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Effect of casting/mould interfacial heat transfer during solidification of aluminium alloys cast in CO_2-sand mould

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The ability of heat to flow across the casting and through the interface from the casting to the mold directly affects the evolution of solidification and plays a notable role in determining the freezing conditions within the casting, mainly in foundry systems of high thermal diffusivity such as chill castings. An experimental procedure has been utilized to measure the formation process of an interfacial gap and metal-mould interfacial movement during solidification of hollow cylindrical castings of Al-4.5 % Cu alloy cast in CO_2-sand mould. Heat flow between the casting and the mould during solidification of Al-4.5 % Cu alloy in CO_2-sand mould was assessed using an inverse modeling technique. The analysis yielded the interfacial heat flux (q), heat transfer coefficient (h) and the surface temperatures of the casting and the mould during solidification of the casting. The peak heat flux was incorporated as a dimensionless number and modeled as a function of the thermal diffusivities of the casting and the mould materials. Heat flux transients were normalized with respect to the peak heat flux and modeled as a function of time. The heat flux model proposed was to estimate the heat flux transients during solidification of Al-4.5 % Cu alloy cast in CO_2-sand moulds.

Keywords: *CO_2-sand mould, interfacial heat flux, heat transfer coefficient, thermal diffusivity*

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1. Introduction

For the simulation of permanent mold casting, the interfacial heat transfer coefficient (IHTC) is the most important factor in determining the cooling rate which must be controlled. In order to make castings solidify directionally, hence resulting in high quality, the role of the IHTC cannot be emphasized enough in the prediction of freezing patterns during solidification. Aluminum alloys with copper as a major alloying element, consist of a class of alloys, which provides the most significant part of all shaped castings manufactured. Gravity or pressure die castings, continuous casting and squeeze castings are some of the processes where product soundness is more directly affected by heat transfer at the metal/mold interface. In recent years, the development of digital computer technology and applied numerical methods has provided a powerful means for simulating casting solidification by calculation. The success of a commercially available solidification simulation package to predict accurately the thermal history and to locate hot spots inside a casting depends to a large extent on a reliable database containing the boundary conditions specified at the casting/mould interface [1]. The rate at which heat is extracted from the mould to the casting is dependent on the thermophysical properties of the casting and the mould material, roughness of the mould surface and the casting conditions [2–6]. Sully observed that the geometry of the interface was the most important factor in determining its thermal behaviour [7].

Several methods are available to control the heat transfer between the casting and the mould wall during the solidification of the metal. For example, the use of chills during freezing of aluminium alloys with a long freezing range is a normal practice for achieving directional solidification [8, 9]. The thermal transport phenomenon plays a major role especially in the continuous/direct chill casting of metals and alloys involving solidification in water-cooled copper moulds [10]. Recently the use of a CO_2-sand mould for better surface finish casting in the manufacture of rail wheels has been reported [11, 12]. The use of CO_2-sand mould provides better lubrication, wear resistance and acts as a reservoir of fluxing powder. Furthermore, the coefficient of thermal expansion of CO_2-sand mould is negligibly small.

In the present work, heat transfer during solidification of Al-4.5 % Cu alloy in CO_2-sand mould, was investigated. Commercially available Al-4.5 % Cu alloy was selected as a casting material to include the effect of varying thermal diffusivities of casting material on the casting/mould interfacial heat transfer.

2. Experimentation

CO_2-sand moulds were used in the present work. Sodium silicate (Na_2SiO_3) of 4 % by weight was mixed with silica sand and used for making moulds. The moulds were hardened using CO_2 gas. The dimensions of the mould were selected to establish good interference. Fig. 1 shows a schematic sketch of the CO_2-sand mould used in the present investigation. The particle size of the silica sand was 50 mesh. Initially, silica gel was obtained by mixing the silica sand with liquid sodium silicate. Moulds were prepared using regular hand moulding technique for the different configurations (Table 1). Then CO_2 gas was passed through the mould at a pressure of 2 kg/cm^2.

