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Modeling and Finite Element Analysis for a Casting Defect in Thin-Wall Structures

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ABSTRACT

The casting of pump impeller blades is a difficult operation due to its thin wall structure. In the casting process for thin wall impeller structure, the prediction of shrinkage defect is a one of the important issue and failure of such thin wall structure is a commonly encountered problem. The non-uniform heat transfer rate is the main cause of such failure. The uniformity of heat transfer rate may enhance by placing the runner at appropriate position and riser based on the geometrical attributes. The flow of liquid metal and its solidification has time based temperature variation, shrinkages and porosity distributions in such structures. An attempt is made for the analysis of optimization in the placement of runner and riser through this experimentation. The experiment contains the analysis of finite element simulation of fluid flow and solidification of metal execution at various temperatures, prediction of shrinkages based on the geometry of the casting and flow curvature and porosity distribution. This work also focuses on the prediction of casting defects in aluminum thin wall pump impeller structure using commercially available software (ANSYS-FLUENT). The experimental validation of the simulation result is also done to confirm the same.

Keywords: Casting, Pump Impeller, Casting Defects, Solidification.

INTRODUCTION

Casting process offers the widest variety in terms of metals and alloys, shape complexity (including internal features), size and weight, production quantity and applications. The apparent ease of producing a casting – melting and pouring metal into a shaped mould – hides the complexity of the physical phenomenon involved. All three modes of heat transfer are involved (conduction, convection and radiation), but their amounts depend on the thermo physical properties of the cast metal and the surrounding mould [1-2]. All regions of a casting do not cool at the same rate, which is driven by part geometry and boundary conditions imposed by various mould elements. Moreover, solidification is accompanied by volumetric contraction, manifesting in defects like shrinkage porosity. Premature solidification (before complete filling of mould) can lead to mis-run and cold shut [6, 9]. Metallurgical factors like grain size and shape, phase distribution and segregation affect mechanical properties (strength, ductility, hardness and fracture toughness). The large number of material and process parameters is exacerbated by the difficulty of controlling them [3,9]. While foundry engineers struggle to produce high quality castings, researchers find it equally difficult to consistently replicate casting defects and properties [4]. The analysis of casting defects which usually occurred in thin structures like a pump impeller is targeted in this work. In casting industries, knowledge of the temperature history, position of solidus and liquidus boundaries, temperature gradients, and liquid velocities is very important because casting engineers can predict the formation of voids, porosity, micro segregation, and the microstructures based on this information. This predictive capability will be very useful in preventing casting defects without carrying out the costly and tedious trial-and-error process [1, 7]. Sand casting, the most widely used casting process, utilizes expendable sand moulds to form complex metal parts that can be made of nearly any alloy. Hence, the sand casting is typically used in this study. The validity of the simulation result is done by some actual casting as a part of experiment. The opacity of mould and difficulty of instrumentation are major obstacles to experimental studies of industrial castings. Hence foundries rely on indirect methods – by trial and error – to develop new castings with the necessary gating and feeding systems. But in spite of this the low yields and the high rejection rates are the major problems faced by the foundries [2, 5, 8]. This

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leads to considerable wastage of melting energy and other production resources, effectively increasing the cost per casting and reducing the production capacity of a foundry. Computer simulation offers an attractive alternative to foundry experiments which helps to study progress of metal flow and solidification. Velocities, temperatures and cooling rates at different locations inside the casting can be measured. Metallurgical models can be applied to predict casting defects and properties. The methods design (gating and feeding system) can be iteratively improved and verified by simulation. This can help in producing castings that are right first time and right every time with high overall yield [2, 10, 11].

