

# Fluidity and Microstructure Formation During Flow of Al-SiC Particle Composites

F.M. Yarandi, P.K. Rohatgi, and S. Ray

This article presents the results of casting and spiral fluidity in a Al-7 wt% Si alloy reinforced with 10, 15, and 20 vol% SiC particles in permanent molds. The fluidity of the Al-SiC slurry increases linearly with temperature up to about 760 °C. Above this temperature, the casting fluidity of the Al-SiC particle slurry does not change significantly with an increase in temperature. In several cases, the fluidity decreased at temperatures above 760 °C. The fluidity of Al-SiC melts containing 9- $\mu$ m SiC particles decreased with an increase in volume percentage of SiC up to 15 vol% (the range studied), presumably due to an increase in the viscosity of the melt with increasing volume percentage of dispersoid and changes in thermophysical properties of the composite. However, the fluidity of Al-20 vol% SiC of 14- $\mu$ m particle size is higher than the fluidity of Al-15 vol% SiC 9- $\mu$ m particles, indicating the role of particle size and surface area in decreasing fluidity. Composite slurries travel farther in a channel of larger cross sections compared to channels of smaller cross sections under similar conditions. Casting fluidity increases linearly with an increase in cross section of the channel. A model has been proposed to calculate the values of fluidity of the composite as a function of particle volume percent, superheat, flow velocity of the melt, and the cross section of the flow channel. Experimental observations have been compared with the predictions of the model, and some deviations have been attributed to settling and segregation of SiC particles observed through microstructural examination.

## Keywords

aluminum, fluidity, metal matrix composites, microstructure, particles

## 1. Introduction

METAL matrix/ceramic particle-reinforced composite materials are produced mainly by powder metallurgy and casting. Casting methods of fabricating metal matrix composites (MMCs) have advantages over powder metallurgy in terms of ease of production of components with complex shapes, flexibility, and lower cost.<sup>[1,2]</sup> The casting method used to fabricate metal matrix composites<sup>[1-5]</sup> consists of mixing reinforcement particles in alloy melts and solidifying the slurry in suitable molds to produce shaped components. Some of the most common casting techniques of composite slurries include sand casting, investment casting, permanent mold casting, and pressure die casting. Ingots of selected metal matrix composites are supplied by manufacturers to foundries where they can be remelted and cast into a variety of components. Problems associated with remelting and casting of foundry ingots of MMCs are being addressed and investigated by several workers.<sup>[5,6]</sup> The ability to produce metal matrix near-net shape castings, in particular thin-walled and complex items, requires sufficient fluidity in the composite melts. In the case of composite alloys, the melt reinforcement slurry should not just be able to fill the mold, but the resultant casting should also have a uniform dis-

tribution of particles along the length and cross section of the castings.

Mollard et al.<sup>[7]</sup> states that "fluidity is simply the ability of a molten metal to fill very narrow spaces or channels," whereas Jorstad<sup>[8]</sup> defines fluidity as "a complex combination of things that determine the extent to which a molten metal can flow in a mold or die before it is too solid to flow further." Various types of test molds have been used for measuring fluidity of foundry alloys. The two most common fluidity tests are the spiral fluidity and casting fluidity tests.<sup>[9,10]</sup> The spiral fluidity test mold is made either from sand, metal, or graphite with a half-round cross section. The casting fluidity test uses a metal mold with strips of various thicknesses and has a rectangular cross section. This test is referred to as the "casting fluidity" test, which measures the ability of molten metal to fill narrow cross sections. The fluidity of molten metal is affected by the alloy type and its chemical composition,<sup>[7,8]</sup> the viscosity and density of the molten alloy, the molten metal superheat, and the thermal properties of molten alloy and the mold.<sup>[11]</sup>

The fluidity of composite aluminum alloy suspensions has been studied by earlier workers.<sup>[12-14]</sup> Their results indicate that the fluidity of aluminum alloys at a given temperature decreased with additions of alumina, mica, and graphite particles to the matrix alloy. Generally, for a given particle size, the spiral fluidity of an aluminum alloy decreased with increasing volume percentage of reinforcements suspended in the melt.

The present study investigates fluidity of molten aluminum alloy A356 (Al-7 wt% Si) containing different sizes and volumes of SiC particles in permanent spiral and casting fluidity molds. Fluidity test results of the composites have been compared with that of the base alloy to assess the ability of the composite melt containing particles to flow and fill the mold cavity during casting. The solidification microstructure formed during flow along the spiral and casting fluidity channels has been

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**Fig. 1** Permanent spiral fluidity mold used for fluidity measurements.