For the experiment, the commercial alloy Al-4.5 % was used. The details of the chemical composition of the alloy are:

% Composition

Si	0.343	Mg	0.480	Sn	0.005
Fe	0.602	Zn	0.038	Ti	0.013
Cu	4.36	Ni	0.006	Al	Remainder
Mn	0.683	Pb	0.007		

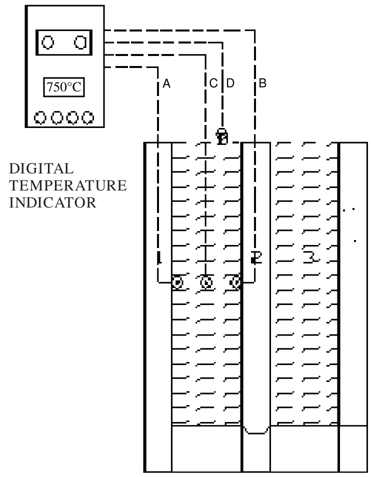

Fig. 1. Experimental set-up and thermocouples locations.
A – Thermocouple placed at the interface of molten metal – mould.
B – Thermocouple placed at the interface of molten metal – core.
C – Thermocouple placed at the center of molten metal.
D – Thermocouple placed at the surface of molten metal.
1 – CO_2-sand mould.
2 – CO_2-sand core.
3 – Molten metal.

Table 1. Dimensions of hollow cylindrical castings.

Sl. No	OD D [mm]	ID d [mm]	Thickness t [mm]	Height of Casting h [mm]
1	75	25	25	250
2	125	25	50	250
		50	37.5	
3	175	25	75	250
		50	62.5	
		75	50	

OD – Outside Diameter of Casting
ID – Core Diameter or Inner Diameter of Casting
t – Thickness of Casting

On the top surface of the moulds, holes of 1.5 mm were drilled to a depth of 45 mm at various locations from the casting/mould interface for insertion of thermocouples to monitor the mould thermal history. Two varieties of K-Type thermocouples were used. Stainless steel sheathed thermocouples of 1mm diameter were located inside

Table 2. Properties of Al-4.5 % Cu

Solidus Temperature	549 °C
Liquidus Temperature	646 °C
Density of solid	2520 kg/m^3
Specific heat	1086 J/(g·K)
Thermal Conductivity of solid	192 W/(m·K)
Thermal Conductivity of liquid	90 W/(m·K)
Density of liquid	2380 kg/m^3
Thermal Diffusivity, $\alpha = \frac{k}{(\rho.C_p)}$, (m^2/s)	8.418×10^{-5} m^2/s

the mould material and a 0.45 mm K-Type thermocouple was inserted in twin bore ceramic beads of 5 mm diameter and used for monitoring the solidification behavior of the casting at the geometric centre of the casting. The sheathed thermocouples were reused for the next set of experiments. However, the ceramic beaded thermocouple could not be reused and was sacrificial. All thermocouples were connected to a portable high-speed data acquisition system.

The casting material was melted in a fireclay crucible using a resistance furnace. The top surface of the mould was insulated with ceramic wool to prevent dissipation of heat. The liquid metal was superheated to 75 °C above its freezing temperature. The crucible was then taken out from the furnace and the liquid metal was poured into the mould. The temperature data were logged for about five minutes and then transferred to a PC by an off-line procedure. Table 2 and 3 give the thermophysical properties of the casting and the mould materials used during this experiment.

