Determination of interfacial heat transfer coefficient and its application in high pressure die casting process

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Abstract: In this paper, the research progress of the interfacial heat transfer in high pressure die casting (HPDC) is reviewed. Results including determination of the interfacial heat transfer coefficient (IHTC), influence of casting thickness, process parameters and casting alloys on the IHTC are summarized and discussed. A thermal boundary condition model was developed based on the two correlations: (a) IHTC and casting solid fraction and (b) IHTC peak value and initial die surface temperature. The boundary model was then applied during the determination of the temperature field in HPDC and excellent agreement was found.

Key words: high pressure die casting; interfacial heat transfer coefficient; inverse method

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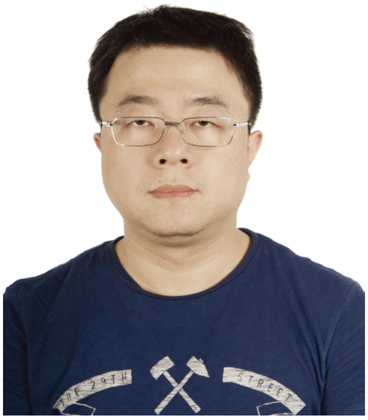

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High pressure die casting (HPDC) is a net shape process for producing thin wall components for the manufacturing industry. Due to the excellent properties of die castings, an increasing number of die cast products are currently used in the automotive, aerospace, medical, electronic, and other industries. The technique of numerical simulation to predict the mold filling, solidification, and the distribution of temperature in the die has become very important in foundry technology and cast product developments. However, the effectiveness of the simulation is dependent on the accuracy of the material properties as well as the metal-mold boundary and the initial conditions in the simulation software. The interfacial heat transfer coefficient (IHTC), which characterizes the heat transfer behavior at the metal-mold interface, is believed to be one of the most important parameters during the solidification process for computer simulations. The determination and application of IHTC are now becoming key issues to researchers.

According to Newton's law of heat transfer, IHTC can be estimated from the following equation:

$$h = \frac{q}{T_m - T_d} \qquad (1)$$

where q is the heat flux density crossing the casting-mold interface, T_m and T_d are the casting surface temperature and mold surface temperature, respectively.

The parameters in Equation 1 are in fact interconnected during solidification. The changes of heat flux density and the casting surface temperature that take place during solidification are related to the evolution of the latent heat released from the casting, whereas the increase in mold surface temperature occurs as a result of the absorption of the heat removed from the casting. Thus, in order to determine the IHTC during HPDC, it is necessary to have accurate knowledge about the variation of heat flux density; and the casting and die surface temperatures during casting and solidification. Unfortunately, it is difficult to measure these quantities directly in a real casting environment. The only zones which are actually accessible for installing devices to measure the temperature histories are in the mold wall or in the die cavity, which are far from the interface. Therefore, numerical techniques are unavoidable in order to estimate the boundary conditions and hence the transient heat flux density and IHTC at the casting-mold interface.

1 Determination of IHTC

The objective of the HPDC processes is to solidify the molten alloys in a relatively cold metallic mold into the shape of the desired component. The high cooling rate achieved in HPDC of light alloys is a major advantage. This is due to the relatively high thermal conductivity (30–50 $W \cdot m^{-1} \cdot K^{-1}$) and heat diffusivity of the steel dies usually used in these processes. Because the alloys and the steel are good conductors, the heat transfer is limited by the interface. As a consequence, the cooling rate of the casting can be characterized by the heat transfer at the metal-mold interface. A high cooling rate is advantageous because it ensures a very fine microstructure for the produced castings and assists in the achievement of high rates of production. However, it may cause premature solidification of the molten alloy before the filling is complete. Therefore it has to be controlled in some way. This control is performed in HPDC by injecting the molten alloy into the cavity of the die with high velocity and high pressure.

In order to quantify the interfacial heat transfer behavior at the metal-mold interfaces, extensive efforts have been made relating to the HPDC process since the 1970s [1] to determine the precise interfacial heat fluxes and heat transfer coefficients at the metal-mold interface. Among the mathematical methods described in literature, three main approaches can be distinguished in order to determine IHTC at the metal-mold interface including:

(1) Purely analytical approaches;

(2) Semi-analytical approaches based on empirical correlations; and

(3) Numerical approaches.