OBJECTIVE

The objective of this work is to simulate the casting of a thin wall structure like pump impeller and compare the results of simulation with the results of experimentation done by changing the position of runners and risers. The analysis points the effect of changing the positions of runners and risers and also the related defects which may arise in the casting. To simulate solidification in metal casting processes, solution of a transient, nonlinear heat transfer problem is considered. This work opens the new avenue for the prediction of shrinkage based on the geometry of the casting and the flow curvature. Further, the analysis also points towards the optimization in the placement of the runner and riser based on the thickness, geometrical attributes (curvature of the blades) for uniform heat transfer. This reveals lesser thermal stresses and better conformance to the desired geometrical attributes.

RESEARCH METHODOLOGY

The CAD model of the most commonly used impeller is selected and prepared for the analysis at first stage. Figure 2 illustrates the CAD model of the impeller pattern selected for the study. The type of impeller selected is open type of impeller having smaller thickness of the blades. The impeller is designed to have 6 radial blades for the study. Open type impeller was taken so that the construction can be easily exposed to the observer and it will be easy to prepare the actual casting of the impeller at the time of experimentation. For detecting the surface and subsurface crakes magnetic crack detection was done as shown in figure 1. In this test red magnaflux powder was applied over the test surface of the casting, and then the two copper tips prods connected to the supply were applied on the surface parallel to each other with the help of prod handle. The intensity of the current shots was increased gradually. The ferromagnetic particles form an outline of the discontinuity and indicate its location. But, Al only shows a weak magnetic moment in presence of an external magnetic field. When this external field is released, the Al loses his magnetism, hence dye penetrant testing was conducted to confirm the results and detect other crakes and blow holes.

Figure1. *Set Up of Magnetic Crack Detection*

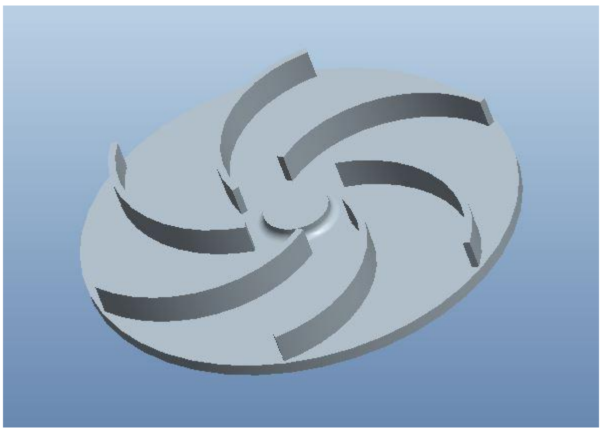


Figure2. *Impeller Pattern*

For this hydrophilic type cleaner was used to clean the surface then washable penetrant RP90 was applied on the surface and kept for some time and the surface was again cleaned by cleaner. Then the developer was applied on the surface. The surface was inspected under black (UV radiation lamp) light. The defects appear as dark purple spots. Figure 3 shows the experimental set up to record the temperature at three different locations of the casting by using three separate K-type thermocouples which were capable of measuring the temperature up to 1200°c. The temperatures were recorded by a camera till the solidification.

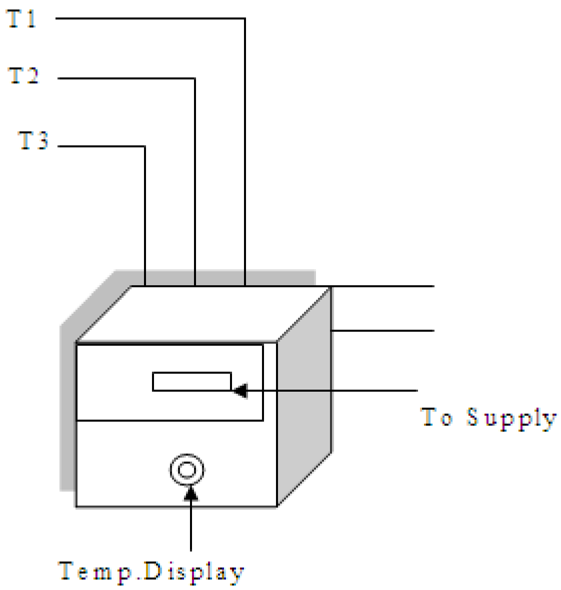


Figure3. *Experimental set up for determination of spatial temperature distribution.*

