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Effect of section thickness and modification on thermal analysis parameters of A357 alloy

S. Hegde, G. Kumar and K. N. Prabhu*

Thermal analysis technique relies on the cooling curve obtained when the sample is cooled in a sampling cup. This may not represent the cooling behaviour of the real casting. The microstructure developed during solidification depends not only on the nucleation and modification potential of the melt but also on the thermal gradient imposed during solidification by the mould. The factors affecting the thermal gradient are the mould material and casting section thickness. In the present investigation the effect of modification melt treatment, cooling rate and casting section thickness on the thermal analysis parameters of A357 alloy was studied. It is found that the dimensionless heat flux parameter is high for small section thickness castings. The metal/mould interfacial heat flux is high in a copper mould. Thermal analysis parameters of A357 alloy are found to be affected significantly by the combined action of modification, chilling and section thickness.

Keywords: Modification, Thermal analysis, Section thickness, Heat transfer

Introduction

Melt quality control plays a significant role in producing high quality, zero defect castings. In the case of Al–Si alloys an important contributor is the level of modification of the melt before pouring. Conventionally the degree of modification is assessed after pouring, by microscopic examination of solidified castings. This is time consuming and the melt quality may deteriorate after the sample has been taken.

In contrast, the thermal analysis technique has been recognised as an efficient non-destructive tool to assess the degree of modification in Al–Si alloys.[1,2] The technique monitors the temperature changes in a sample as it cools through phase transformation intervals and is usually represented by a temperature time cooling curve.[3] The evolution of heat reduces the cooling rate, and may be sufficient to establish a thermal arrest point in the cooling curve. These changes of slope and arrest points are characteristic of transformation and reaction occurring during solidification.[4] Correlation of these characteristic points referred to as thermal analysis parameters, together with the observed microstructure, permit the foundryman to monitor the quality of the melt.[5]

Modifiers alter the growth mechanism of the eutectic silicon crystals. The reason for change in this growth mode is not completely clear. The modifier changes both the nucleation and growth mechanism of silicon with a corresponding change in the nucleation and growth temperature. Both are lowered by 6–10°C when the alloy is properly modified.[6] It is also observed that with an increase in cooling rate the eutectic nucleation temperature drops by up to 15°C.[7]

In practical applications the thermal analysis parameters depend on not only the amount of modifier but various other parameters such as alloying additions, impurities present in the melt, cooling rate[8–11] and melt superheat, etc. Previous studies have shown that there is no linear relationship between the eutectic depression and amount of modifier.[12]

The conventional thermal analysis technique relies on the cooling curve obtained when the sample is cooled in a sampling cup. This may not correlate with the actual casting, because the microstructure developed during solidification depends not only on the nucleation and modification potential of the melt but also on the thermal gradient imposed during solidification by the mould. The factors affecting the thermal gradient are the mould material and casting section thickness. If the thermal analysis technique is to be used for permanent mould casting each characteristic thermal analysis parameter must be established at an appropriate rate to define the state of modification.

In the present investigation, the effects of modification melt treatment and cooling rate on thermal analysis parameters were studied for the alloy A357 treated with a predetermined quantity of metallic sodium to cause modification. The cooling rate was varied by pouring the molten alloy into moulds with different thermal conductivities k. The moulds used were permanent moulds of stainless steel (k=16 W m^{-1} K^{-1}) and copper (k=383 W m^{-1} K^{-1}). The effect of section thickness was studied by varying the diameter of the mould. Cylindrical moulds with diameters of 50 and 30 mm were used.

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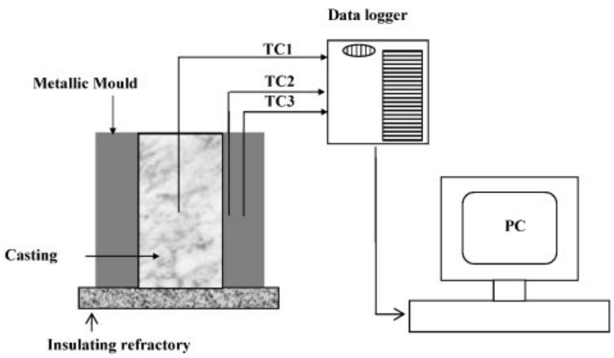


1 Schematic sketch of experimental set-up

Experimental

The composition (wt-%) of the A357 alloy used in these experiments is given in Table 1.

