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Design Optimization of Gating System by Fluid Flow and Solidification Simulation for Front Axle Housing

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Abstract— *In spite of knowledge of conventional gating design casting defects such as shrinkage and gas porosities were found in front axle housing a critical automotive component. This component is generally made out of spheroidal graphite iron. A flawed gating system was found to be the reason for improper fluid flow and melt solidification which in turn produced casting defects. Optimization of the gating and risering system by using casting simulation software ADSTEFAN was carried out. Through several simulation iterations, it was concluded that defect free casting could be obtained by modifying the initial gating ratio 2:2:1 to 2:1.76:1. Also shifting of sprue location from centre to end and providing the risers at location prone to formation of shrinkage porosity led to the decrease in size of the shrinkage porosity about 97%.*
Keywords— *Front Axle Housing, Casting Simulation, Gating Design Optimization, Fluid Flow and Solidification Simulation, Shrinkage Porosity.*

I. INTRODUCTION

Inspite of conventional knowledge of gating system design and suggestions by experienced foundry engineers front axle housing castings showed presence of internal shrinkage porosities. Producing defect free casting is a challenge in manufacturing environment. The formation of various casting defects is directly related to fluid flow phenomena during the mold filling stage and in the cast metal [1]. The rate of solidification greatly affects the mechanical properties such as strength, hardness, machinability etc [2]. One of the critical elements that has to be considered for producing a high quality sand casting product is the gating system design and risering system design [3-4]. Any improper designing of gating system and risering system results in cold shut and shrinkage porosities. Therefore adequate care is necessary in designing gating and risering systems for improved yield of defect free castings.

Casting design is primarily done on a shop floor by trial and error basis [5]. Conventionally experimental routes are often used for design and development of product with optimum process parameters. But the process is costly, time consuming, and may be impossible in some cases. Hence with conventional approach, finding an acceptable gating system design proves to be an expensive and arduous process. Presently use of casting simulation software is increasing, as it essentially replaces or minimizes the shop floor trials to achieve sound castings [2]. With the availability of modern numerical software and good hardware capabilities, simulation has become an important tool for the design, analysis and optimization of casting processes. Use of casting process simulation software can significantly reduce the casting cost and in turn cost benefit can be passed over to the customer. It also provides reduced research and development lead times, better first time castings and higher quality of the casting.

