Numerical Simulation of Solidification Structure of Al Alloy During Centrifugal Casting

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Abstract. The centrifugal casting process of 6082 Al alloy was simulated by ProCAST software. The effects of rotation speed and heat transfer coefficient on the filling and solidification behaviour were analysed. The porosity of the cast pipe increases with the increase of the rotation speed and decreases with the increase of heat transfer coefficient. The CAFE model was used to simulate the grain structure of centrifugal cast Al alloy under different process conditions. When the rotation speed and heat transfer coefficient increase, the length of columnar crystal region will increase and the grain will be refined.

1. Introduction

Centrifugal casting is a kind of special casting, which uses the pressure produced by centrifugal rotation to make the molten metal lean against the mold wall and solidify under external pressure to produce dense castings[1]. The castings produced by centrifugal casting have many advantages, such as fewer shrinkage, porosity and other defects. And the efficiency can be improved in the production of sleeve and pipe castings. Chirita[2] et al. have studied the performance advantages of centrifugally cast Al-Si alloy and found that its fracture strength, Young's modulus, fatigue life and limit have been improved.

Due to the complicated relationship between process parameters and the high cost of experiments of centrifugal casting, the numerical simulation method is a rapid research method to explore the process parameters of centrifugal casting. Keerthiprasad[3] et al. and Muralidhara[4] et al. studied the mold filling process of centrifugal casting through hydrodynamic cold modeling experiments. Lu[5] et al. used ProCAST software to simulate the temperature field of centrifugal casting, and discussed the influence of process parameters on defects. Chang[6] et al. used the cellular automata method to simulate the ‘band’ feature of the centrifugal casting ingot structure. Numerical simulation of centrifugal casting makes it develop from invisible to visible.

However, there are few analyses in combination with the grain structure of casting, and there are few studies on the process parameters of vertical centrifugal castings. Therefore, this paper simulates the flow field and temperature field of vertical centrifugal casting based on the ProCAST. And the process parameters of centrifugal casting are analysed in combination with defects. Then the grain structure of the casting is further calculated.
2. Description of the models

2.1. Mathematical Models
The flow of molten metal at high temperature can be regarded as a three-dimensional unsteady flow of viscous incompressible Newtonian fluid with free surface. The state of motion can be described by the N-S equation and continuity equation. The above finite element models are described in detail in reference[5, 7].

The following are cellular automaton models, which is used to solve the problem of microscopic grain structure calculation. One of them is the heterogeneous nucleation model, which is a continuous nucleation model based on Gaussian distribution proposed by Rappaz[8]. Under a certain undercooling, the amount of nucleation during solidification can be expressed by the following formula:

$$n(\Delta T) = \int_{0}^{\Delta T} \frac{dn}{d(\Delta T)} d(\Delta T)$$

where $\Delta T$ is the calculated local undercooling, $T_m$ is the mean undercooling, $\Delta T_{\sigma}$ is the standard deviation, $n_{\text{max}}$ is the maximum nucleation density.

The other is dendrite tip growth kinetics model, which is proposed by Kurz[9] et al., also called KGT model. In this model, solute diffusion determines the undercooling of dendrite tip. The KGT model can be simplified into the following form:

$$v = a_2 \Delta T^2 + a_3 \Delta T^3$$

where $v$ is the growth rate of the dendrite tip, $a_2$ and $a_3$ are the growth coefficients associated with the alloy.

2.2. Boundary and initial conditions
In this paper, the vertical centrifugal casting mold is shown in figure 1. The metal used in the simulation is 6082 aluminum alloy. The liquidus temperature can be calculated from chemical composition and is 647℃, and the pouring temperature is set to 737℃. There are many industry-proven materials in ProCAST's material database. The mold material used in this paper is Steel H13, with preheating temperature of 300℃. Air cooling is used between the mold and the environment. A total of 14kg of metal is poured and the pouring speed is 2kg/s. In order to study the influence of different process parameters on defects and grain structure, the heat transfer coefficient and rotation speed are used as variables. The heat transfer coefficient takes into account the factors of coating and heat transfer between Al alloy and steel mold, and is set to be 1000 W/m², 2000 W/m², 4000 W/m². The rotation speeds are determined by gravity coefficient formula to be 800r/min, 1200r/min, 1600r/min.

