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Experimental and numerical studies on the influence of centrifugal casting parameters on the solidification structure of Al-Cu alloy

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Abstract

A horizontal centrifugal casting experiment was designed to determine the change in the solidification structure of Al-Cu alloy casting and the underlying variation in temperature, then obtained interface heat transfer coefficient by inverse calculation. The continuous simulation of metal melt filling from the gate to copper mold cavity is realized. The influence of centrifugal speed, pouring temperature, and mold preheating temperature on the solidified structure was analyzed. Simulation results showed that increasing the centrifugal speed mainly enhance the solidification rate of the molten metal and then refined the solidified structure of the Al-Cu alloy. Increasing the pouring temperature and mold preheating temperatures coarsen the grain size of the casting, but the range of change is small.

1. Introduction

Centrifugal casting is a casting method in which a certain amount of molten metal is poured into a rotating mold, and the molten metal is filled and solidified under centrifugal force and gravity [1]. This process has the advantages of high density and less defects and has been widely used to cast cylindrical parts, such as composite rolls, composite steel pipes, and cylinder liners [2]. Milyutin et al [3] studied the performance advantages of centrifugally cast Al/Si alloy and found that its fracture strength, Young’s modulus, fatigue life, and limit were improved. However, centrifugal casting tubes are subject to complex forces, high speed, high temperature and opacity. Thus, determining the variations in the flow and temperature of the molten metal is difficult [4]. In addition, the production cost of such tubes is high, the application range is narrow, and the safety is poor. The production of traditional horizontal centrifugal casting relies on production experience, which seriously affects the progress and development of this technology.

After decades of development, numerical simulation of casting has shown great progress, such as the optimization of the process design, ensuring the casting quality, and reducing the test cycle, cost, and casting defects. These developments have an important impact on the actual production [5]. The numerical simulation of the centrifugal casting process, especially centrifugal filling and tissue evolution, has been performed relatively later than other casting methods [6]. Nevertheless, centrifugal casting has been attracting increasing attention of relevant researchers and industry professionals. Tao et al [7] used the weakly compressible model, nonuniform finite difference mesh, and a self-developed software to numerically simulate the centrifugal casting of titanium (Ti) alloy thin-walled shell under different process conditions. They predicted the potential distribution characteristics of shrinkage crater defects. Humphreys et al [8] investigated the complex free surface of Ti/Al alloy castings in gravity casting and centrifugal casting processes. Keerthiprasad et al [9] and Muralidhara et al [10] studied the mold filling of centrifugal casting through hydrodynamic cold modeling experiments. Chen et al [11] used Fluent software to simulate the horizontal centrifugal casting process under the action of multiphysical field coupling and investigated the influence of electromagnetic fields on such process.

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However, current simulation of the centrifugal casting process is still limited to the filling and temperature parameters. Little is known about the change in alloy structure with the working conditions, and experimental verification of the simulation results is lacking. In this study, a horizontal centrifugal casting experiment was designed and completed. The casting experiment was simulated using ProCast. The experimental results verified the accuracy of the simulation results.

2. Centrifugal casting experiment

2.1. Experimental equipment

The centrifugal casting system was divided into three parts: centrifugal casting machine, cooling water machine, and air storage tank. The centrifugal casting machine was the main part of the system. The interior of the centrifugal casting machine was mainly composed of a mold, a crucible, a rotating shaft, and a resistance wire (figure 1). The interior of the device was kept in a vacuum state, and the material in the crucible was heated and melted by the resistance wire. After heating to a suitable pouring temperature, the rotating shaft drove the mold and the crucible to rotate at a high speed. Under centrifugal force, the molten metal began to fill the mold and solidified. The whole experimental process could be divided into eight parts: inspection, cleaning, weighing, placing crucible, gas washing, heating, centrifugal casting, and cooling sampling. To determine the change in temperature during the solidification of the molten metal, a wireless temperature collector was fixed on the upper part of the wedge-shaped mold. The installation position is shown in figure 2. The probe of the K-type thermocouple was inserted into the mold, and the other end was connected to the temperature collector. Then, the temperature in real time was recorded through the wireless receiver. The diameter of the K-type thermocouple probe used in the experiment is 0.5 mm, and its small size has limited influence on the temperature change of the alloy liquid and the pouring process. The time constant of the K-type thermocouple used in the experimental condition is less than 0.5 s. The K-type thermocouple meets the requirements of Class I accuracy, and the measurement error is within 0.75%. The acquisition frequency of the temperature collector was 300 ms. The mold had a wedge-shaped structure with a thick top and a thin bottom to analyze the influence of the thickness of the casting on the performance of the casting.

