Simulation of temperature field of A356 aluminum alloy in freeze casting

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Abstract. In this paper, the temperature change curve of the casting and frozen sand mould during the solidification process of the A356 aluminum alloy in the frozen sand mould is tested. According to the actual temperature change curve of the casting surface and the sand mould surface, the interface heat transfer coefficient between the frozen sand mould and the A356 aluminum alloy could be reversed analysis. The results show that when the casting temperature is lower than 550 °C, the interface heat transfer coefficient remains about 750 W.(m2.K)-1; When the casting temperature is between 550 °C and 610 °C, the interface heat transfer coefficient increases significantly; when the casting temperature is higher than 610 °C, the interface heat transfer coefficient reaches the maximum value, which is about 2300W. (m2.K) -1. At this time, this study simulates the solidification temperature field of aluminum alloy hub parts in the frozen sand mould according to the interface heat transfer coefficient calculated by inverse analysis, and the temperature field of resin sand mould casting was used as for comparison. The results show that: under the same solidification time, the temperature field of A356 aluminum alloy hub parts in frozen sand mould is lower than that of resin sand casting, freezing casting can realize the high-speed solidification process of different parts of complex castings.

Keywords: freezing casting; interface heat transfer coefficient; temperature field.

1. Introduction
Freeze casting is a green casting method using water as a binder and moulding sand materials (silica sand, zircon sand, chromite sand, etc.) as refractory aggregates, it obtains qualified casting mould by directly milling after the moulding sand particles premixed with about 4wt% water and frozen in the low-temperature environment of -30 °C. No harmful gas is produced during the casting process of freezing casting, and the moulding sand can be recycled, which is a green forming method that adheres to the concept of sustainable development. At present, the computer simulation technology of the casting process can improve the production efficiency of the casting process effectively, such as saving trial costs, optimizing the process, shortening the research and development cycle, and ensuring the quality of castings[1,2]. During the solidification process of sand mould or metal mould, the volume shrinkage
of casting and the thermal expansion of the mould lead to the formation of the interface gap, the formed interface gap significantly affects the steady-state heat transfer process of the casting-mould. Therefore, there is a large temperature difference between the casting interface and the mould interface, in view of this situation, the parameters for calculating the heat transfer capacity of the mould, namely the interface heat transfer coefficient are introduced [3]. The interface heat transfer coefficient between the casting and the mould determines the solidification process of the metal, and to a large extent determines the structure and performance of the casting [4,5]. At present, the methods for calculating the interface heat transfer coefficient mainly include multi-factor regression method, interface gap method and numerical inverse algorithm, among which: the numerical inverse algorithm is to calculate the interface heat transfer coefficient by using the casting and mould temperature curve collected in the casting experiment, the interface heat transfer coefficient is closest to the actual casting conditions [6]. Yang Hongmei [7] used a numerical inverse algorithm to study the interface heat transfer coefficient between the casting and the mould during the vacuum die casting process, and found that the application of the vacuum system can increase the interface heat transfer coefficient and reduce the grain size of the casting significantly . Huang [8] et al. studied the interface heat transfer coefficient of A356 aluminum alloy in resin sand mould, and found that the interface heat transfer coefficient between A356 aluminum alloy and resin sand mould varied within 250-700 W / (m².K). At present, in the research of the casting-mould interface heat transfer coefficient, it mainly involves metal mould casting and pressure casting [9], and there is a lack of research on the interface heat transfer coefficient of the freezing casting solidification process. Therefore, based on the temperature data of the casting surface and the sand surface, the change law of the interface heat transfer coefficient between the A356 aluminum alloy and the frozen sand mould with temperature was calculated inversely, and the temperature field of the frozen casting hub was solved by combining with the interface heat transfer coefficient.

2. Experimental materials and methods

2.1. Experimental materials
In this experiment, 100-mesh silica sand was used as moulding sand particles for freezing casting. The moulding sand particles mixed with 4wt% water were used to make frozen sand blank by low-temperature freezing (-30 °C). Then, the frozen sand blank is cut directly by the digital patternless forming machine to obtain the sand mould and to be poured. A complex hub part was selected as the temperature field simulation test piece, the experimental material was A356 aluminum alloy, its liquidus temperature was about 610 °C and the solidus temperature was about 565 °C, the chemical composition of the alloy is shown in Tab 1.

| Si   | Mg  | Ti  | Fe  | Cu  | Zn  | Al   |
|------|-----|-----|-----|-----|-----|------|
| 7.24 | 0.324 | 0.192 | 0.154 | 0.007 | 0.012 | Bal. |