Figure 1. Schematic diagram of mold size.  Figure 2. Finite element model of the mold.

The calculation of the grain structure used the CAFE model in ProCAST and the calculation area is the white part in figure 2. The macroscopic mesh size is 5mm. The microscopic mesh, also called cell,
with a size of 0.2mm. The Gibbs-Thompson coefficient is 2.4×10^{-7}, and the growth coefficient is calculated according to the alloy composition: \(a_2=3.989\times10^{-7}\text{m/(s·K)}^2\), \(a_3=1.316\times10^{-6}\text{m/(s·K)}^2\). Other nucleation parameters are shown in table 1.

Table 1. Nucleation parameters employed in the present work.

| Casting temperature (°C) | \(\Delta T_{s, \text{max}}\) (°C) | \(\Delta T_{s, \sigma}\) (°C) | \(n_s\) (m^{-2}) | \(\Delta T_{v, \text{max}}\) (°C) | \(\Delta T_{v, \sigma}\) (°C) | \(n_v\) (m^{-3}) |
|-------------------------|-------------------------------|----------------------------|-----------------|-----------------------------|-----------------------------|-----------------|
| 737                     | 0.5                           | 0.1                        | 1.8×10^6        | 3                           | 0.1                         | 3.6×10^3        |

3. Results and discussion

3.1. Effect of different process parameters on defects
The inner surface of centrifugal casting is considered to be the most likely to form pores, shrinkage and other defects[10]. The heat transfer coefficient used in the results of shrinkage defects in (a), (b) and (c) of figure 3 are 1000W/m^2, 2000W/m^2 and 4000W/m^2, and the simulation results show the ratio of shrinkage porosity.

![Figure 3. Simulation results of defects with different heat transfer coefficients.](image)

For all the simulation results, the volume and proportion of defects with a porosity ratio greater than 3% are calculated and shown in figure 4, in which (a), (b) and (c) represent heat transfer coefficients of 1000W/m^2, 2000W/m^2 and 4000W/m^2, too. It can be seen that the rotational speed of 1600r/min is too high, which leads to the instability of molten metal flow, then causes to the irregular change of cooling rate, and finally causes the irregular change of defect volume. With larger heat transfer coefficient, there is a lower temperature gradient on the cross section of centrifugal cast pipe during the solidification. Therefore, the difference in local solidification time between internal and external surfaces is shorter, and the overall solidification time is also shorter, so that the tendency of porosity is reduced.

![Figure 4. Total statistics of defect volume and its proportion.](image)

3.2. Effect of different process parameters on grain structure

3.2.1. Effect of rotation speed. The rotation speed used in the results of a, b and c of figure 5 are 800r/min, 1200r/min and 1600r/min. It is found from the figure that when increasing from 800r/min to 1200r/min, the columnar crystal region becomes longer, because the front of the columnar crystal is difficult form
the composition undercooling of the equiaxed region. When increasing from 1200r/min to 1600r/min, the columnar crystal region becomes shorter and the grains are refined. This is because violent turbulence leads to broken dendrites.

![Figure 5. Simulation results of grain structure at different rotation speeds.](image)

3.2.2. Effect of heat transfer coefficient. The heat transfer coefficients used in the results of (a), (b) and (c) of figure 6 are 1000 W/m², 2000 W/m² and 4000 W/m². When the heat transfer coefficient increases, the proportion of columnar crystals increases. When the heat transfer coefficient is small, the formation time of solidified shell on mold wall is longer and there are more grains dissociate into the liquid phase, which hinder the formation of columnar crystals. Moreover, when the heat transfer coefficient is large, the solidification time is shortened and the grain growth is limited, so the grains in equiaxed crystal region are refined.

![Figure 6. Simulation results of grain structure at different heat transfer coefficients.](image)

4. Conclusion
The volume of shrinkage defects and the distribution of equiaxed crystal and columnar crystal are calculated by finite element method and cellular automaton method.

The volume of defects increases with the increase of rotation speed, and decreases with the increase of heat transfer coefficient. But when the rotation speed is too high, the turbulence of molten metal will affect the change law of defect volume.

To some extent, the increase of rotation speed will make the columnar crystal region longer. But when the rotation speed is too high, it will lead to grain refinement. When the heat transfer coefficient is larger, the cooling rate is faster, the columnar crystal region will become longer and the equiaxed crystal will be refined.

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