The composition of the Al-Cu alloy is shown in table 1. The liquidus temperature of the Al-Cu alloy is 629.4 °C, and the solidus temperature is 460 °C as calculated from the ProCast material database. Other thermophysical parameters were all preset parameters of ProCast, as shown in figure 2. The initial temperature of the mold was 25 °C. The centrifugal casting machine was set to rotate at 250 rpm, and the centrifugal acceleration is 11.19G. Under centrifugal force, the alloy liquid at 730 °C was poured into the mold and cooled naturally in a vacuum environment. The casting was taken out after the Al-Cu liquid had solidified and formed.
2.2. Analysis of experimental results

The Al-Cu alloy casting obtained in the experiment is shown in figure 3. The cast had a wedge-shaped structure with a 4-mm thick bottom and an 8-mm thick top, and the filling was complete. Sufficient pouring of the metal was accomplished.

The temperature data started to record after the installation of thermocouple. As shown in figure 4, the position of the thermocouple probe was fixed at the center of the casting at 5 mm from the bottom of the casting. Figure 5 shows the measured temperature of the thermocouple in the experiment for measuring the temperature of the wedge-shaped casting. The actual pouring temperature was 730 °C, and the initial mold temperature was 25 °C. In the early stage of pouring, the heat loss of the alloy liquid into the mold cavity was relatively large, and the highest measured temperature of the thermocouple was 650 °C. In the initial stage, the temperature of the alloy liquid dropped sharply due to the chilling effect, and the temperature reached the solidus temperature in 2–3 s. Afterward, as the temperature of the alloy liquid decreased, the cooling rate also decreased and then finally tended to balance. According to the pouring and solidus temperatures, the cooling rate of the casting above solidus was 421.49 °C s⁻¹, which belonged to sub-rapid solidification.

Table 1. Chemical composition of Al-Cu alloys.

| Chemical element | Cu | Zn | Mg | Li | Al |
|------------------|----|----|----|----|----|
| Mass fraction (wt%) | 4.0 | 1.1 | 0.6 | 2.0 | Balance |

Figure 2. Assembly drawing of temperature collector: (a) temperature sensor, (b) mold, (c) crucible, (d) rotating shaft, and (e) counterweight.

Figure 3. Al-Cu alloy casting.
The Al-Cu alloy casting obtained at a centrifugal speed of 250 rpm was cut, grinded, and polished. Then, its microstructure was observed, and the images of the microstructure and grain orientation were determined as shown in figures 6 and 7, respectively. The obtained metallographic images were observed using Image-Pro Plus software. The grain size of the alloy casted at 250 rpm was 19 μm.

3. Numerical simulations of centrifugal casting

3.1. Mathematical model of the filling process
During horizontal centrifugal casting, the filling of molten metal was completed under centrifugal force, and the flow of the metal liquid belonged to the three-dimensional unsteady incompressible viscous flow with free surface. The metallic liquid could be assumed as an incompressible Newtonian fluid, and the flow conformed to the continuity equation, momentum equation, and energy conservation equation [12].

(1) Continuity equation

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \tag{1}
\]

where \( \rho \) is the fluid density (kg m\(^{-3}\)), and \( u, v, w \) are the velocity components in \( x, y, z \) direction respectively (m s\(^{-1}\)).

(2) Momentum equation
The liquid metal flow velocity and flow momentum transport can be described by the Navier–Stokes equation as follows:
\[ \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \frac{\partial p}{\partial x} + \mu \nabla^2 u + \rho f_x \]  
\[ \rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \frac{\partial p}{\partial y} + \mu \nabla^2 v + \rho f_y \]  
\[ \rho \left( \frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \nabla^2 w + \rho f_z \]  

where \( p \) is the pressure (Pa); \( f_x, f_y, \) and \( f_z \) are the \( x, \) \( y, \) and \( z \) components of the mass force (m s\(^{-2}\)); and \( \mu \) is the dynamic viscosity (Pa·s).

(3) Energy conservation equation

Heat transfer occurred in the contact between the molten metal and the mold, as well as between the molten metal and the air. Such transfer is mathematically described by the heat transfer equation as follows:

\[ \rho_c \frac{\partial T}{\partial t} + \rho_c \left[ \frac{\partial (uT)}{\partial x} + \frac{\partial (vT)}{\partial y} + \frac{\partial (wT)}{\partial z} \right] = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \rho L \frac{\partial f_t}{\partial t} \]  

Figure 6. Microstructure of the centrifugally cast Al-Cu alloy.

