Chapter

Simulation and Validation of Castings in Shop Floor

Partha Haldar and Goutam Sutradhar

Abstract

Production of sound casting demands a thorough understanding of whole casting process. But still, defects and rejection of castings are ubiquitous because in general, the designer lacks domain knowledge about casting processes and hardly have any methodology to find out the parameters that produce sound casting. Casting simulation software simulates the way how casting engineers decide the casting process in a virtual platform and also analyzes each decision to point out the design modifications needed to enhance the quality of casting as well as reduce lead time, tooling and manufacturing costs. The application of simulation software enables us to say, "Get it right, the first time and every time". Simulation software can be very helpful in calculating tedious formulas, constructing solid modeling which will be helpful to visualise the actual situation like core/mould assembly, gating and feeding arrangements with the main casting before going into actual practice. It can be adopted for troubleshooting existing castings, and for producing new castings without or minimum shop-floor trials. This chapter illustrates the advantages of casting simulation (both tangible and intangible), bottlenecks (technical and resource-related), and some best practices to subdue the bottlenecks. In this chapter some of the live examples have been cited to understand the process logically and scientifically.

Keywords: casting simulation, concurrent engineering, design for manufacture, solid modeling, quality assurance

1. Introduction

Simulation imitates a real phenomenon by the use of certain mathematical equations. Metal casting is a manufacturing process where molten metal is poured into a mould cavity of required shape and size and allowed to solidify. Naturally, metal casting simulation is a very complex phenomenon which involves flow of fluid, heat transfer between mould and molten metal etc. It is often said that the development of accurate simulation software is a 'rocket science for rocket scientists'. Actually, metal casting is a process which has numerous associated controlling factors. Therefore, the key to develop a practical useful casting simulation software is to figure out the related most important parameters. Several researchers have worked hard for several decades to find out the same. Geometry, material, and process are three major influencing factors related to metal casting [1].

The casting simulation software producing farms always keep target to accurately simulate the physical phenomena as far as possible like the mould filling, associated heat-transfer, solidification pattern of the metal/alloy, and the involved phase transformation of castings [2]. It is ubiquitous that a set of governing equations are required to model these phenomenon in a computer program. Now a days, these modeling methodologies are so strong that they can accurately predict the microstructure and mechanical properties of the castings. It can also pin point the position of internal defects like shrinkage porosity, sand inclusions and cold shuts etc. The simulation software can be used for the development of any new castings or it can be used for standardize any existing casting for any design change to improve yield of the casting without shop floor trial. For these reasons, casting simulation has become an indispensable tool in modern foundries. No foundry can produce high-quality castings particularly integrated castings without simulation for the first time. The present dynamic market demands fast response to customer needs at the right cost and also within stipulated time.

Some popular casting simulation softwares which are available to foundry engineers are AutoCAST, MAGMASoft, ProCAST, SOLIDCast, CAP/WRAFTS, CastCAE, Castflow, Castherm, JSCast, MAVIS, Nova-Solid/Flow, PAM-CAST, RAPID/CAST, and SIMTEC etc. These simulation software generally follow any one the following numerical technique to solve the related differential equations, Finite Differences Method (FDM), Finite Volumes Method (FVM), Finite Element Method (FEM) and Vector Element Method (VEM) etc. ProCAST, SOLID Cast, OPTI Cast and FLOW Cast are based on the FEM technique while QuikCAST is based on FDM technique and AutoCAST is based on VEM technique.

It is easily understandable that the simulation software will perform well if and only if the input parametrs are close to the real world values. Most critical input values for such simulation software are the thermo-physical properties of cast metal and mold, as well as interface boundary conditions. But these values are temperature dependent. Therefore, the values are difficult to acquire for different metal-mold-process combinations. As a result, the outcome of simulation software may deviate from reality.

In this chapter, advantages of casting simulation software, limitations, and some best practices are illustrated. In addition, some live examples have been cited to understand the process logically and scientifically.

2. Application of casting simulation software

Casting troubleshooting, method optimization and part design improvement are the main three applications of casting simulation software. Therefore, these are described here in brief.

2.1 Casting Troubleshooting

As the title suggests, trouble in existing casting like high or varying level of internal defects (shrinkage porosity, sand inclusions, cold shuts, etc.), or poor yield of castings can be eliminated by using the simulation software. To address such problems, casting engineers' first use to calibrate the software by making the exact platform in the virtual world. Now the simulation defect and real world defects are compared for calibration. Once achieved, the engineer can change the inadequate size or location of feeder or gate. It is also a fact that the simulation software reveals the defect positions where otherwise in general engineer don't look for. Regarding the improvement of yield, the foundry engineer can play with the simulation software in a hope to reduce the oversized feeders or risers (if any). If no defect is observed in simulation software by reducing the feeder dimensions then the engineer can go for shop floor trial. If the result agrees then definitely, the yield will improve.

2.2 Method optimization

In methoding of castings, solidification simulation executes an essential role in acquiring the best possible quality of castings. Simulation software is beneficial for both under development as well as existing castings, and reduces number of shop-floor trials. The methodings for example, casting orientation, mould layout, feeders, feed-aids, and gating etc. are altered on a computer, and pretended to review for defects, if any. Numerous iterations are performed until the coveted quality and yield are obtained. It is noteworthy to mention that even trivial, insignificant advancements in existing castings that are being manufactured in huge numbers, can direct to notable enhancements in the utilization of matter, energy, machinery and labour resources. Likewise, simulation is decisive for large, heavy castings under development since the cost of trials or repair is limited. Several programs have been included in the algorithms for automated (user-guided) optimization of feeders and gating channels [3]. Many researchers have proclaimed that approximately 90% of the defects in parts are due to errors in design and hardly 10% are due to production difficulties. The casting simulation software can also be used for calculating the cost of the job in an indirect manner. In the very initial step of design of a to be cast part should be simulated, otherwise it may so happen that the proposed part is not at all castable. A thumb rule says that the cost to change in design increases ten times in every step of the design and manufacturing process. Therefore, method optimization should be done using the casting simulation software as early as possible in a designing process and this practice can save a lot of money both in foundry and machine shop.

2.3 Part design improvement

Thick junction and long thin section in a casting may result in shrinkage porosity and cold shut. Therefore, if a part designer encounters such situations then he should immediately consult the foundry engineer to check the castability of the part using casting simulation software. Early detection of castability may also insist the part designer to do minor change without affecting the functionality of the part.

3. Operational Methodology of simulation software

This section has been discussed in following three subsections.

3.1 Inputs

Maximum commercially available casting simulation software are Finite Element Method based [4]. So this discussion is applicable for FEM based simulation software.

- 3D CAD model is the main input for any casting simulation software. The CAD model can be created using a solid modeling program. Model of the part can be obtained from OEM customer.