2.2. Experimental method

2.2.1. Frozen sand specific heat and thermal conductivity test. In this study, the specific heat and thermal conductivity of 100-mesh silica sand were tested using the LFA427 laser thermal conductivity tester produced by Netz, the specific heat and thermal conductivity of the moulding sand was tested at 200°C, 400°C, 600°C, and 800°C. The state of the frozen sand mould after being impacted by the high-temperature metal liquid shows a discontinuous characteristic, that is, the frozen state below 0 °C, the wet sand state between 0 °C and 100 °C, and the loose sand state above 100 °C. Therefore, for the thermal physical parameters (including specific heat and thermal conductivity) of the frozen sand mould at room temperature (20 °C) and critical temperature (100 °C), the wet sand thermal conductivity \( \lambda \) (equation 1) and specific heat capacity \( C_p \) (equation 2) were given in documents[10,11], therefore, the thermal conductivity and specific heat value at each temperature after optimization are shown in Tab 2.
Thermal conductivity (W/m.K)

\[ \lambda = 0.9467 - 9.0314 \times 10^{-4}(T+273) + 5.6416 \times 10^{-7}(T+273)^2 \]  

(1)

Specific heat capacity (kJ/kg.K)

\[ C_p = 0.4071T^{0.154} \]  

(2)

| Temperature/°C | 20     | 100  | 200  | 400  | 600   | 800  |
|---------------|--------|------|------|------|-------|------|
| \( \lambda/(\text{W}\cdot\text{m}\cdot\text{K})^{-1} \) | 0.724  | 0.682 | 0.365 | 0.401 | 0.423 | 0.460 |
| \( C_p/(\text{kJ}\cdot\text{kg}\cdot\text{K})^{-1} \) | 0.644  | 0.826 | 0.742 | 0.886 | 1.131 | 1.232 |

2.2.2. Inverse calculation of interface heat transfer coefficient. In order to obtain the interface heat transfer coefficient between the frozen sand mould and A356 aluminum alloy, the temperature of the casting and frozen sand mould were measured. In order to make the reverse calculation less and the operation time shorter, the casting was designed as \( \Phi 100 \times 100\text{mm} \), and the mesh division was shown in Fig. 1. Among them, a K-type thermocouple with a diameter of 0.3mm was buried in the casting and the surface of the sand mould, the thermocouple of the casting core was 50mm from the interface of the casting and sand mould, the thermocouple of the casting surface was 5mm from the interface of the casting and sand mould, the thermocouple of the sand mould surface was 5mm from the interface of the casting and sand mould, the thermocouple of the sand mould surface was 5mm from the interface of the casting and sand mould, its temperature measurement range is \(-40^\circ\text{C}\) to \(1300^\circ\text{C}\). In the process of freezing casting, the temperature of casting and frozen sand mould were collected by the Agilent 34972A model temperature collector, with a data acquisition time step of 10s. The network nodes 1, 2 and 3 in the figure correspond to the embedded positions of the thermocouples on the casting and sand mould, and then use the two sets of collected temperature data on the casting surface and sand surface to reverse the interface heat transfer coefficient. The interface heat transfer coefficient is a function of the interface temperature between the casting and the frozen mould during the solidification process. Importing the temperature field data of the casting surface and sand mould surface into the inverse module of the Procast software, the initial interface heat transfer coefficient is 800W / (m².K), the casting temperature is set to 680 °C, the initial temperature of the frozen sand mould is set to 20 °C, the initial filling rate of the mould is 100%. By calculating the temperature of the corresponding network point and comparing it with the measured value, the interface heat transfer coefficient between the casting and the frozen sand mould is obtained through cyclic iteration until the calculated temperature and the measured temperature meet the deviation requirements.

3. Experimental results and discussion

3.1. Inverse calculation of interface heat transfer coefficient

Fig. 2 is the measured temperature curve of the casting and the surface of the sand mould during the freezing casting process. It can be seen that when the high-temperature molten metal contacts the frozen sand mould, the surface temperature of the molten metal decreases to a phase transition temperature of
about 610 ℃ rapidly, during this process, the casting transitions from liquid to solid and releases latent heat of crystallization. The maximum temperature of the surface of the frozen sand mould is only 101.66 ℃. Tab. 3 shows the selected reverse temperature point and the interface heat transfer coefficients at the corresponding temperature points. It can be seen from Tab. 3 that when the casting temperature is lower than 565 ℃, the interface heat transfer coefficient remains at 750W. (m².K)⁻¹; between 565 ℃ and 610 ℃, the interface heat transfer coefficient increases significantly; above 610 ℃, the interface heat transfer coefficient reaches a peak value, which remains around 2300W. (m².K)⁻¹. The reason is that during the cooling process of the casting, the interface status between the casting and the sand mould is divided into three types: close contact between the metal liquid and the sand mould, the partial contact between the casting and the sand mould, and the complete contact between the casting and the sand mould [12, 13]. When the metal liquid fills the cavity and before solidification, the metal liquid and the sand mould are complete contact, at this time, the interface heat transfer coefficient reaches 2300W. (m².K)⁻¹, which is because the high temperature metal liquid contacts the frozen sand mould, The evaporation of water in the sand mould takes away a lot of heat, which increases the heat transfer between the interfaces; when the temperature of the castings decreases to near the liquidus (about 610 ℃), the metal liquid starts to solidify, and the volume shrinkage leads to the appearance of interface gaps, the interface heat transfer coefficient drops sharply; when the temperature of the castings decreases to near the solidus (about 565 ℃), the metal liquid solidifies completely, and the interface heat transfer coefficient is about 750W. (m².K)⁻¹.

