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Solidification studies on sand cast Al 6061–SiC_p composites

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ABSTRACT

Most of the automotive components are cast and their performance depends very much on the solidification phenomenon. Solidification is primarily a process of achieving solid crystals from the liquid melt by promoting zones possessing very high cooling rates to ensure super cooling of the melt. Till date enormous data is available as regards the solidification behaviour of popular light alloys such as Al 6061 and A 356 with regard to the casting process, mould materials used and other important processing parameters. Effect of chills on the solidification behaviour of the above materials has also been reported suggesting chills to be an important promoter of directional solidification. Directional solidification results in minimized solidification defects. However, there is a lack of information regarding the effect of chills on solidification behaviour of aluminium based metal matrix composites which are currently the most potential candidate materials in automotive industries as a replacement for conventional light alloys. In the light of the above, this work is aimed at experimentally studying the solidification behaviour of Al 6061–SiC_p castings in sand mould using copper and mild steel chills. Further, commercially available finite element analysis (FEA) software has been used to predict the cooling curves with and without the use of chills for the developed composite. The experimental and predicted cooling rates of the developed composites are not in good agreement. Use of copper chills resulted in promoting higher cooling rates during the solidification of developed composites.

1. Introduction

Silicon carbide reinforced aluminium metal matrix composites are gaining popularity in the manufacture of automotive components such as valve rods, brakes and clutches owing to their excellent wear resistance and strength, higher thermal conductivity coupled with lower density [1]. Currently, these metal matrix composites are being manufactured by stir casting technique which is the simplest, economical and commercially viable fabrication method. Since solidification is involved in the above manufacturing method of composites, the prevailing cooling rates within the castings do dictate to a great extent the evolution of microstructure and its related effects on mechanical properties of the final cast products. Rajan et al. [2] have reported that higher volume fractions of SiC and graphite particles in A356 matrix alloy reduced cooling rate and liquidus temperature, and increased the total solidification time in all moulds (sand, steel and graphite). Hanumanth and Irons [3] have measured the temperature of solidifying A356/SiC_p composite with varying volume fractions of SiC particles and have reported a slight depression of the liquidus and solidus temperatures as well as a higher solidification rate compared with that of un-reinforced matrix alloy. Gowri and Samuel [4] have reported that the addition of silicon carbide particles decreased the liquidus temperature of the Al–7%Si alloy and Al–7%Si–SiC_p composite melts. The investigations carried out by Hemanth [5] have revealed that the chill material and its thickness affected the strength and soundness of aluminium alloy-quartz particulate composites cast in a mould containing metallic and non-metallic chills. Increased rate of chilling and dispersoid content of the composite resulted in an increase of ultimate tensile strength of the composite. Ramesh et al. [6] have carried out modeling studies on solidification of metal matrix composites using Fourier series technique and concluded that the predicted trend in the solidification behaviour of composites matched closely with experimental results. It is observed from previous works that information available on solidification behaviour of chilled sand cast Al 6061–SiC_p composites is limited. Further, no work has been published in the area of prediction of cooling curves during the solidification of sand cast Al 6061–SiC_p composites on use of different chills. Aluminium based composite castings have already made significant impact in automotive industries. The performance of these castings is dictated mainly by their mechanical properties which in turn depend on the way in which the castings are solidified. Change in cooling rates during the solidification of complex and intricate automotive castings do alter the

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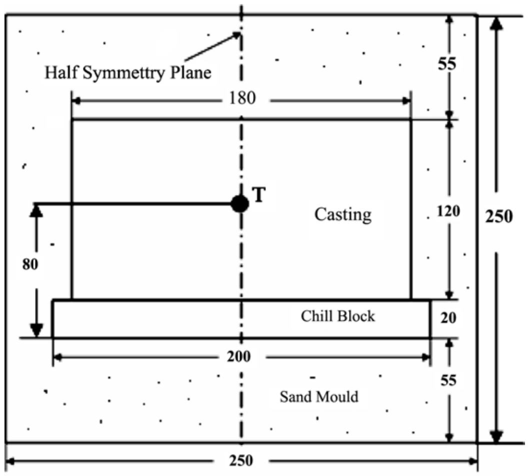

Fig. 1. Dimensions of the rectangular casting with chill block indicating thermocouple location, 'T'.

