

Geometry Dependency of Filling Related Defects

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Abstract— During mould filling in casting process, defects such as misrun, cold shut, gas and oxide film entrapment and shrinkage often occur. The development of filling related defects are mainly governed by metal fillability. In practice, these defects are eliminated by iteratively designing casting filling (gating) system through experience and experiments, but it requires large number of shop floor trials; taking huge amount of resources (cost) and time. This can be avoided by conducting trials on computer using casting simulation technology. Three varying thickness parts with different shape complexity have been designed to quantify the mould filling characteristic. Part shape complexity depends on geometry parameters such as volume and surface area of part, volume of thin section, section thickness, number of cored features, core volume etc. Mould filling and solidification analysis of these parts have been carried out using ANSYS. The information derived from the simulation is used to quantify the metal fillability index. A linear correlation has been found between shape complexity and mould fillability index. It is observed that more complex part has poor fillability index (and thus, poor manufacturability) as compared with less complex parts.

Keywords- casting simulation, casting defects, coldshut, misrun, shape complexity, fillability.

I. INTRODUCTION

Development of defects like misrun, cold shuts, gas entrainment, mould erosion, hot tear and shrinkage porosity during mould filling process leads to poor part integrity and high casting rejection. A misrun defect occurs due to incomplete filling of mould cavity. A portion of the casting may be not filled, and necessary sharp corners may be rounded. A cold shut is visual and structural discontinuity formed where two or more metal streams meet below liquidus temperature of the cast metal. This can occur especially in large thin sections of the casting. The misrun and cold shut defects form when casting filling time is comparable with solidification time. These defects are attributed to casting design and pouring practice, and all casting methods (green sand, chemically bonded sand, permanent and semi-permanent mould) are susceptible [1].

The casting filling (gating) system design in the foundry has long been based on the intuition and experience of the foundry engineers. Foundry engineers attempt to design the filling system so that smooth, uniform and complete filling occurs. In practice, it requires to conduct a large number of shop floors trials to evaluate influence of cast geometry and pouring parameters on formation of the defects. This is a laborious process requiring huge amount of time and resources.

Alternatively, the design process can be integrated with scientific analysis of melt flow and heat transfer using computers. Development and availability of high-end computers facilitates penetration of simulation technology in casting filed in last three decades. During simulation, underlying physics is mathematically modeled (governing equations) and solved numerically so that important process variables can be identified and controlled, resulting in saving in development time. The shop floor iterations can be significantly reduced and will be primarily used for concept validation [3]. Many dedicated casting simulation softwares are available today- MAGMASOFT, ProCAST, SolidCAST, and AutoCAST. Modules of typical casting simulation software are shown in Fig.2 [4].

The mould filling process can be modeled to predict formation of filling related defects. But computer simulation cannot directly reveal formation of a defect. It gives temporal temperature and velocity information which can be processed further to comment on development of a particular casting defect. In present work an attempt is made to predict these defects by quantifying a fillability index. This index indicates the ease with metal flows inside mould cavity during mould filling.

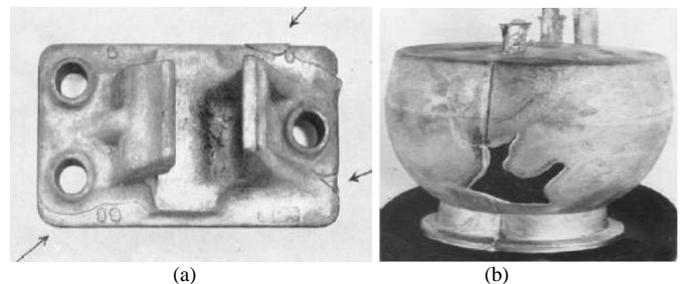


Fig. 1 Flow related defects (a) Coldshut (b) Misrun [2]

