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Equivalent heat transfer coefficient at casting/Cu mould interface and temperature field simulation①

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Abstract: Using the inverse algorithm of heat transfer and the nonlinear estimation method, matching calculated values with measured ones, the interfacial heat transfer coefficient at casting/Cu mould interface was determined. The results show that the interfacial heat transfer coefficient at Al/Cu interface changes in a range of $4.0\times10^3-1.0\times10^5$ W·m^{-2}·K^{-1} and its average value is in a range of $5.0\times10^3-7.0\times10^3$ W·m^{-2}·K^{-1}.

Key words: interfacial heat transfer coefficient; inverse problem; nonlinear estimation method

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1 INTRODUCTION

The solidified microstructures of alloys depend on their solidifying process whose primary characteristics are the temperature drop of the superheated melt and the release of the latent heat. So the study on the heat transfer during the solidification process is the essential problem in the solidification theory study. The researchers working on the numerical simulation of the solidification process all know that the interfacial heat transfer coefficient at the casting/mould is a variable changing with time. Thus the determination of the interfacial heat transfer coefficient is the key factor of influencing the calculation accuracy of the temperature field.

Although there were some studies[1-7] on the interfacial heat transfer coefficient at casting/mould interface, there are a few of literatures about their interfacial heat transfer coefficients for aluminum alloys castings/copper mould interfaces. Using inverse algorithm of heat transfer and nonlinear estimation method, matching calculated values with measured ones, the determination of the interfacial heat transfer coefficient during the solidification process of Al castings in copper mould was investigated. This work is an important basis for studying the copper mould rapid preparation of Al-In immiscible alloys and simulating the microstructural evolution during their rapid cooling process[8-10].

2 ESTABLISHMENT OF HEAT TRANSFER MODEL

Considering the release of the latent heat, the 3-D heat transfer formula is as follows:

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+Q \quad (1)$$

where ρ is the density of the alloy (kg·m^{-3}), c is the specific heat capacity (J·kg^{-1}·K^{-1}); λ is the thermal conductivity (W·m^{-1}·K^{-1}), Q is the internal energy generation per unit volume (J·m^{-3}).

The finite differential expression of the heat transfer formula is

$$(\rho c V)_i\frac{T_i^{t+\Delta t}-T_i^t}{\Delta t}=\sum_{j=1}^{n}\omega(i,j)(T_j^t-T_i^t)+\frac{Q}{\Delta t} \quad (2)$$

$$\omega(i,j)=\frac{S(i,j)}{1/h(i,j)+L(i,j)/\lambda} \quad (3)$$

where Δt is the time step(s), V is the volume of unit (m^3), $h(i,j)$ is the interfacial heat transfer coefficient between unit i and unit j (W·m^{-2}·K^{-1}), $L(i,j)$, $\omega(i,j)$ and $S(i,j)$ are the distance(m), thermal resistance (W·K^{-1}) and the heat transfer area (m^2) between unit i and unit j, respectively.

After arranging the above formula, the following equation can be obtained:

$$T_i^{t+\Delta t}=T_i^t+\frac{\Delta t}{(\rho c V)_i}=\sum_{j=1}^{n}\omega(i,j)(T_j^t-T_i^t)+\frac{Q}{(\rho t V)_i} \quad (4)$$

Taking an iterative operation to equation 4, going with the corresponding initial conditions and boundary conditions, the temperature of unit i at $t+n\Delta t$ (n is the positive integer) moment can be obtained.

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3 INVERSE ALGORITHM AND NONLINEAR ESTIMATION METHOD OF INTERFACIAL EQUIVALENT HEAT TRANSFER COEFFICIENT

The inverse algorithm is used to find the "lost information" which may be the thermophysical properties or the interfacial heat transfer coefficient. In order to find the lost information, some supplementary information is necessary. In general, the supplementary information is the temperature record of one or several points in castings, in other words, the recorded temperature curve by experiment. The aim of the paper is to find the interfacial heat transfer coefficient at casting/copper mould by means of inverse algorithm. The actual procedure is as follows: firstly measure the temperature evolution curves of some points in the casting or the mould, then compare the calculated values from theoretical model with the experimental values. Through continually changing the magnitude of the unknown variable (the interfacial heat transfer coefficient) during the calculation process, the error between the calculated values and the experimental values can be reduced. When the discrepancy is in the pre-set error range, the value of the variable at this time is thought of as its true value. Actually, the above problem is a kind of reciprocal problem.