1. 1 Purely analytical approaches

In purely analytical approaches, the assumption of a constant interfacial heat transfer coefficient is made in order to obtain an analytical solution for the Fourier unsteady state heat conduction equation. Purely analytical approaches were developed to derive the IHTC at the metal-mold interface from experimental data. Garcia et al. [2, 3] developed a mathematical heat transfer model by considering the solidification of metal under the superimposed effects of thermal conduction and interfacial thermal contact, with no mathematical approximations for temperature profile. They assumed that the thermal properties of the metal and mold, including the heat transfer coefficient, are invariant during solidification. Lead and aluminum alloys were used as cast metals and the virtual system was set up in which the contact resistance was represented by a pre-existing adjunct of material to predict the temperature profiles within the metal and cooling mold, namely the virtual adjunct method (VAM). However, a significant limitation to these approaches was the necessity to assume constant interfacial heat transfer coefficients in order to solve the heat conduction equation.

1.2 Semi-analytical approaches based on empirical correlations

Semi-analytical approaches, which also assume a constant heat transfer coefficient, have also been documented. Prates et al. [4] developed the fluidity test in order to determine the average heat transfer coefficient at the metal-mold interface during solidification of an Al-Cu alloy by assuming that the heat flow is constant during the fluidity test. The data obtained from the fluidity tests were put into the heat transfer equation in order to determine the IHTC at the metal-mold interface using the following equation:

$$h = \frac{2A\rho v C_p}{p\left(T_m - T_0\right)} \frac{\partial S}{\partial L} \qquad (2)$$

where A is cross-sectional area of the fluidity channel, ρ is metal density, v is mean velocity of the liquid metal into the channel, C_p is metal specific heat, p is perimeter of the fluidity channel, T_m is metal temperature, T_0 is initial mold temperature, S is metal superheat, and L is final metal length resulting from the test.

It has been known since 1970 that when the alloy is solidifying against a mold, phase transformations occur that produces a dynamic change in the metal-mold contact conditions which cause the variation of IHTC during solidification. Knowledge about this variation is very important when attempting to understand the mechanisms of heat transfer in die casting processes. The semi-analytical approaches are unable to determine the variation of IHTC at the metal-mold interface as a function of time during solidification.

1.3 Numerical approaches (Inverse method)

Regardless of the physical impediments and uncertainty when directly measuring the die surface or casting surface temperatures with thermocouples, determination of the IHTC during solidification requires, in fact, the history of the heat flux density crossing the casting-mold interface mentioned in Equation 1 during solidification as well as the die and casting surface temperature histories. The analytical and related numerical methods mentioned above are unable, in fact, to determine the heat flux history crossing the interface. It was not until the emergence and development of new numerical approaches associated with inverse heat conduction problems (IHCP) that the heat flux history across the interface could be more completely explored. IHCP implies the determination of the surface heat flux history of a body from the bulk temperature measurements. This has been studied widely and many techniques have been applied [5, 6]. A common approach is based on the minimization of the sum of the squared errors between the calculated and the measured data, i.e.

$$F(h)=\sum_{i=1}^{N}\left(T_i-Y_i\right)^2 \tag{3}$$

where T_i and Y_i are calculated and measured temperatures at various thermocouple locations and times. Unavoidable measurement errors in the data Y_i result in a lack of continuous dependence of the solution on the data and this is an ill-posed problem. To overcome such difficulties and yield a solution, many techniques for solving inverse heat conduction problems have been proposed [5, 6]. From the measured interior temperature histories, the transient metal-die interface heat flux and temperature distribution can be estimated by using the following techniques:

(1) Control volume method: The energy balance is applied at each control volume. Partial heat conduction equations can be reduced to ordinary differential equations in the time factor. But, this involves many complex equations (4th order difference), which are difficult to program (using computer languages), and can only be applied to simple geometrical shapes.

(2) Polynomial extrapolation method: The temperature is deduced by extrapolating to the die-metal interface by a polynomial curve fitting technique, which requires many measurement points inside the body. It was lacking in other mathematical tools to minimize measurement errors.

(3) Regularization method: Based on Tikhonov regularization theory, a regularized function is established to decrease the sensitivity of the measurement data, thus improving the accuracy and stability of the solution. The method can achieve excellent solutions and be applied to complex geometry, but the calculation takes a longer time.

(4) Boundary element method and Laplace transform: It can transform equations to matrix which can easily be coded into a program, which is an effective method to solve a linear problem. The temperature data can tolerate more noise, but the heat flux fluctuates with measuring errors.

