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Die filling behavior of Mg alloy slurry in semi-solid processing

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In this study, to produce a thin product for a nocturnal fluoroscope cover from a Mg alloy by semi-solid processing, the die filling behavior of a semi-solid slurry was simulated with an ANYCAST program which was compared with the real product. The rheological behavior of the semi-solid slurry of the Mg alloy was considered in a computational fluid dynamic study using the reported data between the viscosity and shear rate of a semi-solid slurry of the Mg alloy. Also, in order to analyze precisely the rheological behavior, the ANYCAST program based on the Carreau model was used to simulate the flow behavior during the filling by the semi-solid slurry into a die mold in a high pressure diecasting machine. Further the time-dependent heat transfer coefficient between the die mold and casting was considered in the simulation study. The predicted defects from the simulated study with the ANYCAST program matched well with those in the actual product.

Key words: semi-solid processing, rheology, Carreau model, viscosity, Mg alloy, die filling behavior.

Introduction

Semi-solid processing of metallic alloys and composites utilizes the thixotropic behavior of materials with non-dendritic microstructures in the semi-solid state. Innovative manufacturing methods based on this behavior has been developing over the last 20 years or so which originates from scientific investigation at MIT in the early 1970s [1, 2]. Semi-solid processing has been demonstrated to have the advantages of both the conventional casting and forging processes [3]. As the application range of magnesium alloys has recently been extended to not only automotive parts but electronic devices demanding a higher dimensional precision, many studies of semi-solid casting or thixomolding have been performed on Mg alloys and thixomolding has become popular in the marketplace especially in Japan [4, 5].

This recent commercialization has highlighted the need to model slurry flow into die cavities [6]. Die design and processing conditions such as injection speed, dwell time and pressure have been a matter of trial and error. In particular, die design rules from diecasting are not transferable to thixoforming because the physical and so flow properties of a semi-solid slurry are quite different from a liquid melt used in the diecasting process, where it is assumed the fluid has a constant viscosity, independent of the shear rate and time. However this is not the case in semi-solid processing. Also, the heat transfer in the die and die friction at the die surfaces should be considered in the simulation investigation as part of die design and processing parameters in semi-solid processing. Therefore, there is real potential commercial benefit to be obtained from a better understanding of the flow of semi-solid slurry in dies, alongside the academic interest.

In thixoforming, a reheated solid billet or pellet in the semi-solid state is injected and cast into a die mold. The reheated semi-solid billet should keep its own shape at a high viscosity and could be transformed into a fluid of a lower viscosity during the injection by a rapid shearing process. In rheoforming, a semi-solid slurry fabricated by stirring or agitating a melt during continuous casting is injected. Also to produce more complicated and thinner parts the semi-solid slurry is injected at a high shear rate to cause the slurry to have a viscosity of one to ten poises which makes it moldable. Also it is considered that the heat capacity of Mg castings is small compared to Al alloy castings when using the same shot volume.

In this study, computational fluid dynamics have been used to predict the die filling. However, some of the work reported has been based on rheological data obtained in steady state experiments, where the semi-solid slurry has been maintained at a particular shear rate for some time. In reality, in semi-solid processing, the slurry undergoes a sudden increase in shear rate from rest to 100 s^{-1} or more as it enters the die. This change takes place in less than a second. Hence, measuring the transient rheological response under rapid changes in shear rate is critical to the development of modeling of die filling and successful die design for industrial processes. Therefore, in this study, using a fundamental knowledge of the flow characteristics and

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the solidification behavior of a semi-solid slurry of Mg alloy obtained through the experiment reported, the die filling behavior of a semi-solid slurry in semi-solid processing was simulated with the ANYCAST program to produce the thin product of a nocturnal fluoroscope cover which was compared with the real product.