![Fig. 2 Temperature change curve of casting surface and sand mould surface](image)

**Fig. 2** Temperature change curve of casting surface and sand mould surface

| Temperature/℃ | 400 | 450 | 500 | 565 | 585 | 610 | 630 |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| Inverse value/W. (m².K)⁻¹ | 739 | 747 | 756 | 769 | 1634 | 2365 | 2372 |

**Tab. 3** The inverse values of interface heat transfer coefficient between casting and frozen sand mould

Fig. 3 is a comparison result of casting measured temperature and simulated temperature obtained by inverse calculation of the interface heat transfer coefficient. As can be seen from the figure, the temperature curve of the Procast inverse calculation test can better track the actual temperature curve, below the highest temperature. The slope of the simulated temperature curve and the experimental curve are the same. After 2000s, the maximum temperature difference is less than 10%, ensure that the temperature field has a high accuracy of frozen casting.
3.2. **Simulation of temperature field of A356 aluminum alloy hub parts**

Fig. 4 to Fig. 7 show the temperature fields of A356 aluminum alloy hub parts in the freezing casting and resin sand casting at 600s, 1200s, 1800s, and 2400s, respectively. Using the thermophysical parameters and interface heat transfer coefficients recommended by the procast database to calculate the temperature field of resin sand casting. It can be seen from Fig.4 (a) that a large amount of solid phase has appeared at the edge of frozen sand casting at 600 s, the shape of the edge of the casting has been determined, and has a excellent casting formability, at this time, the most of the area of the resin sand casting is still in the liquid state; by 1200s, the temperature of the aluminum alloy hub parts further decreases, the temperature of the frozen sand mould casting is about 490 °C, and the temperature of the resin sand casting is about 570 °C; By 1800s, the temperature of the frozen sand mould casting is about 361 °C, and the temperature of the resin sand casting is about 446 °C; by 2400s, the temperature of the frozen sand mould casting is about 276 °C, and the temperature of the resin sand casting is about 360 °C. It can be seen that as time goes, the cooling rate of freeze casting is higher than that of resin sand casting, and rapid solidification of metal components can be achieved. Document [14] shows that: with the increase of cooling rate, the mechanical properties of the alloy have been improved significantly, so freeze casting can achieve the greening of the casting process and the excellent production of casting quality.

![Fig. 3 Surface (a) and core (b) temperature values of castings](image)

**Fig. 3** Surface (a) and core (b) temperature values of castings

![Fig. 4 Temperature field of freezing casting (a) and resin sand casting (b) at 600s](image)

**Fig. 4** Temperature field of freezing casting (a) and resin sand casting (b) at 600s
Fig. 5  Temperature field of freezing casting (a) and resin sand casting (b) at 1200s

Fig. 6  Temperature field of freezing casting (a) and resin sand casting (b) at 1800s

Fig. 7  Temperature field of freezing casting (a) and resin sand casting (b) at 2400s

4. Conclusion
(1) The interface heat transfer coefficient of frozen sand mould is obtained by temperature curves of casting and sand mould of frozen sand casting. The results show that when the casting temperature is lower than 565 ℃, the interface heat transfer coefficient remains at 750 W. (m².K)⁻¹; when the casting temperature is between 565 ℃ and 610 ℃, the interface heat transfer coefficient increases obviously, and when the casting temperature is higher than 610 ℃, the interface heat transfer coefficient reaches the maximum value, about 2300 W. (m².K)⁻¹.

(2) The temperature of casting that calculated by inverse heat transfer coefficient agrees well with that measured by experiment, the maximum error is less than 10%.

(3) Under the same solidification time, the temperature field of freezing casting hub parts is lower than that of resin sand hub parts, which can achieve rapid solidification of metal components.
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