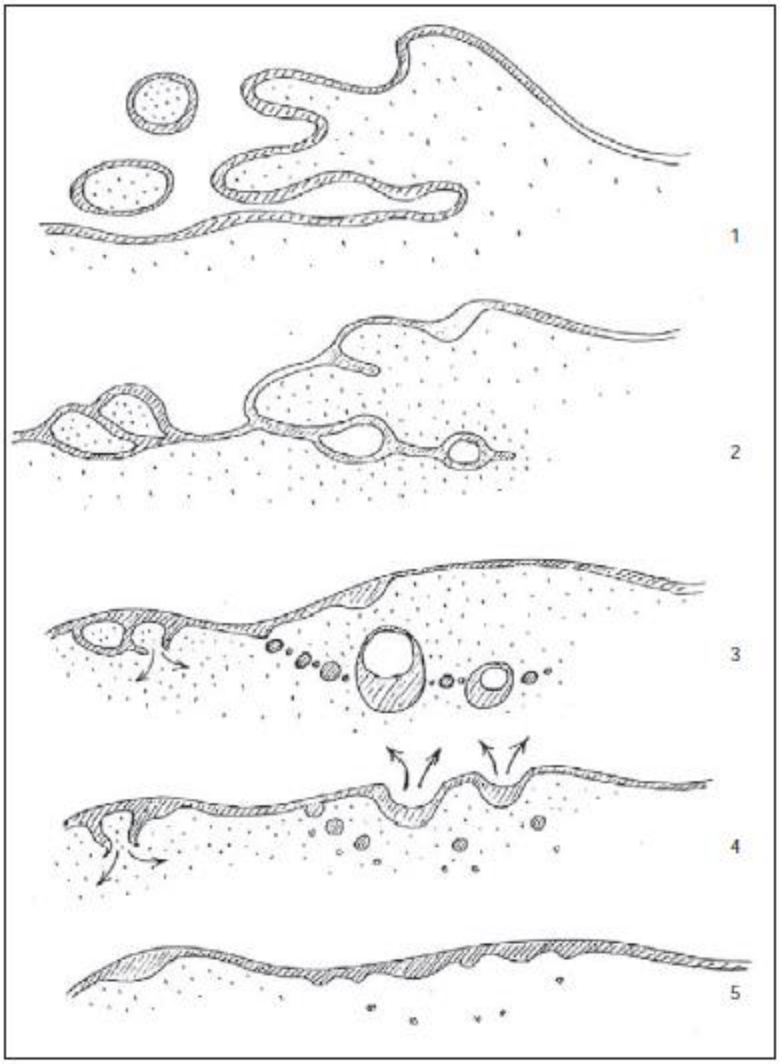


Figure 1. 4 The entrainment of gases and liquid [14]

The mold sand inclusion in molten metal is the common type of extrinsic inclusions and its mechanism of entrapment is rather very complicated. In case if the design of the molding system is good enough then the molten metal poured in the mold will entirely fill the cavity. The hydrostatic pressure will apply pressure on the walls in order to give support the mold and holding particles of sand intact. On contact with molten metal the mold surfaces temperature will increase. In case if the sand is bonded with the help of resin then at first the binder will get soft and then hardens and get strengthen after the volatiles evaporates. As the whole process takes place the binding agents gets enough degraded and left with only carbon particles. The mold gets hard at that point and be like coke which will result in greater mechanical links between sand particles.

In case of poor molding system, the liquid metal flow in not laminar and the molten metal bounces from the walls of mold. It causes the air flow gets reversed inside the mold and so burns away the binder. And when all the carbon gets burned from the surface of sand grains then the sand particles no longer bond with each other. The eroded sand particles are then entrapped by oxides. These oxide films can be seen enfolding sand grains using microscope. In a similar manner sand particles are also found in the bubbles inner surfaces.

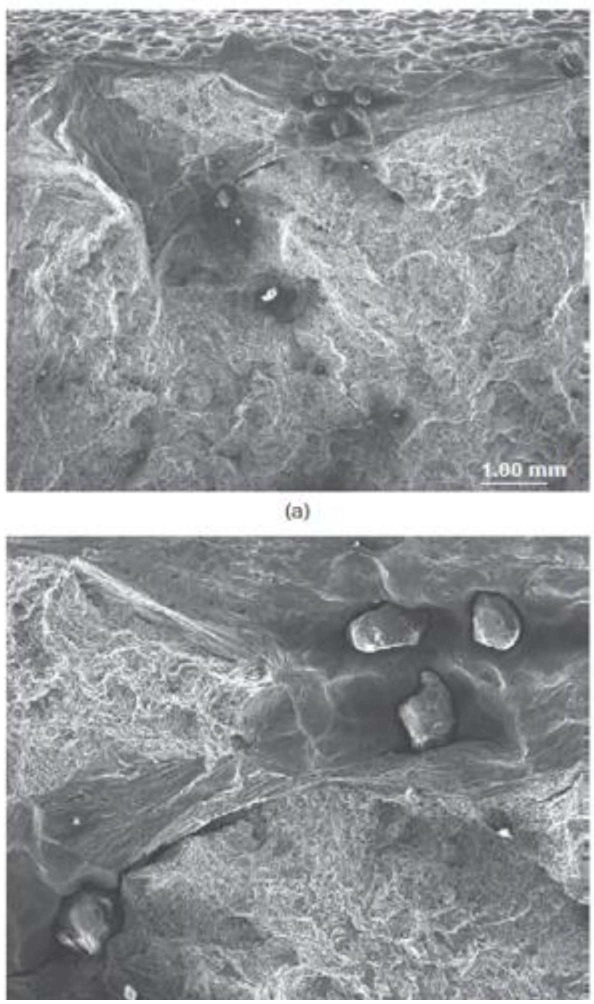


Figure 1. 5 Al-7Si-0.4Mg Alloy Fracture surface (a) Casted surface in sand with oxide film in connection (b) sand inclusion [4]

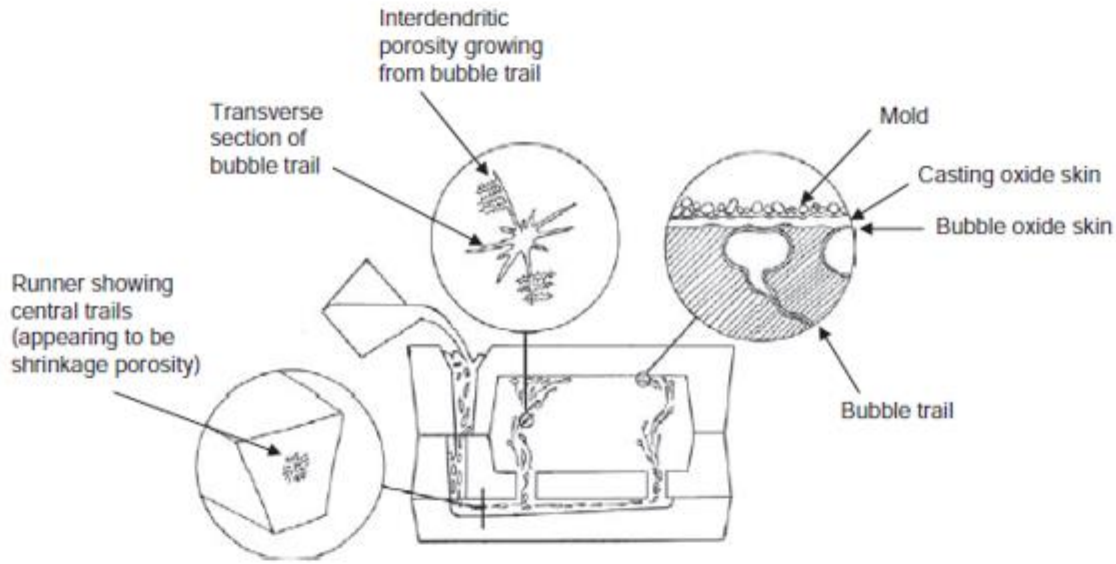


Figure 1. 6 Pattern of bubble damage in a casting [13]

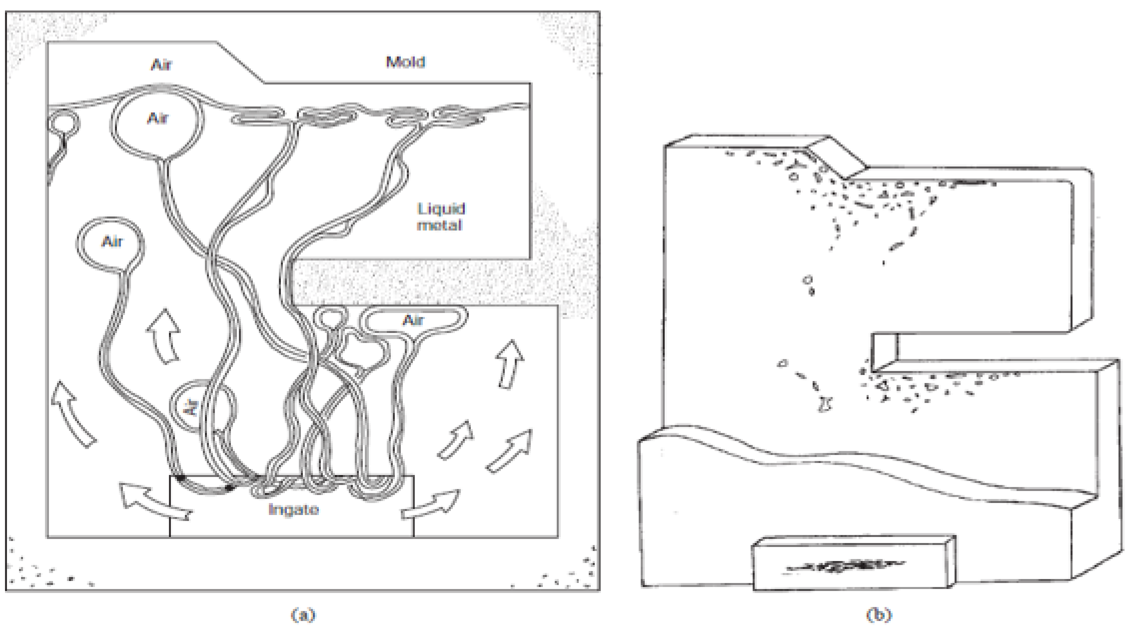


Figure 1. 7 (a) bubbles entering in casting (b) permanent damage in resulted part [4]

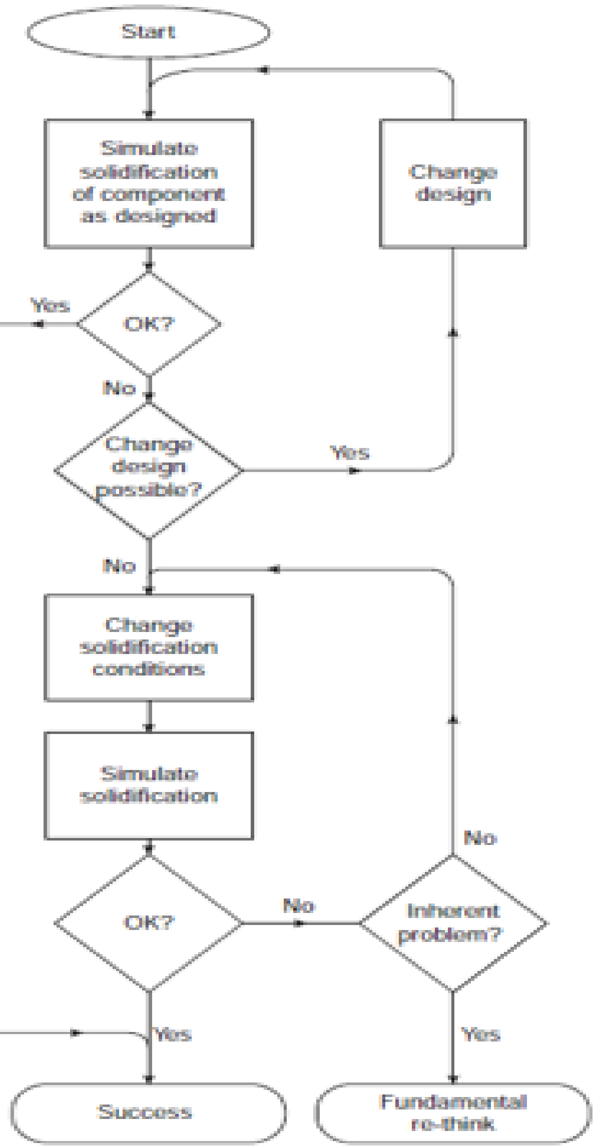


Figure 1. 8 Complete simulation layout [13]

Simulation parameters flowchart explains all the necessary procedure in Fig. 1.8. After getting results we can finalize the model with gating/ feeding and proceed towards castings.

CHAPTER 2: FLOW OF MOLTEN METAL

Fluidity is the ability of molten metal to carryon its flow even though it loses its temperature and even if the solidification process has also started during liquid flow. In casting terminology the fluidity is defined as the maximum distance travelled by the liquefied metal within the standard mold. There is also one more concept of fluidity that has been introduced by Feliu in 1966 and it gives the quantitative parameter which is denoted by Lc. Lc is kown as continuous fluidity length.

The surface of the mold implies a considerable impact of the flow of liquid metal flowing in the mold cavity. In order to penetrate with in the mold cavity it is necessary to consider the surface tension of a pure metal outer surface. This process is called capillary repulsion. The surface activity becomes more prominent when it reacts with its environment and results in creation of a surface film. The most problematic issue here is the penetration in narrow sections and appearance of small holes. Due to the creation of surface film and its mechanical strength it will now hold back the flow of liquid molten film within the mold and will create hindrance in the flow. When the below layer matrix increase in strength and started freezing then this causes creation of elusive phenomenon of the rolling waves. This method of advancement in the liquid front is not very common. A cold lap defect also appear in severe cases which is generated due to the rolling effect and causes entrainments of oxides which causes bifilm creation. But when the remaining section is very thin then any advance of the front faces hindrance and becomes difficult. Flowability is limited by heat transfer whilst fillability has been restrained by surface tension.

2.1 STEELS

Steel is present in wide variety of steel with different properties and these are generalized using extreme caution. The steel is normally of two forms i.e. Carbon steel and stainless steel. Further stainless steel fall into the following two groups.

a) Ferritic
b) Austenitic
c) Duplex (which consists of both ferrite and austenite)

Steel is further subdivided based on its microstructure, that's includes ferritic, austenitic, pearlitic, Martensitic and bainitic. One other form that is widely used in manufacturing is called Tool steel. This type of steel helps in creating cutting tools and consists of high Mo in order to form hard carbides. In order to achieve high strengths further heat treatments process are performed on the parts.

Steel can be differentiated from the rest of the light weight alloys based on:

i. To resist cores and molds floatation the steel with higher density and heavy weights is used to prevent the copes to lift.
ii. The reaction of steel with the environment is high due to its higher melting and casting temperature.
iii. The higher strength of the steel.

2.1.1 Carbon Steel

Steel making originated from pig iron which is produced in blast furnace. In the stack of the furnace the liquid iron infiltrating down through the coke resulting high carbon in the iron. After that oxygen is added intentionally to level down the amount of carbon. As the carbon burns it increases the temperature which helps to maintain steel in its molten form. "Carbon boil" is the process when millions of bubbles of CO is evolved and it occurs vigorously.

After reducing the amount of carbon to the required specification, the amount of excess oxygen is then reduced by inducing the deoxidizing agents. Aluminium, silicon and manganese is mostly used as a deoxidizer agent.

Steel is melted in most of the foundries using scrap steel. It does not require or utilize pig iron that is utilized during steel making. There is no need of carbon boil as the amount of carbon is already low.

The main problem is the existence of hydrogen in the melt as the carbon boil does not happens. The oxygen that is present in the melt can be reduced by using a deoxidizing agent. As far as the hydrogen is concerned there is no quick fix. If a hydrogen free environment is maintained only then hydrogen will leave the melt. Hydrogen will tend to form equilibrium with the surroundings and will gradually evaporate from the melt. On the other hand we can quickly reduce hydrogen content by inducing carbon boil. Some artificial methods like vacuum degassing are also utilized that reduces the level of hydrogen to a very low level.

2.1.2 Stainless Steel:

The presence of ferrite percentage in cast stainless steel is dependent upon the alloy composition at a room temperature. From the weight percentage of a specific alloy the contribution of Cr and Ni can be calculated.

$$Cr_{equiv} = \%Cr + 1.5(\%Si) + 1.4(\%Mo) + \%Nb - 4.99$$

$$Ni_{equiv} = \%Ni + 30(\%C) + 0.5(\%Mn) + 26(\%N - 0.02) + 2.77$$

The type of steel castings that are completely either Austenitic or Ferritic experiences problems due to the presence of formation of bifilm and appears corrosion issues, which then extrapolates due to the dendrite straightening and results in propagation of cracks within the the casting body. In most cases of austenitic steel the casting do not result in single structure and results in duplex steel. Ferrite within the range of 5-25% can be valuable in achieving the following material attributes.

a) Increase in Strength.
b) Reduces casting issues and improved welding.
c) Resistance to corrosion issue and reduce stress corrosion cracks.

The interruption of bifilm strengthening can also be due to the creation of initial ferrite dendrites.

The duplex stainless steel structure has an advantage over others at about 50/50 vol. % mixture. These steel are very much introduced in our manufacturing industry by its name “duplex stainless steel”. And this steel is very common in used in environment where we need to avoid rust i.e. in centrifugal water pumps etc. There is one more variant that is very common is called super duplex and it is the composition of austenitic/ferritic iron and nickel and chromium steel with minute addition of molybdenum. It is has stronger corrosion resistant properties as compare to simple duplex steel.

