
Solidification behavior and detection of Hotspots in Aluminium Alloy castings: Computer Aided Analysis and experimental validation

Rabindra Behera¹, Kayal.S¹, Sutradhar.G²

1-Research Scholar, Department of Mechanical Engineering, Faculty of Engineering and Technology, Jadavpur University, Kolkata 700032

2- Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, Jadavpur University, Kolkata 700032

rabi_lisha@yahoo.com

ABSTRACT

Manufacturing of sound casting is the main aim for foundry men. To achieve this number of trial casting has carried out on the shop floor and one repetition can take up a week or more, which affects the regular production. Many researchers reported that about 90% of the defects in castings are due to wrong design of gating & risering system and only 10% due to manufacturing problems. Casting simulation process can able to overcome these problems. It has observed that various type of simulation software has used in foundry, out of which FEM and VEM based casting simulations are widely used in foundry. In the present paper, a benchmark model has considered to study the solidification behavior of aluminium alloy (LM6) and detection of hot spots in castings with the help of mentioned above casting simulation softwares. The simulated results also compared with the experimental works.

Keywords: Sand castings, Mold filling, solidification, Hotspot and Simulation.

1. Introduction

Casting, one of the economical manufacturing processes used in industries, is a complicated process, which involves considerable metallurgical and mechanical aspects. The rate of solidification governs the microstructure largely, which in turn controls the mechanical properties like strength, hardness, machinability, etc. The location, size and shape of riser in a casting depend on the geometry of the casting, mould design and thermal properties of metal, old and other process parameters. Wrong designed riser results either defective casting with shrinkage cavity or lower yield, as directional solidification has not achieved. Hence, proper design of risering system and good control over the process parameters are necessary for quality castings. From realistic considerations, the experimental routes are always better for design and development of mould and for arriving at the optimum process parameters. However, it is costly, time consuming, and may be impossible in some cases. Therefore, casting simulation process is a convenient way of proper design of risering system and analyzing the effect of various parameters. There are number of casting simulation software are developed and are used in foundry worldwide. The application of casting simulation softwares are also increasing day to day in Indian foundry as it essentially replaces or minimizes the shop-floor trials to achieve the desired internal quality at the highest possible time. The list of various casting simulation softwares have given in the Table-1.

Table 1: A list of casting simulation programs, along with their vendor addresses

SYSTEM	VENDOR
AFSOLID	AFS, INC., 505 STATE STREET DES PLAINES, ILLINOIS 60016 USA
AUTOCAST	ADVANCED REASONING TECHNOLOGIES PVT. LTD., MUMBAI 400 703, INDIA
FLOW-3D	FLOW SCIENCE, INC., 1257 40 TH STREET, LOS ALAMOS, NEW MEXICO 87544 USA
MAGMASOFT	MAGMA GmbH, KACKERSTRASSE 11, 52072 AACHEN, GERMANY
NOVASOLID	NovaCast AB SOFTCENTER, S-RONNEBY, 37225 SWEDEN
ProCAST	UES SOFTWARE, INC., 4401 DATONE-XENIA ROAD, DAYTON, OHIO, 45432 USA
SIMTEC	RWP GmbH, ALT-HAARENER-STRASSE 251 D-52080 AACHEN, GERMANY

The main inputs for the casting simulation process are

- The geometry of the mould cavity (3D model of the casting, feeders, and gating channels),
- Thermo-physical properties (density, specific heat, and thermal conductivity of the cast metal as well as the mould material, as a function of temperature),
- Boundary conditions (i.e. the metal-mould heat transfer coefficient, for normal mould as well as feed-aids including chills, insulation and exothermic materials),
- Process parameters (such as pouring rate, time and temperature).

There were lot of research work had been done on casting simulation by using different casting simulation softwares. Such as Prabhakara Rao et.al studied on the simulation of mould filling solidification of casting of green sand ductile iron castings and concluded that the use of casting simulation software like Pro CAST can able to eliminate the defects like shrinkage, porosity etc. in the casting. It also improves yield of the casting, optimize the gating system design and the mould filling .B. Ravi Studied on optimization of mold cavities, feeders and gating system of an industrial component by using Auto CAST casting simulation process. Author shown that the total time for method design and optimization of the casting reduces to about one hour .B. Ravi also studied on Casting Simulation and Optimization: Benefits, Bottlenecks, and Best Practices. B.Ravi et.al. studied on 3D Junctions in Castings: Simulation-based DFM Analysis and Guidelines. They have also studied on defect like shrinkage porosity at casting of 3D junctions such as L/V, T/Y and X/K. Authors were predicted the location of shrinkage porosity by casting solidification simulation, and corrected by minor modification to part design .Authors were investigates the best values and ratios of junction parameters by using casting simulation software like Auto CAST.

