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A study of the interfacial heat transfer between an iron casting and a metallic mould

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Abstract

Computer simulation of the solidification process is used widely in industry in the design of the mould and the die configuration. The heat-transfer coefficient between the mould and the cast metal is one of the important variables. In this work, the heat-transfer behavior and the time-dependent heat-transfer coefficient between an iron casting and a metallic mould were investigated by inverse heat-conduction analysis. A one-dimensional inverse heat calculation program, which can be used in both rectangular and cylindrical coordinate systems, was developed based on a non-linear estimation method. Temperature distributions along the direction of heat flux from the casting to the mould were measured, the predicted temperature profile being found to compare well with the experimental results. The heat-transfer coefficient was found to drop rapidly during the initial stage of solidification and then increase with the solidification process after a short time period of steady stage. It is concluded that a three stage segmented linear equation of the coefficient can be used to represent the heat-transfer behavior and be implemented in numerical analysis of the casting process.

Keywords: Inverse heat calculation; Heat-transfer coefficient; Casting; Metallic mould

1. Introduction

During the solidification of a casting in a metallic mould or against a chill, the heat-transfer between the casting and the mould is one of the most important factors that influence the solidification process, the resulting mechanical properties and the soundness of the cast product. Early investigations were undertaken to study the thermal aspects between the cast metal and the metallic mould interface [1–4] to improve the casting quality through better control of the heat-transfer across the metal–mould interface.

With the growing use of computer simulation of the casting process, more accurate data on the thermal properties and boundary conditions are needed to obtain better simulation results. The determination of the transient metal–mould interfacial heat-transfer coefficient is of great interest to many investigators [5–12], generally two kinds of methods being used in the investigations: (i) the first method is to measure the variation of the interfacial gap size since an air gap usually develops at the metal–mould interface during the solidification process, and then to derive the interfacial heat-transfer coefficient from the heat-transfer data across the gap; whilst (ii) the second method is to conduct inverse heat-transfer calculations based on the temperature measurements at selected locations in the casting and the mould or chill.

Through these investigations, significant achievements have been made for non-ferrous alloys under specific conditions and applications. Nevertheless, the determination of the metal–mould interfacial heat-transfer coefficient for use in mathematical modeling of the casting process remains unresolved.

The present work is dedicated to implement the second approach, namely the inverse heat conduction method, to study the heat-transfer behavior between an iron casting and a metallic mould, and to determine the time-dependent metal–mould interfacial heat-transfer coefficient, which will be valuable for computer simula-

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tion purposes. Discussion on mathematical implementation of the heat-transfer coefficient is also presented.

2. Inverse heat calculation method

In ordinary direct heat conduction problems, the interior temperature distribution of a body is solved by the boundary heat-transfer conditions, such as the surface temperature or heat flux. Contrarily, the purpose of the inverse heat conduction problem is to determine the surface temperature or heat flux by a given temperature distribution at internal points near to the surface.

To solve the inverse heat conduction problem, Beck [13–15] put forward a non-linear estimation method, which can be used to deal with the phase change and temperature-dependent thermal properties of a solidification process. From the standpoint of the effective treatment of experimental data, statistical principles and the concept of 'future temperatures' were implemented successfully in the non-linear estimation method to solve the delayed and diminished thermal response problems due to the thermal capacity and heat conduction, and the thermal inertia effect of the thermal transducer itself during the temperature measurement. The future temperatures are the measured temperatures at internal points ahead of each time interval, which are used for solving the heat flux or the temperature at the current time interval in a numerical method.

The basic principle of the non-linear estimation technique of Beck is to assume that the heat flux is a constant or a linear function of time within a given time interval (usually, a constant heat flux is assumed), and then to determine the heat flux in that period of time by solving the least-squares problem of the following function:

$$F(q) = \sum_{i}^{N_1} \sum_{j}^{N_2(N_3+1)} (T_{ij} - Y_{ij})^2 \tag{1}$$

where N_1 is the number of internal points in temperature measurement (excluding those used for boundary conditions), N_2 is the number of temperature measurements per time interval, N_3 is the future time intervals considered for heat flux calculation in each time interval, and T_{ij}, Y_{ij} are the calculated and measured temperatures of location i and time instant j respectively.