- Various allowances like draft, machining, shrinkage, distortion etc. are to be provided on the CAD model if not given earlier.

- Now, the model has to mesh. Meshing means that the model is to be split into several simple elements. A tinier mesh size returns more delayed but more stable outcomes. Adaptive meshing (finer in decisive domains and coarse elsewhere) provides quicker outcomes without compromising on the precision.

- Following meshing, material characteristics like density, thermal conductivity, specific heat, latent heat etc. are to be provided as input to the software.

- Next, the boundary conditions have to be defined.

- Simulation software furnishes reliable and precise outcomes if the CAD model, FEM mesh, material characteristics and boundary conditions are exact.

3.2 Outputs

- The principal outputs of simulation applications incorporate animated visualization of mould filling, casting solidification, and further cooling to room temperature.

- Mould filling simulation assists in forecasting the total filling time as well as help in predicting following casting defects like mould erosion (heading to sand inclusions), incomplete filling (cold shuts and misruns), and air entrapment. Blowholes, produced by entrapment of gases, are yet difficult to predict.

- The outcomes of solidification simulation incorporate colour-coded freezing profiles with respect to time. These temperatures profiles help in predicting the position of shrinkage porosity based on Niyama criteria.

- The casting simulation software can also predict the microstructure, mechanical properties, residual stresses etc.

3.3 Analysis

Casting simulation software can only help foundry engineers to analyze the effect of a particular method design on the yield and quality. The software enables us to 'look through' the virtual mould. However, it can not perform better by itself. The outcomes should be analyzed by a knowledgeable foundry engineer. Application of casting simulation software can improve the productivity of a company and also it is a tool for the foundrymen to succeed but it cannot substitute him.

4. Intelligent design assistant

As stated earlier, Simulation software furnishes reliable and precise outcomes if the CAD model, FEM mesh, material characteristics and boundary conditions are exact (otherwise: garbage in, garbage out). Material characteristic and boundary conditions data usually have to be ascertained and fine-tuned by experimentation. This exercise may take numerous weeks, which is beyond the scope of average organizations. Simulation programs demand engineers with higher educational qualifications, CAD/CAM experiences and casting design knowledge to conduct the simulation and interpret the outcomes correctly. The programs are computation-intensive and need robust engineering workstations. Even then, any particular iteration of CAD model making, mesh creation, boundary condition stipulation, simulation and visualization can consume 2–5 days for an intricate component. Thus it may demand many days to reach an optimal casting scheme.

DOI: http://dx.doi.org/10.5772/intechopen.94596

To address these issues now a days, some simulation software provides a single integrated environment for casting design, modeling, simulation, analysis and project data management. Advanced geometric reasoning and knowledge-based functions have been incorporated in the software, making it work like an intelligent assistant to casting engineers [5]. The methodology for casting design (mainly feeding and gating systems), process simulation, castability analysis and optimization is performed by intelligent simulation software is explained below.

- The CAD model of the part is exported in standard. STL format and imported into the simulation software.

- The program automatically recommends the mould size and subsequently upon the approval from the user, generates the mould model encompassing the part model.

- Now, an initial casting solidification simulation was performed.

- The program automatically produces the mesh, fixes the boundary conditions, measures the advancement of solidification, post-processes the results and demonstrates the position and degree of shrinkage porosity. All the events, as mentioned above, take less than 15 minutes on a Pentium computer.

- Now if any porosity is observed in the simulation results then a chill is modeled automatically in that zone to increase the heat transfer rate. Modified simulation reveals that there is reduction in porosity.

- Likewise, the simulation software automatically calculates modulus (ratio of volume of the casting to the surface area of the casting) in the hot spot zone of the casting and properly designs the feeder dimensions in such a way that its solidification time is more than the hot spot. After user approval, the feeder model is built automatically.

- Additionally, the gating plan is designed by this program semi-automatically. The user exclusively defines the ingate joining points on the part surface. The program automatically proposes the sprue location and the runner path, which can be altered by the user if needed. Then the dimensions of all gating parts are automatically calculated, and a solid model of the gating system is built.

- The solid models of the feeder, chill and gating system, are represented for visual feedback. The size of feeder and chill are optimized through several iterations of design-model-simulate-analyze until simulation prognosticates zero porosity defects even for the highest quality requirements.

- Finally, casting is designed on a scale of 0-100. A value of zero implies impossible to cast and 100 indicates ideal castability. The actual values usually lie in-between.

5. Example: workflow of a casting simulation software (Z-CAST)

The Z-CAST is Finite Difference Method (FDM) based simulation software. To create a new project following steps are to be followed.

- The 3D model in. STL format is required to be imported
- Virtual mould is to be created
- Meshing is done. It is dependent on three parameters, Geometry complexity, Minimum wall thickness and Weight of the component.
- Material and initial temperature are to be provided
- Ingate of the casting is to be designed
- To obtain the graphcal representation of simulation behavior, some virtual thermo-couples are to be set on some strategic locations
- Next, the solver environment is to be declared. Here some typical inputs are required from users. For example, the analysis terminate conditions are flow rate and time are to be declared. Input wall condition is to be provided. For this, there may be two situations like slip condition and no-slip condition and hence the input value will vary between 0-1 respectively. For sand casting input wall value is between 0.4 to 0.6 whereas for die casting the value is 1. Next, the riser material type, whether it is exothermic or not is to be given as input. Heat transfer coefficient is to be provided thereafter.
- Once done, the software will provide the results with flow temperature, solid time, solid temperature, details on shrinkage condition etc.

6. Case study 1

For preparing some wedge blocks, a scheme of preparation mechanism used by a manufacturing company is shown in **Figure 1**. The product being manufactured with the existing method design contains shrinkage defect. The simulation result also confirms the same. The shrinkage defect and its associated simulation result are shown in **Figure 2**. Therefore to eliminate the defect and also improve overall process associated with the production stack moulding is adopted as shown in **Figure 3**. Due to this modification various related parameters also improve as shown in **Table 1**. The techno-economy analysis of wedge casting per ton shows that cost per piece reduces and productivity increases with stack moulding approach.