In the present work, simulation of mould filling, solidification behavior of green sand aluminium alloy castings have carried out by using VEM based and FEM based casting simulation process and the effect of riser neck on the nature of solidification have studied.

Author also detects the level of porosity, location of hotspot and rate of solidification of metal with respect to time.

2. Objective computer modeling of solidification of castings

Many computer simulation programs now exist, but some require computers of a power not generally available to practical foundry men, while others take an unacceptably long time to obtain meaningful results.

The aim of computer modeling is to-

- Predict the pattern of solidification, indicating where shrinkage cavities and associated defects may arise.
- Simulate solidification with the casting in various positions, so that the optimum position may be selected.
- Calculate the volumes and weights of all the different materials in the solid model.
- Provide a choice of quality levels, allowing, for example, the highlighting or ignoring of micro-porosity.
- Perform over a range of metals, including steel, white iron, grey iron and ductile iron and non-ferrous metals.

3. Numerical simulation of solidification

The numerical simulation of solidification involves the following steps

- a. Formulation of an accurate mathematical model of the solidification process
- b. Specifying accurate values for thermal properties of material involved.
- c. Performing the analysis to obtain the temperature history of casting and mould points.
- d. Post- processing the results to visualize the solidification the solidification pattern and identify defects in the casting

The solidification of the molten metal in the mould cavity take place due to heat transfer from the metal to mould (shown in Figure-1) ^[9], which follows an unsteady heat transfer equation i.e.

$$\rho C_p \left\{ \frac{\partial T}{\partial \tau} \right\} = K \left[\left\{ \frac{\partial T^2}{\partial x^2} \right\} + \left\{ \frac{\partial T^2}{\partial y^2} \right\} + \left\{ \frac{\partial T^2}{\partial z^2} \right\} \right]$$

The heat flux across the metal – mould interface= h x ΔT

where,

h= heat transfer co-efficient

ΔT= Temperature difference across the interface.

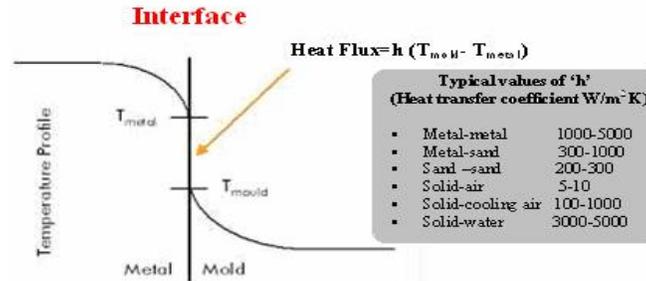


Figure 1: Heat transfer between metal - mould interface

3.1 Solid-liquid Interface

The energy balance has obtained by equating the rate of heat removed from the solid phase to the sum of the rate of heat supplied to the interface from the liquid phase and the rate of heat liberated at the interface during solidification. Hence, K_{sc} and K_{lc} are the thermal conductivity of the solid and liquid metal respectively. The L denotes the latent heat, n denotes the normal to the surface (Direction of heat transfer) and s denotes fraction solidified (That release the latent heat).

$$-K_{sc} \frac{\partial T_{sc}}{\partial n} = -K_{lc} \frac{\partial T_{lc}}{\partial n} + \rho_{sc} L \frac{\partial s(n)}{\partial n}$$

3.2 Casting-Mould Interface

Before the air gap formation, heat transferred from casting to mould by conduction. Given T_c and T_m are the temperature of the casting and mould; the temperature at casting mould interface can be found from heat flux ω

$$\omega = K_c \frac{\partial T_c}{\partial n} = K_m \frac{\partial T_m}{\partial n}$$

After air gap formation, heat transfer is by convection and radiation. Thus the heat flux equation between casting and mould side is

$$\omega = \sigma \epsilon F [(T_{sc} + 273)^4 - (T_{ms} + 273)^4] + h_c \Delta T = -K \left(\frac{\partial T}{\partial n} \right)$$

Where, T_{cs} and T_{ms} are the temperature at the casting and mould side of the interface, σ is the Boltzmann's constant, ϵ is the emissivity, and F is the form factor.

