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Casting/mould interfacial heat transfer during solidification in graphite, steel and graphite lined steel moulds

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Heat flow between the casting and the mould during solidification of three commercially pure metals, in graphite, steel and graphite lined steel moulds, was assessed using an inverse modelling 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 normalised with respect to the peak heat flux and modeled as a function of time. The heat flux model proposed was used to estimate the heat flux transients during solidification in graphite lined copper composite moulds.

Keywords: Composite mould, interfacial heat flux, heat transfer coefficient, thermal diffusivity

Introduction

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 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 composite mould made up of graphite lined copper for continuous casting of non-ferrous alloys and graphite-moulds for the manufacture of rail wheels has been reported.[11,12] The use of graphite provides better lubrication, wear resistance and acts as a reservoir of fluxing powder. Further, the coefficient of thermal expansion of graphite is negligibly small.

In the present work, heat transfer during solidification of pure metals, in graphite, steel and graphite lined steel moulds, was investigated. Commercially available lead, aluminium and zinc were selected as casting materials to include the effect of varying thermal diffusivities of casting material on the casting/mould interfacial heat transfer.

Experiment

The composite mould consisted of a graphite inner cylinder and a mild steel outer cylinder. The graphite block was initially cut to the approximate size and then it was turned to exact dimensions. A hole of 30 mm diameter was drilled in the cylindrical graphite block. The dimensions of the mould were selected so that an interference fit was obtained between the inner graphite and outer mild steel cylinders. The single material moulds of graphite and mild steel were similarly prepared. Fig. 1 shows a schematic sketch of the graphite lined steel mould used in the present investigation. The wall thickness of the single material mould was equal to the sum of the thickness of the graphite lining and the outer steel mould used for preparing the composite mould.

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 1 mm diameter were located inside 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 behaviour 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 40 °C above its

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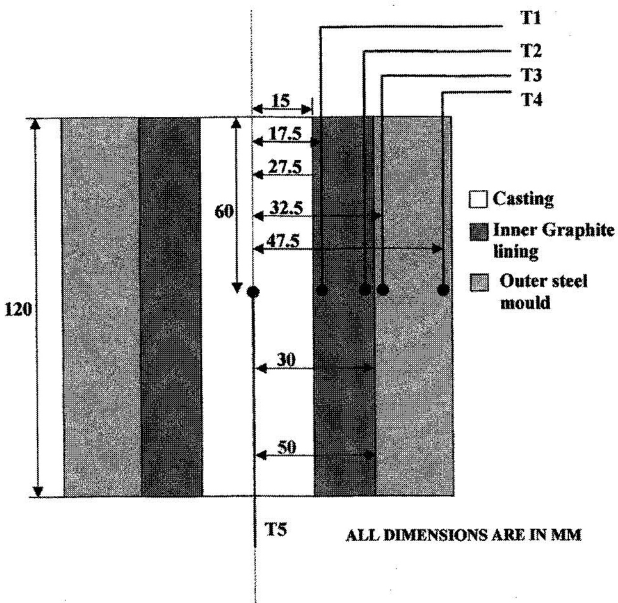

Fig. 1 Schematic sketch of the graphite lined steel mould instrumented with thermocouples

freezing temperature. The crucible was then taken out from the furnace and the liquid metal was poured into the mould. The temperature data was logged for about three minutes and was then transferred to a PC by an offline procedure. Table 1 gives the thermophysical properties of the casting and mould materials used during this experiment. The following equation was used to determine the bulk thermal conductivity of the graphite lined steel composite mould.

$$\frac{1}{k_{\mathrm{composite}}} = \frac{d_g}{k_g} + \frac{d_s}{k_s}$$

where d_g and d_s are the thickness fractions defined as:

$$d_g = \frac{D_g}{D_g + D_s} \qquad d_s = \frac{D_s}{D_g + D_s} \tag{1}$$

D_g and D_s are the thickness of the graphite lining and the outer steel wall respectively. The density and the specific heat of the composite moulds were calculated in a similar manner.

