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Semi-Solid Processing of Magnesium Alloys*

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Semi-solid processing is an emerging technology for near net-shape production of engineering components. Although there has been significant progress in semi-solid processing of Al alloys, very limited information is available on semi-solid processing of Mg alloys, except for the thixomolding process. In semi-solid casting process, it is necessary to properly control the flow and solidification behavior of semi-solid slurries for high quality products. There are a number of parameters that affect the flow and solidification behavior of semi-solid slurries such as viscosity, casting pressure, shapes of gate and mold cavity, gate velocity, mold temperature, etc. In the present study, the effects of various thermo-mechanical treatments were investigated on the change in viscosity of the semi-solid AZ91D magnesium alloys by using a concentric cylinder type viscometer. The effects of gate velocity and thickness on mold filling behavior of the semi-solid AZ91D alloys were also investigated by using a high-speed camera and the results were compared with those obtained from computer simulations. From these results and microstructure examination, a processing map for high pressure die casting of the semi-solid AZ91D alloy was constructed in order to produce sound castings.

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Keywords: *semi-solid processing, magnesium alloy, rheological behavior, filling behavior, processing map*

1. Introduction

The semi-solid metal (SSM) processing is an emerging new technology for near net-shape production of engineering components, in which alloys are processed in the temperature range where the liquid and solid phases coexist.[1–4] The semi-solid slurry with a non-dendritic microstructure exhibits distinct rheological behavior, namely, thixotropy and pseudo-plasticity.[5–7] These rheological properties make the SSM processing as unique and effective process for near net-shape product and property enhancement. The flow of the semi-solid slurry, however, must be controlled to a laminar flow in order to avoid the gas and oxide entrapments. The flow behavior of the semi-solid slurry is known to be dependent on the various processing parameters such as the viscosity and velocity of the slurry and the shapes of the gate and die cavity. Magnesium alloys have a number of distinct advantages, including low density and high specific strength and the need for Mg alloys has been rapidly increased in the automotive industry. At present, die-casting is mainly utilized to produce the Mg alloy products. In recent years, the modification of alloy compositions and/or heat treatments has been attempted to increase the mechanical properties[8–10] and corrosion resistance[11–13] of casting alloys. In the present study, the thixotropic behavior of the semi-solid AZ91D magnesium alloy was investigated with the changes in the rest time and the up time. The effects of the gate thickness and velocity on the flow behavior of the slurry during the mold filling process were investigated by using a high-speed camera and a transparent die cover.

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Table 1 Experimental conditions for the observation of thixotropic behavior.

Stirring temperature (°C)	Rest time (s)	Up time (s)
580	0	7
	10	14
	30	28
	60	70
	300	140

2. Experimental Procedures

2.1 Thixotropic behavior of the semi-solid AZ91D magnesium alloy

One hundred and fifty grams of AZ91D magnesium alloy were charged into a low carbon steel crucible attached to a concentric cylinder-type viscometer and heated to 620°C. The molten alloy was cooled from 620 to 580°C at a cooling rate of 1°C/min. and then held isothermally for 2 h, while it was continuously stirred at 100 rpm. The stirring was temporarily stopped and the semi-solid slurry was held isothermally for a predetermined amount of time (rest time, t_r) without stirring. After the desired amount of rest time, the shear rate imposed on the slurry increased from 0 to 1021 s^{-1} in a given period of time (up time, t_u) and then decreased from 1021 to 0 s^{-1} within the same period of time as the up time. Table 1 shows the experimental conditions employed for observing thixotropic behavior of the semi-solid AZ91D magnesium alloy.

2.2 Flow behavior of the semi-solid AZ91D magnesium alloy

The AZ91D magnesium alloy billets of 178 mm diameter were cast in a low carbon steel mold. After homogenization, these billets were subsequently extruded at an extrusion ratio of 22 : 1. The raw materials for the slugs for producing pressure die castings were cut from the extruded bar and compressed by 25% in order to induce strain. The slug was heated to 583°C in order to produce the semi-solid alloy and then inserted into the sleeve of a 75 ton horizontal pressure die casting machine. The flow behavior of the semi-solid slurry during the mold filling process was visualized by using a high-speed camera and a transparent die cover, under the various injection conditions by changing either the gate thickness or the gate velocity. The gate thickness was changed from 2 to 8 mm and the gate velocity was varied from 2 to 36 m/s.

