# Material Matters

## Steel Casting Design Considerations

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### INTRODUCTION

Needless to say, that as a pump manufacturing company, IPG is highly dependent on castings. Performance characteristics such as flow, pressure, temperature, corrosion and wear resistance are all contained in one set of cast parts forming the liquid end of a pump.

Despite their bad rapport in issues of quality and delivery, castings represent the simplest path from an engineering design to a complex metal shape. They provide a freedom of design and choice of engineering materials unequaled by any other metal forming process.

Furthermore quality castings are not more difficult to attain than any other quality product in other fields of manufacture. Typical of all engineered items, castings reflect quality only after a detailed study, application of basic principles and adherence to proven methods.

The casting process has gained a reputation as a technique to create almost any shape the designer can envision, but whether or not that shape can be cast economically is another matter. Many casting defects are not due to lack of foundry capability.

Acceptable castings, both in quality and cost, start at the design stage, therefore close cooperation between competent foundry and design engineering groups is paramount. This is an important consideration when selecting High Alloy casting suppliers.

Regrettably, many cast parts for all types of machinery have been designed without much consideration to the casting process itself, and it is left to metal casters to implement ingenious but costly means to overcome manufacturing odds posed by the design. In Lean-Six Sigma terms, this is inherent waste and variation that generates scrap, rework and excessive cycle time and cost. None of that can be fully corrected until both, design and tooling are improved.

In this article we will cover steel castings, which are particularly sensitive to geometric factors. In the case of IPG, we are mainly concerned with materials from the High Alloy Steel family, representing a wide variety of complex corrosion resistant alloys used in some of the most demanding applications.

Some of the fundamental metal casting principles required to understand steel casting design will be discussed. Further related material such as design rules and methodology, engineering specification aspects, process simulation etc. may be covered at a later date if interest exists.

### NOTE ON GRAPHICAL INFORMATION:

Most of the pictures in this article are graphic outputs from the casting simulation program ProCast, which is an advanced finite element software package, capable of reproducing casting processes with a high degree of accuracy.

### HEAT TRANSFER

The production of a casting is, to a large extent, the manipulation of heat in a mass of metal. Starting at the beginning, melting and refining furnaces convert electrical or chemical energy into heat. This heat is put into the metal to melt it and provide the energy required for various chemical reactions. Hence we have liquid metal of the desired chemical analysis. How we remove the contained heat in the metal between the furnace and the mold shakeout operation will govern much of the quality in the casting.

After metal is poured, heat is extracted by the mold mass. Heat flow occurs by all three modes of transfer – conduction, convection and radiation. In the case of sand molds the mode is predominantly conduction by the sand grains with some convection through vapor transfer. In the case of investment castings, where the shell mold is preheated at high temperatures, the mode is predominantly radiation.

In sand molds the heat transfer driving force is, of course, the temperature difference between casting and mold. The temperature difference over a finite length is called the thermal gradient; this variable is a major factor in our ability to produce sound sections as we will see. Of course, the thermal gradient changes with time, in other words, as the casting cools down the mold get hotter (Figs. 1 and 2).

### THE SOLIDIFICATION PROCESS

Depending on section size, liquid steel may take seconds or hours to become solid. It is during this period of time that many important characteristics affecting casting quality are determined. The primary crystal structure is established upon which many physical and mechanical properties depend. It is also during this time that a variety of major defects are formed such as shrinkage and hot tears. Thus it is important to consider the mechanisms by which a metal solidifies and the techniques which the metal caster has at his disposal to control the solidification process.