Applying the condition $\partial F/\partial q = 0$ to Eq. (1) for minimization, we have (the accumulation variables are omitted for the sake of clarity and simplification):

$$\sum\sum(Y_{ij} - T_{ij})\frac{\partial T_{ij}}{\partial q} = 0 \tag{2}$$

and then using the Taylor series expression of $T_{ij}(q)$:

$$T_{ij}(q_{l+1}) \approx T_{ij}(q_l) + \Phi_{ij}\delta q_{l+1} \tag{3}$$

where $\Phi_{ij} = \partial T_{ij}/\partial q$, which can be solved by a numerical method, the following iterative expression for solving the heat flux at each time interval is obtained:

$$\delta q_{l+1} = \frac{\sum\sum(Y_{ij} - T_{ij}(q_l))\Phi_{ij}}{\sum\sum\Phi_{ij}^2} \tag{4}$$

By repeatedly applying the expression $q_{l+1} = q_l + \delta q_{l+1}$ to correct the heat flux at location $q = q_0(l=0)$, the heat flux q at the time interval can be found when $\delta q_{l+1}/q_l$ is small enough.

According to the prescribed mathematical technique, a one-dimensional inverse heat calculation program, which can be used in either a cylindrical or a rectangular coordinate system, was developed to determine the interfacial heat-transfer coefficient of metal–mould interface during the casting process. Phase changes of different type of alloys and temperature-dependent thermal properties were considered in the program. The flow chart of the program is shown in Fig. 1.

3. Experimental set-up

The experimental set-up consists of a cylindrical cast iron mould with heat insulating materials on the top and bottom to ensure that a one-dimensional heat flux from the casting to the mould can be created along the radial direction. The mould is of 32 mm thickness with an inner dimension of 150 mm diameter and a height of 250 mm. The inner surface of the mould is machine finished and no coatings had been applied. Cast irons including gray cast iron and spheroidal graphite (S.G.) iron, were used as the cast metals. In addition, pure aluminum was used also for comparison.

In order to obtain the temperature measurements for inverse calculation and to investigate the insulation conditions in the axial direction, chromel–alumel thermocouples were located in three sections, namely, at the top, the middle and the bottom of the mould. Fig. 2 presents a schematic diagram of the experimental set-up and the layout of thermocouples in the middle section, where thermocouple No. 6 in the mould and No. 7 in the casting are both 5 mm from the interface, No. 5 in the mould is 5 mm from the outer surface and No. 8 is at the centre of the casting.

Temperature measurements were conducted by a computer-aided data logging system with a capability of 16 channels. The sampling rate used in the testing process was one reading per second per channel for the first two min and one reading every 2.5 s for each channel thereafter.

