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Effect of modification melt treatment on casting/chill interfacial heat transfer and electrical conductivity of Al–13% Si alloy

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Abstract

For successful modelling of the solidification process, a reliable heat transfer boundary condition data is required. These boundary conditions are significantly influenced by the casting and mould parameters. In the present work, the effect of sodium modification melt treatment on casting/chill interfacial heat transfer during upward solidification of an Al–13% Si alloy against metallic chills is investigated using thermal analysis and inverse modelling techniques. In the presence of chills, modification melt treatment resulted in an increase in the cooling rate of the solidifying casting near the casting/chill interfacial region. The corresponding interfacial heat flux transients and electrical conductivities are also found to be higher. This is attributed to (i) improvement in the casting/chill interfacial thermal contact condition brought about by the decrease in the surface tension of the liquid metal on addition of sodium and (ii) increase in the electronic heat conduction in the initial solidified shell due to change in the morphology of silicon from a acicular type to a fine fibrous structure and increase in the ratio of the modification rating to the secondary dendrite arm spacing.

Keywords: Modification; Chilling; Heat transfer; Modification rating; DAS; Electrical conductivity

1. Introduction

The success of simulation based process design of castings to predict accurately the thermal history and to locate hot spots inside the casting depends to a large extent on a reliable data base on the heat transfer boundary conditions specified at the casting/mould interface [1–3]. Further, when the metal and the mould have good rates of conductance, the boundary between the two becomes the region of dominant resistance [4]. Gravity die casting, pressure die casting and continuous casting are some of the processes where the product quality is affected by interfacial heat transfer conditions [5].

Modelling of the casting/mould interfacial heat transfer is one of the critical problems in numerical simulation of casting solidification as it is influenced by casting parameters like the type of alloy, super heat, latent heat of fusion and mould variables that include the roughness of the mould surface in contact with the solidifying alloy, thermophysical properties of the mould, preheat temperature etc [6–9]. However, the effect of melt treatments like modification and grain refinement on the casting/mould interfacial heat transfer is yet to be investigated. For example in cast Al–Si alloys, the coarse silicon present is undesirable as it results in poor mechanical properties. The coarse acicular Si morphology can be transformed into a fine fibrous structure by proper melt treatment techniques like addition of elemental sodium, antimony, salts of sodium and use of master alloys containing strontium. The process is called ‘modification’ since it modifies the growth of the eutectic silicon to produce an irregular fibrous form rather than the usual acicular structure [10]. The modification treatment of the Al–Si alloy leads to a considerable improvement in elongation and strength.

Similarly dendrites of aluminium can be refined by proper casting conditions. One way of refining alumi-

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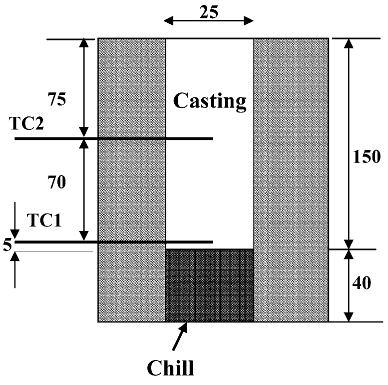

All dimensions are in mm

Fig. 1. Schematic sketch of the experimental set-up.

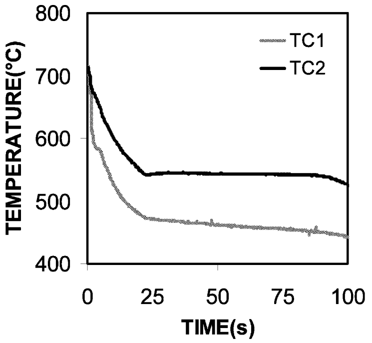

Fig. 2. Thermal history inside the unmodified casting solidifying against a copper chill.

nium dendrite structure is by the addition of grain refiners or by enhanced heat transfer to the mould during solidification of the casting. Metallic chills are generally used to achieve directional solidification. The dendrite refinement and the modification melt treatment result in finer microstructures with fibrous silicon, which lead to better mechanical properties.

It is also observed that the modifier efficiency improves in the presence of a chill [11]. Since the modification treatment procedure significantly alters the solidification behaviour of the alloy, it could also influence the casting/chill interfacial heat transfer by affecting the casting/mould contact condition during solidification of the alloy. Under these conditions the boundary heat flux transients estimated for an untreated alloy may not be suitable for the simulation of solidification of the same alloy subjected to melt treatment. In this work, the effect of sodium modification melt treatment on casting/mould interfacial thermal contact conductance during solidification of an Al–12.9% Si alloy cast against metallic chills is investigated using an inverse modelling approach.

