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ABSTRACT

Semi-solid metal casting is gaining interest in the casting industry. It offers distinct advantages over other near-net-shape casting technologies, e.g., a more homogeneous microstructure, less porosity and improved mechanical properties.

Numerical simulation can be used to predict die filling, and hence to optimize die design. However, the non-Newtonian behavior of semi-solid metals is quite complex. Simulation tools developed for conventional die casting cannot be applied to semi-solid die casting.

In this study, a program based on the finite different method (FDM) has been developed to predict the filling pattern in semi-solid casting of metal alloys. A power law equation was used to describe the constitutive behavior of semi-solid metals. A series of short-shots experiments was conducted to validate the simulation results.

Keywords: Computer simulation, Mold filling, Semi-solid casting, SSM, Magnesium alloys, AZ91D

INTRODUCTION

The rheology of semi-solid metal alloys was first discovered by Spencer et al. in the early 1970s[1]. After over 30 years of development work and a few industrial parts in production, semi-solid metal processing is gaining increasing interest in the casting industry. Compared with the conventional pressure die casting process, semi-solid casting has some distinct advantages such as a more homogeneous microstructure, less porosity and improved mechanical properties. However, the complex rheology involved in the casting of semi-solid metal alloys can result in flow instabilities. Therefore, the optimization of semi-solid metal casting often requires a trial-and-error approach whenever a new die is produced. An accurate filling simulation program for semi-solid casting should therefore reduce the number of casting trials and errors needed and speed up new product development time. It should be noted that simulation programs developed for conventional casting processes cannot be used for semi-solid casting because of the complex rheology associated with semi-solid metals during die filling.

Yang et al studied the rheological behavior of semi-solid A356 aluminum alloy[2]. They reported a rheological equation of partially solidified aluminum alloy at the temperature range of 570-580℃. A simulation study of the thixoforming process[3] was also conducted by Kim et al. using a commercial software. The study used the Ostwald-deWaele model to simulate the filing phenomena in a die cavity for A356 aluminum alloy during semi-solid casting. Alexandrou et al. used a commercial code to compare Newtonian and Binham filling of a three-dimensional cavity containing a core[4].

In the above works, die filling was conducted using a commercial package and the semi-solid material was an aluminum alloy. In this study, a simulation system for die-casting semi-solid metal alloys has been developed. Numerical simulations were conducted using a complex box-like component and the semi-solid material was assumed to be the AZ91D magnesium alloy. A series of shots were thixocast from semi-solid AZ91D billets to validate results from numerical simulations.

MATHEMATICAL METHOD

PHYSICAL SYSTEM

Figure 1 is an illustration of the AZ91D magnesium box-like casting. The direction of g indicates the direction of gravity force. This box-like component was produced using a 600-ton Buhler die casting machine. A number of AZ91D magnesium billets with non-dendritic microstructure were thixocast in this study and the feedstock was reheated to 575 °C and injected at a ram speed of 0.5 m/s. General conditions for thixocasting these billets have previously been reported[5].

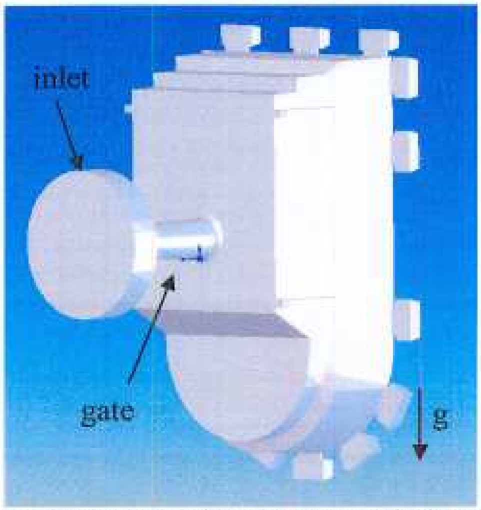


Figure 1 A schematic illustration (computer model) of the box-like casting

MODELING ASSUMPTIONS

In order to simulate the filling phenomenon of semi-solid metal alloys in this study, the following assumptions are required:

(1) The semi-solid metal alloys are treated as a one-phase incompressible fluid.
(2) Because the filling time is very short (usually well below a second), the temperature of the semi-solid metal is assumed constant during filling.