(5) Beck's function specification with finite difference method (implicit & explicit): It is effective in minimizing the sum of squares function with respect to heat flux and the errors between calculated and measured data. The method can be used for linear or non-linear problems. Also, it can achieve an accurate result with efficient computation.

Analytical and numerical methods are available for solving the heat flow equations. By using measured temperatures in both casting and mold, together with numerical [1, 7-20] or analytical [2, 3] solutions of the solidification problem, many researchers have attempted to calculate the metal-mold interfacial heat transfer in terms either of a heat transfer coefficient or heat flux.

The analytical procedures attempt to develop expressions for the boundary condition for a given temperature history in the body. A few temperature sensors are placed at arbitrary locations in the conducting body. However, IHTC is difficult to solve analytically because the temperature response at an interior location in a body to a given stimulus at the surface is both delayed and diminished in amplitude. Measurement of temperatures at discrete locations at discrete time intervals provides incomplete information for obtaining an accurate solution. The limitations exposed by the analytical solutions are overcome by the use of numerical methods. For the numerical solution, an approximate form of the variation of the unknown boundary condition with time is assumed. Using this form of the boundary condition with the unknown coefficient, the interior temperature field is determined in the domain by numerical procedures such as the finite difference method (FDM) or the finite element method (FEM). An objective function based on the values of measured and calculated temperatures at various internal points is then determined. It is minimized or maximized as the case may be, by correcting the values chosen for coefficients used in the boundary conditions. This is carried out iteratively until a stationary value of the objective function is obtained. Thus, measurement errors can be minimized by this numerical procedure.

2 Interfacial heat transfer in HPDC

Unlike the situation in a permanent mold casting where a thick thermal barrier coating is applied to the mold, in the HPDC process, a very thin film of lubricant or release agent (some nanometers to micrometers thick) is applied on the die surface in order to assist with ejection of the casting. The interfacial heat transfer is then related less to the coating material itself but more to the surface quality of the die. With a thinner coating and high applied pressure, heat transfer is initially dominated by mold properties, but as the casting solidifies and the interface changes, the interface becomes increasingly important. Early studies have been conducted on the heat transfer through the castings by Ho and Pehlke [17, 21]. They suggested that a metal-mold interface may generally exist in the states of (i) a conforming contact, (ii) a nonconforming contact, and (iii) a clearance gap, with a corresponding trend toward decreasing the IHTC during solidification and the cooling of the casting. In terms of research on the IHTC at the metal-mold interface, the most frequently investigated casting method has been that of permanent mold or chill casting, there is very little literature concerning the transient heat transfer during HPDC.

2.1 Difficulties in IHTC determination

The lack of literature about the transient heat transfer in HPDC compared to that of conventional casting is due to the practical difficulties associated with performing the required temperature measurements in the HPDC environment of high molten metal cavity filling velocity and pressures. Dour et al. [22] studied the difficulties in interfacial heat transfer determination during a rapid solidification process and suggested that some rules should be followed when determining the interface heat transfer by using the inverse method:

(1) Accurate temperature measurements in a metallic die require a very good contact between the sensor and the bulk metal along its isothermal surfaces.

(2) The sensors should be as thin as possible, to minimize the perturbation caused to the heat flow and to have the short response time essential for accurate measurement under rapid transient heat transfer conditions.

(3) The first thermocouple must be as close as possible to the surface to minimize both deterministic and stochastic inaccuracies. The limit to this will usually be determined by practical difficulties (proximity to the surface). When the distance of the thermocouple from the surface approaches the dimension of the thermocouple, the distortion of the thermal field increases, leading to errors.

(4) The time step for the measurement must be chosen as a compromise between the amplification of stochastic errors and the propagation of deterministic errors.

As listed above, in HPDC, two main problems can be identified when using thermocouples to measure the casting and the die temperatures: (I) Accurate and reproducible measurements are not possible on the casting side due to the severe filling conditions, (II) The fast solidification rate in HPDC means that the thermocouple response time and their installation in the die including their distances from the casting-mold interface introduce significant uncertainties in the IHTC estimation.