2. Experimental

The composition of the alloy (wt.%) used in the present investigation is given in Table 1. A schematic sketch of the experimental set up consisting of a sand mould with chill in position is shown in Fig. 1. The sand mould was prepared by CO_2 process.

Two calibrated K-type thermocouples (TC1 and TC2) of 0.45-mm diameter and 20-cm length protected in twin bore ceramic beads were placed at two different locations inside the casting to monitor the casting solidification. The thermocouples were connected to a portable temperature data logger. The alloy was melted in an electric resistance furnace. The melt was degassed using hexachloroethane tablets. The dross was removed from the melt surface and calculated amount (0.1 wt.%) of metallic sodium was added. The melt was stirred for achieving uniform distribution of the modifier in the melt. The holding time of melt was around 3 min and the crucible was removed from the furnace at a melt temperature 720 °C for pouring. The temperature was logged for every 0.2 s during solidification of the casting. The thermal history recorded was used for the estimation of the casting/chill interfacial heat flux transients.

3. Results and discussion

Figs. 2 and 3 show the cooling curves measured inside a solidifying Al–Si alloy without sodium and doped with 0.1% Na cast against a copper chill, respectively. TC1 and TC2 show the temperature at locations 5 and 75 mm from the casting/chill interface, respectively. Similar cooling curves are obtained during solidification against steel chill. It is evident from the figures that the modification process results in the depression of the eutectic arrest. The cooling curves are used to calculate the cooling rates at the corresponding locations inside the casting. Figs. 4 and 5 show the effect of sodium doping on the cooling rates at location TC1 during solidification against copper and steel chills, respectively.

It is observed that modification melt treatment increased the melt cooling rate significantly in the region

Table 1
Composition of Al–13% Si alloy

%Si	%Cu	%Fe	%Mn	%Mg	%Zn	%Ni	%Sn	%Pb	%Ti	%Al
12.976	0.056	0.466	0.229	0.599	0.050	< 0.010	< 0.010	0.014	0.008	balance

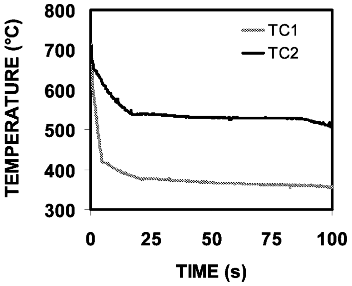

Fig. 3. Thermal history inside the modified casting solidifying against a copper chill.

of casting/chill interface. This effect was not observed for unchilled castings. The use of chills increases the freezing rate and promotes directional solidification. In the presence of chemical modifier, it is known that both the twinning frequency and the angle of branching increase with freezing rate which promote modification and lead to fine structures. The modification process is accompanied by an increase in the undercooling for nucleation of the eutectic, depression of the eutectic temperature and increase in the eutectic undercooling time [12,13]. The present work shows that in chilled castings the modification process also results in an increase in the cooling rate at locations near to the chill compared to unmodified castings. The modification and the chilling process have a synergistic effect on the rate of cooling of the alloy. However, this effect is observed only in the vicinity of the chill and disappears at locations far away from the casting/chill interface since the chilling efficiency decreases at locations far away from the interface. Durham and Berry observed that the effect of casting/chill interfacial contact conductance is only upto a distance of 5 cm from the surface and decreases markedly as the solidification front progresses further into the casting [14]. The instantaneous cooling rates for the modified alloy between temperatures 600 and 500 °C are found to be approximately 50 °C s^{-1} with copper chills. This is around 25–30 °C s^{-1} for steel chills. For the unmodified alloy the cooling rates are less than 20 and 10 °C s^{-1} for copper and steel chills, respectively. The effect of modification melt treatment on the cooling curve of the alloy is significant. For example, the time taken for the modified alloy to cool from 717 to 559 °C was only 1.8 s. In the non-modified condition the alloy took about 7 s to cool to a similar temperature. The corresponding cooling rates are estimated to be around 87 and 23 °C s^{-1}. For steel chill, the estimated cooling rates for the modified and unmodified alloy to cool from a pouring temperature of 715 to 563 °C were found to be 51 and 15 °C s^{-1}, respectively. With both copper and steel chills, it was observed that the modification treatment increases the cooling rate of the solidifying alloy near the chill by about 350%. The cooling rates are found to be lower at around 6 °C s^{-1} at a distance of 75 mm from the surface for both modified and unmodified alloys.