Experimental

It was attempted to produce a thin walled nocturnal fluoroscope cover demanding a high dimensional precision by injecting the semi-solid slurry into a die mold in a high pressure diecasting machine. AZ91D and SKD61 were utilized as the Mg alloy and the steel material for the die mold, respectively, to produce the nocturnal fluoroscope cover having a thickness range of 1 mm to 1.5 mm, which needed to be lightweight for fast mobility of an army and was produced by a complete machining process of an extrusion billet. The nocturnal fluoroscope cover was produced in a 250 tonne high pressure diecasting machine with the process parameters such as a die mold temperature of 230 °C, a semi-solid slurry temperature of 588 °C, and a plunger diameter of 65 mm. The plunger speed of the semi-solid slurry into die the mold was varied to 0.5 to 2 m/s for the experiment.

For the basic viscoelastic property, the data supported by ANYCAST were applied in the simulation work and the solid fraction as a function of temperature was calculated by using the phase equilibrium diagram shown in Fig. 1. For the analysis of flow behavior, the k-ε turbulent flow model was used in addition to the Carreau model. The solid model for the simulation work was composed of three parts of the mold, core and casting using Pro/E 3D modeling as shown in Fig. 2.

In the simulation of a casting process it is very important to analyze heat transfer between disparate materials. There exist thermal contact resistance from imperfect contact and thermal resistance coefficients by heat transfer between disparate materials, and due to these two factors the heat transfer coefficient depends on pressure, temperature and surface conditions. The heat transfer coefficient between the semi-solid slurry and the die mold was differently applied with respect to injection time as shown in Fig. 3. The other basic heat transfer coefficients between disparate materials are shown in Table 1.

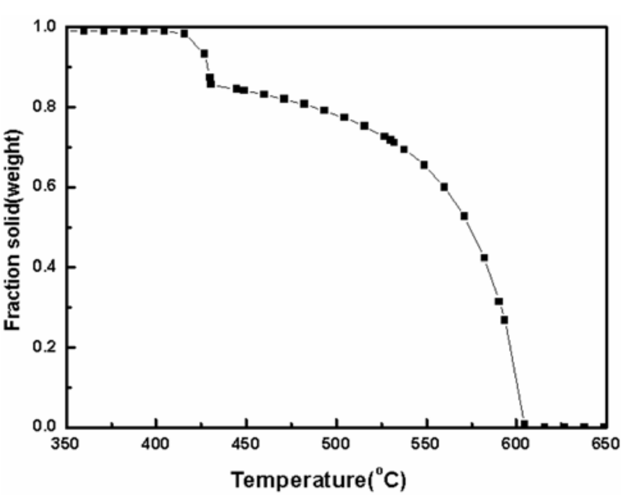


Fig. 1. The calculated solid fraction as a function of temperature in the equilibrium phase diagram used in the simulation study.

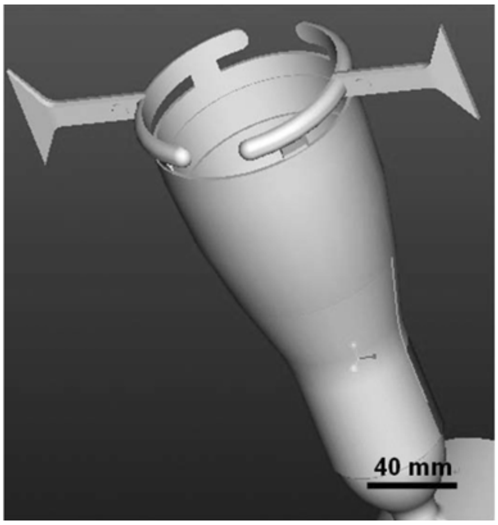


Fig. 2. The solid model of the product composed of the three parts of the mold, core and casting using Pro/E 3D modeling.