Till date several researchers have used casting software for design optimization of gating system, Zhizhong Sun et al have studied [6] optimization of gating system of an automotive component by Magma Soft casting simulation process. They showed that the runner height and width as well an ingate height and width affect the quality of magnesium castings. In case of aluminium plate casting, runner cross section area is the other factor affecting the casting quality. T.Nandi et al studied [2] the optimization of riser size for Aluminium Alloy (LM6) castings. They designed different risers based on conventional method and they were simulated using vector element based computer simulation technique. Some researchers studied the design optimization of gating system of telecommunication [7] and brake disc [14] parts made by die casting and sand casting process respectively using Numerical simulation software like Magma Soft. They have concluded that split gating system led to swirl filling and insufficient central flow, which resulted in air entrapment. They also concluded that the new design with continuous gating system and a bigger runner size with increased gate area provided a homogeneous mould filling pattern. Kermanpur et al presented [8] the simulation of metal filling and the solidification behavior of the automotive components using Computational Fluid Dynamics (CFD) code FLOW-3D cast into the multi-cavity sand moulds. They concluded that increasing to a four-cavity mould is more suitable than the three-cavity one in getting a more uniform casting quality for all cast parts. The reason for this was longer distance from sprue to the Ingate. So the gating system was designed to four cavity mould. J-H. Chen, et al simulated [11] the fluid flow and solidification heat transfer of die casting process for the top cover of an automobile generator made of aluminium alloy using the ADSTEFAN Simulation software. They have concluded that the fluid flow and the temperature distribution improved by the double runner system. The modified system significantly improved the quality of the die casting and eliminated the surface defects. The replacement of the single runner system by the double runner system noticeably reduced the velocity of the molten alloy at the gate, which extended the life of the die, also they showed that the use of a double runner system design enabled a more uniform distribution of temperature and improved the final filling in the casting process, thus reducing the amount of gas entrapment. Shamsuddin Sulaiman et al studied [12] simulation of molten metal flow along runner and gating system with four gates in pressure die casting using network analysis with the aid of a program written in FORTRAN language. The author concluded that smaller branch angle will require less pressure to fill the runner and gating system, also showed that time required to fill with this runner and gating system took longer when smaller branch angle is used. Lubos Pavlak et al investigated [13] the effect of shape of pouring process and position of ingates on the formation of oxide film in Aluminum cylinder heads. Based on the experimental observations, the author concluded that the main factor for smooth filling of the mould is the pouring process and the position of ingates. The shape of the pouring basin has significant influence on the smoothness of the pouring stream and further on the oxide formation, Pouring distance is also one of the very important factors that have impact on the formation of oxides consequently increasing porosity in cast structure. The point at which the falling stream of melt fall down into pouring basin define the smoothness of melt velocity (laminar or turbulent) through the sprue and the mould contributing to the later quality of cast product. V. Vazquez et al investigated [15] the solidification process on a lead free tap of yellow brass alloy, for permanent mould casting using ProCAST simulation software. Based on the experimental observations after casting simulation, they have concluded that the lower tilt angle resulted in a convergence of the metal flow resulting in a formation of a big cold shut. With the increase in the tilt angle of the mould from 68°-78° convergent metal flow moves further up and the castability and fluidity increased and the cold shut failure defect disappeared as observed experimentally.

Review of available information reveals application of commercially available casting simulation codes to simple parts like plates and cylinders rather than complex part like front axle housing. Many software use finite element method (FEM) to simulate casting process, which needs manual meshing and are prone to human errors. The casting simulation software used in the present work uses Finite Difference Method (FDM) using cubes as the basic elements and has a major advantage over FEM. It meshes automatically eliminates the need to recheck the meshing connectivity thereby speeding up analysis. In the present work, gating system has been designed and optimized by iterative process through fluid flow and solidification simulation for a front axle housing to produce defect free casting.

II. METHODOLOGY

Figure 1 shows drawing of a typical front axle housing and Table 1 shows its specifications. The front axle housing casting model with essential elements of the gating system like In-gate, runner, sprue and risering system were generated in CATIA V5 CAD modeling software. Three gating designs were implemented to optimize the gating system for front axle housing. The methodology adopted for gating and risering system design is explained in 2.1 & 2.2 sections.

***Table I:* Specifications of front axle housing**

Parameters	Value
Component Length	597.987 mm
Minimum wall thickness	12 mm
Weight	35 kg
No of Cavities	2

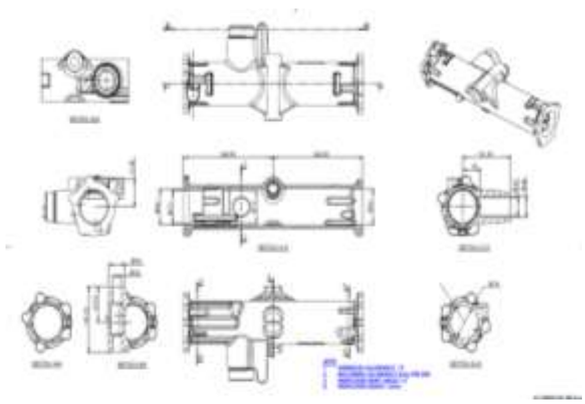

Fig. 1 Typical front axle housing

A. *Designing the Gating System*

Conventional gating system for Spheroidal Graphite Iron (SGI) casting, theoretical concepts and casting rules are some of the design considerations taken into account to calculate gating system needed to ensure shrinkage free casting. Gating system design considered is shown in table 2.