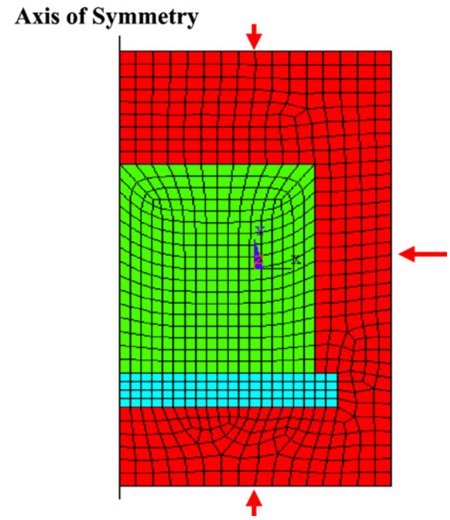

Fig. 2. Meshed finite element model of rectangular shaped casting and mould assembly with chill block.

grain size and also its other microstructural features. Experimental determination of the temperature distribution of these complex and intricate automotive castings will be challenging and tedious. However, the acquisition of this data is inevitable as it supports in redesigning of the castings for better performance. Hence, predictions of the cooling rates of castings in automotive industries gain significance leading to higher productivity with least rejections of castings. Further, the predicted cooling rates can be correlated with the grain size and in turn the strength characteristics of the castings. This aspect has not yet been explored making this study an important one. Hence, the present investigation aims at the experimental study of solidification behaviour of Al 6061–SiC_p composites in rectangular sand moulds using mild steel and copper chills. Further, commercially available finite element analysis software, ANSYS, is used to predict the cooling curves during the solidification of chilled and un-chilled sand cast Al 6061 and Al 6061–SiC_p composites.

2. Experimental methodology

Rectangular shaped green sand moulds were prepared using cope and drag boxes with end chills. The dimensions of the mould cavity with chill block and thermocouple location 'T' are shown in Fig. 1. The assembled mould was dried and then preheated to 75 °C to remove any moisture content. Stir casting technique was adopted for producing the composites as discussed elsewhere [7]. Temperature of the solidifying melt was recorded at intervals of 5 s by using K-type thermocouple located at the geometric centre of the mould cavity. A temperature data scanner was used to capture and store the signals from the thermocouple. These data were then transferred to a personal computer to plot the cooling curves. Experiments were carried out for both chilled and un-chilled sand cast Al 6061 matrix alloy and Al 6061–SiC_p composites with SiC_p percentage varying from 2% to 8% in steps of 2 wt.

2.1. Finite element model and boundary conditions

Commercially available ANSYS software (version 9.0) has been used to predict the cooling curves of solidifying Al 6061 matrix alloy and its composites. A non-linear transient thermal analysis with two-dimensional, four-noded quadrilateral solid element (PLANE 55) is considered for the finite element analysis. The analysis was carried out for half symmetry in 2-D. The meshed elements with boundary conditions applied on the casting and mould assembly are as shown in Fig. 2. The thermophysical properties of materials used in the present work are reported in Tables 1 and 2. Thermal conductivity of composites was calculated using rule of mixtures. The enthalpy of composites was assumed to be the same as that of matrix alloy, since the ceramic particles do not undergo phase change. The initial boundary conditions and convection properties adopted in the present analysis are given in Table 3. A time-history post processor was used to plot cooling curves at the specified location. Cooling curves of solidifying chilled and un-chilled Al 6061 and Al 6061–SiC_p composites were predicted for varying weight percentage incorporation of reinforcements. These were compared with the experimental cooling curves.

Table 1
Temperature dependent thermo physical properties of Al 6061 [8].

Temperature (°C)	100	200	500	600	642	700
Thermal conductivity (W/m °C)	195	203	225	200	85	90
Enthalpy (J/g)	69	166	480	596	981	1049
Density (kg/m^3)	2690	2650	2600	2589	2415	2380
Specific heat (J/kg °C)	950	1020	1150	1160	1180	1170

Table 2
Properties of sand, silicon carbide, mild steel and copper [9].

Material	Thermal conductivity (W/m °C)	Density (kg/m^3)	Specific heat (J/kg °C)
Sand	0.52	1600	1170
Silicon carbide	100	3200	1300
Mild steel	51.9	7850	486
Copper	388	8890	385

Table 3
Initial conditions and convection properties.

Initial conditions		Convection properties	
Temperature of composite (°C)	Temperature of sand (°C)	Film coefficient (W/m^2 °C)	Ambient temperature (°C)
720	75	0.01	30