The problem discussed in this paper belongs to the function estimation problem because the interfacial heat transfer coefficient is a variable changing with time. Essentially, the function estimation has a certain shortage[11] because even a very slight fluctuation of the input can bring about a large vibration of the output (the estimated interfacial heat transfer coefficient), so the estimation method needs a stabilization or regularity to ensure a useful result.

The interfacial heat transfer coefficient is a parameter influenced by many factors including interfacial contact status, interfacial physical condition, interfacial chemical condition and interfacial temperature etc in which the interfacial contact status plays the major role. In other words, the interfacial heat transfer coefficient is an integrated result. In this paper it is defined as equivalent interfacial heat transfer coefficient h_E.

h_E is a function changing with time and can be solved by the nonlinear estimation method and numerical method. The key of the nonlinear estimation method is to make the following function get its minimum.

$$f(h_E) = \sum_{i=1}^{n}\sum_{j=1}^{m}[T_{i,j}(h_E)(-T_{i,j}(m)]^2 \quad (5)$$

where $T_{i,j}(m)$ and $T_{i,j}(h_E)$ are the experimentally measured temperature and the calculated temperature of point i at moment j, respectively.

$$T_{i,j}(h_E) \approx T_{i,j}(h_{E(l)}) + T'_{i,j}\Delta h_{E(l+1)} \quad (6)$$

$$T'_{i,j} = \frac{\partial T_{i,j}(h_E)}{\partial h_{E(l)}} \quad (7)$$

where l is the iterative times. By the nonlinear estimation method, the change of the equivalent interfacial heat transfer coefficient h_E with time can be calculated. When the ratio of the variation of the equivalent interfacial heat transfer coefficient in one time slice to the equivalent interfacial heat transfer coefficient in the previous time slice is less than a given value, the equivalent interfacial heat transfer coefficient at this time is the needed result.

$$\Delta h_{E(l)} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}[T_{i,j}(m) - T_{i,j}(h_E)]\cdot T'_{i,j}}{\sum_{i=1}^{n}\sum_{j=1}^{m}(T'_{i,j})^2} \quad (8)$$

Make Taylor expansion to Eqn. (8) and search for its minimum by iterative method. The iterative process starts with an estimated $h_{E(l)}$. For $l=0$, increasing the iteration times until $\Delta h_{E(l)}/h_{E(l)} < \delta$ (δ is a finite small value), the equivalent interfacial heat transfer coefficient at this time is thought to satisfy the requirement and the calculation process can shift into the next time-interval. Finally h_E can be obtained at any time.

4 MEASUREMEMT OF TEMPERATURE EVOLUTION DURING SOLIDIFICATION PROCESS

4.1 Design of temperature measuring experiment

Fig. 1 shows the experimental scheme. The casting is a cylinder specimen whose radius is 25 mm and height is alterable. Thermocouple 1 is located in the axial line and its height is 15 mm. Thermocouple 2 is located in the side of copper at the copper/casting interface. Pure aluminum was selected to measure the interface heat transfer coefficient. The applied experimental parameters in the designed two experiments are listed in Table 1.