About 750 g of alloy was melted in a resistance heated furnace using a graphite crucible. The melt was degassed at ~700°C using hexachloroethane degassing tablets. After degassing, a predetermined quantity of elemental sodium (0·015%) was added to the molten alloy at 720°C and the melt was held for 4–5 min for effective modification. The melt was poured into moulds. To achieve different cooling rates copper and stainless steel cylindrical moulds of 30 mm thickness and 120 mm height were used. To study the section thickness effect the moulds used were of 50 and 30 mm i.d.. The experimental set-up is shown in Fig. 1. Three calibrated K type thermocouples were used to record temperature data for thermal analysis. A twin bore ceramic beaded thermocouple was placed in the geometrical centre of the mould to monitor the thermal history of the solidified melt. The mould was instrumented with two stainless steel sheathed thermocouples to obtain the thermal history of the mould. This data was used for an inverse analysis to calculate the heat flux.[13] The thermocouples were connected to a high speed online data acquisition system NI SCXI 1000. Temperature data was acquired at 100 samples/second. Metallographic test specimens were prepared using a section from the geometric centre of the casting. The sections cut from samples were metallographically polished and etched. The samples were then subjected to microexamination.

Results and discussion

Figures 2 and 3 show the cooling behaviour of A357 alloy solidified in stainless steel and copper moulds for casting sections of 50 and 30 mm in the unmodified and modified conditions. Both in unmodified and modified conditions the casting of smaller section solidified rapidly as expected. However, the arrest point was not clearly observed for the conditions of fast cooling for the casting solidified in the 30 mm copper mould.

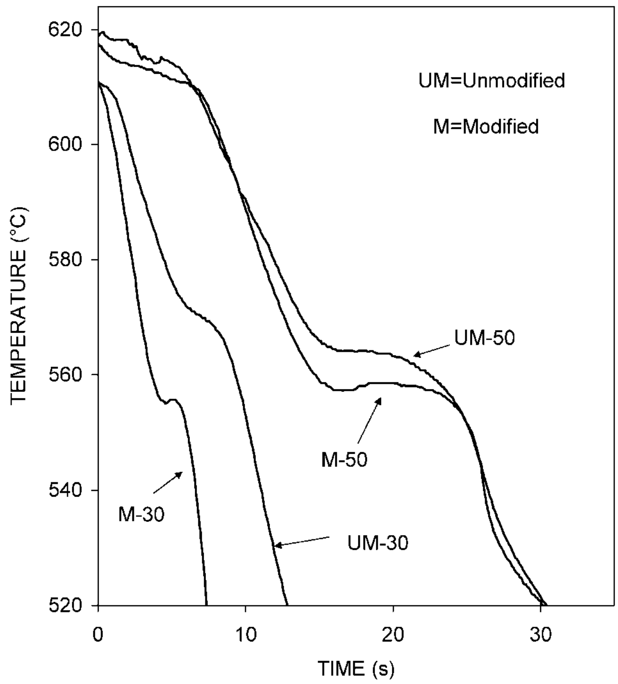
From the thermal analysis curves it is evident that the section thickness has a profound effect on the thermal analysis parameters. As the cooling rate (CR) increases, the thermal parameters like eutectic depression ΔT_G increases, eutectic arrest time θ and total solidification time decreases. The effect of modification on thermal analysis parameters is summarised in Table 2.

It is observed that there is a drastic reduction in eutectic arrest time with decrease in section thickness. For example, for the modified alloy solidified in the copper mould the eutectic arrest time decreased from 2·6 to 0·9 s with decrease in section thickness from 50 to 30 mm.

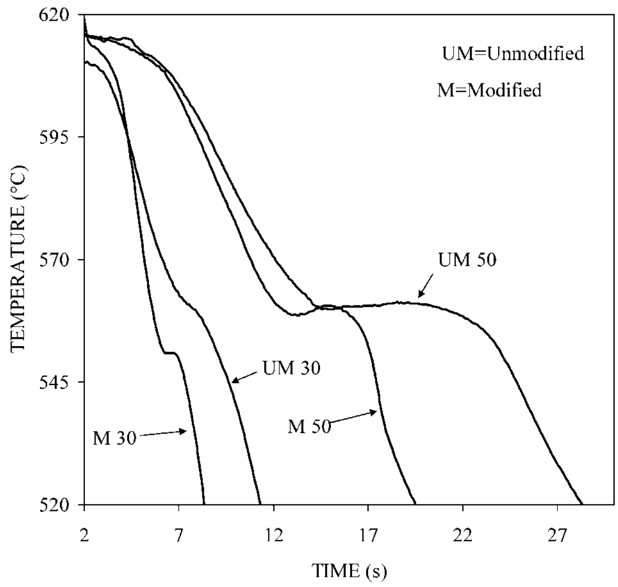
Because the solidification of the smaller section casting is faster, building up the thickness of the solidified metal more quickly, the rate of transport of heat is enhanced additionally as a result of the thermal