2.2 Current research progress of IHTC in HPDC

Studies concerning the metal-mold interfacial heat transfer during the HPDC process have been performed since the 1970s, when Nelson [1] conducted the die-casting experiment using a magnesium alloy AZ91B. The average IHTC during the solidification was estimated to be 19.624 $kW\cdot m^{-2}\cdot K^{-1}$. Hong et al. [19] also performed a die-casting experiment using a plate-shaped casting with the casting alloy A380. A higher average IHTC of about 79.4 $kW\cdot m^{-2}\cdot K^{-1}$ was found to provide the best match between the measured and simulated temperatures. Papai and Mobley [16] determined the heat flux during the HPDC process using an iterative procedure introduced by the inverse method. They used a bowl-shaped casting with the A380 alloy. The result showed that the heat flux changes as a function of the cycle time. In all these studies, the temperature measurement was believed to be the most difficult task. Improper installation of the thermocouples could bring uncertainties in the temperature measurement and, consequently, the accuracy of the determined IHTC would be affected. Dour and Hamasaiid et al. [12, 13] used a nonintrusive heat-transfer gage for the temperature measurements in the HPDC process. They claimed that with such an instrument, the temperature could be accurately measured during the HPDC experiment. An inverse approach was used to evaluate the heat-transfer coefficient at the metal-die interface. The results showed that the fast shot velocity and the die temperature, rather than the casting pressure, had the more prominent influence on the IHTC.

The influence of the applied pressure on the heat transfer coefficient is one of the most contested investigation topics within this area. It is well established that the application of a high pressure could greatly enhance the heat transfer at the metal-mold interface. However, Papai and Mobley [16] found that with a further increase in the applied pressure, the thermal field and the heat flux to the die would be hardly changed. Similar results were observed by El-Mahallawy et al. [15], and Dour and Hamasaiid et al. [12, 13]. However, Sekhar et al. [18] found that when casting the Al-Si alloy against an H13 steel die using a pressurized apparatus, the influence of the pressure on the heat transfer could still be prominent, even under a very high pressure situation. Guo et al. [10] conducted an HPDC experiment using a ‘step shape’ casting. They found that the influence of the pressure would only be prominent if the casting step is sufficiently thick; for the thinner steps, such influence is negligible.

The fast shot velocity and the initial die temperature were also found to have great influences on the heat transfer during the HPDC process. According to Dour et al. [13], a higher velocity always leads to a higher heat transfer coefficient and heat flux. This trend was also observed by Guo et al. [9] and Hamasaiid et al. [23]. They believed that this effect is mainly caused by the in cavity pressure arising from the impact of the melt on the die surface. Furthermore, Papai and Mobley [16] and Dour et al. [13] found that the peak value of heat flux or heat transfer coefficient decreases as the initial die temperature increases. However, according to Guo et al. [9], this trend is only prominent for thicker parts of the casting.

3 Research progress of Tsinghua Group

3.1 Experimental casting and sensor installation

As shown in Fig. 1, the “step-shape” casting, “finger-shape” casting and “cover-plate” casting were specially designed and used during the experiment. In this respect, the influence of casting thickness and type of runner system, as well as the influence of casting geometry and processing parameters on the IHTC during HPDC can be investigated. To gain a sufficiently rapid response time to follow the HPDC process and accurately measure the temperatures inside the die, a special temperature sensor unit (TSU) was designed. By using this TSU, temperatures at 1, 3 and 6 mm from the interface were measured inside the die, corresponding to each location.