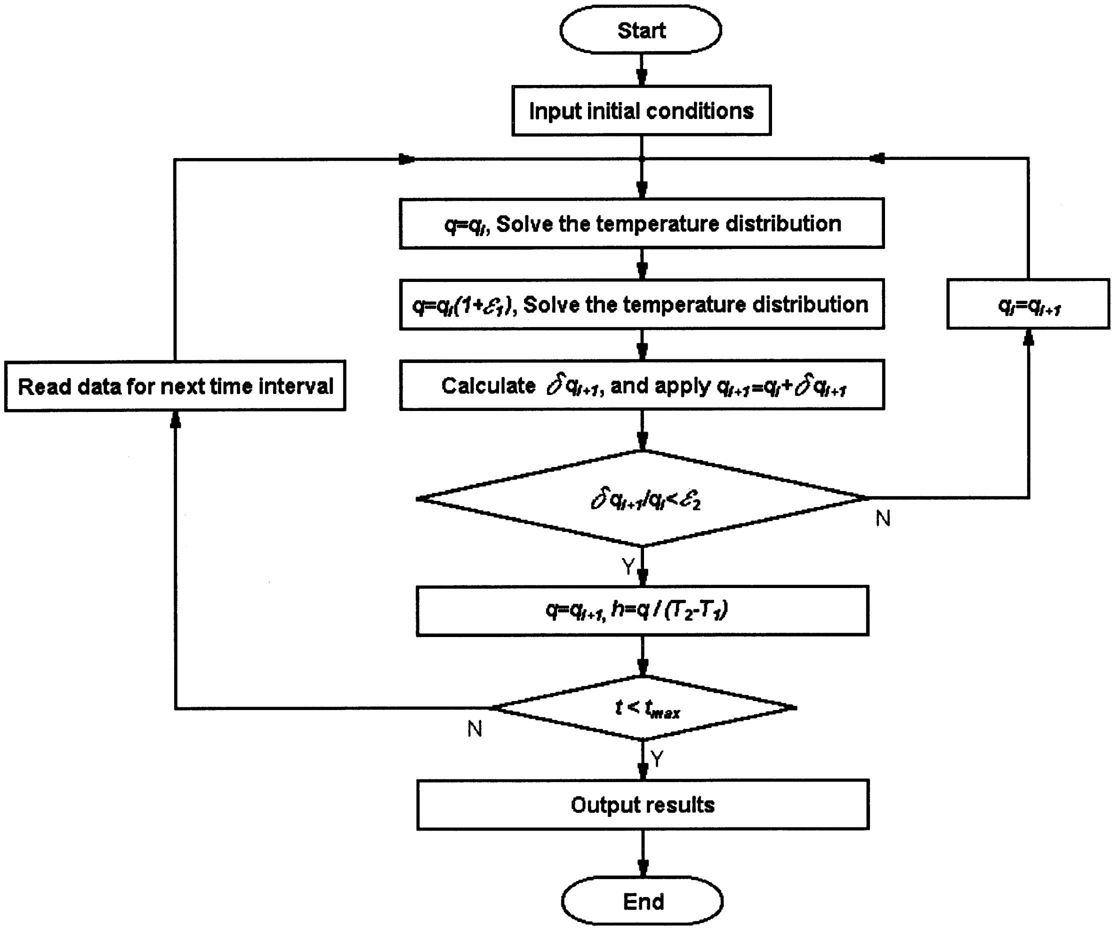

Fig. 1. Flow chart of the inverse heat calculation program.

4. Experimental and inverse calculation results

Experiments were conducted under the afore-mentioned conditions for pure aluminium, gray cast iron and S.G. iron. The results of temperature measurements show that temperatures at the same location in different sections are almost the same, which confirms the experimental requirement for one-dimensional heat conduction along the radial direction. Therefore, only the results of the middle section are considered in the inverse calculation analysis. In addition, the results for pure aluminium are similar to those of other investigators [5] and will not therefore be discussed in detail. Only the inverse calculation result will be implemented for comparison and discussion.

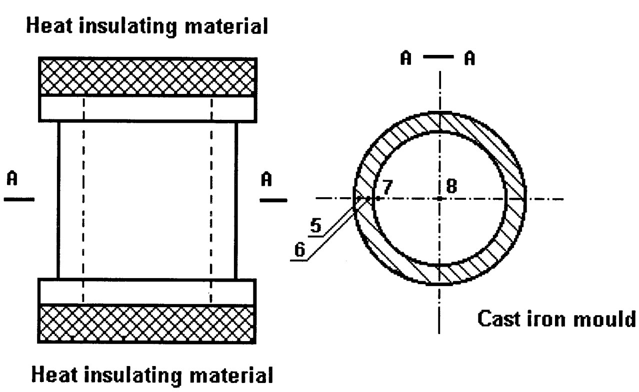

Fig. 2. Schematic diagram of the experimental set-up and the layout of the thermocouples in the middle section.

In the inverse heat conduction analysis, temperatures taken from thermocouples No. 6 and 7 were used as the internal temperature measurements in the mould and the casting, and those of No. 5 and 8 were used as given temperature boundary conditions. The results of the measured temperature and the calculated temperature profile compared with the internal temperature measurements during inverse calculation for gray cast iron and S.G. iron are shown in Figs. 3 and 4 respectively.

