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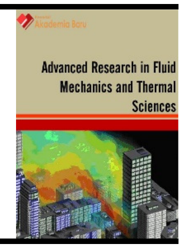

Flow Behaviour of a Feeder at Dendrite Coherency Point In Metal Castings

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ABSTRACT

This study applied heat transfer and fluid flow in numerical simulation of metal casting solidification in order to investigate the solidification behaviour of the metal casting as it reaches dendrite coherency point. The goal is to explore and gain insight about the ability of a given feeder design to feed the casting section to obtain a shrinkage-defect-free casting. The mathematical model of the casting solidification was solved using the finite volume method (FVM). Various feeder designs for a step casting of aluminium alloys were studied. The relationship of the flow characteristic and the soundness of the casting is explored. The objective is to gain insight on how the metal flow behaviour at dendrite coherency may influence the casting performance. The scope of this study is limited to lost-foam sand casting of aluminium-silicon alloys.

1. Introduction

The formation of shrinkage defects or porosities during solidification is a common problem in metal casting. As liquid metal solidifies, the metal shrinks and forms cavities inside the casting. The cavities are normally formed at the last area where the liquid melt solidifies. Risers or feeders are usually added to the casting shape to compensate for the metal shrinkage. The feeder will supply the additional metal when shrinkage occurs during the solidification. Uninterrupted flow of the molten metal to feed the solidifying regions can produce sound castings that are free from the shrinkage defects. This is achieved by controlling the cooling rate to promote directional solidification [1]. As a result, the mold and casting are designed such that the cooling begins at the sections that are furthest away from the feeders and end at the feeders. Consequently, the shrinkage cavities formed are in the feeders which will be cut off later from the casting part [2].

There have been several studies in literatures for effective feeding. Effective feeders are able to provide enough continuous flow into the castings to prevent shrinkage defects without causing waste in material due to their excessive sizes. There are however, various factors than can influence the

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effectiveness of a feeder such as its dimension, shape, location on casting, and the connection type to the casting [3,4]. One of the common techniques to determine the effective feeders is based on the modulus principle that compares the ratios of the section volume to its surface area associated with the casting section and the feeder [5,6]. If the modulus of the feeder is greater enough than that of the casting, the feed metal added to the casting may be sufficient. Many optimization techniques of feeders in literature are based on modulus principle such as seen in [7-9]. So far the use of modulus principle has a limitation in that, it only accounts for the solidification time requirement which is not sufficient to ensure sound castings.

Another common technique that concerns with determining effective feeders involve the use of numerical modeling of metal solidification. There has been considerable numerical research in optimizing the casting process design. However, the optimization particularly in the field of feeder design, has received less attention in spite of its significance [10]. Most of these works obtained the optimal feeder design, i.e., the feeder design that resulted in a sound casting, systematically through numerical modeling and simulation. Hence, the determination of the last region to solidify, called hotspot, and the ability of the feeder to feed this region laid the foundation for the traditional feeder design techniques. Numerical simulation of casting solidification is used to quantify and predict the behavior of the solidifying metal. The results of the simulation such as the temperature distribution throughout the casting, will be used to facilitate feeding evaluation and optimization including the prediction of the shrinkage locations. Much of the numerical simulation studies however, concentrate on using the thermal analysis excluding the fluid flow analysis [11-13]. Campbell warned that caution must be taken when dealing with the results of such models [14]. Analysis based on thermal characteristic only may not produce reliable results especially for aluminium alloys [15].

In metal solidification, fluid flow also plays a major role which creates the effect of heat and mass convection**.** Diffusion in addition, naturally occurs alongside convection and therefore these two terms are often handled together. Natural convection which occurs due to the temperature difference in the liquid phase plays a role by slowing down the solidification process but accelerate the melting process. Convection within the melt influences solidification at both microscopic and macroscopic levels [16]. It can change the shapes of isotherms and reduces thermal gradients in the melt. Most studies that included fluid flow in addition to heat transfer simulation, focus on porosity formation or predicting the exact location of the shrinkage porosities of a casting [17-18]. Recent study by Zhou *et al*., [19] utilized the feed path computation method with the consideration of fluid flow simulation to predict the locations of the casting hotspots. Their results showed that the prediction of shrinkage is more accurate compared to the technique that only consider the heat transfer simulation of solidification. Nonetheless, these studies required running the solidification simulation until the castings completely solidify which consequently, involves extensive computational cost [20]. In regards to that, for practical application there is a need to utilize fluid flow analysis to evaluate feeder designs and predict shrinkage defects in castings in a more effective way with less computational cost.