Figure 7. Grain orientation diagram of the centrifugally cast Al-Cu alloy.
3.2. Mathematical model of the microstructure evolution

The macro–micro coupling model adopts the CAFE method, which is a mathematical model that combines cellular automata and finite elements. The CA model was used to calculate the grain nucleation and growth at the node, which mainly included the nonuniform nucleation model and the dendrite tip growth kinetic model, as follows [13]:

\[
\frac{dn}{d(\Delta T)} = \frac{n_{\text{max}}}{\sqrt{2\pi \Delta T}} \exp \left[ -\frac{1}{2} \left( \frac{\Delta T - \Delta T^*}{\Delta T_{\text{r}}} \right)^2 \right]
\]

(4)

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

(5)

where \( \frac{dn}{d(\Delta T)} \) is the variation of grain nucleation density with undercooling during nonuniform nucleation, \( (\Delta T) \) is the unit degree of undercooling, \( \Delta T^* \) is the Average nucleation undercooling, \( \Delta T_{\text{r}} \) is the standard deviation of undercooling, \( n \) is the grain density, and \( n_{\text{max}} \) is the maximum nucleation density.

The dendrite growth process during liquid metal solidification can be calculated using the developed KGT model [14] as follows:

\[
\Omega = \frac{C_p^+ - C_0}{C_L^+(1 - k)} = L v(P_c) = P_c \cdot \exp (P_c) \cdot \int_{P_c}^{\infty} \frac{\exp (-Z)}{Z}dZ
\]

(6)

\[
R = 2\pi \sqrt{\frac{\Gamma}{mG\xi - \Gamma}}
\]

(7)

\[
P_c = \frac{Rv}{2D}
\]

(8)

\[
\xi_c = 1 - \frac{2k}{(1 + P_c^2) \xi^2 - 1 + 2k}
\]

(9)

\[
G_c = \frac{vC_0(1 - k)}{D_c[1 - (1 - k)\Omega]}
\]

(10)

\[
\Delta T = \Delta T_c = mC_0 \left[ 1 - \frac{1}{\Omega(1 - k)} \right]
\]

(11)

where \( \Omega \) is the solute supersaturation, \( k \) is the solute distribution coefficient, \( R \) is the radius of the dendrite tip, \( \Gamma \) is the Gibbs-Thompson coefficient, \( G_c \) is the solute supersaturation in the liquid phase at the dendrite front, \( G \) is the temperature gradient, \( L v(P_c) \) is the Ivantsov function of the Gibbs-Thompson coefficient, \( \xi_c \) is the function of the Peclet number, \( D \) is the diffusion coefficient of the solute in the liquid phase, \( C_0 \) is the initial concentration of the solute element, \( m \) is the liquidus slope, and \( C_L^+ \) is the solid/liquid concentration at the liquid interface.

3.3. Metal mold casting model and parameters

According to the selected wedge-shaped casting mold, the three-dimensional modeling software Creo 7.0 was used to model the casting and the mold. The size of the mold and its coordinate system are shown in figure 8. ProCAST software was used to simulate the process. First, the casting model was divided into three-dimensional meshes. The mold was divided into coarse meshes, with mesh size of 1 mm. The interior of the mold and the castings were divided into fine meshes, with mesh size of 0.5 mm. The division resulted in a total of 74,246 surface meshes and 2,018,189 volume meshes.

The mold material was copper, and its thermophysical parameters were preset by ProCAST. The chemical composition of the Al-Cu alloy used for the simulation is provided in table 1. The liquidus and solidus temperatures of the Al-Cu alloy calculated by ProCAST were 645 °C and 453 °C, respectively. Other physical parameters are shown in figure 9. The initial pouring temperature of the molten metal was 760 °C, and the initial temperature of the mold was 25 °C. Pouring time was 0.5 s, and pouring speed was 0.0351 kg s^{-1}. ProCAST software can set the rotation axis in the revolution module. According to the structure of the centrifugal casting machine, the distance in the rotating shaft at which pouring was performed was set in the vertical direction at 160 mm on the right side of the ingate. The rotating speed was 250 rpm. Given that the mold was in a vacuum environment, the main heat exchange between the mold and the environment was radiation heat transfer. The
The overall heat transfer coefficient was set to 70 W/(m²·K). The bottom of the mold was in direct contact with the base, resulting in the main heat transfer of heat conduction with heat transfer coefficient set to 700 W/(m²·K).

The interface heat transfer coefficient between the cast and mold is obtained by trial-and-error method. The specific calculation process is as follows:

1. The curve of internal temperature of alloy liquid with respect to time is obtained through centrifugal casting experiment;
Divide the whole centrifugal casting process into a series of time steps. Since the temperature changes dramatically in the first 5 s, set a time step 0.3 s in this stage. And set a time step 1 s after the first 5 s;

Start from the first time step, in each time step, estimate an interface heat transfer coefficient for this time step.