3.2 Evolution of the IHTC

Figure 2 shows the determined IHTC of step-shape casting for

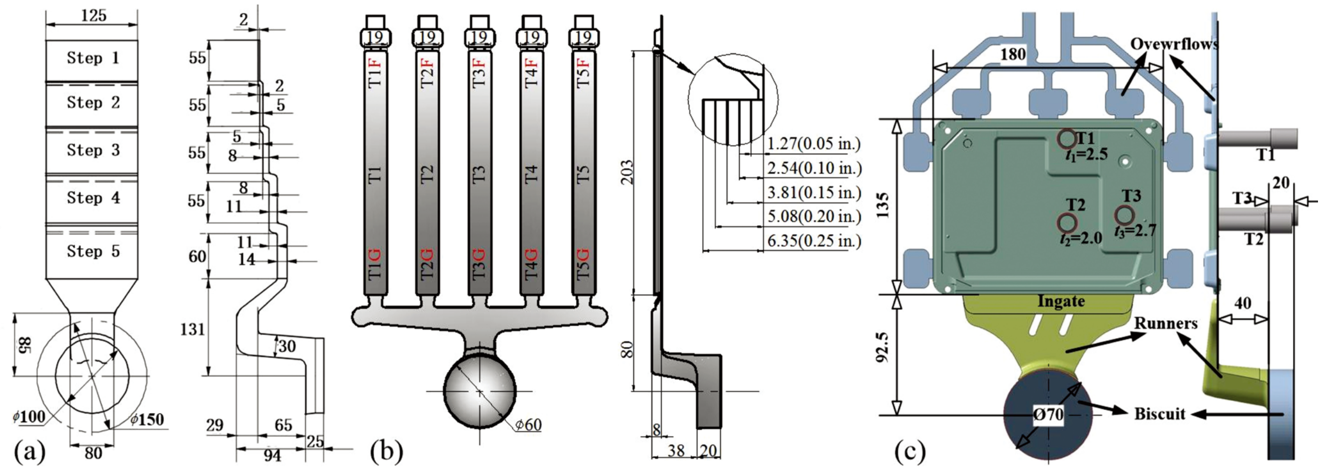

Fig. 1: Configuration of (a) step-shape casting, (b) finger-shape casting, and (c) cover-plate casting

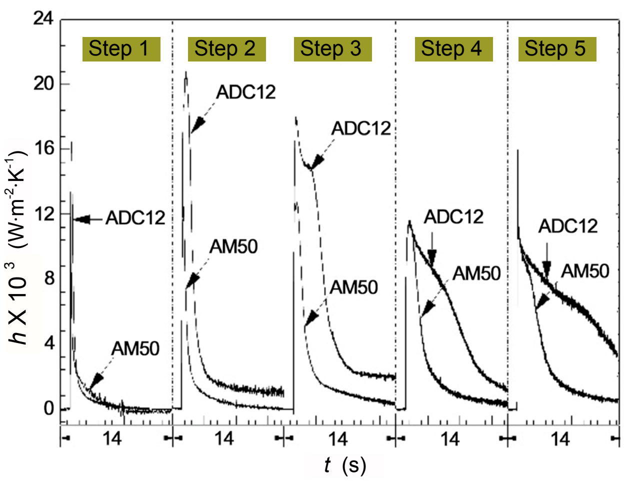

Fig. 2: Calculated heat transfer coefficient profiles at steps 1–5 for AM50 and ADC12 alloys

both AM50 and ADC12 alloys. After the shot was performed the IHTC increased rapidly until reaching its maximum value, after which the IHTC maintained its value at a high level followed by a sharp decrease. It was also observed that the IHTC of the ADC12 alloy is higher than that of the AM50 alloy. Additionally, the duration for the IHTC to maintain the high value was longer for alloy ADC12 rather than AM50. IHTC profiles at the different steps exhibit different characteristics. The thinner the step, the slimmer the IHTC profile. The duration for the IHTC to maintain the high value was longer as the thickness of the step was increased. A greater difference in the IHTC peak values for the two alloys appeared at steps 1 to 3 than at steps 4 to 5, indicating that a closer contact between the metal and mold tends to be achieved at thinner steps for the alloy ADC12. The difference in the wetting mechanism during the initial contact and the difference in the magnitude of the latent heat for the two alloys were responsible for this.

The IHTC profiles of both alloys exhibited an explicit characteristic corresponding to the die casting stages. It was found that the evolution of IHTC can be divided into four stages: namely the initial increasing stage, the high value maintained stage, the fast decreasing stage and the low value maintained stage. For convenience, the Roman numerals I, II, III and IV are used to represent the four different stages for the IHTC in the remaining text.

3.3 Influence of processing parameters on IHTC

Considering the previous research of the current authors [8-11], in addition to the influence of the alloy composition and step thickness, the maximum heat transfer coefficient was mainly affected by the processing parameters. Moreover, it was found that an increase in the fast shot velocity could greatly enhance the maximum heat transfer coefficient at steps 1 and 2. As the step thickness is increased, the influence of the initial die surface temperature θ_{DI} became more prominent, particularly at steps 3 to 5. Figure 3 shows the change of IHTC peak value h_{max} versus θ_{DI} at steps 1 to 5 under all the operation conditions. By applying the correlation analysis, it was found that h_{max} changes as a function of θ_{DI} in the manner of:

$$\ln\frac{h_{\max}}{\theta_{DI}^{2}} = \ln\eta = \beta\ln\theta_{DI} + \alpha \tag{4}$$

where α and β are fitted parameters. For convenience, η is used to represent the expression $h_{\max}/\theta^2_{DI}$. Equation 4 can be written in another way as:

$$h_{\max} = e^{\alpha}\times\theta_{DI}^{2+\beta} \tag{5}$$

For the ADC12 alloy, an increase in the curve slope β occurred when θ_{DI} exceeded about 260 °C. After the transition, η dropped at a much faster rate. From Equation 5, the same positive value of $2+\beta = 0.18$ before the transition for the two alloys illustrated that the fitted lines were parallel. Moreover, during this period, h_{max} increased as θ_{DI} increased, which agreed with the findings of other researchers [13, 14]. After the transition, the variable $2+\beta$ changed to a negative value of -3.32, suggesting that h_{max} dropped if θ_{DI} further increased.