3. Results and Discussion

3.1 Thixotropic behavior of the semi-solid AZ91D magnesium alloy

Figures 1(a) and (b) show the changes in the apparent viscosities of the semi-solid AZ91D magnesium alloy as a function of the shear rate at various rest times and up times, respectively. As shown in Fig. 1, the apparent viscosity decreased rapidly at the beginning with increasing shear rate and then decreased slowly with further increase in the shear rate. As the shear rate decreased after its maximum, the apparent viscosity of the slurry further decreased slowly instead of increasing, indicating that the viscosity of the slurry was path (history)-dependent. These results may come from the difference in the rates at which the microstructure of the semi-solid slurry changed with respect to the change in the shear rate. It has been reported that the rate of the de-agglomeration (breakdown) was faster than the rate of the agglomeration between the primary solid particles.[14–17] The apparent viscosity of the semi-solid slurry, therefore, decreased by the de-agglomeration with increasing the shear rate, but it did not change or even slightly decreased further due to little change in the microstructure of the semi-solid slurry with decreasing shear rate after its maximum in the present study. As shown in Fig. 1(a), the apparent viscosity increased as the rest time increased from 0 to 300 s at the beginning. However, the difference between the viscosities after different rest times decreased rapidly with increasing shear rate. The up time also affected the rate of change of the apparent viscosity of the slurry as shown in Fig. 1(b). As the up time increased, the slurry would experience a larger number of shearing at a given shear rate and thus the apparent viscosity of the slurry would decrease.

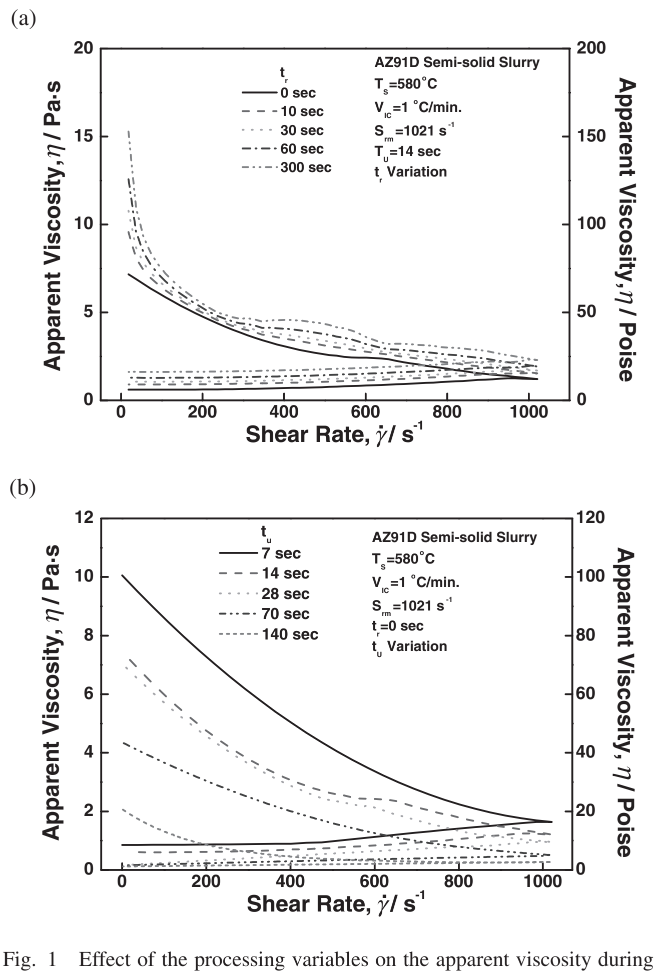

Fig. 1 Effect of the processing variables on the apparent viscosity during shear rate change cycle; (a) variation of rest time, (b) variation of up-time.