Estimation of heat flux transients

The non-linear estimation technique of Beck[14,15] was used to estimate the casting/mould interfacial heat flux transients. The one dimensional heat conduction equation:

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

was solved subject to the following boundary and initial conditions.

$$T(r_1 t) = Y(t) = T1$$

$$T(r_2, t) = B(t) = T3$$

$$T(r, 0) = T_i(x)$$

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

$$F(q) = \sum_{i=1}^{I=mr} \left(T_{\eta+i} Y_{\eta+i}\right)^2 \tag{3}$$

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

$$\nabla q^1_{M+1} = \frac{\sum_{i=1}^{I} \left(Y_{n+i} - T^{1-1}_{n+i}\right)\phi^{1-1}_i}{\sum_{i=1}^{I} \left(\phi^{1-1}_i\right)^2} \tag{4}$$

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 the 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 a part of the inverse

Table 1 Thermophysical properties of the casting and the mould materials[10]

Material	Density ρ (kg/m^3)	Thermal conductivity k (W/mK)	Specific heat C_p (J/kgK)	Thermal diffusivity $\alpha = k/(\rho \cdot C_p)$ (m^2/s)
Casting				
Aluminium	2707	204	896	8.418×10^{-5}
Zinc	7144	112.2	384.3	4.106×10^{-5}
Lead	11 373	35	130	2.343×10^{-5}
Mould				
Steel	7700	42	611	0.892×10^{-5}
Graphite	1890	174.5	670	13.8×10^{-5}
Graphite-lined Steel (Composite)	3321*	67.24*	663*	3.053×10^{-5}

* Calculated using equation (1)

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

$$h = \frac{q}{T_{casting} - T_{mould}} \qquad (5)$$

Comparing the calculated and measured temperatures at a location of 12.5 mm from the casting/mould interface in the graphite layer of the composite mould during solidification of aluminium 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 graphite/steel wall interfacial region in the present analysis.

Results and discussion

Figs. 3 and 4 show the typical thermal history in the casting and the mould during solidification of aluminium inside graphite and graphite lined steel moulds respectively. 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 a peak, the mould temperature decreased at a slower rate compared to the initial rate of heating. For example, the initial heating rate of the graphite mould during solidification of aluminium was 15 °C/sec and

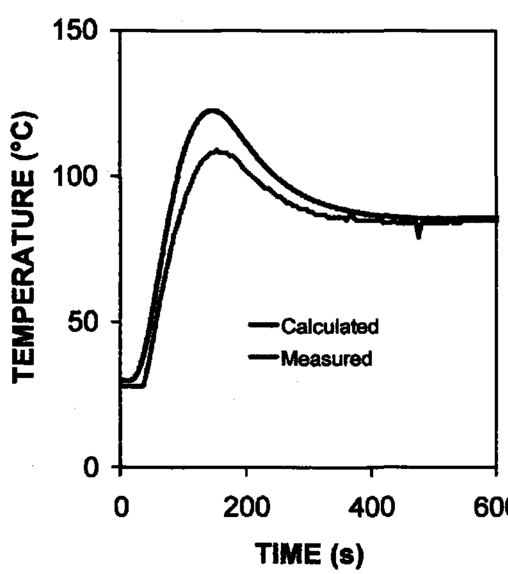

Fig. 2 Measured and calculated temperatures inside the graphite lining of the composite mould

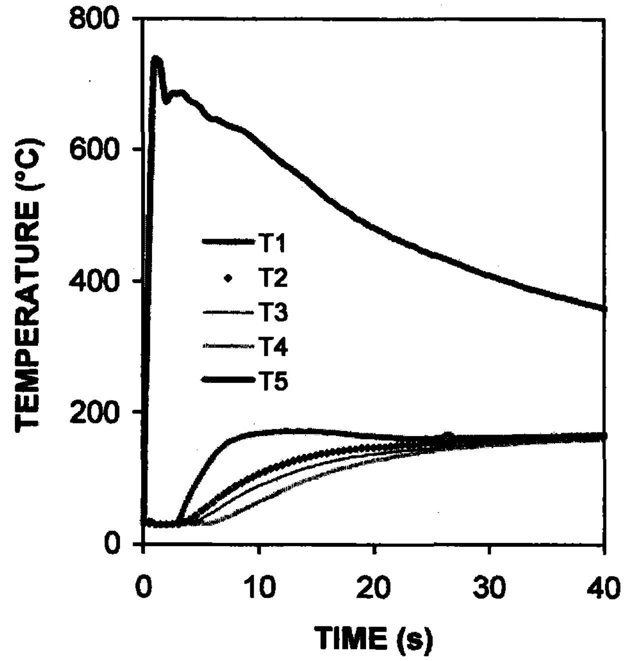

Fig. 3 Typical casting and mould thermal history during solidification of aluminium in a graphite mould