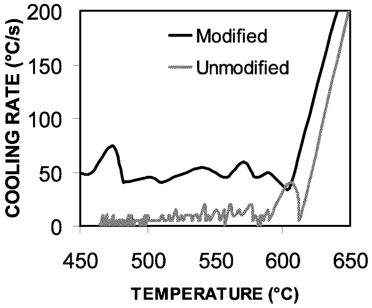

Fig. 4. Cooling rate vs. temperature at location TC1 during solidification against copper chill.

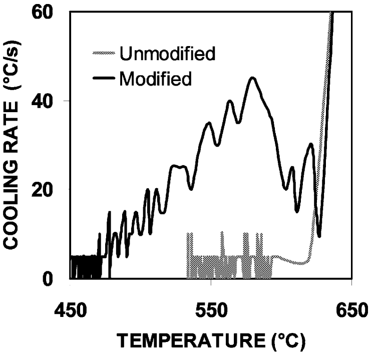

Fig. 5. Cooling rate vs. temperature at location TC1 during solidification against steel chill.

To estimate the interfacial heat flux transients, the temperatures monitored at two different locations inside the casting are used as an input to an inverse heat conduction model. The mathematical description of inverse heat conduction problem (IHCP) is given in Ref. [15]. The liberation of latent heat during solidification was modelled using the 'equivalent degree' method [5]. The heat flux transients estimated by solving the IHCP are shown in Figs. 6 and 7.

The addition of sodium to the melt increased the rate of heat transfer to the chill material in both the cases. For example, the mean value of the heat flux in the initial 10 s during solidification of the unmodified and

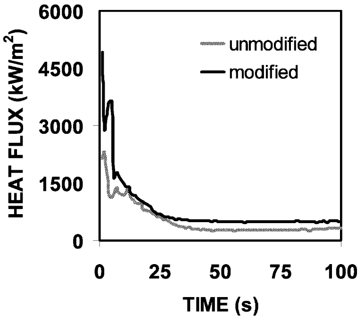

Fig. 6. Effect of modification on casting/chill interfacial heat flux transients for copper chill.

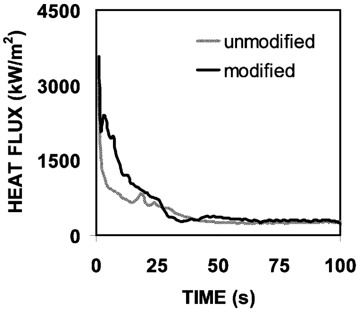

Fig. 7. Effect of modification on casting/chill interfacial heat flux transients for steel chill.

modified alloys against copper chill are 1305 and 2340 kW m^{-2}, respectively. The corresponding heat flux values for the steel chill are 1021 and 1844 kW m^{-2}, respectively. The substantial increase in the heat flow is attributed to the improved wetting of the chill surface by the liquid metal in the presence of sodium. Emadi et al. observed that the addition of 0.005 wt.% sodium decreases the surface tension of the A356 alloy by about 10% [16]. This results in improved wetting of the chill surface by the liquid metal and ensures prevailing of better thermal contact conditions at the metal/chill interface leading to enhanced heat transfer rates from the solidifying alloy to the chill material. Further, the morphology of silicon in the initial solidified shell may play a significant role in heat transfer. It has been found that the unmodified alloy has a lower electrical conductivity since the presence of coarse silicon impedes the flow of electrons. On modification, the morphology changes to a fine fibrous structure and the electrical conductivity of the alloy is found to be higher. Similarly, heat flow from the solidifying casting to the chill through the initial solidified shell with coarse silicon morphology may encounter a greater resistance to electronic heat conduction compared to the transfer of heat via a solidified shell with fine fibrous silicon morphology.

In the present work, the degree of modification measured in terms of the modification rating (MR) and electrical conductivity of the unmodified cast alloy at 5 mm from the copper chill surface are found to be 2.5 and 34% IACS, respectively. On modification, the MR increased to 5 corresponding to a fine fibrous silicon morphology and the electrical conductivity is higher at around 39% IACS. In the case of the steel chill, the corresponding values for the unmodified alloy were 1.5 and 32% IACS, respectively. The modification melt treatment increased the MR to 5 and the electrical conductivity increased to 38% IACS.