3. Estimation of heat flux transients

The non-linear estimation technique of Bech [13, 14] was used to estimate the casting/mould interfacial heat flux transients. The one dimensional heat conduction equation:

$$\frac{\partial^2 T}{\partial^2 r} + \frac{1}{r}\left(\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

was solved subject to the following boundary and initial conditions:

$$T(r_1, T) = Y(t) = T_1,$$
$$T(r_2, T) = B(t) = T_3,$$
$$T(r, 0) = T_i(x).$$

To find the heat flux at $r = 0$, the following function based on a least squares analysis was minimized.

$$F(q) = \sum_{i=1}^{I=mr} (T_{n+i} Y_{n+i})^2, \quad (2)$$

where, $r =$ the number of future time temperatures +1. Y_{n+i} and T_{n+i} are measured and calculated temperatures respectively at the locations near the surface where the boundary condition is unknown. An error term for the surface heat flux was calculated as:

$$F(q) = \frac{\sum_{i=1}^{I} (Y_{n+i} - T_{n+1}^{I-1})\phi_i^{I-1}}{\sum_{i-1}^{I} (\phi_i^{I-1})^2}. \quad (3)$$

The term ϕ is called the sensitivity coefficient and is a measure of the change in temperature inside the heat conducting body with small changes in surface heat flux. The procedure was then repeated for a new heat flux value. The iteration was continued until $\nabla q/q$ was less than 0.005.

The final iterated value of q was used as an initial heat flux for estimating the heat flux for the next time step. The calculation of the heat flux was continued until all the heat flux values were calculated. The mould surface temperatures T_{mould} were obtained as part of the inverse solution. The heat flux transients were then used as one of the boundary conditions for simulation of the solidification of the casting. The latent heat liberated during solidification was modelled by converting the latent heat

Table 3. Properties of CO_2-sand

Density	1580 kg/m^3
Thermal Conductivity	152 W/(m·K)
Specific heat	1045 J/(g·K)
Convective heat transfer coefficient	108 W/(m^2·K)
Thermal Diffusivity, $\alpha = \frac{k}{(\rho.C_p)}$	13.8 × 10^{-5} m^2/s

into an equivalent number of degrees. The analysis yielded the casting surface temperature $T_{casting}$. The heat transfer coefficient was then calculated as:

$$h = \frac{q}{T_{casting} - T_{mould}}. \tag{4}$$

Comparing the calculated and measured temperatures at a location of 12.5 mm from the casting/mould interface in the CO_2-sand mould during solidification of Al-4.5 % Cu alloy validated the inverse model. The measured and calculated temperatures were found to be in close agreement as shown in Fig. 2. For example, at a time of 148 seconds, the calculated and measured temperatures were 122.5 °C and 108 °C respectively, showing a maximum variation of 11.8 %. This variation was reduced to less than 1 % at a time of 471 seconds when the corresponding calculated and measured temperatures were 85.7 °C and 85 °C respectively. The variation between the calculated and experimentally measured temperatures during the initial period could be attributed to the assumption of perfect thermal contact at the casting/mould wall interfacial region in the present analysis.

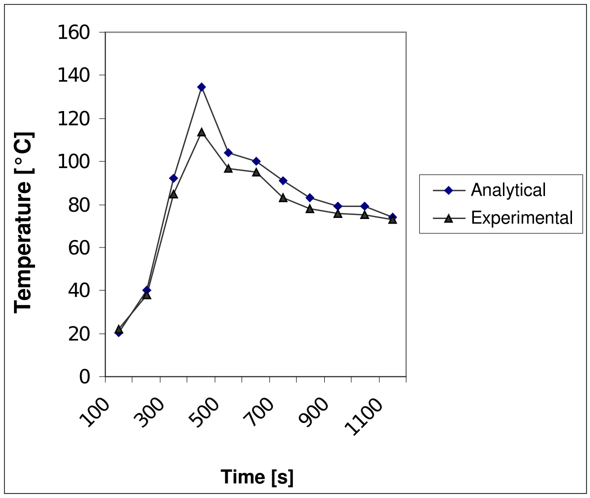

Fig. 2. Experimental and analytical temperatures inside CO_2-sand mould 25 mm thickness (75 mm OD, 25 mm ID).