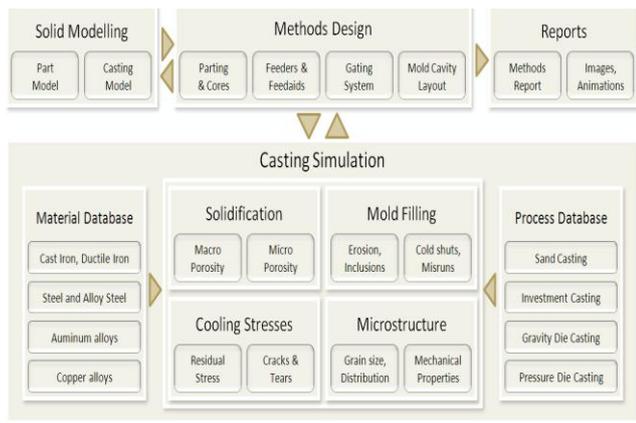


Fig. 2 Different modules of casting simulation system [4]

II. LITERATURE REVIEW

Shamasunder [5] discussed the steps involved, possible sources of errors and care to be taken during the casting process simulation. According to him the designer needs to have full confidence in the casting simulation tool. This can come only by experience and usage of the tool to mimic effect of various process parameters. With the advances in technology and proper care in modeling, it is possible to simulate the defects generated during casting before the casting is practically produced. They presented different case studies using ADSTEFAN software.

Ziolkowski [6] performed sensitivity analysis to examine the influence of mould-metal interfacial heat transfer coefficient, mould thermal conductivity, wall friction factor, pouring temperature, and pouring basin head pressure on mould filling process. Analysis of thin plates and spiral geometry had been carried out using MAGMASOFT casting simulation program to predict occurrence of misrun defect. Jana et al. [7] analyzed mould filling and solidification process of low pressure turbine (LPT) blades to predict misrun defect as shown in Fig. 3. LPT blades for aircraft engine are having high thickness gradient with less than 1 mm thickness at the trailing edges. The effect of surface tension and wetting angle is dominant in these wall-bounded flows during the filling stage. They summarize, possible reasons for misrun defect are low fluidity, lower pouring temperature and inadequate mould design. All simulations were carried out using STAR-Cast which is developed by Access and CD-Adapco.

Ohnaka [8] described that misruns can be estimated by continuously tracking the change in the temperature and solid fraction of the melt-free surface during mould filling process. When the melt pressure affects solid movement as in the case of high pressure die casting, it is necessary to use a proper empirical value of the critical fraction solid. Cold shuts can be estimated at the place where the melt front collides and having a higher fraction solid than some critical value.

Melendez [9] proposed a model for prediction of inclusions during mould filling process. The filling simulation calculates the velocity and free surface geometry of the melt as a

function of time. The inclusion model assumes that the reoxidation-inclusions are spherical, characterized by their diameter. The inclusions form and grow on the melt free surface, and they are transported through the mould cavity by melt flow. The model tracks the inclusions in a Lagrangian framework. During each time step of filling simulation, new free surface is created, and some inclusions on existing regions of the free surface may be swept away from the surface by the local flow pattern. The total number of inclusions nucleated during filling is a direct function of the free surface evolution and the tendency of the flow to draw inclusions away from the free surface.

Yitao [10] presented the computer simulation technique to mimic injection-forming process and to predict defects formed during trial manufacture of automotive parts using semi-solid die cast process. A reasonably close agreement was observed between experimental and simulation results as shown in Fig 4. Internal defects obtained during experiments were analyzed with X-ray and were correlated with filling parameters. Numerical visualization of filling process can assist in correct predictions of cast defects and optimization of process parameters.

Brevick and Miller [11] analyzed simple and complex flat plate geometries using commercially available software Cast View, MAGMASOFT, Nova Cast, Flow3D, dieCAS. They used colored water model and radiography technique to validate the filling behavior and sequence as shown in Fig. 5. The filling time shown in the figure is not the absolute, but rather a relative filling time indicating for the sequence.

Santhi et al. [12] developed a test case to measure mould filling ability of LM6 and LM25 Al alloy. They showed that mould filling ability influences the liquid metal flow, heat transfer and solidification phenomena, ultimately affecting the quality of the castings. Santhi et al. [13] expressed the mould filling ability as a reciprocal of the meniscus diameter. The diameter at the tip of the fin gives the meniscus diameter of the solidifying liquid metal as represented in Fig. 6 for one particular pressure head.