7. Case study 2

The interconnection of coaches by a coupling makes a train. In earlier days screw coupling was used. Screw coupling has certain inherent limitations like haulage of longer train is not possible in freight, climbing of coaches in collisions and derailment, life of shunting staff at risk and higher maintenance staff requirement. On the other hand, central buffer coupling (CBC) has advantages like the coupling is safe for shunting staff, less time is required since quick detachment is possible, less staff for uncoupling, the coaches do not climb on each other during accident and hence prevent damage to life and property during accident. The CBC has three major components, knuckle, coupler body and yoke. The CBC is a cast product. In this present case study the use of casting simulation software on a CBC product is demonstrated. The simulation software is capable of indicating the loop-holes of

DOI: http://dx.doi.org/10.5772/intechopen.94596

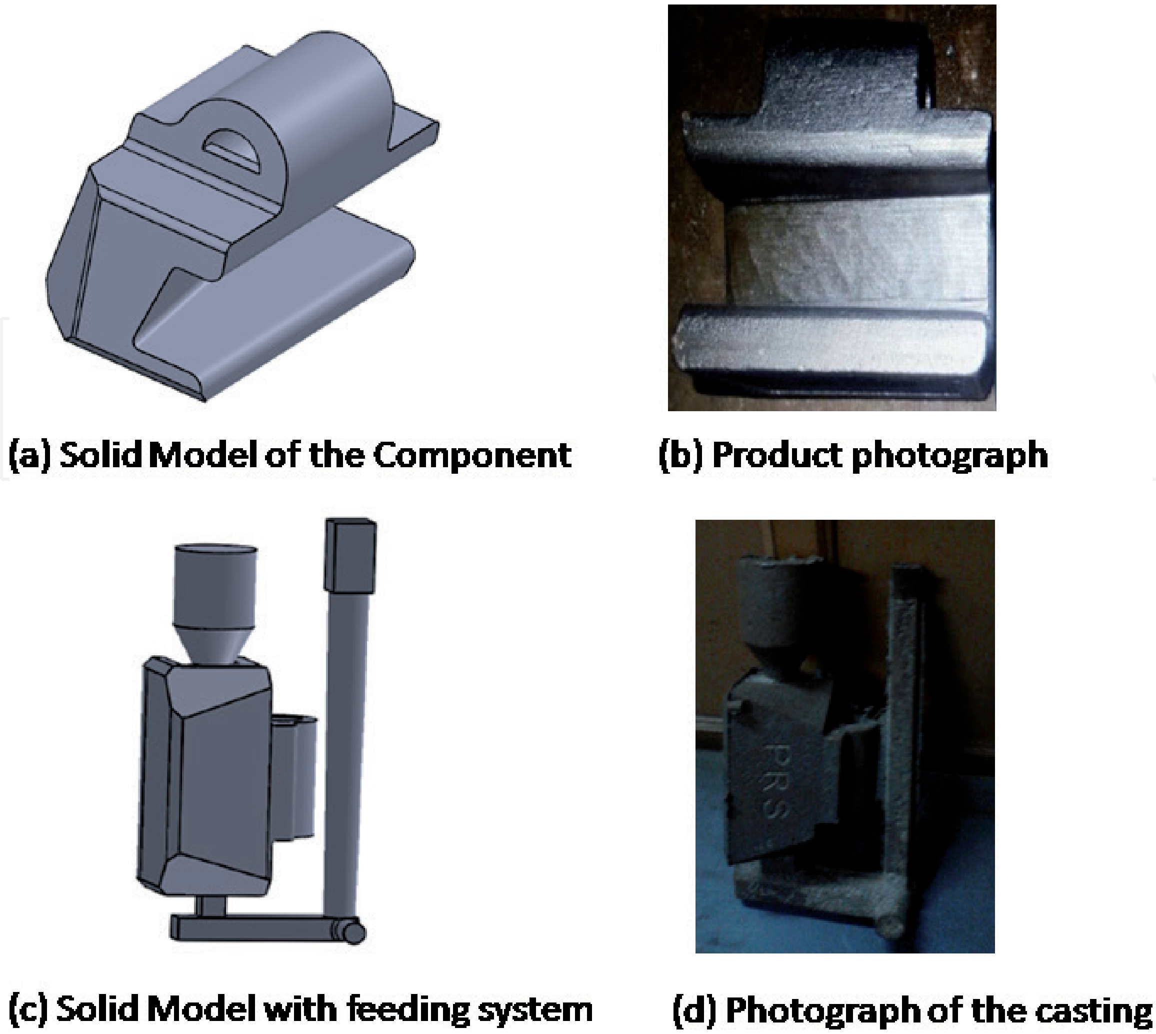


Figure 1.
Scheme of wedge block preparation

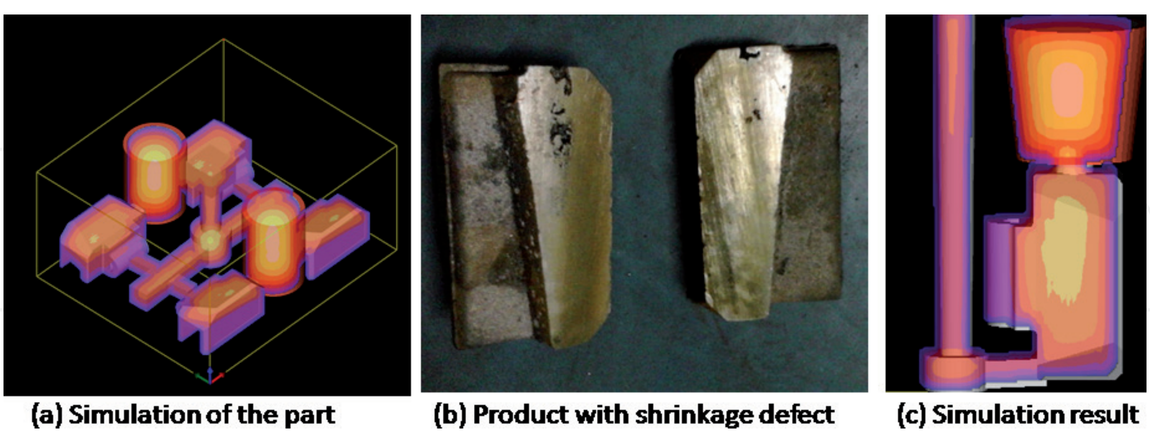


Figure 2.
Product with shrinkage defect and linked simulation

the existing design and the caveats can be ironed out by proper methoding. Final simulation results show that there is hardly any detrimental defect in the cast part and thus a huge cost for trial and error is saved. To demonstrate the role of methoding and solidification criterion on casting defects, one crucial industrial case study is discussed here.

