Casting Design and Simulation of Cover Plate using AutoCAST-X Software for Defect Minimization with Experimental Validation

C. M. Choudhari*a, B. E. Narkhedea, S. K. Mahajana

aDepartment of Production Engineering, Veermata Jijabai Technological Institute, Mumbai, 400019 India
bTechnical Education, Maharashtra State, Mumbai, 400001 India

Abstract

The process of casting solidification is complex in nature and the simulation of such process is required in industry before it is actually undertaken. The defects like shrinkage cavity, porosity, and sink can be minimized by designing an appropriate feeding system to ensure directional solidification in the casting, leading to feeders. Major parameters of a feeding system include: feeder location, feeder shape and size and feed aids. In this study, the component suffered from shrinkage porosity defect leading to premature failure. It also was subjected to incomplete fill due to sudden variation in thickness. Hence, it was necessary to redesign and redevelop the component. Component geometry has been modified without affecting its functionality by providing sufficient draft and radius at the junction. In this paper, an attempt has been made to carry out the entire methoding, simulation and optimization in AutoCAST X software which is based on Vector Gradient Method (VGM). All the design parameters have been set properly in numerical simulation software so that entire shrinkage porosity should get shifted in the feeder. This attempt has shown significant improvement in the quality of casting by optimizing the location and design of feeder for defect minimization. The simulation results were found to be in good agreement, when compared with the experimental trial.

Keywords: simulation; design; analysis; feeder; sand casting.

1. Introduction

Traditional casting trade has a long history and until now it has been the basis of the entire mechanical industry. Metal casting is a 6000 year young process. However, it still faces several problems, such as difficulty in quality control, low production, energy efficiency, material consumption reduction, and the impact of environmental...

* Corresponding author. Tel.: 91-981-976-7199; fax.: +0-222-415-2874
E-mail address: c.choudhari75@gmail.com
protection. Choudhari et al. (2013) have indicated that one of the reasons is the complex casting process; the other is the lack of theoretical guidance. In view of the reasons above, the current casting process is usually designed according to the designers’ experience and intuition. This has inevitably led to repetitions and readjustments in practice, thus giving rise to more scraps and higher cost.

Choudhari et al. (2012) investigated that many casting defects, which cannot be eliminated by making changes due to tooling and process parameters, can be attributed to poor design of the part with respect to manufacturability. One such common defect is shrinkage porosity. The defects can be predicted by casting solidification simulation, and corrected by suitable modification to part design. Hence casting solidification simulation enables predicting and preventing potential problems before freezing the product design, determining ‘goodfirst’ methoding solutions to achieve high yield at the desired quality level, and evolving optimal process plans compatible with both product requirements and foundry capability. This approach also provides immediate tangible benefits such as shorter lead-time, higher productivity and lower rejections, and long-term intangible benefits like better image, higher confidence and stronger partnerships for small and medium foundries. A high percentage of casting defects in jobbing foundries can be attributed to three parameters like low compatibility between part requirements, tool/method design and process capabilities. These three must be optimized in integrated manner to achieve the desired quality at the least cost without shop-floor trials. These facts can make all the small and medium foundries in India to implement casting solidification simulation activity as the need of hour.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_C )</td>
<td>Volume of casting</td>
</tr>
<tr>
<td>( S_{AC} )</td>
<td>Surface area of casting</td>
</tr>
<tr>
<td>( M_C )</td>
<td>Casting modulus</td>
</tr>
</tbody>
</table>