DATA ANALYSIS

As the impeller is symmetric, only three blades were taken for simulation. Thus 1/2 geometry is considered in the simulation. This helps to save the simulation time without sacrificing the results and its investigation. Figure 4 shows the mesh of the selected three blade geometry. At the time of simulation the circular base plate is not considered because focus is on studying the defects in the casting of thin wall structure like impeller blade. Different combinations types, as given in Table1, of inlet velocity, liquids temperature and impeller blade thickness were designed for simulation experiments [1].

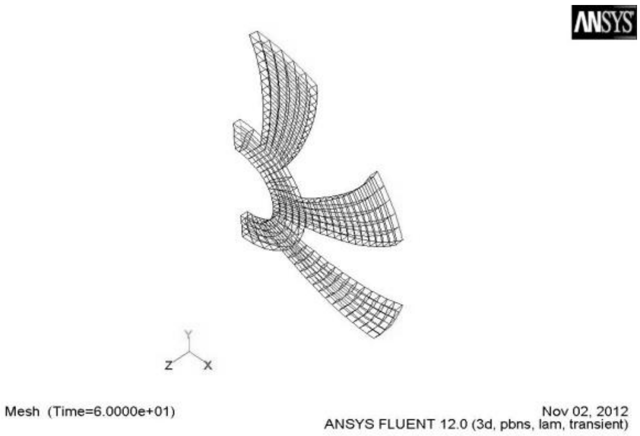


Figure4. *Meshed 1/2 geometry of Impeller*

Table1. *Design of simulation experiments*

Combination Type	Inlet velocity(m/s)	Liquidus Temp.(K)	Thickness(m)
A	0.00101	1000	0.01
B	0.00101	1200	0.01
C	0.002	1200	0.01
D	0.002	1000	0.01
E	0.00101	1000	0.015
F	0.00101	1200	0.015
G	0.002	1000	0.015
H	0.002	1200	0.015

For all the design simulations experiments, the simulation results obtained for the different parameters like mass flow rate, heat transfer rate, wall shear stress, heat flux, heat transfer coefficient, Nusselt number and enthalpy are given in Table 2[1].

EXPERIMENTAL RESULTS

From simulation results it was observed the type G and H gives better result [1], hence the type G was selected during the experiment and three actual castings were made by various following ways

1. Casting 1 –Runner itself acting as a riser.4
2. Casting 2 – one runner and two risers were kept.
3. Casting 3 – one runner and three risers were kept.

During all these castings aluminum (LM6) was used. The castings were tested for blow holes, internal crakes and shrinkage related defects by conducting magnetic crake detection, dye penetrant testing and ultrasonic test. The test revealed that when runner itself was acting as a riser, there were blow holes in the centre as well as at the bottom of the curvature, but with two risers they were reduced at large. In case of three risers the casting was found to be comparatively more sound. The section of casting 1 was taken from the centre to confirm the results of the various tests by conducting visual inspection and then the remaining castings were done by adding risers at various locations along the bottom surface of the base plate. In this section of casting 1 along with blow holes, pin holes and shrinkage cavities were also observe

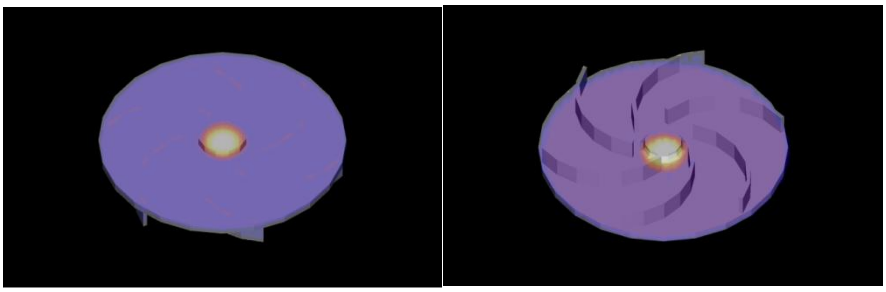
Table2. *Simulation Results of Designed Simulation Experiments*