Fig. 2 shows a computer multi-channel data

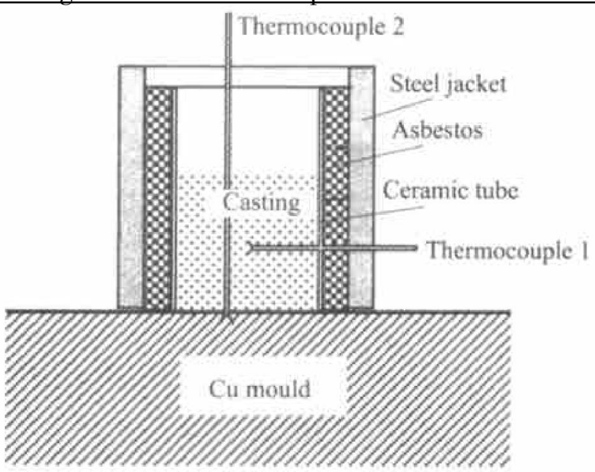

Fig. 1 Metal/mould interface heat transferring experimental set-up

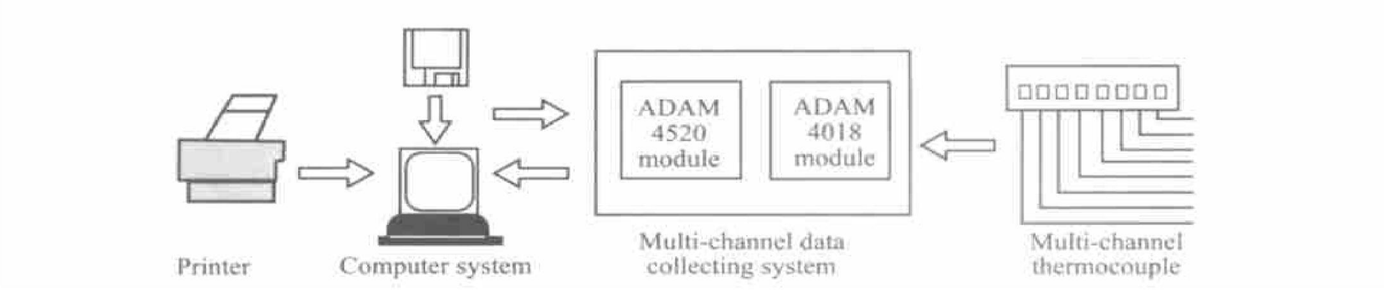

Fig. 2 Multi-channel data collecting system

Table 1 Applied experimental parameters

Specimen height/ mm	Specimen radius/ mm	Pouring temperature/ K	Height of thermocouple 1/ mm
25	25	1 100	15
32	25	1 220	15

collecting system for temperature collection. The measuring element is NiCr-NiSi thermocouple whose diameter is 0. 2 mm. Two channels are used to collect the temperature of thermocouple 1 and 2. The sampling period is 0. 2 s.

4. 2 Measured results

Fig. 3 shows the measured results in two experiments. It can be seen from Fig. 3 that the temperature has a fast falling speed in the liquid region, but a slow falling speed in the solid region. In addition, a platform occurs during the solidification. In the two experiments, the temperature of thermocouple 2 has a same changing tread, that is, it first rises rapidly up to its maximum, then fleetly drops down to its minimum. After that it has a weak recovery followed a platform during a period of time. In the final stage, it drops gently further until the end of solidification.

5 CALCULATION OF INTERFACIAL EQUIVALENT HEAT TRANSFER COEFFICIENT

5. 1 Treatment of latent heat

During the theoretical calculation process, the treatment of latent heat is necessary. In general, temperature compensation method or temperature recovery method is used to treat the term in Eqn. (1) related to the latent heat for pure metal. In this paper, the temperature compensation method is adopted to deal with the latent heat.

5. 2 Boundary conditions

Before the calculation, the boundary conditions and the initial conditions must be defined. Fig. 4 is a sketch of the meshes in the casting for the temperature calculation and the corresponding boundary conditions.

The initial conditions are as follows:

$T_i(t=0) = T_p$ (T_p is the pouring temperature which is the initially measured value of thermocouple 1).