Figures 4 and 5 illustrate the calculated IHTC peaks as a set of functions of the initial die surface temperature of both the finger-shape casting of B390 alloy and the cover-plate casting of AM60B alloy. All data followed a negative slope versus the initial die surface temperature. The other parameters, including the casing pressure, the slow and fast shot speeds, as well as the pouring temperature, did not show such a large influence. The initial die surface temperature had the most dominant influence on the IHTC peak value compared with all the other processing parameters. With increased initial die surface temperature, the IHTC peak decreased. The coefficients of fitting the IHTC peaks varied with the sensor location. By comparing the profiles for the B390 alloy in Fig. 4, the variable (2+β) stayed in a negative range from -0.12 to -0.46 except for the position T1F near the overflow of the thinnest plate (only 1.27 mm), suggesting that h_{max} drops if θ_{DI} further increases except for the position T1F. However, the transition mentioned above could not be clearly observed in the results for the AM50 alloy in Fig. 3 or for the AM60B alloy in Fig. 5. One of the possible reasons is that the initial die temperature was not high enough to cause the transition. It is believed that if the initial die temperature keeps increasing further, the transition should appear. It is also worth mentioning that process parameters such as casting pressure and fast shot velocity only have secondary influence on the IHTC peak values in comparison to that of the initial die temperature.

3.4 Development of thermal boundary condition based on IHTC

A thermal boundary condition model at the metal-mold interface of a HPDC process was developed based on two important correlations. The first is the relationship between the IHTC peak and the initial die surface temperature, as discussed above. The other is between the IHTC and the casting solid fraction.

By applying the regression method, it was found that the maximum heat transfer coefficient during the initial increasing stage changes as a function of the initial die surface temperature; and, during the fast decreasing stage, the heat transfer coefficient changes as a function of the casting solid fraction. Details about the relationship between the IHTC and casting solid fraction can be found in our previous work [24]. As shown in Fig. 6, the four stages of the heat transfer coefficient can be characterized by the following equations:

(i) $h = h_{max}$, before and during the initial increasing stage;

(ii) $h = h_{max} - f_s / f_{sF} \times (1 - f_s)^{\varepsilon}$, high value maintaining stage;

(iii) $h = h_0 + k_{h-f} \times (1 - f_s)^{\varepsilon}$, fast decreasing stage;

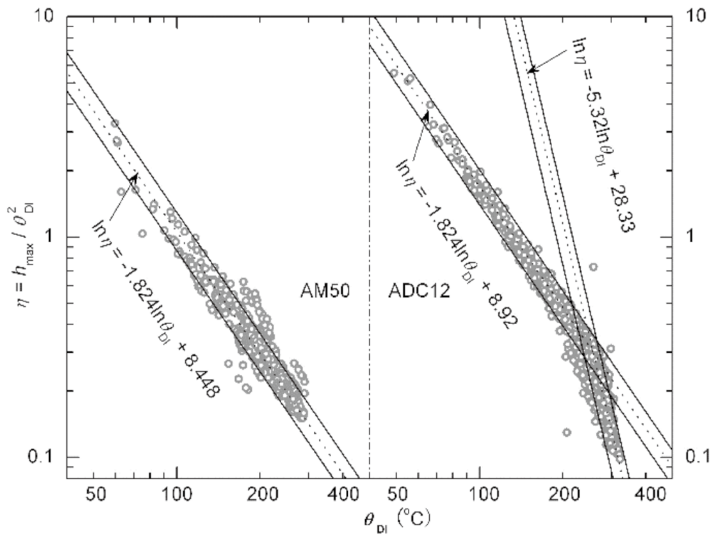

Fig. 3: Calculated IHTC peaks as a function of initial die temperature of steps 1 to 5 for AM50 and ADC12 alloys [24]

