ON THE RELIABILITY OF THE SEMISOLID METAL PROCESS: EFFECTS OF THE YIELD STRESS

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Summary

The purpose of this work is to address lingering concerns about the reliability of the semisolid metal process (SSMP) and its inability to produce consistently high quality parts. We first provide typical examples that lead to questions about the consistency of the process, and then demonstrate that the inconsistent results can be explained by considering the finite yield stress of the slurries. This implies that by controlling the process parameters the instabilities can be avoided.

Keywords: semisolid metal processing, instability, yield stress, finite elements

1 Introduction

Shaping aluminum alloys in the semisolid state by thixoforming produces complex parts with better metallurgical quality when compared to parts produced by classical casting methods. Thixoformed parts can have thinner sections that in squeeze casting have mechanical properties independent of the local cooling rate. Despite the attractive features of the process, its implementation at the industrial level is hampered by technical issues. One such problem is the high scrap rate due to difficulties associated with filling. The rate is often high enough to label the process as unpredictable. While there are still many more unresolved issues related to the semisolid process, it is the belief of the authors that many problems associated with filling can be explained by considering properly the complex rheology of the slurries. Our main objective is to address concerns about the reproducibility of the results in semisolid processing.

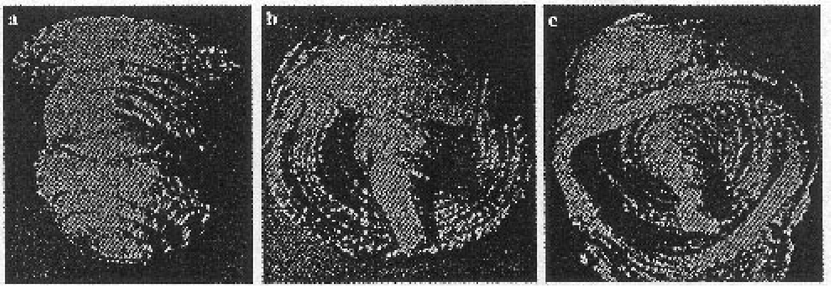


Figure 1: *Photographs of the metal removed from the reservoir following experiments on a die with a 20 mm tube diameter, in order of increasing velocity*

Figure 1 shows three filling patterns in a simple cavity obtained by Paradies and Rappaz [1] for a semisolid aluminum alloy filling a simple cavity. The results indicate that filling can be significantly different when process conditions change, even by a small amount. A common defect observed in SSMP is a behavior known as toothpaste effect (Fig. 2). From a practical point of view, such instabilities are undesirable and can lead to non-uniformities in the final product. Investigations by Midson et al. [2] provide additional examples of irregular fillings (Fig. 3).

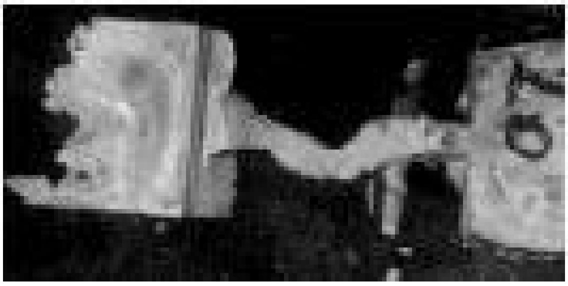


Figure 2: *Toothpaste behavior (Courtesy of Aluminum Pechiney)*

2 Rheology of semisolid materials

Typically, the solid fraction for SSMP varies between 0.3 and 0.6. Therefore, the slurry behaves neither as a solid material (Hookean solid), nor as a liquid material (Newtonian liquid). The semisolid material is considered as a two-phase body composed of a solid porous medium with an interstitial liquid phase. In this state, individual solid particles begin to agglomerate and form a skeleton that can sustain a finite shear stress without deforming. During the injection process the microstructure of the semisolid material is a function of the local temperature and the applied shear rate. Therefore, its rheology varies during processing.