The foundry is producing three major components of CBC i.e. coupler body, knuckle and yoke in a single mould. Cast Steel (ASTM M-211 GRADE-E) was used as the casting material and green sand under high pressure moulding system was

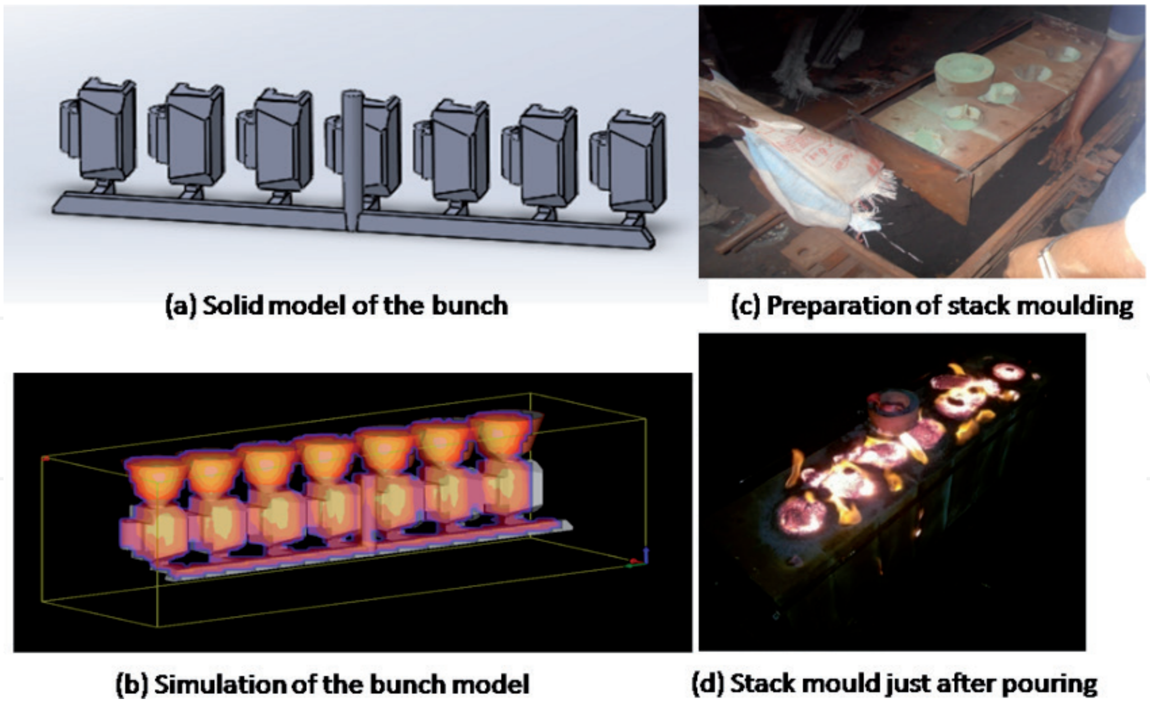


Figure 3.
Scheme to indicate the modification done

used. The 3D CAD model is created in solid modeling software and converted to .STL format. The .STL file imported into the Z-CAST simulation software. Here, pouring temperature is taken as 1610 °C, and pouring time is 30 seconds. Exothermic sleeves are used in this case and the mould temperature is considered as 30°C before the pouring of molten metal. The shrinkage allowance of the material is also considered as 3.5%.

The flow simulation of the product shows filling percentage with respective temperature scales as shown in **Figure 4**. The flow temperature analysis can test fluidity of the molten material and assist to locate the un-filling regions by analyzing temperature plots in thin sections of the cavity. The white colour in the temperature scale corresponds to the highest temperature of the melt i.e. the pouring temperature. Yellow, red, dark blue and finally light blue are indicating temperatures of gradual decreasing order. Filling condition of this product at different filled position (2, 10, 40, 60, 80 and 100%) is shown in the figure. **Figure 4a** shows that the molten metal is entering in the mould cavity through sprue. Mould filling is an essential matter since the melt temperature will commence decreasing when it comes in contact with the cooler mould surface. **Figure 4a** shows that molten metal will flow according the slope of mould cavity. **Figure 4b** shows that 10% volume of the mould cavity is filled by the molten metal. **Figure 4(c-e)** indicate that 40, 60 and 80% space of the mould cavity is filled by the melt and the liquid metal has started solidification process. **Figure 4f** shows that at 100% filled condition the components at the farthest point from the sprue have blue colour which indicate that the temperature at those points are sufficient lower than the pouring temperature. At the end of 30 seconds i.e. the complete pouring of metal, temperature drops from 1610°C to 1490°C

The air entrapment simulation is shown in **Figure 5**. This flow un-filling simulation shows when molten material enters into the mould cavity, how the entrapped air escapes and thus this simulation can predict the unfilled locations of the cavity. Here, the red colour indicates cavity yet to be filled and transparent area shows metal is filled. Small dots indicate the amount of entrapped air in the cavity.

Factors Considered	Conventional	Stack Moulding
Bunch Weight	42.96 kg	75.19 kg
Weight/piece	5.80 kg	5.80 kg
No. of pieces/bunch	4 nos	7 nos
Net Casting weight/bunch	23.20 kg	40.60 kg
Bunch Yield %	54%	54%
Metal Cost	22644.93.(INR)	22644.93 (INR)
Ferro Alloy Cost	2485.40 (INR)	2336.27 (INR)
Electricity Cost	15395.74 (INR)	14472.00 (INR)
Core cost/Molding cost	1640.24 + 6481.00 (INR)	16223.82 (INR)
Store Cost	7408.04 (INR)	6768.32 (INR)
Heat Treatment Cost	3500.00 (INR)	3500.00 (INR)
Shot Blasting Cost	227.00 (INR)	227.00 (INR)
Labor Cost (Production)	4887.45 (INR)	2625.26 (INR)
Labor Cost (Fettling)	2930.00 (INR)	2758.00(INR)
Maintenance Cost	1300.00 (INR)	1300.00 (INR)
Total Variable Cost	68899.80 (INR)	72855.60 (INR)
Fixed Cost	4200.00 (INR)	4200.00 (INR)
Rework	7000.00 (INR)	500.00 (INR)
Total Cost	80,099.80 (INR)	77,555.60 (INR)
Cost per piece	570.57 (INR)	561.55 (INR)
Quality of the casting Rejection	Good 30%	Very Good (ASTM 2) 5%
Aesthetic Look	Standard	World class
Processing time	1 Unit	1/3 Unit
Consistency	Not up to the mark	Very Consistent

Table 1.
Techno-Economy Analysis of Wedge Casting/Ton

Figure 5(a) shows the level of entrapped air at a level of 20% filled mould cavity while **Figure 5(b)** shows when the metal pouring has been completed. The final picture depicts that no air particles have been entrapped observed in cavity during filling.

Solidification temperature pattern shows rate of solidification and time taken to solidify. It is evident from left top corner of **Figure 6(a)** shows after elapse of 123 seconds the solidification is 1%. Similarly **Figure 6(b)** indicates that it takes 2910.558 seconds to solidify 100%. The temperature scale shows that some portion of the product has been delinked with the riser and contains higher heat. This will cause shrinkage defect in those locations. The yellow arrows of **Figure 7** indicates the major shrinkage cavities produced after solid simulation and these hot spots are needed to be taken care of.

