Development and Application of an Inverse Heat Transfer Model for the Shot Sleeve in Die Casting (Postprint)

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Date: 2023-03-19T00:00:00+00:00

Abstract

Based on the inverse heat conduction algorithm, a two-dimensional inverse mathematical model for heat transfer between liquid metal and the shot sleeve was established. A temperature measurement module inside the shot sleeve was designed, and static non-injection and conventional die casting experiments were conducted using Al-9%Si-3%Cu alloy. By solving with temperatures measured at various positions within the shot sleeve during the experiments, the temperature field of the liquid metal in the shot sleeve and the interfacial heat transfer coefficients at different locations were obtained, providing a reliable basis for predicting pre-solidification in the shot sleeve. The results indicate that the interfacial heat transfer between liquid metal and shot sleeve differs substantially between static non-injection and conventional die casting conditions. Moreover, the interfacial heat transfer coefficient in the middle region of the shot sleeve decreases progressively along the flow direction of the liquid metal, while the shot sleeve wall temperature exhibits a distribution pattern of high temperatures at both ends and low temperature in the middle. Under conventional die casting conditions, a dual-peak phenomenon in the heat transfer coefficient at the shot sleeve end was observed due to the influence of plunger movement.

Full Text

Preamble

ChinaXiv Cooperative Journal, Volume 51

June 2015, Issue 6, pp. 745-752
ACTA METALLURGICA SINICA

Development of an Inverse Heat Transfer Model Between Melt and Shot Sleeve and Its Application in High Pressure Die Casting Process

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Supported by National Natural Science Foundation of China (Nos. 51275269 and 51205229) and National Science and Technology Major Project (No. 2012ZX04012011)

Manuscript received: 2014-10-31, in revised form 2015-03-03

Abstract

Based on the inverse heat conduction algorithm, a two-dimensional inverse heat transfer mathematical model between liquid metal and shot sleeve was established. A temperature measurement module inside the shot sleeve was designed, and static non-shot and conventional die casting experiments were conducted using an Al-9%Si-3%Cu alloy. Based on the temperatures measured at different positions inside the shot sleeve, the temperature field of the liquid metal in the shot sleeve and the interfacial heat transfer coefficients at different positions were successfully determined, providing a reliable basis for predicting shot sleeve pre-solidification. The results show that the heat transfer behavior between liquid metal and shot sleeve differs significantly between static non-shot and conventional die casting conditions. Meanwhile, the interfacial heat transfer coefficient in the middle zone of the shot sleeve decreases sequentially along the flow direction of the liquid metal, and the shot sleeve wall temperature exhibits a distribution pattern of being higher at both ends and lower in the middle. Under conventional die casting conditions, due to the influence of plunger movement, a double-peak phenomenon appears in the heat transfer coefficient at the end of the shot sleeve.

Key words: high pressure die casting, shot sleeve, interfacial heat transfer coefficient, inverse method

High pressure die casting (HPDC) is a process in which liquid metal fills a cavity under high pressure and high velocity, and solidifies under high pressure. High pressure and high velocity are the fundamental characteristics that distinguish die casting from other casting methods. Heat transfer of liquid metal in the shot sleeve determines the filling and solidification process, thereby directly affecting the formation of internal microstructure and defects in die castings as well as their final mechanical properties [1~3].

Taking cold chamber die casting as an example, based on changes in plunger speed and pressure at different stages, the flow and solidification of liquid metal inside the shot sleeve can be divided into five stages: pouring stage, slow shot stage, fast shot stage, intensification stage, and holding/solidification stage. Among these five stages, the time and displacement experienced from pouring to slow shot are the longest, and it is essential to ensure minimal heat loss and reduce solidification. Improper control of slow shot process parameters can directly lead to gas entrapment in the liquid metal. Meanwhile, the slow shot process also directly determines the fluid pattern during the fast shot stage, thereby affecting the final casting quality. Due to inevitable heat loss, varying degrees of solidification occur during the slow shot stage, leading to the formation of externally solidified crystals (ESCs) [4~6], which significantly impact the final properties of the casting.

Currently, temperature field simulation technology for die casting has become relatively mature. However, with continuous technological development, improving the accuracy of die casting process simulation has become a key issue that many researchers need to address. An important reason for this problem is that these related computational modules cannot accurately describe boundary and initial conditions. As an important factor affecting the solidification process and an essential boundary condition for solidification simulation, interfacial heat transfer behavior has attracted increasing attention [1,7~12]. However, experimental studies on the interfacial heat transfer mechanism between metal and shot sleeve wall under actual die casting conditions are rarely reported. Through literature review, research on heat transfer between shot sleeve and liquid metal both domestically and internationally has been based on experimental shot sleeve models, which differ significantly from actual working conditions [4,13].