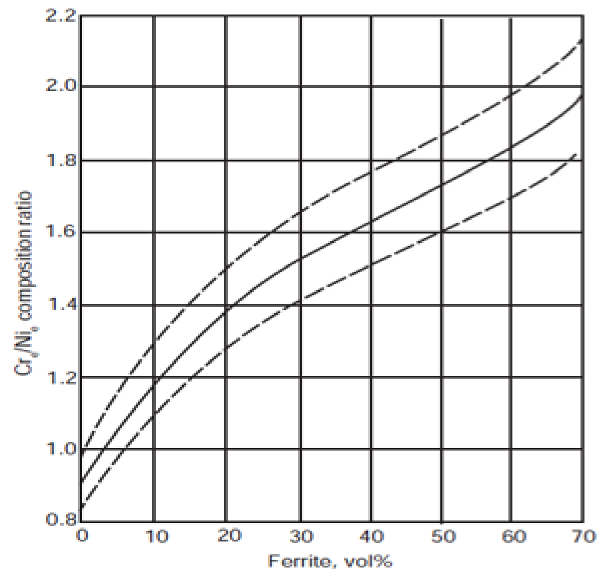


Figure 2. 1 Casting Figure for estimating the ferrite content of steel [14]

CHAPTER 3: CASTING DEFECTS

3.1 Porosity

Porosity, also known as the void fraction, is the measure of volume of voids over the volume of the casting.

There are many ways in which porosity can occur. Usually, it occurs in the form of trapped air bubbles in the casting. Sometimes, shrinkage porosity is like there is no shrinkage at all, instead an amount of oxides is developed due to the entrapped oxides while pouring. Thus porosity is resulted due to core and mold blows fired from the microscopic volatile binder pockets trapped in the mold particles.

General shrinkage behavior:

The space occupied by the molten metal in the casting is greater than the final product that is a solidified casting. The rate of contracting of molten metal as it is cooled to room temperature is different in different cases.

- The contraction starts in the liquid state that is a normal behavior of liquids on cooling. As the temperature is lowered, the molten metal starts contracting as this contraction goes on linearly with decreasing temperature. This shrinkage of liquid metal is not a problem because while pouring, some extra material is poured to compensate this shrinkage or the extra material is available in the riser to compensate this shrinkage.
- The contraction at the freezing point is very different form the one while solidification. This is because the solids have much higher densities as compare to liquids. This contraction results in a number of problems like

i. Feeding is required that is a process to compensate the contraction due to solidification by moving either solid or liquid.

ii. If feeding is failed, shrinkage porosity is caused that is another huge problem.

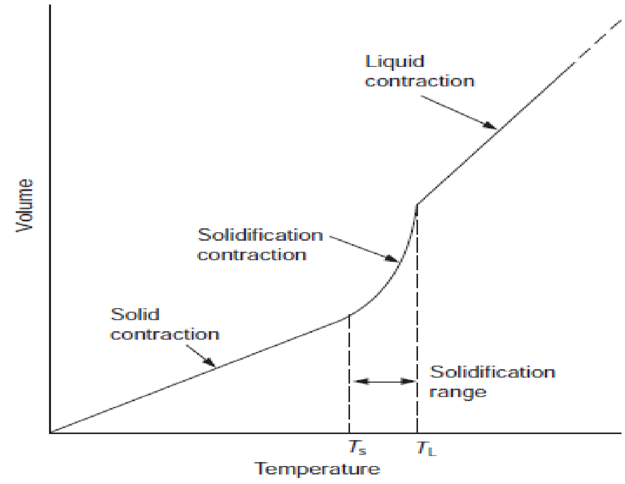


Figure 3. 1 Material Contraction while casting [5]

- The final step of contraction is the contraction of solidified casting. As it is cooled down, it contracts and hence a reduction in size is observed. This contraction is not so free as others because there are certain constraints by the other already cooled parts or the mold itself that limits the contraction. Due to these constraints, the casting is always larger than expectations from free contraction. This raises the problem of predicting the exact size of pattern because the contraction allowance is calculated easily. This constrained contraction can cause some other problems like cracking or hot tearing of the solidified casting.

3.1.1 Solidification shrinkage

The reason of contraction of liquid upon cooling is that the atoms are rearranged from the random arrangement in the liquid state to a closed packed dense arrangement in the solids.
Face centered cubic and hexagonal closed packing are the most densely packed structure of solids and they have the greatest contraction values in a range of 3.2% to 7.2% while this value for less dense metals like body-centered cubes is less and in the range of 2 to 3.2%. Other materials that are even less dense than these are contracted in smaller amounts than these on cooling.
There is a type of materials that either expand on cooling instead of contracting like water, bismuth, silicon and alloys of cast iron.

It is very important to study the casting of materials that expand on cooling instead of contracting. To study this, a cooling sphere of such metal is considered. It is assumed that the sphere is fed through a very small sized ingate to a level where a slid shell with a thickness of x is formed. The feeding is then stopped. As the metal solidifies, a layer of thickness dx is formed by freezing. The reduced volume that is occupied by this layer as compare to the original volume of the liquid is directed towards two cases that are either a pore will be formed or the expansion of liquid will occur leading to a little contraction of surrounding solid. Let us assume that there is no nucleus available for pores to be created so the liquid has to expand to accommodate with the development of a negative pressure or a tension. The liquid is also in mechanical equilibrium at the same time with the solid shell enclosed that is sucking liquid inward. As further layers are formed, the negative pressure is increased, liquid is expanded further, the solid shell that was deforming elastically initially, is collapsed plastically.

The solidification of sphere can be thought of as a material that is expanded upon solidification. In such a case, the liquid is compressed as more solid is formed. This squeezed liquid experiences a compression or a positive pressure. This in turn expands the solid sphere.
So, the situation when pressure falls to 0 or negative value that corresponds hydrostatic stress, this causes the formation of shrinkage porosity. It should also be noted here that at the very same time, the difference of pressure on the inside and outside of casting act as the driving force to feed material that reduces porosity.

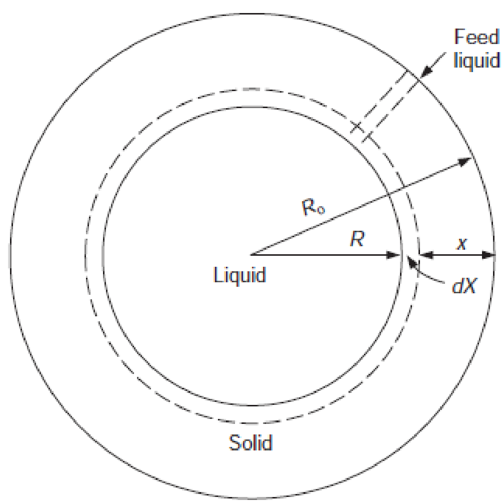


Figure 3. 2 Model of an unfed solidification of sphere[7]

The formation of pores depends on the presence of nuclei for formation of pore. If the metal is clear and there is no nucleus present for pore formation, feeding is continued without any hindrance until the casting reaches to the finishing point and freezes completely while pores will be created in the presence of some favorable nuclei. This will result in the reduction of feeding and porosity will develop in the casting according to the phase change physics. In real, the situation lies between these two extreme points that there is some feeding as indicated by the lowered level of feeder head and also due to sinking of material at the surface while still porosity develops interior of the casting. Thus feeding continues under increasing difference of temperature until a critical internal stress is developed where certain nuclei become active at various points and so pores start developing at such points.

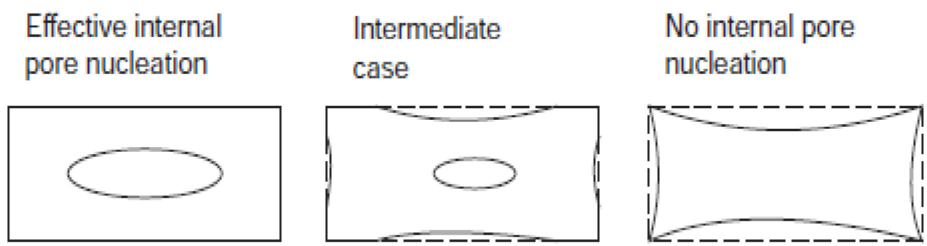


Figure 3. 3 Pore nucleation

3.1.1.1 Feeder:

Since extra material is needed for feeding to the freezing casting for compensation of contraction. For this, there is a reservoir which have metal for feeding and this reservoir is termed as feeder or riser.

Rules for feeding:

There are seven main rules for feeding which are given as below:

1. Avoid feeding unless is unavoidable.
2. The riser/feeder should not get solidified before the casting.
3. The volume of the feeder should be enough to compensate the contraction of casting during solidification.
4. The freezing time of the junction where feeder and casting are meeting should not be greater than the freezing point of either casting or feeder because it can cause under shrinkage in either other case.
5. The path should be clear for feeding of materials to the regions which needs to be fed.
6. Difference of pressure should be sufficient and in the right direction so that material moves to the region where feeding is needed.
7. Pressure at every point in the casting should be sufficient so that development of porosity can be suppressed.

3.1.1.2 Feeding Mechanisms:

As the solidification progresses, the solid is formed in the form of small entangled masses which can block the passage of feeding. Also, during solidification, the pressure falls as the liquid changes to solid and the difference of pressure between outside and inside increases and the pressure inside the casting even fall enough to a negative value which is seriously undesired in casting because this pressure provides the driving force for the development of defects like shrinks and porosity.

However, there are some mechanisms which can help to reduce such negative pressure inside the casting. Each mechanism or a set of mechanism is suitable for certain cases which will help in feeding relieving the internal stresses during solidification and hence reduce the possibilities of development of defects

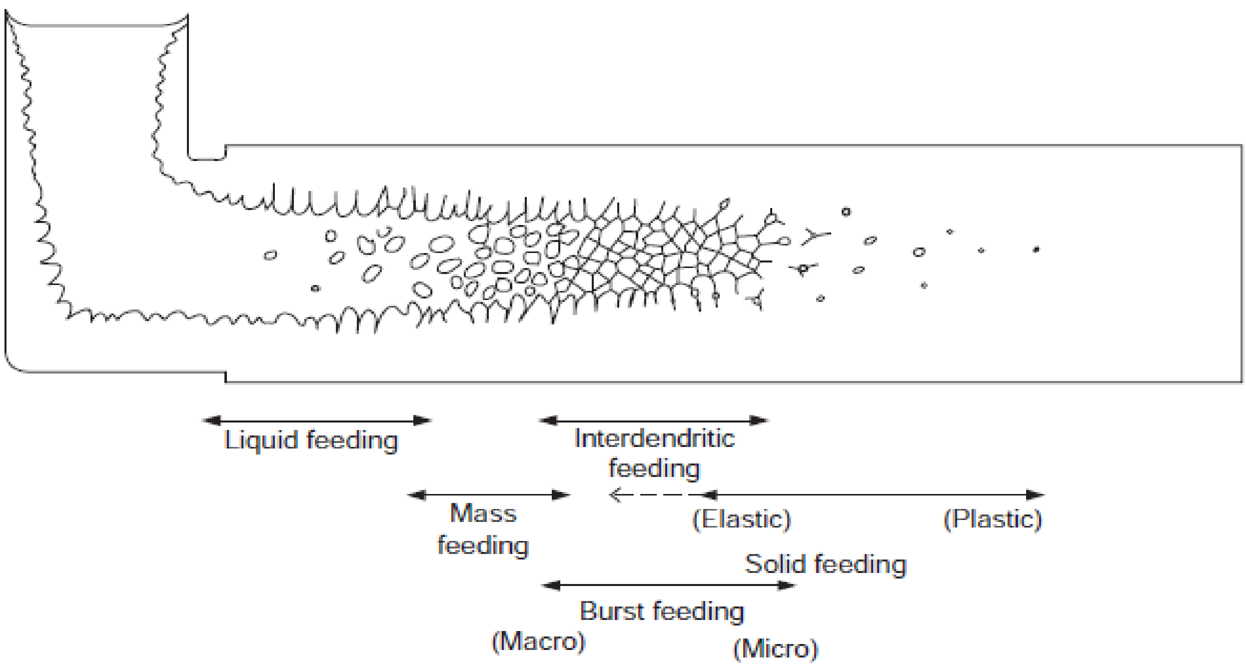


Figure 3. 4 Feeding Mechanisms [3]

1. **Liquid Feeding:**

The most open mechanism of feeding generally preceding all other mechanisms is the liquid feeding mechanism. It is the only mechanism of feeding in skin freezing castings. Since the path for feeding is wide for freezing process mostly and the viscosity of liquid is quite low so required pressure for feeding is very small. A result of theoretical casting model (20mm cylindrical) shows that the pressure developed initially is only 1Pa while by the time 99% solid has been formed, the pressure just reaches 100Pa which is still very low as compare to atmospheric pressure. The temperature of the outer layers of casting is low which causes them to contract and in return compress the internal layers and hence it reduces the internal pressure which can even be a negative value instead of a negative value.

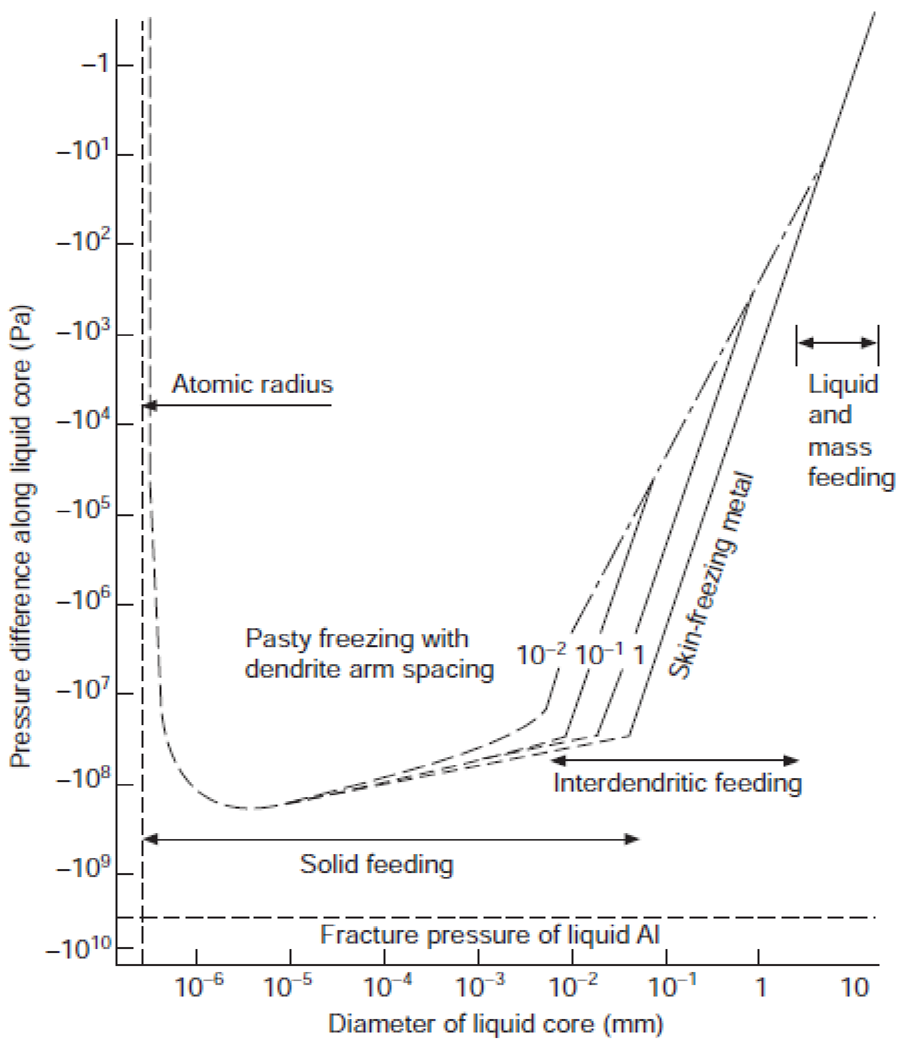


Figure 3. 5 Hydrostatic tensions in the residual liquid[1]

2. **Mass feeding:**

This is a type of feeding which involves movement of a mixture of residual liquid and slurry of solid metal. The fraction of solid volume is between 0 and 50% and the movement depends on the pressure difference that drives the flow and dendrites percentage that are free. It is observed that solid composition can be increased up to 68% to get small movements and at this level the dendrites form a coherent network just like a 3D plastic space frame. If the grains are too large, they stuck to the walls and cease the movement of mass for feeding. Also they can block the narrow passages so the material cannot reach the regions beyond these narrow paths. So if the grains are fine and very small, the movement of slurry is regulated and reduces the pressure difference along the direction of flow. Grain refinement is also very useful to minimize the defects like porosity in the castings.