Table 1 Composition of A357 alloy, wt-%

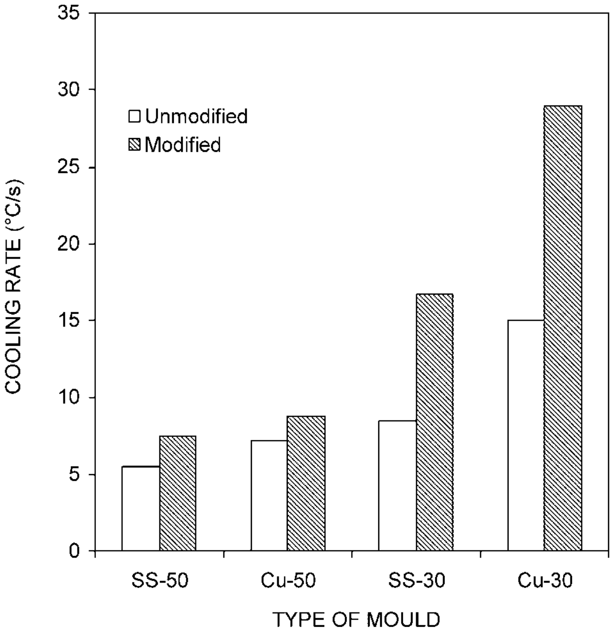
Si	Mg	Fe	Zn	Ti	Al
6·86	0·53	0·12	0·03	0·14	Bal.



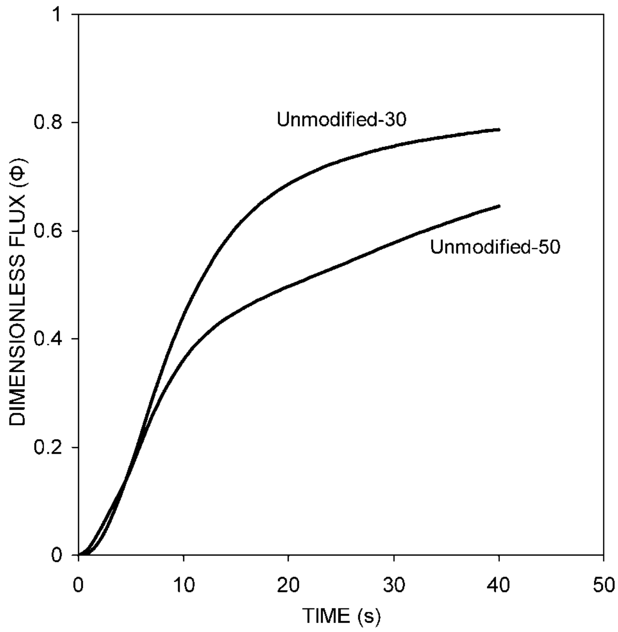
2 Thermal history obtained at casting centre in unmodified and modified melt condition for A357 alloy in 50 and 30mm stainless steel moulds



3 Thermal history obtained at casting centre in unmodified and modified melt condition for A357 alloy in 50 and 30mm copper moulds



4 Variation of cooling rate with type of mould



5 Variation of dimensionless heat flux with time for A357 alloy solidified in stainless steel moulds

conductivity of the solid metal being higher than that of the liquid metal. As a result, freezing times are disproportionally reduced.

Modification treatment of the melt results in the transformation of eutectic silicon from acicular into a fine fibrous morphology. With this morphology, the wetting of the mould wall by the melt has been claimed to be better resulting in improved surface contact.[14] If true, as a result, heat flow would be aided and hence cooling rate increased further. In any case, the castings of smaller diameter showed an increase of ~50% in cooling rate on modification. Figure 4 is a graphical representation of variation of cooling rate for castings of treated and untreated alloy poured into different sized moulds of copper and stainless steel.

