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Assessment of Heat Transfer During Solidification of Al–22% Si Alloy by Inverse Analysis and Surface Roughness Based Predictive Model

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Abstract Heat flux transients were estimated during unidirectional downward solidification of Al–22% Si alloy against copper, die steel and stainless steel chills. The chill instrumented with thermocouples was brought into contact with the liquid metal so as to avoid the effect of convection associated with the pouring of liquid metal. Heat flux transients were estimated by solving the inverse heat conduction problem. Higher thermal conductivity of chill material resulted in increased peak heat flux at the metal/chill interface. Peak heat flux decreased when 100 μm thick alumina coating was applied on the chill surface. The lower thermal conductivity of alumina based coating and the presence of additional thermal resistance decreases the interfacial heat transfer. For uncoated chills, the ratio of the surface roughness (R_a) of the casting to chill decreased from 6.5 to 0.5 with decrease in the thermal conductivity of the chill material. However when coating was applied on the chill, the surface roughness ratio was nearly constant at about 0.2 for all chill materials. The measured roughness data was used in a sum surface roughness model to estimate the heat transfer coefficient. The results of the model are in reasonable agreement with experimentally determined heat-transfer coefficients for coated chills.

Keywords Heat transfer · Solidification · Al–22% Si alloy · IHCP · Surface roughness

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1 Introduction

Modelling of solidification of casting process requires an accurate data base on interfacial heat transfer coefficients for realistic simulation of the temperature field during both the mould filling stage and the solidification of the casting [1]. The successful simulation of the solidification not only enables modellers to accurately locate the casting defects but also enables them predict the microstructures as they depend on the temperature field in the casting. The measurement of heat transfer coefficients generally involves the use of inverse models which use the temperature field within the casting and or/mould in experimental set-ups involving unidirectional solidification [2, 3]. It is generally assumed that the heat transfer occurs only by conduction within the liquid metal. However this assumption is not valid due to liquid metal flow within the casting during pouring of the liquid metal. Further natural convection currents due to temperature gradients particularly in thick section castings cause fluid flow [4]. Thus the reported values of the interfacial heat transfer coefficients may therefore have significant errors particularly in the initial period of experimentation.

Al–Si casting alloys are most important among the various foundry alloys as they have high castability, excellent fluidity, lower coefficient of thermal expansion and comparably low melting point [5]. Alloys containing more than 12 % Si alloy are generally grouped as hypereutectic Al–Si alloys. The addition of silicon to aluminium alloy reduces the coefficient of thermal expansion, improves the wear resistance as well as the fluidity of the alloy. Applications of hypereutectic Al–Si alloys include IC engine parts, connecting rods, rocker arms, cylinder sleeves, piston rings, valve retainers, lightweight optics, and electronic packaging materials for aerospace applications [6].

In the present investigation heat transfer during unidirectional solidification of Al–22% Si alloy against a metallic chill was assessed by solving inverse heat conduction problem (IHCP) using an experimental set-up that minimized the effects of convection introduced during pouring of the liquid metal. The work also involved determination of the heat transfer coefficients using a predictive model based on the roughness of the contacting chill and casting surfaces during solidification of the alloy.

2 Experiment

The chill materials were selected in such a way to obtain different cooling rates during solidification. Copper, hot die steel and stainless steel having varying thermal conductivity were used as chill materials. Chills of dimensions 100 mm length and 20 mm diameter were used in all experiments. Three holes of diameter 1.1 mm were drilled on the cylindrical surface of the chills at distances 2, 14, and 26 mm respectively from the surface to accommodate mineral insulated thermocouples (K-type) during solidification experiments. The surface of the chill was polished using 600 grade SiC paper and the chill roughness was measured prior to the experiment by a surface profilometer (Taylor Hobson Form Talysurf 50). In order to coat the chill, it was heated to a temperature of about 150 °C and alumina coating was sprayed onto the chill surface using a sprayer. The coating thickness was maintained at about 100 µm.