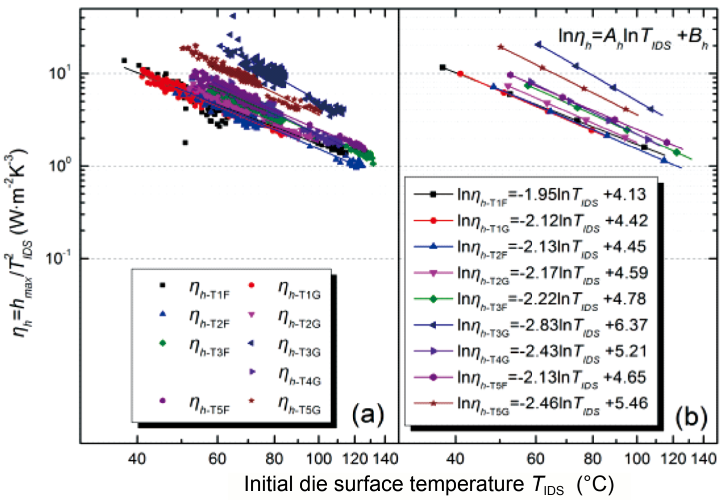

Fig. 4: Calculated IHTC peaks as a function of initial die temperature of finger-shape casting for B390 alloy [8]

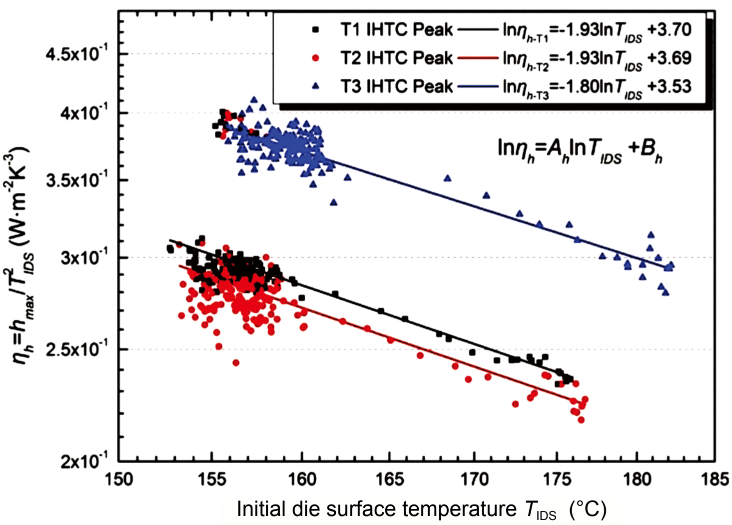

Fig. 5: Calculated IHTC peaks as a function of initial die temperature of cover-plate casting for AM60B alloy [7]

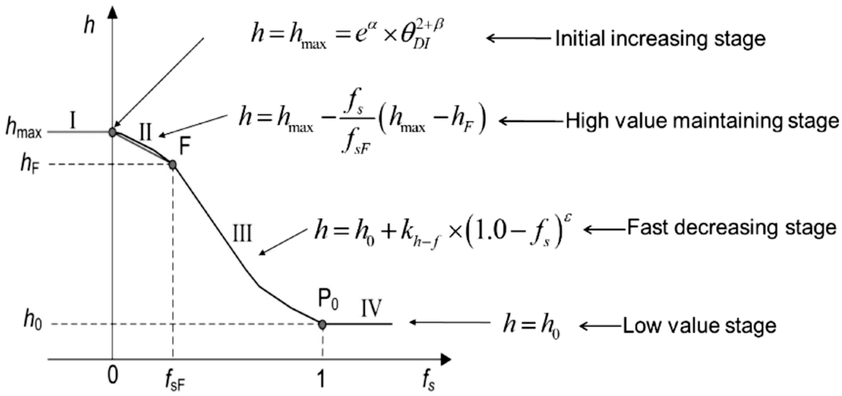

Fig. 6: Four stages of heat transfer coefficient for thermal boundary condition model

(iv) $h = h_0$, low value stage.

where f_s is casting solid fraction, $k_{h\text{-}f}$ and ε are the parameters relating to casting thickness, and h_0 indicates the magnitude of the heat transfer coefficient after the casting is totally solidified.