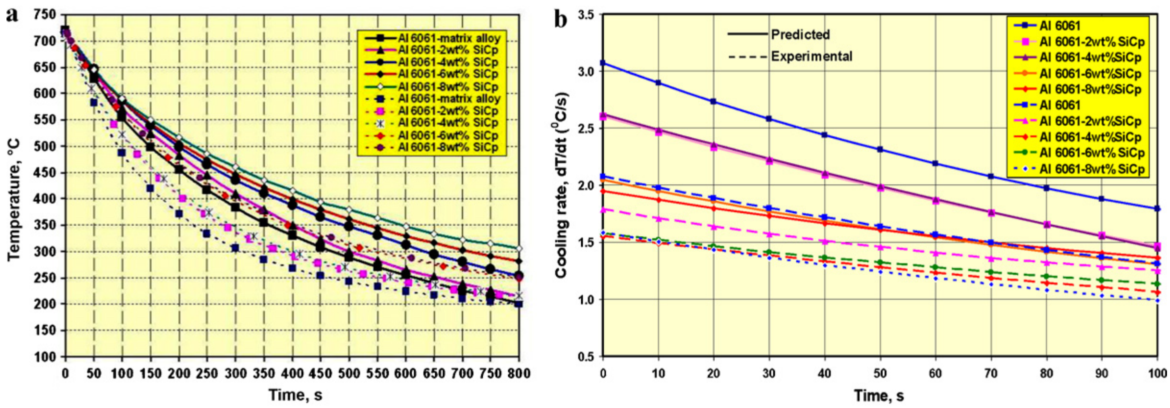

Fig. 3. (a and b) Experimental and predicted cooling curves and cooling rates of Al 6061 and Al 6061–SiC_p composites without the use of chills.

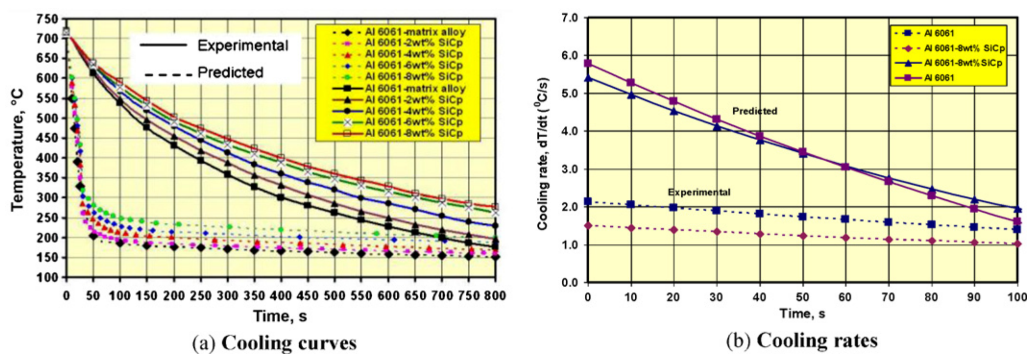

Fig. 4. Experimental and predicted cooling curves and cooling rates of mild steel chilled Al 6061 and Al 6061–SiC_p composites.

3. Results and discussion

3.1. Cooling curves without chills

Fig. 3(a) shows the cooling curves of the matrix alloy and its composites without use of chills. It is observed that the increased content of SiC particles in the matrix alloy has resulted in flattening of cooling curves indicating decreased cooling rate. This effect can be attributed to the fact that the overall thermal conductivity of the composite melt decreases with the addition of SiC particles as compared with un-reinforced Al 6061 matrix alloy. Fig. 3(b) shows the cooling rates of Al 6061alloy and its composites obtained from the derivation of the cooling curves. The initial experimental cooling rate in case of matrix alloy is found to be 2.1 °C/s. The predicted cooling rate of the matrix alloy is observed to be 3.1 °C/s. A lowest experimental cooling rate of 1.6 °C/s has been observed for Al 6061–8 wt% SiC_p composite. The predicted cooling rate of this composite is 2 °C/s. The predicted temperature at the end of 800 s have a maximum deviation of 16% and 20% for the alloy and the composites with 8 wt% SiC respectively. The deviation between the experimental and theoretical cooling rates and the predicted temperatures can be attributed to the following reasons.

(i) Probable marginal change in position of thermocouple due to buoyancy of the molten alloy.
(ii) Presence of air gaps on initial solidification which has not been accounted for in the present analysis.
(iii) Metal flow velocity, rheological behaviour of the alloy and composites are not considered in the present analysis. Flow kinetics has a strong influence in dictating the extent of heat transfer during solidification which in turn affects the cooling rate. An increase in viscosity due to increase in particle volume fraction reduces the degree of convection in composites which in turn promotes coarse grain with increased SiC content [10].

