A study of metal/die interfacial heat transfer behavior of vacuum die cast pure copper

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Abstract: High pressure die casting copper is used to produce rotors for induction motors to improve efficiency. Experiments were carried out for a special “step-shape” casting with different step thicknesses. Based on the measured temperature inside the die, the interfacial heat transfer coefficient (IHTC) at the metal/die interface during vacuum die casting was evaluated by solving the inverse problem. The IHTC peak value was 4.5×10^3 – $11 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ under the basic operation condition. The influences of casting pressure, fast shot speed, pouring temperature and initial die surface temperature on the IHTC peak values were investigated. Results show that a greater casting pressure and faster shot speed could only increase the IHTC peak values at the location close to the ingate. An increase of pouring temperature and/or initial die surface temperature significantly increases the IHTC peak values.

Key words: vacuum die casting; interfacial heat transfer behavior; inverse method; copper; metal/die interface

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Copper rotors have been applied in induction motors for automotive vehicle and aviation industries^[1-5]. Copper rotors are mostly produced by high pressure die casting (HPDC), which is one of the most economical processes for mass production^[5]. However, gas pores and shrinkage porosity often appear in the end ring of copper rotors^[6]. The presence of these defects significantly deteriorates the mechanical properties of the high-speed induction motor^[7]. Vacuum die casting (VDC)^[8], together with modeling and simulation^[9] has been utilized to reduce gas porosity and produce high-integrity rotors. For modeling and simulation, the accuracy of the results is mostly dependent on the input boundary conditions, of which the metal/die interfacial heat transfer coefficient (IHTC) is shown to be crucial for the thermal field estimation. However, studies to evaluate the IHTC for the die casting copper process are very limited.

The IHTC was usually evaluated by solving an inverse heat conduction problem based on the temperature measurements inside the die. Guo et al.^[10,11] developed a special temperature sensor unit (TSU) to measure the

temperature during the HPDC process and evaluated the IHTC based on a one-dimensional inverse heat transfer model. The thermocouple tip was welded to the end wall of the groove inside the TSU to maintain a perfect contact. However, the thermocouple became detached from the end wall of the TSU during the HPDC process of copper because the die surface temperature approached 880 °C^[12-14], which was much higher than that when light alloys were used.

In this work, an optimized TSU was used during the die casting to obtain accurate temperatures. The influence of processing parameters, including casting pressure, fast shot speed, pouring temperature and initial die surface temperature on the IHTC was investigated.

1 Experimental

1.1 Casting

A “step-shape” casting was used in this study. As shown in Fig. 1, the “step-shape” casting has five different thicknesses, i.e., $d = 1.5, 3, 6, 10$ and 15 mm (marked as Step 1, Step 3, Step 6, Step 10 and Step 15, respectively).

1.2 Die configuration and sensor installation

An improved special temperature sensor unit (TSU) was used to measure the temperature inside the die.

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Fig. 1: Configuration of the “step-shape” casting: (a) size and geometry (unit: mm); (b) actual casting

The die material was 4Cr5MoSiV1. The thermocouples were held in a specific temperature sensor unit and fixed in grooves by a thermocouple fixed tool. As shown in Fig. 2, six grooves 1 mm wide and 1 mm deep were machined in the sensor unit for the placement of the thermocouples. At each distance (1, 3, and 6 mm) from the front wall of the TSU, two thermocouples were fixed (i.e. A1 and A2, B1 and B2, C1 and C2). The thermocouples were K-type thermocouples with a diameter of 1 mm (the wire diameter was 0.045 mm).

Figure 3 shows the installation of the TSU inside the die. Five temperature sensor units, designated as TSU1-TSU5, were installed inside the fixed die corresponding to each step.

1.3 Material characterization and the inverse method

Tables 1–3 show the chemical compositions and thermophysical properties of copper and 4Cr5MoSiV1, respectively.

The “step-shape” casting was produced on a Buhler cold chamber die casting machine equipped with a vacuum system

Fig. 2: Configuration of improved temperature sensor unit

Table 1: Chemical composition of copper (wt.%)

Cu+Ag	S	P	Fe	Pb	Zn	As	Sb	Bi
≥99.97	≤0.0025	≤0.001	≤0.0025	≤0.002	≤0.002	≤0.0015	≤0.0015	≤0.0006

Table 2: Chemical composition of 4Cr5MoSiV1 steel (wt.%)

C	Mn	Si	S	P	Cr	Mo	V	Fe
0.396	0.36	0.94	<0.005	<0.025	5.05	1.25	0.82	Bal.

Fig. 3: Schematic illustration of TSU installation inside the die

and chill vent. The vacuum pressure in the cavity managed to approach 10 kPa, using a vacuum system as described by Wang et al.^[15]. The die was preheated to 200 °C, and a total of 45 castings were produced under the basic operation condition (Table 4). Processing parameters including pouring temperature, casting pressure and fast shot speed were varied (Table 4), and five shots were performed for each operation condition. The temperature was recorded using a data acquisition system manufactured by Integrated Measurement Corporation with a data acquisition frequency of 500 Hz.