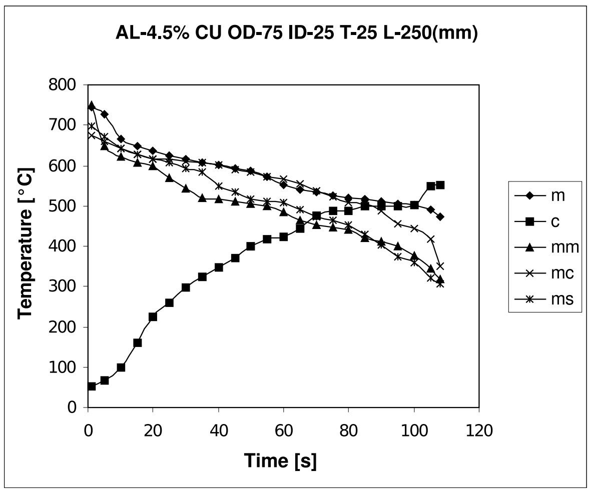

Fig. 3. Experimental cooling curves for 25 mm thickness (75 mm OD, 25 mm ID).

4. Results and discussions

Figs. 3 and 4 show a typical thermal history in the casting and the mould during solidification of the Al-4.5 % alloy. The mould thermal history indicated that after the liquid metal was poured, the locations near the interface heated rapidly to a maximum temperature. After the occurrence of the peak, the mould temperature decreased at a slower rate compared to the initial rate of heating. For example, the initial heating rate of the CO_2-sand mould solidification of Al-4.5 % Cu alloy was 15 °C/sec and the cooling rate of 3 °C/sec after the occurrence of the peak temperature. The temperature remained almost constant after a period of 25 seconds. At the locations away from the interface, the temperature

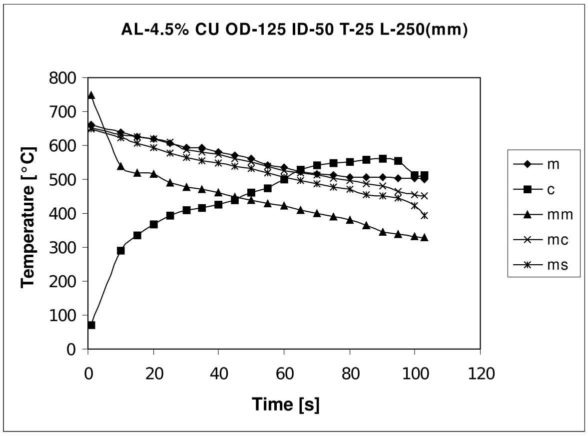

Fig. 4. Experimental cooling curves for 25 mm thickness (125 mm OD, 50 mm ID)
m – metal temperature (center)
c – core temperature (center)
mc –metal-core interface temperature
mm – metal-mould interface temperature
ms – metal-surface temperature

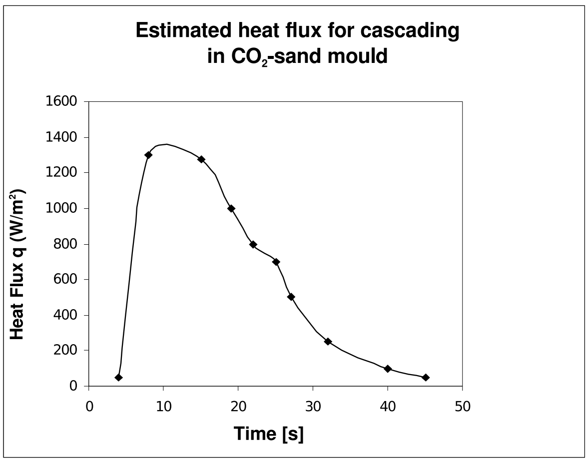

Fig. 5. Heat flux transients estimated by inverse analysis during solidification of Al-4.5 % Cu alloy in CO_2-sand mould for 25 mm thickness (75 mm OD, 25 mm ID).

gradually increased and remained constant after a certain period of time.