2. Literature Review

From the existing literature, it is found that numerical simulations of solidification have received considerable attention from researchers in the past. Casting shape can be broken down into a number of simple elements and the unsteady-state heat conduction equation can be applied to them over a number of time steps in order to obtain the temperatures at different nodes using either finite difference (FDM), finite element (FEM) or, recently, boundary element (BEM) methods. In general, FEM is preferred as it allows a wider choice of element shapes and better accuracy, while FDM based simulation programs are faster and easier to execute. Heat-flow through the sand mould was studied by many researchers and their achievement and limitations are discussed here. Reis et al. (2008) modelled the shrinkage defects during solidification of long and short freezing materials. The shrinkage defects in short freezing materials tends to be internal, as porosity, while in long freezing materials these defects tend to be external in the form of surface depressions. Seetharamu et al. (2001) studied the solidification phenomena in sand mould for thermal stress using FEA and they discussed about the effect of solidification on stress formation in casting where the experimental data was available. Pequet et al. (2002) studied the defects formation during solidification of Al alloy using ABAQUS software and showed that most of the defects formed where the metal solidified last. Sulaiman et al. (2004) investigated the thermal history of the sand casting process for mould filling time using FORTRAN. They have shown that the lastly solidifying area is near the junction. Mirbagheri et al. (2004) has studied the melt flow and effect of mould roughness of sand mould. Computational results were verified by casting of an aluminum alloy within a transparent mould and the mould erosion at different times has been recorded. Lee et al. (2005) studied the thermo mechanical behaviour of sand casting using FEA. In their study the effect of the shakeout time and method on the deformation of the propeller casting has been investigated using a commercial code, ProCast. Kulkarni et al. (2007) studied the solidification time of a hollow cylindrical shape casting in sand mould using ANSYS as FEAsoftware. Kermanpur et al. (2008) studied the melt flow and solidification in the multi-cavity mould for automotive components made of gray cast iron including a brake disc.
and a flywheel. The process model developed was used to investigate the appropriateness of the running and feeding systems. They concluded that in order to establish a similar heat transfer and solidification conditions for all cast parts in each multi-cavity mould, it is necessary to consider symmetrical configuration. Pathak et al. (2009) has discussed the effects of mould filling on evolution of the solid-liquid interface during solidification and showed that the residual flow resulting from the filling process significantly influences the progress of the solidification interface. Masoumi et al. (2005) studied the effect of gating design on mould filling for light metal casting processes. The experimental results showed that the geometry and size of the gate and the ratio of the gating system has a great influence on the pattern of mould filling. Hsu et al. (2009) investigated the multiple-gate runner system for gravity casting in sand mould using computational method. Fras et al. (2005) studied the transition from gray to white during solidification, both mathematically and experimentally, for plate and wedge shaped castings of various sizes. They concluded that solidification rate depends on the modulus of the casting and the heat flow through the mould. Sun et al. (2011) analyzes the reasons of some typical solidification related defects occurring in truck rear axle using 3D FDM and Z-CAST simulation software. Based on the simulation, the casting structure design of the truck rear axle is improved. Hassan et al. (2012) investigated the impeller shaped casting using MAGMASOFT Software. The effect of the location and size of feeders and gates on parameters such as filling pattern, pressure and velocity, cooling rate, solidification and related defects were studied. The predicted results were then compared with experimental data, and an excellent agreement between them was reported. Hosseini et al. (2013) investigated the effect of cooling rate on the microstructure, solidification parameters, and mechanical property of LM13 alloy. To obtain different cooling rates, different mould configuration was used. The cooling rates and the solidification parameters were determined by using computer-aided thermal analysis method. Rao et al. (2009) carried out the simulation of mould filling. It also improves yield of the casting, optimize the gating system design and the mould filling. Ravi et al. (2009) worked on computer-aided casting design and simulation. This paper describes a much better and faster insight for optimizing the feeder and gating design of castings. Behera et al. (2011) has suggested that the application of computer aided methoding, and casting simulation in foundries can minimize the bottlenecks and non-value added time in casting development, as it reduces the number of trial casting required on the shop floor. Here an attempt has been made to solve the shrinkage defects occurring in an industrial component using AutoCAST-X software.

3. Methodology

The entire study has been carried in three section viz. casting design calculation of cover plate, numerical simulation using AutoCAST-X software and finally validation with experimental trial. Sand casting is used as a manufacturing process.