The thermal conductivity of Al–13% Si commercial alloy is 121 W mK^{-1} and its electrical conductivity is 31% IACS at 20 °C [17]. The ratio of the thermal conductivity (k) to the product of electrical conductivity and temperature (σT) for this alloy was calculated and found to be 2.3×10^{-8} W Ω K^{-2}. This value obtained for the non-modified alloy, where the contribution of acicular silicon to electronic conduction is negligible, is close to the Lorenz number (2.45×10^{-8} W Ω K^{-2}). Hence Weidemann-Franz Law, which links the thermal conductivity to the electrical conductivity, was used to find an approximate estimate of thermal conductivity of the modified alloy where the eutectic silicon due to its fibrous morphology allows easy flow of electrons. According to this law,

$$\frac{k}{\sigma T} = L$$

where k is the thermal conductivity in W mK^{-1}, T is the absolute temperature in K, σ is the electrical conductivity in Ω^{-1} m^{-1}, and L is the Lorenz number, equal to 2.45×10^{-8} W Ω K^{-2}.

The measured electrical conductivities in % IACS are converted into electrical conductivities in Ω^{-1} m^{-1} using a suitable conversion factor. These values are then substituted in the Weidemann-Franz law to calculate the thermal conductivities of the alloy at 5 mm from the casting/chill interface. The calculated thermal conductivities at the room temperature of 300 K of the unmodified alloy cast against steel chill, unmodified alloy cast against copper chill, modified alloy cast against steel chill and modified alloy cast against copper chill are found to be 136, 145, 162 and 166 W mK^{-1}, respectively.

The secondary dendrite arm spacing (DAS) decreased at locations in the casting near the chill surface. The decrease in the arm spacing decreases the eutectic pockets between the dendrite and contributes to the increase in the conductivity. Figs. 8 and 9 show the effect of the degree of modification and DAS on the measured electrical conductivity. ‘Modification Rating’ technique is generally used to assess the degree of modification and this rating system grades the silicon morphology into five classes from Class I (acicular) to Class 5 (fine fibrous) structures. MR is then calculated as, MR = Σ(fraction of each class of structure × respec-

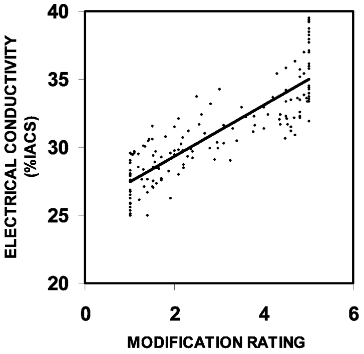

Fig. 8. Electrical conductivity vs. MR.

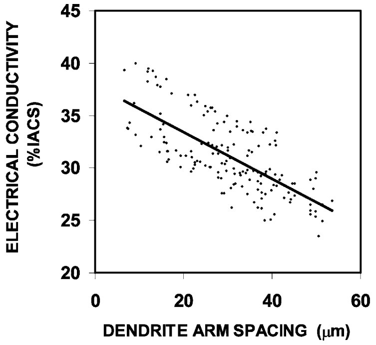

Fig. 9. Electrical conductivity vs. secondary DAS.

tive class). The secondary DAS is measured to assess the refinement of aluminium dendrites. With the use of chills and on modification melt treatment the degree of modification increases. On the other hand, due to the increased heat transfer rates associated with chills, the DAS decreases. A scatter is observed in the measured electrical conductivity as Figs. 8 and 9 do not take into account the variation of DAS and the degree of modification respectively. For example, a fully modified structure with a MR of 5 having coarser dendrites results in lower electrical conductivity compared to a fully modified structure having the same rating but with a finer DAS. The electrical conductivity increases with increase in the degree of modification and decrease in the arm spacing. This implies that ratio of the modification rating to the secondary dendrite arm spacing (MR/DAS) plays a major role in deciding the conductivity of the material. The variation of the electrical conductivity with MR and secondary DAS is quantified by a microstructure parameter (MR/DAS) defined as the ratio of the modification rating to the secondary dendrite arm spacing. The variation of the proposed parameter with electrical conductivity is shown in Fig. 10 and could be described a best fit-equation given by,

$$\text{Electrical conductivity, } \sigma(\%\ \text{IACS}) = 18.848(\text{MR}/\text{DAS})^{0.1104}$$

where MR/DAS is in nm^{-1}. The correlation coefficient of the above equation was estimated to be 0.82. The new parameter could be utilized for nondestructive evaluation of quality of Al–Si alloy castings. Since the electrical conductivity varies with MR/DAS, it could be concluded from Weidemann-Franz Law that the thermal conductivity is also affected by this microstructure parameter. In the present work this ratio was found to be 92 nm^{-1} for the unmodified chilled against steel chill at a location 5 mm from the interface and the ratio increased sharply to 419 nm^{-1} when the alloy was doped with sodium. The corresponding ratios for the alloy solidifying against copper chill were found to be 338 and 769 nm^{-1}, respectively.