Fig. 5 shows the heat flux transients estimated at the interface during solidification of Al-4.5 % Cu cast in CO_2-sand moulds. The heat flux increased rapidly as the liquid metal filled the mould cavity and reached a peak value after a time of about 5 seconds. The time of the occurrence of peak heat flux could be associated with the formulation of an initial solidified shell near the casting/mould interface and/or the completion of mould filling [2, 15, 16]. Since the skin is weak, it may be pushed against the mould wall by the metallostatic pressure of the liquid metal. This may result in intimate contact between the mould wall and casting skin increasing the heat flux to a maximum. The initial low value of the heat flux transient in the experiment is due to the delayed response of the thermocouples in sensing the true temperatures at the instant of pouring. As the thickness of the solidified shell increases, its strength increases, which can resist the metallostatic pressure. This results in a contraction of the casting skin away from the mould wall causing an imperfect contact at the interface. The expansion and contraction characteristics of the mould and the casting material might also influence this transformation and might also lead to the separation of the shell from the mould surface, in turn leading to the formation of a gas gap resulting in a rapid decrease in the heat flux. Fig. 6 shows the heat transfer coefficients estimated for Al-4.5 % Cu alloy solidifying in CO_2-sand moulds. A peak heat transfer coefficient of around 2000 W/m^2K was obtained for CO_2-sand moulds. Initially a solid skin may form and remelt and the occurrence of a double peak represents this instability. This may also be due to reversal heat transfer from the core end.

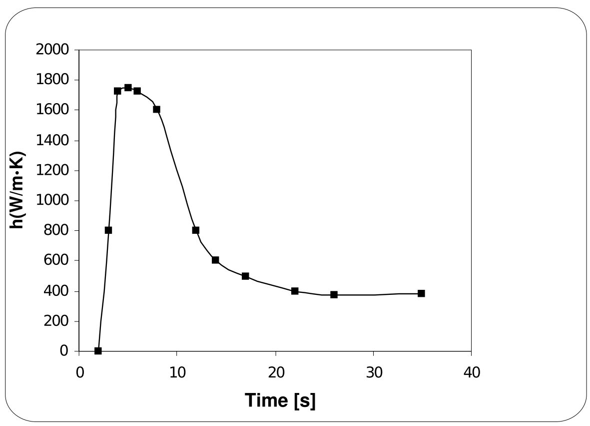

Fig. 6. Casting/Mould interfacial heat transfer coefficient for Al-4.5 % Cu alloy solidifying in CO_2-sand mould of 25 mm thickness (75 mm OD, 25 mm ID).

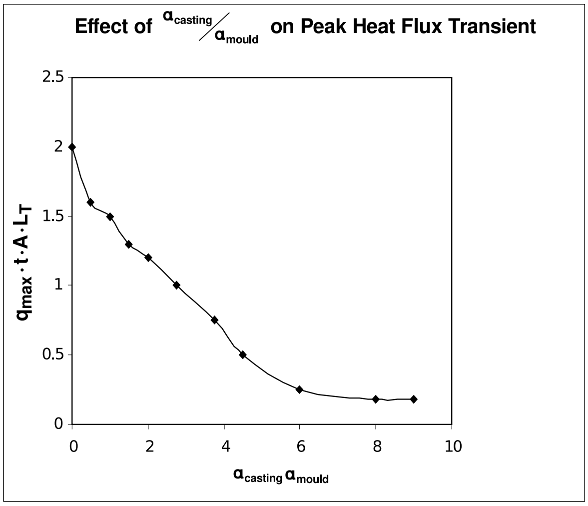

Fig. 7. Effect of $\alpha_{casting}/\alpha_{mould}$ on peak heat transients for 25 mm thickness (75 mm OD, 25 mm ID).

