논 문

Computer Simulation for Die Filling Behavior of Semi-Solid Slurry of Mg Alloy

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Abstract

In order to develop the semi-solid forming technology for magnesium alloy the rheological and thixotropic behavior of Mg alloy slurry with varying shear rates and cooling rates was investigated and simulated with considering the viscosity based on microstructures and processing variables. The viscosity of slurry of Mg alloy (AZ91D) in semi-solid region was exponentially increased with a solid fraction, and was decreased with increasing a shear rate. In order to analyze precisely the rheological behavior, the ANYCAST program modified with the Carreau model and the different heat transfer coefficient between the cast and mold was used to simulate the flow behavior of Mg semi-solid slurry during the injection into a casting mold in a high pressure diecasting machine. The simulated rheological behavior of Mg alloy slurry was matched well with the experimental results.

초 록 : 본 연구에서는 Mg합금의 반응고성형 공정기술을 개발하기 위하여 여러 가지 전단속도와 냉각속도에 따른 Mg합금의 점도와 딕소트러픽 거동을 분석하였으며, 이를 전산모사연구와 비교 검토하였다. 전산모사연구에서는 미세조직과 공정변수를 고려한 반응고 슬러리의 유변학적 거동을 분석하였다. 반응고 온도영역에서의 Mg합금(AZ91D) 슬러리의 점도는 고상율에 따라 지수함수적으로 증가하였으며, 전단속도가 증가하면 감소하는 경향을 나타났다. Mg합금 슬러리의 유변학적 거동을 정확하게 분석하기 위하여 Carreau 모델을 사용하여 ANYCAST 프로그램에서 고압다이캐스팅용 금형으로의 Mg합금 반응고슬러리의 충진거동을 모사하였다. 전산모사된 결과는 동일한 조건에서의 실제 실험결과와 잘 일치하였다.

Key words : Semi-solid Forming, Rheology, Thixotropy, Viscosity, Filling behavior, Mg alloy.

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1. Introduction

Semi-solid casting technology enables to form metallic materials in the mushy zone and only has the advantages of both the conventional casting and forging process. For these reasons, there have been a lot of studies on aluminum alloy for the past 30 years. As the application range of magnesium recently extends to not only parts for vehicle but electronic device demanding a higher level of precision, many studies on semi-solid casting or thixomolding have been performed on Mg alloy and thixomolding is currently getting popular in the market. The semi-solid process can be divided into two processes (rheoforming and thixoforming) in accordance with a production method of slurry [1].

In the thixoforming, a reheated solid billet or pellet in the semi-solid state was injected and cast in a mold. The reheated semi-solid billet should be kept its own shape in a high viscosity and could be transformed into a fluid of a lower viscosity during the injection of a rapid shearing process. In the rheoforming, the semi-solid slurry fabricated by stirring or agitating a melt during continuous casting was injected. Also to produce more complicate and thin part the semi-solid slurry are injected under a high shear rate to bring the slurry having a viscosity of one to ten poises to mold. In this study, using the fundamental knowledge of the flow characteristics and the coagulation behavior of Mg alloy slurry obtained through the experiment, the thin product was simulated with ANYCAST program and was compared with the actual product.

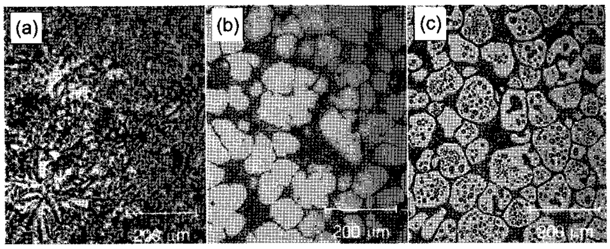

Fig. 1. Microstructures of Mg alloy in variable processes, a)squeeze casting, b)rheocasting, c) thixocasting.

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2. Simulation method

In this study a nocturnal fluoroscope cover was tried to produce by injecting the semi-solid slurry into a mold in a high plunger speed. For simulation work, the data on a solid fraction and viscosity of AZ91D Mg alloy was measured by using a high temperature viscosity measuring equipment [2]. Fig. 2 shows the measured apparent viscosity of semi-solid slurry of AZ91D Mg alloy as a function of a different shear rate [3].