cooled at a rate of 3 °C/s 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 gradually increased and remained constant after a certain a period of time. The cooling rate of the castings solidifying in graphite moulds was significantly higher compared to other moulds. This was due to the higher thermal conductivity of the graphite mould material. In the composite mould, a large difference in temperature was observed between the thermal history recorded by thermocouples 2 and 3. For example, the difference in temperatures was about 100 °C during

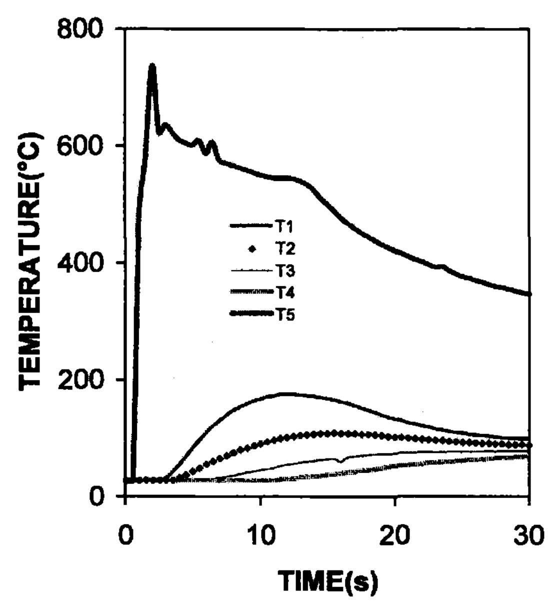

Fig. 4 Typical casting and mould thermal history during solidification of aluminium in a graphite-lined composite mould

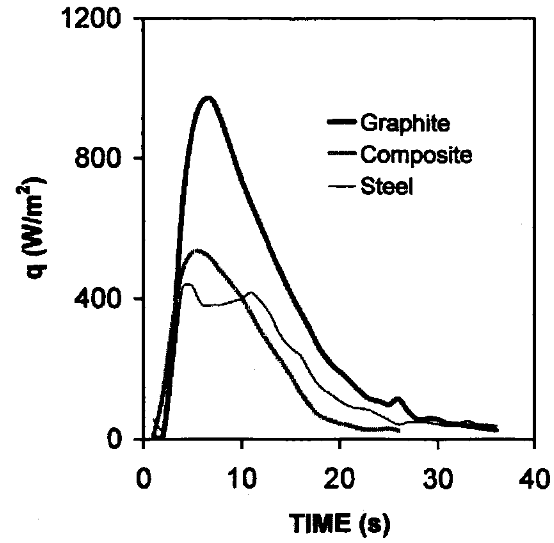

Fig. 5 Heat flux transients estimated by inverse analysis during solidification of aluminium in steel, graphite and graphite lined steel composite moulds

solidification of aluminium at a time of 15 seconds compared to only 20 °C for the graphite mould. This could be explained as resulting from (i) thermal resistance between the inner graphite lining and the outer steel wall, (ii) difference in the thermal conductivity of the outer steel and the inner graphite material and (iii) the difference in thermocouple/graphite and thermocouple/steel contact resistances.

Fig. 5 shows the heat flux transients estimated at the interface during solidification of aluminium in various 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 occurrence of peak heat flux could be associated with the formation of an initial solidified shell near the casting/mould interface and/or the completion of mould filling.[2,17] 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 is a consequence of the experiment and 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 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 lead 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 initial rapid reheating of the casting surface due to the transformation of the interfacial condition from a good to a nonconforming contact.