Fig. 5 shows the interfacial heat-transfer coefficients between the metallic mould and the cast metals of gray cast iron, S.G. iron, and pure aluminium. It can be seen that for all of the cast metals the heat-transfer coefficient h drops rapidly as a result of gap formation at the initial stage of solidification, but then the h value reaches a steady value for a short time period. With the progress of the solidification process, differences in h

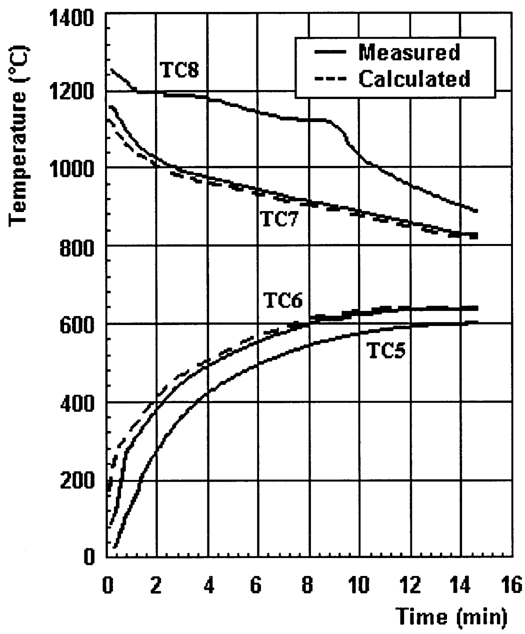

Fig. 3. Temperature profile of the casting and mould in the middle section for grey cast iron.

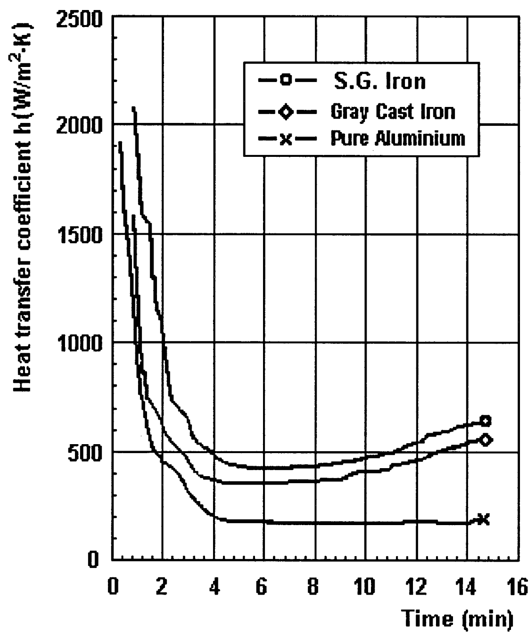

Fig. 5. Time-dependent heat-transfer coefficients for different types of alloys by inverse calculation.

values are generated by the different solidification characteristics of the alloys. For gray cast iron and S.G. iron, the gap size at the metal–mould interface will decrease due to the thermal expansion of cast irons, resulting in an increase in the heat-transfer coefficient. Further, since the thermal expansion of S.G. iron is greater than that of gray cast iron, the gap size of S.G. iron is smaller than that of gray cast iron, resulting in a slightly higher h value for S.G. iron than that for gray cast iron. For pure aluminium, no thermal expansion

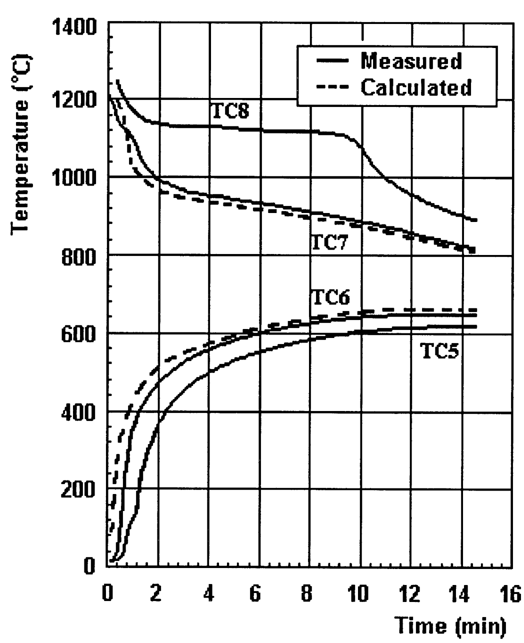

Fig. 4. As for Fig. 3 but for S.G. iron.