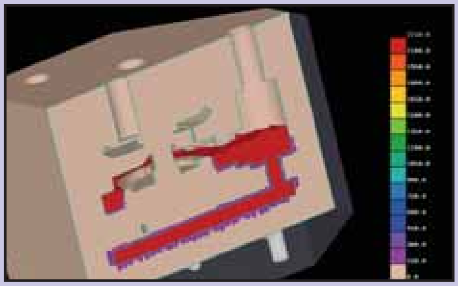

*Fig. 1. Temperature distribution in a sand mold during the pouring of a casting. The mold at large is still at room temperature.*

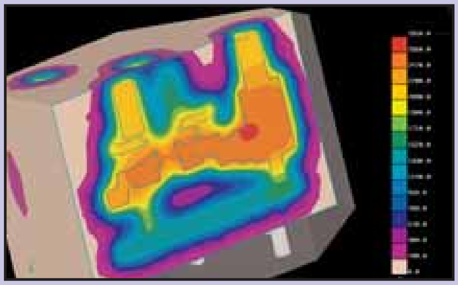

*Fig. 2. The same part later on towards the end of solidification. Notice sand regions as hot as the metal that surrounds them.*

### SOLIDIFICATION MODES

The conditions in a pool of liquid steel can be compared to those inside an erupting volcano, hence highly energized particles of liquid and gas move about violently in a state of apparent disorder. When metal solidifies, its atoms arrange themselves into highly organized primary structures called crystals. These crystals nucleate into tiny grains in the liquid metal and then grow under the physical and thermal conditions that prevail. For metal casting purposes, the most important consideration is dendritic growth, that is, the formation of Christmas tree like structures growing into the liquid in opposite direction to the heat flow (Fig. 3).

The solidification of high alloy steels is highly complex, however for foundry practice purposes they can be treated as binary (two component) solid solutions which solidify over a temperature range. As an example, grade CF8M (type 316) cast stainless steel begins solidification at near 1400°C (Liquidus temperature) and finishes at near 1370°C (Solidus temperature). The difference between these two temperatures is called the "freezing range"; hence the freezing range for CF8M is 30°C.

The freezing range determines to a great degree the way shrinkage porosity forms in castings and how difficult it is to prevent it. CF8M would

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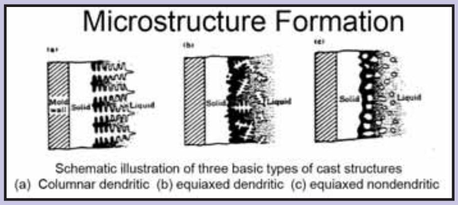

*Fig. 3 – Structure on the left typical of steel castings.*

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be classified as a narrow freezing range alloy while the duplex grade CD4MCU (Around 170°C FR) would be a medium to wide freezing range alloy. Narrow FR alloys tend to concentrate most of the shrinkage at hot spots and centerlines and develop few but large voids, these alloys respond well to feeding with risers and other techniques. Wide FR alloys tend to have the shrinkage dispersed over larger areas and are more difficult to feed with risers.

### VOLUMETRIC CONTRACTION

From pouring to room temperature, steel undergoes three distinct volumetric changes:

**Liquid contraction:** The liquid mass is contracting as it cools towards the melting point. The main result is a loss of volume at the top of the casting. Liquid contraction increases with pouring temperature and will affect the severity of shrinkage cavity defects in many cases.

**Solidification contraction:** There is a major contraction taking place throughout the freezing range. For instance, in the case of CF8M there will be around a 5% volume loss between 1400°C and 1370°C. If not corrected, this volume change will result in shrinkage cavities in the casting.

**Solid state shrinkage:** The contraction from the Solidus to room temperature results in dimensional changes in the casting. The average contraction per unit of length is the patternmaker's shrinkage rule for a particular alloy. This contraction also affects solidification by the formation of air gaps at the mold metal interface, which impair heat flow.

### SHRINKAGE ELIMINATION BY RISERING:

Shrinkage takes place on casting zones last to solidify, therefore solidification time is an important consideration in the prediction of shrinkage cavities and it is influenced by shape and dimensions. This relationship is best expressed by the Chovorinov equation:

$T = k(V/S)^2$

Where T is the solidification time, V the volume of a discrete casting zone and S the cooling surfaces in that zone. The constant k is mainly related to alloy composition. The ratio V/S is the solidification modulus SM. The greater the SM the longer the solidification time, therefore by calculating SM values in the casting we can predict the solidification sequence and the presence of isolated hot spots.