In addition, Dahle and St. John [21] claimed that the development of the dendrites at the effective liquidus temperature characterizes the solidification process of most aluminum alloys. They pointed out that the combined understanding of the casting solidification in terms of the mushy zone development and its rheological behavior with flow induced by the casting and its feeding process, has the potential to explain shrinkage defects found in castings. Based on this claim, authors hypothesized that the flow characteristic of the casting when it reaches the dendrite coherency temperature can give insight about the feeding ability of a feeder design. This can thus help in predicting the shrinkage defect occurrence in the casting with the given feeder design. For that matter, this paper explores the characteristic of the flow behavior of the metal during solidification as the metal reaches dendrite coherency point, the temperature at which the metal has formed dendrite networks as the metal solidifies. The aim of this study is to understand how the feeder designs influence the flow behavior at casting coherency and its relationship to the soundness of the casting. In that manner, the computational cost related to the convective fluid flow analysis can be reduced as the analysis only requires the simulation run at the early stage of the solidification only until the casting developed dendrite coherency. The scope of this study is limited to lost-foam sand casting of aluminum-silicon alloys.

2. Methodology

2.1 Governing Equations

The solidification model used in this study is based on the mixture-based model as described in [22-23]. In this model the liquid and solid phases of the metal are implicitly captured in the formulation of the heat and mass conservation equations. The mass conservation equations is described in Eq. 1

$$\nabla \cdot \boldsymbol{V} = 0 \tag{1}$$

where $\boldsymbol{V}$ is the velocity vector. The momentum equation is described in Eq. 2 as follows

$$\frac{\partial}{\partial t}(\rho \boldsymbol{V}) + \nabla \cdot (\rho \boldsymbol{V}\boldsymbol{V}) - \nabla \cdot (\mu \nabla \boldsymbol{V}) = -\nabla \mathrm{P} + \boldsymbol{S_m}. \tag{2}$$

P is pressure, ρ is the density and $\boldsymbol{S_m}$ represents the momentum source term as in Eq. 3.

$$\boldsymbol{S_m} = \boldsymbol{S_a} + \boldsymbol{S_b} = -\rho K \boldsymbol{V} + \rho \boldsymbol{g}\,(1 - \beta\,(T - T_f)) \tag{3}$$

where $K = C(1 - f_l)^2/({f_l}^3 + \epsilon) \cdot C$ is a large constant and K is a Carman-Kozeny term that denotes the permeability of solid structure formed during solidification which embodies the resistance of the solidifying structure to the feeding flow and is also called the porosity function [24]. The term $\boldsymbol{S_a}$ is the Darcy-type source term used to model the effect of solidification on the momentum, which describes the flow in the mushy region as a function of the liquid fraction, f_l of the solidifying metal. This model is based on the assumption that the solid and the mushy region behaves like a porous medium for the liquid to flow through [25]. Darcy flow model is important when the fraction solid present in the mush is significant enough to form dendrite coherency (rigid dendritic network or structure), and it assumes that the solid phase is fixed to the numerical grid. The fraction of liquid, f_l is computed as in Eq. 4 where T_m is the melting temperature determined by the arithmetic mean between the liquidus temperature, T_l and solidus temperature, T_s [22].

$$f_l = 0.5 \cdot \mathrm{erf}\left(\frac{4(T - T_m}{(T_l - T_s)}\right) + 0.5 \tag{4}$$

The natural convection in the fluid is approximated by the Boussinesq model described by the source term $\boldsymbol{S_b}$. β is the volumetric thermal expansion coefficient and $\boldsymbol{g}$ is the gravity vector.