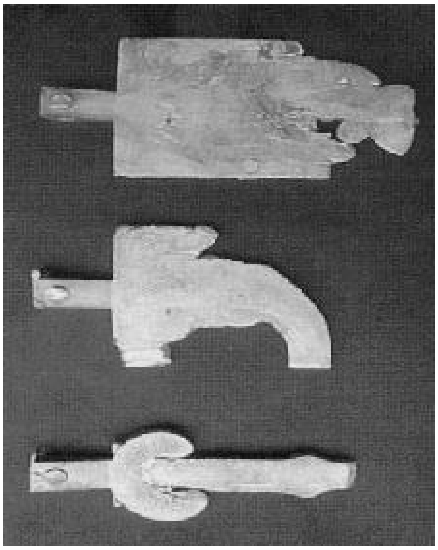


Figure 3: *Photographs of a series of castings made with a 19 mm by 9 mm gate*

Below a finite level of stress, the slurry behaves and reacts as a solid. Above this level, it exhibits flow characteristics and can be described by rheological properties. The minimum shear stress for deformation (τ_o) is known as the *yield stress* and is a property of the material. For semisolid aluminum slurries it is easily understood that the finite yield stress is a strong function of the solid fraction, i.e., of the temperature. At very low solid fractions the yield stress is negligible and the slurry is mainly liquid. At high solid fractions the yield stress is significant and the material becomes a porous solid that can no longer be considered as liquid.

3 Material and flow modeling

A common approach to avoid the numerical difficulties exhibited by the discontinuous Bingham constitutive model is to approximate the rheological behavior of the material to be valid uniformly at all stress levels. Papanastasiou [3] introduced the regularized model:

$$\tau = \left[\eta + \tau_{\mathbf{o}} \frac{1 - exp(-m\gamma\ )}{\gamma} \right] \dot{\gamma} \qquad (1)$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, and γ is the second invariant of $\dot{\gamma}$. The parameter *m,* which has dimensions of time, controls the exponential rise in the stress at low rates of strain. The material parameters, τ_o and η, are determined from experimental data. The ideal Bingham-plastic behavior is approximated by relatively large values of *m*. The accuracy and effectiveness of the Papanastasiou model has been demonstrated my many researchers (see [4] and references therein).

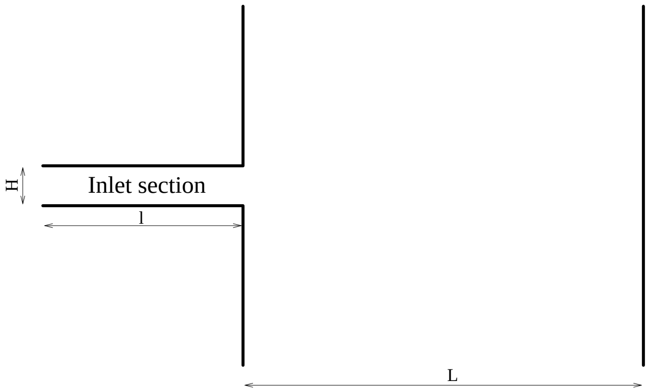


Figure 4: *Geometry of the two-dimensional cavity*

The schematic of the problem considered here is shown in Fig. 4. The 2-D geometry is characterized by the inlet region (length *l* and height *H*). The material is injected in the die from the left side and hits the vertical solid surface at a distance *L* away. We have worked with the non-dimensionalized continuity and momentum equations. Our nondimensionalization yields two dimensionless numbers, the Reynolds and Bingham numbers given by

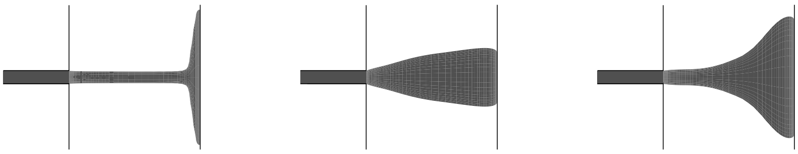
$$Re = \frac{\rho\ U_0\ H}{\eta} \qquad \text{and} \qquad Bi = \frac{\tau_{\mathbf{o}}\ H}{\eta\ U_0} \qquad (2)$$

where ρ is the density and U_0 is the average inlet velocity.