Figure 5 is the comparative plot of the variation of dimensionless flux ϕ with time for the unmodified A357 castings of sections 30 and 50 mm solidified in a stainless steel mould. Figure 6 shows identical conditions for the modified alloy. The dimensionless flux is the fraction of heat transferred to the mould relative to the heat originally contained in the poured casting. It is defined as

$$\phi = \frac{\left(\int_0^t q\mathrm{d}t\right)A}{m(C_\mathrm{p}\Delta T + L_\mathrm{f})} \tag{1}$$

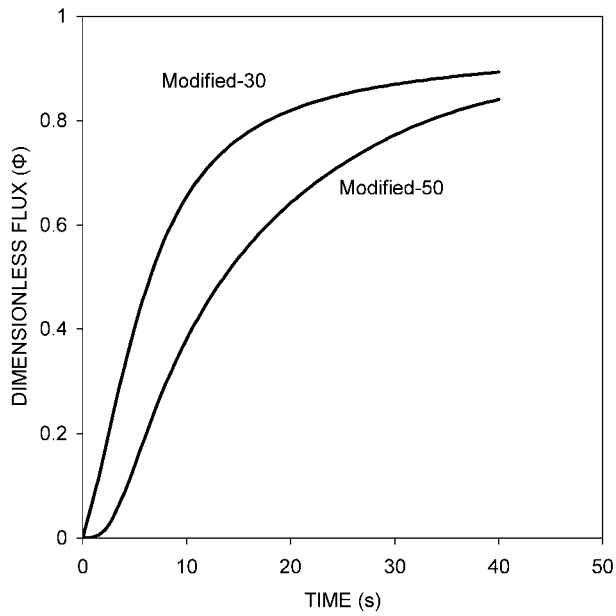
where C_p is the specific heat of the molten alloy, ΔT the superheat of the melt, L_f the latent heat of solidification, A the surface area of the mould/metal interface, $\int_0^t q\mathrm{d}t$ the total heat flux in time t. and m the mass of casting.

Table 2 Thermal analysis parameters for modified alloy

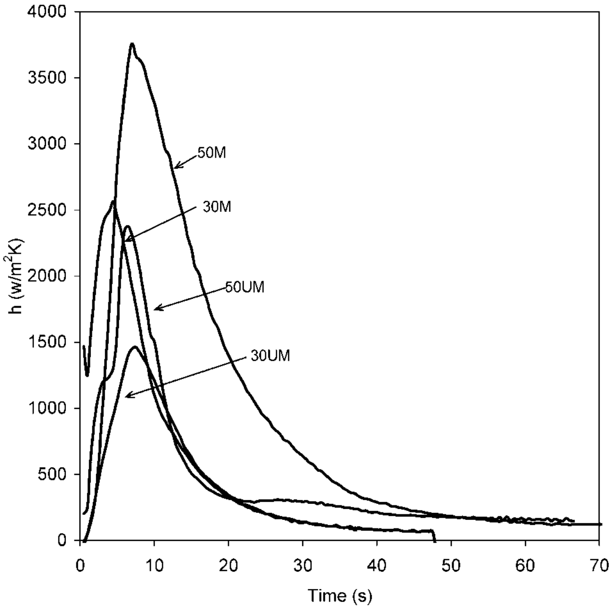
Mould	CR, °C s^{-1}	ΔT_G, °C	θ, s
SS50	7·5	7·5	7·5
SS30	16·7	10·3	1·6
Cu50	8·8	5·4	2·6
Cu30	29	15	0·9

CR: cooling rate.

It can be seen from these plots that the dimensionless flux is larger for castings of smaller section even though the absolute values of the flux are lower. The peak flux for the unmodified alloy casting solidified in the stainless steel mould of 50 mm section is 687 kW m^{-2} whereas the corresponding peak flux for the same alloy casting of 30 mm section is only ~491 kW m^{-2}. However, the dimensionless flux values in the respective cases were increased by ~15% in the smaller castings. In the case of the modified alloy solidified in the stainless steel mould, the peak heat flux values for 50 and 30 mm section were 852 and 691 kW m^{-2} respectively. The percentage increase of dimensionless flux value for 30 mm casting was ~20%, although the increase was not uniform. A similar trend was observed with the castings solidified in



6 Variation of dimensionless heat flux with time for A357 alloy modified in stainless steel moulds



7 Variation of heat transfer coefficient with time for modified and unmodified A357 alloy solidified in stainless steel moulds

the copper mould. The peak heat flux values are summarised in Table 3.

Heat transfer coefficient for the solidifying alloy is calculated as

$$h = \frac{q}{T_C - T_M} \quad (2)$$

Where q, T_C and T_M are heat flux, casting surface temperature and mould surface temperature respectively.