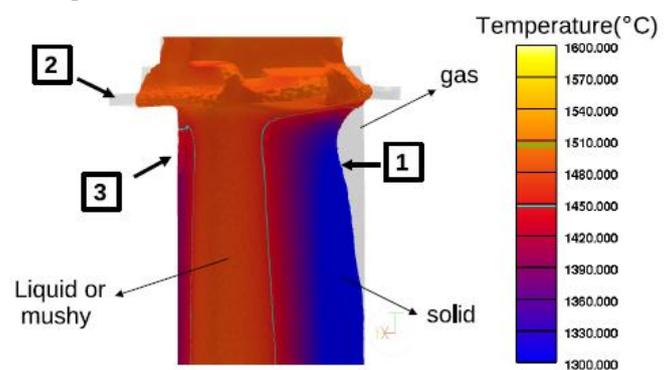


Fig.3 Simulation results after 6.5 seconds (1.Misrun on trailing edge, 2. Misrun on blade platform, 3.Misrun on the leading edge) [7]

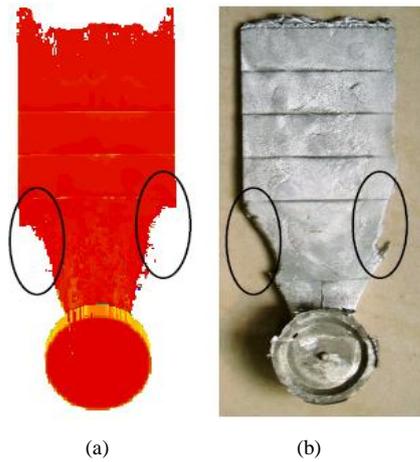


Fig.4 Comparison of filling process in slow type between simulation and experiment: (a) Simulation (b) Experiment [10]

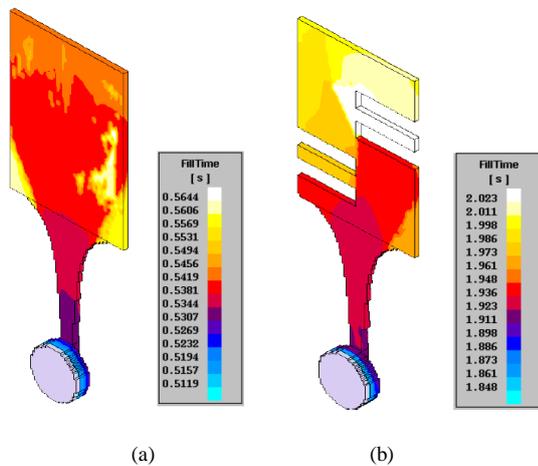


Fig.5 MAGMASOFT filling time simulation: (a) simple complexity part (b) intermediate complexity part [11]

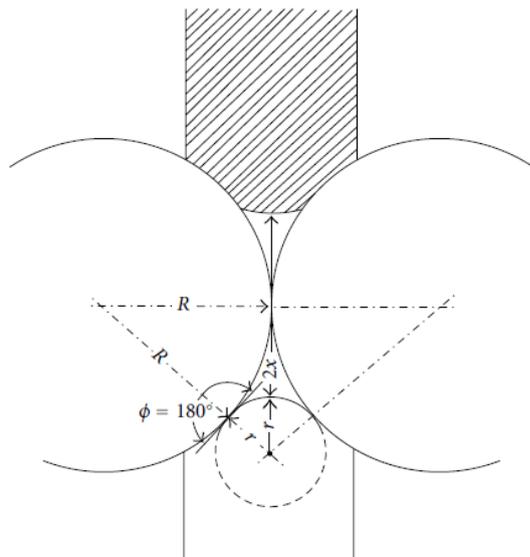


Fig.6 Measurement of mould filling ability

III. CORRELATE COMPLEXITY OF PARTS WITH MOULD FILLABILITY

Mould filling is a very small event in casting manufacturing but its impact is huge on casting life cycle, as internal soundness and quality depend on it. It involves flow of molten metal from pouring end to other sections of the cavity, and flow of heat from molten metal to mould and ultimately to air. Rapid heat transfer may leads to on-set of solidification before mould cavity is completely filled with molten metal [13]. If mould filling time is comparable with solidification time, then there may occur cold shut defect. The mould filling characteristics mainly depend on geometry of cast component, alloy composition, mould material, mould coating [14], gating system [14, 15], pouring temperature, and filters [16].