Type	Mass flow inlet(kg/s) $*10^{-7}$	Heat transf.(w)$*10^{9}$	Wall shear stress(Pascal)	Heat Flux (w/m^2)	Heat transfer coei(w/m^2k)	Nusselt no	Enthalpy (J/Kg)
A	5.085	$6.788*10^{14}$	$1.2529*10^{11}$	1779.18	2.59	107.4	102504.92
B	5.085	$3.66*10^{9}$	$7.932*10^{5}$	299.69	25.31	1046.03	151961
C	0.10069	$5.94*10^{9}$	$3.1799*10^{6}$	312.31	26.37	1090.03	102504.92
D	0.10069	$1.489*10^{9}$	$1.483*10^{6}$	288.84	24.39	1008.14	151961
E	5.085	$6.78*10^{14}$	$7.6353*10^{10}$	1671.27	2.44	100.98	102504.92
F	7.62	$4.214*10^{11}$	$1.71024*10^{7}$	1191.93	1.73	71.51	138965
G	0.10069	$1.642*10^{11}$	156.6	1190.958	1.72	71.24	102504.92
H	0.10069	$1.642*10^{11}$	156.6	1190.58	1.72	71.24	102504.92

This may be because of absorption of hydrogen or carbon monoxide due to improper degasification of molten metal and because of the absence of the risers the gases could not escape through the cavity. The simulation of the casting for hot spots was done using the website e-foundry. The results of this simulation given in figure 5 were helpful to decide the locations of runner and riser to avoid the hot spots [9] in the casting. Hot spots are indicated by the yellow color in this simulation. The comparative variation of simulation temperature and experimental temperature given by thermocouples T1, T2, and T3 and recorded by a camera are given in table 3. However the difference between these two value may be because the use of camera for recording the temperatures in place of data acquisition system and the time lag of the thermocouples to give the reading when the selector position was changed.Contours of static temperature at 80 sec are given in the following figure 6.

Table3. *Simulation and experimental temperatures*

Time (sec)	Simulation temp(°C)			Experimental temp(°C)		
	T1	T2	T3	T1	T2	T3
80	722	401	176	780	470	201
140	691	344	154	721	398	174
320	664	301	151	689	346	162



(a) Bottom side of the impeller **(b)Top side of the impeller**

Figure5. *Simulation results of impeller solidification for determination of hot*

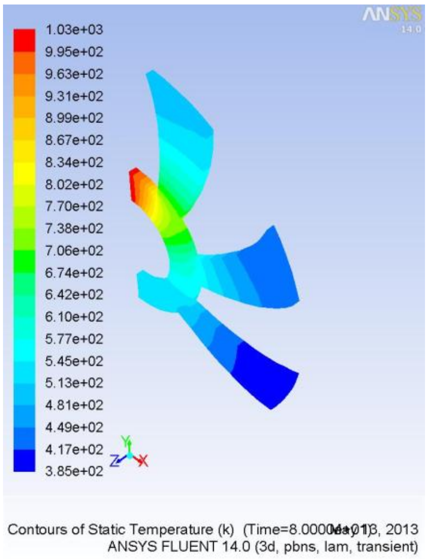


Figure6. *Contours of Static Temperature*

CONCLUSION

In case of aluminum, the volumetric contraction being very high, the positioning of the risers plays a very important role to produce a defect free casting. During simulation it has been observed that the heat dissipation rate depends on the ratio of surface area to the volume of the casting. It is also observed that the higher ratio results in faster and proper directional solidification of fluid metals.

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