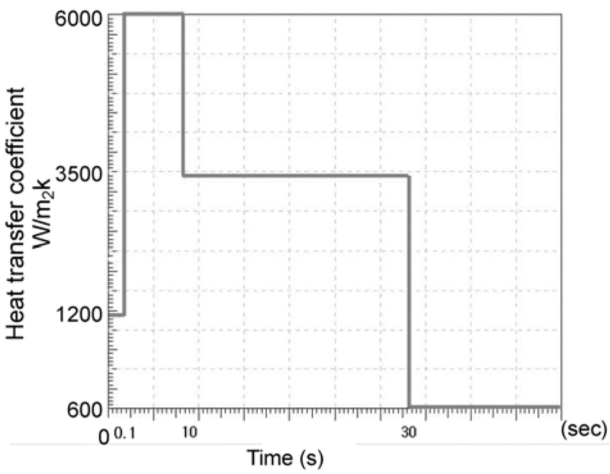


Fig. 3. The heat transfer coefficient between the semi-solid slurry and die mold with respect to injection time used in the simulation study.

Table 1. The basic heat transfer coefficients between disparate materials used in this simulation study

interface	Heat transfer coefficient (W/m^2s)
Mod-mold	600
Mold-Air	25
Mold-Cast	Time dependent

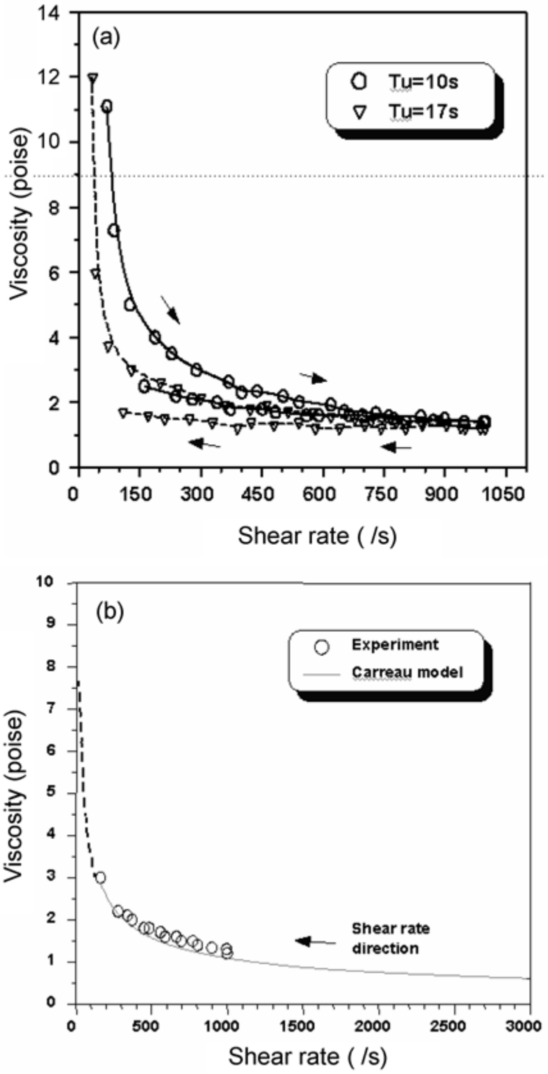


Fig. 4. The (a) measured [7] and (b) calculated viscosity of semi-solid slurry of Mg alloy (AZ91D) using the Carreau model for a non-Newtonian fluid.

Results and Discussion

The reported data [7] on the measured apparent viscosity of the semi-solid slurry of AZ91D Mg alloy as a function of different shear rates using a high temperature viscosity measuring equipment is shown in Fig. 4 (a) and was applied to find the model for a non-Newtonian fluid like a semi-solid slurry for the simulation study. The Carreau model [6] was selected as the well-fitted non-Newtonian model for a semi-solid slurry through matching the calculated data with the measured data as shown Fig. 4(b).

Eq. (1) of the Carreau model was applied for this simulation study and the constants for Carreau model were obtained as a viscosity at zero strain rate, μ_o=15, a viscosity at infinite strain rate, μ_∞=0.005, a time constant, λ=0.75, and a power law coefficient, n=0.4.

$$\mu=(\mu_o-\mu_\infty)[1+(\lambda\cdot D)^2]^{(n-1)/2}+\mu_\infty \quad (1)$$

, where D is a shear rate. In order to ascertain the Carreau model with the above constants, the reported flow behavior of the semi-solid slurry of AZ91D Mg alloy through the recorded photographs [8] was compared with the results from the numerical simulation as shown in Fig. 5. Also the k-ε turbulent flow model was applied to the simulation study to observe the flow behavior more precisely. The flow behavior of the semi-solid slurry of the Mg alloy during the injection at a gate speed of 8.25 m/s in the simulation study matched well with the visualized flow behavior as shown in Fig. 5. Accordingly, the Carreau model with the above constants was applied in the simulation study for the prediction of casting defects and the optimization of process parameters to produce the nocturnal fluoroscope cover using the Mg alloy slurry in semi-solid processing.

