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Effect of Solid Particles on Fluidity of Semisolid Aluminum Alloy Slurry

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Abstract

Semisolid processing is considered as an attractive and promising manufacturing method for producing near net-shape metal products that have reduced porosity and shrinkage. In this study, the fluidity of Al-Si-Mg alloy slurry was evaluated by injection into a spiral metallic mold. Image analysis showed that solid particles in specimens became small and spherical with increasing shear rate on the gate. Fluidity was increased with increasing shear rate, with decreasing particle size and with particle roundness. Furthermore, particle roundness has a greater effect on fluidity than particle size.

Introduction

Recently, the development of environmental protection programs and green technology has become increasingly important. In particular, reduction of carbon dioxide emissions and improvement of fuel efficiency are pressing issues for the automobile industry. In this regard, reducing vehicle weight by the use of lightweight materials would be a highly effective means for resolving these issues.

Production of lightweight metal components from aluminum is primarily performed by die casting, which directly fabricates the required shape from metal in a liquid state. However, components molded by die casting exhibit low engineering performance due to the existence of inherent defects, such as pores, hot cracks and oxide inclusions. In such cases, heat treatment is not viable. In addition, the die casting process has a number of problems including dimensional instability through solidification contraction and short die life due to superheating.

Semisolid processing is the fabrication of a material that co-exists in both solid and liquid states. A semisolid metal has higher viscosity than that of a liquid metal. For this reason, flow patterns will not become turbulent, and so there will be fewer gas defects. Additionally, solidification shrinkage is reduced linearly with the solidified fraction within the semisolid alloy, which reduces shrinkage porosity and improves dimensional accuracy. The associated decrease in the process temperature also extends die life. As a result of these benefits, semisolid processing has been studied since the 1970s [1, 2], and more recently techniques have been developed such that high-quality aluminum alloy products can be fabricated [3–5].

In contrast, a semisolid metal has lower fluidity than molten metal. The lower fluidity of semisolid metallic slurries causes misrun, and considerably limits their mold filling ability. Therefore, the fluidity of semisolid metallic slurries must be investigated in order to evaluate formability in semisolid processes.

The morphology (such as the diameter and roundness) of solid particles in slurry is recognized as having a significant effect on the viscosity and fluidity of the slurry [6–8]. In this study, the fluidity of semisolid aluminum alloy AC4C (A356) slurry was investigated during semisolid die casting under various gate velocities. By measuring the diameters and roundness of solid particles in the slurry, comparisons between the character of the solid particles and fluidity of the slurry were then possible.

Experimental procedure

In the experiments an Al-7wt%Si-0.3wt%Mg alloy (AC4CH in the Japanese International Standards was utilized. This alloy is equivalent to A356 in the American Society for Testing and Materials standards. The semisolid slurry was prepared by a nanocasting method [9]. Here, to perform nanocasting, approximately 220 g of molten alloy was poured at 700 °C into a stainless steel cup (90 mm high, 38.7 mm inner diameter and 2.0 mm thick) at room temperature. The cup drew heat from the molten alloy such that the temperature of the molten alloy fell to semisolid temperatures, and electromagnetic stirring was applied in the vertical direction for 5 s, then rotationally for 10 s, during this cooling. Consequently, slurry with dispersed solid particles was obtained.

Specimens were then cast in a permanent mold using a 135 t HPDC machine. The injection velocity (plunger velocity) was set at either 0.1 or 0.35 m/s. A schematic of the specimen is shown in Fig. 1. The permanent mold had spiral cavities 5.7 mm wide, 1350 mm long and 4.0 mm thick. The mold also possessed a 5 mm wide gate, and the gate velocity was controlled by changing the