Risers are added metal shapes with a greater solidification modulus than that of the casting; therefore they are last to solidify and act as a reservoir of liquid that compensates for the loss of volume in the casting. Thus the risers will contain the shrinkage cavities and, after they are removed, the actual casting will be sound (Figs. 4 and 5).

Mold yield or the ratio of saleable casting weight to poured weight is an important cost factor. In the design of risers we strive for shapes that contain the least amount of metal for a given SM, and that are easy to mold. Hence cylinders of high aspect ratio are the most common shapes. The following rule is most important in the performance of risers:

SM (riser) > SM (riser connection) > SM (casting section being fed)

The metal caster also makes use of a variety of mold materials to manipulate heat flow. Some materials increase solidification time (insulating and exothermic), some decrease solidification time (chilling).

### PROGRESSIVE AND DIRECTIONAL SOLIDIFICATION

In the case of uniform thickness plates, steels begin to solidify at the mold wall and progress more or less evenly towards the center of the casting, we call this progressive solidification. When solidification fronts meet at the thermal center, shrinkage accompanies the solidification of the remaining liquid. Because any channels for additional feed metal are closed off, this results in centerline shrinkage. (Fig. 6)

When solidification begins at a point in the mold far from the riser and moves uniformly towards it, because of the shape of the solidification front, feed metal can reach this area and centerline shrinkage is eliminated. This is directional solidification.

Both types of solidification will occur in the same casting. We attempt to design our castings so that directional solidification prevails and castings can be produced functionally sound with a minimum number of risers (Figs. 7 and 8).

### HOT SPOTS

Hot spots are slow solidifying localized casting zones that can result in major shrinkage defects. A typical hot spot is the "Y" junction at the cutwater in casings. Hot spots are formed by section junctions of various types. For instance "T" junctions caused by the addition of ribs and bosses to the pressure wall of a casting are difficult and costly to feed and will increase the probability of defectives.

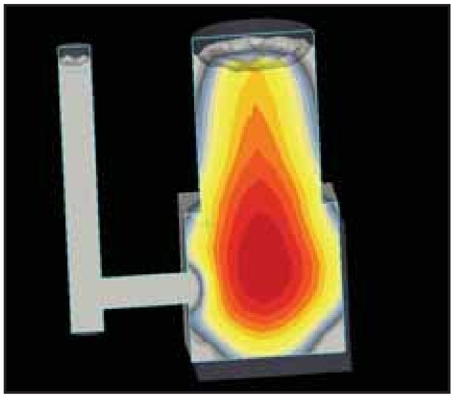

*Fig. 4. Solidification of cube casting with improperly designed riser and riser connection. Shrinkage will occur in the dark red zone.*

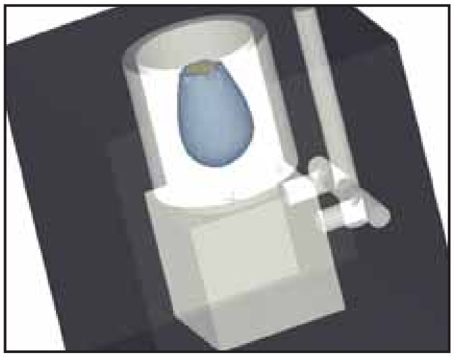

*Fig. 5. Shrinkage porosity plot of the same cube casting with a well designed risering system. Notice, the shrinkage is only in the riser,*

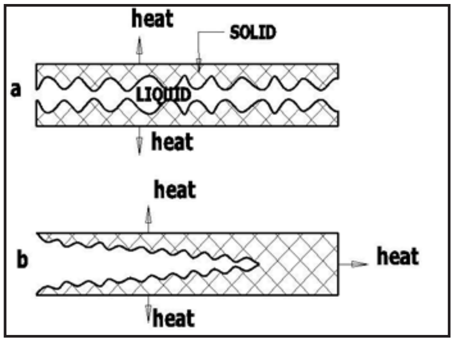

*Fig. 6. Solidification of steel plates:*
*(a) - Progressive solidification.*
*(b) - Directional solidification.*

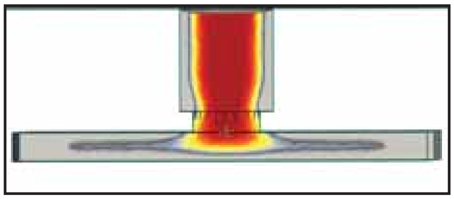

*Fig. 7. Progressive solidification taking place between riser temperature gradient and plate end zones. This will result in centerline shrinkage.*

In designing for improved castability we attempt to reduce the number of hot spots by eliminating or simplifying junctions and by bridging two or more hot spots into one. The aim is to design directional solidification along as few solidification paths as possible, thus minimizing the number of risers required.