GOVERNING EQUATIONS

In an incompressible Non-Newtonian fluid, the governing differential equations in this model are the continuity equation and the momentum equation expressed as follows:

$$\nabla \cdot \vec{u} = 0 \qquad \text{Equation 1}$$

$$\partial_t \vec{u} + \nabla \cdot (\vec{u} \otimes \vec{u}) = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla \cdot (\mu_a D) + \vec{g} \qquad \text{Equation 2}$$

where $\vec{u}$ is the velocity field, ρ is the density, p is the pressure, μ_a is the apparent viscosity, and $\vec{g}$ is the gravitational force. D in the momentum equation is a tensor with components defined as follows:

$$D_{ij} = \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \qquad \text{Equation 3}$$

The numerical technique used to solve these equations is the finite difference method. The SOLA solution algorithm is used to resolve the velocity field.

CONSTITUTIVE EQUATION

For a one-phase model, the rheology of the semi-solid fluid is represented by the apparent viscosity. The apparent viscosity of semi-solid fluid is affected by sheer and temperature. However, the temperature during whole process is assumed constant. Therefore, the apparent viscosity only changes with the sheer rate. In this study, a power law relation was used. The constitutive equation can be expressed as follows:

$$\mu_a = M \left| \dot{\gamma} \right|^n \qquad \text{Equation 4}$$

where μ_a is apparent viscosity, M is a constant, n is a constant of power law, $|\dot{\gamma}|$ is a scalar quantity associated with sheer rate. $|\dot{\gamma}|$ is defined as follows:

$$|\dot{\gamma}| = \sqrt{\frac{\dot{\gamma} : \dot{\gamma}}{2}}$$ Equation 5

TREATMENTS FOR FREE SURFACE FLOW

There are three crucial concerns for modeling free-surface flow: (a) How to estimate the free surface location, (b) How to monitor the evolution of the fluid domain, and (c) How to handle the free surface boundary conditions. In this study, a VOF interface tracking method is adapted to represent the fluid domain and to track the evolution of its free boundaries[6].
With the VOF method, a field variable, $F(x, y, z, t)$, is designated to each computational element to indicate the volume fraction of liquid in that particular cell. When F is equal to 1, it means the cell is full of liquid. When F is equal to 0, it means the cell is full of gas (or empty of liquid). When F is between 0 and 1, the element contains both liquid and gas and an interface is then allocated in that particular cell. Thus, the F-value can indicate the domain of fluid flow and it is a step function. From the law of mass conservation, the volume fraction of fluid, F, is governed by the following equation:

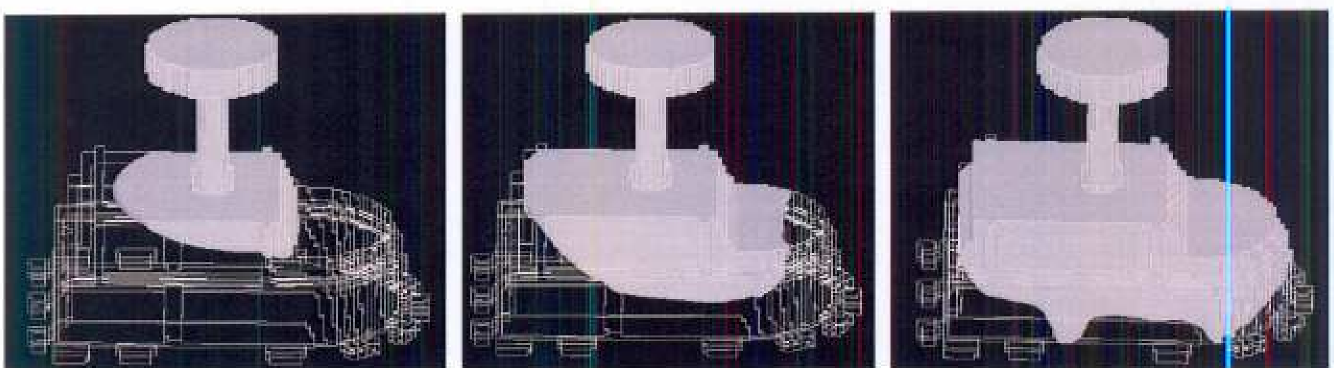
$$\frac{\partial F}{\partial t} + (\vec{u} \cdot \nabla) F = 0$$ Equation 6