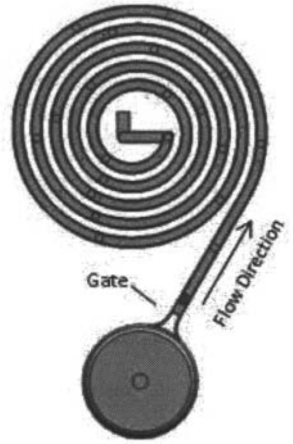


Fig. 1 Schematic of spiral specimen

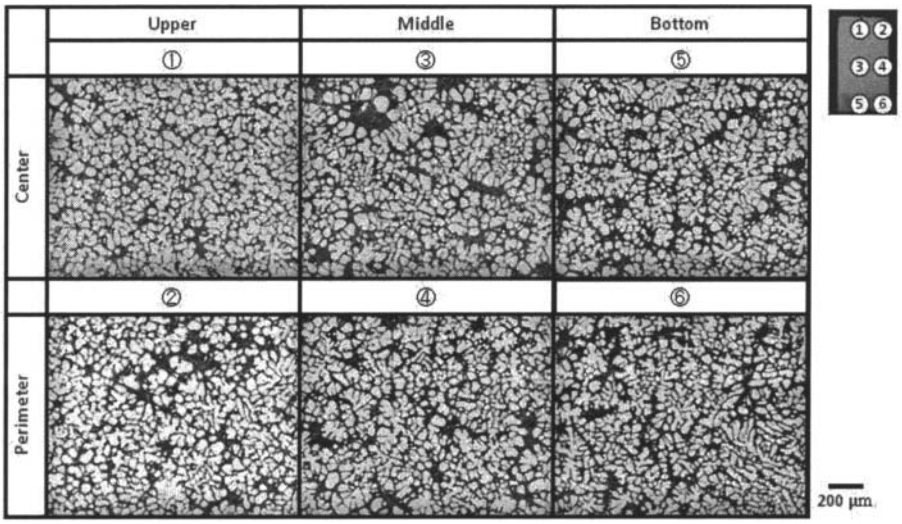


Fig. 2 Microstructures of the nanocast slurry of AC4CH aluminum alloy

thickness of the gate from 1.0 mm, to 2.2 mm and 3.1 mm.

Fluidity was evaluated over the length of the spiral, from the spiral tip to the riser. Moreover, metallographic observation was conducted along the surface perpendicular to the flow direction. Fabricated specimens were ground with SiC paper, and then polished with diamond paste. Finally, the specimens were etched in a 0.5% HF solution. The microstructures of these specimens were observed by optical microscopy.

Results and discussion

Microstructure before injection

Fig. 2 shows an example of the typical microstructures found in the nanocast AC4CH (A356) aluminum alloy slurry. These micrographs show that the agglomerated primary α-Al particles were dispersed in the matrix (eutectic α-Al and Si) of the alloys. The images suggest that, when the slurry was injected, primary α-Al particles were in the solid phase and the matrix was in the liquid phase. This consideration is supported by Fig. 4, which shows the distribution of the solid fraction in the nanocast aluminum alloy slurry calculated from the micrographs.

In addition, the primary α-Al particle diameter (equivalent circle diameter), d [µm], and the roundness, R, were measured at the six locations in each specimen highlighted above by image analysis. Here, the roundness of a particle is calculated from

$$R = L^2/(4\pi A), \qquad (1)$$

where L [µm] and A [µm^2] are the boundary length and area of the primary α-Al particle, respectively, and when $R = 1$, the particle is spherical.

The area-weighted mean diameter, d_s [µm], and area-weighted mean roundness, R_s, were also calculated from the following equations:

$$d_s = \Sigma d_i A_i / \Sigma A_i \qquad (2)$$

and

$$R_s = \Sigma R_i A_i / \Sigma A_i, \qquad (3)$$

where d_i [µm], A_i [µm^2] and R_i are the diameter, area and roundness of a primary α-Al particle, respectively. Fig. 4 shows

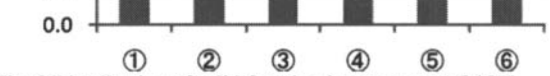


Fig. 3 Distribution of solid fraction in nanocast AC4CH aluminum alloy slurry

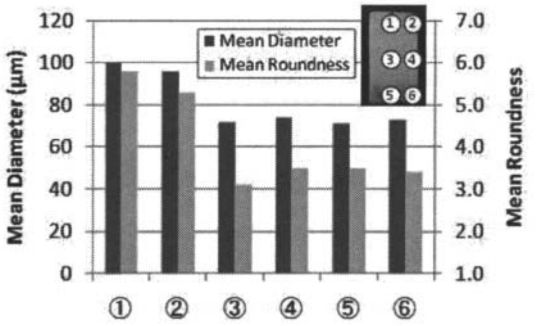
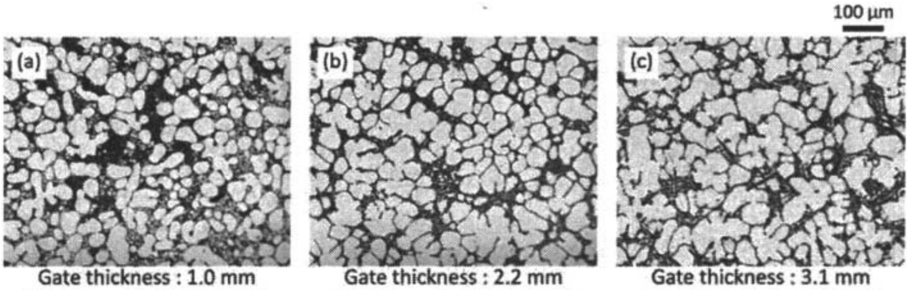