Heat flux transients were significantly higher for graphite moulds. This could be attributed to the higher thermal conductivity of the graphite. For example, the peak heat flux transients for aluminium solidifying in graphite, composite and steel moulds were 968 kW/m^2, 530 kW/m^2 and 435 kW/m^2 respectively. Fig. 7 shows the heat transfer coefficients estimated for aluminium solidifying in steel, graphite and graphite lined steel composite moulds. A peak heat transfer coefficient of around 2000 W/m^2K was obtained for graphite moulds. The occurrence of a double peak for steel moulds indicated that a longer time is needed for the formation of a stable shell during solidification against a steel mould, which has lower thermal conductivity compared to graphite. Initially a solid skin may form and remelt and the occurrence of a double peak represents this instability.

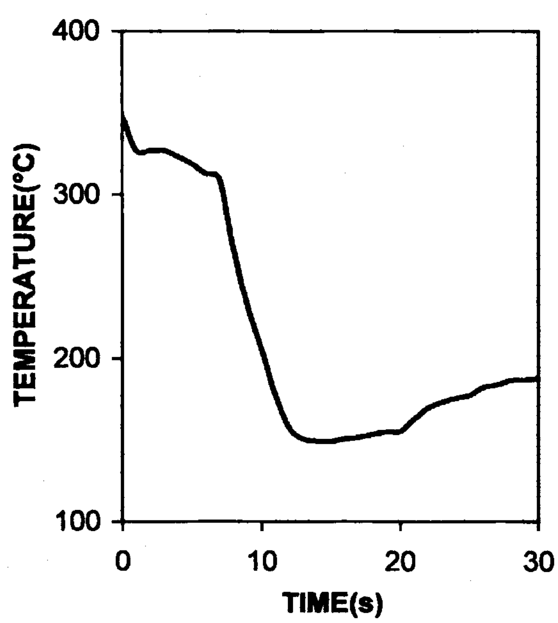

Fig. 6 Calculated casting surface temperatures during solidification of lead in a graphite mould

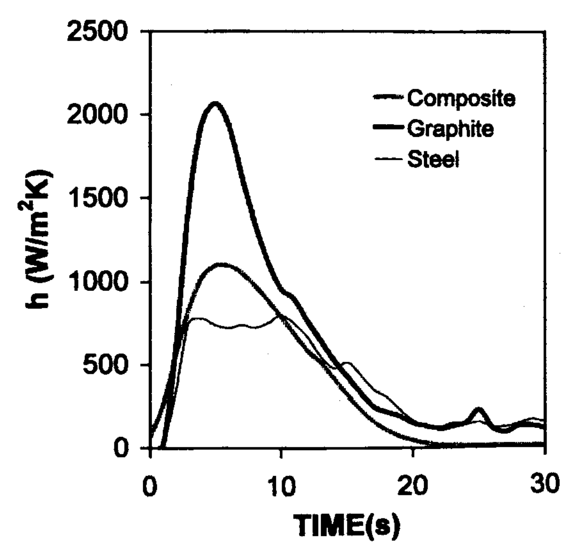

Fig. 7 Casting/mould interfacial heat transfer coefficients for aluminium solidifying in steel, graphite and graphite lined steel composite moulds

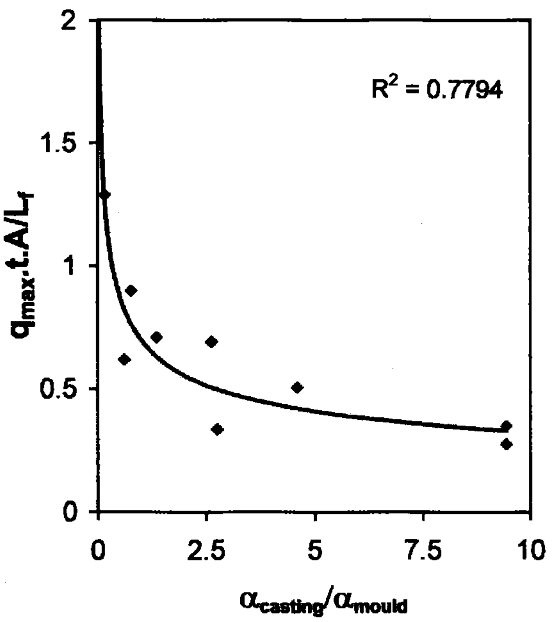

Fig. 8 Effect of $\alpha_{casting}/\alpha_{mould}$ on peak heat flux transients

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

$$\alpha_R = \frac{\alpha_{casting}}{\alpha_{mould}} \tag{6}$$

was used. The effect of α_R on peak heat flux values is shown in Fig. 8 and could be described by a regression equation of the type;