Now, the detail component wise defect analyses of the knuckle, coupler body and yoke have been shown in **Figures 8**, **9** and **10** respectively. **Figure 8** shows that the knuckle is free from shrinkage, blow holes and air entrapment issues. As per Research Designs and Standards Organization (RDSO) standard, there is no porosity

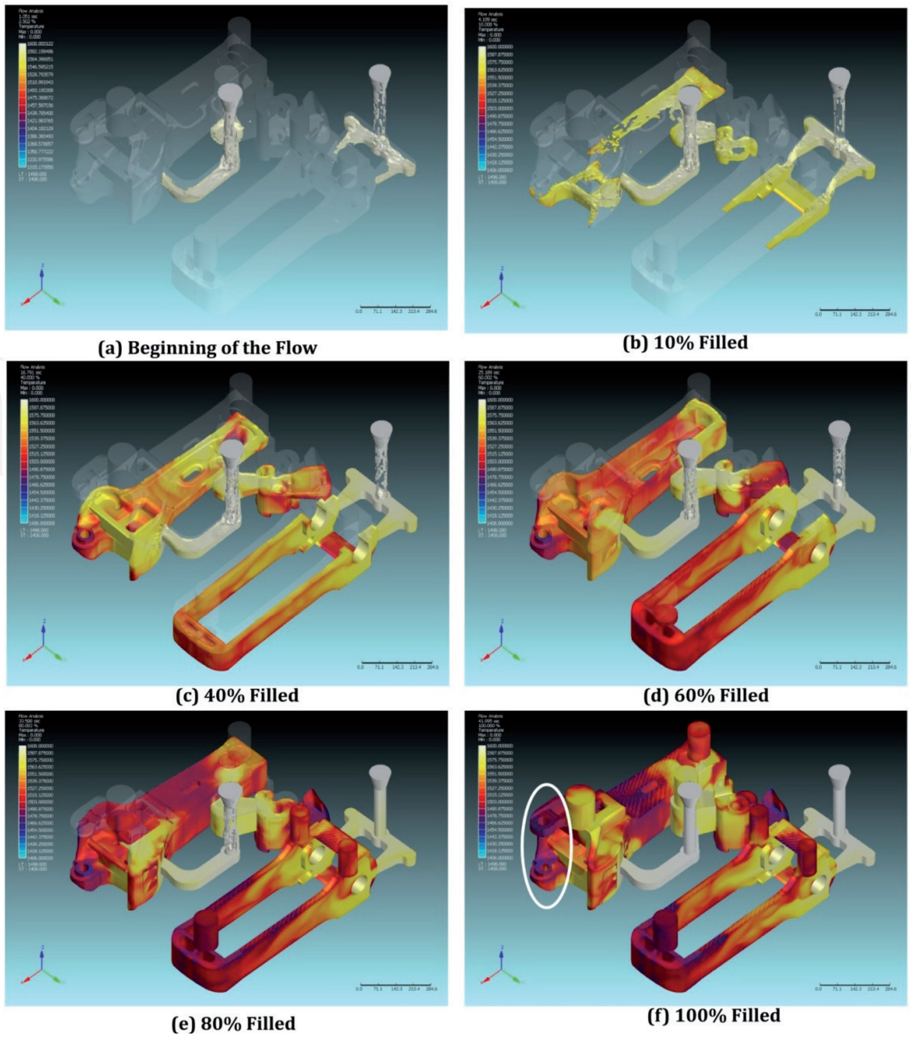


Figure 4.
Simulated filling conditions at different filled positions

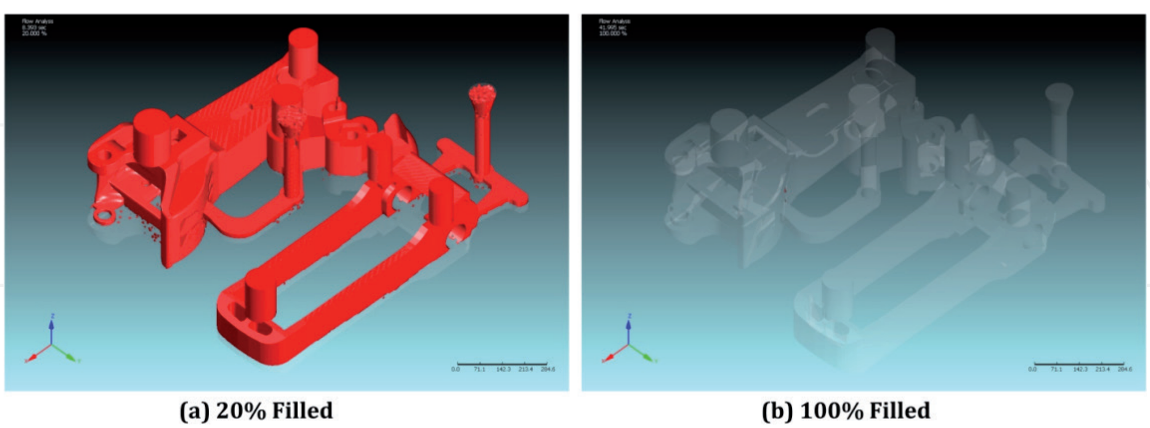


Figure 5.
Air entrapment simulation

in critical location of the knuckle component. But in other non-critical locations some porosity can be observed but those would be passed through the radiography NDT testing of level 2.

Figure 9 indicates that major shrinkage defects have formed in the coupler body and these are to be removed by adopting proper casting methodology. The figure also indicates some major porosity formation which are crossing the level 2 of radiography testing, therefore, these porosities are also needed to be eliminated