3.2 Flow behavior of the semi-solid AZ91D magnesium alloy

Figures 2(a) and (b) show the mold filling pattern of the semi-solid AZ91D magnesium alloy as a function of time at two different gate velocities of 4 m/s and 8.25 m/s, respectively, when the gate thickness was 8 mm. At a gate velocity of 4 m/s, the front surface of the semi-solid slurry remained rather smooth as shown in Fig. 2(a), indicating a laminar type flow. The front surface of the slurry remained smooth even after the slurry collided with the obstacles.

As the gate velocity increased to 8.25 m/s, however, the front surface of the semi-solid slurry was shattered after collision with obstacles and air pockets were trapped within the cavity as indicated by the arrows in Fig. 2(b). Figures 3(a) and (b) show the results of a computer simulation for the mold filling behavior of the semi-solid slurry as a function of time at two different gate velocities of 4 m/s and 8.25 m/s, respectively, when the gate thickness was 8 mm. The mold filling behavior of the semi-solid slurry is predicted well by computer simulation by using the proper values for the parameters that were determined from the separate experiments.

Figures 4(a) and (b) show the optical micrographs obtained from the semi-solid pressure die castings at gate velocities of 4 m/s and 8.25 m/s, respectively, when the gate thickness was 8 mm. As predicted from the mold filling pattern shown in Figs. 2 and 3, the sound casting was produced at a gate velocity of 4 m/s. However, micro-pores were observed in the casting produced at a gate velocity of 8.25 m/s.

Figure 5 shows the change in the critical velocity at which the flow would transfer from a laminar flow to a turbulent flow as a function of the gate thickness. As the gate thickness increased, external and internal defects were formed at the lower gate velocity. In general, the Reynolds number (Re) is used to describe the flow behavior of the fluid. The value of Re at which transition from the laminar to the turbulent flow occurs is known to be approximately 2100 in usual engineering applications of flows in pipes.[18] The critical gate velocity, therefore, could be approximately predicted by using the Reynolds number and the equivalent diameter in the case of rectangular gate. It was reported that the effect of

(a)

(b)

