Experimental Thermal and Fluid Science 34 (2010) 1068–1076

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Application of an optimization method and experiment in inverse determination of interfacial heat transfer coefficients in the blade casting process

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ARTICLE INFO

Article history:
Received 21 December 2009
Received in revised form 18 March 2010
Accepted 20 March 2010

Keywords:
Interfacial heat transfer coefficient
Numerical prediction
Experimental measurement
Optimization method

ABSTRACT

In order to effectively improve the numerical prediction accuracy in a blade investment casting process, a new method is proposed to determine the interfacial heat transfer coefficient (IHTC) in a complicated blade casting by combining the numerical prediction, optimization and limited experimental data. An investment experiment of the blade is conducted to acquire the surface temperature of the casting and the shell mould. Regarding the complicated mechanism of the interfacial heat transfer in the progressive solidification, a new continuous model with three-step evolution is established for the casting–mould IHTC, and a power function is proposed to correlate the mould–environment IHTC with solidification time as well. A globally convergent method is employed to search the optimal coefficients involved in the IHTCs correlations. Results show that the predicted temperature based on proposed models agrees well with the experimental data with the maximum deviation being less than 5.5%, and a significant variation of the casting–mould IHTC is observed. It is concluded that the prediction accuracy and efficiency associated with the optimization method can be greatly improved with the present IHTC models.

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1. Introduction

It is known that the shape of the casting depends on the cavity geometry of the metal die significantly in the investment casting process. An exact die profile, which generally takes into account the various shrinkages involved in the casting process, is therefore, important to improve the quality of net-shaped products. In this sense, an accurate numerical simulation of the entire casting process is very helpful to realize optimal designs of the die-cavity profile [1]. Many commercial solidification simulation softwares can be used to obtain reliable simulation results if the appropriate data of thermal properties and boundary conditions are provided [2]. For the heat transfer in solidification, how the heat transfers through the casting–mould interface is one of the most important boundary conditions to be characterized because this problem directly dominates the evolution of solidification and controls the freezing conditions within the casting. Therefore, the determination of interfacial heat transfer coefficient (IHTC) is vital ahead of the simulation of the solidification process. In fact, the IHTC depends upon multiple factors such as die coating thickness, insulating pads, chill and casting geometries, pouring temperature, surface roughness, alloy composition, metallostatic head, mould temperature and other mechanical boundary conditions [3–6]. Its determination is often carried out by manual adjustments to reduce the difference between the experimental observation and the numerical prediction.

Generally, two kinds of methods exist. The first one is to measure the size variation of the interfacial gap that usually appears at the metal/mould interface during the solidification process. For example, Prates and Biloni [7] and Nishida et al. [8] measured the IHTCs based on the immersion method, fluidity test, unidirectional method and one-dimensional solidification in a mould. The formation process of the air gap and the involved heat transfer mechanism were investigated by measuring the displacements and temperatures for both cylindrical and flat castings of aluminum alloys. The second one is to evaluate the IHTC inversely based on the temperature data measured at selected locations in both the casting and the mould or chill. Note that the surface temperature or heat flux is determined based on the measured temperatures at internal points near the surface. Since the solidification of a casting involves both the material phase change and the variation of thermal properties with respect to the temperature, the inverse heat conduction is a nonlinear problem and can be solved by means of the nonlinear estimation methods [9,10]. For instance, Lau et al. [11] studied the IHTC between an iron casting and a metallic mould. Souza et al. [12] analyzed the heat transfer along the circumference of cylinders made up of Sn–Pb alloys in the mould.

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doi:10.1016/j.expthermflusci.2010.03.009

Nomenclature

a_1, a_2	coefficient of casting–mould IHTC function
b_1, b_2	coefficient of mould–environment IHTC function
f_s	solid fraction
h	heat transfer coefficient
k	number of thermocouples in the mould
L	latent heat of fusion
m	number of time steps
n	number of thermocouples in the casting
q	interface heat flux
t	solidification time
t_c	critical solidification time
T	temperature
Greek symbol	
λ	thermal conductivity
Subscripts	
0	initial state
c	casting
cr	critical
h	heat transfer coefficient
l	liquidus
m	mould
s	solidus
T	temperature
Superscripts	
est	predicted values
exp	experimental data
max	maximum
min	minimum