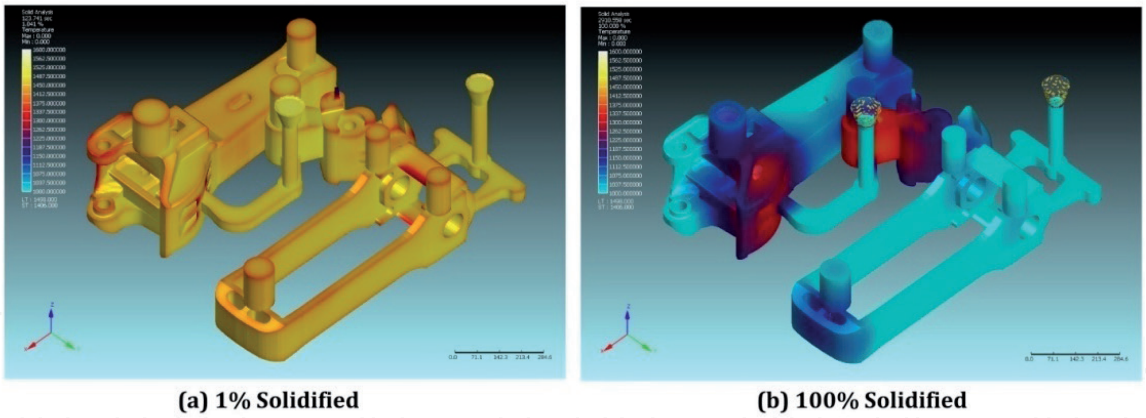


Figure 6.
Solid simulation of product

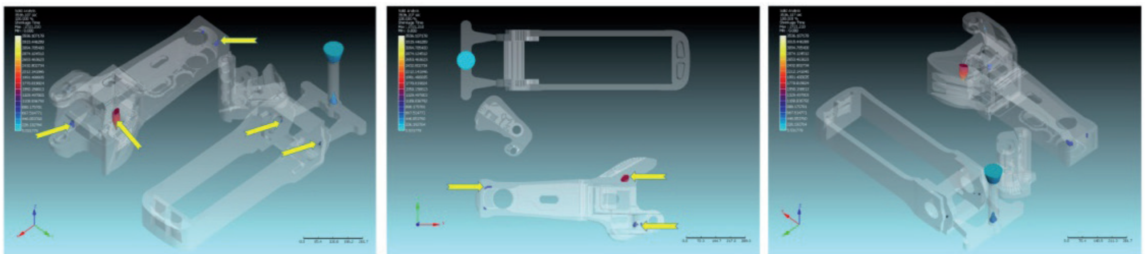


Figure 7.
Indicating shrinkage cavities after solid simulation

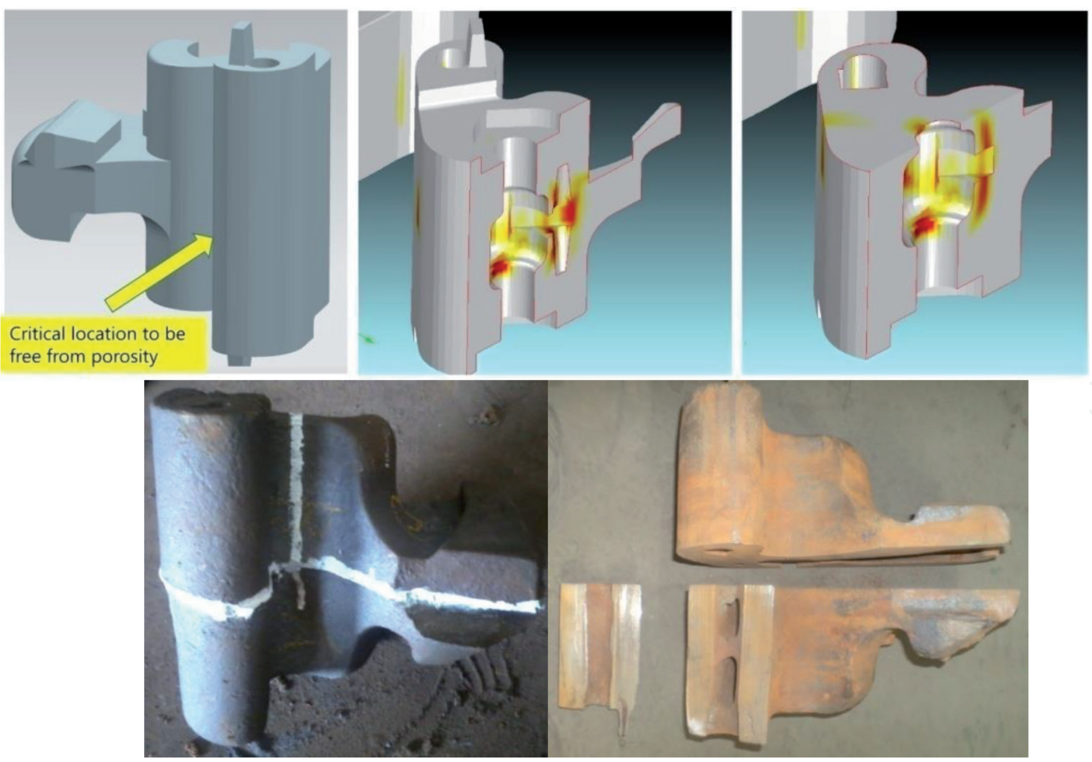


Figure 8.
Defect analysis of the knuckle and real cross section of critical location indicating zero defect

from the cavity. In some non-critical locations, some minor porosity has formed but these are under level 2.

While analyzing **Figure 10**, it is found that the yoke is free from major shrinkage defect but some minor shrinkage defects have been observed (indicated by yellow