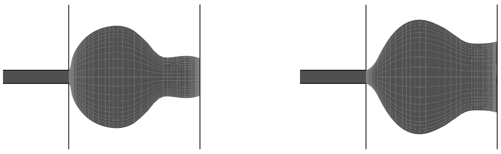
The governing equations together with the constitutive relation and appropriate boundary conditions along the free surface were discretized using the mixed-Galerkin finite element method with nine-node rectangular elements. The resulting non-linear system of equations was linearized using a Newton-Raphson iteration procedure. For converged results in the Newton-Raphson iterative scheme, usually three to four iterations were necessary at each time steep. More details on the method of solution can be found in [5].

4 Results

In this section, we examine the early stages of filling of the simple 2-D cavity of Fig. 4 (H=1, l=5). The parameter m is fixed at m=1000. The unsteady simulations start when the jet hits the vertical wall (t=0). The initial conditions were taken from the steady solution of the problem for the configuration when the jet is about to touch the wall.



(a) shell (b) mound (c) disk



(d) bubble (e) transition

Figure 5: *Summary of the flow patterns observed in the filling of a 2-D cavity*

In a recent study, Alexandrou et al. [6] examined the relative importance of inertial, viscous and yield effects in filling of a simple cavity by using a finite-volume code. In their study, in addition to the patterns shown in Fig. 1, they also identified two other patterns, labeled respectively as *bubble* and *transition*. For the purpose of the present study, we simulated the same problem as in [6] using "exact" finite element simulations along with a moving mesh scheme. The simulations are considered "exact" since the mesh of the finite element method while following the motion of the fluid with fidelity it also satisfies the boundary conditions exactly.

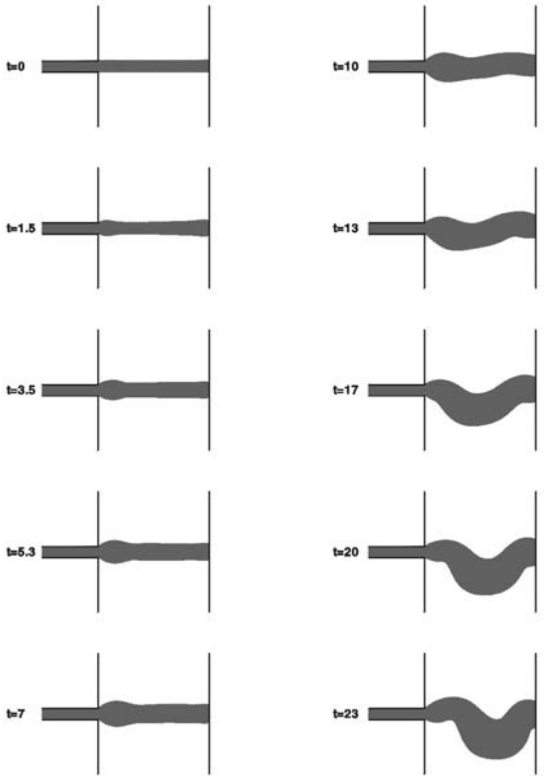


Figure 6: *Toothpaste behavior, Re=1, Bi=3 and L=10. The disturbance is imposed from t=0 until t=1.5*

Figure 5 shows that the five typical flow patterns reported in [6] have also been reproduced here as well.

Figure 6 shows the jet behavior for *Re*=1, and *Bi*=3. Under "ideal" conditions this flow leads to a bubble pattern. If a small disturbance is introduced, the flow grows as a bubble pattern and then it develops an instability, which is similar to what is observed experimentally and described as the toothpaste effect. However, under other conditions (*Re* and *Bi*) the flow does not become unstable. Figure 7 shows a complete map of the jet behavior. As shown, depending on *Re* and *Bi*, there are two distinct regions defined as "stable" and "unstable." It is worth pointing out that, while the bubble pattern leads to unstable jet behavior, the shell, disk and mound patterns remain stable. Most of the transition cases lead to stable jet profiles. These numerical results explain why experimental observations of the bubble pattern are not common in practice, as the pattern is very sensitive to flow instabilities. From the processing point of view the above simulations indicate that instabilities can be avoided by properly selecting the operating conditions.