Figure 6 shows the die filling behavior of the semi-solid slurry of the Mg alloy with respect to the die

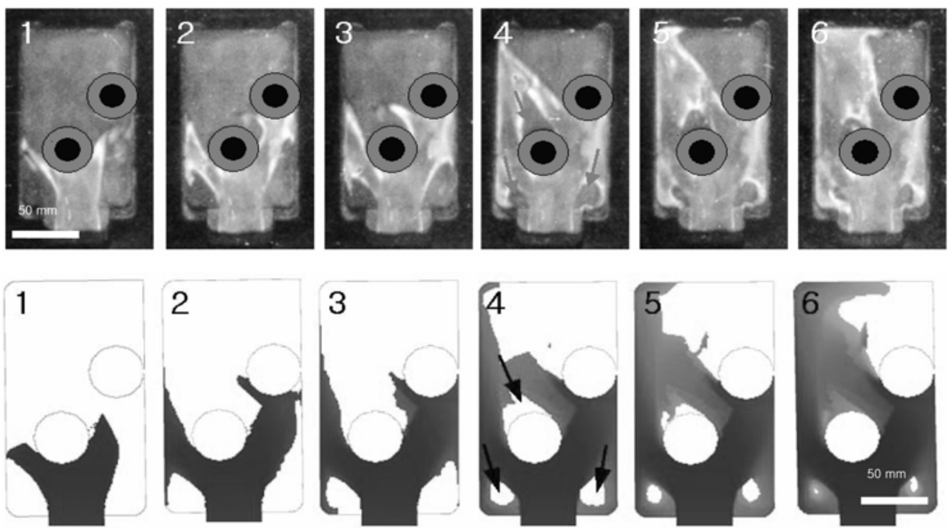


Fig. 5. The visualized (upper) and simulated (lower) flow behavior of the semi-solid slurry of AZ91D Mg alloy during the die filling at a gate speed of 8.25 m/s.

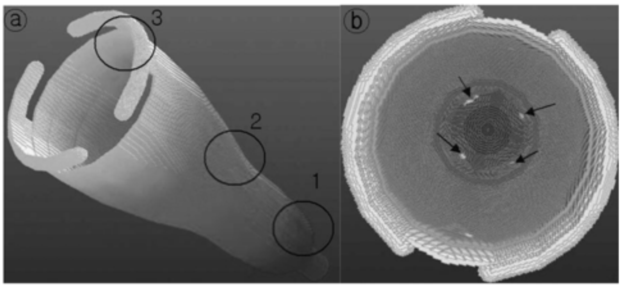


Fig. 6. The die filling behavior of the semi-solid slurry of the Mg alloy with respect to the die filling time as the result of simulation work. The different colors in this figure represent the different die filling times.