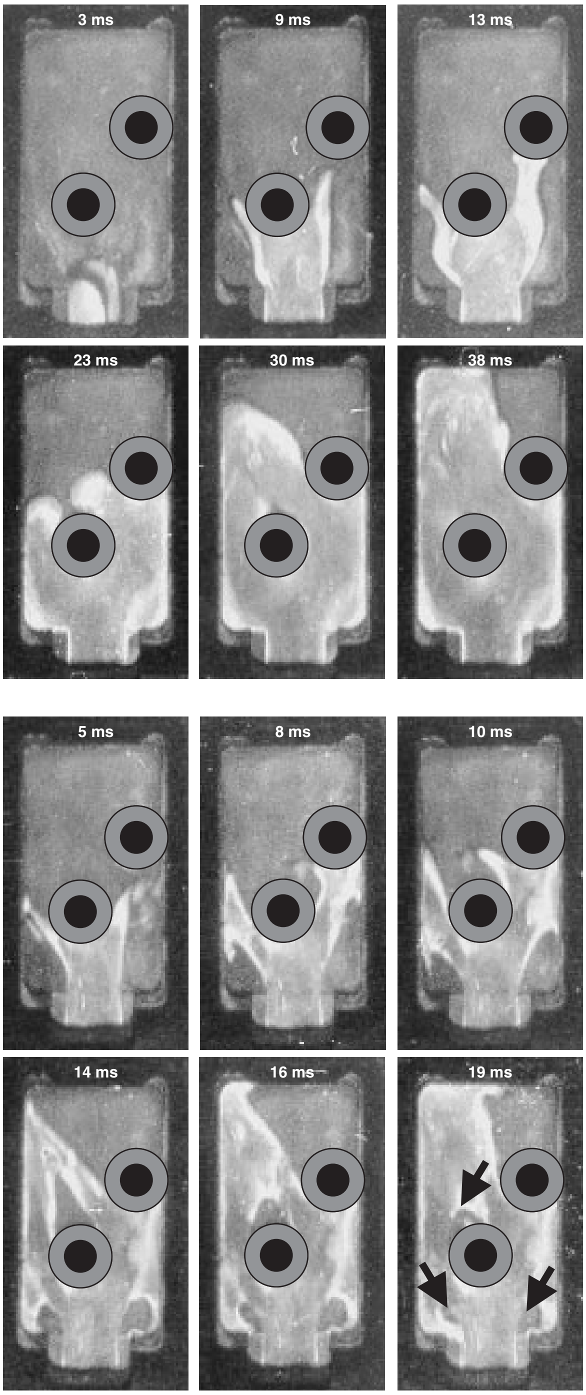

Fig. 2 Visualization of the mold filling pattern of the semi-solid AZ91D magnesium alloy with the gate thickness of 8 mm; (a) $V_g = 4$ m/s, (b) $V_g = 8.25$ m/s.

(a)

(b)

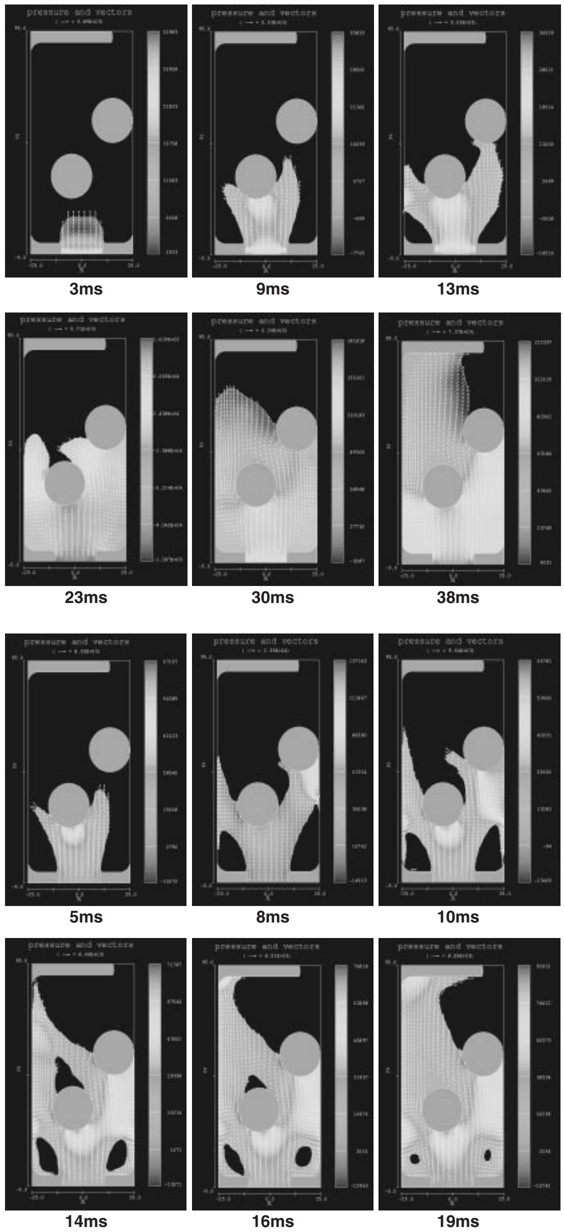

Fig. 3 Simulation of the mold filling pattern of the semi-solid AZ91D magnesium alloy with the gate thickness of 8 mm; (a) $V_g = 4$ m/s, (b) $V_g = 8.25$ m/s.

the gate width on the flow behavior could be neglected when the gate width was much larger than the gate thickness and thus the critical velocity could be described as a function of the gate thickness.[19] As shown in Fig. 5, the theoretical value calculated from the Reynolds number and the measured apparent viscosity well predicted the transition from laminar to turbulent flow.