Table 3: Thermal properties of copper and 4Cr5MoSiV1

Thermal properties	Copper	4Cr5MoSiV1
Thermal conductivity, λ ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)	398	$31.2 - 0.013 T^a$
Specific heat, C_p ($\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	386	$478 - 0.219 T$
Density, ρ ($\text{kg}\cdot\text{m}^{-3}$)	8,900	$7,730 - 0.24 T$
Solidus temperature, T_s ($^{\circ}\text{C}$)	1,065	1,471
Liquidus temperature, T_L ($^{\circ}\text{C}$)	1,083	1,404
Latent heat, L_s ($\text{J}\cdot\text{kg}^{-1}$)	211,500	209,350

^a T stands for temperature ($^{\circ}\text{C}$)

Table 4: Processing parameters during the experiment

Processing parameters	Basic	Variable
Pouring temperature (T_p , $^{\circ}\text{C}$)	1,200	1,300
Initial die temperature (T_m , $^{\circ}\text{C}$)	300	200–450
Casting pressure (MPa)	87	60
Slow shot speed (V_L , $\text{m}\cdot\text{s}^{-1}$)	0.5	
Fast shot speed (V_H , $\text{m}\cdot\text{s}^{-1}$)	2	3.5

The IHTC was estimated by solving an inverse heat condition problem based on the principle proposed by Beck et al [16, 17]. The target is to minimize the sum of the squared errors between the calculated and the measured data:

$$F(h) = \sum_{i=1}^N (T_i - Y_i)^2 \rightarrow \min \quad (1)$$

where T_i and Y_i are calculated and measured temperatures at various thermocouple locations, respectively, and N designates the number of future time steps.

2 Results and discussion

2.1 Validation of measured temperatures

Figure 4 shows the measured temperature curves inside the die according to Step 6 under the basic operation condition. The temperature curves measured at each distance in the sensor unit, such as T_{A1} and T_{A2} or T_{C1} and T_{C3} , are almost overlapping. The largest difference was $\sim 7^{\circ}\text{C}$, indicating that the one-dimensional heat-transfer assumption was reasonable [18]. The IHTC was determined based on the temperature measurements at 1 mm (average of T_{A1} and T_{A2}) and 6 mm (average of T_{C1} and T_{C2}) away from the cavity surface. The temperature measurements at 3 mm (average of T_{B1} and T_{B2}) away from the cavity surface were compared with the inversely determined temperatures to testify the accuracy of the inverse model. Figure 5 shows that the measured and simulated temperatures at 3 mm (T_{3m} and T_{3c}) agreed well with each other and a maximum difference was about 5°C , indicating the accuracy of model.

Fig. 4: Measured temperatures inside the die at Step 6 under basic operation condition

2.2 Interfacial heat transfer behavior during VDC

Figure 5 shows the determined IHTC and heat flux profiles at Step 6. The surface temperature of copper decreased immediately after the melt contacted the die surface. The IHTC increased abruptly until reaching a maximum of $4.76 \times 10^3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. The heat flux also increased rapidly until reaching $2.96 \times 10^6 \text{ W}\cdot\text{m}^{-2}$. The IHTC then decreased rapidly until reaching a lower value of $2.48 \times 10^3 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. At the later stage of solidification, the contact between the casting and the die deteriorated, and the IHTC became lower than $1,000 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$.

Fig. 5: Measured temperatures and determined IHTC at Step 6 (T_{cs} , T_{cc} —the inversely calculated temperatures of the step surface and center; T_1 , T_6 —average measured temperatures at 1 mm and 6 mm away from the cavity surface; T_{3m} —average measured temperatures at 3 mm away from the cavity surface; T_{3c} —the inversely calculated temperature at 3 mm away from the cavity surface; ΔT —the temperature difference between metal and die surfaces; h —the interfacial heat transfer coefficient; q —the interfacial heat flux density)

Figure 6 shows the calculated IHTC profiles at five steps under the basic condition. All IHTC profiles changed similarly as that at Step 6. The IHTC always exhibited an abrupt increase after filling until reaching its maximum value, and then decreased to a much lower level. Despite the difference of the IHTC peak value ($h_{\max}$), the duration for the IHTC to maintain a higher value increased with the step thickness