Table 3 Effect of section thickness, mould material and modification on peak heat flux values

Peak heat flux, kW m^{-2}	Copper		Stainless steel	
	50 mm	30 mm	50 mm	30 mm
Unmodified	761	745	687	491
Modified	1332	772	852	691

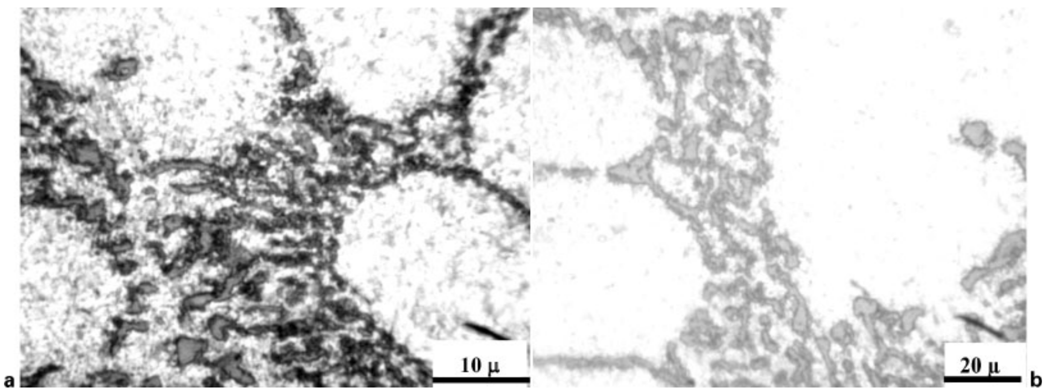
Figure 7 is the variation of heat transfer coefficient h with time for castings solidified in stainless steel mould. It is observed that with modification the peak value of h increases from 2376 to 3758 W m^{-2} K^{-1} for a 50 mm mould. A similar trend was observed with the castings solidified in other moulds. Peak heat transfer coefficient increases with section thickness and modification melt treatment.

The optical micrographs shown in Figs. 8 and 9 indicate clearly the change in silicon morphology with a decrease in section thickness and also the effect of increase in thermal conductivity of the mould material. It is evident that 30 mm copper mould yielded a highly refined structure compared with 50 mm castings with the same level of modifier.

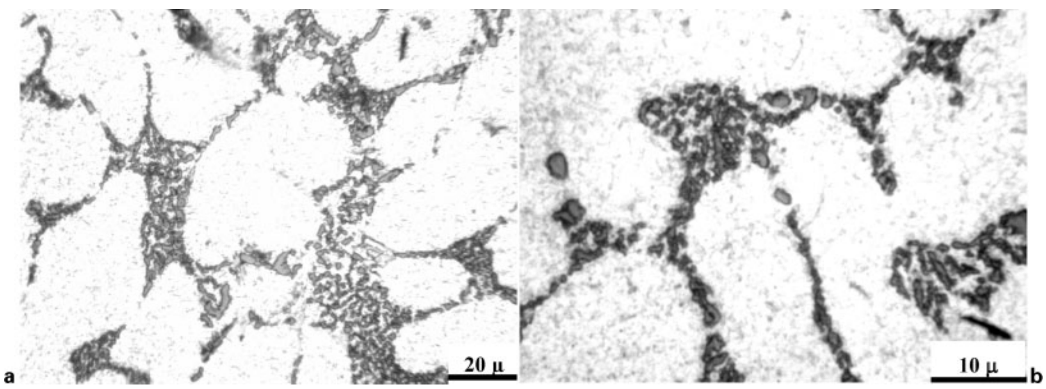
Conclusions

1. The dimensionless heat flux (the fraction of heat in the mould relative to the heat contained in the casting) is high for small section thickness castings and increases with modification.

2. Thermal analysis parameters of A357 alloy are found to be affected significantly by the combined action



8 Photomicrographs of modified A357 alloy in *a* 30 and *b* 50 mm stainless steel moulds



9 Photomicrographs of modified A357 alloy in *a* 30 and *b* 50 mm copper moulds

of modification, the chilling power of the mould and section thickness.

3. Cooling rate approximately doubles for a reduction in diameter of cast section from 50 to 30 mm.

4. The metal/mould interfacial heat flux is high in copper moulds for both values of section thickness tested here.

5. The metal/mould interfacial heat transfer increases with increase in section thickness and modification melt treatment.

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