![Fig. 1. Wooden pattern with allowances for cover plate casting](image-url)
Casting material used as LM6 and mould material is taken as silica sand, as per the foundry requirement. Design calculation begins with calculation for pattern allowances followed by gating system and finally design of the feeder (Rao (2008) and Campbell (2004)). Pattern design helps in getting a good quality of mould which in turn helps in getting a good quality of casting. Fig. 1 shows wooden pattern with allowances for cover plate casting. The design of the gating system consists of various elements like pouring basin sprue, sprue well runner and ingates. They act as passageways for the flow of molten metal from the ladle to various portions of the mold cavity, influencing the casting quality and economy. Nearly 40% of casting defects are attributed to faulty design of gating systems and poor pouring practices. Proper design of feeder ensures casting free from solidification related defects (hot spot). This also helps in improving the yield of the casting. Here, feeder having higher value of the modulus has been designed so that it should take larger solidification time compared to casting. Component shown in the Fig.1 has,

Volume of casting, $V_C = 559534 \, \text{mm}^3$, Surface area of casting, $SA_C = 86461 \, \text{mm}^2$ and Casting modulus, $M_C = 6.471 \, \text{mm}$. Here, a non-pressurized gating ratio as 1:4:4 is used. Design dimensions obtained for gating system and feeder has been mentioned in Table 1.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Designed value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mass of Casting</td>
<td>1.51 Kg</td>
</tr>
<tr>
<td>2</td>
<td>Pouring Time</td>
<td>12.6 sec</td>
</tr>
<tr>
<td>3</td>
<td>Diameter of sprue at top, bottom and sprue length</td>
<td>24mm, 16mm and 50 mm respectively</td>
</tr>
<tr>
<td>4</td>
<td>Sprue well:Diameter and Height</td>
<td>24 mm and 28 mm respectively</td>
</tr>
<tr>
<td>5</td>
<td>Runner dimensions:Width, height and length</td>
<td>16 mm, 24 mm and 105 mm respectively</td>
</tr>
<tr>
<td>6</td>
<td>Ingate dimensions: Width, height and length</td>
<td>24,14 and 28 mm respectively</td>
</tr>
<tr>
<td>7</td>
<td>Feeder design based on Caine’s method: Diameter and Height of feeder</td>
<td>50 and 70mm respectively</td>
</tr>
</tbody>
</table>

Simulation has been performed in AutoCAST-X environment according to the design dimensions obtained for pattern with allowances, gating system and feeder. Later on, the optimum location of the feeder was identified based on hot spot. The location of hot spot has been used as criterion to place the feeder. Based on this location as an input, feeder shape and size has been modeled using AutoCAST-X software. Other objectives of performing the simulation have been mentioned below:

- To check the part-process compatibility
- To check parting plane and moldability index
- To identify the last solidifying regions in the casting i.e. hotspot.
- To identify feeder location, its shape and dimensions
- To check feed aid requirement
- To check cooling animation: progressive solidification (casting surface to interior).
- To check feed metal paths: directional solidification (thin to thicker regions).
- To predict the location of shrinkage defects such as porosity and cracks.
- To check feedability index

Finally, the experimental trial has been performed based on simulation which resulted in defect free casting.

4. Numerical simulation using AutoCAST-X software of cover plate

Simulation based trials do not involve wastage of material, energy and labour, and do not hold up regular production. Computer simulation provides a clear understanding of the casting phenomena to identify the location and extent of internal defects, ensuring defect-free castings. Thus, numerical simulation of casting can be considered.
as an important method to make casting technique change from experience test to science guidance. It requires a standard .stl file of the methods layout. However, the application of proper boundary conditions leads to accurate results of simulation.

This section highlights the application of AutoCAST-X software for method design, simulation and optimization of cover plate casting. It has thick cylindrical guiding block carrying through holes in it at the center with a depth of 52 mm, internal diameter of 40 mm attached to flat rectangular surface of 242mm x 134mm x 13 mm in size as shown in Fig. 1. The present component suffered from shrinkage porosity defect leading to premature failure. It also was subjected to incomplete fill due to sudden variations in thickness. Hence the component was redesigned and developed. Component geometry has been modified without affecting the functionality of the component by providing sufficient draft and radius at the junction. All the parameters have been set properly in numerical simulation so that entire shrinkage porosity should get shifted in the feeder.