To model the peak heat transfer at the casting/mould wall interface, a dimensionless ratio of the thermal diffusivities defined as:

$$\alpha_R = \frac{\alpha_{casting}}{\alpha_{mould}} \tag{5}$$

was used. The effect of α_R on peak heat flux values is shown in Fig. 7 and can be described by a regression equation of the type:

$$\frac{q_{max}}{L_f} = 12.23 \left(\frac{\alpha_{casting}}{\alpha_{mould}}\right)^{-0.333} \tag{6}$$

where L_f is the latent heat liberated and q_{max} is the peak heat transfer rate during solidification of the casting. Table 4 gives the latent heat of fusion of the casting materials used in the present investigation. To make equation (6) dimensionally consistent, the left hand side of the equation was multiplied by the product of the casting/mould interfacial area and the time required for the heat flux to reach a peak value. If the time required for the heat flux to reach a peak value is associated with the time required for the interfacial condition to change over from a conforming contact to a nonconforming contact, then the product of heat flux and the time could be considered as the heat required for initial solidification of the casting shell. In the present investigation, the time to reach peak flux was nearly 5 seconds and the interfacial area was 56.55 cm^2. The resulting equation is:

Table 4. Latent heat of fusion of casting materials [14].

Casting material	Latent heat [kJ/kg], H_f	Heat content of the casting [kJ], $L_f = \rho \cdot V \cdot H_f$
Al-4.5 % Cu	395.041	90.464

$$\frac{q_{max} \cdot t \cdot A}{L_f} = 0.697 \left(\frac{\alpha_{casting}}{\alpha_{mould}}\right)^{-0.333} \tag{7}$$

or approximately

$$\frac{q_{max} \cdot t \cdot A}{L_f} = \frac{0.7}{\sqrt[3]{\frac{\alpha_{casting}}{\alpha_{mould}}}}. \tag{8}$$

The correlation coefficient for the above equation was 0.78 and the equation is valid for thermal diffusivity ratios ranging from 0.17 to 9.4. The left hand side of equation (8) can be considered as a dimensional interfacial heat flux transient and denotes the ratio of the heat flow at the interface to the heat of fusion liberated during solidification of the casting.

In terms of the interfacial heat transfer coefficient (h_{max}), equation (9) could be written as:

$$\frac{h_{max} \cdot \Delta T \cdot t \cdot A}{L_f} = \frac{0.7}{\sqrt[3]{\frac{\alpha_{casting}}{\alpha_{mould}}}}, \tag{9}$$

where ΔT is the temperature drop at the casting/mould interface.

The heat flux normalized with respect to peak flux and its variation with time for different metal/mould combinations is shown in Fig. 8. The variation could be approximated by a best-fit equation given by:

$$\frac{q}{q_{max}} = 1.18e^{-0.212t}. \tag{10}$$

Figs. 7 and 8 can be used to estimate the heat flux transients in CO_2-sand moulds from the

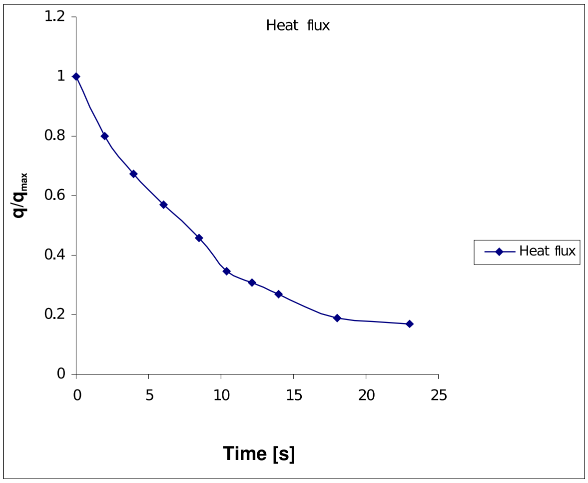

Fig. 8. Variation of normalized heat flux transient with time for 25 mm thickness (75 mm OD, 25 mm ID).