To address these existing problems, this study conducted experiments using an actual cold chamber die casting machine while designing a temperature measurement scheme inside the shot sleeve. Static non-shot and conventional die casting experiments were performed, focusing on the influence law of liquid metal flow in the shot sleeve on heat transfer. By measuring temperature variation curves at different positions inside the shot sleeve, an inverse heat conduction model was established to solve for the interfacial heat transfer coefficients between the shot sleeve and liquid metal during slow and fast shot processes, laying a foundation for achieving accurate solidification process simulation. This research holds important reference and application value for accurately understanding the heat transfer process inside the shot sleeve, formulating effective production process plans, and thereby improving casting quality.

1.1 Analysis of Shot Sleeve Heat Transfer Process

Based on the working state of the shot sleeve, after liquid metal is poured into the shot sleeve through a dosing pump or ladle, it enters the cavity under the action of the plunger from low to high velocity. The flow and heat transfer of liquid metal in the shot sleeve is an extremely complex process; therefore, relevant assumptions must be made when establishing a mathematical model for shot sleeve heat transfer.

As shown in [Figure 1: see original paper], considering the symmetry of the shot sleeve cross-section, this work only studies the heat transfer between the shot sleeve and liquid metal at the midline symmetry plane (plane P in Fig. 1a). The specific structure of this symmetry plane is shown in Fig. 1b. It can be seen that heat transfer inside the shot sleeve includes: contact heat transfer between liquid metal and shot sleeve at the lower surface boundary, heat transfer between the left mold and right plunger with liquid metal, and radiation and convection heat transfer between the upper surface of liquid metal and air inside the shot sleeve. Based on the characteristics of the shot process, thermocouples were only installed in the lower part of the shot sleeve for temperature measurement in this study, as shown in Fig. 1b.

Since heat transfer between the shot sleeve wall and liquid metal is mainly concentrated in a thin layer near the interface, the effects of turbulence and gas entrapment during liquid metal flow in the shot sleeve were ignored. It was assumed that the liquid metal interface advances uniformly throughout the entire filling process. Considering the above boundary conditions, a finite difference mesh was used for two-dimensional temperature field solution. The plunger velocity curve was introduced into the solution. When the plunger moved, the number of liquid metal grids remained constant, and gradually changing grid sizes in the z and x directions were used to describe the uniform advancement of the liquid metal interface. When the upper surface of the liquid metal contacted the shot sleeve wall, the heat transfer boundary condition of the upper surface was changed. As the plunger advanced, the grid sizes in the z and x directions remained constant, and the number of grids in the x direction was reduced to represent the liquid metal entering the mold cavity.

For different positions in the shot sleeve, symmetry line F in Fig. 1b can be selected to study the heat transfer between liquid metal and shot sleeve wall, as specifically shown in Fig. 1c. A two-dimensional heat transfer model was used to solve for the temperature field of the liquid metal. For the thin thermal-sensitive layer sufficiently close to the shot sleeve wall, heat transfer can be approximated as one-dimensional heat transfer perpendicular to the interface. Inverse heat conduction was used to solve for the interface temperature and heat flux, and interpolation fitting methods were employed to provide heat flux boundary conditions for solving the temperature field of liquid metal inside the shot sleeve.

1.2 Inverse Heat Conduction Algorithm

The inverse heat conduction algorithm primarily determines the interfacial heat transfer coefficient based on measured temperatures inside the shot sleeve. However, due to phase transformation and temperature-dependent thermophysical parameters during solidification, the inverse heat conduction problem becomes nonlinear. Additionally, because temperature measurement elements themselves have heat capacity, thermal conductivity, and thermal inertia, temperature measurement exhibits certain attenuation and lag. Beck et al. [14] conducted extensive work in this area and proposed the nonlinear estimation method, whose basic principle is to minimize the objective function F of temperature differences between measured and calculated values at specific positions:

$$F(q_M) = \sum_{j=1}^{J} \sum_{i=1}^{R} (T_{j,i} - Y_{j,i})^2 \rightarrow \min$$

where j and i represent temperature measurement positions and time respectively, J is the total number of temperature measurement positions, R is the future time step length, and qM is the interface heat flux at time M. T and Y are the calculated and measured temperatures respectively. Through mathematical derivation, the following two equations are obtained to solve for the interface heat flux:

$$\Delta q_M = \frac{\sum_{j=1}^{J} \sum_{i=1}^{R} (Y_{j,i} - T_{j,i})\phi_{j,i}}{\sum_{j=1}^{J} \sum_{i=1}^{R} \phi_{j,i}^2}$$

$$q_M^{k+1} = q_M^k + \Delta q_M$$

where $\phi_{j,i}$ is the sensitivity coefficient, defined as $\phi_{j,i} = \partial T_{j,i} / \partial q_M$. Using these equations, the qM value is continuously corrected through iteration while coupling the solution of temperature fields for the shot sleeve and liquid metal to obtain their interface temperatures Tsi and Tmi respectively. When the absolute value of ΔqM is sufficiently small (generally less than 0.0001), the interface heat flux value q at that moment can be determined. Then the interfacial heat transfer coefficient h can be obtained according to the following equation:

$$h = \frac{q}{T_{mi} - T_{si}}$$

1.3 Temperature Field Solution for Liquid Metal Inside Shot Sleeve

A two-dimensional coordinate system was used to represent the heat transfer process of liquid metal inside the shot sleeve. The heat transfer equation is as follows:

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

where ρ, C_p, λ, L and f_s are density, specific heat, thermal conductivity, latent heat of solidification and solid fraction, respectively; $\rho L \frac{\partial f_s}{\partial t}$ is the latent heat release rate during metal solidification. Kirchhoff transformation and equivalent specific heat treatment were performed to eliminate the nonlinearity of material C_p and λ:

$$U = \int_{T_0}^{T} \frac{\lambda(T')}{\lambda_0} dT'$$

where λ_0 is the thermal conductivity at reference temperature T_0. Therefore, equation (5) becomes a linear equation for the transformed temperature U:

$$\frac{\partial U}{\partial t} = \alpha \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial z^2} \right)$$

Using the alternating implicit difference method, the time step from t_k to t_{k+1} was divided into two segments. The equation was applied to node (i, j) at $t_{k+0.5}$ and t_{k+1} moments, alternating between z-direction implicit and x-direction implicit difference schemes. After discretization, the following equation was obtained, and the Thomas algorithm was used for iterative solution of the temperature field of liquid metal inside the shot sleeve:

$$-r_z U_{i,j-1}^{k+0.5} + (1 + 2r_z) U_{i,j}^{k+0.5} - r_z U_{i,j+1}^{k+0.5} = r_x U_{i-1,j}^{k} + (1 - 2r_x) U_{i,j}^{k} + r_x U_{i+1,j}^{k}$$

$$-r_x U_{i-1,j}^{k+1} + (1 + 2r_x) U_{i,j}^{k+1} - r_x U_{i+1,j}^{k+1} = r_z U_{i,j-1}^{k+0.5} + (1 - 2r_z) U_{i,j}^{k+0.5} + r_z U_{i,j+1}^{k+0.5}$$

Based on the aforementioned assumptions of the shot sleeve model, the boundary conditions between liquid metal and shot sleeve wall are as follows:

$$q = -\lambda \frac{\partial T}{\partial n}$$

The upper surface of liquid metal in the shot sleeve has radiation and convection heat transfer boundary conditions as follows:

$$q = q_c + q_r = h_c (T_{mu} - T_{air}) + \varepsilon \sigma (T_{mu}^4 - T_{air}^4)$$

where q, q_c and q_r are the total interfacial heat flux density, convective heat transfer flux density and radiative heat transfer flux density at the liquid metal upper surface, respectively; h_c is the convective heat transfer coefficient between the liquid metal upper surface and air; T_{mu} is the temperature of the liquid metal upper surface; T_{air} is the ambient temperature at the liquid metal upper surface; ε is the total emissivity, which can be set to 0.12 for aluminum alloy; $\sigma = 5.67 \times 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$ is the Stefan-Boltzmann constant.

1.4 Temperature Field Solution for Shot Sleeve Wall

For the shot sleeve wall, with no latent heat release, its one-dimensional heat transfer equation according to the model in Fig. 1c is:

$$\rho C_p \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}$$

Substituting into equation (7) yields:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

where $\alpha = \lambda/(\rho C_p)$. Using implicit finite difference to discretize this equation, then using Thomas algorithm to iteratively solve for shot sleeve wall temperature. The discretized form is:

$$-Fo \cdot T_{i-1}^{k+1} + (1 + 2Fo) \cdot T_i^{k+1} - Fo \cdot T_{i+1}^{k+1} = T_i^k$$

where $Fo = \alpha \Delta t / \Delta x^2$ is the Fourier number.