Conventional design procedure states sprue diameter shall be 85% the weight of the casting and for parting line gating system sprue height is typically taken as 0.5 to 1 times the height of mould cavity [10]. The diameter and height of riser are calculated by modulus method [2].

***Table III*: Summary of the parameters and dimensions of gating system**

Parameter	Value/Type/Dimension
Gating system adopted	Parting line and pressurized gating system
Gate Type	Edge
Runner Type	Trapezoidal
Sprue type	Circular cross section
Pouring Time	35 seconds (1 to 1.5 kg per second for SG Iron)

Gating Ratio Considered	Sprue Area: Runner Area: In-gate Area = 2:1.76:1
Sprue Area	706.85 mm²
Runner Area	625 mm²
Ingate Area	360 mm²
Mould cavity height	215 mm

B. *Design of Risering System*

Figure 2 shows feeding graph for SG Iron by pressure control risering method (PCR). The design sequence of PCR involved firstly determining casting significant (largest) modulus (MS), then corresponding modulus of riser neck (MN) and modulus of riser (MR) using feeding graph of SGI. as shown by the blue line in figure 2.

Table 3 shows modulus parameters for the riser. Riser neck dimensions are measured at the bottom of the radius between riser and casting. Additional notching of the contact was introduced with notch depth not more than one fifth contact thickness. Feeding distance is assumed to be a maximum of 10 x MN.

Dimensions: Thickness = 1 x MN, Length = 3 x MN, Width = 6 x MN.

From Graph figure 2, for Ms (Modulus of Casting) = 7.5 mm MN (Modulus of Neck) = 6 mm

Thickness = 1×MN = 6 mm

Length = 3×MN = 18 mm

Width = 6×MN = 36 mm

Table IIII: **Modulus calculation for riser**

Parameter	**Formula/Source**	**Value**
Volume of the Casting	--	4925684 mm³
Surface Area of the casting section	--	656757 mm²
Modulus of the casting Section (M_S)	Volume / Surface Area	7.5 mm
Modulus of the Neck (M_N)	Fig 2	6 mm
Modulus of the Riser (M_R)	Fig 2 or 1.2×M_N	7.2 mm
Diameter of the Riser	6×Modulus of the Riser Diameter (D)= 5 M_R to 6 M_R	45 mm
Height of the Riser	1.5 x D	70 mm
Number of Risers	Based on Number of major region of shrinkage porosities.	2

C. *Simulation Process.*

ADSTEFAN is casting simulation software developed by Hitachi Corporation Ltd, Japan. This was used to simulate fluid flow and solidification process for three gating designs. Casting simulation and result analysis was done to predict the molten metal solidification behavior inside the mold. The casting component with gating system was imported in STL (Stereo lithography) format to the ADSTEFAN software and meshing of the model was done in the pre-processor mesh generator module. The mesh size of casting was 2 mm which is infact less than the minimum wall thickness of the casting and for the mould mesh was 10 mm. The structural boundary conditions are automatically taken care by the software.

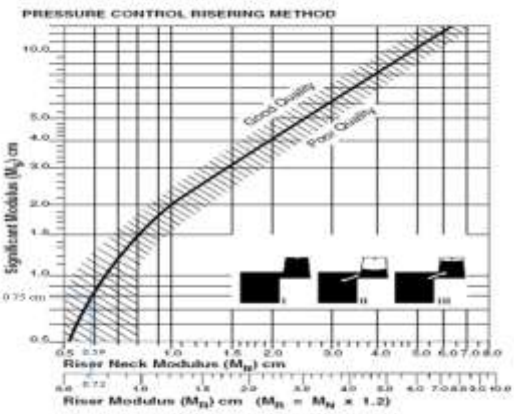

Fig. 2 Feeding graph for SGI [9].