4.1. Part and Mould box

The prerequisite of this software is to create the part model in CAD software and save it as a standard .stl file for importing in AutoCAST. The mould box dimensions have been taken as 300x300x160mm as shown in Fig. 2. The entire mould containing the casting is automatically subdivided into cubic elements for internal computations such as thickness, solidification and mould filling. The element size is defined as 2.23 mm.

![Fig.2. Mould shape and size](image)

Three ratios identifying the shape complexity of the part are:
- **Volume ratio** = 1 – (volume of part / volume of bounding box) = 87.20%
- **Area ratio** = 1 – (area of a sphere of equal volume / area of part) = 68.68%
- **Thickness ratio** = 1 – (minimum thickness of part / maximum thickness of part) = 78.31%

A high value of the above ratios is taken as an indication of more intricate shape. The thickness function allows two types of thickness computations: section thickness 33.59 mm (Fig. 3) and X-Ray (Radiography) thickness: 242.91 mm (Fig. 4).
Part process compatibility has been checked using the optimize function. Here three parameters are checked for part-process compatibility viz. part weight, part size and minimum thickness as shown in Fig. 5.
Compatibility index = \( \sum \text{importance of parameter } i \times \text{compatibility of parameter } i = 100 \% \).

The parting line is created using the volumetric mesh elements. Parting direction is selected as horizontal. Moldability index is 100 % which is computed on the basis of metal to mold volume ratio, and number of mold elements as shown in Fig. 6.
4.2. Feeder Design

The feed module enables designing and optimizing the feeders and feed aids to obtain the desired quality with high yield. Casting solidification is simulated and the results are shown as cooling animation, feed metal paths, and shrinkage porosity distribution. The feeder design can be automatically optimized, driven by user constraints. Here, the last solidifying region of the casting or hotspots in casting has been identified as shown in Fig. 7(a). Green colored dot in the Fig.7 (b) indicates the location of the feeder.

Feeders have been located closest to major hotspots to allow feed metal transfer during volumetric contraction that accompanies solidification shrinkage. The feeder according to the design dimensions has been placed exactly on the top of the hotspot as shown in Fig. 8. In this case, various modulus obtained are; modulus of feeder is 10.36 mm, modulus of neck is 9.75 mm whereas the casting modulus is 6.471 mm.
After attaching the feeder to the casting, once again the hotspot has been inspected. The hotspot got completely shifted in the feeder as shown in Fig. 9. This confirms the theoretical design of the feeder.

4.3. Solidification Simulation

Casting solidification is simulated to view the progress of cooling from casting surface to interior, and to predict the location of shrinkage defects such as porosity and cracks. This helps in verifying and optimizing the design of feeders, so that the desired quality and high yield are achieved. Here, two main results are produced:

- Cooling animation: progressive solidification (casting surface to interior).
- Feed metal paths: directional solidification (thin to thicker regions)

The progressive solidification is indicated by isothermal maps (equal temperature). The directional solidification is indicated by feed paths (temperature gradients). Both are color coded (white=high temperature, blue=low temperature) as per the scale displayed. A third result, shrinkage porosity is also generated by interpreting the above two results. This is expected in regions of high temperature and low gradient.

Visualizations of 3D as well as 2D cooling simulation have shown that there exists no isolation in the casting. This result also validates the proper design and location of the feeder. The total solidification time required was
27.38 min and maximum and minimum temperatures of the casting observed at the end of solidification were 574°C and 150°C respectively. Fig. 10 shows casting cooling simulation.