Boundary 1 is a combined heat transferring boundary:

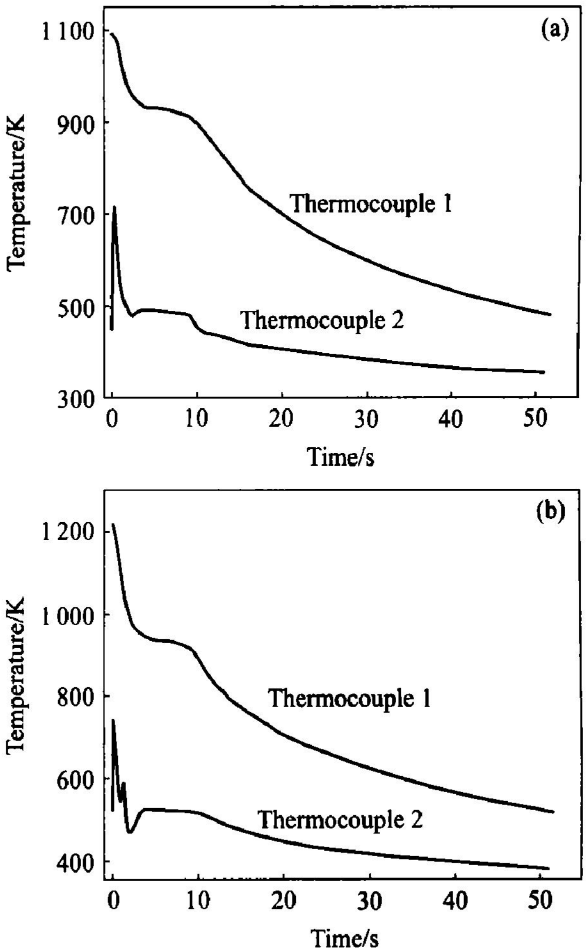

Fig. 3 Measured temperature evolutions in two experiments
(a) —Specimen height is 25 mm, T_p= 1 100 K;
(b) —Specimen height is 32 mm, T_p= 1 220 K

$$q_1 = h_E(T_1 - T_{Cu(i)}) \quad (9)$$

Boundary 2 is a radiation boundary:

$$q_2 = \varepsilon\Gamma(T_n^4 - T_a^4) \quad (10)$$

Boundary 3 and 4 are heat-insulated boundaries:

$q_3 = q_4 = 0$.

In these equations, h_E is the equivalent interfacial heat transfer coefficient, $T_{Cu(i)}$ is the temperature of copper at the mould/ casting interface which is the measured value of thermocouple 2 in the previous temperature measuring experiments, T_a is the air temperature near the top of the casting, T_1 and T_n are the temperature of unit 1

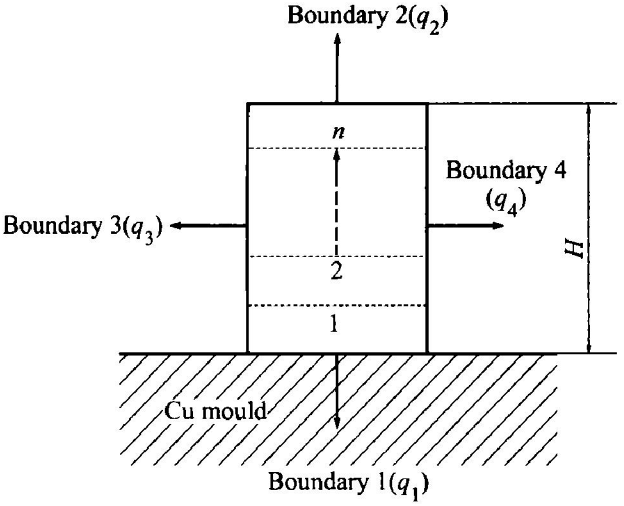

Fig. 4 Sketch of meshes in casting and boundary conditions

and n, ε is the blackness of the casting, Γ is Steffen-Boltzmann constant (5.67×10^{-8} W·m^{-2}·K^{-4}). It is obvious that the heat transfer is an one-dimensional problem.

5.3 Calculated results and discussion

The program primarily includes two modules. One is for the temperature field calculation and the other is for the calculation of the equivalent interfacial heat transfer coefficient. The computation is a repeatedly adjustable process. The solid ratio f_s ($f_s = l'(t)/H$, where l' is the height of solidified part. H is the total height of the specimen) is used to describe the solidification process. $f_s = 1$ expresses the end of total solidification process.