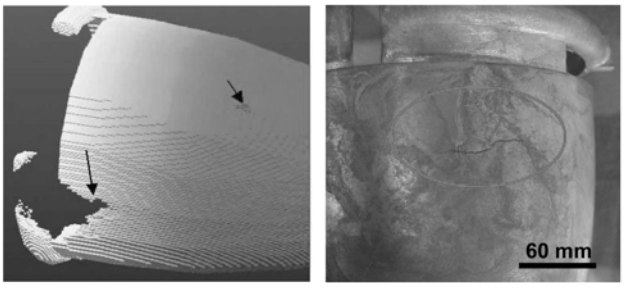
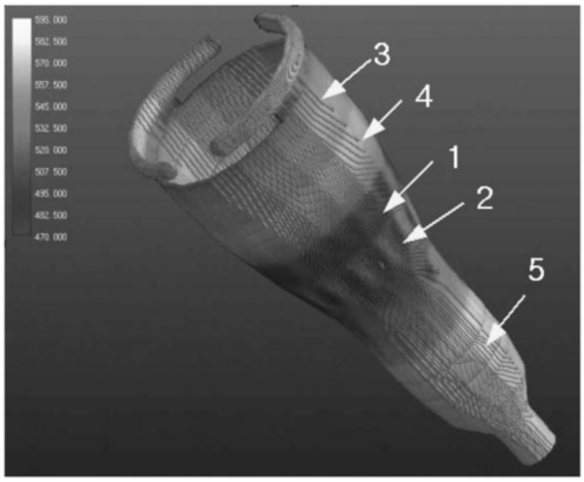


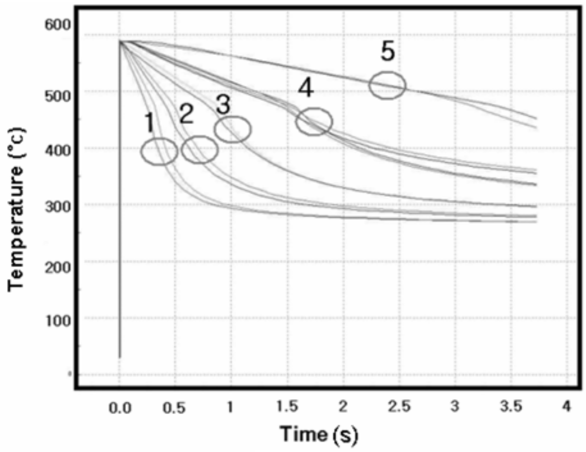
Fig. 7. The predicted defects in the simulation study and a failed part of the real product around a similar position.

filling time as the result of the simulation study. The different brightness in this figure represents the different die filling times. Figure 6(a) shows the die filling behavior of the Mg alloy slurry at a plunger speed of 0.8 to 2 m/s and the brightness changed smoothly. Accordingly, the semi-solid slurry of the Mg alloy well filled into the die mold at a plunger speed of 0.8 to 2 m/s because of its low viscosity due to the high shear rate. However, below a plunger speed of 0.5 m/s, some bright images appeared at both the internal and the external parts on the thinner area parts as marked by the arrows in Fig. 6(b), and these bright images represented the unfilled regions. This phenomenon was considered to be caused from the irregular die filling behavior due to the relatively high viscosity at the low shear rate. In addition, above a plunger speed of 2 m/s, the tendency of turbulent flow was enhanced leading to an increase in the number of casting defects [9]. Figure 7 (a) shows the unfilled region around the upper part of the product, which was predicted below an injection speed of 0.5 m/s as a result of the simulation study. Also some casting defects related to unfilled slurry due to the rapid cooling appeared around a similar position as shown Fig. 7(b). Therefore, compared with the experimental results the modified numerical simulation study using the ANYCAST program was considered to be very successful.

Figure 8 shows the temperature distribution and the expected cooling rates at the positions marked from the simulation study using the ANYCAST program. As the result of the simulation the thinnest part of the product marked Parts 1 and 2 having thicknesses of 1 mm to 1.5 mm have significantly high cooling rates and begin to solidify rapidly as shown in Fig. 8. When the liquid phase begins to solidify during the die filling process due to the high cooling rate, the viscosity of the semi-solid slurry around the thin part should increase significantly. Also, relatively intensive frictional resistance during the die filling process will be created at the die surfaces of the thin parts of the product. In the experiment below a plunger speed of 0.5 m/s, a sound thin casting could not be produced because of an insufficient shear rate and increased viscosity. Therefore, the injection speed should be increased to 0.8 m/s or more.



(a)



(b)

Fig. 8. The temperature distribution (a) and the predicted cooling rates (b) at the positions marked from the simulation study using the ANYCAST program.