3. **Interdendritic Feeding:**

At some points, the grains are stopped due to impinging to the walls and feeding become very difficult. The movement of residual liquid in such a pasty zone is called interdendritic feeding. Poisseuille gave an equation to estimate the value of Dp/dx that is required for the fluid to flow through the passage.

$$\frac{dP}{dx} = \frac{8\eta v}{\pi R^4}$$

Where η, v, and R are the viscosity, volume flow rate and radius of the tube respectively.
If there are N number of tubes to make a bunch of capillaries, the equation becomes:

$$\frac{dP}{dx} = \frac{8\eta v}{\pi N R^4}$$

To consider a more real case, the relation should involve the effect produced by the simultaneous freezing of the material. If the average velocity is, as calculated from volume flow rate, $V = v/\pi R^2$, using conservation of volume that is by equating the volume deficit due to solidification and the flow through the element dx, we get:

$$V\pi R^2 = 2\pi R\left(\frac{\alpha}{1-\alpha}\right)(L-x)\frac{dR}{dt}$$

From the above two equations we get after integration:

$$\Delta P = \frac{16\eta}{N}\left(\frac{\alpha}{1-\alpha}\right)\frac{1}{R^3}\left(Lx - \frac{x^2}{2}\right)\frac{dR}{dt}$$

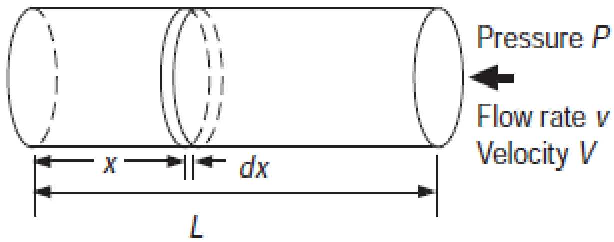


Figure 3. 6 Inwardly solidifying tube [8]

Maximum drop in pressure can be found out by putting x=0. Also substitute the freezing rate relation,

$\frac{dR}{dt} = -4\lambda^2/R$ And $Nd^2 = D^2$ where λ, d and D are the heat flow constant, spacing of dendrite arm and side length of the pasty zone, we get:

$$\Delta P = 32\eta\left(\frac{\alpha}{1-\alpha}\right)\frac{L^2\lambda^2 d^2}{R^4 D^2}$$

Finally, we can conclude that pressure drop due to this viscous flow depends on various factors including shrinkage, viscosity, spacing of dendrite arm, freezing rate and area of pasty zone. But the factor that affects this pressure drop is the radius of capillary.

4. **Burst Feeding:**

As the hydrostatic pressure increases in the region where feeding is poor a barrier is developed at such a region and suddenly feeding metal will flood through the barrier into this region. Such a mechanism of feeding is called burst feeding because it has a burst type action. With the solidification process goes on, the strength of the barrier as well as the stress also goes on increasing but the rate at which they are increasing is different from each other so the point at which the stress becomes more than the strength of the barrier, bursting takes place and feeding material move into the poorly fed region like a flood.

5. **Solid Feeding:**

The casting sometimes solidifies before feeding reaches to the completion point and highly stressed regions are developed with liquid entrapped in them. Sometimes, the stress is so high that the solid is deformed and sucked inward by creepy flow. This inward movement of the solid relieves the stress in the same way as in liquid feeding. Solid feeding is very similar to liquid feeding and it is also known as self-feeding.

3.1.1.3 Initiation of Porosity:

If there is no air present and the feeding is done perfectly, no porosity will occur in the solidified casting. But if take a realistic view of the casting process, we observe that in every casting there are some regions in the casting that are complex and feeding is not reached to these regions properly which results in the development of high hydrostatic pressure and hence in the development of pores at various points in the casting. If the feeding is done properly, the hydrostatic stresses developed are not too intense to start developing pores. In this case, only surface shrinkage occurs.

3.1.1.4 Internal shrinkage porosity:

Pressure inside the casting drops if the feeding is stopped from the feeder. In this case, liquid from the outside surface is drawn into the casting and porosity development starts at the surface. Air is also gets trapped during sucking of material form surface which spread along the route of movement of material inside the casting following the interdendritic passages. This develops pores inside the casting which are hard to distinguish from micro-porosity. The origin of this porosity can be identified by the oxidized internal surface of the casting near the outer surface.

The castings with thin sections usually do not face much withdrawal of surface liquid into the casting that’s why they usually do not require feeding or very small feeding at all. Such castings exhibit very sound surfaces. While the casting with intermediate thickness have some withdrawal of surface liquid due to which they have local frosting of the surface. This indicates that feeding is required in such cases to avoid these dull patches.

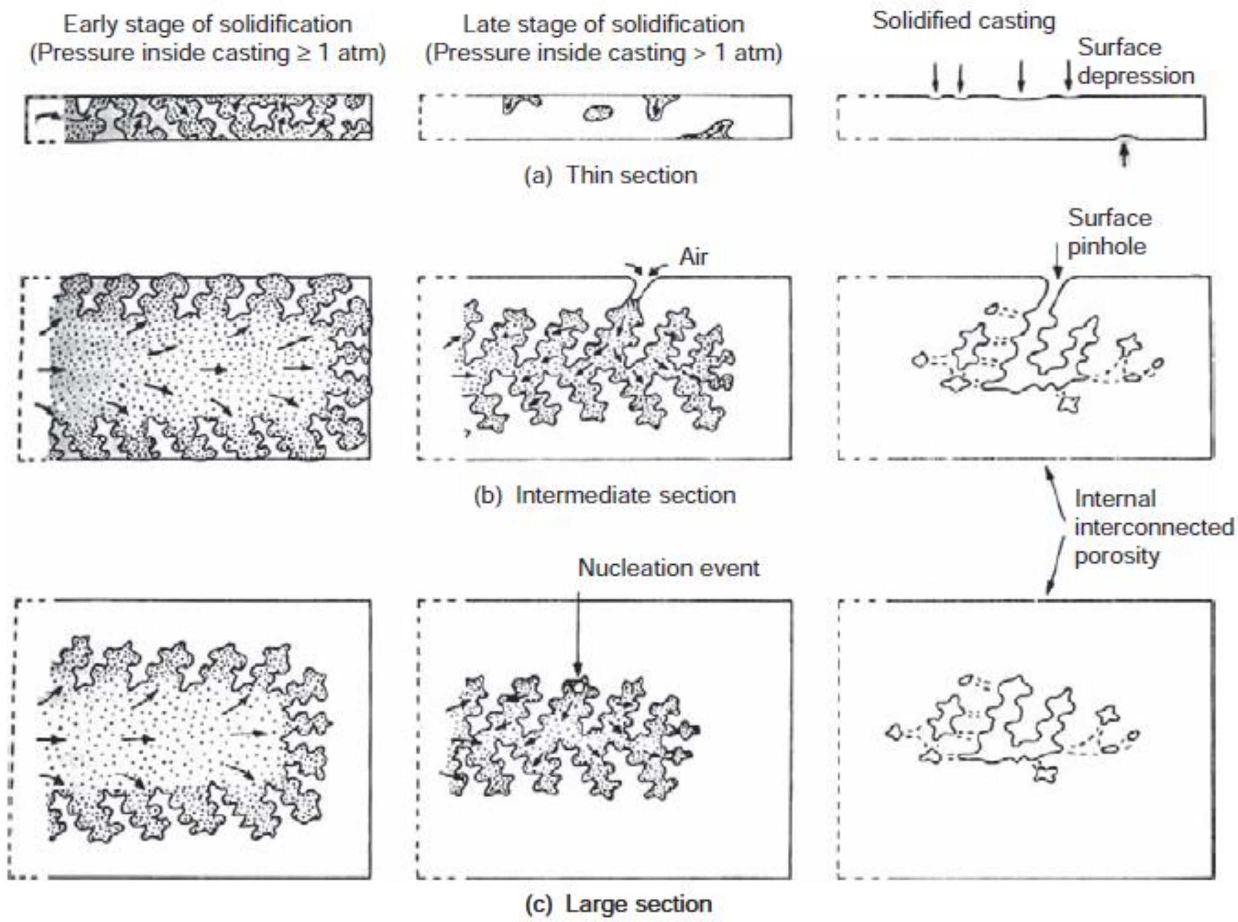


Figure 3. 7 (a) No porosity in thin section (b) surface porosity in intermediate section (c) internal porosity of thick section [15]

3.1.1.5 External porosity:

In case that internal porosity is not generated, the reduced internal pressure will result into the inward movement of the surface material of the casting. If this movement is localized and too severe, it results into a defect called draw or a sink. This can also be accounted for self or solid feeding.

If the internal pressure is such that there is no self-feeding then no porosity will be generated, neither external nor internal. If the internal pressure is controlled too much that required, it is possible that the inward movement of the material is reversed and the casting is swelled. It happens when the casting is taken out of the die before it gets solidified completely.

3.1.1.6 Nucleation of internal porosity:

Alloys with short freezing range usually do not develop surface porosity. A sound solid surface is formed in the early stages of freezing while liquid feeding goes on through the wide passages. If the feeding process in interrupted at the end of freezing, pores are developed by nucleation inside the casting. Once nucleation is started, further solidification will help to grow because it will act as the driving force for the growth of porosity.

3.1.2 Gas porosity:

3.1.2.1 External pores:

This is a common defect in casting. This defect is not usually traceable until machining cut is developed and it appears at that region. This defect, subsurface pores, are developed due to the entrapped air bubbles in the molten metal while pouring of metal is being done in the mold. If the diameter of bubbles is less than 5mm, they are not broken and just settle inside the casting causing pores.

3.1.2.2 Blow holes:

The rounded or oval shaped pores on the surface of the casting due to entrapped gases on the surface of the casting are usually known as blow holes. This defect is usually associated with oxides or slag and nearly always present in the upper part of the casting that is cope, due to undercuts and poor ventilation.

3.1.2.3 Hydrogen Porosity:

Solubility of hydrogen in some metals is much greater in liquid form than in solid form. So when the metal is in molten state, a huge amount of atmospheric hydrogen is dissolved in the metal but when the casting is solidified, the hydrogen gets separated from the solution and results in the formation of pores inside the casting.

CHAPTER 4: DESIGN OF FILLING SYSTEM

For casting process the critical step is to get the liquid metal out from the ladle and pour it into the mold. Mostly the defects /damage is generated in castings by creating poor filling design and it has been observed in liquid metal using video X Ray radiography methods. Within a gravity casting of liquid metal the most important and difficult job is to eliminate the occurrence of surface turbulence.

4.1 The critical velocity

The rule 2 of casting i.e. "The riser/feeder should not get solidified before the casting." Should be followed but if the velocity of liquid metal is below the critical velocity limit. When the velocity of liquid metal reaches to 1.2 m/s then the defects generated by entrainment gets severe. The best possible limit for filling liquid metal is between 0.5 to 1 m/s.

4.2 Gravitational Pouring

The law of pouring prevents the fall of liquid metal but in case of gravity casting its all about a perfect fall into a mold. The critical fall heights for most of the liquids ranges between 3 to 15 mm. The dominant factor in such castings is the surface tension due to this we can avoid surface that ultimately results in entrainment defects. To achieve these the ladle should be very close to the mold bottom face and it can only happen in case of open mold as shown in below figure 4.11(a). As per our recent practice the molds are mostly closed and hence require a gating system that help liquid metal flow into the mold. It is very unfortunate for the pattern makers that the fall height is in very low range. Almost all of the gating and feeding design violated these strict requirements.

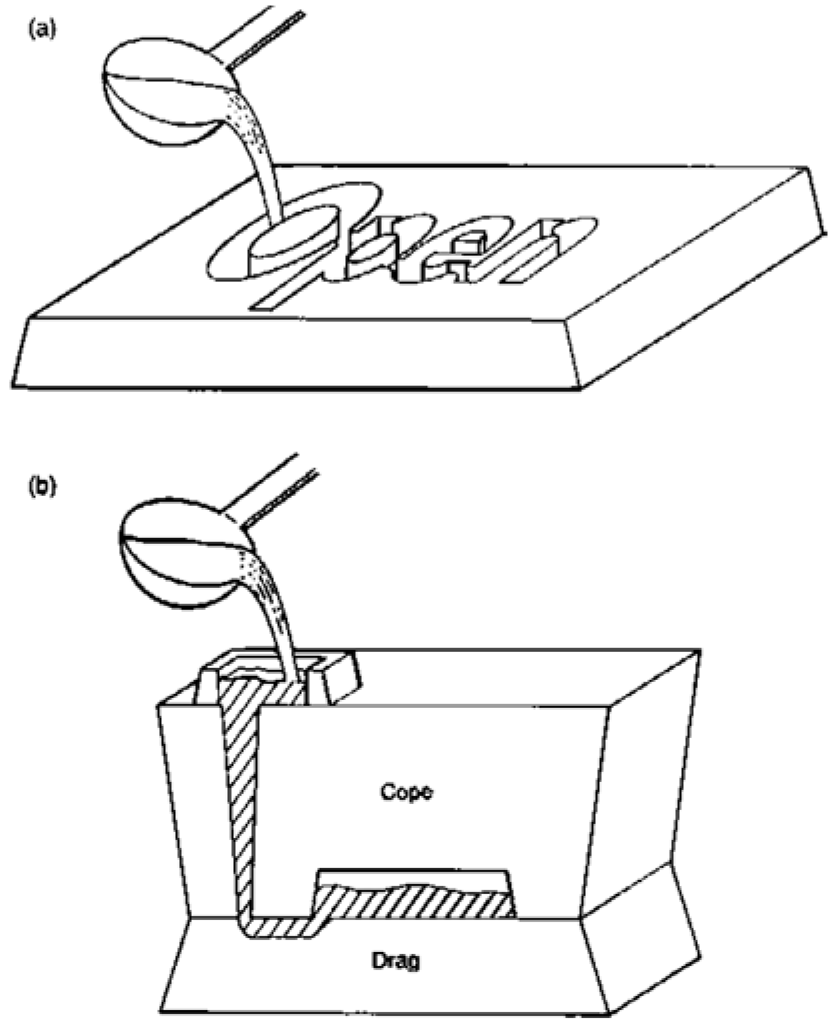


Figure 4. 1 (a) open mold (b) close mold [16]

The gating system should be designed in a way that the liquid metal should not fall Right in center line of mold as it will create a fall which will intend create the defects. During mold creation process, any part of the mold remains under the entry point then it violates the basic rule. This translates that the separate channel should be inserted from the bottom of the mold to streamline the molten metal flow.

In below shown figure 4.12 it can be seen that the top gating of the casting without any ambiguity violates the "avoidance of increase from critical velocity".

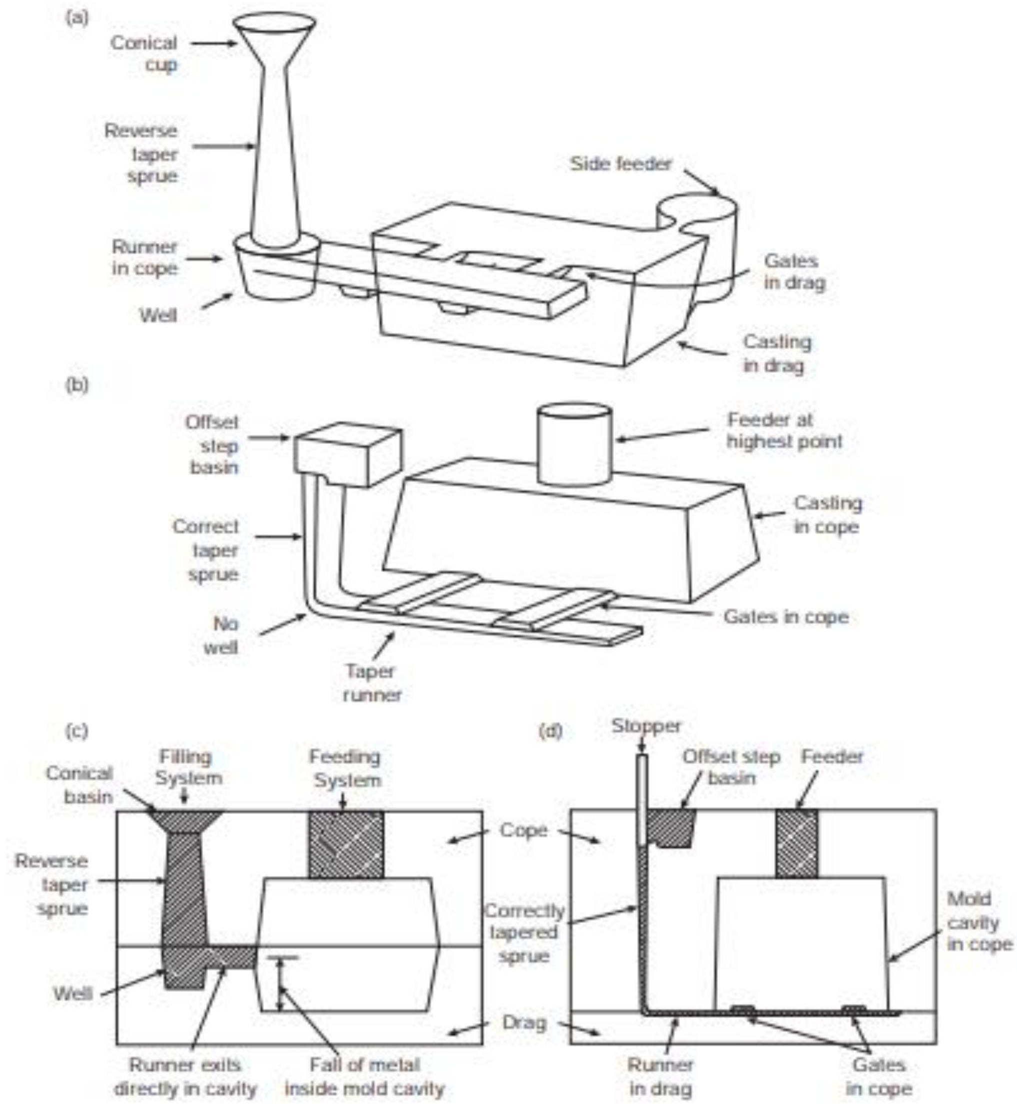


Figure 4. 2 (a) (b)(c) Not recommended top and side fed mold (d)A well designed mold entry from bottom [2]

4.2.1 MINIMIZATION OF GRAVITATIONAL EFFECTS:

There is a number of techniques being used to minimize the effects of gravity problems while pouring. Some of the most important ones are given below:

- Narrow channels are used for the melt to flow so that molten metal cannot fold over itself and hence this pressurized filling system avoid the entrainment damages and the undesired gravitational acceleration.
- Another technique to avoid gravitational effects is horizontal pouring or level pouring.