2.1 Shot Sleeve Temperature Measurement Scheme

The shot sleeve structure used in the die casting process is shown in [Figure 2: see original paper]. K-type thermocouples with wire diameter of 0.048 mm and sheath outer diameter of 0.5 mm were used for temperature measurement. The thermocouple response time is less than 20 ms, enabling accurate acquisition of temperature data during rapid solidification in the shot sleeve. The thermocouple measuring junctions were arranged along the isothermal line direction of the shot sleeve circumference in blind holes 9 mm deep and 1 mm in diameter, causing minimal disturbance to the inner wall temperature of the shot sleeve and allowing relatively accurate measurement of temperatures near the shot sleeve inner wall. Three thermocouples were installed at each measurement point to measure temperatures at distances of 1, 3, and 6 mm from the shot sleeve wall. The thermocouples were integrated into three temperature measurement sliders made of the same material as the shot sleeve and installed in slots on the inner wall of a 60 mm inner diameter shot sleeve, avoiding cooling sleeves and ensuring the original structure and function of the shot sleeve. Thermocouple compensation wires were led out from the stationary platen side of the die casting machine and the outer side of the shot sleeve pouring gate, and connected to multi-channel temperature acquisition equipment from IMC Company for data collection.

The experimental die material was H13 steel, and the casting metal was Al-9%Si-3%Cu alloy. Related thermophysical parameters are shown in (where the thermal conductivity, specific heat capacity, and density of H13 steel all vary with temperature).

The shot sleeve was installed on a TOYO 350 t cold chamber die casting machine. First, static non-shot experiments were conducted, followed by conventional die casting experiments. For the static non-shot experiments, 8 cycles were selected, with 870 g of molten aluminum alloy at 680 °C poured into the shot sleeve using a quantitative ladle each time. The metal was held for a period until solidification, then manually and slowly pushed out by controlling the plunger. For the conventional die casting experiments, a set of 7 stable shot cycles under specific process conditions were selected for analysis and discussion. The process conditions included a pouring temperature of 680 °C, slow shot speed of 0.3 m/s, fast shot speed of 5 m/s, fast shot position of 230 mm, and casting pressure of 37 MPa.

3.1 Temperature Field Variation in Shot Sleeve Heat Transfer Process

[Figure 3: see original paper] shows the temperature curves at 1 mm from the interface at positions S2, S5, and S10 (see Fig. 2) in the shot sleeve during 8 continuous pouring cycles under static non-shot conditions. It can be seen that under continuous cycles, the internal temperature of the shot sleeve continuously rises. Comparing the temperature rise rates, it is evident that the temperature rise rate of the shot sleeve wall gradually slows down along the direction from S2 to S10. After 8 continuous pouring cycles, the initial temperature of the shot sleeve wall at the front end S2 position gradually increased from 160 °C to 410 °C, with a peak temperature reaching 512 °C. Meanwhile, the initial temperatures at the middle S5 position and end S10 position increased from 90 °C to 225 °C and 258 °C respectively, with peak temperatures reaching 400 °C and 442 °C respectively.

[Figure 4: see original paper] shows the metal log obtained in the 8th cycle under static non-shot conditions. Three distinct zones can be observed on the log surface morphology: a smooth pouring zone near the pouring gate, a non-smooth middle zone, and a smooth end zone. At the shot sleeve pouring gate, the liquid metal flow velocity was relatively high, causing splashing and oxide film formation. On the contact surface with the shot sleeve wall, the log surface formed an 80 mm long smooth zone, indicating good interfacial contact between liquid metal and shot sleeve wall near the pouring gate. Oxide films and turbulence-induced splashing attached to the liquid metal, forming a middle non-smooth zone containing oxide films and gas pores at a location 30 mm away from the pouring gate, with a length of approximately 50 mm. At the end of the shot sleeve, the liquid metal flow was relatively stable, resulting in the formation of an end smooth zone.