$$\frac{q_{max}}{L_f} = 12.23\left(\frac{\alpha_{casting}}{\alpha_{mould}}\right)^{-0.333} \tag{7}$$

where, L_f is the latent heat liberated and q_{max} is the peak heat transfer rate during solidification of the casting. Table 2 gives the latent heat of fusion of casting materials used in the present investigation. To make equation (7) 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 peak heat flux and the time could be considered as the heat removed during initial solidification of the casting shell. In the present investigation, the time to reach peak flux was nearly 5 seconds and the interfacial contact area

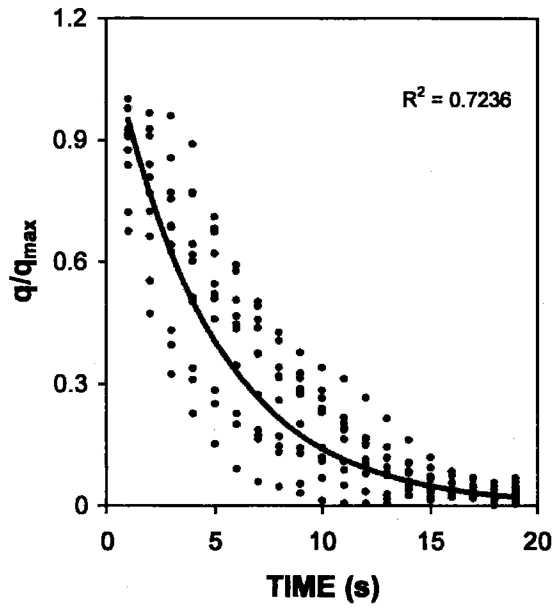

Fig. 9 Variation of normalized heat flux transients with time

was 56.55 cm^2. The resulting equation is;

$$\frac{q_{max} \cdot t \cdot A}{L_f} = 0.697\left(\frac{\alpha_{casting}}{\alpha_{mould}}\right)^{-0.333} \tag{8}$$

or approximately;

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

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 (9) can be called as a dimensionless 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 peak interfacial heat transfer coefficient (h_{max}), equation (9) could be written as;

$$\frac{h_{max} \cdot \Delta T \cdot t \cdot A}{L_f} = \frac{0.7}{\sqrt[3]{\frac{\alpha_{casting}}{\alpha_{mould}}}} \tag{10}$$

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

The heat flux was normalized with respect to peak flux and its variation with time for different metal/mould combinations is shown in Fig. 9. The variation could be

Table 2 Latent heat of fusion of casting materials[16]

Casting material	Latent heat, kJ/kg H_f	Heat content of the casting, kJ $L_f = \rho \cdot V \cdot H_f$
Aluminium	395.041	90.464
Zinc	101.951	61.685
Lead	24.693	23.681

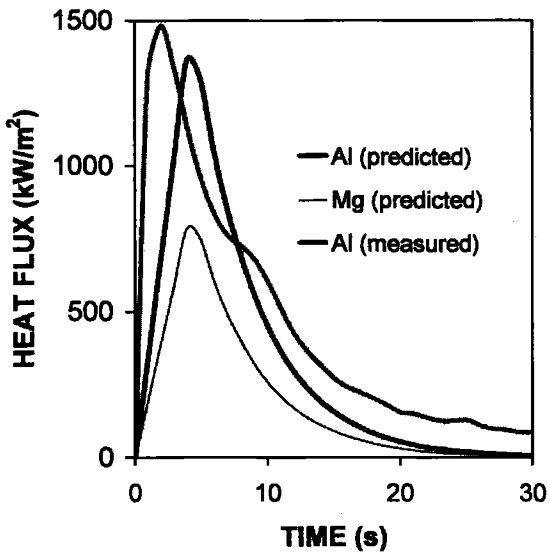

Fig. 10 Heat flux transients during solidification of Al and Mg in a graphite lined copper mould