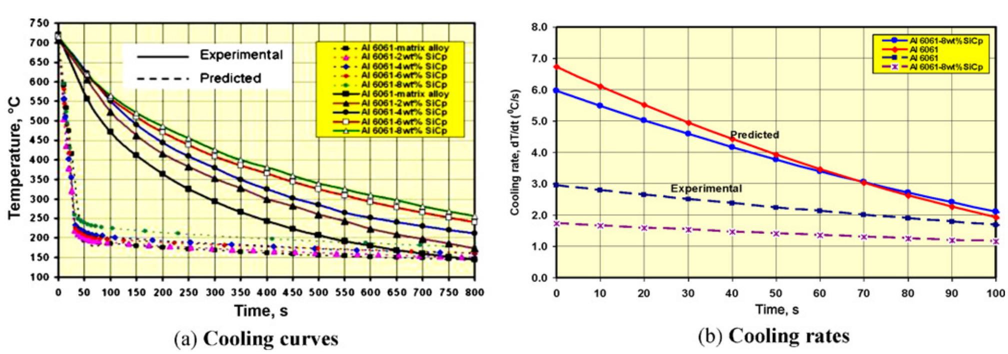

Fig. 5. Experimental and predicted cooling curves and cooling rates of copper chilled Al 6061 and Al 6061–SiC_p composites.

(iv) Particle pushing and settling in metal matrix composites have not been accounted. Increased concentration of silicon carbide particles leads to clustering of the particles. This increase in cluster size leads to the reduction in critical velocity of the solidification front which alters the kinetics of solidification in metal matrix composites. Similar observations have been observed by Youssef et al. [11].

(v) Interfacial reaction between silicon carbide and molten aluminium. It is reported from the DSC studies on Al 6061–SiC composites processed by casting technique that reaction occurs between aluminium and silicon carbide resulting in the formation of Al_4C_3 and free silicon. The released silicon alters the composition of base alloy resulting in drastic changes in the solidification kinetics of the alloy [12].

(vi) Rejection of heat by the solidifying alloy due to its latent heat results in increase in temperature of the ceramic clusters leading to slowing down of the velocity of the solidification front thereby increasing the solidification time at localized locations.

3.2. Cooling curves with chills

Fig. 4(a) shows the experimental and predicted cooling curves obtained during the solidification of mild steel chilled sand cast Al 6061 matrix alloy and Al 6061–SiC_p composites. It is observed from the figure that there is a considerable increase in the cooling rate of all castings produced on use of mild steel chills when compared with un-chilled castings. The temperature profiles of chilled castings are found to be steeper than the respective un-chilled castings. This trend is mainly attributed to the fact that mild steel, having a higher value of thermal conductivity, increases the solidification rate of the composite melt. The initial experimental cooling rates of Al 6061 matrix alloy and Al 6061–8 wt% SiC_p composite is found to be 2.5 °C/s and 1.5 °C/s respectively. The predicted cooling rates of the matrix alloy and 8 wt% SiC_p-reinforced composite are 5.8 °C/s and 5.4 °C/s respectively as shown in Fig. 4(b).

Fig. 5(a) shows the experimental and predicted cooling curves of copper chilled sand cast Al 6061 and Al 6061–SiC_p composites. It is observed from figure that there is a substantial increase in the cooling rate of all castings produced on use of copper chills. The temperature profiles of copper chilled castings are steeper than mild steel chilled castings. This is attributed to the fact that the copper chill having thermal conductivity higher than the mild steel chill extracts heat at a faster rate from the solidifying melt and hence the molten metal solidifies faster. Further, the volumetric heat capacity of copper is higher than that of mild steel due to its higher density and thermal conductivity. The initial experimental cooling rates of Al 6061 matrix alloy and Al 6061–8 wt% SiC_p composite on use of copper chill is found to be 2.9 °C/s and 1.7 °C/s respectively. A similar trend is observed in predicted cooling curves of Al 6061 and its SiC_p-reinforced composites. The predicted cooling rates of the matrix alloy and 8 wt% SiC_p-reinforced composite are 6.7 °C/s and 6 °C/s respectively as shown in Fig. 5(b). However, for a given reinforcement content, Al6061–SiC_p composite possessed lower cooling rate when compared with Al 6061 matrix alloy on use of both mild steel and copper chills. This is due to the fact that addition of silicon carbide particles into the matrix alloy retards the solidification as the overall thermal conductivity of the composite melt decreases.

4. Conclusions

Cooling curves have been experimentally recorded for chilled and un-chilled sand cast Al 6061 and Al 6061–SiC_p composites with 2–8 wt% incorporation of SiC particles. It was revealed that the temperature profiles of chilled Al 6061 and its SiC_p-reinforced composites have become steeper when compared to un-chilled castings, indicating that the solidification rate has increased substantially. The copper chills have resulted in higher cooling rates when compared with mild steel chills. Cooling curves were predicted for all the castings produced by using commercially available ANSYS finite element analysis software and compared with experimental cooling curves. The experimental and predicted cooling rates of the developed composites are not in good agreement.

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