Fig. 5(a) shows the calculated equivalent interfacial heat transfer coefficient according to the measured temperature in Fig. 3(a). Fig. 5(b) shows the comparison between the calculated temperature and the measured one in the relative position. The used thermodynamic parameters are listed in Table 2, where T_m is the melting point of the metal; L is the latent heat of the metal; C_{pl} and C_{ps} are the specific heat capacity of liquid metal and solid metal, respectively; k_{pl} and k_{ps} are the heat conductivity of liquid metal and solid metal, respectively. The equivalent interfacial heat transfer coefficient has two distinct changing trends during the solidification in which it first falls steeply then keeps a constant on the whole. When the liquid metal is poured onto the surface of the copper mould, the interfacial heat transfer coefficient attains its maximum about 10^5 W·m^{-2}·K^{-1} because the contact is liquid/solid contact. With the interface changing from the liquid/solid contact to the solid/solid one, the interfacial heat transfer coefficient drops sharply down to its minimum about 6.0×10^3 W·m^{-2}·K^{-1} when f_s is about 0.35. Another reason for the drop of the interfacial heat transfer coefficient may be the existence of a layer of gas film.

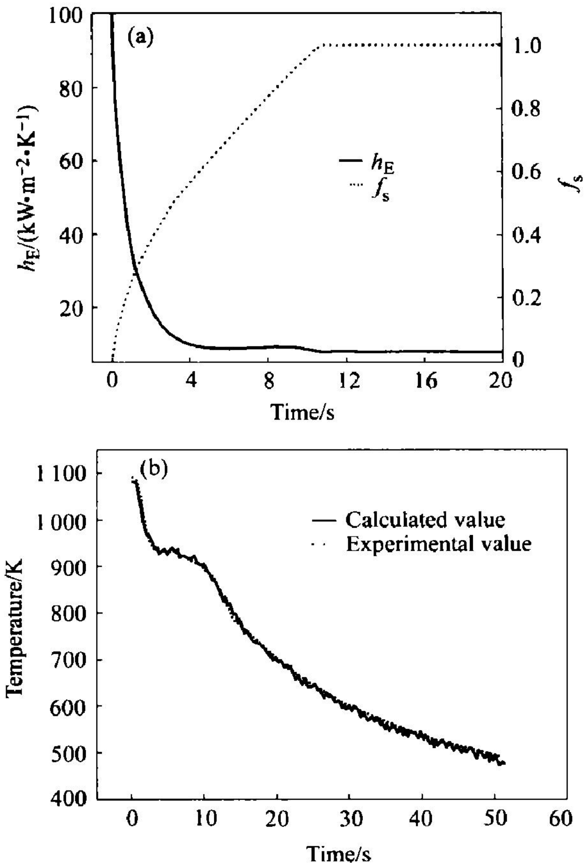

Fig. 5 Calculated heat transfer coefficient(a) according to measured temperature in Fig. 3(a) and comparison(b) between calculated and measured temperature in relative position

Table 2 Properties of Al used in computation

T_M/K	L/(kJ·kg^{-1})	C_{pl}/(J·kg^{-1}·K^{-1})	C_{ps}/(J·kg^{-1}·K^{-1})
933	395	1 200	1 060
k_l/(W·m^{-1}·K^{-1})	k_s/(W·m^{-1}·K^{-1})	ρ_l/(kg·m^{-3})	ρ_s/(kg·m^{-3})
100	200	2 340	2 700

Fig. 6 shows the calculated equivalent interfacial heat transfer coefficient according to the measured temperature in Fig. 3(b) and the corresponding comparison between the calculated temperature and the measured one in the relative position. In this case, the changing trend of the interfacial heat transfer coefficient is the same as that shown in Fig. 5(a). The only difference between them lies in their minimums. In this case, its minimum is about 4.0×10^3 W·m^{-2}·K^{-1} lower than that shown in Fig. 5(a).