Feed metal paths enable visualizing the directional solidification of a casting. It flows microscopically along the feed paths from regions that solidify later, to regions that solidify earlier (along highest temperature gradients) to compensate the solidification shrinkage. Ideally, feedpaths should end inside a feeder. Long and hot feedpaths converging inside the casting imply a local hot spot that can result in a shrinkage porosity defect. Short and cold feedpaths are usually harmless. The feed paths from casting interior to surface were computed and displayed. Feed paths were obtained in XZ plane. They ended inside a feeder. Fig. 11 shows feed metal paths in 3D and in cross section, all converging inside the feeder thereby indicating directional solidification.

4.4. Shrinkage Porosity

The shrinkage porosity was computed from the temperature and gradients using metal-specific process characteristics, which can be adjusted to calibrate the results with respect to the observed location of shrinkage porosity. The shrinkage porosity is displayed as dots inside the casting: red for macroporosity and orange for micro-porosity in Fig. 12. In this simulation, both macroporosity and micro-porosity were identified as 4.47 cm³ with 100% quality. It can be seen that the entire shrinkage porosity has been shifted into the feeder.
4.5. Feeding Optimization

The feeding design is evaluated and optimized in terms of feedability index indicating the percentage volume free from shrinkage porosity. The feeding design is evaluated in terms of three criteria:

- **Quality** = casting volume free from shrinkage porosity / casting volume
- **Feeding yield** = casting volume / (casting volume + feeder volume)
- **Feeding efficiency** = shrinkage volume requirement / feeder volume

Here quality, feeding yield and feeding efficiency obtained from software were 99.89, 84.66 and 22.82 % respectively.

5. Experimental Validation

First step of experimental analysis was to prepare a wooden pattern with various allowances for shrinkage, draft, machining etc. Second step was to make wooden pattern for pouring basin, sprue and sprue well, runner, ingate and feeder as per the design dimensions for cover plate casting. Fig.13(a) shows rigging system with pattern. Silica sand was mixed with bentonite in the ratio of 10:1. Bentonite has a property to retain moisture. It also acts a binder and holds the sand firmly when pattern is withdrawn from the mould box. A standard size mould box of dimension 300mm × 300mm × 160mm was used. The mould cavity was prepared in two parts, cope - the upper part and drag - the lower part as shown in Fig 13(b)(Choudhari et al.(2013)).
Fig. 14 (a). Top view of final casting (b) Bottom view of final casting

The top view and the bottom view of the final casting are shown in Fig. 14(a) and Fig. 14(b). Radiographic test were performed on the final casting. The test confirmed that there exist no internal defects (shrinkage porosity) in the casting. With manual inspection, it has been observed that the casting was free from surface defects. Hence it was concluded that experimental results were confirmed with simulation results.

6. Conclusion

In this study, it was observed that solidification simulation enables visualization of the progress of freezing inside a casting and identification of the last freezing regions or hot spots. This facilitated the optimized placement and design of feeders with improvement in yield by 15 % while ensuring casting soundness without expensive and time-consuming trial runs. In this case, the thick portion of the component was subjected to shrinkage porosity. It was the root cause for the poor strength which was leading to premature failure of the component. Proper design of gating system has immensely helped in achieving the directional solidification leading towards the feeder; thereby solving the problems of premature failure due to junction solidification and incomplete fill due to sudden variations in thickness.

Feeder was placed at last solidifying region using AutoCAST-X software. This approach has helped in minimizing the solidification related defects, thereby providing a defect free casting. This study shows that simulation can be of great use in optimizing the feeder dimensions and increasing the feeding efficiency of the casting. Both macroporosity and micro-porosity were identified as 4.47 cm$^3$ with 100% quality. Quality, feeding yield and feeding efficiency obtained from software were 99.89, 84.66 and 22.82 % respectively.

References

Choudhari C., M., Narkhede B., E., and Mahajan S., K., 2012. Finite Element Simulation of Temperature Distribution during Solidification in Cylindrical Sand Casting with Experimental Validation, 4th International and 25th All India Machine Tool Design and Research (AIMTDR 2012), Jadavpur University, Kolkata, India, 1, 3-8