### OTHER TOPICS RELATED TO CASTING DESIGN NOT COVERED IN THIS PAPER:

- Natural end zones and feeding distances.
- Analysis of solidification by the inscribed

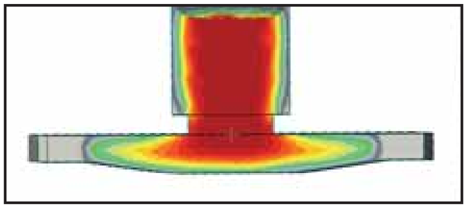

*Fig. 8. Same plate as on Fig. 7 with directional solidification artificially generated by adding taper to the plate. Casting will be sound.*

circle method (Heuvers).

- Increasing the thermal gradient by chilling or insulating.
- Sequential feeding of plate sections.
- Feeding pads and tapers.
- Metal flow in molds- Gating systems.
- Hot tearing and hot cracking: Stress-strain casting cooling considerations.
- Casting design and heat treatment distortion issues.
- Improving ease of molding and cleaning through casting design.

## A WORD ABOUT PROCESS SIMULATION

The application of 3D modeling and process simulation techniques are a great aid in casting design engineering. As stated earlier the Ashland Foundry uses the program ProCast to evaluate many of our castings. At present we have the ability to simulate coupled metal flow and heat flow, solidification and cooling. Other software modules exist to simulate mold cooling stresses, and to predict as cast microstructure and mechanical properties.

With the metal flow module we can evaluate cooling conditions during pouring as well as turbulence, air pockets, speed of fill and unbalance in the flow rates at the different points of entry into the mold cavity (ingates). This information is helpful for improving gating systems that is the set of channels that direct molten metal from a pouring ladle into the mold cavity.

With the solidification package we can evaluate feeding, hot spots and predict casting soundness.

The output is empirical data in the way of various color coded animations and maps. We can also obtain charts of various kinds. The quality of the information depends on the accuracy of the CAD models and on input variables, such as the thermo physical properties of the materials involved. As a rule, simulation results should not be taken as criteria for conclusive action but rather as guidelines for quality decision making.

## COMMENTARY

A few examples of design improvements in actual IPG stainless steel parts are shown in Figs. 9 to 14. As mentioned in the introduction the material covered in this text is only intended to give an idea of the possibilities for improvement by an understanding of the basic principles involved.

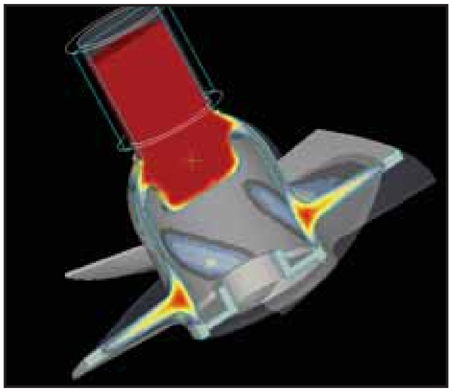

*Fig. 9. Axial flow impeller with hot spot at the vane-hub junctions. Major shrinkage will take place near cavitation prone surfaces.*

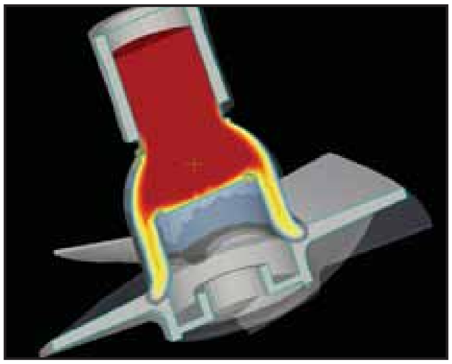

*Fig. 10. Axial flow impeller junctions made sound by providing directional solidification towards the riser though desing change.*

Many cast metals do not respond to directional solidification feeding, thus the approaches indicated in this write up do not apply to them. Such is the case with gray iron, ductile iron, white irons, high carbon steels and the majority of non ferrous alloys.