4. Result and discussion

4.1. Analysis of mould filling by simulation process

The gating design has driven by the ideal mould filling time, which depends on the cast metal, casting weight and minimum wall thickness. Fast filling leads to turbulence-related defects (such as mould erosion, air aspiration and inclusions). On the other hand, slow filling may

cause defects related to premature solidification (such as cold shuts and miss-runs). To optimize the gating design, the program simulates the mould filling and computes the total fill time.

The casting simulation softwares have solved for mould filling and solidification processes at the same time. The discussion about mould filling has solely based on VEM based and FEM based casting simulation results. In the present investigation, a benchmark study on stepped (three) casting has considered, shown in Figure2 and four 3D models of the casting has prepared with their gating and risering system by using solid works software with different size of riser neck at constant size of riser. The size of riser and its neck of different models have given in the Table-2 and the different parameters used in casing simulation processes have given in Table-3. The mould filling processes at different step has visualized from Figure3 (a-c). It has found that for every succession of one second, the fraction of solid and temperatures are changing (encompasses sprue , ingate, casting and feeder) will be filled up. Due to the design of taper sprue and unpressurized gating system (gating ratio 1:1.5), the molten metal enters the mould through gate and rises almost uniformly in the cavity of the mould until it has completely filled up. This is a good filling because it ensures no sand erosion in the mould and solidification of liquid metal immediately starts in the mould cavity. On changing the dimension of the riser neck, the total mould filing time is not so much changed. The total mould filling time is approx. 6.111 second in case all models.

Table 2: Dimension of gating system, riser and riser neck

	Ingate Size	Riser Height	Riser Diameter	Neck Height	Neck Diameter
Model - 1	10mm.x 12mm.	82.00 mm	55.00mm	6 mm	18.00 mm
Model - 2	10mm.x 12mm.	82.00 mm	55.00mm	6 mm	22.00mm
Model - 3	10mm.x 12mm.	82.00 mm	55.00mm	6 mm	40.70 mm
Model - 4	10mm.x 12mm.	82.00 mm	55.00mm	No riser neck	

Table-3: The Input Parameters for Casting Simulation

Casting material-	LM6
Moulding material –	Green silica sand
Pouring Temperature of Liquid metal into the mould-	680 °C.
Mould Temperature-	30 °C
Heat transfer co-efficient (h)-	200 W/m2 K
(Between sand and mould)	
Pouring Rate -	0.250 Kg/sec.

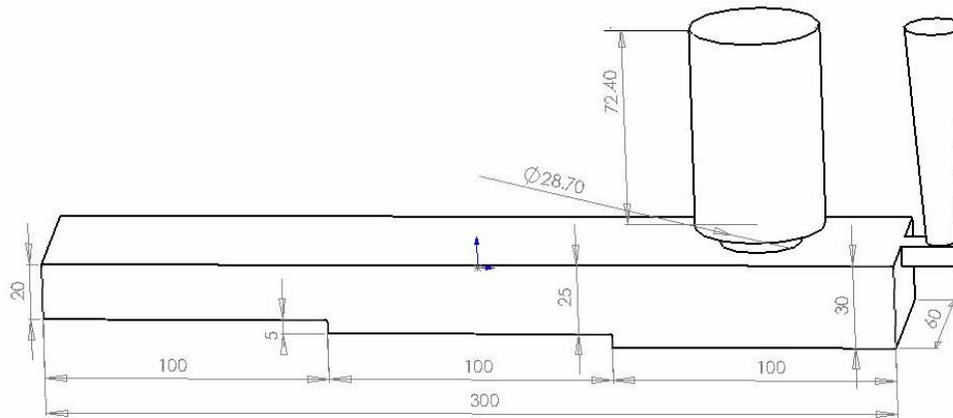
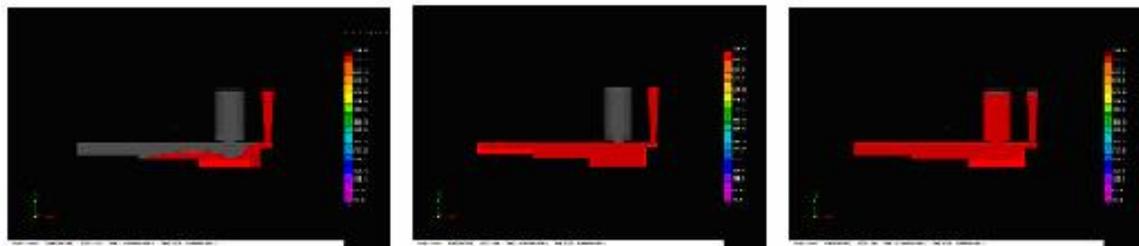


Figure 2: 3D model of the casing part with its risering system



(a) At step-150

(b) At step-200

(c) At step-590

Figure 3 (a-c): Mould filling at different step for model –I, using FEM based casting simulation software.