Assignment of material properties, fluid flow and solidification parameters: The meshed model was taken into the precast environment of the software, where the number of materials, type of mold used, density of cast material, liquidus and solidus temperatures of SG Iron and other input parameters of fluid flow and solidification conditions like pouring time, pouring type, direction of gravity etc. were assigned. Table 4 & 5 show the material properties, fluid flow & solidification parameters. After the assignment of material properties and simulation conditions, prediction of air entrapment, temperature distribution and shrinkage porosity are carried out. Casting simulation program provides output files in the form of graphical images and video files which are analyzed to predict defects after the successful execution.

***Table IVV:* Input material properties and conditions**

Parameter	Type of Mould	Conditions
Material	Green Sand	SG 450/10
Density	1.5 gm/cm3	6.9 gm/cm^3
Initial Temperature	20°C	1300°C
Liquidus temperature	--	1200°C
Solidus temperature	--	1145°C

***Table V:* Input fluid flow and solidification parameters**

Parameter	Input condition
Velocity of fluid flow	19.8 cm/s
Fill time	35 sec
Critical solid fraction	0.8 (maximum 1)
Pouring type	Gravity Pouring
Output files	1) Air entrapment 2) Filling temperature 3) Solidification pattern 4) Shrinkage and gas porosity
Riser Type	Closed

III. RESULTS & DISCUSSION

A. *Air Entrapment.*

Figures 3 (a) (b) & (c) shows the molten metal (grey colour) at the bottom portion and air sweeping (blue colour) from the top portion of mould cavity. From the simulation results it is clear that as the mould is filled with molten metal, air escapes through the top of the housing. The metal enters through the four end gates and four center gates into two mould cavities in first iteration shown in figure 3(a). In second and third iterations as shown in fig 3(b) & 3(c)

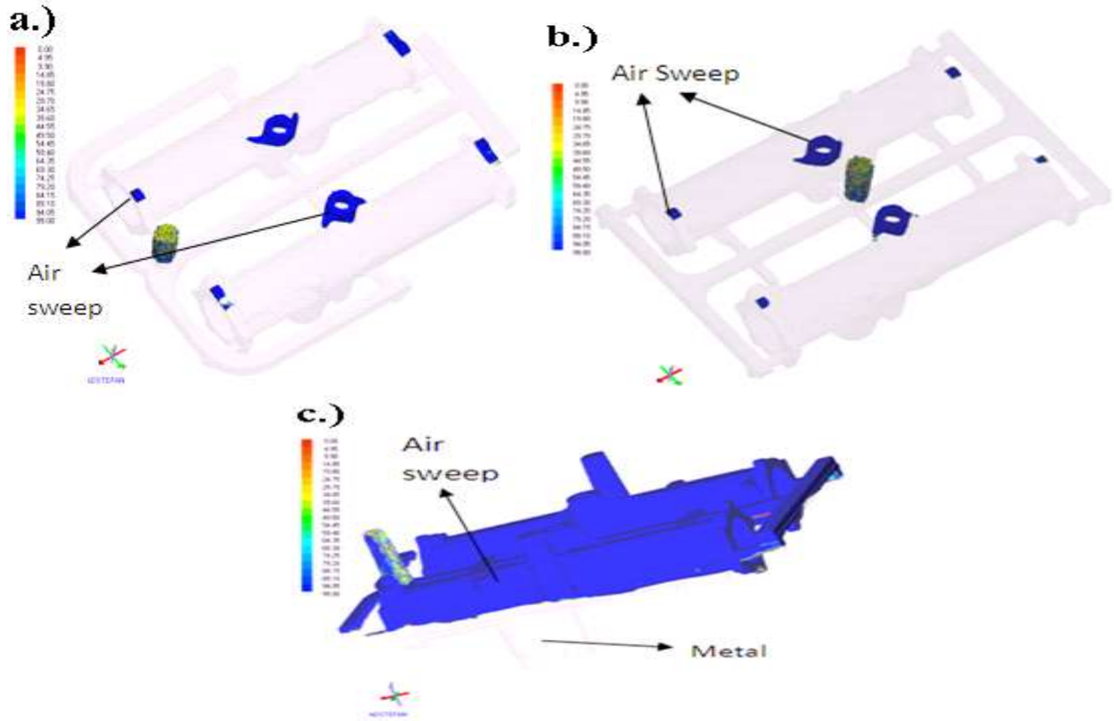

Fig. 3 Air sweeping from mould cavity.