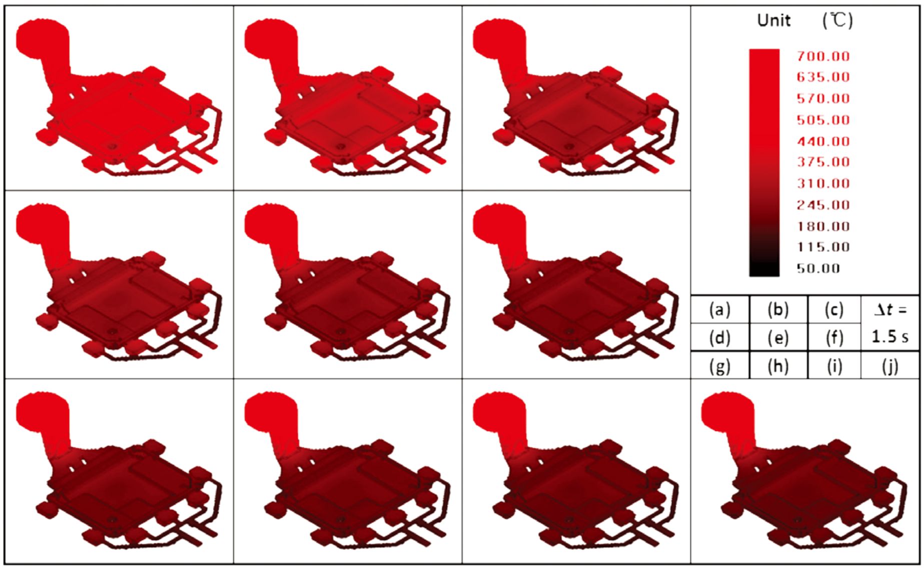

Fig. 7: Casting surface temperature changes during one cycle of cover-plate casting

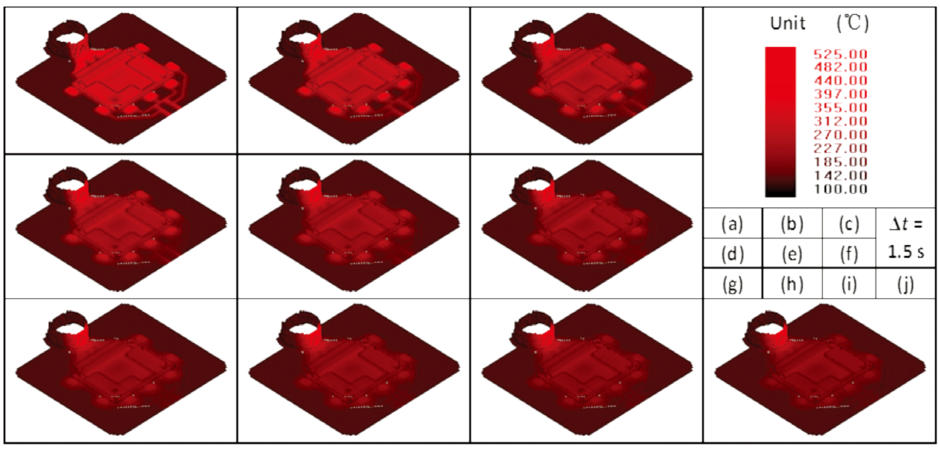

Fig. 8: Die surface temperature changes during one cycle of cover-plate casting

4 Application of IHTC

Based on the relationship between the IHTC and the casting solid fraction, the boundary condition model described above was applied to calculate the thermal field and thermal equilibrium of the cover-plate casting. Figures 7 and 8 show the determined temperatures for both the casting and the mold during one cycle. Results showed that the proposed model could precisely simulate the boundary condition at the metal-mold interface during the solidification process. Particularly, the proposed model could accurately demonstrate the fast change in the temperature of both the casting and the die at the initial stage of the solidification process and therefore could be used practically to predict the actual solidification status of the casting in a HPDC process.

5 Summary

Research progress relating to the interfacial heat transfer in HPDC was reviewed, and the following conclusions can be drawn:

(1) Three main approaches were normally employed to determine IHTC at the metal-mold interface, including the purely analytical method, semi-analytical method based on empirical correlations and numerical methods.

(2) Two main problems in HPDC can be identified when using thermocouples to

measure the casting and the die temperatures: (I) accurate and reproducible measurements are not possible on the casting side due to the severe filling conditions, (II) The fast solidification rate in HPDC means that the thermocouple response times and their installation in the die, including their distances from the casting-mold interface, introduce significant uncertainties in the IHTC estimation.

(3) By summarizing and discussing the research progress of the Tsinghua Group, a thermal boundary condition model was then developed based on the two correlations: (a) IHTC and casting solid fraction, and (b) IHTC peak value and initial die surface temperature. The boundary model was then applied during the determination of the temperature field in HPDC and excellent agreement was found.

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