The preheated refractory crucible containing about 400 g of the Al–22% Si alloy was heated to 750 °C in a electric resistance furnace and maintained at that temperature at about 20 min to ensure complete melting of the alloy. The molten alloy was degassed by introducing hexachloroethane tablets wrapped in aluminum foil into the melt. About 4 g of degasser tablet was used for degassing. The crucible containing the molten alloy was quickly transferred to the insulated base of the solidification experimental set-up and a twin-bore ceramic beaded K-type thermocouple was inserted into the melt. The instrumented chill was lowered into the crucible such that its bottom surface just comes into contact with the liquid melt. Temperature data from both casting and chill were recorded at 0.02 s interval using computerized data acquisition system (NI SCXI 1000). Experimental set-up is shown in Fig. 1. The roughness of the casting and chill surfaces were measured after completion of solidification.

The non-linear estimation of the surface heat flux from measured temperatures inside the heat conduction solid based on Beck's Method [2] was adopted in this work. The method analyses the transient heat transfer at the surface. The thermocouples located at three different locations in the chill are used to estimate the interfacial heat flux and the chill surface temperature.

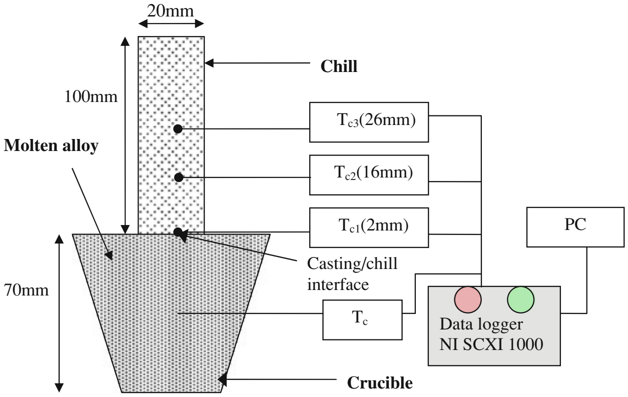

Fig. 1 Schematic sketch of the experimental set-up

3 Results and Discussion

The results of the thermal analysis experiments are presented. The cooling and heating curve obtained from the thermocouple readings for the casting and chill are plotted with respect to time. Figures 2 and 3 show the typical casting and chill thermal history during solidification of the alloy solidified against uncoated chills. The measured roughness of the uncoated chill and casting surfaces are given in Table 1. The corresponding data for the coated chills are given in Table 2. The thermal history of the

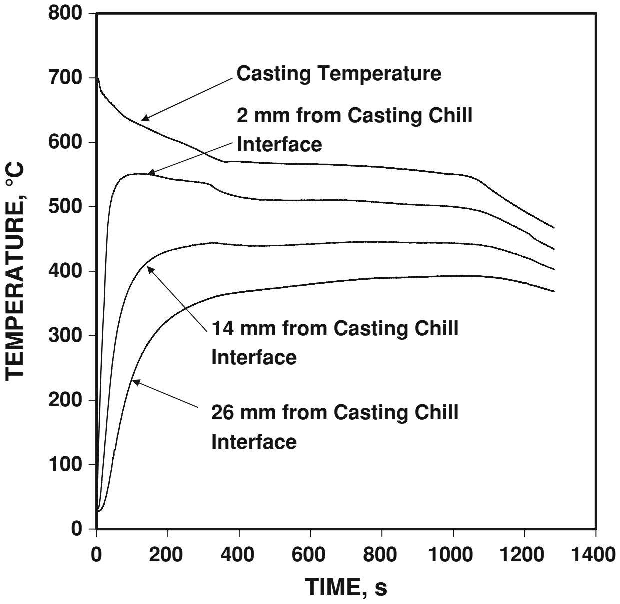

Fig. 2 Typical thermal history during solidification of the alloy against uncoated chills

unchilled alloy solidifying in a crucible was also determined.

The chill material had a significant effect on solidification time. According to results obtained from cooling curves, the high thermal conductivity chill material copper did not show considerable temperature lag between locations 2, 14, and 26 mm measured from the casting/chill interface. Copper being the metal high thermal diffusivity ($\alpha = 1.173 \times 10^{-4}$ m^2/s), extracts heat rapidly from the castings, which resulted in higher chilling effect than die steel ($\alpha = 3.44116 \times 10^{-6}$ m^2/s) and stainless steel ($\alpha = 50.34 \times 10^{-6}$ m^2/s) chills. In order to obtain better surface finish and for longer die life, die surfaces are generally coated with a coating material. A thin layer of nonconductive alumina coating on the chill surface results in significant change in cooling and heating rates compared to that for uncoated chills. It was observed that the cooling rate decreased when the chill was coated with a thin layer of alumina (thickness of about 100 μ) because of its non-conducting properties ($k_{alumina}$ at 600 °C is 9 W/mK).