Complex shaped metal parts with internal and external features and varying wall thickness can most economically produced by casting process. The major challenge is to achieve smooth, uniform and complete filling. A higher shape complexity however, leads to non-uniform and turbulent metal flow. Part shape complexity is evaluated based on normalized (on the scale of 0 to 100) geometric ratios proposed by Joshi and Ravi [17]. Mould filling characteristic is quantified by proposing a mould fillability index and it is correlated with shape complexity.

Fillability index is defined as the function of volume of cavity filled before metal gets solidified, and maximum and minimum temperature of the metal at the instance when flow stops. As volume of cavity filled is higher and range of temperature is lower, fillability will be higher.

$$\text{Fillability} = \frac{V_{filled}}{V_{cavity}} \times \frac{T_{min}}{T_{max}} \times 100$$

$$\text{Shape complexity} = (C_{VR} + C_{AR} + C_{CR} + C_{TR} + C_{TFVR}) / 5$$

Where, C_{VR} is part volume ratio and it depends on volume of part (V_p) and volume of part bounding box (V_b). The bounding box is given by the maximum length, width, and height of the part geometry. When the volume of part is close to its bounding box, shape complexity will be lower.

$$C_{VR} = 1 - V_p / V_b$$

C_{AR} is area ratio and it depends on surface area of an equivalent sphere (with the same volume as that of the part, S_s) and surface area of the part (S_p). This ratio is based on the fact that sphere has minimum surface area as compared to any other geometry.

$$C_{AR} = 1 - S_s / S_p$$

C_{CR} is core volume ratio defined as ratio of core volume ($\sum V_c$) to bounding box volume (V_b). Larger the core volume shape complexity will be higher.

$$C_{CR} = (\sum V_c) / V_b$$

C_{TR} is thickness ratio depends on minimum and maximum thickness of the part. Larger the variation in section thickness higher will be shape complexity.

$$C_{TR} = 1 - T_{min} / T_{max}$$

C_{TFVR} is thin feature volume ratio defined as ratio of volume of thin feature ($\sum V_{tf}$) to the total volume of the part (V_p). Larger the volume of thin features higher will be shape complexity.

$$C_{TFVR} = (\sum V_{tf}) / V_p$$

Three aluminum parts having varying thickness are designed in such a manner that minor change in geometry result in significant change in the shape complexity. Keeping first part as base, a hole and closed slot is provided in second part, whereas two way open slots are provided in third part as shown in Fig.7. Shape complexity of first, second and third part are 24%, 33% and 35% respectively. Mould filling and solidification analysis of these parts are carried out using ANSYS keeping same mesh size, cast metal, mould material, inlet condition (mass flow rate and pouring temp) and boundary condition (heat transfer coefficient value). Percentage volume filled, maximum and minimum temperature is logged and fillability is calculated for each part (Table I). Temperature contours when metal flow front solidifies and flow stops are shown in Fig.8. As part complexity increases metal fillability decreases linearly as shown in Fig. 8.

All dimensions are in mm.