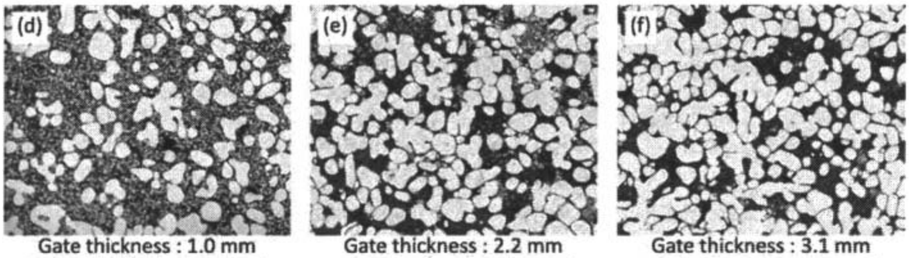
Fig. 4 Distribution of mean diameter and mean roundness in nanocast AC4CH aluminum alloy slurry



Gate thickness : 1.0 mm
Injection velocity : 0.1 m/s
Gate velocity : 34.5 m/s

Gate thickness : 2.2 mm
Injection velocity : 0.1 m/s
Gate velocity : 15.7 m/s

Gate thickness : 3.1 mm
Injection velocity : 0.1 m/s
Gate velocity : 11.1 m/s



Gate thickness : 1.0 mm
Injection velocity : 0.35 m/s
Gate velocity : 120.8 m/s

Gate thickness : 2.2 mm
Injection velocity : 0.35 m/s
Gate velocity : 54.9 m/s

Gate thickness : 3.1 mm
Injection velocity : 0.35 m/s
Gate velocity : 39.0 m/s

Fig. 5 Microstructures of the central section of the specimen (200 mm from gate)

the values of d_s [μm] and R_s calculated from eqs. (2) and (3) for the specimens. The trends of diameter and roundness distributions are similar to that of the solid fraction; particles at the top of the slurry were coarse and non-circular, whereas there was little variation in the particle shapes at other areas. From Fig. 3, the solid fraction at the top of the slurry was also high compared with other areas. High variation in the solid fraction and shape of the particles is expected to cause an adverse effect on fluidity. Therefore, in this study, a capture space was created between the sleeve and the mold, such that the top layer of slurry was trapped by this space. As a result, slurry of low quality remained in a thin crust, and only homogeneous material was injected into the mold.

Effect of gate velocity on microstructure

Fig. 5 shows examples of typical microstructures found in the central section of the spiral specimen when injection was performed under various conditions. Here, the observation point was 200 mm from the gate. From the images, primary α-Al particles at low gate velocity (e.g., Fig. 5(b) and (c)) are seen to have rosette-like shapes. Conversely, the particles became fine and spherical with increasing gate velocity, had globular shapes at high gate velocity (e.g., Fig. 5(d)). Additionally, the primary α-Al particles in the specimens appeared more globular and smaller (Fig. 5) when compared with the slurry before injection (Fig. 2). Relations between both the mean diameter (from eq. (2)) and the mean roundness (from eq. (3)) of the primary α-Al particles, and the gate velocity are shown in Fig. 6. If the gate speed was greater than 20 m/s, the mean particle diameter and the mean particle roundness in the spiral specimen were less than those for the slurry. Furthermore, these particle parameters for the spiral specimen decreased logarithmically with increasing gate velocity. The correlation coefficient between the gate velocity and mean particle diameter was -0.71, and that between the gate velocity and mean particle roundness was -0.76. Thus, both the mean diameter and roundness had a high correlation with the gate velocity.

These trends are attributed to the effect of the shear stress at the gate. The primary α-Al particles were subjected to shear stress at the gate, and were therefore deformed into fine spheres [10]. Since shear stress is expressed as the product of the shear rate and

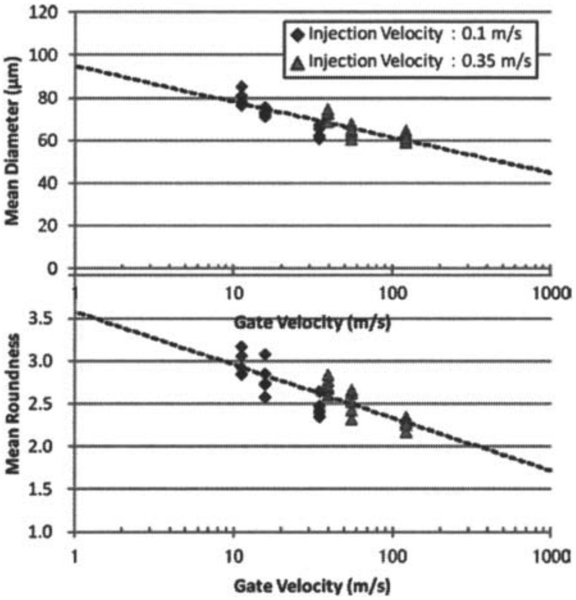


Fig. 6 Relations among mean diameter, roundness of primary α-Al particles and gate velocity