RESULTS AND DISCUSSION

CONSTANT OF POWER LAW

In the one-phase model, the rheology of the material is represented by the constitutive equation. Therefore, setting appropriate constants for the constitutive equation is critical. In characterizing the semi-solid AZ91D alloy, Gebelin et al[7] used two methods to find the relation between apparent viscosity and sheer rate. One was a compression experiment and the other was a backward extrusion experiment. In their study, the constant of power law was close to -0.65 in the compressing test and -0.95 in the backward extrusion. When they put all the data together, the results showed that the exponent n was close to -0.87. This result is very similar to the -0.85 value reported by Ghosh et al[8]. In order to obtain the suitable exponent n of the constitutive equation, values of -0.65 and -0.85 were tested in the simulation system in this study.

The negative sign in n signifies that during injection of the semi-solid AZ91D alloy there is sheer thinning. This means that when a semi-solid magnesium alloy is under sheer, its apparent viscosity will decrease. Figure 2 are the filling patterns at different stages of fill using n of -0.65. At first, the AZ91D semi-solid slurry flow front advanced very smoothly. This is because the apparent viscosity of the semi-solid AZ91D alloy is higher. Higher apparent viscosity leads to laminar flow. In the second stage, the semi-solid front began to fill the circular front of the casting. At this stage, there was a divergence of flow around the circular edges as well as flow in the centre as illustrated in Figure 3. Since the front section of the casting is round, the material flowing into this part of the cavity (identified by locations A and B) displays a greater degree of deformation compared to the material at the centre (location C). In other words, the sheer rate of the slurry in locations A and B is higher than that in location C. Because of sheer thinning, the material at points A and B should flow faster compared with the material at point C. This is why there was flow divergence in this part of the casting. Finally, the slurry descended smoothly and more uniformly down towards the remaining part of the cavity.



(a) 28.4% (b) 50.9% (c) 74.9%

Figure 2 Flow patterns of semi-solid AZ91D magnesium alloys using n of -0.65.

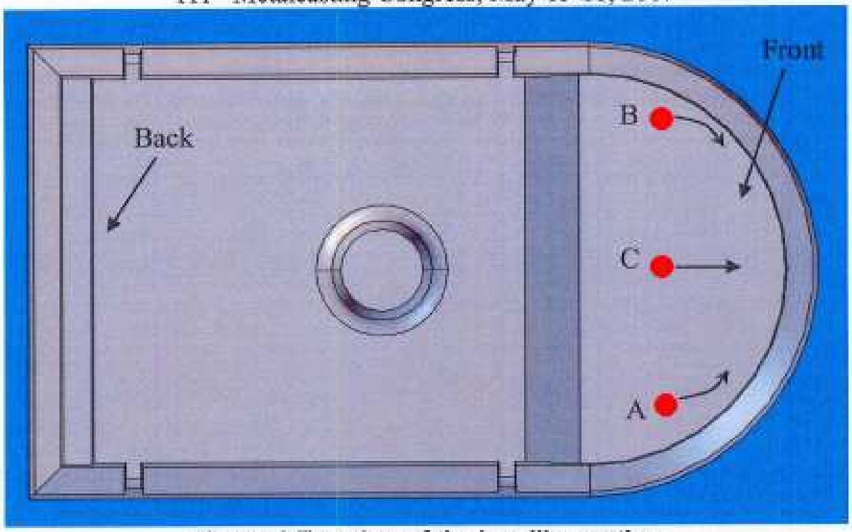
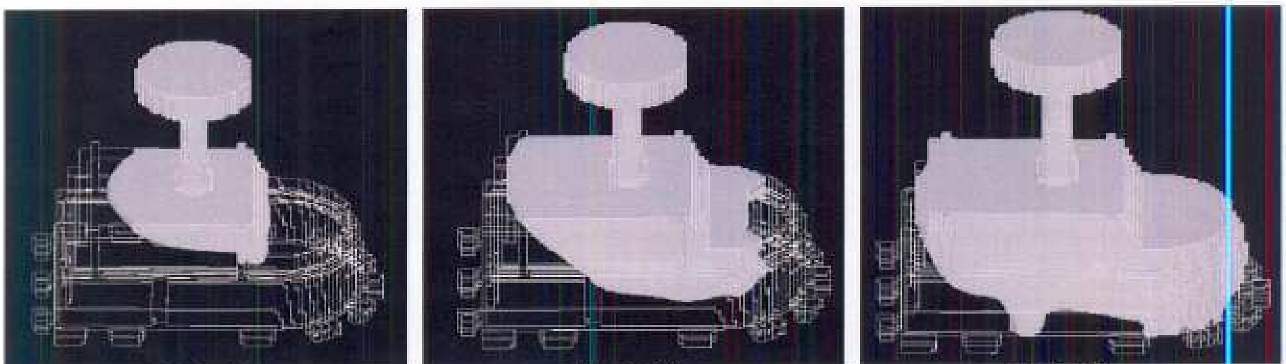