The Carreau model, which was considered as the best model complying with the simulation condition was applied to the measured data. The Carreau model in this study was shown in Eq. (1) and (2). The constant of Carreau model could be obtained as $\mu_0 = 15$, $\mu_\infty = 0.005$, $\lambda = 0.75$, and $n = 0.4$ from the measured viscosity of Fig. 2.

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

$$D = \frac{1}{2}\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right) \tag{2}$$

Fig. 3 shows the optimized Carreau model matches well the actual experiment values. The viscosity was measured as a range of 1.5 to 2 poises with respect to a shear rate as shown in Fig. 3(a). Also these data were compared with the expected viscosity from the Carreau model and showed almost identical results as shown in Fig. 3(b). In the experimental result, the viscosity was rapidly decreased due to a high initial shear rate and then was kept on its initial value. However, according to Eq. (1), the viscosity was increased again as decreasing the shear rate. By this phenomenon the difference between the measured viscosity and the expected viscosity from Eq. (1) of the Carreau model was generated. Therefore, an alternative was needed to reduce the difference. The shear rate could be gained through Eq. (2), and the appropriate value similar to the measured viscosity could be found by the substitution of the optimum value. If a range of D value was limited to $25 < D < 2{,}000$ to control the shear rate, the flow behavior similar to that of the Carreau model could be obtained as shown in Fig. 4.

The flow behavior of the semi-solid slurry of AZ91D Mg alloy through the visualized photos and the simulation work during the injection at a gate speed of 8.25 m/s was compared and matched well as shown in Fig. 4 [3]. Also the k-ε

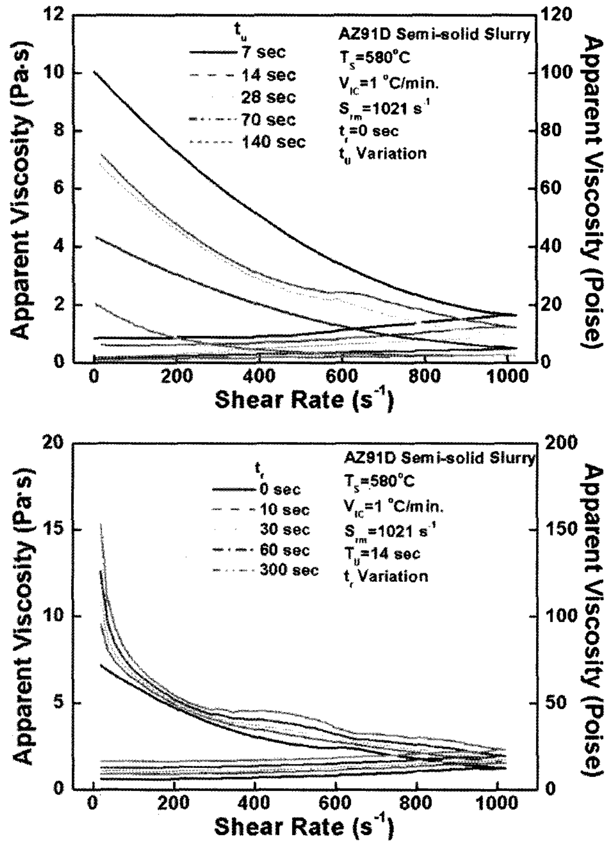


Fig. 2. Effect of the processing variables on the apparent viscosity during the shear rate change cycle [2,3].