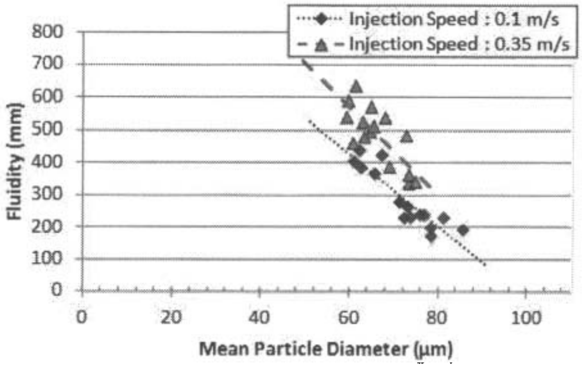


Fig. 7 Relation between mean diameter of primary α-Al particles and fluidity

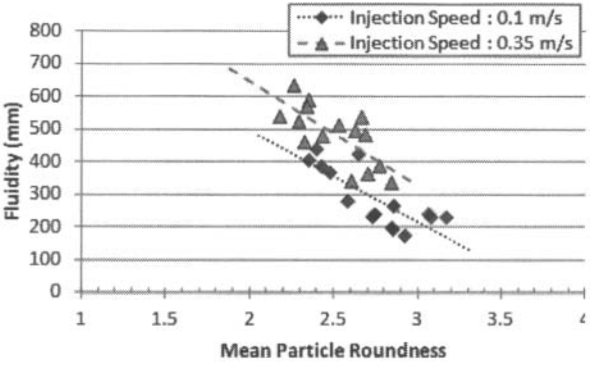


Fig. 8 Relation between mean roundness of primary α-Al particles and fluidity

the shear viscosity, and a high gate velocity generates a high shear rate, both the mean particle diameter and roundness decreased with increasing gate velocity. Hence, slurry with fine spherical primary α-Al particles can be obtained by applying shear stress at the gate only if the gate speed is greater than 20 m/s.

Effect of solid particle parameters on fluidity

Fig. 7 shows the relation between the mean particle diameter and fluidity, and Fig. 8 shows the relation between the mean particle roundness and fluidity. Fluidity was evaluated over the length of the spiral, from the tip to the riser. The fluidity was affected by injection speed, and was highly correlated with the mean particle diameter and the mean particle roundness. Thus, at a constant injection speed, fluidity increased with both the mean particle diameter and the mean particle roundness. The correlation coefficient between the fluidity and mean particle diameter was -0.91 (injection speed: 0.1 m/s) and -0.78 (injection speed: 0.35 m/s). In contrast, the correlation coefficient between the fluidity and mean particle roundness was -0.80 (injection speed: 0.1 m/s) and -0.73 (injection speed: 0.35 m/s). Therefore, the fluidity of the Al-Si-Mg alloy slurry was affected by the mean particle diameter and the mean particle roundness.

The particle diameter and particle roundness also have a considerable effect on the viscosity of the slurry. Hirai et al. showed that slurry viscosity decreases with decreased particle diameter and decreased volume base specific surface [11]. The volume base specific surface in that study was expressed as the surface area divided by the volume, and has the same meaning as the particle roundness used here. Additionally, fluidity has been predicted to increase with a decrease in viscosity [12]. The observations found in the current study are, hence, consistent with the above considerations.

Thus, high formability is required to obtain a slurry with fine spherical solid particles. When the mean particle diameter and roundness are less than 70 mm and 2.5, respectively, the fluidity was doubled, and this effect can be obtained by control of the gate velocity.

Conclusions

Fluidity of die cast semisolid aluminum alloy AC4C (A356) slurry was investigated for varying particle diameters and particle roundness of the solid particles in the slurry, and gate velocities. Moreover, relations between the solid particle properties and fluidity of the slurry were examined, and the following conclusions are drawn.

Both the mean particle diameter and roundness decreased with increased gate velocity, and therefore slurry composed of fine, spherical primary α-Al particles can be obtained with a high gate velocity. Since fluidity was found to be affected by the mean particle diameter and the mean particle roundness, it can be improved by controlling the gate velocity.

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