Figure 3 Top view of the box-like casting

Figure 4 shows the flow patterns at different stages using an n value of -0.85. The general tendency of the filling pattern is almost the same as that observed using an n value of -0.65. However, an n of -0.85 means that the apparent viscosity decreases more drastically with increasing sheer rate. This is why the fork in the diverging front in Figure 4 (b) is more easily distinguishable compared with that in Figure 2(b). Moreover, the average viscosity of the results using an n of -0.85 seems lower than that using an n of -0.65. It should be noted that in both Figure 2(c) and Figure 4(c) where the same percentage of fill (74.9%) is simulated, the circular front of in the casting appears more complete compared with the rest of the cavity towards the back. This is most probably due to the effect of gravity as the circular section is below the gate and thus the metal injected would tend to flow down the lower part of the cavity where this section is located.



(a) 28.4% (b) 50.9% (c) 74.9%

Figure 4 Flow patterns of semi-solid AZ91D magnesium alloy using n of -0.85.

EXPERIMENT VALIDATION

In order to validate the results of the simulations, a series of short-shot experiments was conducted to compare the flow patterns generated by the computer with actual partial shots produced in the die casting machine. Different volumes of the alloy were injected to obtain partial shots that would correspond to the flow patterns of the different filling stages. Figure 5 shows the flow patterns of the semi-solid AZ91D magnesium alloy from partial shots. As shown in the results, the semi-solid magnesium alloy came in smoothly and filled the rectangular flat surface adjacent to the gate at the beginning, with quite a bit of metal entering the sloppy 'window' and some down the other three edges. When the semi-solid slurry advanced to the circular front, there was evidence of forking and flow was preferential around the circular edge as observed in the simulation study. Finally, the rest of the cavity was filled by the semi-solid slurry front which now advanced towards the square end and completed the filling process, as observed in the simulation study. Thus, these results compare very favorably with the simulation results in Figure 2 and Figure 4. However, the match between simulation and partial shot results is better in Figure 4. Therefore, it would appear that an n value of -0.85 is a more suitable exponent constant in the constitutive equation for the mold filling simulation of semi-solid AZ91D magnesium alloys with a piston speed of 0.5 m/s and feedstock temperature of 575°C.

(a) 0.388 kg (b) 0.619 kg (c) 0.694 kg

Figure 5 Short-shots of the semi-solid AZ91D magnesium box with different shot weights.

SUMMARY

In this study, a mold filling simulation system has been developed for the semi-solid casting process. A magnesium alloy box-like component was analyzed. Two exponent constants (-0.65 and -0.85) of the constitutive equation were tested in the simulation system. The simulation results showed that the semi-solid magnesium alloy filled smoothly at the beginning but began to assume a divergent fork-like flow front when the slurry started to fill the circular front the casting. Finally, the semi-solid slurry front advanced to fill the rest of the cavity with vertical edges in a smooth and more uniform manner. A series of short-shot experiments were conducted to validate the simulation results. The experimental results and simulation results were comparable. These results also showed that an exponent constant of -0.85 is a suitable input in the constitutive equation for mold filling simulation of semi-solid AZ91D magnesium alloy with a piston speed of 0.5 m/s and feedstock temperature of 575°C.

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