4. Conclusion

(1) The apparent viscosity of the semi-solid AZ91D magnesium alloy decreased rapidly at the beginning with increasing shear rate and then decreased slowly with further increase in the shear rate. As the shear rate decreased after its maximum, the apparent viscosity further decreased slowly, indicating that the viscosity of the slurry was path-dependent. These results come from the difference between the rates of the de-agglomeration and the agglomeration of the primary solid particles at different shear rates.

(2) The flow behavior of the semi-solid slurry during the mold filling process was strongly dependent on the gate velocity and the gate thickness. The transition from the laminar flow to the turbulent flow could be well predicted by the theoretical value calculated from the Reynolds number and the measured apparent viscosity.

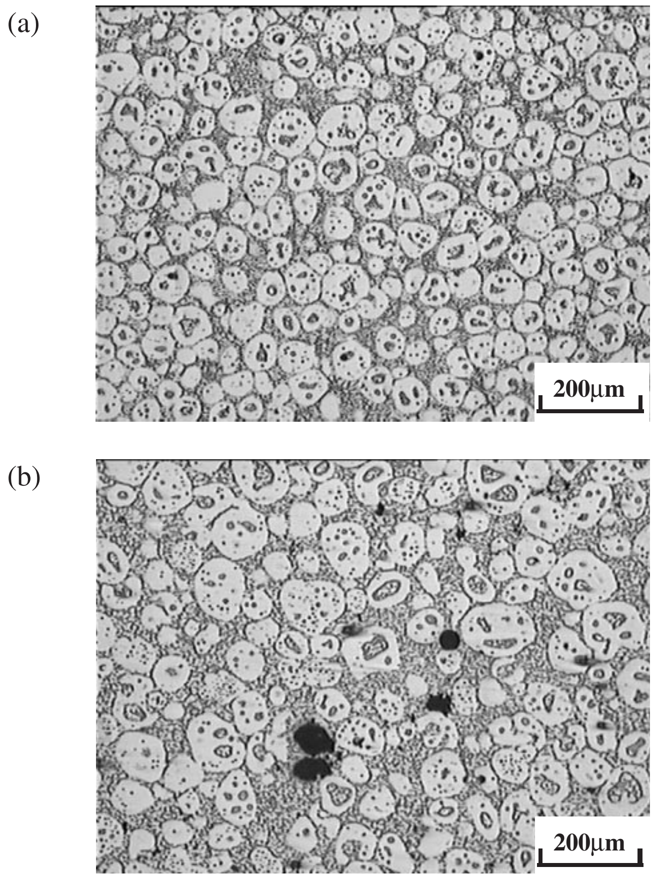

Fig. 4 Optical micrographs obtained from the semi-solid pressure die castings at different gate velocities with the gate thickness of 8 mm; (a) $V_g = 4$ m/s, (b) $V_g = 8.25$ m/s.

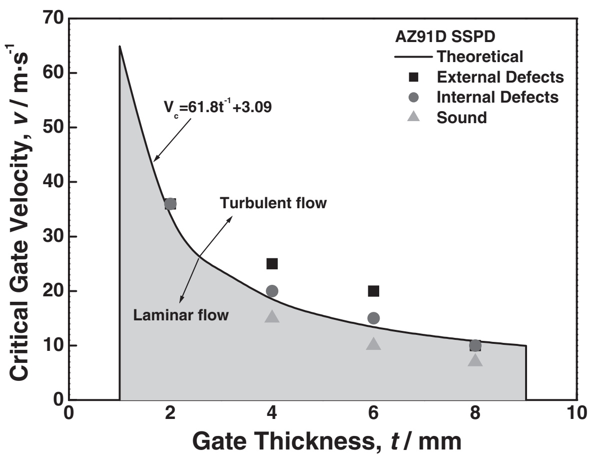

Fig. 5 Comparison between the theoretical and experimental critical gate velocities as a function of gate thickness.

Acknowledgments

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