4.2. Analysis of solidification and hot spots in castings by using simulation software's

The solidification of liquid metal in the mould cavity takes place immediately after entering into the cavity. For the cast material i.e.LM6, solidification will start when the temperature drops below 572°C and fully completed beneath 570°C . Solidification is a result of heat transfer from internal casting to external environment. As it was a stepped casting, the rate of solidification is not uniform through out the casting. The solidification of liquid metal in the mould cavity starts from the edges of the casting and it progress towards the center of the casting. The solidification front directed from the thinnest section towards the thickest section and the thinner section solidifies quicker comparison to the thickest section. The position of hotspot detected in different casting models. It has observed that the position of hotspot changed due to change in diameter of riser neck keeping the riser size constant. The dimensions of shrinkage defects are also different at different riser neck.

4.3 Model-I

The input parameters for casting simulation in all cases are same as given in the Table-2 and the size of gating and risering system has given in the Table-1. In model-I, the size of riser neck is 18.0mm i.e. about 33% of riser diameter. The Figure 4 (a-c) shows the simulated results obtained by using FEM based casting simulation of model-I, the simulated results indicated that the shrinkage defect and shrinkage porosity remains in the casting. The same

results are also found in the simulated results of VEM based casting simulation, shown in Figure5 and the actual casting shown in Figure6. The Figure 7 shows the cut section of the casting. However, the position of hot spot in the actual casting is almost matching with the simulated result obtained by Pro CAST and MAGMA soft. The Auto CAST simulated result shows slightly different to the actual casting.



(a) At step-1330

(b) At step-1350

(c) Porosity in the casting

Figure 4: Solidification simulation of the casting-using FEM based cast casting simulation software

(a & b) Fraction of solid (F.S.) at different step and (c) Porosity in the casting

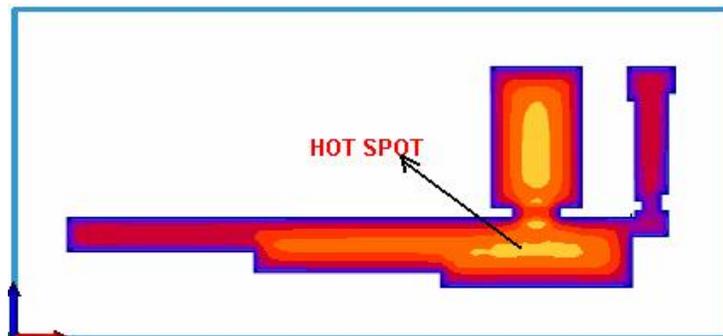


Figure 5: Solidification simulation of the casting-using VEM based cast casting simulation software.



Figure 6: Casting of model-I



Figure7:Section of casting with shrinkage defect

4.4 Model-II

The gating and risering of the three-stepped casting has given in the Table-1. In model-II, the size of riser neck is 22.0mm i.e. about 40% of the riser diameter for the same gating system.

The Figure8 (a-c) shows the simulated results obtained by using FEM based casting simulation, the simulated results indicated that the no shrinkage defect present in the casting but, slightly shrinkage porosity visible at the bottom of the riser neck. The simulated result of VEM based simulation process has shown in Figure9, the result indicates that a very small size of hot spot present at the bottom of the riser neck. The Figure 10 shows the cut sections of the actual casting, it has observed that casting is sound and there is neither shrinkage defect nor porosity in the casting. This result almost same as the simulated results obtained from the three casting simulation softwares.

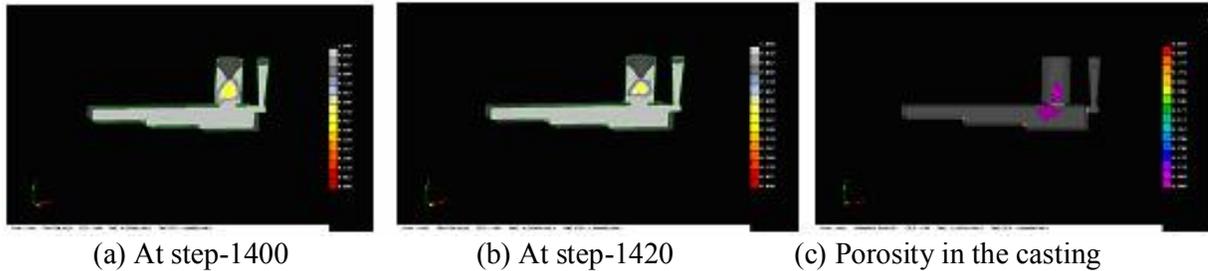


Figure 8: Solidification simulation of the casting-using FEM based cast casting simulation software

(a & b) Fraction of solid (F.S.) at different step and (c) Porosity in the casting.