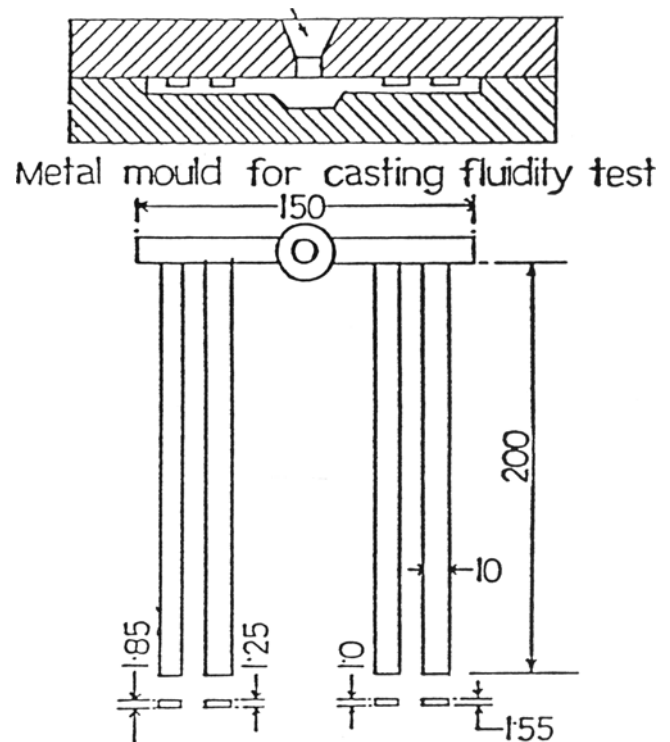
examined to understand the role of the particles in influencing fluidity of the composite slurry and the settling behavior of silicon carbide particles. A model for predicting fluidity of composite alloys as a function of melt superheat, particle volume fraction, channel diameter, melt velocity in the mold, and thermophysical properties of the melt has been presented. The predictions of the model have been compared with experimental measurements.

## 2. Experimental Procedure

Foundry ingots of aluminum A356 and aluminum A356 reinforced with 10, 15, and 20 vol% of SiC particles were reinforced to conduct the fluidity experiments. All materials were supplied by DURALCAN Co., USA. The average diameter of SiC particles in the composite containing 10 and 15 vol% was 9  $\mu\text{m}$  and for the composite containing 20 vol% SiC was 14  $\mu\text{m}$ .

The permanent spiral fluidity mold used in this study was an aluminum permanent mold with a spiral channel approximately 1.3 cm wide and 0.64 cm deep, as shown in Fig. 1. The spiral channel had a semicircular cross section and was coated with a graphite coating to prevent adherence of molten aluminum to the mold. The permanent casting fluidity mold used for measuring casting fluidity test (Fig. 2) was adopted from the standard casting fluidity mold reported in *American Foundrymen's Society (AFS) Transaction*.<sup>[9,10]</sup> An insulating refractory material was used as a pouring basin to reduce the turbulence in the metal while pouring and to provide constant metallostatic head during filling. The spiral and casting fluidity molds were heated electrically to ensure constancy in the temperature of the mold.

The molds were preheated to approximately 370 °C. Melts of matrix alloys containing SiC particles were poured into the mold at the desired pouring temperature, and after solidifica-



**Fig. 2** Schematic drawing of the standard permanent casting fluidity mold used for casting fluidity measurements of aluminum A356-SiC particle composites.

tion, the length of the fluidity sample cast was measured for a given composite at a given pouring temperature.

## 3. Results and Discussion

### 3.1 Theoretical Models for Prediction of Fluidity in Monolithic Alloys and Composites

As described earlier, fluidity relates to the ability of the melt to flow into and fill narrow channels of the casting and reproduce intricate casting details. Fluidity depends on the alloy type, superheat of the melt, oxidation of the alloy during melting, amount of impurities and inclusions in the melt, and solidification behavior under flow conditions.<sup>[7,8,11]</sup> For composite slurry, fluidity also depends on the particle content, shape, chemistry, size, and state of the suspension.

A theoretical model to predict the length of the fluidity channel in monolithic alloys was derived by Flemings<sup>[15]</sup> as:

$$L_f = \left[ \frac{\rho_s a v}{2h(T_m - T_o)} \right] (H + C\Delta T) \quad [1]$$

where  $L_f$  is the fluidity length;  $\rho_s$  is the density of the solid alloy;  $a$  is the radius of the spiral fluidity channel;  $v$  is the velocity of the fluid;  $H$  is the latent heat of fusion;  $C$  is the heat capacity;  $\Delta T$  is the superheat of the melt;  $T_o$  is the mold tem-

perature;  $T_m$  is the melting temperature; and  $h$  is the heat transfer coefficient.