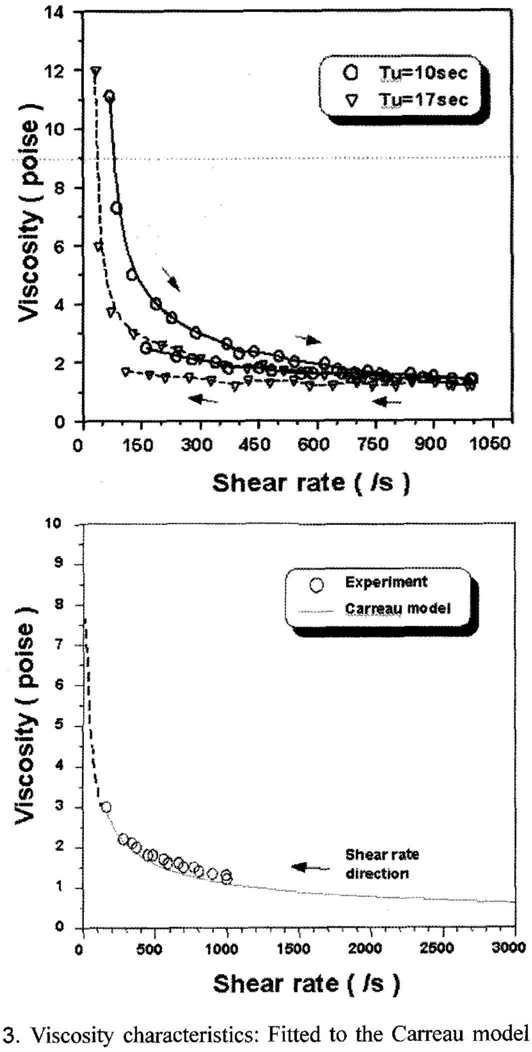


Fig. 3. Viscosity characteristics: Fitted to the Carreau model [5].

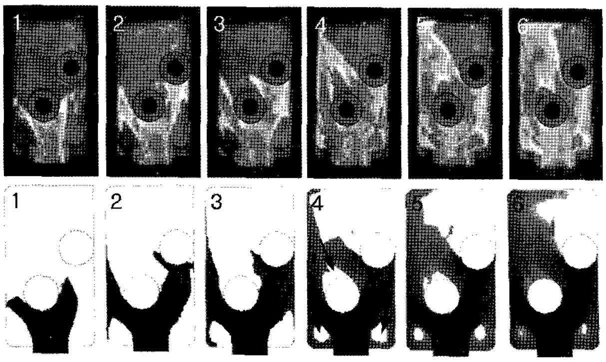
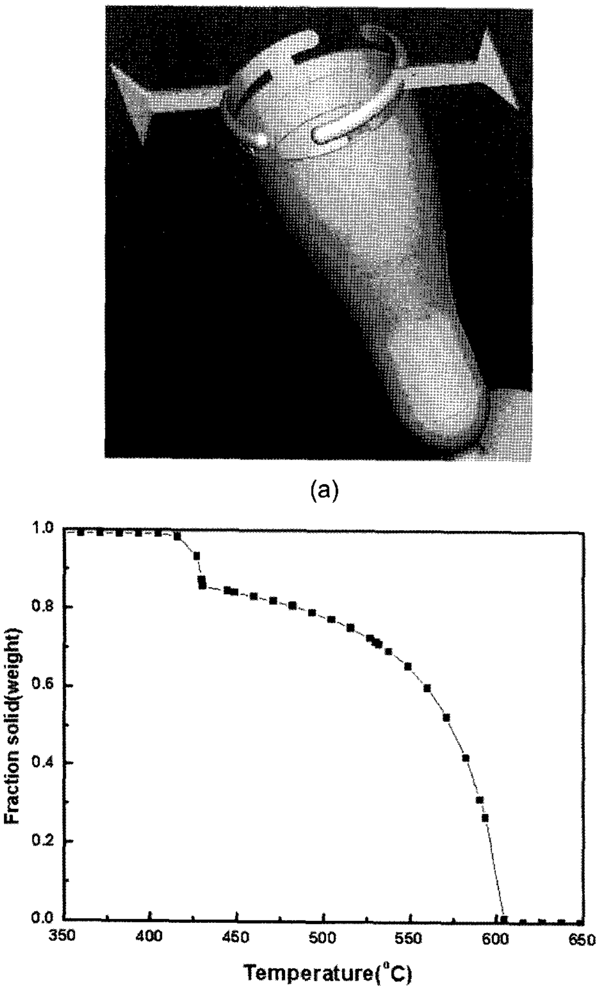


Fig. 4. The flow behavior of the semi-solid slurry of AZ91D Mg alloy through the visualized photos and the simulation work during the injection at a gate speed of 8.25 m/s [3].



(a)

(b)

Fig. 5. Pro/E 3D modeling and the solid fraction data.

turbulent flow model was applied to the simulation work to observe the flow behavior more precisely.

Referring to the simulation method of the Fig. 5, the authors made an attempt to simulate the nocturnal fluoroscope cover.

Table 1. Chemical compositions of AZ91D Mg alloy.

Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
8.29	0.68	0.12	0.011	0.0057	0.0	0.0033	90.89

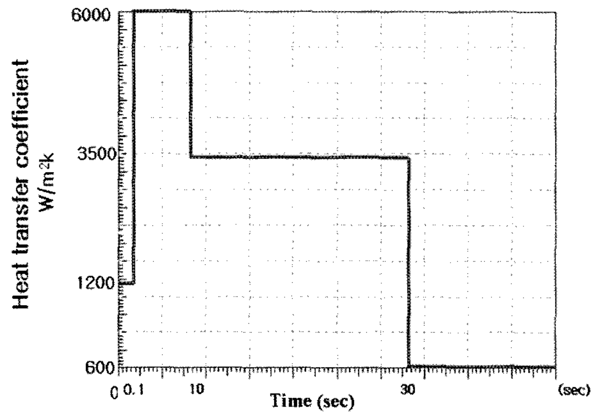


Fig. 6. Heat transfer coefficient between the cast and the mold

Table 2. Each heat transfer coefficients.

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

3. Casting simulation condition

AZ91D (Table 1) and SKD61 was utilized as a Mg alloy and a mold die, respectively, to produce the cover. For basic viscoelastic property, the data supported by ANYCAST were applied in the simulation work. For the analysis of flow behavior, the k-ε turbulent flow model was used in addition to the Carreau model. A mold die temperature of 230°C, a semi-solid slurry temperature of 588°C, a plunger diameter of 65 mm, a moving speed of 0.5 to 2 m/s were adjusted for the experiment, and the measured viscosity of semi-solid slurry was obtained from the graph of Fig. 3.

The model for the simulation work was composed of the three parts of the mold, core and cast as shown in Fig. 5. A solid fraction as a function of temperature in Fig. 5(b) was applied.

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 was dependent on pressure, temperature and surface condition. A heat transfer coefficient between the molten metal and the mold was differently measured according to an injection time (Fig. 6). The basic heat transfer coefficient was shown in Table 2.

4. Results and Discussions

At a plunger speed of 0.8 to 2 m/s, the slurry was well injected into the mold because of its low viscosity due to a high shear rate. Fig. 7(a) shows a different color with respect to an injection time. However, below a plunger speed of 0.5 m/s, short shots was observed in both the internal and the external parts and these shots caused a different color as marked in Fig. 7(b).

This phenomenon was considered to be caused from irregular behavior due to a relatively higher viscosity at the initial shear rate applied to all parts evenly. In addition, above an injection speed of 2 m/s, the tendency of turbulent flow was enhanced to lead an increase in the number of casting defect [4]. In the comparison with the result of the experiment and simulation work some defect was appeared on the upper part under an injection speed of 0.5 m/s as shown in Fig. 8.

As the result of the simulation work Fig. 9 shows that the thinnest part of the mold marked Part 1 and 2 having a thickness of 1 mm to 1.5 mm begin to coagulate and have a significantly high cooling rate. Due to the rapid coagulation the viscosity around there was significantly increased [5]. Under an initial plunger speed of 0.5 m/s, the sound casting could not produced because of the insufficient shear rate. Also, the injection speed should be increased because the relatively intensive frictional resistance was created at the surface of the thin part of the casting.

The microstructure around a different part of the casting was shown in Fig. 10 The number of 3-2-1 was marked as a sequence of the farther instance from the injection gate. The microstructure having a more liquid fraction was observed at

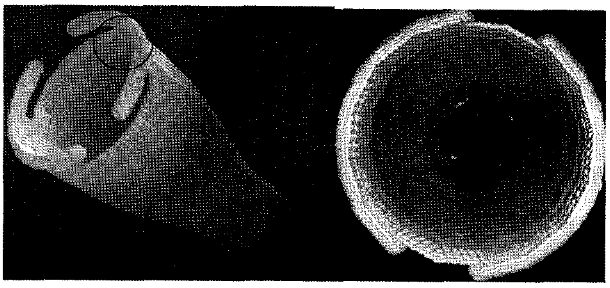


Fig. 7. Analyzed and visualized picture by ANYCAST.