However, few reliable data of the IHTCs are available for the investment casting process in practice. Sturm and Kallien [13] identified the IHTC involved in the model of an aluminum alloy investment casting where the resultant data of IHTC (1000 W/m^2 K) was assumed to be unchanged throughout the solidification. Anderson et al. [14] combined the simulation and experiment to study thermal behaviors of a two-dimensional symmetrical aluminum casting where the IHTC was buried in an overall heat transfer coefficient. Based on the nonlinear estimation technique mentioned above, Sahai and Overfelt [15] completed a study of the IHTC for both cylindrical and plate investment castings of a nickel-based alloy. For the cylindrical casting (mould preheated to 745 °C), it was found that the IHTC varied linearly from 200 W/m^2 K at 1300 °C to 100 W/m^2 K at 850 °C. For the plate casting, the IHTC was found to vary between 5000 W/m^2 K at 1400 °C and 100 W/m^2 K at 1100 °C. The results showed that the casting shape had a great impact upon the IHTC in the investment casting. O'Mahoney and Browne [16] suggested that cares should be taken of the solidification process, the alloy type and the metallostatic head effect. The aluminum casting alloys, 413, A356, 319, were used in their study.

For these reasons, this work is to develop a simple and universal inverse methodology, which makes use of the existing simulation softwares such as ProCAST to resolve the IHTCs in the investment casting process of a complicated blade. Based on a switch function of solidification time, a novel model of IHTC is proposed to replace the original power function. With the obtained IHTCs, the predicted temperature is compared with the experimental data. Besides, thermocouples are placed in a very thin mould cavity without manufacturing a special mould. This methodology is helpful for a foundry engineer to look for a reference effectively on how to apply boundary conditions for simulation of a specific casting process.

2. Mathematical model of casting process

Fig. 1 depicts the heat transfer through between the two contacting surfaces. When the mould is suddenly filled with the liquid metal, the effects of fluid flow in the liquid phase, the convective heat transfer and the radiative heat transfer are negligible. Therefore, the direct problem for the casting region is formulated only in terms of unsteady-state heat conduction.

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

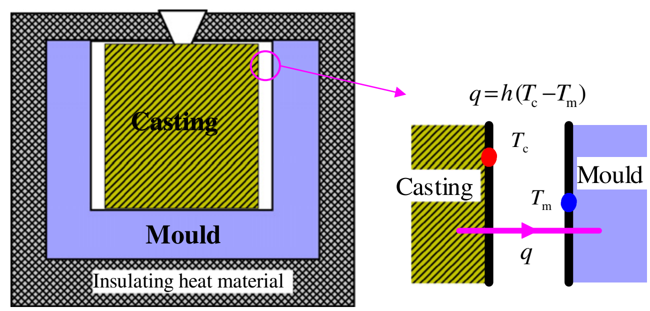

Fig. 1. Schematic of a casting–mould interface.

where ρ is the cast density, c and λ are specific heat and thermal conductivity, respectively. L is the latent heat of fusion and f_s is the solid fraction. Note that the thermal properties are known during the investment process. The initial and boundary conditions for the casting region are

$$\text{initial condition} \quad T|_{t=t_0} = T_0(x, y, z) \qquad (2a)$$

$$\text{at cast—mould interface} \quad -\lambda \frac{\partial T}{\partial n} = q = h_c(T - T_m) \qquad (2b)$$

The casting temperature field is governed by the above heat conduction equation and boundary conditions. Numerical solutions can be obtained by means of the finite element method.

Obviously, h_c, the IHTC at the casting–mould interface, affects the calculated temperature field and is thus of importance for the numerical solution of the casting temperature. Likewise, the governing equation related to the mould region is similar to the above one except that the source term, $\rho_L \frac{\partial f_s}{\partial t}$, is not included. Moreover, h_m at the mould–environment interface has to be determined in advance. For an inverse heat transfer problem, the aim is to predict the unknown IHTCs from the knowledge of measured or/and calculated temperatures at specific positions on the interface. This paper is to determine h_c and h_m in the blade investment casting process.

3. Determination of interfacial heat transfer coefficient

3.1. Inverse parameter estimation

Inverse estimation methods are based on the minimization of an objective function containing both estimated and measured

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