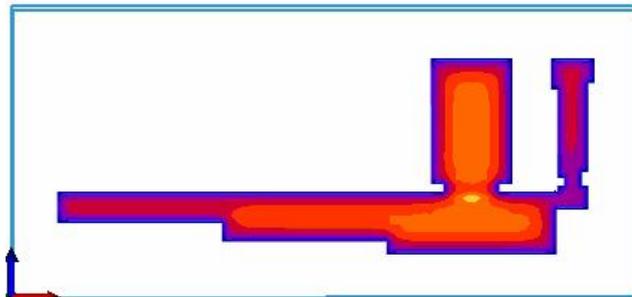


Figure 9: Solidification simulation of the casting-using VEM casting simulation software.



Figure10: Section of casting shows no shrinkage defect

4.5 Model-III

The gating and risering of the three-stepped casting has given in the Table-1. For the model-III, the size of riser neck is 40.7mm i.e. about 74 % of the riser diameter, for the same gating system. The Figure 11 (a-c) shows the simulated results obtained by using FEM based casting simulation; the simulated results indicated that the very small shrinkage defect and porosity visible at the bottom of the riser neck of the casting. The simulated result of VEM based simulation process has shows in Figure12; the result indicates that small size of hot spot present at the bottom of the riser neck. The Figure13 shows the cut sections of the actual casting, it has observed that a small shrinkage defect present at the bottom of the riser neck in the casting. This result matched to some extent with the simulated results of the three casting simulation softwares.

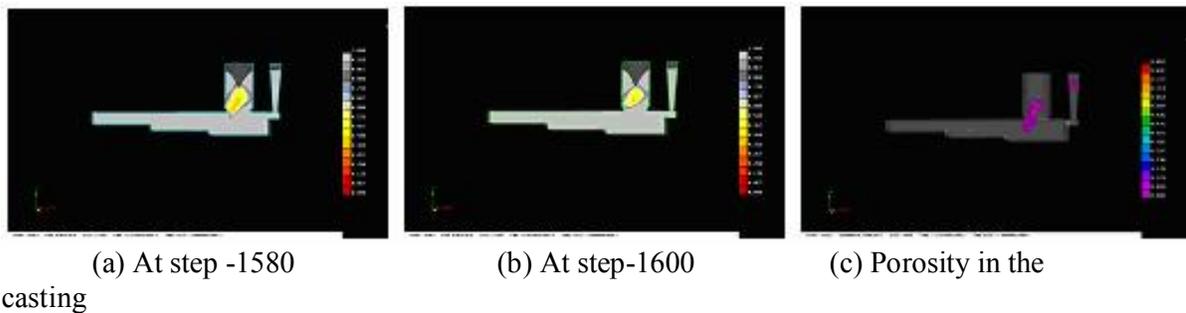


Figure11: Solidification simulation of the casting-using FEM based cast casting simulation software, (a & b) Fraction of solid at different step and (c) Porosity in the casting.

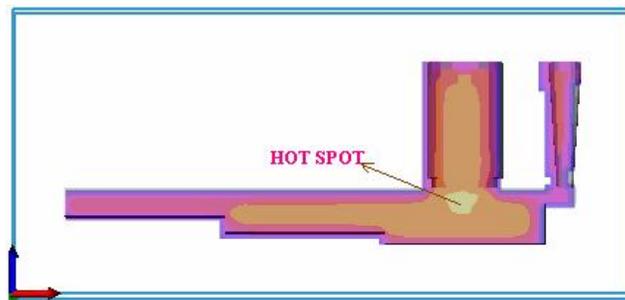


Figure12: Solidification simulation of the casting-using auto cast casting simulation software.