- Filling the melt in upward direction from below the casting against the gravity.
- Transfer the melt through very narrow passages so that the effect of surface tension is increased comparably to gravitational force. So this balances the gravitational effect and melt is transferred smoothly.

The uphill transfer of melt against the gravity has also provided a solution to minimize the turbulence effects of fluid. The figure below illustrates the different types of gates that ranges from directly top to bottom or from bottom against the gravity to avoid turbulence as much as possible and also increase the control over velocity of the melt to keep it below the critical value.

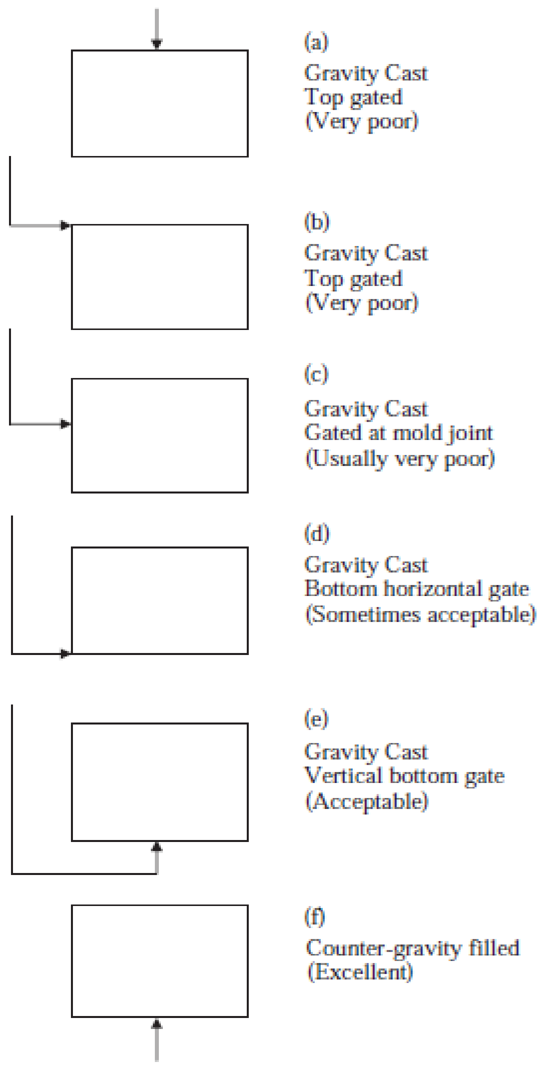


Figure 4. 3 Gating various designs of molten metal in mold entry locations

It is a common practice to use bottom gated systems with a turned base of the runner through which melt enters the mold directly. Such gating systems are economical until scrap percentage is evaluated. In a down sprue, the velocity of the melt is high and in not under control which results in splashing like a jet due to turbulence and hence more oxides and air is entrained causing more defective casting.

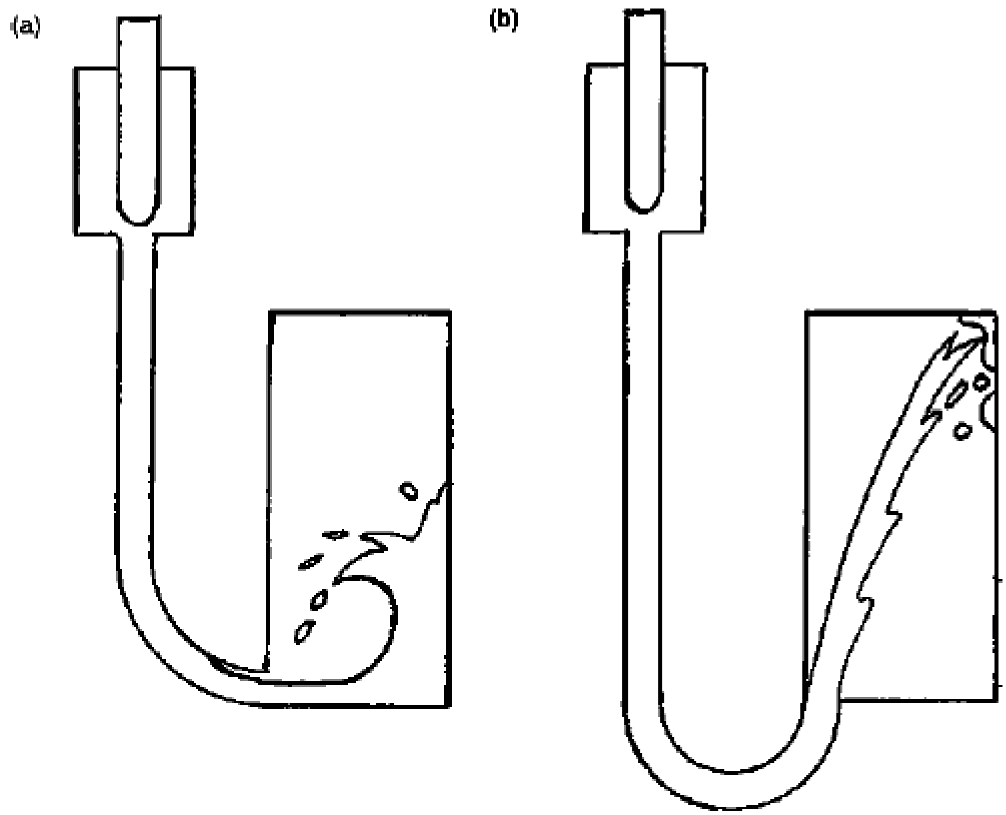


Figure 4. 4 Two bottom-gated systems [4]

So it is very important to keep this factor in mind while designing down sprue to avoid splashing as much as possible and melt can be transferred in a controlled manner. Also gating system with reduced height is a good option because this can reduce the velocity and gravitational effects. Reorientation of mold time by time during filling is also a good technique being used for the very same purpose.

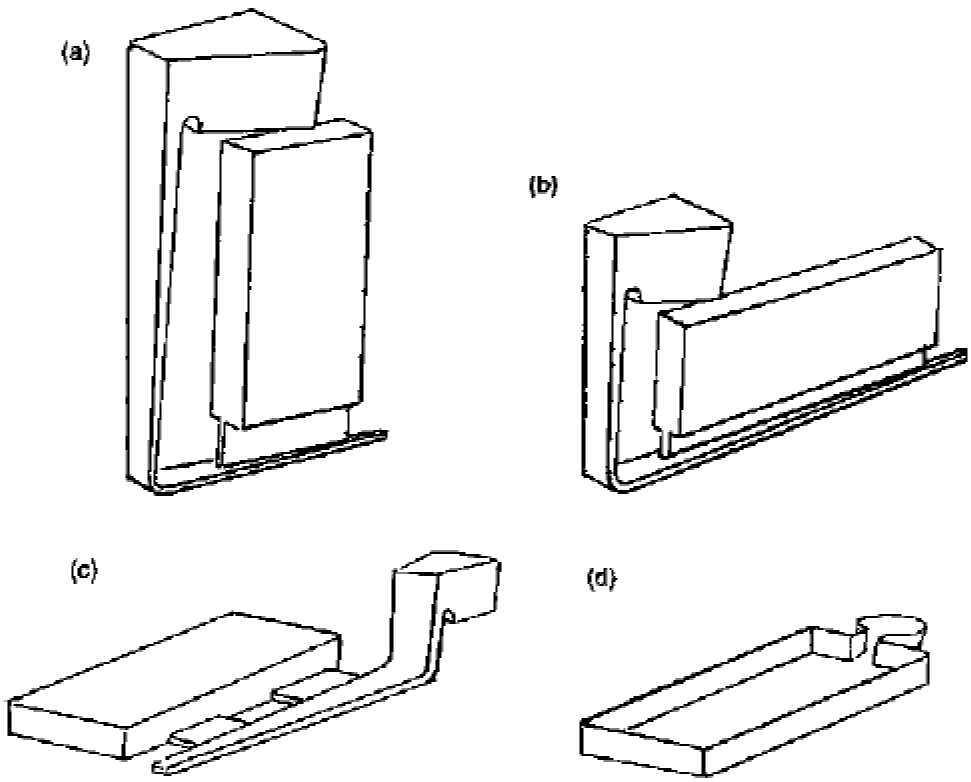


Figure 4. 5 Improved bottom-gated system

4.2.2 Surface tension controlled filling:

If the passage of filling metal to the mold is narrow of the order of few millimeters it offers a resistance to the flow of metal through it due to surface tension. If the passage is too narrow and pressure of the melt is too low, the melt will not flow through the passage rather the flow direction will be reversed so although it is a good technique to nullify the gravitational effects but care should be taken of pressure of the melt so that flow can be directed into the right direction with the desired speed.

4.3 POURING BASIN:

Basin is the reservoir of the melt from where it enters the sprue and travels down to mold via runner and gates. The volume of the basin is according to the emptying time of the basin. For example, if this time is 1s and the basin is a cube with side length A then the flow rate is given by:

$$Q = A^3$$

$$A = Q^{\frac{1}{3}}$$

4.3.1 Conical basin:

The in line conical basin used in various industries has been proved to be more defect causing technique than any useful result. Following are some of the factors due to which it is not much useful:

- The velocity with which metal is entering is uncertain so it is difficult to design the runner to get a certain velocity.
- Also it becomes difficult to reduce the turbulence.
- Any slag or other impurities that are present in the melt are not filtered before entering the runner.
- It concentrates the air into the flow with a composition of about 50% air that is highly unacceptable.

Different cases of such basin type are given below:

- The least bad yet unacceptable case is that the size of entrance of basin i.e. sprue exactly matches the size of sprue so that sprue fits rightly into the basin.
- The size of the basin entrance is larger and the sprue does not fit in it. This is even worse than previous one because here more turbulence is created at the entrance due to mismatch.
- Cup shaped sprue.
- Too small basin entrance as compare to the runner.
- Extend the sprue throughout to the casting to act as the runner too. This traps a lot of air

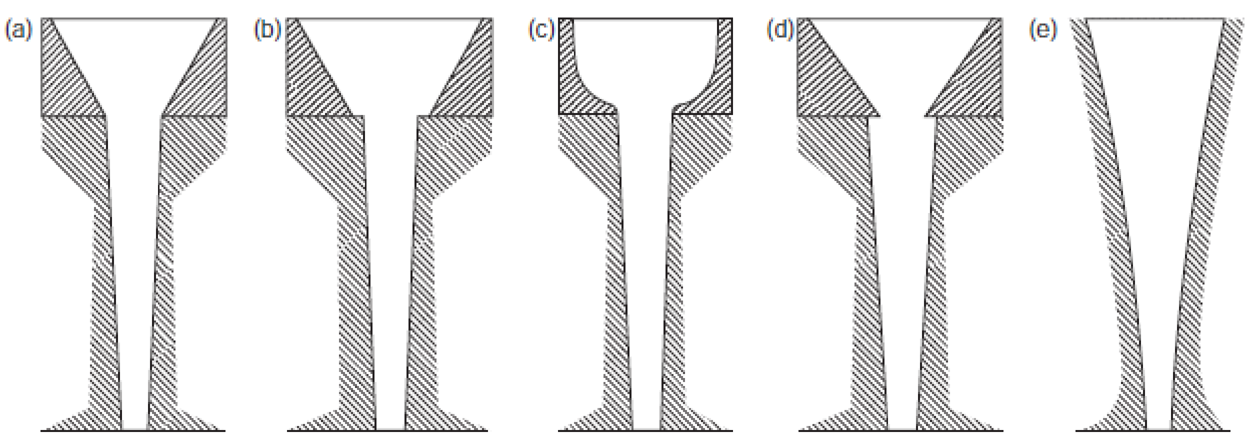


Figure 4. 6 Design recommendations of conical basin and sprue combinations

and is really unacceptable at all.

4.3.2 Inert gas shroud:

It is a draping of inert gases used in various casting like steel castings to avoid oxidation by the air present in the atmosphere.

4.3.3 Contact Pouring:

In order to exclude air during pouring of metal is being carried out, the ultimate solution is contact pouring where basin and the mold are brought to contact with each other and this contact is sealed for air.

In such cases, bottom pour ladle is used that is directly placed over the runner. There is an automated controlled stopper that can be controlled via remote control. This stopper is opened and metal runs down the runner and when it is completed, the stopper is closed and ladle is lifted out.

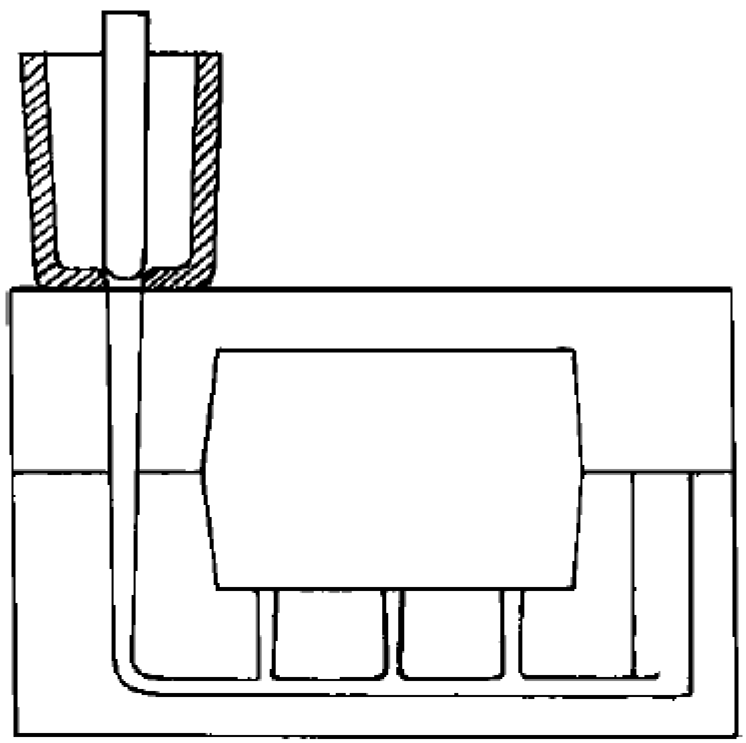


Figure 4. 7 Contact pour, avoiding basin problems [14]

4.3.4 Offset Basin:

There is also another type of basin called offset basic also known as bush. It has a horizontal floor and before entering the sprue, the stream is brought to rest. The vertical flow is absolutely zero while the horizontal is not under check. The sideway stream flow does not fill the sprue fully, instead only 50% sprue is filled and remaining air is entrained so this method is not recommended at all because it is really defective.

4.3.5 The offset step basin:

The horizontal stream flow over the top of sprue can be stopped by providing a step or weir in the basin. Further it is recommended that the step should be curved instead of a sharp step because sharp step can increase the turbulence due to splashing. This turbulence can cause the entrainment of air and hence result in a defective casting so the step should be there with fillets at the edges of step.

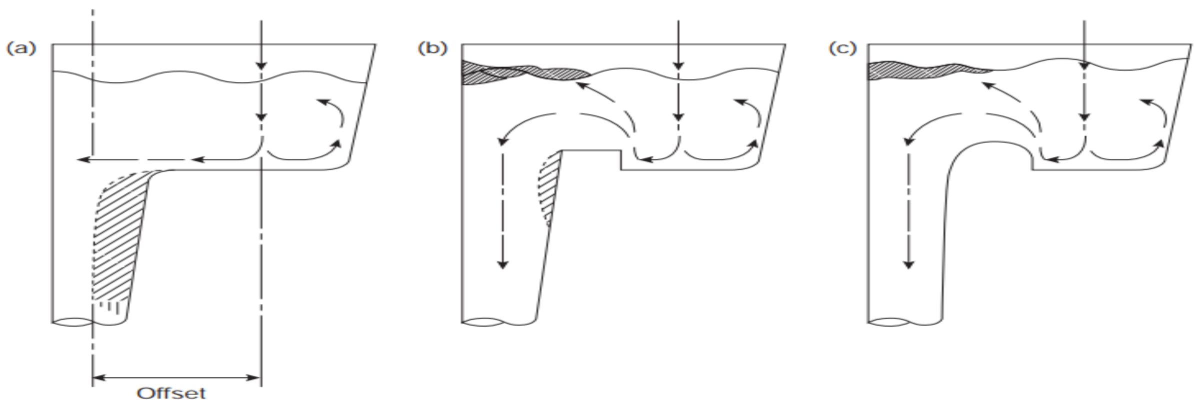


Figure 4. 8 Basin for offset pouring (a) without any step (not recommended); (b) small sharp step (not recommended)[11]

4.3.6 Undercut basin:

There are some other problems associated with bottom poured ladles. Since the velocity of the melt at the bottom of ladle as it enters the sprue is extremely high because the melt is highly pressurized. If this high speed melt is pointed in the sprue it can splash out and spread, all over around the space. The splashing tendency can greatly be minimized by introducing sharp corners to all four sides of the basin. Also a re-entrant undercut can be introduced at the base of basin to reduce the splashing.