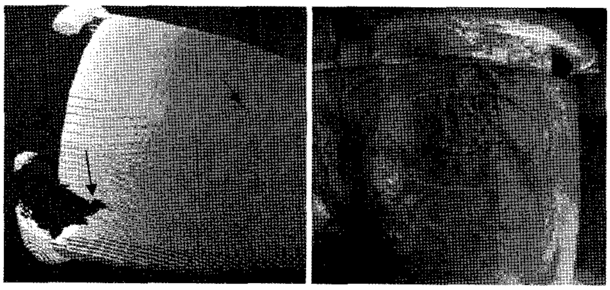


Fig. 8. The expected defect in simulation work and the actual failure part.

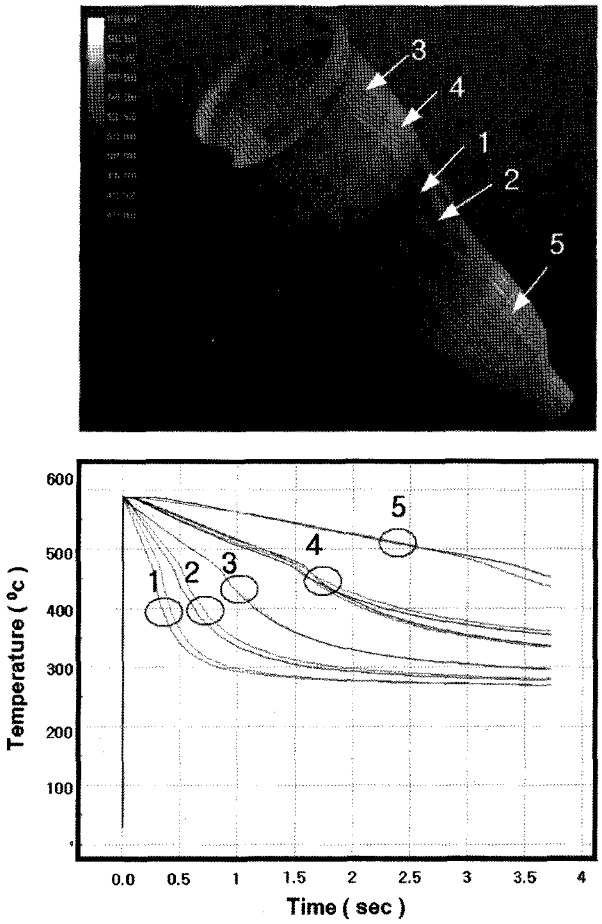


Fig. 9. The temperature distribution and cooling rate expected from the simulation work by using ANYCAST.

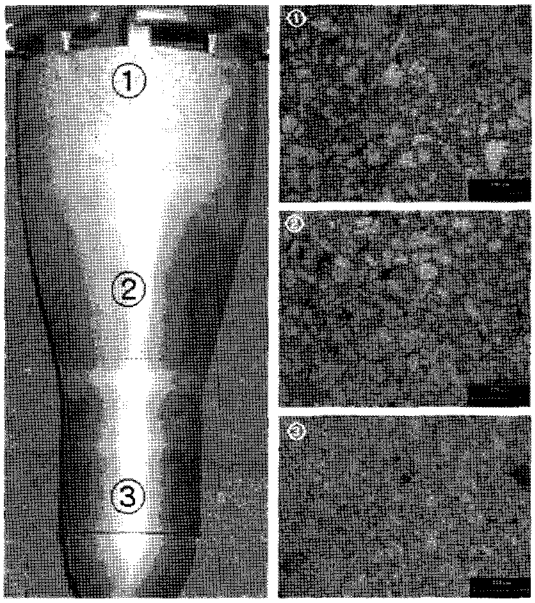


Fig. 10. The microstructure around a different part of the nocturnal fluoroscope cover.

the farther distance from the injection gate.

5. Conclusions

In this study, using the fundamental knowledge of the flow characteristics and the coagulation behavior of Mg alloy slurry obtained through the experiment, the thin product was simulated with ANYCAST program and was compared with the actual product. In simulation work the Carreau model matched with the measured viscosity and the k-ε turbulent flow model was applied.

External defect was generated under a plunger speed of 0.5 m/s because the coagulation was occurred rapidly in the thin part with a thickness of mm to 1.5 mm of the product. Above a plunger speed of 2 m/s, the internal defect due to the turbulent flow was appeared. The microstructure having a more liquid fraction was observed at the farther distance from the injection gate in the production of thin part.

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