Obtain the temperature filed at the end of this time step by mathematical model in section 2.

Comparing the numerical results with the experimental data to verify the estimated interface heat transfer coefficient. And according the error between numerical and experimental data, adjust the interface heat transfer coefficient, repeat step (3) to (5) until the error is less than 3%.

Go to the next time step, and repeat step (3) to (6).

The temperature curves at the measurement point obtained by simulation and experimentally were consistent, as shown in figure 10. The error between the experimental temperature data and the relative error was within 3.1%. The obtained heat transfer coefficients are shown in figure 11.

The grain size distribution of the casting with thickness of 4 mm was also obtained, as shown in figure 12. The average grain size of the castings was 19 μm, which was close to the experimental value. Therefore, the interface heat transfer coefficient obtained by inverse calculation in this chapter was accurate.

For the case of higher rotational speed, the ratio of the centrifugal acceleration of a certain working condition to the centrifugal acceleration of 250 rpm was calculated. This ratio was the growth ratio of the centrifugal
acceleration. Then, the interface heat transfer coefficient between the casting and the mold was set to be linearly, positively related to the growth ratio of the centrifugal acceleration. Equation (12) was used to obtain the solidification characteristics of the castings under different casting conditions. The interfacial heat transfer coefficient and centrifugal acceleration from 250 rpm to 1500 rpm are shown in figure 13.

\[ \lambda_n = \frac{F_n}{F_1} \cdot \lambda_1 \]  

where \( \lambda_n \) is the interface heat transfer coefficient at a higher speed, \( \lambda_1 \) is the interface heat transfer coefficient at 250 rpm, \( F_n \) is the centrifugal acceleration at a higher speed, and \( F_1 \) is the centrifugal acceleration at 250 rpm.

4. Numerical simulation results and discussion

4.1. Filling process
Centrifugal casting was used to simulate and analyze the filling process of the casting as shown in figure 14. The simulation results showed that the flow of the fluid in the mold was consistent with the actual situation. After the filling was started, under centrifugal force, the alloy liquid entered the bottom of the mold along the mold wall. The alloy liquid filled the bottom of the mold and then filled up the mold. A void was generated in the middle of the cavity. Finally, the alloy liquid filled the middle void, resulting in sufficiently poured molten metal.

4.2. Effect of centrifugal casting speed on the solidified structure
The grain size (figure 15) and the average secondary dendrite arm spacing (figure 16) at various sections of the cast with different thicknesses (4–8 mm) under distinct centrifugal speeds were obtained. As the centrifugal...
speed was increased from 250 rpm to 1500 rpm, the average grain size of the casting decreased to varying degrees at the different section thicknesses. In addition, the average grain size at the section with thickness of 8 mm decreased from 38 μm to 20 μm, and the drop in grain size was the largest. Similarly, the average secondary dendrite arm spacing in the different sections of the casting also decreased as the rotational speed increased. The average secondary dendrite arm spacing decreased from 19 μm to 11 μm at the section with thickness of 8 mm.

During the mold filling and solidification of Al-Cu alloy centrifugal casting, the alloy melt was simultaneously affected by gravity, centrifugal force, and Coriolis force, and indicating a complex force system. When the molten metal was affected by these inertial forces, its flow speed increased, and the heat transfer capacity was also enhanced accordingly. These characteristics led to a larger cooling rate, providing a good opportunity for the formation of crystal nuclei in the melt [15]. These conditions promoted nucleation and then refinement of the solidified structure of the Al-Cu alloy centrifugal castings.

4.3. Effect of pouring temperature on the solidified structure
The average grain size and secondary dendrite arm spacing for the castings at pouring temperature of 730 °C, 800 °C and 850 °C are shown in figures 17 and 18, respectively. As the pouring temperature increased, the
Figure 16. Variation curve of the secondary dendrite arm spacing with the rotational speed at different casting thicknesses.

Figure 17. Variation curve of the average grain size with pouring temperature.

Figure 18. Variation curve of the average secondary dendrite arm spacing with pouring temperature.
average grain size and secondary dendrite arm spacing of the castings also evidently increased, but the increase was small (both at 1 \( \mu \)m). When the rotation speed was 300–600 rpm, the average grain size of the castings at the same pouring temperature and the change range was obviously larger than those at rotation speed of 600–900 rpm.