Equation 1 is based on the premise that the flow of liquid metal in a channel stops when an element of the composite melt solidifies due to heat extraction in the channel. The model assumes that (1) all resistance to heat flow is at the mold metal interface, (2) there is no significant effect of surface tension on flow velocity, and (3) the flow channel is filled with liquid metal and there is no decrease in velocity from friction effects.

Equation 1 for fluidity of monolithic alloys predicts an increase in fluidity of alloys with increasing superheat of the melt, cross section of the channel, velocity of the fluid and latent heat of the melt; it also predicts a decrease in fluidity with an increase in heat transfer coefficient. Several of these predicted trends have been confirmed experimentally, partly confirming the validity of this equation for monolithic alloys.

Equation 1 can be extended to predict the fluidity of composites by substituting the properties of composites instead of monolithic metal:

$$\rho_c = \rho_m \phi_m + \rho_d \phi_d \quad [2]$$

$$C_{\text{eff}} = C_m W_m + C_d W_d \quad [3]$$

$$\Delta H_m^c = \Delta H_m (1 - \phi_d) \quad [4]$$

where  $m$  and  $d$  stand for metal and dispersoid, respectively, and  $\phi_d$  is the fraction of reinforcement (dispersoid).

These substitutions lead to an equation predicting the fluidity of composite materials as:

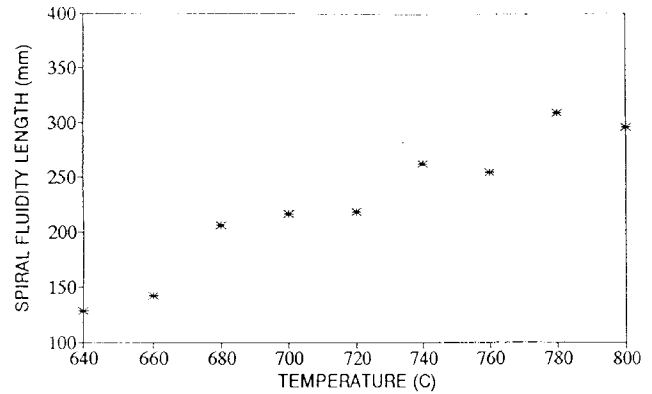
$$L_f = \frac{\rho_c a V}{2h(T_m - T_o)} [\phi_m \Delta H_m + C_{\text{eff}} \Delta T] \quad [5]$$

$$L_f = \left[ \frac{(\rho_m \phi_m + \rho_d \phi_d) a V}{2h(T_m - T_o)} \right] \left[ \Delta H_m (1 - \phi_d) + (C_m W_m + C_d W_d) \Delta T \right] \quad [6]$$

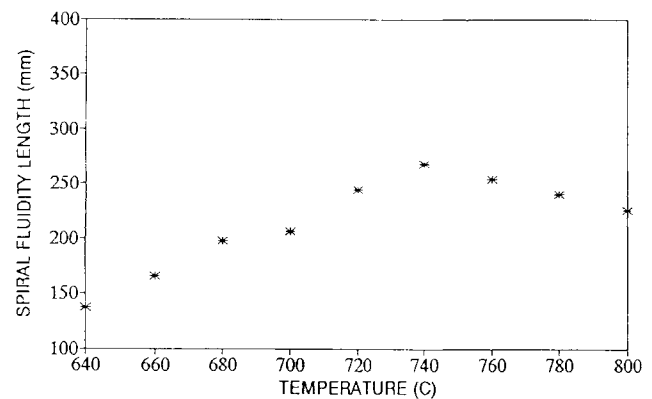
This equation predicts an increase in fluidity with melt superheat and latent heat, cross section of the channel, and velocity of the fluid. The equation also predicts a decrease in fluidity with an increase in heat transfer coefficient for the aluminum silicon carbide system. The equation predicts a decrease in fluidity with an increase in volume percentage of silicon carbide, if the melt velocity and the heat transfer coefficient have not changed significantly with additions of silicon carbide.