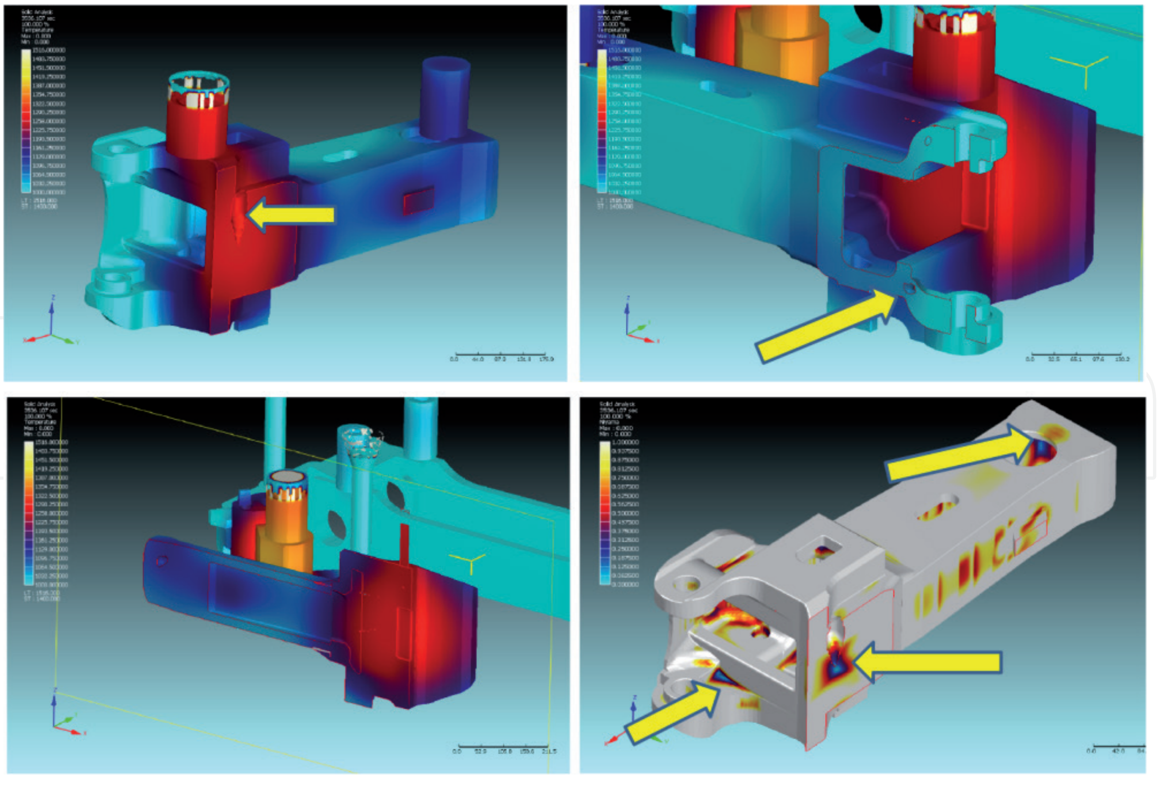


Figure 9.
Defect analysis of the coupler body

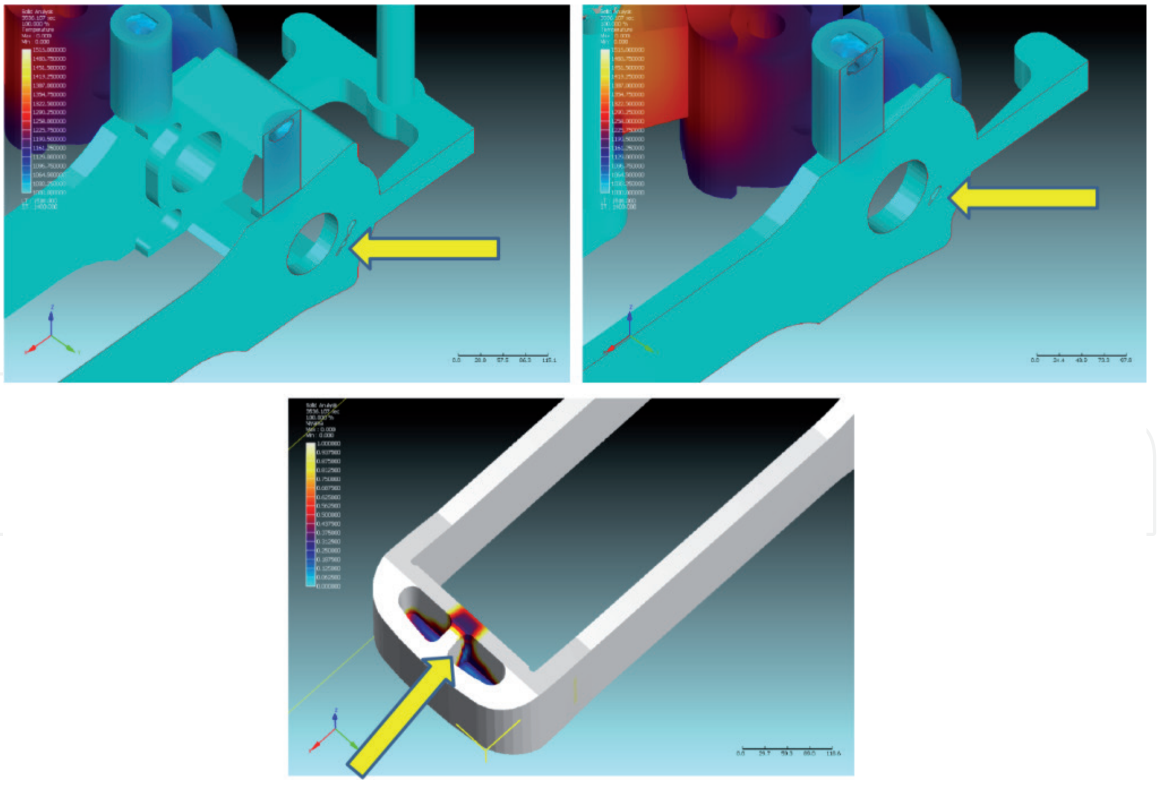


Figure 10.
Defect analysis of the yoke

arrows) along with some minor porosity below the riser, which needs to be eliminated from casting. The porosities crosses the radiography level 2 and therefore, needs to be eliminated from the cavity.

7.1 Iteration

By analyzing **Figures 4–10**, it can be concluded that knuckle has no major issues to be solved but the coupler body mouth and one end of yoke are prone to shrinkage defect and porosity respectively. Cross-section of critical section before modified methoding is shown in **Figure 11**. To solve the issues, two sprue with existing gating system is used with following minor modifications.

a. Minor modification in riser sizes: If a close comparison is done between **Figure 6(a)** and **Figure 12(a)**, it can be found that the dimensions of the risers are different. It is needless to mention that the authors are unable to share such data in detail.

b. In mouth area of coupler body, chromite sand core (shown as the red arrow in **Figure 13(a)** and the schematic of the core shape is shown in detail in **Figure 13(b)**) is to be used to have effect of chill in order to minimize the major hot spot in the critical location. **Figure 9** indicates that the mouth of the coupler body is most prone to shrinkage defect and to eliminate that use of chromite sand core is necessary since it has high thermal conductivity and good chilling effect.

c. The yoke is also prone to shrinkage and porosity defect as discussed in **Figure 10**. To eliminate this defect, a riser should be used as shown by a brown arrow in **Figure 13(a)**.

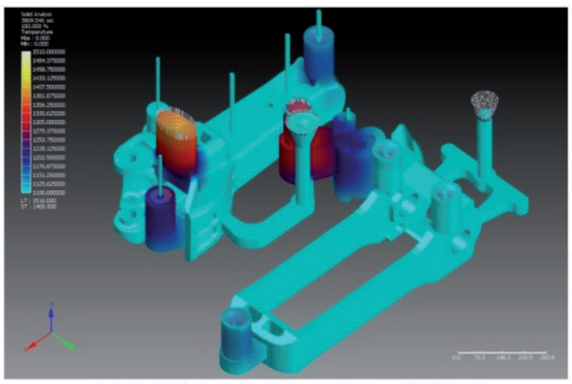
d. Additional three more chills are required and suggested to be placed in the mouth core of the coupler body else a small riser should be incorporated. The use of chills or a riser is technically equivalent but both chill and riser have certain pros and cons. The use of extra riser is associated with some extra cost related to material, energy to melt, cutting, re-melting etc. Whereas use of chills does not have such extra cost, they are to be purchased or fabricated once. But in practical shop floor, it is seen that after several production runs, the labours forgot to collect all the chills while breaking the sand mould and eventually the chills are misplaced. Therefore, it becomes a decision of the proprietor of the company, whether he will go for chill or a riser. In this case a riser is used which is marked as a deep blue arrow in **Figure 13(a)**.