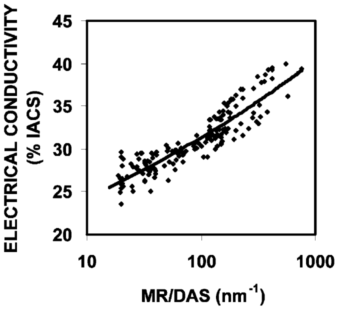

Fig. 10. Variation of electrical conductivity with MR/DAS.

Thus during modification melt treatment the following two phenomena can occur compared to the unmodified alloy. One is the lowering of the surface tension of the melt leading to improved wetting. The other is the increase in MR/DAS ratio of the solidified shell. The first phenomenon improves the thermal contact conductance at the interface. The second phenomenon reduces the thermal resistance to heat transfer in the initial solidified shell. The combined effect of the two phenomena is the higher heat transfer rate from the solidifying casting to the chill surface resulting in increased casting cooling rates in the interfacial region. The effect of modification melt treatment on the casting/chill interfacial contact condition is shown schematically in Fig. 11. The increased heat flow rates obtained with copper chills is due to its higher thermal conductivity ($k_{\text{copper}} = 383\ \text{W mK}^{-1}$) compared to that of the steel chill ($k_{\text{steel}} = 42\ \text{W mK}^{-1}$).

4. Conclusions

The modification melt treatment in chill castings has a significant effect on the casting/chill interfacial heat transfer. With both copper and steel chills, it was observed that the modification treatment increases the cooling rate of the solidifying alloy near the chill by about 350%. Modification and chilling have a synergistic effect in increasing the rate of heat transfer from the solidifying casting to the chill material. It implies that the modification melt treatment also improves the efficiency of the chilling ability of a mould. This is attributed to the increased ability of the liquid metal to wet the chill surface due to decrease in its surface tension on addition of the chemical modifier. The fine fibrous morphology of silicon of the initial solidified shell in the modified condition and the increased ratio of the MR/DAS in the casting/chill interfacial region also facilitates the rate of heat removal from the casting by increasing the electronic heat conduction. The study brings out the effect of modification and chilling on both casting/chill interfacial heat transfer and electrical conductivity.

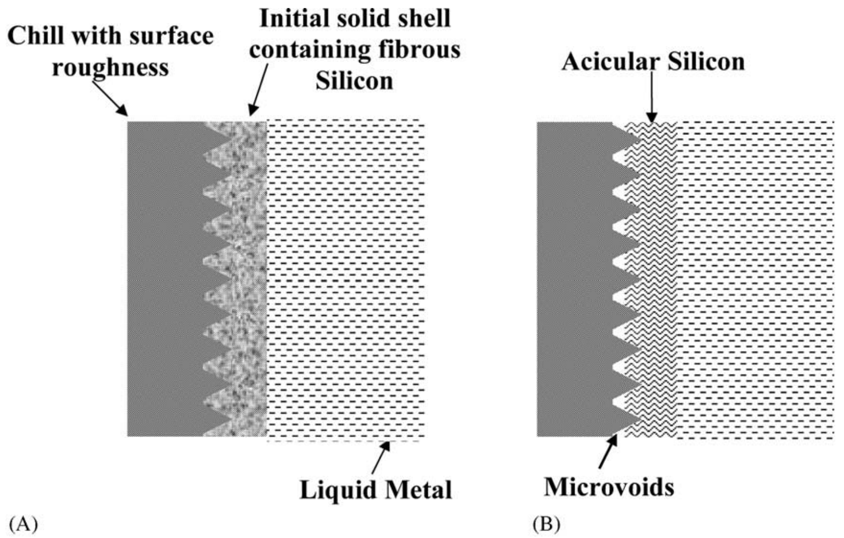

Fig. 11. Schematic representation of the effect of modification on the casting/chill interfacial thermal contact condition. (A) Modified—*Better thermal contact due to lower surface tension*; *fine fibrous silicon morphology facilitates electronic heat conduction*. (B) Non-modified—*Poor thermal contact due to higher surface tension*; *coarse silicon morphology impedes electronic heat conduction*.

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