Impact of the pressure between the casting and water-cooled mode on the interfacial heat transfer coefficient under LPDC

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Abstract. Low pressure die casting (LPDC) is the main method for aluminum alloy castings. In order to obtain no porous castings, a top-down progressive solidification is required. Owing to the complicated casting shape and the uneven wall thickness, it is difficult to achieve the above requirement, which limits the application of the method. The water-cooled mode, with controllable cooling capacity, can solve this problem, and great importance has been attached to the heat exchange between water-cooled mode and castings. In the present paper, the inverse solution method is adopted to study the influence of the casting mold/casting interface pressure and circulating water flow rate on the interface heat transfer coefficient (IHTC). The results show that the increasing interface pressure and the circulating water flow rate can lead to the highest IHTC of 781.6~1002.4 W/(m²·K) and 1002.4~1657.6 W/(m²·K) respectively. The calculation result of IHTC provides a basis for the design of low pressure casting with water-cooled mode.

1. Introduction

Low pressure die casting is an ultra-precision forming process with a metal utilization rate of 90 to 98%. The castings produced through this technical process are characterized by no porous structures and high mechanical properties. Therefore, nearly 50% of the castings are produced by adopting this technique, and low pressure die casting has become the main method for aluminum alloy castings. In the exertion of pressure, low pressure die casting aims to press the melt at the bottom of the mold into the model cavity from the stalk. The casting solidifies from the top to the gate, and the melt in the stalk provides the feeding for the casting. Therefore, in the low pressure die casting, the top-down progressive solidification must be ensured in order to obtain a non-porous structure of the casting. However, in general, the shape of the casting is complicated, and the wall thickness is not uniform, and it is difficult to ensure the up-bottom solidification sequence. For this reason, forced cooling is required to improve the heat exchange condition between the partial mold and the casting to ensure the casting is sequentially solidified. Water-cooled mode with controllable heat transfer strength are valued by casting workers at home and abroad, and heat exchange between water-cooled mode and castings becomes the key to low pressure die casting process design.

Foreign researches on water-cooled mode are relatively conducted early, and it is possible to produce complex parts such as large gear box [1]. Domestic researches have been carried out in recent years, but there is still a certain gap in the types of castings compared with foreign countries. An important reason lies in the lack of researches on heat exchange between water-cooled mode and castings, and basically designs on empirical formula. Thus, in order to improve the quality of the casting, it is necessary to study the interfacial heat transfer of the casting/water-cooled mode. The heat transfer of the casting/water-cooled mold is usually described by IHTC. For low pressure die casting, the casting/mold pressure and the mold cooling capacity are the main factors which affect IHTC. The former is related to the pressure of the low pressure casting (hereinafter referred to as...
“pressure”), and the latter is related to the cooling water flow rate (hereinafter referred to as “water flow rate”). Therefore, the study of the heat exchange of castings/molds is attributed to the study of the influence of pressure and water flow rate on IHTC.

The difficulties in the study of IHTC are manifested in the following aspects. Due to the influence of many factors, IHTC has no accurate theoretical solution, and it is difficult to measure IHTC directly under complicated interference of various factors.

The combination of the measured temperature field of the casting and the inverse calculation is an effective way to obtain IHTC. Extensive investigation has been made in terms of calculation methods and models [2,3], as well as the solution of casting/mold IHTC from perspectives of casting materials and casting temperature [4], initial mold temperature and material [5,6], geometry of casting [7], the mold surface coating material and thickness [8], the mold surface roughness and the air gap [9,10], etc. In this paper, IHTC of casting/water-cooled die is taken as the core case, along with the method of inverse solution. Firstly, a new experimental model is proposed to accurately control the interface pressure of casting/mold and water flow rate, and to measure the cooling curve of the casting feature points. Then, the inverse calculation method is used to calculate IHTC, and the influence of pressure and water flow rate on IHTC is studied. The results of the study will provide a more accurate basis for the design of low pressure casting process.

2. Experiment

2.1. Experimental model

The experimental model is a combined mold (Fig. 1). The inner cavity is a rectangular paralleled pipe, and the upper and lower bottoms and three walls of the mold are made of heat insulating material. The remaining is a metal water-cooled wall. The water-cooled wall has a water channel inside, which can be cooled by circulating water. The water-cooled wall can move relatively to the other five walls. The push rod on the water-cooled wall is equipped with a pressure sensor to accurately grasp the contact state of the water-cooled wall and the casting and the interfacial pressure. Changing the water flow rate controls the cooling capacity of the water-cooled wall.

In the experiment, after the molten metal is poured into the mold, the water-cooled wall is kept closely with the casting. When the solidification thickness reaches the preset value, the water-cooled wall quickly moves to the left side to reach a preset interface pressure.

2.2. Experimental Protocol

In order to study the heat exchange of the castings under low-pressure/water-cooled mode, the water flow rate and pressure are selected as the controllable factors in the experiment. In actual production, the pressure of low pressure die casting is applied according to the filling and pressurizing sections. According to the actual production, the pressure is set to 0, 70, 200, 300 kg; the water flow rate is set to 23.4, 38.4, 67.2 kg/ Min.
2.3. Temperature Measurement
The thermocouple temperature measurement point distribution is shown in Figure 1. The 1, 2, and 3 points are 5mm, 10mm, and 40mm away from the casting/water-cooled interface. The temperature of the water-cooled wall is measured at 4 points and placed in the water-cooled wall, 1 mm from the surface. K-type exposed thermocouples with a diameter of 0.1 mm is used to measure the temperature. The data is collected by the DAQ-USB-2401 module at a sampling frequency of 100 Hz. The temperature change at a temperature measurement point during the experiment is recorded.