It should be recognized that Eq 6 does not account for the effects of the following variables on the fluidity of composites:

- Particle settling and segregation, and progressive solidification, during flow of composites in channels
- Pushing of particles by moving solidification fronts during the flow of composites in channels
- Gas bubbles and oxide films in the composite melts



(a)



(b)

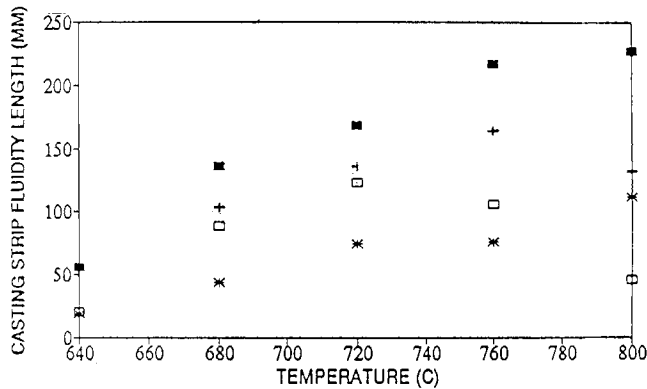
**Fig. 3** Spiral fluidity length as a function of temperature. (a) No SiC. (b) 15 vol% SiC, 9  $\mu\text{m}$ .

- Chemical reactions between particles and the matrix metal
- Size, shape, and surface area of particles

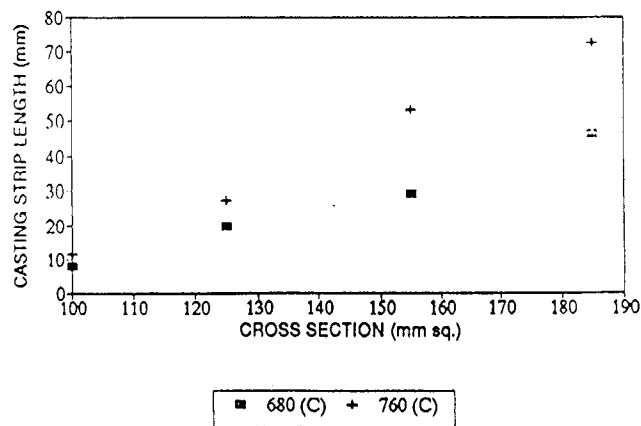
Results of experimental studies to investigate the influence of superheat, volume percentage of silicon carbide, particle size of silicon carbide, and cross section of channel are reported in the following section.

Variation of permanent mold spiral fluidity lengths with pouring temperature for the base alloy and the composite containing 15 vol% silicon carbide particles are shown in Fig. 3.<sup>[16]</sup> Similar variations in fluidity with temperatures were observed for Al-10% SiC and Al-20% SiC alloys. In the base alloy, the fluidity length increased in a continuous manner between 640 and 800 °C; the length more than doubles in this temperature range. On the other hand, in 15 vol% SiC composite (9  $\mu\text{m}$ ), the length increased up to 740 °C and then decreased or reached a plateau.

Theoretical calculations of spiral fluidity lengths in permanent molds predict a continual increase in fluidity lengths for



**Fig. 4** Comparison of casting strip fluidity data for aluminum A356 base alloy and aluminum A356 reinforced with 10, 15 (9  $\mu\text{m}$ ), and 20 (14  $\mu\text{m}$ ) vol% SiC particles as a function of temperature.

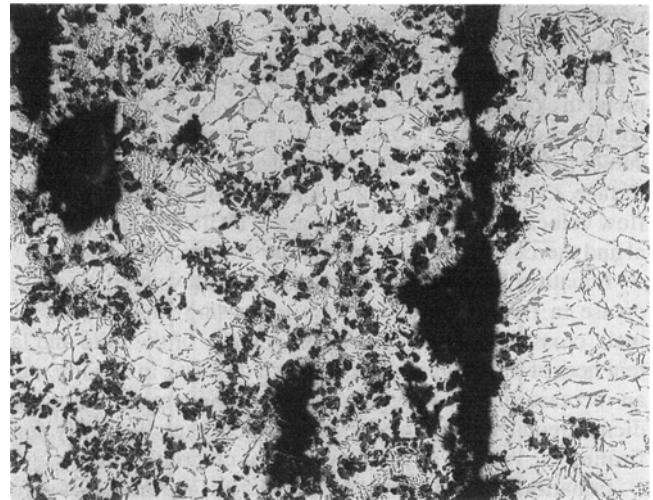


**Fig. 5** Variation in casting fluidity length with cross-sectional area of strip channel for aluminum A356-10 vol% SiC composite.