It can be seen from the calculated results in the two cases above that, on the whole, the interfacial heat transfer coefficient at Al/Cu interface is in a range of $4.0 \times 10^3 - 1.0 \times 10^5$ W·m^{-2}·K^{-1} and its average value is in a range of $5.0 \times 10^3 - 7.0 \times 10^3$ W·m^{-2}·K^{-1}. In addition, it has a

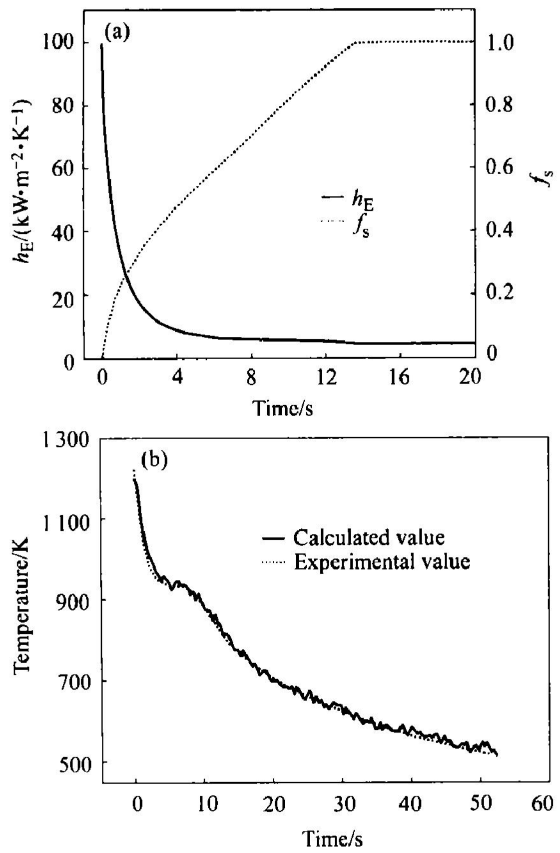

Fig. 6 Calculated heat transfer coefficient(a) according to measured temperature in Fig. 3(b) and comparison(b) between calculated and measured temperature in relative position

slight drop with increasing size or thickness of the casting.

Compared with the empirical value of 1 700 − 2 600 $W\cdot m^{-2}\cdot K^{-1}$ for the case in which aluminum alloys are solidified in a miniative copper mould[12], the interfacial heat transfer coefficient presented in this paper is as high as double of the supported empirical value. There are two factors leading to the difference. One is the interfacial physical condition and the other is the relative size of the casting and the copper mould. In our experiments, the surface of the copper mould has been finishing-machined and its surface finish is as high as Ra6.4, which undoubtedly enhances the contact area between the casting and the copper mould, then enhances the interfacial heat transfer coefficient. In addition, in our experiments, compared with the size of the copper mould, the size of casting is smaller, which can also enhance the interfacial heat transfer coefficient. But the situation in Ref.[8] is just inverse. In other words, the interfacial heat transfer coefficient is related to the size of casting. The obtained values above are effective only for the situation in which a smaller casting not thicker than 40 mm is solidified rapidly in a copper mould.

6 CONCLUSIONS

1) Using the inverse algorithm of heat transfer and the nonlinear estimation method, matching calculated values with measured ones, the determination of the interfacial heat transfer coefficient at casting/Cu mould interface is solved. This method is also effective to other alloy systems and other mould materials.

2) On the whole, the interfacial heat transfer coefficient at Al/Cu interface changes in a range of $4.0\times10^3 - 1.0\times10^5$ $W\cdot m^{-2}\cdot K^{-1}$ and its average value is in a range of $5.0\times10^3 - 7.0\times10^3$ $m^{-2}\cdot K^{-1}$. The interfacial heat transfer coefficient is a parameter influenced by many factors including interfacial contact status, interfacial physical condition, interfacial chemical condition and interfacial temperature (the relative size of the casting and the mould) etc. in which the interfacial contact status and the relative size of the casting and the mould play the major roles.

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