2.4. Experimental Materials
The experimental casting material is A356 aluminum alloy, and the pouring temperature is controlled at about 730°C, and the top gating is adopted in this process. PROCAST software is used to calculate the thermal properties of castings and mode materials.

2.5. Inverse Calculation of IHTC
The nonlinear inverse algorithm proposed by Beck et al. [11] was used to compute the IHTC. A random initial value \( h \) was set under the assumption that IHTC would remain constant within a certain time interval \( \Delta t \). Casting and mold temperature fields were computed with this initial value. Squared differences between the simulated temperature field and the measured temperature field (point 1~3) were calculated, and \( h \) was modified repeatedly to minimize the square difference, and the final \( h \) value obtained was then considered IHTC.

3. Experimental results and analysis

3.1. Curves of measured temperature
Fig. 2 shows the temperature curve of the measuring point 1~3 when the water flow rate is 23.4 kg/s and the pressure is 0, 70, 200, 300 kg. When the pressure is 0kg (Fig. 2a), the temperature drops slowly at the measuring points of 1~3. At 400s, the temperature at 1-3 points is 564.5, 568.1, 577.4°C.

Figure 2. Measured temperature at different pressures
(a) pressure 0kg (b) pressure 70kg (c) pressure 200kg (d) pressure 300kg
The pressure is 70kg (Fig. 2b), and the temperature drop of the measuring point 1~3 is accelerated. At 400s, the temperature of 1~3 points is 354.2, 356.5, 365.1℃. Based on the comparison of two temperatures, it can be found that the pressure change will lead to a change in the cooling rate in the casting, which in turn affects the solidification process and the final microstructure. Comparing Fig. 2b, c, and d, indication can be made that as the pressure increases, the temperature drop rate increases, as is seen from 1 to 3 points; At 400 s, the temperatures are 354.2, 356.5, 365.1℃, 349.0, 352.1, 368.7℃ and 330.8, 336.0, 348.4℃, respectively.

Fig.3 is the temperature curve of 1~3 measuring points when the pressure is 300kg and the water flow rate is 23.4, 38.4, 67.2kg/min respectively. The water flow rate increases, and the temperature drop of 1~3 is accelerated. At 400s, the temperatures are 330.8, 336.0, 348.4℃, 324.7, 330.3, 347.1℃, and 323.8, 332.3, 338.7℃, respectively. Therefore, the water flow rate is increased, and the cooling capacity of the mold is improved. Under the high mold pressure, the cooling effect of the mold on the casting is enhanced.

3.2. Solution of the IHTC

It can be seen from the temperature measurement results that the pressure and water flow rate affect the cooling of the casting, and IHTC is used to quantify the interface heat transfer.

Fig.4 shows the calculation results of IHTC when the water flow rate is 23.4 kg/min and the pressure is 0, 70, 200, and 300 kg, respectively. When the pressure is 0kg (Fig. 4a), IHTC reaches the highest value and then decreases rapidly after the pouring. IHTC decreases slowly after 150s, and then remains basically unchanged. When the solidification time is 400s, IHTC drops to 291.8 W/(m²·K). IHTC curve of the pressure applied after pouring is shown in Fig. 4b~d, which shows a rebounding of IHTC, and then decreases slowly over time. Through the three IHTC, it is obvious that the stronger the pressure, the greater IHTC recovery. Under the experimental conditions, the pressure increased from 70 to 300 kg at a flow rate of 23.4 kg/min, and IHTC increased from 781.6 to 1002.4 W/(m²·K).

In addition, IHTC of 400s is greater than that of no pressure applied. We can easily conclude that IHTC can more accurately reflect the influence of pressure on heat transfer than the temperature change of the casting.
Fig. 5 shows the calculation results of IHTC when the pressure is 300 kg and the water flow rate is 23.4, 38.4, and 67.2 kg/min, respectively. As the water flow rate increases, IHTC increases, which is 1002.4, 1335.9 and 1657.6 W/(m²·K), respectively, and IHTC of 400s also increases.

Fig. 6 presents the relationship between the highest and lowest IHTC and pressure combined with water flow rate in the above experiment. The portion between lines 1 and 2 of Fig. 6a is the change
range of IHTC after the water flow rate changes. The portion between lines 1 and 2 of Fig. 6b indicates the change range of IHTC after pressure changes. This range of values can provide reference for low pressure casting mold design. In summary, the pressure and cooling water flow rate will cause the change of heat exchange rate of the casting/mode interface. In the low pressure die casting process, the joint regulation of these two parameters can effectively control IHTC and further control the partial cooling rate and the solidification sequence of the casting to ensure that the castings are progressively solidified from the top to the gate, and finally a high-quality die-casting part with complicated shape is achieved.

4. Conclusions
(1) IHTC increases with the interface pressure. In this test, the highest IHTC increased from 781.6 to 1002.4 W/(m²·K). When the solidification time is 400s, IHTC is still 41.3% higher than that without pressure.
(2) The water flow rate has a great influence on IHTC. When the water flow rate increases, IHTC grows. The water flow velocity increases from 23.4 kg/min to 67.2 kg/min, and IHTC rises from 1002.4 to 1657.6 W/(m²·K). The pressure enhances the cooling capacity of circulating water cooling mold.
(3) The experimental model which can accurately control the casting/mode pressure and circulating water flow rate is designed to study IHTC of low pressure die casting. The calculation result of IHTC provides the basis for the design of low pressure die casting water-cooled mode.

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