The energy conservation is

$$\frac{\partial}{\partial t}(\rho c_p T) + \nabla(\rho c_p \boldsymbol{V} T) - \nabla(k \nabla \mathrm{T}) = S_e. \tag{5}$$

In Eq. 5, c_p is the specific heat, k is thermal conductivity, and S_e is the energy source term. The term S_e (Eq. 6) takes into account the change in the enthalpy during the phase change from liquid to solid. H is the latent heat of fusion.

$$S_e = -\rho H \frac{4 \cdot \exp\left(\left(\frac{4(T-T_m)}{T_l-T_s}\right)^2\right)}{(T_l-T_s)\sqrt{\pi}} \cdot \left(\frac{\partial T}{\partial t} + \boldsymbol{V}\nabla T\right) \tag{6}$$

In the mold, phase change does not occur and conduction is the only heat transfer mechanism considered governed by Eq. 7

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p}\nabla^2 T \tag{7}$$

To simplify the numerical simulation of the casting solidification, the flow of the liquid is assumed laminar and the fluid is Newtonian and incompressible. The Boussinesq approximation is assumed valid for modeling the buoyancy effect. The mold is assumed instantaneously filled with molten metal and the thermophysical properties of the metal are assumed constant in both liquid and solid regions. The numerical simulation of solidification was solved using the finite volume method using opensource software, OpenFOAM. More detail about the solidification model and numerical method used can also be found in [15].

2.2 Boundary Conditions

Between the metal casting and the mold, the heat transfer mechanism is through conduction only with the assumption that the thermal contact resistance between the mold and the metal interface is negligible. At the mold wall, the boundary condition is set using a convective heat transfer coefficient between the mold and the environment. The boundary condition at the wall of the metal casting is assumed zero velocity (non-slip condition).

2.3 Experimental Analysis

To investigate the flow behavior associated with the various design of feeders, multi-steps casting geometry was used as portrayed in Figure 1. Four feeder designs were utilized in the study as detailed in Table 1. A neck was added to the feeder design when the diameter of the feeder exceeds the width of the multi-steps casting. The simulations for the above casting models were carried at the pouring temperature of 973.15 K (700 °C). The model of the sand casting was of dry silica sand with initial temperature of about 300K. The dimension of the mold used was 280 mm x 140mm x 260 mm. the interfacial heat transfer coefficient between the mold and atmosphere used was 11.2 W/ m^{2}K. The properties of the sand mold used in the simulation are shown in Table 2.

The meshes of 2, 040, 000 cells were generated using the SnappyHexMesh utility in OpenFOAM. The simulations were run using 0.5 second time step. Finally, the experimental castings of the casting models were performed using the lost foam sand casting. Two types of aluminum silicon alloys were utilized in this study: AlSi9Cu and AlSi7Mg alloys. AlSi9Cu has dendrite coherency temperature at about 849.15K (576 °C) while AlSi7Mg alloy has coherency temperature at about 4 degree Celsius below its liquidus temperature (609 °C)[26].

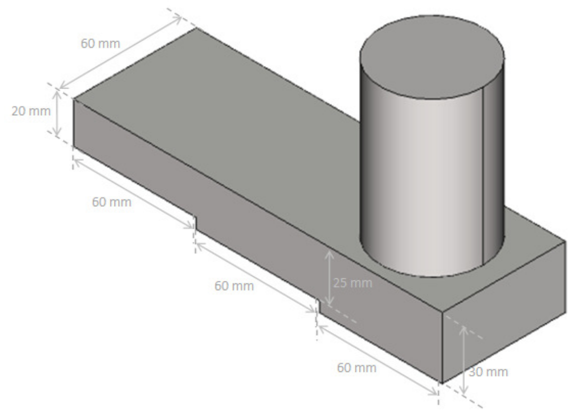

Fig. 1. Multi-steps casting geometry with a feeder on top

Table 1
Feeder designs used in simulations

Model	Feeder diameter, ***d*** (mm)	Feeder Height, ***h*** (mm)	Neck dimension, (***dxh***) mm
1	55	50	-
2	60	100	-
3	80	100	55 x 10
4	100	100	55 x 10

Table 2
Silica sand mold properties used

Properties	Values
Density , ρ	1520 Kg/m^3
Thermal conductivity, *k*	0.6 W/m K
Specific heat capacity, c_p	1170 J/kg K

3. Results and Discussions

This section illustrates the flow patterns from the numerical simulations of the four multi-step castings. The aim of this section is to analyse the flow characteristics of the casting when the entire casting section had reached dendrite coherency (the section without the feeder). The results analysed were taken from the simulation results at the time when the entire casting section had reached coherency. Figure 2-3 display the distribution of the flow velocity. For the purpose of making comparison, the flow that is relatively higher than .0001 m/s which is approximately the minimum flow rate occurs above the liquidus temperature inside the feeder, is defined as the liquidus flow rate. The coherency flow rate is defined as the flow relatively higher than .00001 m/s as this flow rate was approximately found to be the minimum above the metal coherency temperature.

