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# Mold Filling Simulation of Semi-Solid Magnesium Alloys

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**Keywords:** Semi-solid metal; Magnesium alloy; Mold filling; 3D Modeling; Finite elements.

**Abstract.** Magnesium alloys are increasingly used in automotive, aeronautic and electronic applications to produce high performance, light weight parts. In the thixomolding process the semi-solid slurry is injected into a mold at controlled temperature such that the melt has specific flow behavior. This allows the fabrication of near net shape components with controlled microstructure and good mechanical properties. The numerical modeling of such applications presents unusual challenges for both the physical modeling and the solution algorithm. This paper presents 3D solutions of the injection molding of semi-solid AZ91 magnesium alloys. The methodology deals with the shear thinning, temperature dependent viscosity behavior and is able to accurately solve the high velocity flows encountered during semi-solid magnesium molding. The approach is applied to the injection of a tensile bar and the results compared with experimental data. The numerical solutions indicate that the material forms a jet at the exit of the gate and a swirling flow forms as the material advances along the first larger diameter section. The wall regions are filled first, leaving a void inside. This agrees very well with the experimental observation.

## Introduction

The use of magnesium (Mg) alloys in the fabrication of structural and non-structural parts for various industries has grown continuously in the past years. In the automotive industry this growth was driven by the ever increasing demands for reduced vehicle emissions and improved fuel consumption which can be achieved in part by the reduction of vehicle weight [1,2]. The ability to reliably cast components of various shapes and section thickness for structural components could further increase the use of Mg alloys in vehicles. The resulting physical and mechanical properties are very sensitive to the forming process and the rate of solidification. The control of the mold filling and solidification is therefore essential in attaining high integrity parts. The highest rate of solidification is achieved in die casting whereas the lowest rates occur in sand and plaster castings. In semi-solid forming one can combine controlled flow of the slurry having higher viscosity and high solidification rates as a partially solidified material requires less heat extraction [3,4]. In these processes a semi-solid slurry is injected into the mold at controlled temperature such that the melt has specific flow behavior. The alloy chemistry and morphology of the solid particles need also to be controlled in order to achieve a solidified alloy structure that will result in optimal mechanical properties.

The objective of this work is to develop numerical simulation tools for the prediction of the semi-solid metal mold filling. Such applications involve free-surface flow coupled with heat transfer, non constant material properties, and complicated three-dimensional geometries. The flow is at high Reynolds number, on geometries having high aspect ratio components. Strong nonlinear dependence of flow properties on velocity are common place, such as large and rapid spatial variations of the apparent viscosity. The viscosity of semi-solid Mg alloys exhibit an important shear thinning and solid fraction dependence. During the injection of complex industrial parts, the semi-solid alloy flows through converging and diverging sections as well as in areas presenting drastic changes in thickness and flow directions. In many cases these regions can be the source of molding problems (air entrapment, porosity, etc.) and a more detailed understanding of the flow characteristics in these areas might be useful in solving undesirable situations. Such problems place special demands on the solution algorithm. The technique must be robust and provide accurate solutions for a wide range of parameters. This paper presents solutions using a finite element method. Similar algorithms were previously used by the authors to solve a variety of molding applications, such as in die casting [5], polymer injection molding [6], gas-assisted injection molding [7], co-injection [8] and injection of metal powders [9]. The work presented here is an extension to semi-solid metal injection molding. At this point there are very few published simulation results for the injection molding of semi-solid magnesium [10,11,12]. Kim et al. [10] used the commercial software MAGMA to make 3D computations. They use a power law model to describe the viscosity and obtain almost isothermal flow conditions. Results are shown for 40% and 2% solid fraction on a relatively simple geometry. Lohmüller et al. [11] carried out simulations at constant viscosity and analyzed the influence of different values of the viscosity on the filling pattern.

The paper is organized as follows. First, the equations describing time-dependent laminar flow along with their boundary and initial conditions are presented. The rheological behavior of AZ91 alloys in semi-solid state is then discussed. The transient momentum, continuity, energy and front tracking equations are solved using linear finite elements. The methodology is applied to the simulation of the filling pattern during the injection molding of a tensile bar and the numerical prediction is compared with experimental observation.