Figure 9 shows an overview of the nocturnal fluoroscope cover produced and microstructures around different parts of the product. Microstructures of the product were composed of primary solid phases (white imaging) and eutectic phases between the primary solid phases (dark imaging) which have a lower melting

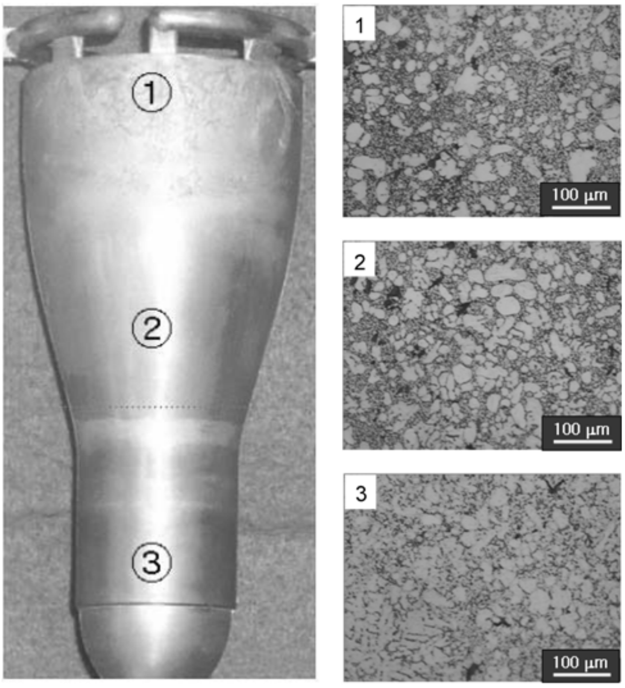


Fig. 9. An overview of the nocturnal fluoroscope cover produced and microstructures around different marked parts of the product.

temperature. The primary solid phase appeared in the semi-solid slurry before the die filling and the eutectic phase solidified in the die mold during and after the die filling. A finer eutectic phase was observed in Part 2 compared with that in Part 3. Therefore, it was considered that the thin part solidified more rapidly due to a significantly higher cooling rate because the fineness of the eutectic phase was increased by the higher cooling rate. The numbers of 1, 2, and 3 in Fig. 9 are marked as a sequence with greater distances from the injection gate. The volume fraction of eutectic phase was observed to vary with the distance from the injection gate and so the initial volume fraction of the liquid phase should be different because the liquid phase during the die filling process will solidify to become the eutectic phase. The liquid fraction was then observed to be greater at distances further from the injection gate. Therefore it was considered that the liquid phase in the semi-solid slurry was able to run faster in the thinner parts than was the primary solid phase. That means that two phase model, where the solid and liquid phase is considered separately, is necessary in a numerical simulation study of the semi-solid slurry.

Conclusions

In this study, to produce a thin nocturnal fluoroscope cover by semi-solid processing the die filling behavior of a semi-solid slurry of a Mg alloy was simulated with the ANYCAST program using the fundamental knowledge of the flow characteristics of the semi-solid slurry of the Mg alloy obtained through the reported experiment and this was compared with the real product. The Carreau model was matched with the reported viscosity and the k-ε turbulent flow model was applied in the simulation study. The constants for the Carreau model were obtained as a viscosity at zero strain rate, μ_o=15, a viscosity at infinite strain rate, μ_∞=0.005, a time constant, λ=0.75, and a power law coefficient, n=0.4. The semi-solid slurry of the Mg alloy well filled the die mold at plunger speeds of 0.8 to 2 m/s, but below a plunger speed of 0.5 m/s, some unfilled regions were predicted in the thinner parts and this was the same case in the real product. The liquid fraction was observed to be greater at distances further from the injection gate, and so it was considered that the liquid phase of the semi-solid slurry was able to run faster in the thinner parts than the primary solid phase. Therefore, the modified numerical simulation study using the ANYCAST program was considered to be very successful for the prediction of casting defects and the optimization of process parameters to produce the nocturnal fluoroscope cover using the Mg alloy slurry by semi-solid processing.

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