3.2 Inverse Heat Conduction Calculation Results

[Figure 5: see original paper] shows the inverse calculation results at the middle position (S5, 142 mm) of the shot sleeve during the 8th cycle under static non-shot conditions. In the figure, Tmu and Tmi represent the upper and lower interface temperatures of the liquid metal in the shot sleeve respectively; Tsi is the shot sleeve wall surface temperature; T1, T3, and T6 are the measured temperatures at 1, 3, and 6 mm from the shot sleeve wall; h and q are the interfacial heat transfer coefficient and heat flux density between liquid metal and shot sleeve wall respectively. T3c is the calculated temperature at 3 mm from the shot sleeve wall, which shows good agreement with the measured temperature with a maximum temperature difference not exceeding 5 °C, effectively validating the accuracy of the inverse solution and demonstrating high reliability of the calculation results. When the poured liquid metal flowed along the shot sleeve wall to the middle of the shot sleeve, some superheat had already been dissipated by the shot sleeve wall. Tmi rapidly decreased from the pouring temperature of 680 °C to the liquidus temperature of 595 °C within 0.67 s, with a cooling rate of 125.7 °C/s. As subsequently poured liquid metal flowed to this position, its temperature rose again above the liquidus temperature. Meanwhile, Tsi first rapidly increased to 446 °C, corresponding to the rapid decrease in liquid metal surface temperature, and the interfacial heat flux density rapidly increased from near zero to a peak value of approximately 2.51 $\mathrm{MW \cdot m^{-2}}$. At this time, the interfacial heat transfer coefficient also rapidly increased from its initial value to a peak of approximately 13.7 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$.

[Figure 6: see original paper] shows the temperature distribution contours inside the shot sleeve obtained through inverse solution under static non-shot conditions for 8 continuous cycles. The solidification time for each figure is 18 s. It can be seen that as the die casting cycles progressed, the poured liquid metal continuously heated the shot sleeve wall. Since the shot sleeve wall below the pouring gate was continuously eroded and heated by superheated liquid metal, the overheated zone at the interface between the metal log and shot sleeve wall gradually moved from the middle to the front pouring gate of the shot sleeve. The width of the overheated zone increased from 30 mm to 120 mm. The solidified shell width of the metal log at the end of the shot sleeve was wider than that at the front end, but as the shot process continued, the length of this solidified shell decreased from 30 mm to 20 mm.

[Figure 7: see original paper] shows the variation of interfacial heat transfer coefficients at different positions in the shot sleeve during the 8th cycle under static non-shot conditions. At the front end of the shot sleeve, as liquid metal was poured in, the interfacial heat transfer coefficient at position S2 rapidly rose from its initial value to a peak of approximately 4.4 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ within 1.3 s, then gradually decreased to 1.9 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ within 1.4 s as the metal solidified, and gradually stabilized. The interfacial heat transfer coefficient at position S1 exhibited fluctuations during the rising stage, with a peak of only 2.4 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$, likely due to oxide film formation caused by fluid splashing during pouring (Fig. 4), which affected the contact between liquid metal and shot sleeve wall surface, leading to fluctuations in the heat transfer coefficient. Subsequently, during solidification, the interfacial heat transfer coefficient stabilized and then slowly increased.

In the middle zone of the shot sleeve, the heat transfer coefficient profiles at positions S5, S6, and S7 were basically consistent in shape. Due to gradual heat loss during liquid metal flow, the peak heat transfer coefficient values decreased sequentially along the flow direction, being 13.7, 9.2, and 4.5 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ respectively. Since position S5 also experienced splashing turbulence causing fluctuations, a non-smooth zone was eventually formed on the log (Fig. 4).

At the end of the shot sleeve, as liquid metal was poured in, the heat transfer coefficient at position S9 rapidly reached a peak of 4.2 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$. Subsequently, due to partial solidification of the metal that flowed to this area earlier, forming a solidified shell, its shrinkage led to lower interfacial heat transfer efficiency and a corresponding decrease in the heat transfer coefficient. However, as liquid metal with higher superheat continued to flow to the end of the shot sleeve, the solidified shell in this area underwent remelting, improving interfacial heat transfer efficiency and causing the heat transfer coefficient to slowly increase again.