the ingates and runner bars are placed symmetrically due to which even flow of melt makes the air gently to rise above, as the metal starts filling from the bottom of the cavity. This allows all the air and gases to escape from the mould cavity. There is no air entrapped zone in the casting component and gating system in any of the iterations.

B. ***Temperature Distribution.***

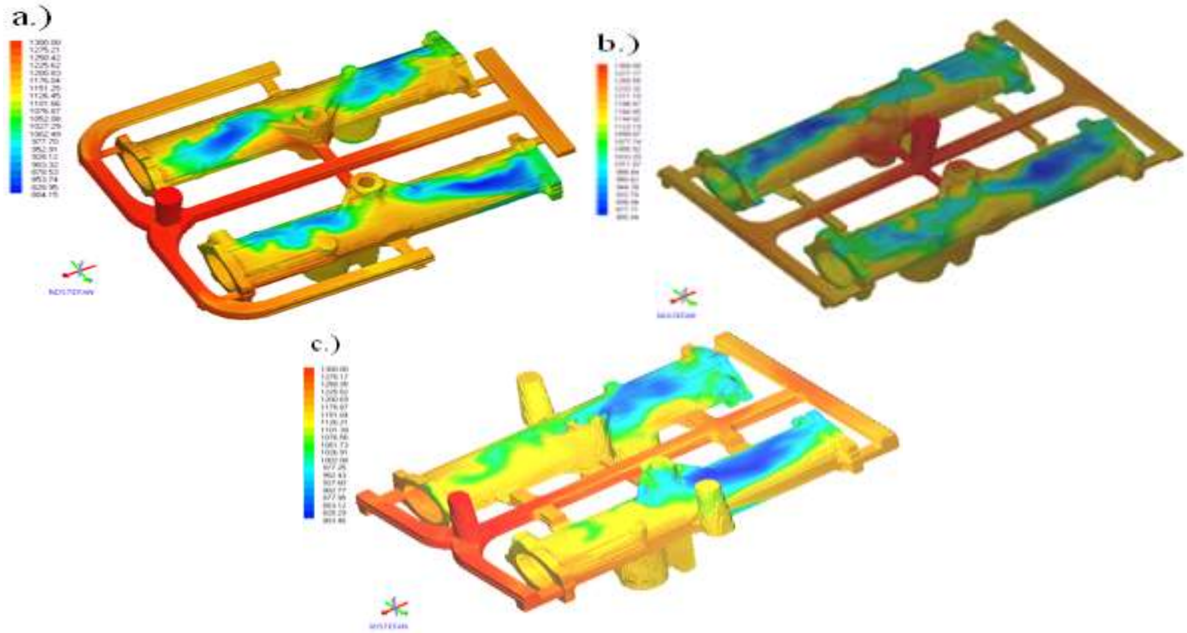

Fig. 4 Temperature distribution in casting component.

The actual solidification of metal begins at liquidus temperature of 1200 °C (reddish yellow colour). The solidification of metal ends at solidus temperature 1145 °C (yellow colour).

Figure 4(a) shows the temperature distribution of the molten metal in the first iteration of the gating system. At no part of the melt, did the temperature fall below the liquidus temperature. In second and third iterations as shown in figure 4(b) & (c) the ingates and runner bars are symmetrically placed. The temperature distribution is also uniform. In all the iterations it can be seen that runner bars and in-gates have temperature distribution within the limit i.e. above liquidus temperature. Any fall in temperature within the gating elements would have resulted in formation of cold shuts and blockage of further entry of molten metal which has not been observed in the simulation.