both the base alloy and the 15 vol% composite. The trend of an increase in fluidity with temperature of the base alloy melt is in agreement with predictions of Eq 1 and 6 for the base alloy. However, for the composite, the observed decrease in fluidity above 740  $^{\circ}\text{C}$  is not predicted by these equations. This discrepancy between the theoretical and measured values of fluidity can be due to various factors including errors in the values of fluid velocity and heat transfer coefficient used for calculations and the chemical reaction between SiC and aluminum at these high temperatures. Quantitatively, the observed values of fluidity of the composites are about 50% lower than the calculated values of fluidity. This discrepancy can again be due to errors in the estimated values of velocity, heat transfer coefficient, and the inhomogeneous distribution of particles in the slurries, as well as several other related factors mentioned earlier.

### 3.2 Casting Fluidity

Casting fluidity indicates the ability of molten metal to flow in channels of narrow cross sections. Casting fluidity is meas-



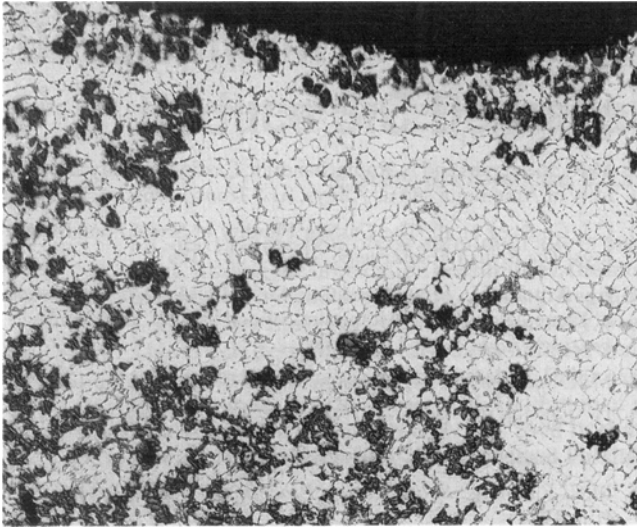
**Fig. 6** Microstructure of spiral fluidity, casting longitudinal cross section of aluminum A356-15 vol% SiC particles, near the last freezing zone of the spiral channel, poured at 800  $^{\circ}\text{C}$ , 200 $\times$ .

ured by the total length traveled by molten metal in four channels of decreasing cross sections (Fig. 2). Figure 4 compares casting fluidity for aluminum A356 base alloy and aluminum A356 containing 10, 15, and 20 vol% SiC particles.

The general trends of measured values of casting fluidity are similar to spiral fluidity tests. Casting fluidity of the base alloy increased continuously with temperature and was larger than that of the composites. Casting fluidity of the composite slurry containing 10, 15, and 20 vol% SiC increased with temperature almost linearly up to 720 to 740  $^{\circ}\text{C}$ , indicating a behavior very similar to spiral fluidity lengths. Above this temperature range, casting fluidity either leveled off or decreased with temperature. However, the rate of increase in fluidity length with temperature in both the base alloy and the alloy containing SiC particles was similar at temperatures of 640 to 720  $^{\circ}\text{C}$ .

Note that in both the 10% and 15% SiC composites (9  $\mu\text{m}$ ), the lengths progressively decreased from the base alloy (0% SiC). However, the 20 vol% SiC composite (14  $\mu\text{m}$ ) exhibited an intermediate level of fluidity. The 14- $\mu\text{m}$  particle size had a surface area of about one third of that of the 9- $\mu\text{m}$  particle on equal weight bases, and this may have caused this decrease in fluidity length.

The variation of the individual casting strip lengths for different strip thickness with temperature for the base alloy containing 10 vol% SiC particles is shown in Fig. 5. The aluminum A356-10 vol% SiC composite slurry travels longer in channels with larger cross section for a given temperature. The solidification rate in channels with larger cross sections are lower; therefore, the slurry of Al-SiC can travel longer before the movement of flow is stopped by the solidification process. The observed linear increase in fluidity length with the channel cross section (Fig. 5) is in agreement with the predictions of the theoretical model as given in Eq 6.