3.3 Heat Transfer Inside Shot Sleeve Under Conventional Die Casting Conditions

[Figure 8: see original paper]a-c shows the temperature field distribution of liquid metal at the moment of slow shot start, fast shot start, and filling end under conventional die casting conditions. It can be seen that at the slow shot start moment, after liquid metal was poured into the shot sleeve and contacted the overcooled plunger wall and mold wall on both sides, the temperature rapidly dropped below the solidus temperature of 540 °C, forming a pre-solidified shell. The upper surface of the liquid metal lost relatively little heat through radiation to air, basically maintaining at 670 °C. It can also be observed that in the region directly opposite the pouring gate at the front end of the shot sleeve, center superheat was formed due to direct pouring of superheated liquid metal, while a chill layer formed near the shot sleeve wall at the bottom (Fig. 8a). At the fast shot start moment, the plunger smoothly pushed the liquid metal to the 230 mm position at a speed of 0.3 m/s. At this time, the liquid metal had completely filled the shot sleeve. From Fig. 8b, a solidified shell of about 3 mm can be clearly seen forming near the plunger side. At the mold side at the end of the shot sleeve, superheated metal continuously filled, causing partial remelting of the originally pre-solidified shell. At this time, the upper surface of the liquid metal had already contacted the shot sleeve wall, changing the heat transfer from radiation and convection with air to heat transfer with the shot sleeve wall, resulting in faster temperature decrease. The bottom surface in contact with the shot sleeve wall also experienced accelerated temperature decrease, basically maintaining at 600 °C. At the filling end moment, after the plunger rapidly pushed the melt to fill the cavity at 5 m/s, the solidified shell near the mold side at the end of the shot sleeve disappeared, possibly due to the action of high speed and superheated melt causing complete remelting of the solidified shell. Moreover, the solidified shell near the plunger side also nearly disappeared, and these remelted coarse structures would enter the cavity with the melt (Fig. 8c).

[Figure 9: see original paper] shows the interfacial heat transfer coefficients at different positions in the shot sleeve under conventional die casting conditions. It can be clearly seen that the variation pattern of interfacial heat transfer coefficients under die casting conditions differs significantly from that under static non-shot conditions. At the front end of the shot sleeve, the heat transfer coefficients at positions S1 and S2 reached peaks of 4.1 and 21.9 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ respectively as the liquid metal was poured in. However, position S2 experienced fluctuations due to the impact of poured superheated liquid metal, resulting in particularly intense heat transfer at the interface. In the middle zone of the shot sleeve, the heat transfer coefficient profiles at positions S5, S6, and S7 were basically consistent in shape. Similar to the variation under static non-shot conditions, due to gradual heat loss during liquid metal flow, the peak heat transfer coefficient values decreased sequentially along the flow direction, being 7.0, 4.5, and 3.7 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ respectively. At the end of the shot sleeve, as liquid metal was poured in, the heat transfer coefficients at positions S9 and S10 rapidly reached peaks of 3.5 and 4.2 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ respectively. The heat transfer coefficients then decreased. However, as the plunger pushed liquid metal with higher superheat to the end of the shot sleeve, remelting of the solidified shell in this area improved interfacial heat transfer efficiency, causing the heat transfer coefficient to slowly increase again until the end of fast filling. The second peak value appearing at S10 was 9.1 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$. As can be seen from Fig. 9, after the end of fast filling, there was no liquid metal at position S9, so only position S10 exhibited the second peak, which then slowly decreased to the initial value due to contact with the plunger and air.

Conclusions

1. Under static non-shot conditions, the heat transfer coefficient at the front end of the shot sleeve fluctuated significantly, with peak values of 2.4~4.4 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$. The peak heat transfer coefficient in the middle zone of the shot sleeve was 4.5~13.7 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$, while at the end of the shot sleeve, the peak heat transfer coefficient was 4.2 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$. Under conventional die casting conditions, the peak heat transfer coefficient at the front end of the shot sleeve reached 21.9 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$. The peak heat transfer coefficient in the middle zone was 3.7~7.0 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$, while at the end of the shot sleeve, it rapidly rose to the first peak of 3.5~4.2 $\mathrm{kW \cdot m^{-2} \cdot K^{-1}}$ during pouring, and reached the second peak of

approximately 9.1 $\mathrm{kW} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$ as the shot process proceeded.

2. Both static non-shot and conventional die casting processes exhibit certain common characteristics in heat transfer inside the shot sleeve: interfacial heat transfer is relatively intense at the front end (pouring gate) of the shot sleeve; the interfacial heat transfer coefficient in the middle zone decreases sequentially along the flow direction of the liquid metal; and the shot sleeve wall temperature shows a distribution pattern of being higher at both ends and lower in the middle.
3. The heat transfer behavior between liquid metal and shot sleeve differs significantly between static non-shot and conventional die casting conditions, mainly manifested in the values and profiles of the heat transfer coefficients. Under conventional die casting conditions, the variation trend of the heat transfer coefficient is directly affected by plunger movement, and a double-peak phenomenon appears in the heat transfer coefficient at the end of the shot sleeve.

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Note: Figure translations are in progress. See original paper for figures.