## Model Equations

**Flow Equations.** During the filling of the mold, the Mg alloy is considered to be incompressible and to behave as a generalized Newtonian fluid. The flow is considered laminar. The flow of incompressible fluids is described by the Navier-Stokes equations:

$$\rho\left(\frac{\partial u}{\partial t}+u\cdot\nabla u\right)=-\nabla p+\nabla\cdot\left(2\eta D_{ij}\right), \tag{1}$$

$$\nabla\cdot u=0\,, \tag{2}$$

where $t$, $\mathbf{u}$, $p$, □ and □ denote time, velocity, pressure, density and viscosity respectively and $D_{ij}=(\nabla u+\nabla u^{T})/2$ is the strain rate tensor.

**Rheological Model.** Several experimental studies were carried out to characterize the rheological behavior of the AZ91D magnesium alloy in the semi-solid state. The measured viscosities indicate large discrepancies between the different studies. The tests performed by Ghosh *et al.* [13] resulted in the lowest viscosity, whereas those of Mao *et al.* [14] result in a viscosity about one order of magnitude higher. Measurements of Gebelin *et al.* [15] lead to a viscosity of the slurry three orders of magnitude higher that the one measured by Ghosh *et al.* [13]. All experiments agree on the fact that the slurry has a shear thinning behavior (i.e. the viscosity decreases with increasing shear rate) and depends on the solid fraction. The following expression for the viscosity is used in this study:

$$\eta=Ae^{Bf_s}\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^{-n}, \tag{3}$$

where $A$ and $B$ are model parameters, $n$ is a positive power law coefficient, $f_s$ is the solid fraction and $\dot{\gamma}_0$ is a reference shear rate defining the scale for the rate of shear $\dot{\gamma}$. The shear thinning behavior is characterized by the exponential coefficient $n$ of the power-law model. The solid fraction at equilibrium depends on the temperature and is given by the Scheil equation:

$$f_s = 1 - \left( \frac{T_s - T}{T_s - T_m} \right)^{\frac{1}{1-k_0}}, \tag{4}$$

where $T$ is the alloy temperature, $T_s$ is the freezing temperature, $T_m$ is the liquidus temperature and $k_0$ is the partition coefficient.

In the present work, simulations were carried out using the viscosity data from Ghosh *et al.* [13] (Figure 1) with the following model constants: $n$=0.85, $A$=24Pa·s, $B$=2, $\dot{\gamma}_0$=1s$^{-1}$, $T_s$=470$^0$C, $T_m$=595$^0$C, $k_0$=0.65.

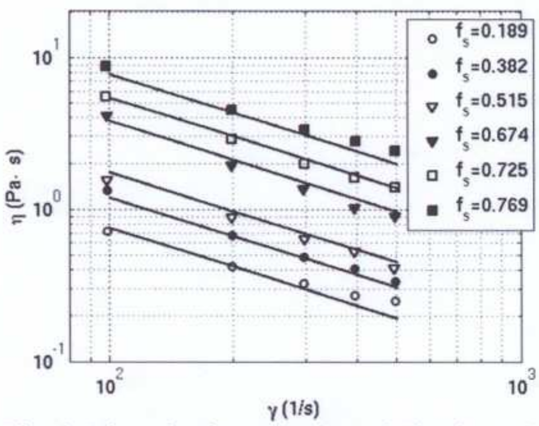


Fig. 1: Viscosity from the data of Ghosh *et al.*

**Heat Transfer.** The heat transfer is modeled by the energy equation:

$$\rho c_p \left( \frac{\partial T}{\partial t} + u \cdot \nabla T \right) = \nabla \cdot (k \nabla T), \tag{5}$$

where $T$, $c_p$ and $k$ denote temperature, specific heat and conductivity respectively. Because the slurry is injected at a temperature where both solid and liquid phases are present, any change in the temperature determines a change in the solid fraction. To account for the change in the solid fraction, we use an effective specific heat in the energy equation which incorporates the effect of the latent heat of fusion, $c_p = c_{p0} + \lambda(df_s / dT)$, where $c_{p0}$=1050 J/kg·K and □=3.73·10$^5$ J/kg. The derivative of the solid fraction with respect to temperature is obtained by differentiating Eq. (4). The density and thermal conductivity are □=1830kg/m$^3$ and $k$=72W/m·K respectively.

**Mold Filling Simulation.** For mold filling applications in addition to solving for the flow equations we need to track the position of the interface in time, between the filling material and the air/void inside the cavity. Front tracking is done using a level-set method [5]. For this, a smooth function $F(x,t)$ is introduced such that a pre-determined value, $F_c$, represents the position of the interface. A value larger than $F_c$ indicates a filled region. The front tracking function is transported using the velocity field provided by the solution of the momentum-continuity equations.