Figure 3 shows the effect of chill material on surface temperatures estimated using the inverse model. The surface temperature first increases rapidly and then stabilizes to a constant value particularly for low conductivity chills. The copper chill extracts more heat from hot metal which results in small temperature gradient between chill and hot metal. On the other hand, lower thermal conductivity materials like stainless steel extracts less heat from the hot metal yielding higher surface temperatures and steeper gradient between hot metal and chill material.

Table 1 Roughness data the for castings and uncoated chills

Chill used	Chill roughness (μm)			Casting roughness (μm)		
	R_a	R_z	R_t	R_a	R_z	R_t
Copper	0.2604	1.4754	2.4871	1.7081	8.1624	12.3730
Stainless steel	1.0486	5.5251	5.5251	2.2144	10.4402	18.2882
Hot die steel	4.1736	18.3871	26.4488	2.0138	9.2268	12.1268

Table 2 Roughness data the for castings and coated chills

Chill used	Chill roughness (μm)			Casting roughness (μm)		
	R_a	R_z	R_t	R_a	R_z	R_t
Copper	13.4750	59.9605	92.1705	3.0367	12.2821	21.8402
Stainless steel	13.6456	58.8348	87.9989	2.6325	11.4823	16.0631
HDS	9.2744	35.2654	57.9707	2.2016	10.9557	19.4509

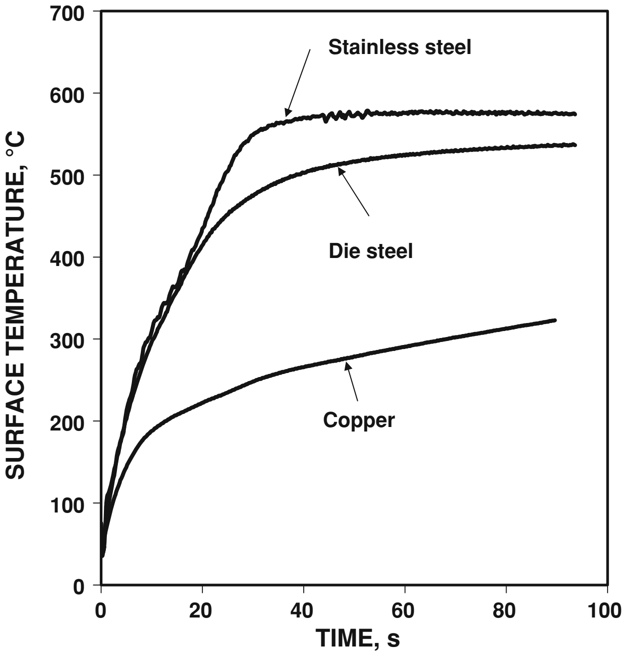

Fig. 3 Effect of chill material on estimated surface temperature for Al–22Si alloy solidified against various chill materials

The estimated heat flux transients for uncoated and coated chill materials are shown in Figs. 4 and 5 respectively. The heat flux increased rapidly and reached a peak value after a time of about 10 s and then decreases gradually. Liquid metal first spreads throughout the contact surface of the chill resulting in the rapid increase of heat flux. Due to conforming contact, the heat is extracted rapidly from the casting surface by the chill. As a result liquid metal at the contact surface solidifies rapidly, forming a thin layer of solidified metal at the casting/chill interface. However, the weak solidified thin shell may be pushed against the chill surface by metallographic pressure of the liquid metal, which may result in an intimate contact between chill surface and casting skin. Since good contact is made between the casting skin and chill, heat flux rises to a maximum value. As the thickness of the solidified shell increases with time, it gains strength to resist metallostatic pressure. This results in contraction of casting skin away from the chill, leading to nonconforming contact at the interface. Heat flux drastically decreases due to transformation of casting/chill interfacial condition, from conforming contact to non conforming contact [8]. Low conductivity stainless steel chill showed a double peak. This indicates delayed formation of the stable shell. The peak heat fluxes obtained under different chill conditions are given in Table 3. A typical plot showing the effect of coating on heat flux transient is shown in Fig. 6. It is clear that the chill coat decreases the peak heat flux by over 40 %. The effect is more pronounced in the case of low conductivity stainless steel chill.