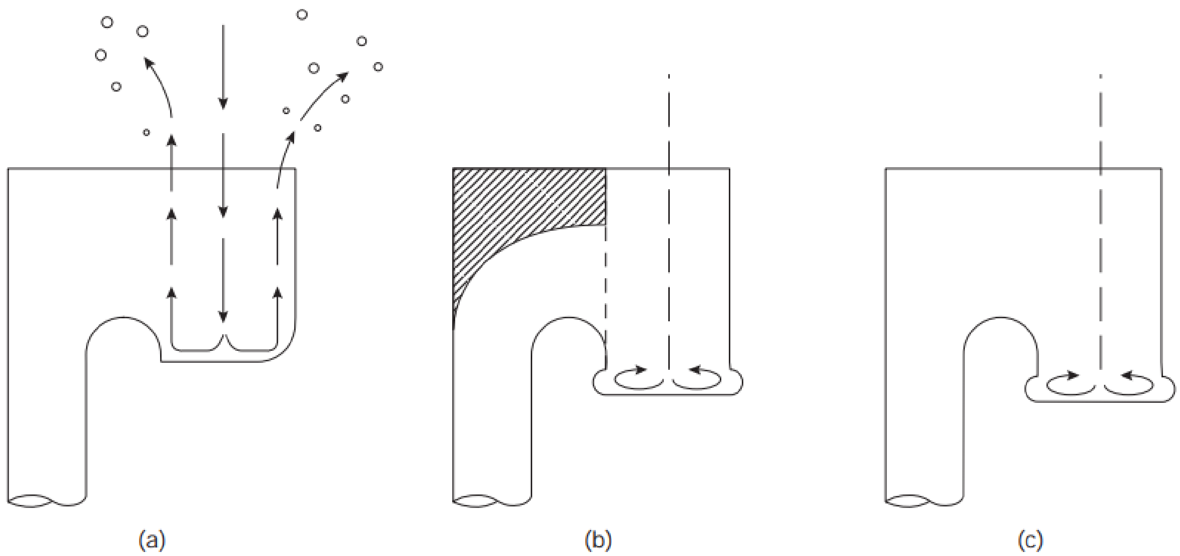


Figure 4. 9 High velocity offset basin. (a) No undercut given and has empties spectacularly upwards. (b) and (c) undercut is given inorder to reduce molten metal pouring splashing while filling mold [13]

4.3.7 Stopper:

Usually a small core of sand is placed at the top of sprue which floats only when bush is full and in this way help in making sure that the only clean melt is entering the sprue. Another way to control this stopper is that a stopper rod or a wire is attached to the stopper that can be controlled manually. However it should be taken care of that the mechanical force required in case of large casting to operate the stopper so that it can justify the mechanical effort and cost.

4.4 SPRUE/DOWN RUNNER:

The job of a sprue is to carry the melt to the minimum set level of mold without adding defects in the casting even due to the high velocity of melt.

There is a quite convenient way to calculate the dimensions of sprue theoretically. As the melt will fall through a height h from the basin to the runner, it will lose gravitational potential energy mgh that will be converted into kinetic energy $mv^2/2$. This gives a relation for velocity as:

$$v = (2gh)^{\frac{1}{2}}$$

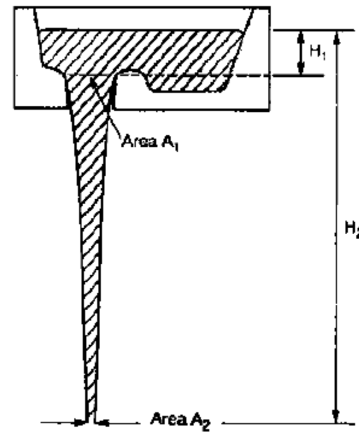


Figure 4. 10 The stream of molten metal falling freely from a basin inlet

The size of the sprue can be calculated by the idea that flow rate must be the same throughout the sprue so according to the velocity changes, area should be changed accordingly as:

$$Q = A_1 v_1 = A_2 v_2$$

The problems associated with a sprue are:

- The speed of the melt in the sprue is very high that causes turbulence and in turn trapping of air and oxides which further leads to defects like porosity etc.
- The freely falling melt in an oversized sprue in the presence of air can oxidize the binder in the sand which is highly risky in damaging and destroying the mold.

As a fluid fall freely, it adopts a taper path naturally due to gravitational effects so a sprue is designed tapered. The relation of the area with the height of the sprue is given by a hyperbola equation but usually sprues are straight tapers because melt can be detached at curved surfaces as shown in the figure below. The straight tapered sprues with an enlarged area at the entrance by 20% work reasonably well.

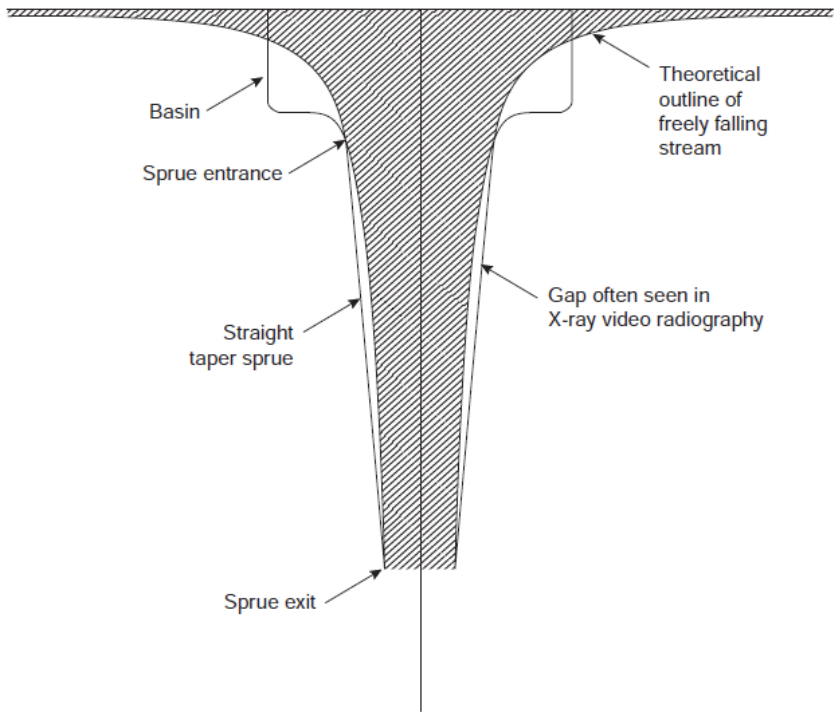


Figure 4. 11 Theoretical layout of the falling stream [12]

For a negative tapered and zero tapered sprue, velocity of the melt is all due to gravitational effects. So in this case the rate can be controlled by the area of the sprue. If the sprue is correctly tapered, it nullifies the gravitational effects and velocity and rate of the melt is controlled throughout along the length of the sprue. If the sprues are too much tapered, there is a considerable increase in the speed of the melt even greater than the critical value. Which can be proved damaging for the mold or may result some other defects in the casting.

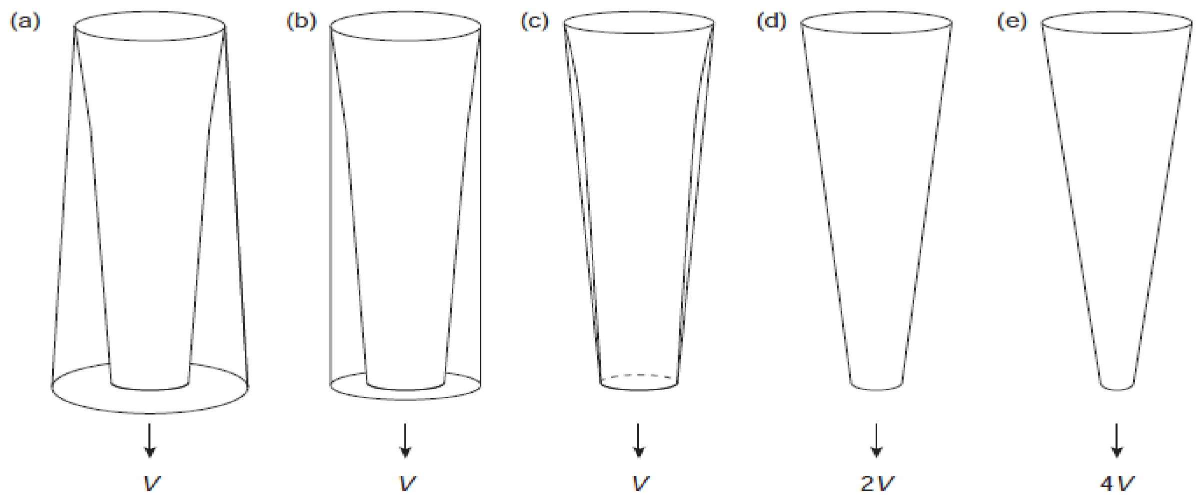


Figure 4. 12 A variety of straight tapered sprues

4.4.1 The well:

A very efficient design of the sprue base is a well with right dimensions and the shape. A design with a round sprue attached to a rectangular runner is not recommended because in such a case the melt bounds off the surface and turbulence is increased while the designs shown in section b and c of the figure shown below are perfectly alright.

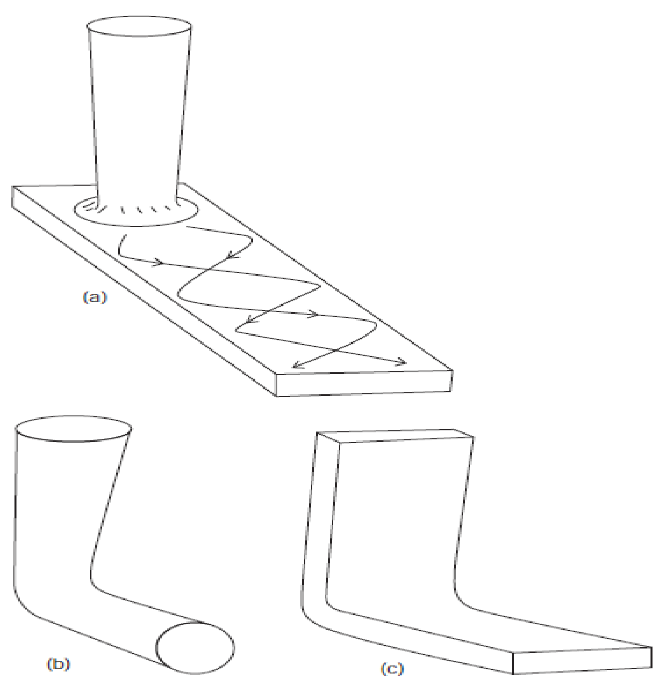


Figure 4. 13 (a) The joing of two different geometries has no solution other than adopting the other options (b) and (c) Either of these shapes are perfect [4]

4.4.2 Sprue/Runner Junction:

The junction where the sprue and runner are attached to each other must be curved instead of a sharp junction because a sharp junction can result in the creation of a vena contract which cause splashing of the melt and introduction of bubbles in the melt which is highly undesired. To avoid such situation, a fillet of suitable radius should be introduced at the junction which can minimize this undesired effects.1.

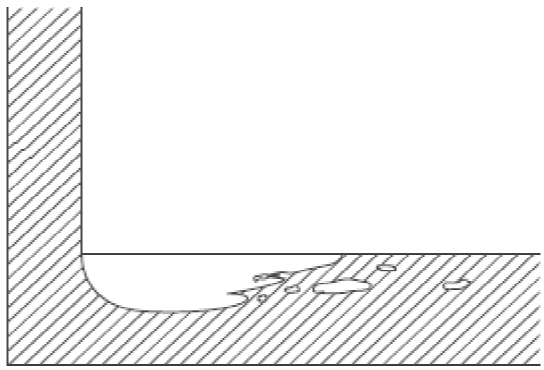


Figure 4. 14 The right angle problem during pouring

4.5 THE RUNNER

The runner is an important part of the casting process with the purpose to carry the melt horizontally under the mold or around the mold and to carry the metal to distant parts and cavities of the mold quickly. A runner is mostly horizontal in conventional casting process while there are inclined runners being used in vertically jointed-molds and investment molds.

The runner should be in such a way that helps to control the velocity of the melt to keep in under the critical value. Some of the strategies for this include:

- Filtration
- Introduction of some 90 degree turns in the runner. This can appreciably

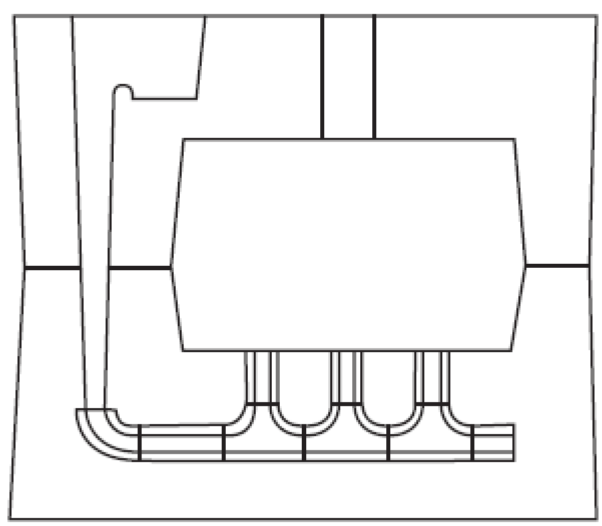


Figure 4. 15 A mold consisting of two halves i.e. cope and drag [9]

reduce the speed of melt but will introduce a lot of turbulence.

- Taper the runner to maintain the speed and introduce a number of gates instead of a single gate.

The process through which melt reaches from basin to farther most areas of the mold is described in following points:

- The metal reaches the bottom of the sprue from basin in some chaos.
- After this, it is gathered by the integration of filter and choke and provides some back pressure and delay.
- Now it moves up filling the running system against the gravitational force.
- Finally, it reaches the mold after runner with a speed under critical speed without having too much damages.

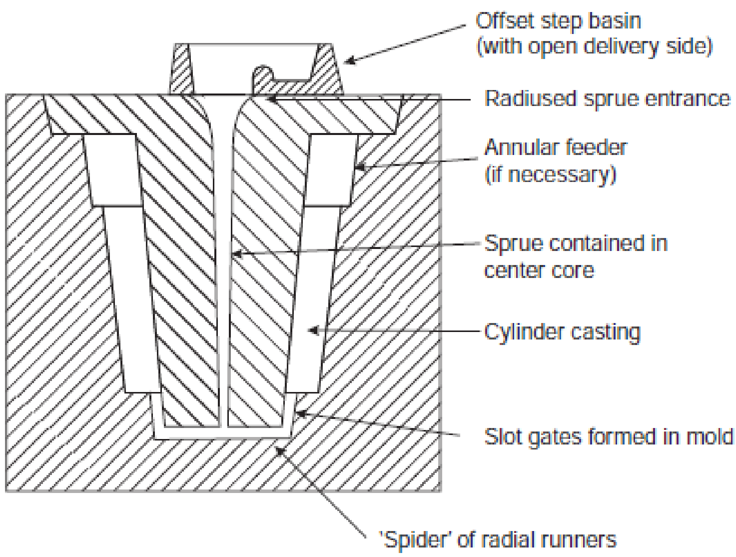


Figure 4. 16 Cylinder section of a casting pouring system [6]

4.6 THE GATE:

The gate is another very important part of the filling system that is responsible for direct transfer of melt from runner into the mold cavity. This part is highly critical in the success of the casting process.

4.6.1 Direct/Indirect Gates:

If the melt enters the mold through a direct gate, it will be entering with a high velocity which can cause turbulence within the mold cavity that is the most destructive turbulence anywhere during the casting process. So in order to minimize this problem, indirect gates are used that incorporate some right angled changes of direction before entering the mold reducing the speed of the melt.

Total area of the gates:

The total area of the gates should be such that the velocity of the melt entering the mold should not be higher than 0.5m/s to 1m/s

Multiple gates:

Multiple gates can be used instead of a single gate due to following reasons:

- Distribution of heat in the mold evenly
- Reducing hot spots
- Reduction in velocity
- To carry melt to the melt more evenly

4.7 ESTIMATION OF WEIGHT AND VOLUME:

Casting's weight is usually known or can be found out by estimation. This weight is actually an estimate to the weight of melt to be poured and if this weight is divided by the density of the melt, its volume will be estimated. Although the weight of the melt is difficult to calculate exactly but a near estimate is good enough for the calculation.

4.8 PRESSURIZED VS UNPRESSURIZED:

The unpressurized system where the measures taken to reduce the speed are enlargement of areas of the channels as melt flows through them so the speed faces a reduction in its magnitude as the area is increased but this is not good enough. An X-ray videography or simulation shows that the speed of the melt is still so high that it enters the runner like a jet and strike the opposite side of the runner. After striking, the melt splashes in the opposite direction and bubbles are formed within the cavity. Air and oxides are entrained in the casting and cause porosity at the end. In order to resolve the issue a pressurized mechanism is introduced where the metal flow is choked at the gate which the last point of the filling system. The choking causes the back filling and pressurized flow which force the system to fill and expels the air and oxides. In this way, there are less entrainment and better results are achieved. This mechanism too results in a jet of stream into the it is pressurized or unpressurized, have their own disadvantages or need further research to find a mold and cause damages to both, the mold and the casting in turn. So both the mechanisms either better solution of the problem.