**Mold Filling Application**

This section presents the application of the numerical solution for the injection molding of a AZ91D alloy tensile bar, 190mm in length. The part has a circular cross section with an initial diameter of 10mm on a length of 50mm; the section diameter decreases to 6mm towards the middle of the part and then increases back to the same 10mm diameter for the last 50mm. Diameter changes are gradual occurring over a length of 8mm. The mold cavity contains four identical tensile bars. The initial flow inside the sprue separates first into two opposite flow channels and then each channel feeds two tensile bar cavities (see Figure 2). Each tensile bar is injected at one extremity with a gate angle of $45^0$ with respect to the part axis. The gate is located under the symmetry plane of the part to allow for part ejection. The sprue is 20mm in diameter and the semi-solid slurry enters the sprue at 12m/s (2.5m/s plunger speed). The material is injected at a temperature of $580^0$C and the mold is heated to $204^0$C. The filling of the parts takes about 0.03s.

Fig. 2: Solid model for the four cavities tensile bar mold.

**Experimental Observations.** Several series of partial (short shots) and complete fillings were carried out in order to determine the flow pattern during the filling of the mold. The following observations can be drawn from the analysis of the molded parts (see Figures 3 and 4):

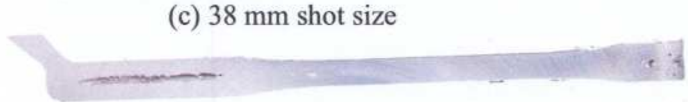
- On several short shots the mold cavities were not all filled to the same extend. This may be caused by the fact that the mold is positioned in a way where the tensile bars are oriented along the vertical axis, and gravity can act differently at the top and bottom cavities. However, the overall effect of the gravity on the filling pattern is negligible due to the high injection speed and hence it was not included in the simulation.
- The material exits the gate at high speed forming a jet that impacts on the opposite wall when entering the tensile bar cavity (Figure 3(a)). The asymmetry of the jet generates a swirling flow as the material advances along the tensile bar axis. The material fills regions near the wall and leaves the core empty (Figure 3).
- When filling the central portion of the tensile bar (smaller diameter) the material flows mostly along the cavity wall and a void is formed along the axis of symmetry. The void near the gate is still present on several parts.
- The material forms a jet when entering the last portion of the cavity. The jet goes directly towards the end of the tensile bar cavity and fills this portion of the mold from the end back towards the gate. This can be seen in Figure 3(c). The jet is quite thin and most of the 32mm short shots had the far end portion of the tensile bar broken from the rest of the part.
- The cavity seems to be filled for a shot size of 38mm. However, at this point the material had flown mostly along the cavity walls and the parts are hollow. The complete filling is obtained for a shot size greater than 48mm. Once the wall regions are filled, the material will fill the interior empty regions, starting from the end of the cavity and then progressively filling the

zone towards the gate. The last volume to be filled is located in the larger diameter region near the gate. This is confirmed by the larger porosity observed in this region (Figure 3(d)).

(a) 30 mm shot size

(b) 34 mm shot size

(c) 38 mm shot size



(d) 42 mm shot size

Fig. 3: Longitudinal sections of molded bars

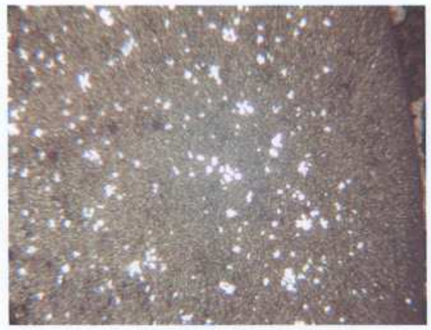
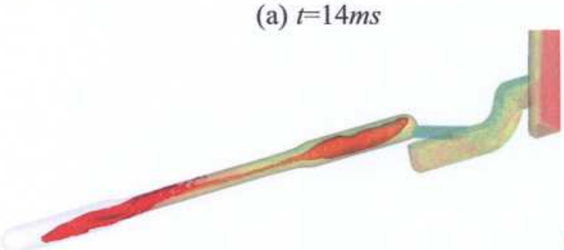


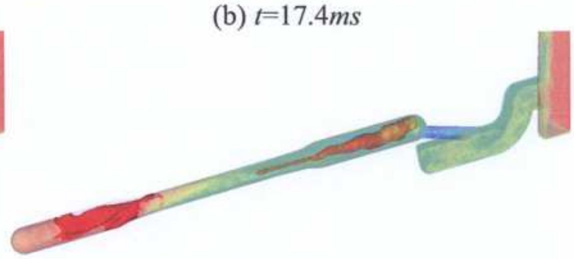
Fig. 4: Microstructure showing primary Mg particles