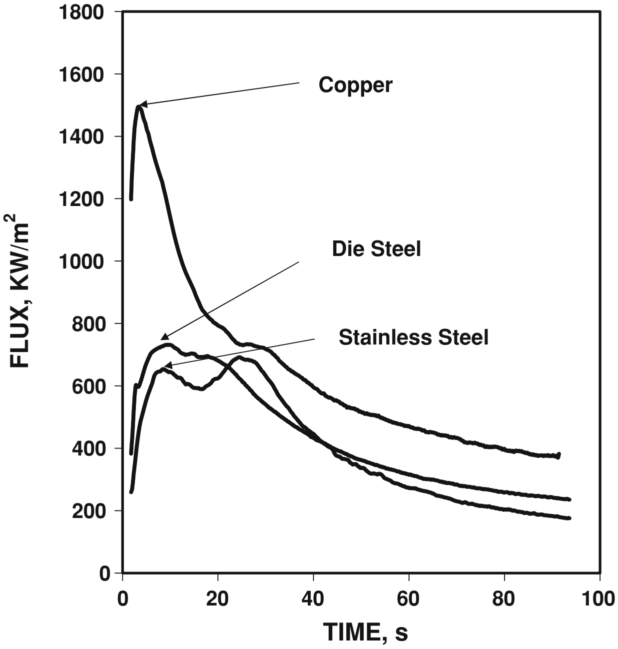

Fig. 4 Variation of estimated heat flux for uncoated chill materials

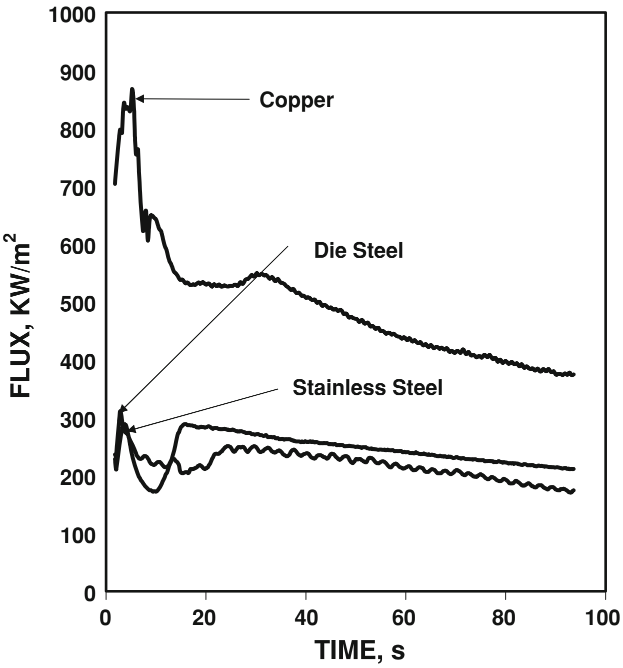

Fig. 5 Variation of estimated heat flux for coated chill materials

Table 3 Estimated peak heat flux values for various chill materials

Chill used	q_{max} (kW/m^2) uncoated	q_{max} (kW/m^2) coated
Copper	1,630	944
Hot die steel	734	397
Stainless steel	665	317