Some other options to reduce the velocity include:

- Filters
- Special designed runner extension system
- Vertical fan gate at the end of runner
- Surge control system
- Using vortices

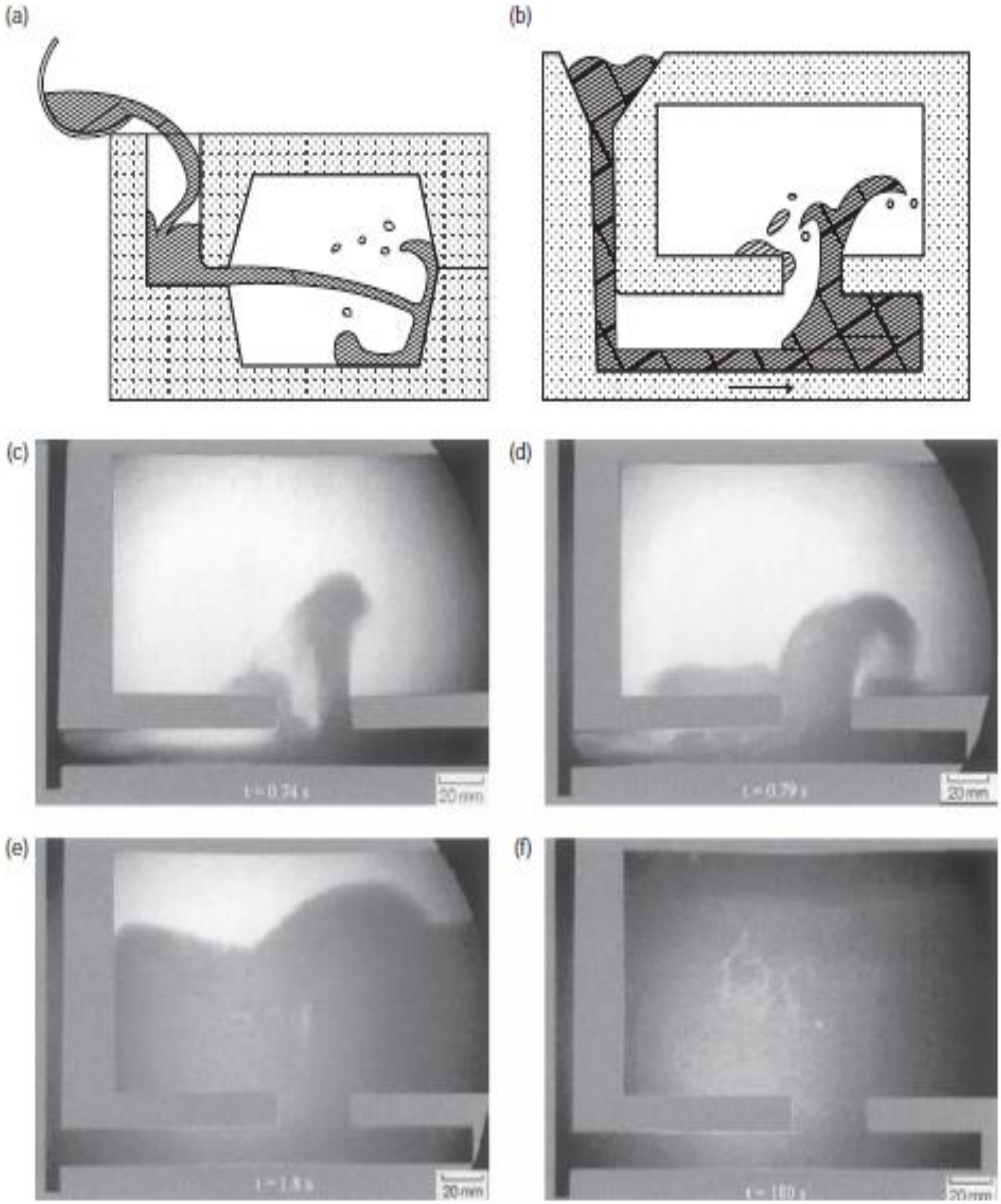


Figure 4. 17 Types of filling a) Side Pouring b) Bottom Pouring
(c-f) Bottom pouring at step time t=0.74, 0.79, 1.5 and 1.8 seconds [8]

4.9 POURING TIME:

It is a very important question that how fast a mold must get filled by the melt keeping in mind that velocity should not be over its critical value that is 0.5m/s. Since the pouring time depends directly on the volume flow rate of the melt which in turn depends on the speed of melt and area of the channels. Speed is limited and cannot cross the critical value so we can say the pouring time directly depends on the area of the channels. If the area of gates is increased, surely more melt can be transferred in less time and less velocity.

A very important thing needs to be considered while estimating pouring time that the thinnest section or smallest modulus of the casting should not be freeze before filling gets completed. An estimate of the time for these thin section can be taken from following graph:

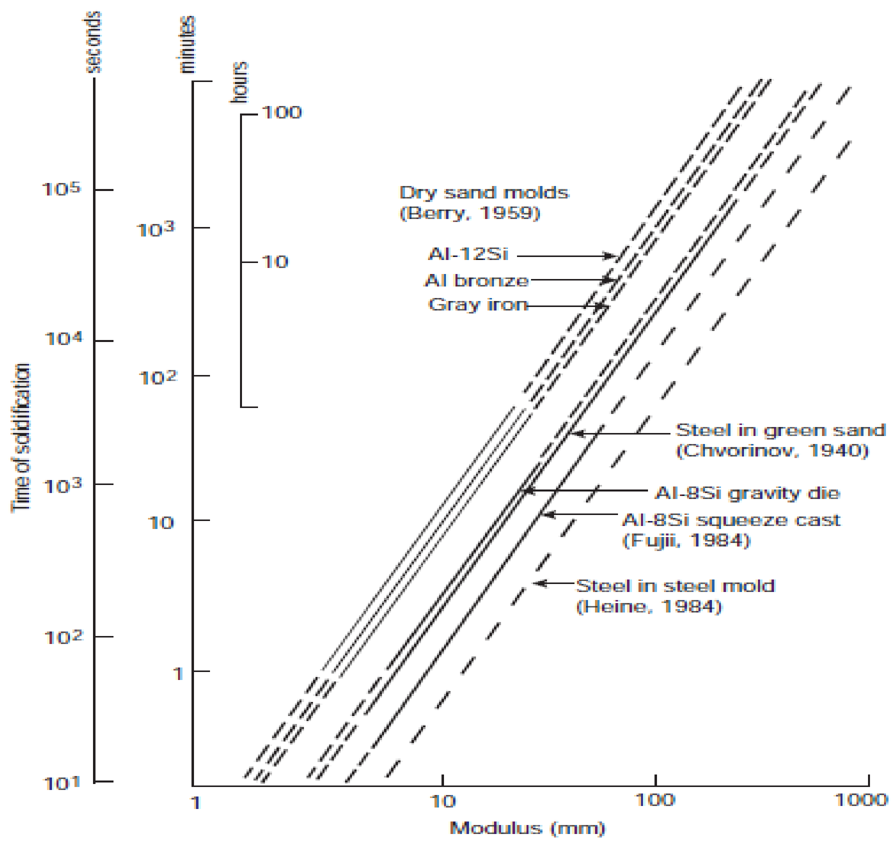


Figure 4. 18 Different alloys and molds freezing time for plates [10]

4.10 THIN SECTION AND SLOW FILLING:

It is important that thin sections should be filled as quickly as possible before freezing because freezing can stop these section to get filled but following are some points that show that slow filling is more successful:

- The high speed will cause more turbulence which leads to the entrainment of oxides and in result a defective casting is obtained.
- Filling mold at a lower speed will help the fluid to keep its meniscus together and in this way as the fluid travels together, it will keep itself warm because during splashing, oxidation takes place and fluid freezes quickly and gets attached to the walls of the mold. So when the fluid is travelling slowly and all together, it will remain hot for longer and thin sections will be easily filled and a better casting will be resulted with minimum defects.

4.11 FILL RATE:

Fill rate is simply the instantaneous volume flow rate of the melt. The average fill rate can be calculated by dividing the total volume by the total filling time. But it is usually the case that initial flow rate is higher than the average flow rate because as the mold is filled, the flow rate goes on decreasing and eventually becomes zero when the level of melt reaches the level of basin. A factor of 1.5 is generally taken to find the initial flow rate from average and it is true in most of the cases. Another factor that is observed from the experience that flow rate is reduced by a factor of 30% along the way due to drag and friction so we can find the design flow rate by multiplying 1.5 with 1.3.

$$1.5 \times 1.3 = 2.0$$

These values can be adjusted with experience. For example, after one trial it is clear that casting rate should be slower or faster so dimensions can be altered that is required only in a few millimeter.

CHAPTER 5: SYSTEM DESIGN AND SIMMULATION

Within a hydraulic system impeller plays an important role and can affect the pump efficiency if it's not in sound condition. Impeller casting of this particular subject impeller is very critical since it come up with multiple defects including shrinkage cavity, Porosity and cold shut etc. A lot of trial run were made but the casting results were not satisfactory. Before running the actual test run in casting the impeller was first simulated in Procast. The results that arrive in Procast are mentioned below.

5.1 Model Views:

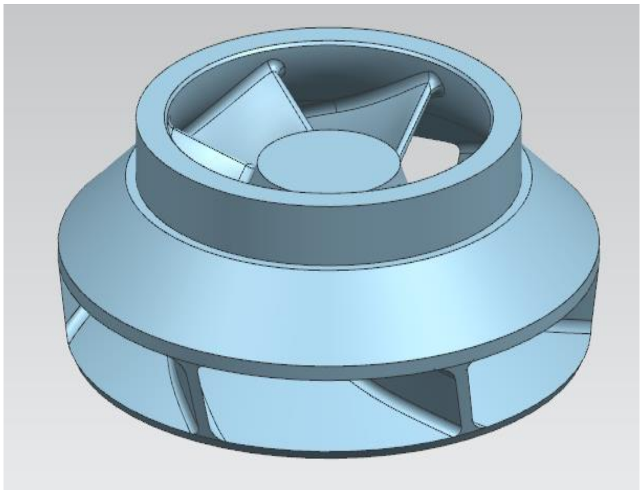


Figure 5. 2 Isometric View

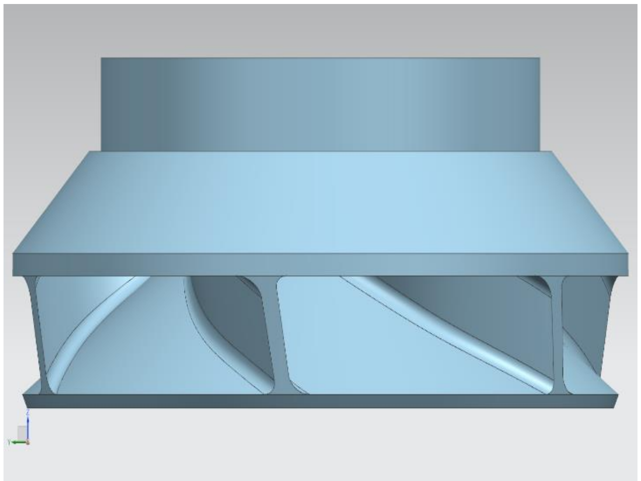


Figure 5. 1 Front View

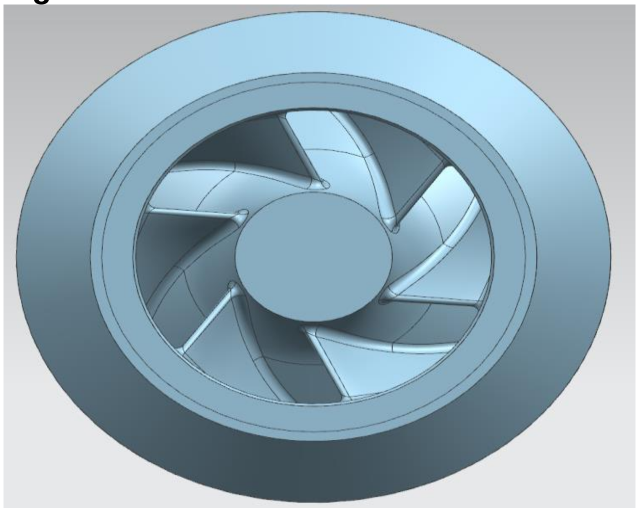


Figure 5. 4 Top View

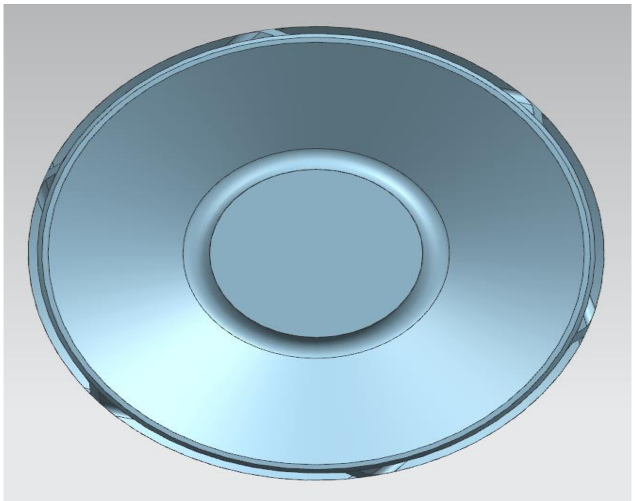


Figure 5. 3 Bottom View

5.2 Model Views with gating/feeding:

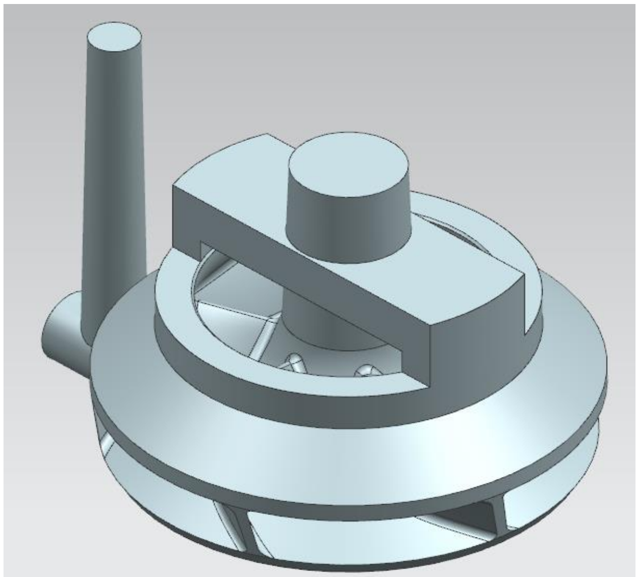


Figure 5. 6 Isometric view of model with gating/feeding

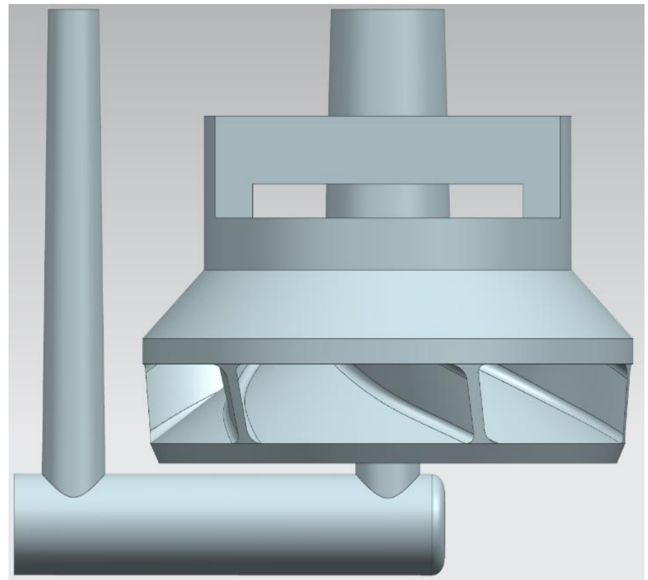


Figure 5. 5 Front view of model with gating/feeding

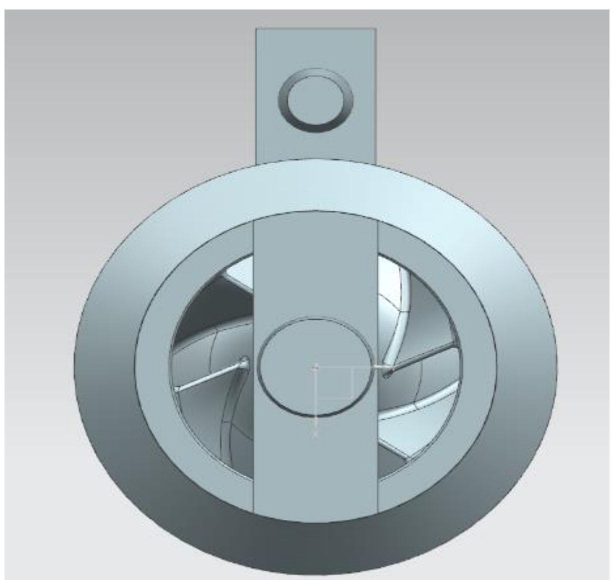
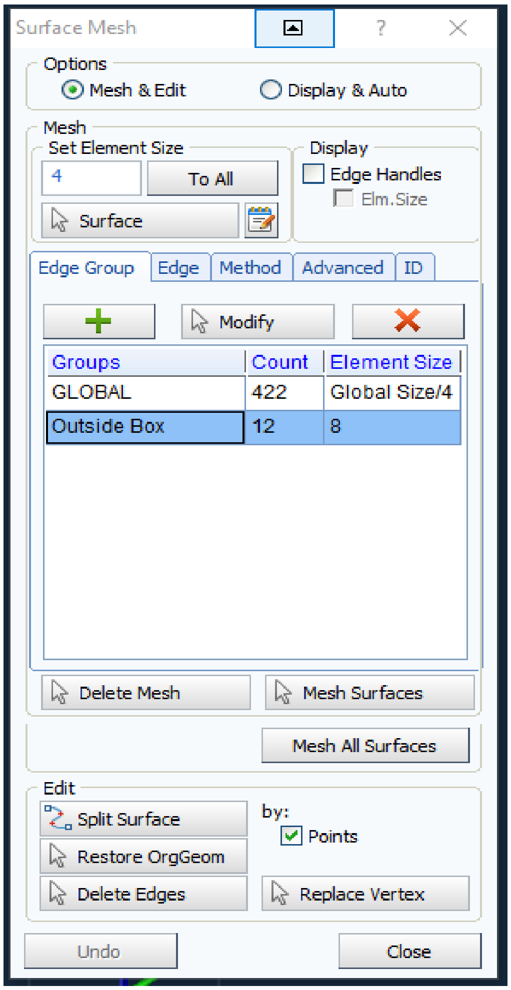


Figure 5. 7 Top View of model with gating/feeding

5.3 Mesh Creation in ProCAST (Visual Mesh):

After part 3D model generation it will imported in ProCAST Visual Mesh and the mold box will be created around it. After mold creation mesh will be generated. Mesh size can vary and depend on the criticality of the part. Smaller the mesh size the more accurate results we can get. After mesh generation part will be taken ProCAST visual Cast interface. Rough Mesh size of 8mm selected for outer Box and for Impeller Mesh size of 4mm has been selected.