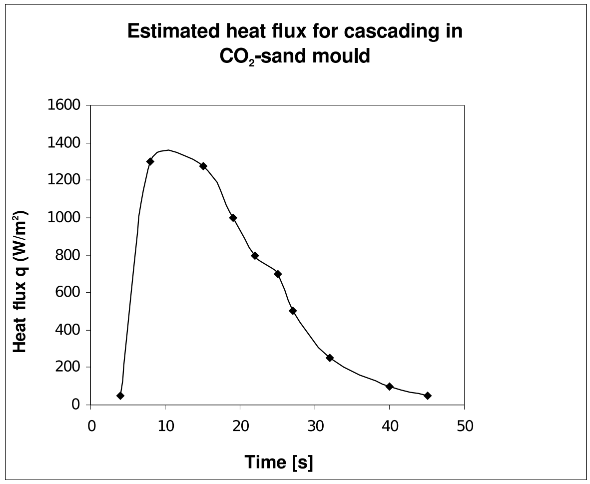

Fig. 9. Heat flux transients during solidification of Al-4.5 % Cu alloy in CO_2-sand moulds for 25 mm thickness (75 mm OD, 25 mm ID).

knowledge of their thermophysical properties. The methodology is explained in the following steps:

1. The peak heat flux (q_{max}) was calculated from the thermal diffusivity ratio α_R using equation (5).
2. The peak heat flux occurrence was taken as 5 seconds and was estimated by linear interpolation.
3. The heat flux transients after the occurrence of peak flux could be approximated using Fig. 8.

Although the heat transfer model presented above gives only an approximate estimate of the heat flux transients, it can be used to assess the heat transfer during solidification of non-ferrous alloys solidifying in various metallic moulds not used in building the heat flow model and for which the α_R lies between 0.17 and 9.44. Fig. 9 shows the flux values estimated for Al-4.5 % Cu ($\alpha = 8.414 * 10^{-5}$ m^2/s) solidifying in CO_2-sand mould.

5. Conclusions

Heat transfer during solidification of commercially available Al-4.5 % Cu alloy cast in CO_2-sand mould was assessed using an inverse analysis technique. The casting/mould interfacial heat flux and heat transfer coefficients were reported for various casting/mould configurations (Table 1).

The peak heat flux represented the maximum heat transfer from the casting to the CO_2-sand mould for various configurations at the time of formation of an initial solidified shell. The time of occurrence of the peak heat flux transients was nearly five seconds after pouring. This time could be associated with the time for transformation of the interfacial condition from a near perfect contact to a non-conforming contact.

The ratio of thermal diffusivity of the casting to the mould material had a significant effect on the magnitude of the peak heat flux at the interface of the mould and casting. The variation of peak heat flux with the thermal diffusivity ratio α_R was modeled using a dimensionless number. The peak heat transfer regression model could be used to calculate the maximum heat transfer at the casting/mould interface for any metal/mould combination having a thermal diffusivity ratio between 0.16 and 9.3. Heat flux transients after the formation of the solidified shell was approximated by an exponential best fit.

Comparing the predicted and measured heat flux transients for Al-4.5 % Cu solidifying in CO_2-sand mould validated the heat transfer model. A good agreement between the predicted and measured heat flux transients showed that the effect of thermal resistance at the interface and thermocouple/mould material contact resistance on casting/mould interfacial heat transfer is negligible.

List of symbols

A	Casting/mould interfacial area (m^2)
C_p	Specific heat (J/kg/K)
D	Mould wall thickness (m)
H_f	Latent heat of fusion (J/kg)
h	Heat transfer coefficient (W/m^{2}K)
L_f	$\rho V H_f$, Latent heat liberated (J)
q	Interfacial heat flux (W/m^2)
$r-1$	No. of future temperatures
t	Time (sec)
T	Estimated temperatures (K)
Y	Measured temperature (K)
α	Thermal diffusivity (m^2/sec)
ρ	Density (kg/m^3)

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