Figure 11.
Cross-section of Critical Section before modified methoding

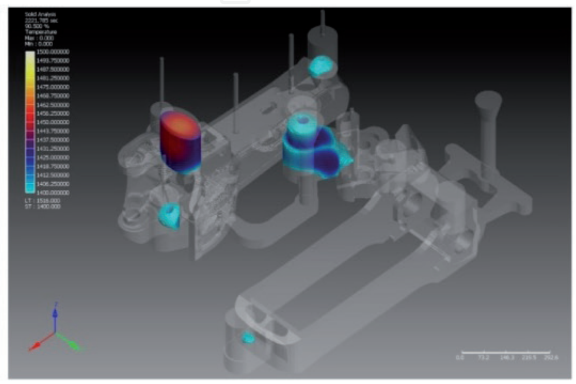
e. Some ventings (shown by black arrow in **Figure 13(a)**) are suggested to increase permeability. In this case the mould is made using high pressure moulding so the permeability of the mould is very low, and making of manual conventional vent just before metal pouring is very tough in such cases. So while, making the mould cavity, some rods f small diameter are attached with the pattern strategically.

f. Exothermic powder is also advised to be used immediately after pouring the metal to minimize heat loss.

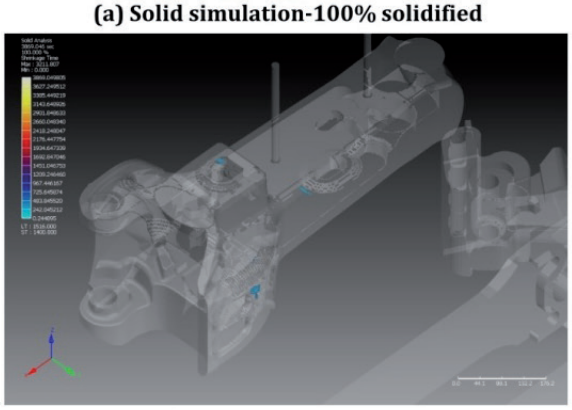
Figure 12(a) clearly indicates that the total solidification time is 3869 seconds i.e. 958 seconds (Approximate 16 minutes) more time than the solidification time



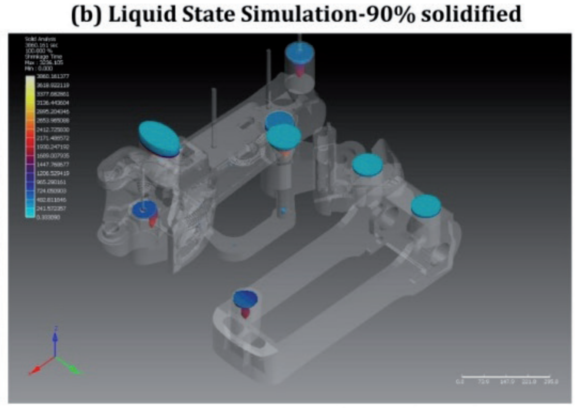
(a) Solid simulation-100% solidified



(b) Liquid State Simulation-90% solidified

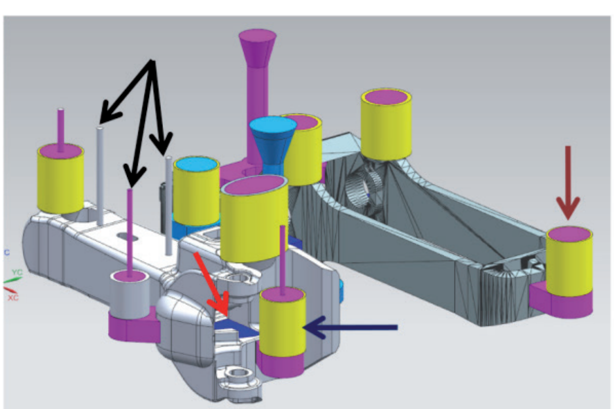


(c) Checking for shrinkage defect-1

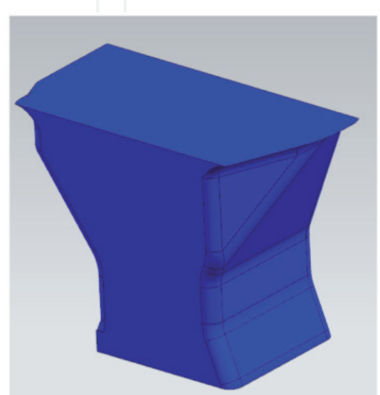


(d) Checking for shrinkage defect-2

Figure 12.
Defect analysis of the product after modifications



(a) Modifications done in existing design



(b) Chomite sand core

Figure 13.
Modifications done in the existing design to obtain sound casting

consumed before modification. Liquid state simulation of **Figure 12(b)** shows that a smooth directional solidification has been achieved and all major hot spots have been eliminated from the cast components. **Figure 12(c-d)** indicates occurrence of minor shrinkage defect in the casting but these are not detrimental to the component.

8. Conclusions

In this study, the advantages of casting simulation software, limitations, and some best practices have been observed along with some case studies to understand the process logically and scientifically. Simulation technology has appeared as a blessing to foundry engineers to implement virtual experimentations, forecast casting defects and enhance the existing casting design without melting metal in furnace. This not only reduces the expense of die modification and material/energy costs but also contributes a more beneficial insight into the process. On the other hand, with the advancement of technology, to produce zero defect castings with improved yield, it is very much required to optimize the casting design (feeding and gating). This goal can be accomplished by coupling intelligent design assistant module of simulation software. This will enable us to complete the design-simulate-analyze cycle within a time less than one hour. This tool enables us to optimize complex castings in a single day. This also assures more acceptable casting design, quicker than ever before.

Acknowledgements

Authors wish to convey their heartfelt thanks to Mr. Prashant K, Senior Ex-Application Manager, DHIO research and engineering private limited for his support in while making the Z-Cast simulations for this case study. The authors are also indebted to D N Ganesh Babu, General Manager, Product Sales & Services, DHIO Research & Engineering Pvt. Ltd. for his continuous support for giving the Z-Cast software. Author also thankfully acknowledge the contribution of Mr. Abresh Ranjan Das for his continuous support & help for sharing his profound experiences to complete this work unless otherwise this work could not get the present shape.

Conflict of interest

The authors declare no conflict of interest.

Author details

Partha Haldar[1] and Goutam Sutradhar[2]*

1 Department of Mechanical Engineering, Government College of Engineering and Ceramic Technology, Kolkata-700 010, West Bengal, India

2 National Institute of Technology, Langol, Imphal-795004, Manipur, India

*Address all correspondence to: cast_1963@rediffmail.com

References

[1] Ravi B. Computer-Aided Casting-Past. Present and Future. Indian Foundry Journal. 1999;**45**(1):65-74

[2] Ravi B: Casting Simulations - Best Practices. Transactions of 58th Indian Foundry Congress. 2010.

[3] Ravi B, Joshi D: Feedability Analysis and Optimisation Driven by Casting Simulation, Indian Foundry Journal. 2007: 53(6): 71-78.

[4] Lewis RW, Huang HC, Usmani AS, Tadayon MR. Solidification in castings by finite element method. Materials science and technology. 1990;*6*(5):482-490

[5] Ravi B. Computer Aided Design And Analysis For Zero Defects. In: International Conference on Aluminium; December 2000; p. 1-6.