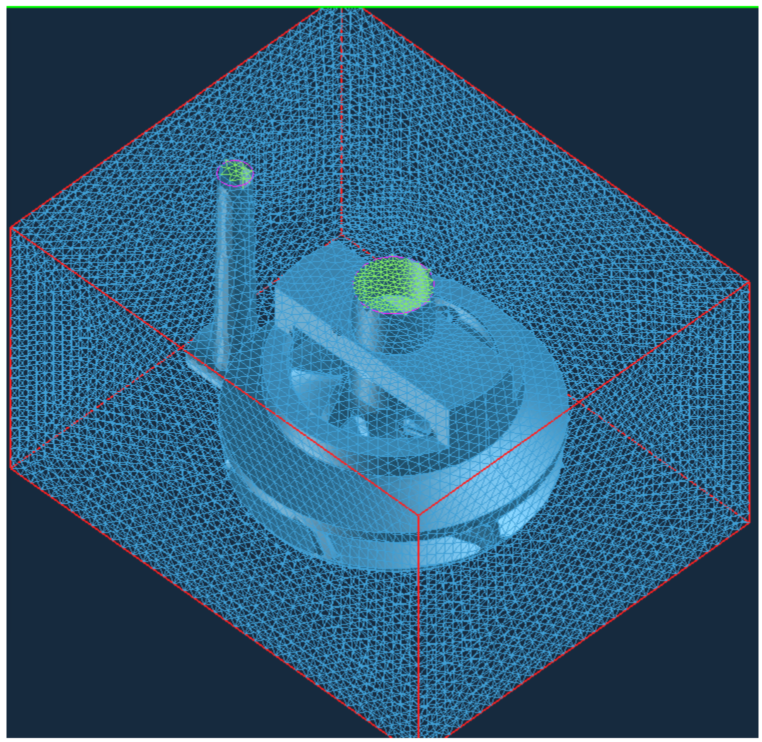


Figure 5. 8 Surface Mesh creation

Figure 5. 9 Surface Mesh size selection

After mesh size selection surface mesh has been generated and mesh error has been resolved later by using Auto Mesh correction option. Now tetra mesh has been generated after resolving mesh errors.

5.4 Visual-Cast:

After completing meshing process go to the Visual-Cast option. In visual-cast following parameters has been set for simulation run.

1. Pressure on mold.

   Pressure on outer box of mold is added i.e. 1 atm pressure.

2. Heat dissipation.

   Heat is absorbed by air cooling from the outside body of Mold box.

3. Inlet for pouring.

   Inlet point of pouring require fill time and temperature for mass flow rate

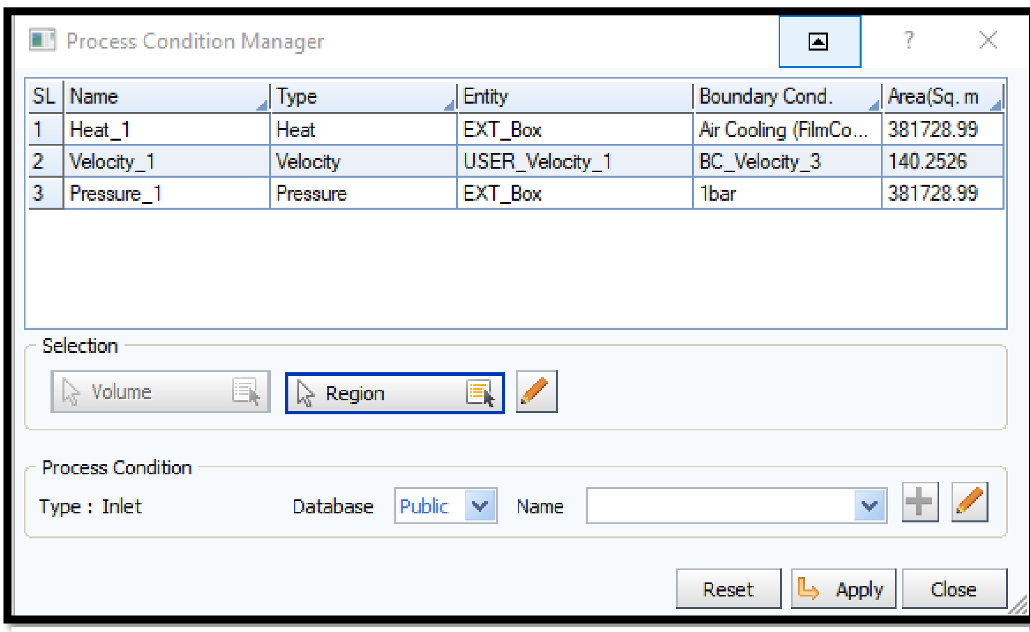


Figure 5. 10 Process condition variables

calculation. Also specify the inlet area by selecting the inlet surface.

Volume Manager is then used to assign material to the casted part and mold material selection. Pouring temperature that is also known as initial temperature. Also set the mold sand initial temperature.

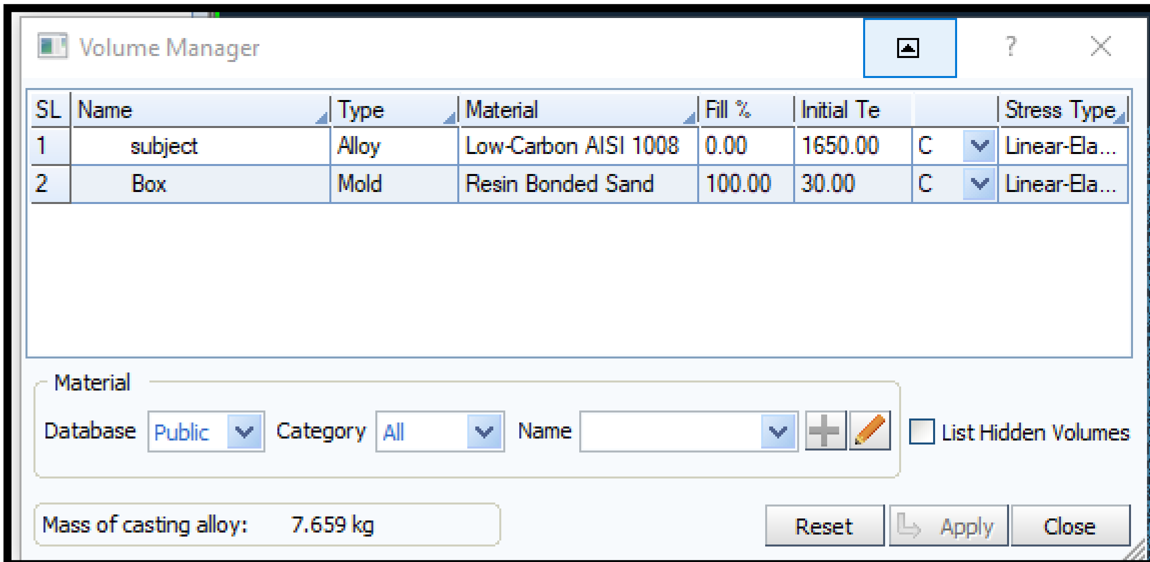


Figure 5. 11 Mass Flow rate calculator

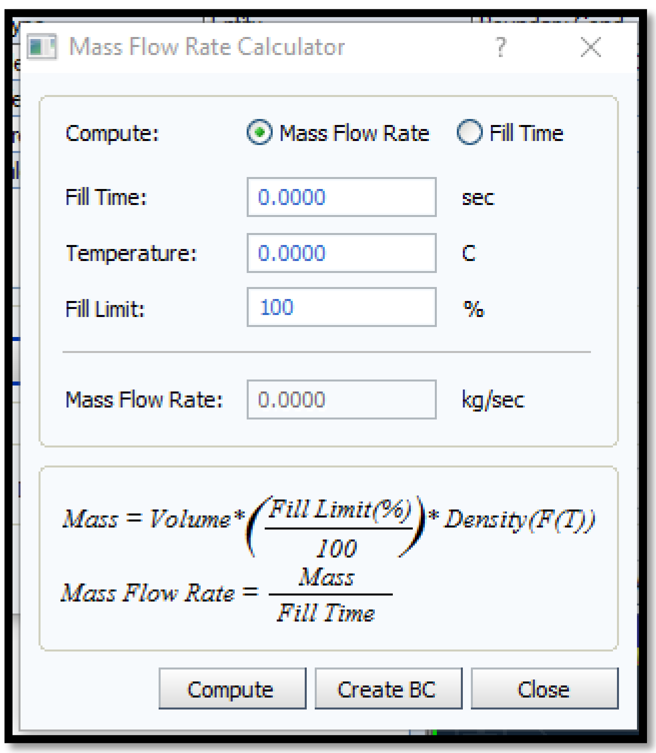


Figure 5. 12 Volume Manager, includes selection of material and temperature.

Interface heat manager is used to distinguish between materials whether the material is same or not. Following types of interface can be selected at two material interface. i.e.

1. Coincident (For different materials like mold and part differentiation.)
2. Non Coincident (For materials that have gap in between them and have different nodes location on their junction)
3. Equivalence (Both materials are similar)

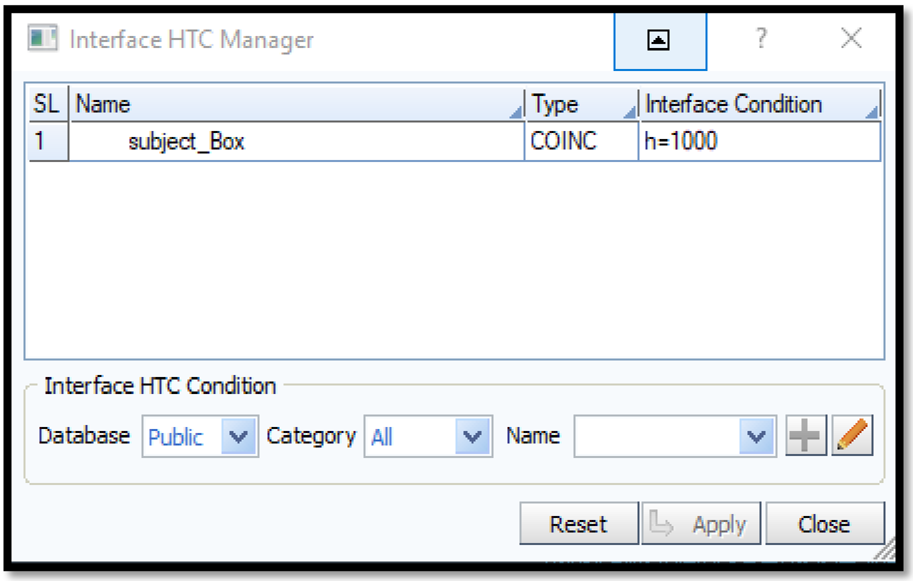


Figure 5. 13 Material interface manager

4. After setting initial parameters we have to set simulation parameter that can be seen in below figure. That includes Simulation time, Final simulation temperature and number of frames. Also we can set Advance Porosity Module (APM) and hotspot selection for simulation.

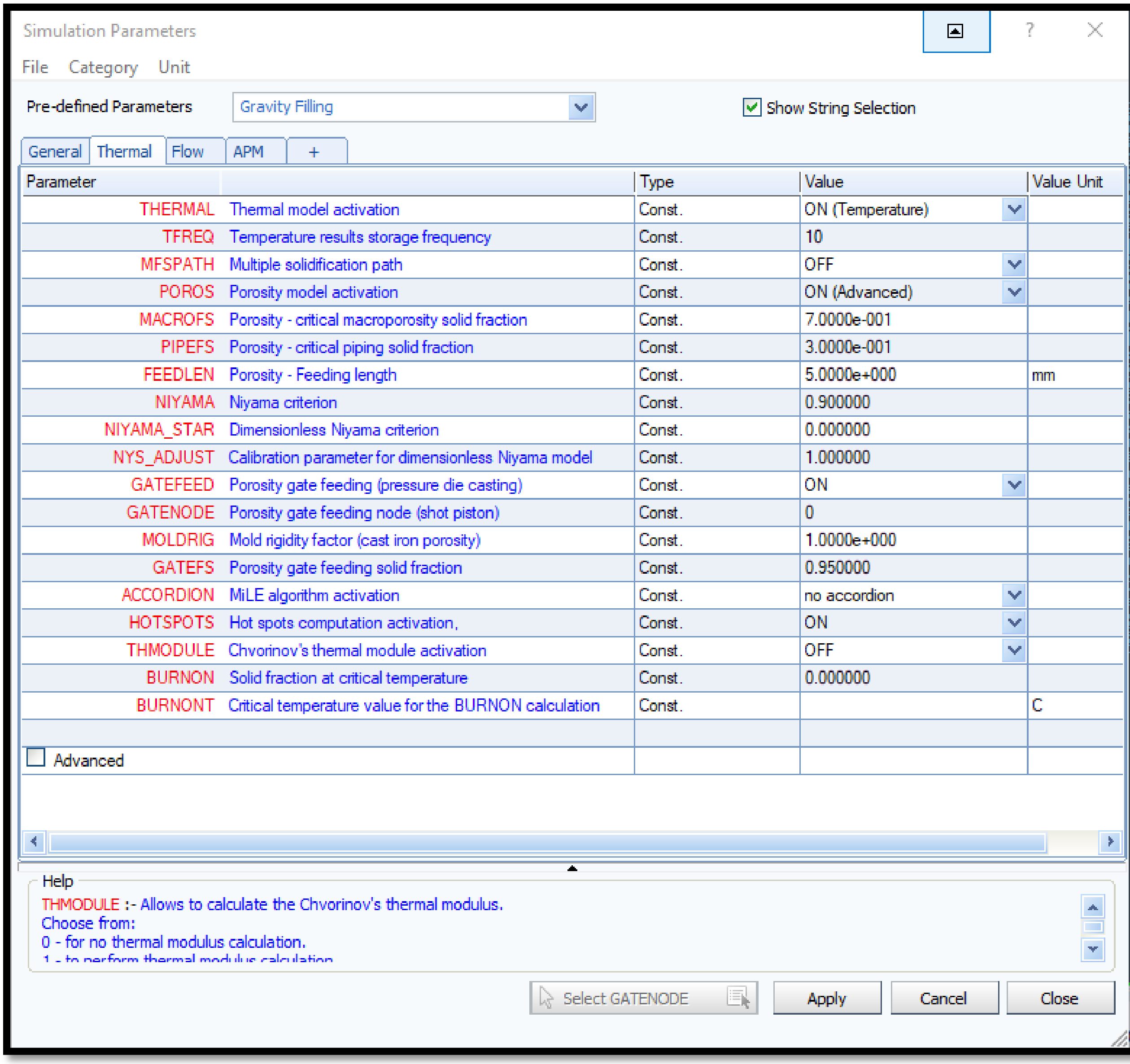


Figure 5. 14 Simulation Parameters

5.5 Visual-Cast:

After running simulation we will go to visual viewer for results that include following

1. Temperature
2. Fraction solid
3. Total shrinkage porosity
4. Hot spots
5. Temperature at fill time.
6. Fluid velocity

7. Voids
8. Fill time.
9. Displacement
10. Microstructure etc.

In our study we will focus on temperature, Shrinkage porosity, Niyama criterion and Hotspots.

CHAPTER 6: RESULTS AND DISCUSSION

In this chapter we will discuss the parameters taken for the test and their results after number of casting trails. The casting variables are mentioned below.

6.1 Pouring Temperature (C)

For steel it is recommended to go to temperature above 1600 C. That range is considered a good practice. For this particular case we took temperature 1600, 1625 and 1650.

6.2 Pour time (sec)

The pouring time should be such that to avoid back pressure and splashing and to avoid critical speed. If pouring time is very fast it can damage the mold. On the other hand if the inler velocity is very low then it will cause misrun.
We have taken an optimum range of 5, 7 and 9 seconds in this case.

6.3 Particle Size (AFS)

It is expressed as number of meshes per inch of the sieve which the sample sand would pass through. Bigger the AFS finer will be the grain size and smaller the AFS value bigger will be the grain size. The method used to calculate this number is called sieve analysis.

For mold making particle size 43, 45 and 47 has been taken into consideration. AFS of grain can be calculated using below mentioned formula.

$$\text{AFS}= \frac{\textit{Total product}}{\textit{Total percent of sand retained}}$$

6.4 Binder percentage

Three levels have been defined against each variable and using Taguchi L9 array we have plotted a matrix as shown in below figure. 7. In this case we took silica sand and the feron binder. The composition of binder was 1.5, 1.9 and 2.2.
Minimum 3 levels were defined for each variable and L9 matrix has been created as a result of which we have come up with 9 experimental trials.

Table 6. 1 Casting Parameters and Level Selection

Parameters	Unit	Level 1	Level 2	Level 3
Pouring Temperature	C	1600	1625	1650
Pouring Time	Sec	5	7	9
Grain Size	AFS	43	45	47
Binder Percentage	%	1.5	1.9	2.2

Table 6. 2 L9 Array of Casting Parameters

S.No.	**Pouring Temperature (C^o) ± 5C°**	**Pour time (Sec)**	**Particle size (AFS)**	**Binder Percentage**
1	1600	5	43	1.5
2	1600	7	45	1.9
3	1600	9	47	2.2
4	1625	5	45	2.2
5	1625	7	47	1.5
6	1625	9	43	1.9
7	1650	5	47	1.9
8	1650	7	43	2.2
9	1650	9	45	1.5

6.5 Main Effect Plot:

The main effect plot against misrun, Shrinkage porosity and Blow holes has been extracted from the experimental results and has been plotted. The effect of all changing variables can be seen in this plot.