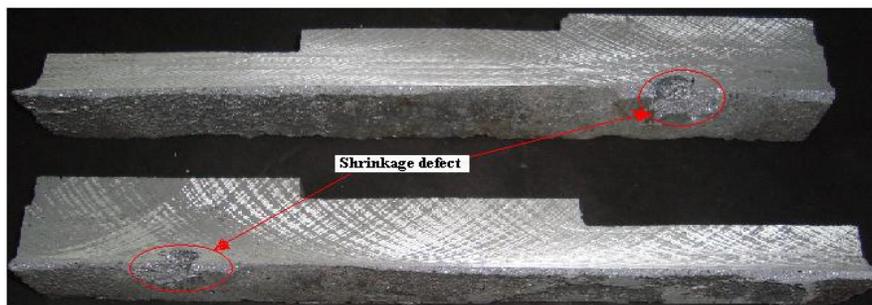


Figure13: Section of casting with shrinkage defect

4.6 Model-IV

For the model-IV, no riser neck has used with the risering system of the casting. The Figure14 (a-c) shows the simulated results obtained by using FEM based casting simulation, the simulated results indicated that the position of the hot spot moving towards the riser and the porosity in the casting visible at the bottom of the riser. The simulated result of VEM based casting simulation has shown in Figure15; the result indicates that a small size of hot spot present in the casting at the bottom of the riser. The Figure16 shows the cut sections of the actual casting, it has observed that the casting having neither shrinkage defect nor porosity. This result matched with the simulated results of FEM & VEM based casting simulation software.

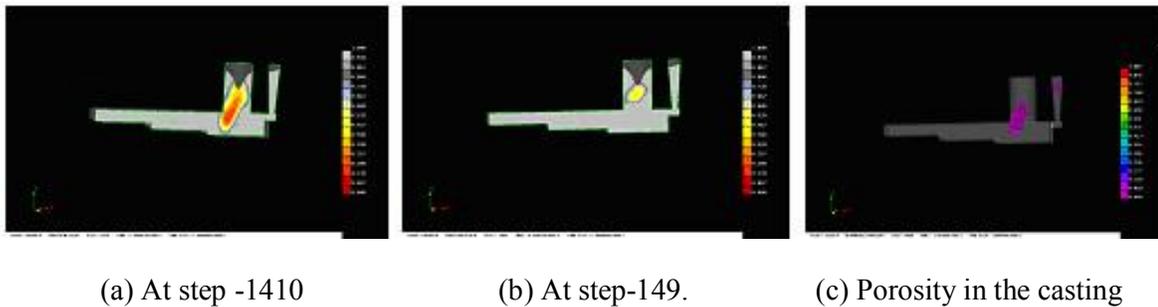


Figure14: Solidification simulation of the casting-using FEM based cast casting simulation software, (a & b) Fraction of solid (F.S.) at different step and (c) Porosity in the casting.

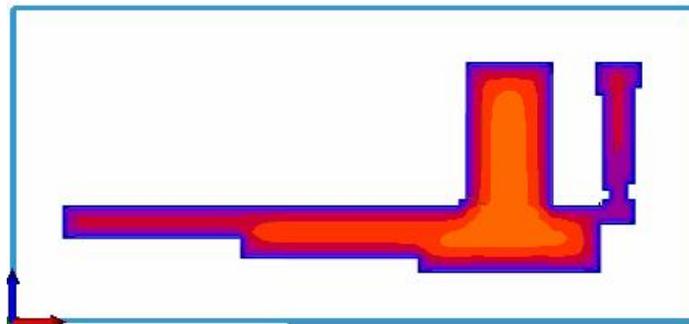


Figure15: Solidification simulation of the casting-using VEM based casting simulation software.



Figure16: Section of casting shows no shrinkage defect.

The above simulation and experimental work shows that the riser neck plays a vital role casting process. The use of casting simulation process can able to optimize the design of riser neck in very short time comparable to the conventional methods.

5. Conclusion

The application of computer-aided methoding, solid modeling, and casting simulation technologies in foundries can able to minimize the bottlenecks and non-value added time in casting development, as it reduces the number of trial casting required on the shop floor. In addition, the optimization of riser neck reduces or completely removes the occurrence of shrinkage defect in the casting. The application of casting simulation software based on finite element method and vector element method, shows good results and matched with the experimental results. The benchmark study reveals that the use of casting simulation softwares reduces the iteration time for modification of methoding and to reach at a safe design of riser neck. It has also proven to be very useful for verifying the manufacturability of a casting and improving it by minor modifications to part geometry, before freezing the design in early stages of product lifecycle. Application of casting simulation softwares in foundries can be able to optimize the size and the position of the riser neck to avoid shrinkage defect in the casting.

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