Model 1 casting had the maximum velocity only slightly higher than the minimum coherency flow rate while other models had maximum flow higher than the minimum liquidus flow rate. From Figures 2-3, it can also be seen that all models except Model 1 had the feeders dominated by the liquidus flow rate. Model 3 and 4 indicate that the liquid supply is still abundant in the feeder for the casting sections. Model 2 however had liquidus flow rate at a higher region from the casting section. Model 3 and 4 had liquidus flow rate close to the regions between the feeder and the casting section. Figure 3 also shows that Model 4 still had a significant buoyancy effect in the feeder as the flow in the feeder was less smooth than the flow in the other feeders. This indicated that Model 4 feeder had the highest fluidity while Model 3 feeder had a more rigid metal flow. In Figure 4, through visual inspection as described in [27], it can be seen that all of the casting models except the model in part (d) contain shrinkage porosities in the casting sections. By comparing with the experimental results in Figure 4, it can be concluded that the casting sections that are disconnected from the regions with liquidus flow rate in the feeders at casting coherency, will be more prone to shrinkage defect.

From the above analysis, it can be seen that the feeder sizes have significant effect on the flows of the molten metal inside the feeders when the casting sections had reached coherency. Insufficient feeder will result in a very small flow at the region between the feeder and the casting causing difficulty to feed the casting with the feed metal. Therefore, it is important to design the feeder that would be dominated by the liquidus flow rate at the time when the casting section has reached coherency. This suggests that there would be sufficient pressure gradient to drive the metal flow to ensure continuous feeding from the feeder.