6.5.1 Against Misrun:

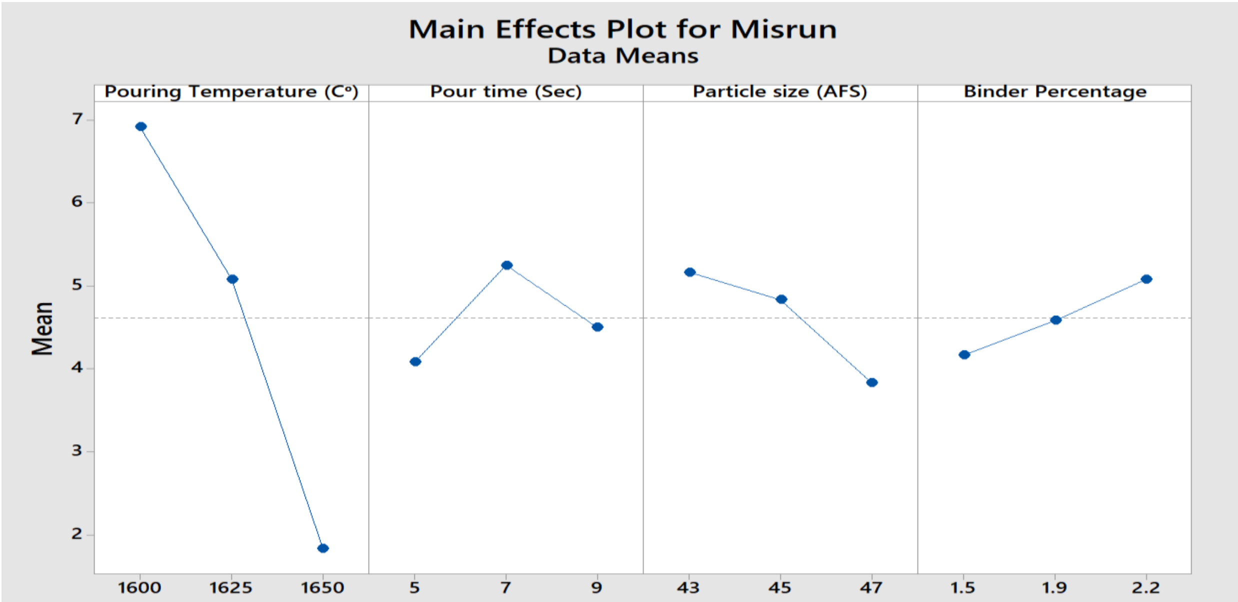


Figure 6. 1 Main effects Plot for Misrun

After running ANOVA the results has been shown below.

Table 6. 3 ANOVA result against Misrun

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value	Significance
Pouring Temperature(C°)	2	62.53	78.71%	62.527	31.263	53.6	0	Significant
Pour time (Sec)	2	10.78	13.57%	10.777	5.388	9.24	0.007	Significant
Particle size (AFS)	2	0.361	0.45%	0.361	0.18	0.31	0.741	Not Significant
Binder Percentage	2	0.528	0.66%	0.527	0.263	0.45	0.65	Not Significant
Error	9	5.25	6.61%	5.25	0.583			
Total	17	79.44	100.00%					

6.5.2 Against Shrinkage Porosity:

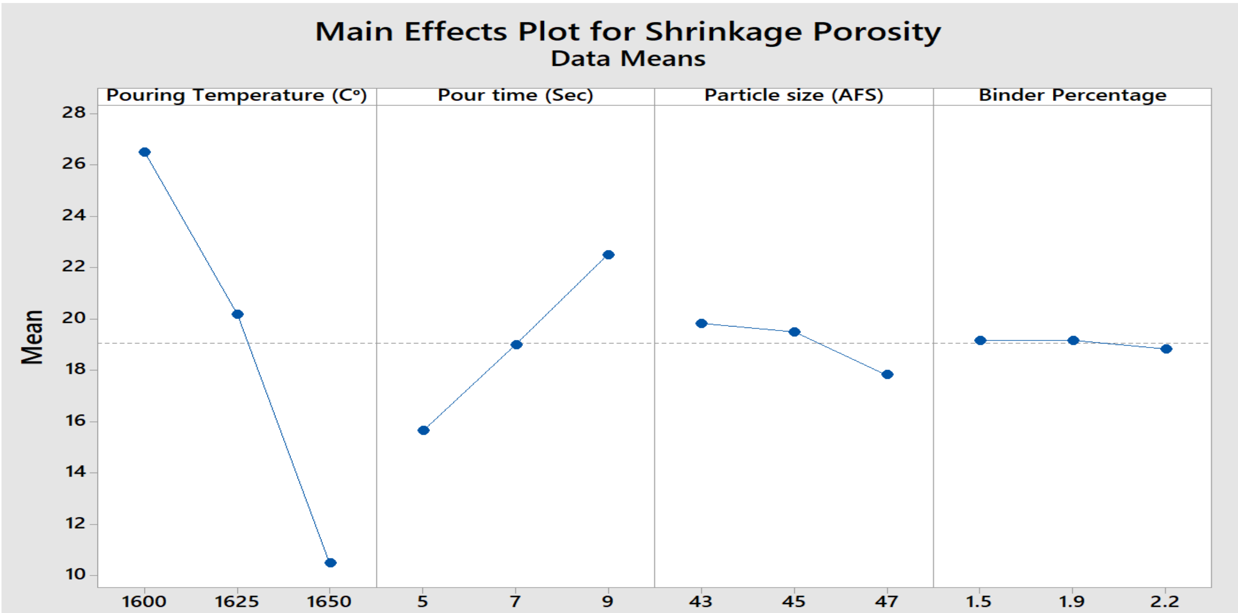


Figure 6. 2 Main Effects Plot for Shrinkage Porosity

After running ANOVA the results has been shown below.

Table 6. 4 ANOVA results against Shrinkage Porosity

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value	Significance
Pouring Temperature (C°)	2	779.1	82.45%	779.11	389.556	304.87	0	Significant
Pour time (Sec)	2	140.1	14.83%	140.11	70.056	54.83	0	Significant
Particle size (AFS)	2	13.78	1.46%	13.77	6.889	5.39	0.029	Significant
Binder Percentage	2	0.444	0.05%	0.44	0.222	0.17	0.843	Not Significant
Error	9	11.5	1.22%	11.5	1.278			
Total	17	944.9	100.00%					

6.5.3 Against Blow hole:

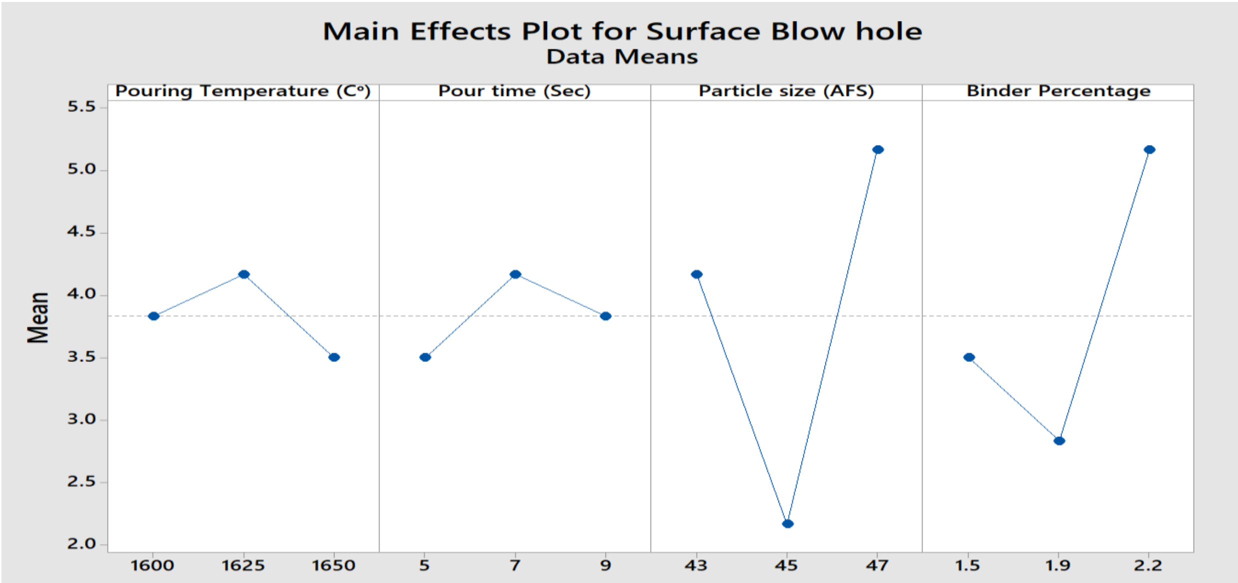


Figure 6. 3 Main Effects Plot for Surface Blow Hole

Table 6. 5 ANOVA results against Blow Hole

Source	DF	Seq. SS	Contribution	Adj. SS	Adj. MS	F-Value	P-Value	Significance
Pouring Temperature (C°)	2	1.33	2.54%	1.333	0.667	1.33	0.311	Not Significant
Pour time (Sec)	2	1.33	2.54%	1.333	0.667	1.33	0.311	Not Significant
Particle size (AFS)	2	28	53.33%	28	14	28	0	Significant
Binder Percentage	2	17.3	33.02%	17.33	8.667	17.33	0.001	Significant
Error	9	4.5	8.57%	4.5	0.5			
Total	17	52.5	100.00%					

6.6 Confirmation Experiments:

After getting the required results a confirmation test has been run on all variables based on their best and worst conditions.

Table 6. 6 Confirmation experiments for Misrun, Shrinkage porosity and Blow hole

Confirmation Experiment								
	Input Parameters						**Results**	
Exp.	**Temp(C) ± 5C°**	**Pouring Time (Sec)**	**Grain size (AFS)**	**Binder%**	**conditions**	**Responses**	**Obs. 1**	**Obs. 2**
1	1650	5	47	1.5	Best	Misrun	0	0
2	1600	9	43	2.2	Worst	Misrun	7	6
3	1650	5	45	1.9	Best	Shrinkage porosity	5mm	6mm
4	1600	9	43	1.9	Worst	Shrinkage porosity	30mm	35mm
3	1650	5	45	1.9	Best	Blow hole	0	0

6.6.1 Confirmation test for Shrinkage porosity.

Figure 6. 4 Confirmation test for Shrinkage porosity

Best Worst

6.6.2 Confirmation test for Misrun.

Best Worst

Figure 6. 5 Confirmation test for Misrun

6.6.3 Confirmation test for Blow hole.

Best Worst

Figure 6. 6 Confirmation test for Blow hole

6.7 Simulation results of Shrinkage Porosity confirmatory experiments:

6.7.1 Boundary Condition:

- T=1650 C; t=5 sec, grain size: 47; Binder: 1.5% (Best)
- T=1600 C; t=9 sec, grain size: 43; Binder: 2.2% (Worst)

6.7.2 Shrinkage Porosity:

Shrinkage porosity simulation result of both best and worse condition is shown in below Figure 6.7. The simulation condition matches with the earlier experimentations that were conducted.

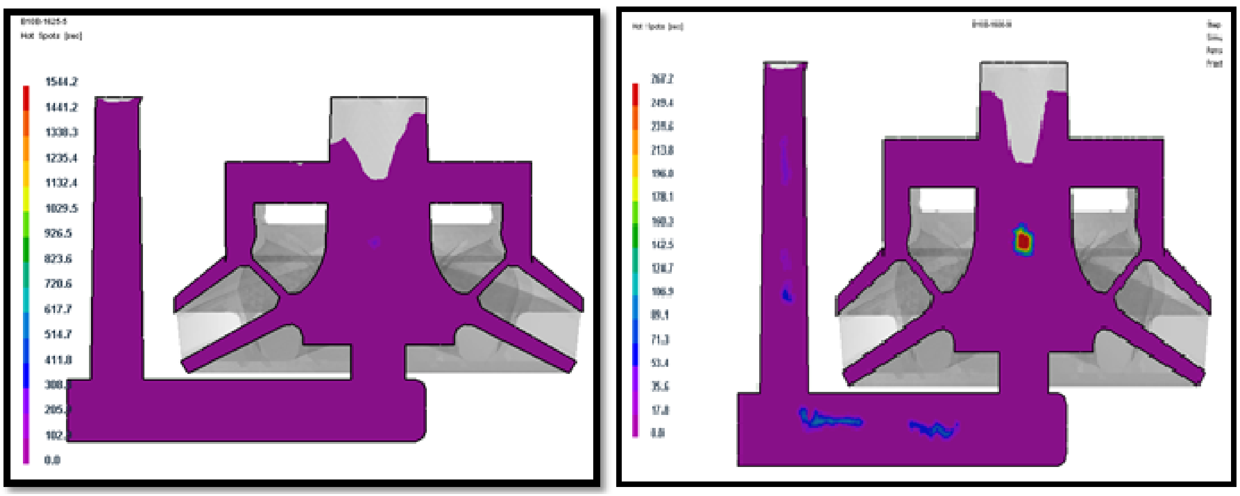


Figure 6. 7 Shrinkage Porosity Simulation Results of the best and worst condition

6.7.3 Voids:

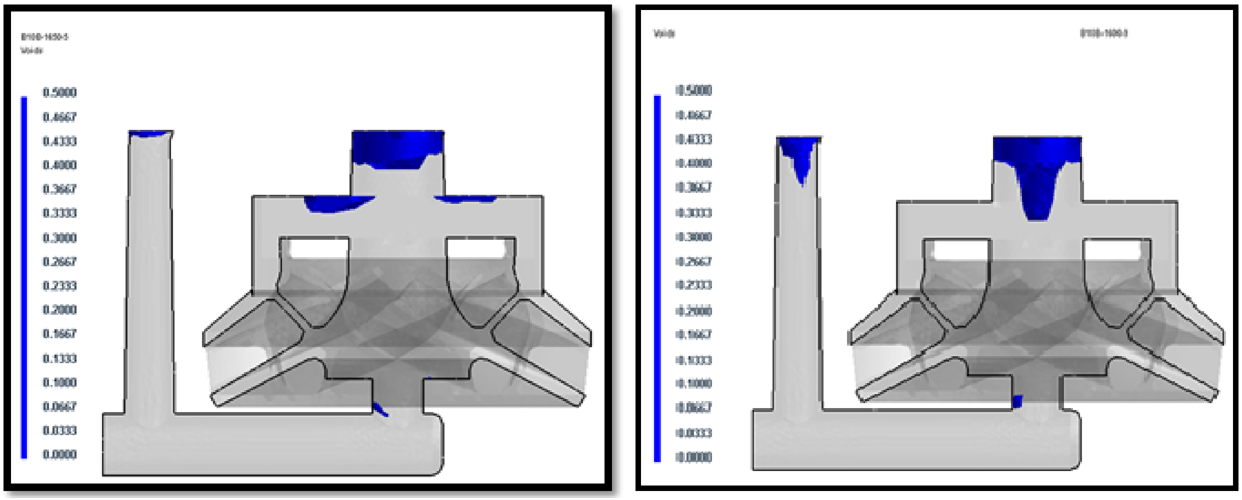


Figure 6. 8 Voids Simulation Results of the best and worst condition

6.7.4 Solidification Time:

The simulation time result of cross sectional view provides the complete overview of rate of solidification in the subject part. The solidification rate has been shown in below Figure 6.9.

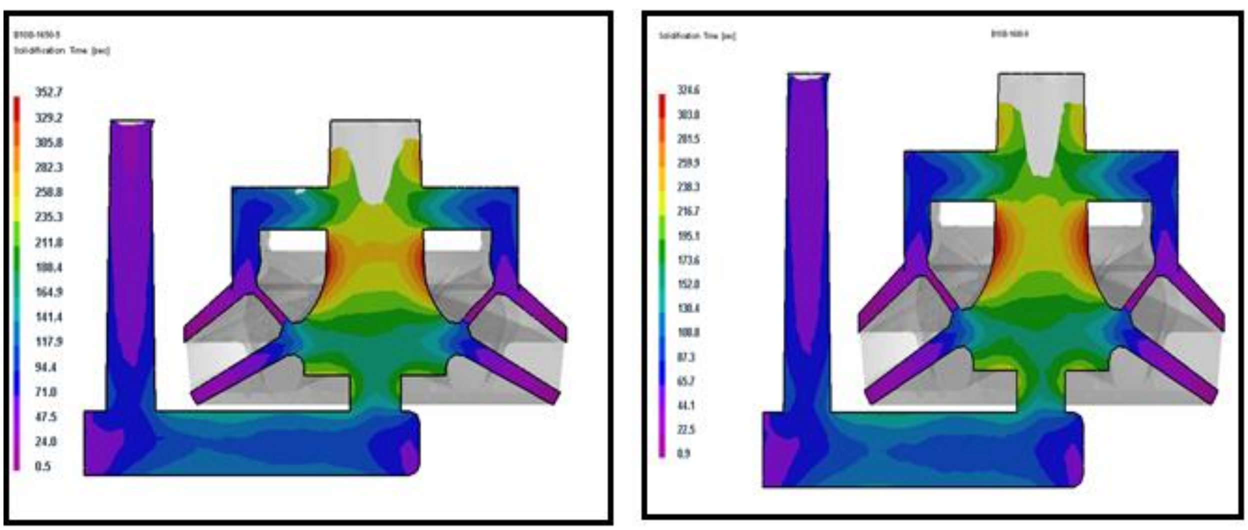


Figure 6. 9 Solidification Time Simulation results of the best and worst condition

APPENDIX A

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