exists during the solidification process, so that the gap size should increase due to the thermal contraction. However, this effect is not obvious since no considerable reduction of h value was observed under both the current conditions and phase in other investigations [5]

5. Discussion

It is known that an air gap will develop between the cast metal and the metallic mould during the solidification process, the gap size and its variation with time depending on the characteristics of the cast alloys, the mould condition, the casting geometry, and other process parameters. In order to efficiently handle the heat-transfer coefficient at the metal–mould interface in numerical analysis, investigations [5,10] had been undertaken to study the relationship between the h value and interface temperature of the cast metal or the mould: however, no general formulations were found or implemented for the numerical simulation of the casting process. According to the air gap formation mechanism, a schematic variation of the heat-transfer coefficient with time, as shown in Fig. 6, was summarized by Sharma and Krishnan [9,11]. The h variation is divided into three stages: stage I with a high fluctuating value of h; stage II with a steady value; and stage III with either an increasing value of h, due to an increase in the contact pressure at the interface, or a decrease in h, due to the increase in the air gap between the casting and the mould. The current results of inverse calculation for S.G. iron and gray cast iron are in accordance with that of the increasing pressure condition and no step rise at the first stage was observed since the filling stage was not considered in the inverse analysis. For the pure aluminium, no significant changes in h value was found in stage II and stage III.Therefore, according to the results of the present analysis and for easy implementation, the linearized three stages of h variation in Fig. 6 can be assumed and the inverse calculation results of the h variation with time in the present study formulated easily based on the linear-segment assumption, in which the step rise period during the filling stage is not considered. Further investigations will be carried out on the application of this assumption in numerical simulation of the casting process.

6. Conclusions

Based on the non-linear estimation method, a one-dimensional inverse heat calculation program that can be used for both rectangular and cylindrical coordinate systems has been developed and used in the determination of the metal–mould interfacial heat-transfer coefficient in a casting process with different types of alloys and temperature-dependent thermal properties.

Experimentation has been designed and undertaken to create a one-dimensional heat flux and to measure the internal temperature profile between the cast metal and the metallic mould for gray cast iron, S.G. iron and pure aluminium.

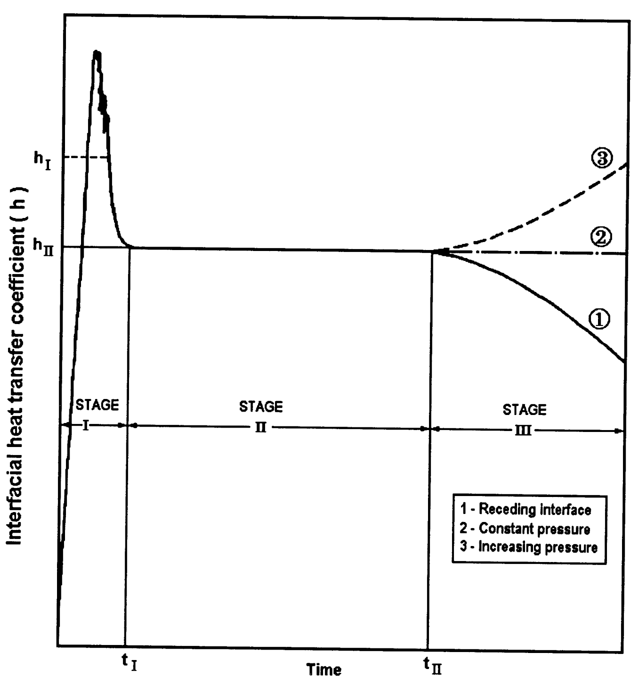

Fig. 6. Variation of h with time (schematic).

The inverse calculation results show that for all of the cast metals, the heat-transfer coefficient h drops rapidly during the initial stage of the solidification process, and then reaches a steady value for a short time period. With the progress of the solidification process, an increase in the heat-transfer coefficient was observed for gray cast iron and S.G. iron. In addition, the value of the heat-transfer coefficient of S.G. iron is slightly greater than that of gray cast iron. For pure aluminium, no significant change in h value was found after the steady stage.

A three stages of linear variation of the heat-transfer coefficient can be used in the computer simulation of the casting process.

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