approximated by a best-fit equation given by;

$$\frac{q}{q_{max}} = 1.18e^{-0.212t} \qquad (11)$$

Figs. 8 and 9 could be used to estimate the heat flux transients in single and composite moulds from the 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 (7).
2 The peak heat flux occurrence was taken as 5 seconds and the heat flux values for the initial 5 seconds were estimated by linear interpolation.
3 The heat flux transients after the occurrence of peak flux could be approximated using Fig. 9.

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 nonferrous 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. For example, Fig. 10 shows the heat flux values estimated for pure aluminium ($\alpha = 8.414 \times 10^{-5}$ m^2/s) and magnesium ($\alpha = 9.708 \times 10^{-5}$ m^2/s) metals solidifying in a graphite lined copper composite mould. The thermophysical properties of the graphite lined copper composite mould were computed using equation (1) and are given in Table 3. The predicted heat flux transients for pure aluminium were found to be higher than magnesium, although the thermal diffusivity ratios (α_R) for aluminium and magnesium solidifying in a similar graphite lined copper mould are nearly the same at around 0.55. This is due to the higher heat content of the aluminium test casting used in the present investigation ($L_{Al} = 90.5$ kJ) being significantly higher than the heat content of the magnesium casting ($L_{Mg} = 53.6$ kJ) of similar dimensions, that has to be extracted through the metal/mould interfacial area for the completion of solidification. The heat transfer model was also validated by estimating the heat flux transients during solidification of pure aluminium in a graphite lined copper composite mould having dimensions similar to that of the steel composite mould. The measured interfacial heat flux transients shown in Fig. 10 for aluminium solidifying in a copper composite mould proved that the heat flux transients predicted using equations 7–11 are reasonably correct.

Conclusions

Heat transfer during solidification of commercially pure aluminium, lead and zinc metals in single graphite, steel and graphite lined steel composite moulds was assessed using an inverse analysis technique. The casting/mould interfacial heat flux and heat transfer coefficients were reported for various casting/mould systems.

The peak heat flux represented the maximum heat transfer from the casting to the composite mould at the time of formation of an initial solidified shell. The time of occurrence of the peak heat flux transient was nearly five seconds after pouring. This time could be associated with

Table 3 Thermophysical properties of the casting and mould materials used in the prediction of heat flux transients[10]

Material	Density ρ (kg/m^3)	Thermal conductivity k (W/mK)	Specific heat C_p (J/kgK)	Thermal diffusivity $\alpha = k/(\rho \cdot C_p)$ (m^2/s)
Casting				
Aluminium	2707	204	896	8.418×10^{-5}
Magnesium	1746	171	1013	9.708×10^{-5}
Mould				
Copper	8960	386	383.1	11.234×10^{-5}
Graphite	1890	174.5	670	13.8×10^{-5}
Graphite-lined Copper (Composite)	3442*	254*	469*	15.74×10^{-5}

* Calculated using equation (1)

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 mould and casting. The variation of peak heat flux with the thermal diffusivity ratio (α_R) was modelled 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 0.17 and 9.4. 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 aluminium solidifying in a graphite lined copper composite mould validated the heat transfer model. A good agreement between the predicted and measured heat flux transients showed that the effect of inner lining/outer wall thermal resistance and thermocouple/mould material contact resistance on casting/mould interfacial heat transfer is negligible.

Acknowledgement

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List of symbols

A	casting/mould interfacial area (m^2)
C_p	specific heat (J/kgK)
D	mould wall thickness (m)
H_f	Latent heat of fusion (J/kg)
h	heat transfer coefficient (W/m^{2}K)
k	thermal conductivity (W/mK)
$L_f = \rho V H_f$	latent heat liberated (J)
q	interfacial heat flux (W/m^2)
$r - 1$	no. of future temperatures
t	time (s)
T	estimated temperatures (K)
Y	measured temperature (K)
α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)

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