C. ***Shrinkage Porosity***

Figure 5 shows shrinkage porosity in the casting component for first & second iteration gating system. It is observed that in first iteration gating system simulation showed shrinkage porosities at five different locations with total volume of 1.545 cm3 ranging from 0.26 to 0.355 cm3 and in second iteration gating system the solidification process led to decrease in the number of shrinkage porosities from 5 to 2, Also total size of shrinkage porosity decreased by about 32%.

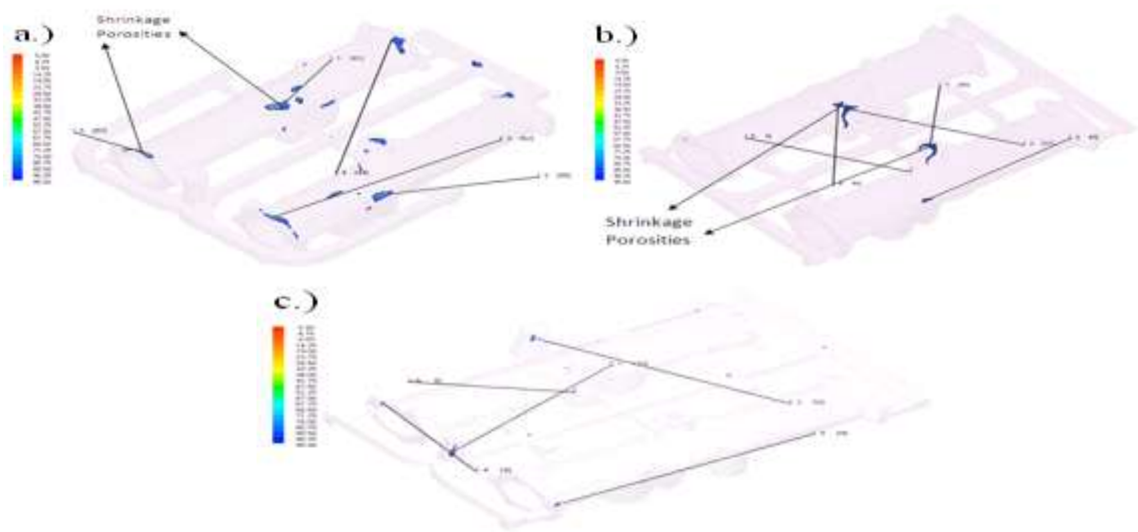

Fig. 5 Shrinkage porosity in the casting.

In the final iteration very small size shrinkage porosity was found in the casting component about 0.042 cm3, Also porosities were found in the sprue and riser which are removable parts from the component. Thus the shrinkage porosity decreased significantly by 97%. These studies thus helped in arriving at an optimum gating system.

IV. CONCLUSIONS

In the present work a 3D component model was developed using casting simulation software ADSTEFAN to evaluate possible casting defects under various gating system designs for sand casting of front axle housing. Three types of gating system were examined through numerical simulation and an optimized design was choosen through this process. Notable conclusions from this study are:

- By adopting the parting line and pressurized gating system, the fluid flow was smooth and air was expelled without any entrapment inside the mould cavity. Simulation showed that the molten metal was able to fill the mould within the desired time. Therefore fluid heat distribution was good and no cold shut was observed.
- In first iteration improper location of ingates led to formation of shrinkage porosities where in the second iteration symmetric locations of ingates helped to drive solidification front towards one region and in third iteration final solidifying regions were compensated by providing risers.
- The second iteration resulted in reducing the number of shrinkages by 60% and the total size of porosity decreased by 32%. In the third iteration two shrinkage pores were found, however they were in the sprue and riser and thus insignificant for the component. Also the size of the porosity decreased by 97% which by industry standards is acceptable.
- It is apparent that theoretical methods like symmetrically balanced gating system are good for simple parts but for complex designs, verification of process with casting simulations would yield better product at lesser time.

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