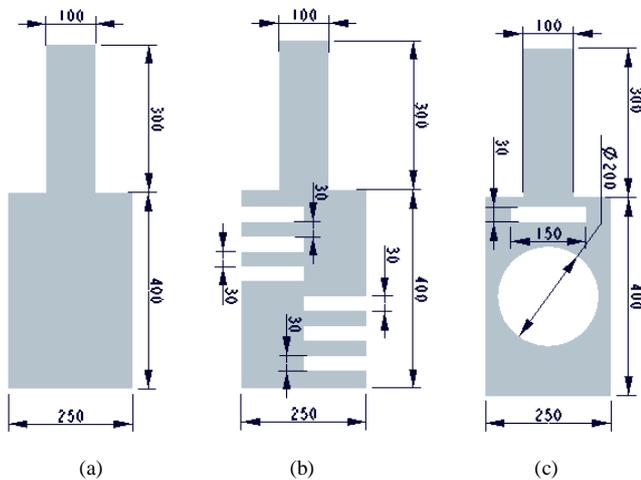


Fig.7 Part design (a) simple complexity part (b) intermediate complexity part (c) final complexity part

Table II: Shape complexity and fillability of the parts

Sr. No.	Shape Complexity	Fill	T_{max} (k)	T_{min} (k)	Fillability
a	24%	54%	937.2	879.7	50 %
b	33%	49%	936	871.8	46 %
c	35%	44%	937	864.7	40 %

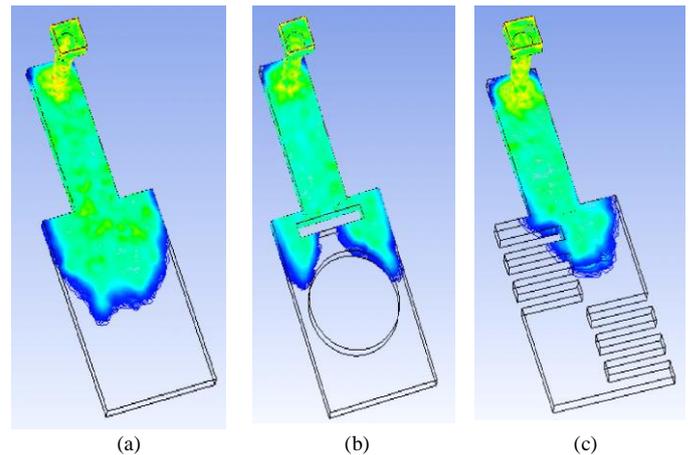


Fig.8 Temperature contour (a) simple complexity part (b) intermediate complexity part (c) final complexity part

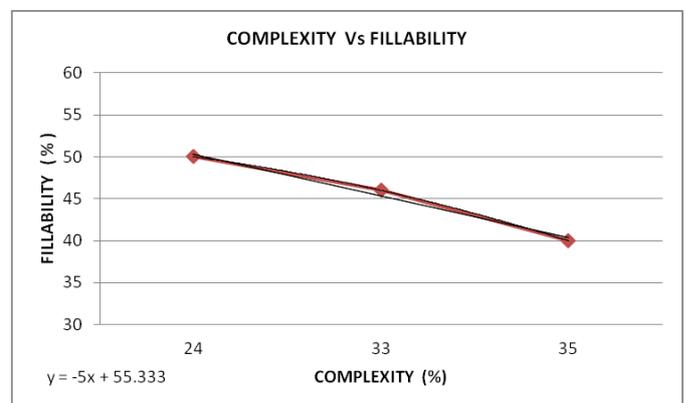


Fig.9 Variation in fillability with shape complexity

IV. CONCLUSIONS

Mould filling characteristic depends on part geometry, thermo-physical properties of cast metal, mould thermal conductivity, wall friction factor, pouring temperature, and pouring basin head, as well as surface tension and wetting angle. Mould filling characteristic is quantified by defining fillability index. Poor fillability results in development of filling related defects.

Metal fillability is evaluated for three part having mirror variation in geometry. Shape complexity of first, second and third part are 24%, 33% and 35%, respectively and corresponding values of fillability are 50%, 46% and 40% respectively. Part with lower shape complexity fills more cavity volume before metal gets solidify and corresponding fillability is observed to be higher. Part with higher shape complexity experiences large difference in maximum and minimum temperature at the instance when metal flow front solidifies and corresponding value of fillability is observed to be lower. The correlation between shape complexity and fillability is found to be linear. If fillability analysis is carried out at design stage, significant saving in cost can be achieved by avoiding time-consuming shop floor trials.

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