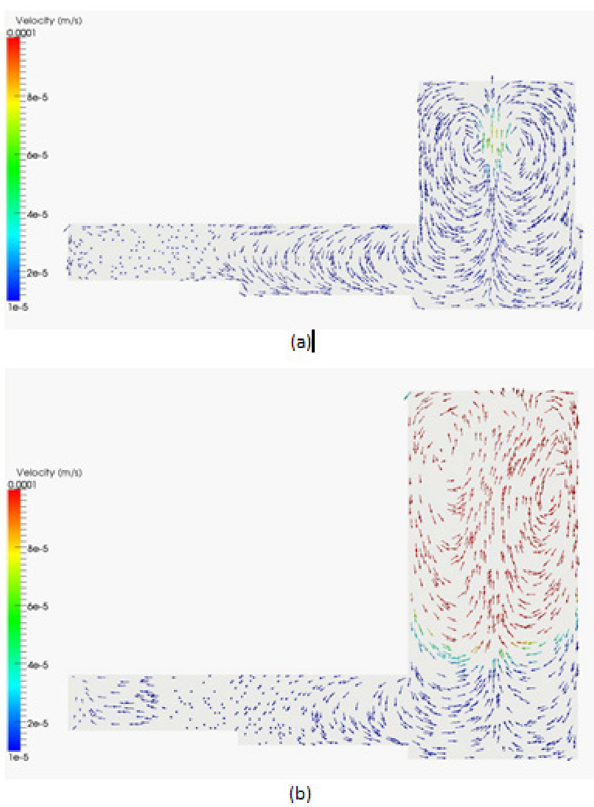

Fig. 2. Velocity fields at casting coherency for (a) Model 1 and (b) Model 2

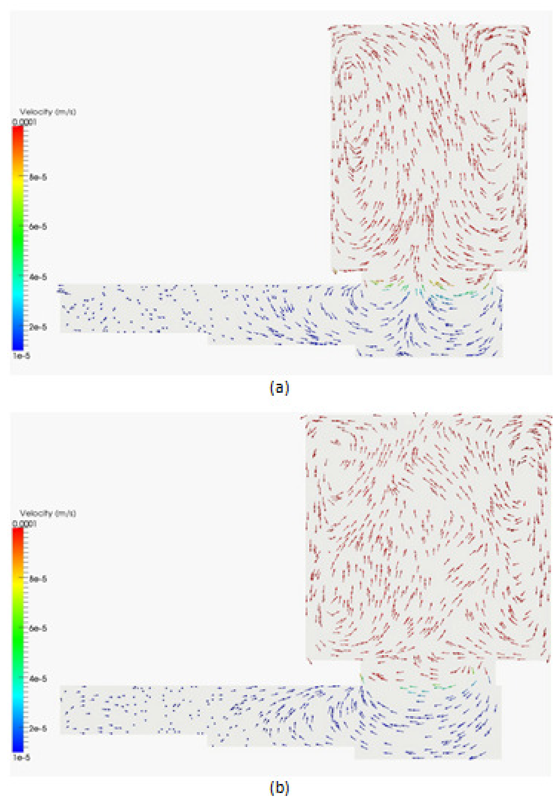

Fig. 3. Velocity fields at casting coherency for (a) Model 3 and (b) Model 4

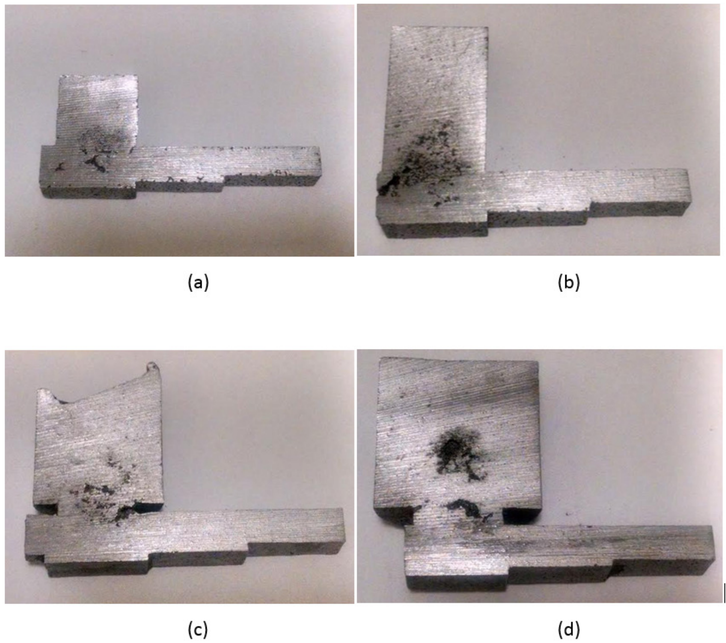

Fig. 4. Experimental EPC castings of (a) Model 1, (b) Model 2, (c) Model 3 and (d) Model 4