**Fig. 7** Microstructure of permanent mold spiral fluidity casting cross section of aluminum A356-15 vol% SiC particles near the entrance to the spiral fluidity channel, poured at 800 °C, showing settling of SiC particles. 100×

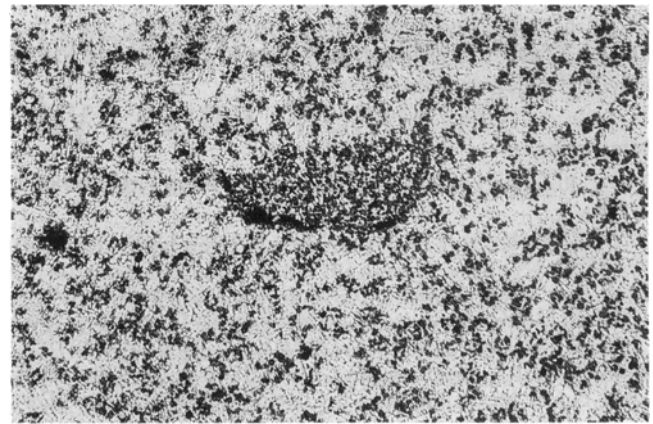
### 3.3 Microstructure along Fluidity Channels

The microstructures of the cast spiral fluidity and casting fluidity lengths were examined at different locations along the length to understand the role of particles during flow and the formation of a solidification microstructure in the channels. It was observed that, although SiC particles have been carried by the melt up to the end of the spiral, the distribution of SiC particles is far from homogeneous.

To examine the reason for a decrease in fluidity length with temperature above 740 °C, the microstructure of a longitudinal section at the end of a spiral fluidity length poured at 800 °C was analyzed (Fig. 6). The microstructure reveals reaction between the melt and the particles at these temperatures, presumably leading to the formation of  $Al_4C_3$ . This would result in an increase in the volume fraction and surface area of suspended particles, thus decreasing the fluidity. In addition to these reactions, there appear to be formations of clusters of particles of aluminum oxide.

Figure 7 shows the microstructure near the entrance of spiral fluidity channels of aluminum A356-15 vol% SiC composite poured at 800 °C. There is clear evidence of particle settling even in permanent mold spiral fluidity. The settling of particles during holding, flow, and solidification has been discussed elsewhere.<sup>[16]</sup>

Entrapment of SiC particles by oxide films in aluminum 20% SiC in a casting strip of 1.25-mm thickness poured at 800 °C near the last freezing zone is shown in Fig. 8. This microstructure suggests that the formation of aluminum oxide film can lead to segregation of SiC even in very thin casting thicknesses. In addition, in certain locations, there are gas porosities and oxide associated with particles. These heterogeneities in microstructure in casting fluidity lengths indicate the possibility of similar heterogeneities in actual castings made from these alloys. These heterogeneities in the microstructure may



**Fig. 8** Microstructure of casting strip (1.25-mm thick) cross section of aluminum A356-20 vol% SiC particles poured at 800 °C near the last freezing zone, showing that the oxide film has disturbed the distribution of SiC particles, 50×

be responsible for the disagreement between the calculated values and measured values of fluidity. It is clear that, in the case of composites, a complete definition of fluidity should include the length a slurry can travel while resulting in a solid bar with uniform distribution of unreacted particles.

## 4. Conclusions

In general, permanent mold fluidity values of aluminum A356 with 10, 15, and 20 vol% SiC particles increase with temperature in the range of 640 to 720 °C. The values of the fluidity of composite alloys, although somewhat lower than the base alloy, appear to be adequate for casting into a variety of shapes similar to the base alloy. The fluidity of Al-SiC composite alloys either remained constant or decreased with an increase in melt temperature above 740 °C, presumably due to reactions between the particles and the melt that enhance the effective surface area and volume percent of the particles.

The fluidity of the base alloy decreased with an increase in the volume percentage of SiC particles of a given size in the range investigated. The particle size and therefore surface area of SiC particles has a significant effect on fluidity lengths. Composites with larger SiC particle sizes exhibited longer fluidity lengths, even when the total volume percentage of particles increased.

The heat transfer model developed for the prediction of spiral fluidity lengths of monolithic alloys was modified to predict the fluidity of composite alloys. The experimentally observed increase in the fluidity of composite alloys with temperature in the range of 640 to 720 °C and with cross section of the flow channel are in agreement with the predictions of the model. The microstructures of Al-SiC from the fluidity channels indicate that the distribution of SiC particles during the flow in channels is influenced by settling of SiC particles due to gravity, pushing of SiC particles by the growing  $\alpha$  aluminum dendrites, formation of gas porosity and inclusions, and blocking of SiC particles by the oxide films resulting in clustering of particles. These result in nonuniformity in the distribution of SiC parti-

cles in the fluidity test specimens, which could be one of the reasons for the experimentally measured values being lower than the predicted values of fluidity.

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