Fig. 6: Determined IHTC profiles at five steps under basic condition

(such duration was 0.064 s for Step 1, 0.136 s for Step 6 and 0.46 s for Step 10, respectively). The IHTCs at Steps 1 and 3 dropped much faster than other steps. It took much longer for the IHTC to decrease when the step thickness was greater. Figure 7 shows the filling process of the liquid copper simulated by a CAE cloud computing platform namely Ares by Supreim Co. Ltd. under the basic operation condition. The melt copper flowed inside the cavity of Step 3 from the gating system towards the surface of the fixed die inside which the temperature sensor units were installed. The flow then moved toward the surface of the movable die until reaching the cavity of Step 15 where the direction of the flow changed. In this respect, the melt flowed directly towards the fixed die surface for Steps 3, 15 and 1, and towards the movable die surface for Steps 6 and 10. The heat transfer during the initial increasing

Fig. 7: Simulation of the filling process inside the "step-shape" casting (a) Steps 3 and 6; (b) Steps 6 and 10; (c) Steps 15 and 1

stage was dependent on such filling behavior, but the peak value of the determined IHTC was greatly dependent on the contact status between the alloy melt and the die.

Comparing the results of the five steps, the peak values of IHTC exhibited three levels. It was about $5 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for Steps 1 and 6, and $7 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for Step 15. The larger peak values of IHTC were $\sim 10 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for Steps 3 and

10. The difference between every two levels was about $2,000\text{--}3,000 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$.

2.3 Influence of processing parameters

Figure 8 shows the influence of the casting pressure and fast shot speed on the IHTC peak values. The IHTC peak value at Step 3 increased from 10.5×10^3 to $11.3 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ as

Fig. 8: Calculated IHTC peak values under different casting pressures (a) and fast shot speeds (b)

the casting pressure increased. The IHTC peak values hardly changed for other steps when the pressure was varied. This is because a better contact was achieved between the casting and the die when the vacuum die casting was applied. Besides, the casting pressure could not be effectively transferred farther away from the ingate due to solidification^[19]. The influence of fast shot speed on the IHTC was similar (Fig. 8b). As the fast shot speed increased, the IHTC peak value at Step 3 increased from 9.5×10^3 to $11.3 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$, and slightly increased for other steps. A faster shot speed induced a stronger impact between the molten metal and the die during filling.

Figure 9 shows $h_{\max}$ under different pouring temperatures. Increasing the pouring temperature from 1,200 °C to 1,300 °C led to an increase of $h_{\max}$ by 33.6% at Step 3, 19.6% at Step 6, 22.0% at Step 10, 25.3% at Step 15, and 4% at Step 1. The IHTC peak value increased from 10.7×10^3 to $14.3 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at Step 3 near the gate and from 4.9×10^3 to $5.1 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at Step 1 near the overflow, respectively.

Figure 10(a) shows the IHTC peak values as a function of the initial die surface temperature at Step 6 under basic condition. The IHTC peak values increased when the initial die surface temperature increased. Figure 10(b) shows the change of IHTC peak values ($h_{\max}$) versus initial die surface temperature (T_{IDS}) at five steps under the basic condition. According to Ref. [20], the IHTC peak values ($h_{\max}$) changed

Fig. 9: Estimated IHTC peak values under different pouring temperatures

as a function of T_{IDS} :

$$\ln \eta_h = \ln(h_{\max} / T_{\text{IDS}}^2) = A \ln T_{\text{IDS}} + B \quad (2)$$

where A and B are fitted parameters. $h_{\max}$ was:

$$h_{\max} = e^B \times T_{\text{IDS}}^{2+A} \quad (3)$$

Equation (3) illustrates $h_{\max}$ changes as a function of T_{IDS} . The largest variance or deviation was 12.2% for steps 3 and 10. It is found that $\ln \eta_h$ decreased as $\ln T_{\text{IDS}}$. The initial die surface temperature (T_{IDS}) exhibited the most dominant influence on the IHTC peak value.

Fig. 10: IHTC peak values as a function of the initial die surface temperature at Steps 1 and 6 (a) and five steps under the basic conditions (b)

3 Conclusions

In this work, the interfacial heat transfer coefficient (IHTC) between copper and die during vacuum die casting was estimated by solving an inverse thermal problem based on the measured temperatures inside the die. The influence of processing parameters on the IHTC was investigated, based on which the following conclusions can be drawn:

(1) During the die casting process, the IHTC first increases abruptly to a maximum when the liquid metal comes in contact with the die surface, then decreases until the value approaches

a much lower level.

(2) Under the basic operation condition, the IHTC peak values are $5 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at Steps 1 and 6, $7 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at Step 15, and $10 \times 10^3 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ at Steps 3 and 10, respectively.

(3) The IHTC peak values are shown to be dependent on the processing parameters. As the casting pressure and the fast shot speed increase, the IHTC peak values increase at Step 3 near the gate, whereas the IHTC at other steps changes insignificantly. As the pouring temperature increases from 1,200 °C to 1,300 °C, the IHTC increases significantly at all steps.

(4) The IHTC peak values are mostly dominated by the initial die surface temperature according to $h_{\max} = e^B \times T_{\text{IDS}}^{2+A}$.

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