(a) $t$=14$ms$

(b) $t$=17.4$ms$



(d) $t$=22$ms$



(d) $t$=25.2$ms$

Fig. 5: Computed filling pattern

**Numerical Results.** Given the symmetry of the mold, only a quarter of the cavity is modeled for the simulation. The mesh is formed by 354560 tetrahedral elements and has 65759 nodes. A typical transient solution for the complete mold filling contains around 2000 time steps and is computed in about 10 hours when using 32 Pentium IV processors at 4.3 GHz.

The filling pattern is shown in Figure 5. The filling material is shown in transparency to allow the visualization of the empty regions formed inside the cavity. The numerical solutions indicate that the material forms a jet at the exit of the gate and a swirling flow forms as the material advances along the first larger diameter section. The wall regions are filled first, leaving a void inside. This agrees very well with the experimental observation. The first larger section remains hollow during the filling of the central smaller diameter section. The void continues along the center of the smaller diameter section and the material flows along the walls in a spiral motion. Filling of the larger diameter end section occurs by the return of the peripheral flow along the central region after it reaches the end of the tensile bar. This agrees again very well with the experimental observations. The void located in the larger section near the gate is filled last explaining the observed porosity on the molded parts.

## Conclusion

A three-dimensional finite element algorithm was used to successfully model the injection molding of semi-solid Mg alloys. The viscosity was described using a generalized non-Newtonian model. The solution algorithm is able to tackle the high Reynolds number, high shear rate flow and to predict jetting, recirculating flow and formation of voids. Computations predict an important zone where porosity is likely to occur agreeing well with experimental observation. Such a simulation tool could be of great help for mold makers and mold designers. It can assist the prototyping and production phase for optimizing molding conditions.

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## References

[1] R.E. Brown: *Magnesium Industry Growth in the 1990 Period* (Magn. Tech., TMS, 2000, p. 3).

[2] A.A. Luo: *Materials Comparison and Potential Applications of Magnesium in Automobile* (Magn. Tech., TMS, 2000, p. 89).

[3] N.L. Bradley, R.D. Weiland, W.J. Achafer: US Patent 5040589 (1989).

[4] P.S. Frederick, N.L. Bradley, and S.C. Erickson: Adv. Mat. Proc., Vol. 134 (1988), p. 53.

[5] F. Ilinca, and J.-F. Hétu: Int. J. Num. Methods Fluids, Vol. 34 (2000), p. 729.

[6] F. Ilinca, and J.-F. Hétu: Int. Polym. Proc., Vol. 16 (2001), p. 291.

[7] F. Ilinca, and J.-F. Hétu: Int. J. Num. Methods Engng., Vol. 53 (2002), p. 2003.

[8] F. Ilinca, J.-F. Hétu, and A. Derdouri: Int. J. Num. Methods Fluids, Vol. 50 (2006), p. 1445.

[9] F. Ilinca, J.-F. Hétu, A. Derdouri, and J. Stevenson: Pol. Eng. Sc., Vol. 42 (2002), p. 760.

[10] I.K. Kim, T.H. Kang, Y.S. Kim, Y.D. Jeong, and J.S. Kwak: Int. J. Adv. Manuf. Technol., Vol. 23 (2004), p. 566.

[11] A. Lohmüller, M. Scharrer, R. Jenning, M. Hilbinger, M. Hartmann, and R.F. Singer: *Injection molding of magnesium alloys* (Proc. 6th Int. Conf. Magn. Alloys and Their Appl., 2003, p. 738).

[12] C.D. Yim, and K.S. Shin: Mat. Trans., Vol. 44 (2003), p. 558.

[13] D. Ghosh, R. Fan, and C. VanSchilt: *Thixotropic Properties of Semi-Solid Magnesium Alloys AZ91D and AM50* (Proc. Third Int. Conf. on Proc. of Semi-Solid Alloys and Comp., 1994, p. 85).

[14] C.C. Mao, J.C. Chen, H. Peng, and M.L. Chang: J. of the Chinese Soc. of Mech. Eng., Vol. 24 (2003), p. 385.

[15] J.C. Gebelin, M. Suery, and D. Favier: Mat. Sc. and Eng., Vol. A272 (1999), p. 134.