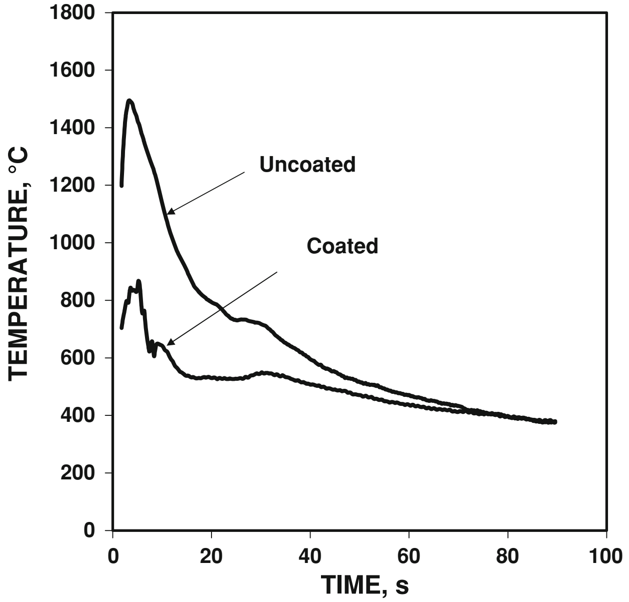

Fig. 6 Effect of coating on heat flux transients during solidification against coated copper chill

For uncoated chills, the ratio of the surface roughness (R_a) of the casting to chill decreased from 6.5 to 0.5 with decrease in the thermal conductivity of the chill material. However when coating was applied on the chill the surface roughness ratio was nearly constant at about 0.2 for all chill materials. Surface roughness is one of the parameters that affects the heat transfer coefficient. The roughness data was used to find the heat flux value by using predictive model [7]. The heat transfer owing to conduction was calculated by using the sum surface roughness given by

$$R_{z(\sum)} = \left(R^2_{z\,(casting)} + R^2_{z\,(chill)}\right)^{1/2}$$

Roughness dependent heat transfer coefficient due to conduction was estimated as,

$$h_c = \frac{k_g}{X}$$

where, k_g is the thermal conductivity of air at casting/chill interface temperature and X was calculated as

$$X = \frac{R_{z(\sum)}}{2}$$

From the estimated h_c the value the heat flux was computed as,

$$q_{\max} = h_c \times (T_c - T_{sur})$$

where, q_{max} is the peak heat flux and h_c is the heat transfer coefficient by conduction, T_c and T_{sur} are the casting and chill surface temperatures respectively. The heat transfer coefficient due to radiation (h_r) was neglected because of the lower temperatures involved with Al–Si alloys.

Table 4 Heat transfer coefficients estimated using a predictive model based on surface texture for the alloy solidifying against uncoated chill materials

Chill used	$R_{z(sum)}$ (μm)	T_{sur} (°C)	k_{air} (W/mK)	$h_c = k_{air}/X$ (W/m^{2}K)	$q_{max} = h_c \times (T_c - T_{sur})$ (kW/m^2)
Copper	8.2946	156	0.035511	8,562	3,587
Stainless steel	11.812	193	0.036796	6,230	2,379
Hot die steel	20.5722	265	0.03921	3,812	1,182

Table 5 Heat transfer coefficients estimated using a predictive model based on surface texture for the alloy solidifying against coated chill materials

Chill used	$R_{z(sum)}$ (μm)	T_{sur} (°C)	k_{air} (W/mK)	$h_c = k_{air}/X$ (W/m^{2}K)	$q_{max} = h_c \times (T_c - T_{sur})$ (kW/m^2)
Copper	36.928	65	0.032295	1,749	892
Stainless steel	59.9448	217	0.037611	1,255	449
HDS	61.2055	88	0.033104	1,082	526

Tables 4 and 5 give the heat transfer coefficients estimated for the alloy solidifying against uncoated and coated chills respectively. Peak heat flux of the alloy solidified against coated chill estimated by using the roughness model was reasonably in good agreement with peak flux calculated by the inverse model particularly for coated chills.

4 Conclusions

Heat transfer during downward solidification of Al–22Si alloy against chills having varying thermal conductivity was assessed using an inverse model. Chilling and coating on the chill surface improved the surface finish of castings. For uncoated chills, the ratio of the surface roughness (R_a) of the casting to chill decreased from 6.5 to 0.5 with decrease in the thermal conductivity of the chill material. The surface roughness ratio was nearly constant at about 0.2 for coated chills. materials. A predictive heat transfer model based on sum surface roughness of the casting and chill was used to estimate the heat transfer coefficient. A good agreement is found between the modelled and experimentally determined values in castings solidified against coated chills.

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