Over-specification and the fear of it is another common cause for excessive risering and non value added foundry operations. Attaining level 2 radiographic quality may be easy in a stuffing box cover but it is nearly impossible with a double suction impeller. The goal in the manufacture of a product is to provide the required performance and functionality at minimum cost. In the case of castings, it may mean avoiding overly conservative risering systems and allowing the possibility of centerline shrinkage in ways that the service of the part is not affected. It may also mean talking our customers away from costly NDE inspections and upgrade repairs, which do not improve part performance at all.

## CONCLUSION

Reiterating previous comments, good design improves ease of manufacture. Ease of manufacture translates into castings that are purchased at a lower cost, are of high quality and are delivered on time. We should add that, over the years, the Ashland Foundry has received excellent cooperation by the SFO, AO and VPO engineering groups in the design improvement of many cast parts.

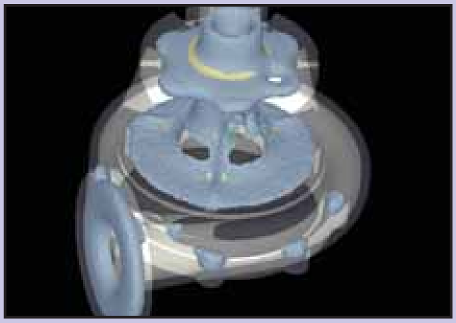

*Fig. 11. Solidification of 3171 casing showing eleven isolated liquid pools likely to result in shrinkage.*

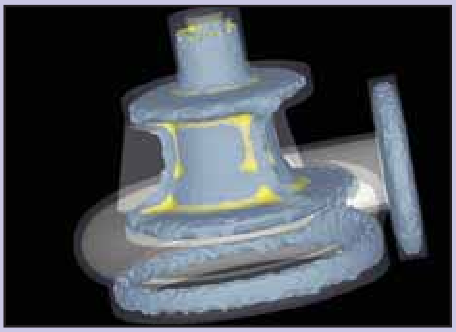

*Fig. 12. Design modifications in the 3171 casing have reduced the number of feeding zones from eleven to three. The result will be an improvement in integrity and manufacturing costs.*

All aspects of this topic cannot be covered in a single article, however much can be accomplished through an understanding of the basic principles involved. If anyone would like to probe deeper into this subject, please contact the writer.

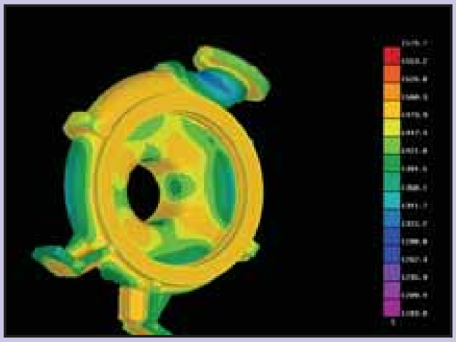

*Fig. 13. Temperature plot of casing with a ribbed design. This part needed eleven risers and was prone to hot cracking.*

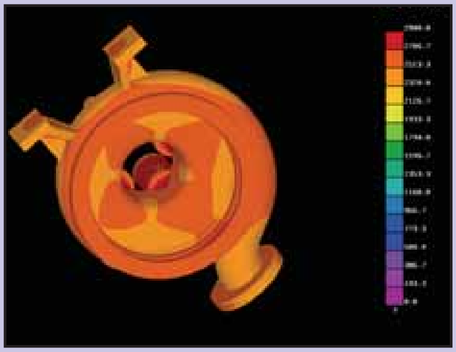

*Fig.14 – Reductions in the number and size of ribs resulted in improved temperature uniformity. The number of risers was reduced to seven.*