The pouring temperature is one of the important factors that affect the quality of castings. Properly increasing the pouring temperature can increase the superheating of the molten metal. Thus, the time for the molten metal to remain liquid increases, which is conducive to the completion of the filling process and effectively avoids insufficient pouring, cold isolation, and occurrence of defects [16]. However, excessive pouring temperature will prolong the grain growth time, cause coarse grains, increase the shrinkage of the alloy, increase the solubility of the gas in the molten metal, and intensify the oxidation of the molten metal [17]. Defects, such as pores, are also produced. When the pouring temperature is too low, the front-end alloy liquid solidifies very easily after being cooled, the fluidity becomes poor, and the mold is difficult to fill. Therefore, finding the right pouring temperature is crucial.

### 4.4. Effect of mold preheating temperature on the solidified structure

The effects of different mold preheating temperatures on the grain size and the spacing of secondary dendrite arms were investigated. ProCast software was used to simulate and analyze the average grain size and secondary dendrite arm spacing of the castings at thermal temperatures of 25 °C, 100 °C, and 300 °C when the pouring temperature was 730 °C and the rotation speeds were 300, 600, and 900 rpm. The results are shown in figures 19 and 20. As the mold preheat temperature increased, the average grain size and secondary dendrite arm spacing of the castings also increased. When the preheating temperature was elevated from 25 °C to 300 °C, the grain size of the castings increased by 5 \( \mu \)m, and the average grain size of the castings with the same mold preheating temperature at a rotational speed of 300–600 rpm was significantly larger than that at a rotational speed of 600–900 rpm. Theoretically, increasing the mold preheating temperature will extend the solidification time of the alloy liquid, and the metal elements will have sufficient time to grow [18]. In such circumstances, the grain size and the secondary diameter arm spacing will increase to varying degrees, which is consistent with the simulation results.

### 4.5. Influence of cooling rate on the solidified microstructure

Combined with the simulation results in sections 3.1–3.4, the centrifugal castings under different working conditions and casting thicknesses were also simulated. Variations in the grain size and secondary dendrite arm spacing with cooling rate were determined and are shown in figures 21 and 22, respectively. When the cooling rate of the castings was increased from 137.34 °C s\(^{-1}\) to 1355.26 °C s\(^{-1}\), the average grain size of the castings decreased from 27 \( \mu \)m to 13 \( \mu \)m, and the average secondary dendrite arm spacing of the castings decreased from 16 \( \mu \)m to 8 \( \mu \)m.

During the continuous cooling process, the dendrite growth had a development process from nucleation to coarsening, and the degree of undercooling \( \Delta T \) increased with the cooling rate. According to the classical solidification theory, the degree of undercooling \( \Delta T \) affects the nucleation rate, and the nucleation rate increases exponentially with the increase of \( \Delta T \). Therefore, as the cooling rate increases, the nucleation number increases,
Figure 20. Variation curve of the average secondary dendrite arm spacing with the mold preheating temperature.

Figure 21. Variation curve of the grain size with the cooling rate.

Figure 22. Variation curve of the secondary dendrite arm spacing with the cooling rate.
and the grain size decreases. Higher undercooling $\Delta T$ also leads to a higher driving force for dendrite growth. This characteristic promotes the development of secondary dendrites and the appearance of tertiary dendrites. As the coarsening time of dendrites decreases, and the spacing of secondary dendrite arms decreases [19].

5. Conclusion

In this paper, an experiment to measure the temperature of centrifugal casting Al-Cu alloy was designed and completed. The casting experiment under different working conditions was simulated, and the following conclusions were drawn:

(1) Using the measured internal temperature data of the centrifugally cast Al-Cu alloy, the interfacial heat transfer coefficient was obtained by continuous inverse calculation and iteration. When the temperature of the alloy liquid at the initial stage of casting was 590 °C, the interfacial heat transfer coefficient reached 5000 W/(m²·K), the interface heat transfer coefficient also decreased as temperature decreased. When the temperature reached 330 °C, the interface heat transfer coefficient dropped to 1100 W/(m²·K). In the simulation, using the obtained interface heat transfer coefficient, the error between simulated and the measured temperature data had a small error, which proved that the interface heat transfer coefficient was accurate.

(2) Metallographic observation of the Al-Cu alloy casting obtained using the centrifugal casting experiment showed that the grain size was 19 μm at a thickness of 4 mm and a rotation speed of 250 rpm. Under the same conditions, the numerical simulation result was 19 μm, which indicates that the simulation result was credible.

(3) The increase in centrifugal speed can play a role in refining the grains of the Al-Cu alloys. As the centrifugal acceleration increased, the grain size and the spacing of secondary dendrite arms decreased rapidly. Increasing the pouring and mold preheating temperatures increased the grain size of the casting, but not considerably.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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