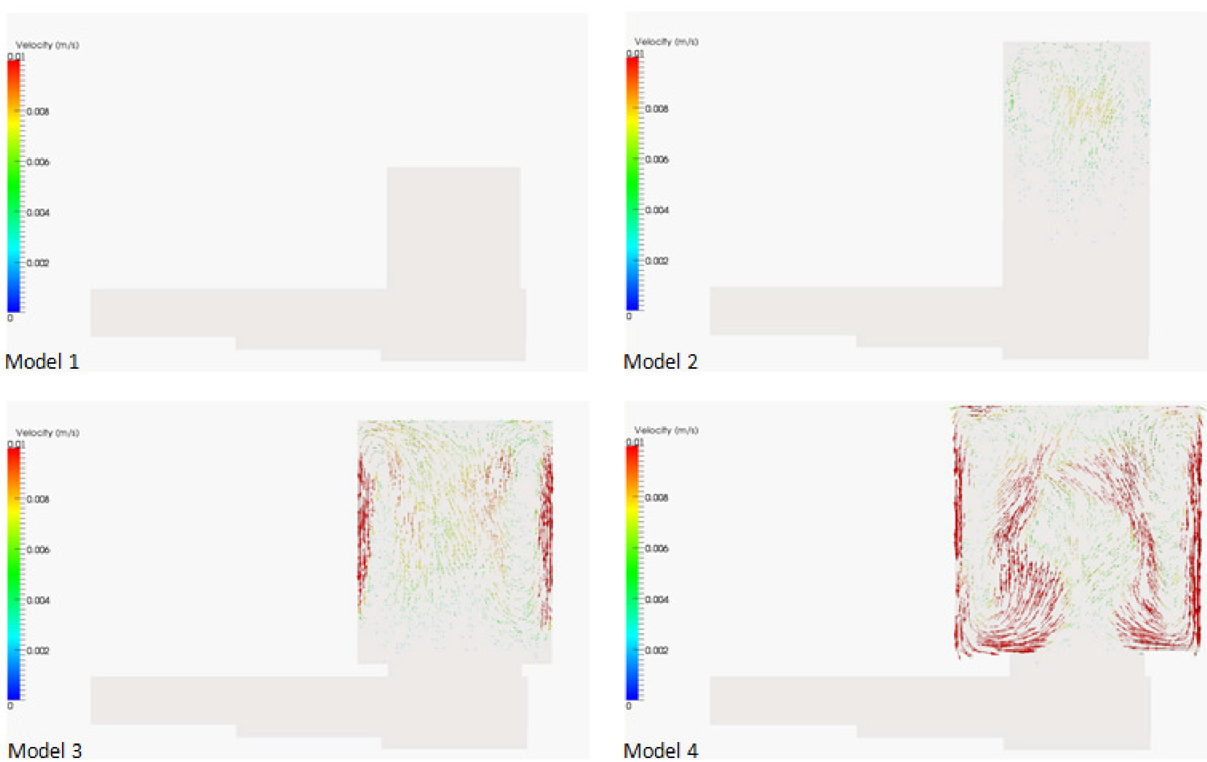

Fig. 5. Scaled velocity vectors when the casting sections reached coherency.

The above results imply that the appearance of visible flow field inside the feeder is critical in determining a continuous feed flow from the feeder when the casting section has reached coherency.

When the casting section is disconnected from the visible flow field, the casting will be prone to shrinkage porosities. For that regards, it is important for a good feeder to maintain a distinct flow of the metal inside the entire feeder at the time the casting section has reached coherency.

Similar flow pattern was also found for AlSi7Mg. The results of the analysis on the long-freezing-range alloy, AlSi7Mg are consistent with the results on the short-freezing-range alloy, AlSI9Cu. Even though the solidification characteristics of long freezing range alloys are distinct from short freezing range alloys, the analysis of the flow behavior at casting coherency seems promising in investigating the feedability of a feeder and its effectiveness. It is therefore evident that the influence of the convective fluid flow on the solidification and shrinkage behavior is important in understanding the feedability of the feeders.

The analysis presented above shows that the behaviour of the fluid flow during the early stage of the solidification particularly during the interdendritic structure development can be essentially useful in identifying any feeding difficulty based on the feeder characteristics. This recognition can help detect the feeding problem without having to run full simulation of the casting solidification. The results of this study verify the claim by Dahle and St John [21] that dendrites development after liquidus temperature is able to characterize the solidification of most aluminium alloys.

The analysis using thermal and convective fluid flow models proves to be important to understand the feeding of the feeders and help determine the best feeders that produce sound castings. This analysis is seen to be consistent for long freezing alloy as shown by the analysis on AlSi7Mg. Such outcome could be due to better accuracy gained from including convective fluid flow analysis. Even so, current technique only requires partial simulation of the solidification process making it reasonable for practical application in foundries.

4. Conclusions

Solidification model using heat transfer and convective fluid flow with natural convection was simulated for multi-steps castings with various feeder designs for aluminium silicon alloys. The solidification results particularly the fluid flow behaviour at the time when the entire casting section has developed dendrite coherency, was analysed. It was found that sound casting has significant flow occurring at the area that connects the casting section and the feeder, suggesting continuity in feed flow from the feeder into the casting even when the casting has reached coherency. On the other hand, unsound casting shows disconnection from the feed flow as no apparent flow was seen at the connection area between the feeder and the casting. This study presents a novel solidification analysis approach to investigate the ability of a feeder design to produce a sound casting utilizing the fluid flow model in addition to thermal model of solidification without the need to simulate a complete casting solidification.

Further studies however are required to investigate the reliability and consistency of the results through different solidification modelling approach and casting processes. More accurate analysis may be obtained with simulation models that consider variable densities and thermophysical properties. Analysis using more complex casting geometry is also needed to be explored.

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