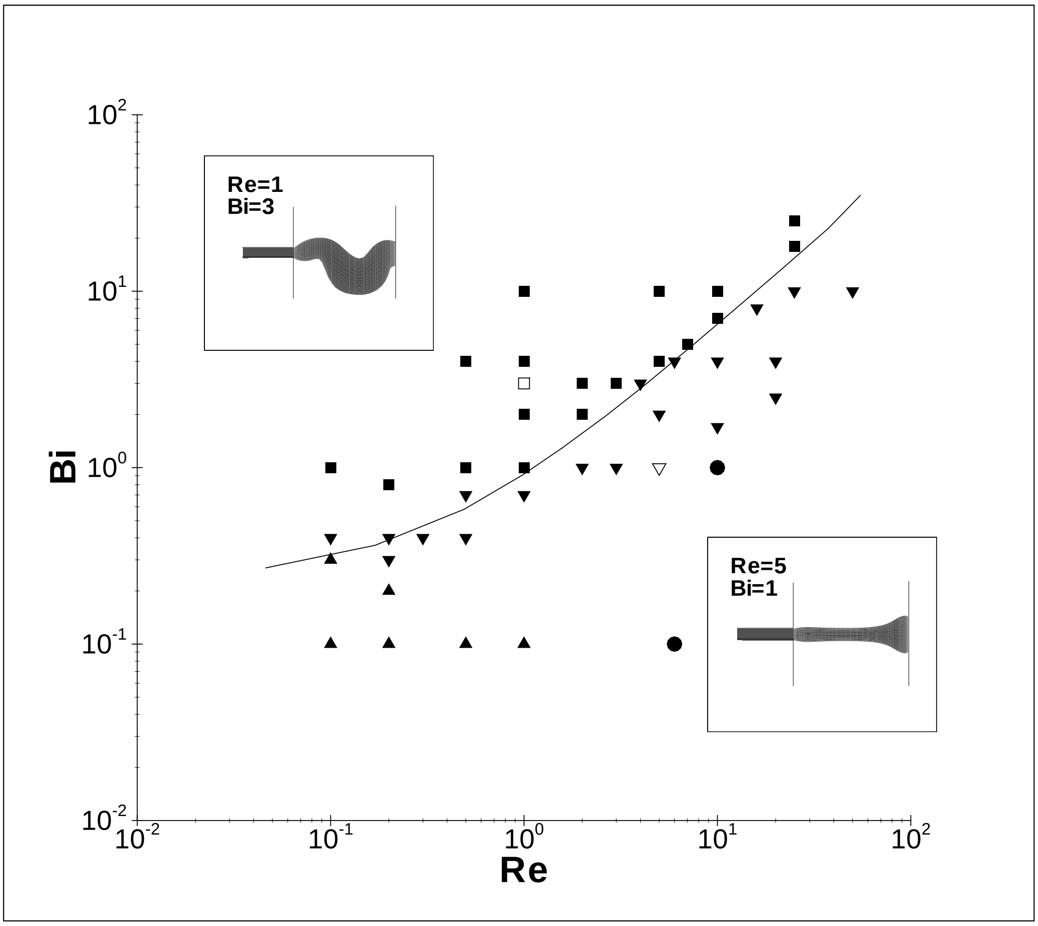


Figure 7: *Stability of the jet as function of Re and Bi. The symbols indicate various flow patterns:* ▲ *mound pattern;* ● *disk pattern;* ■ *bubble pattern;* ▼ *transition pattern.*

5 Conclusions

Due to the unique rheology of semisolid suspensions, dies fill in very distinct ways which can affect the final mechanical properties of the parts being made. In this work, by using appropriate fluid models we confirmed experimentally observed flow patterns and instabilities. The fluid model used here includes the finite yield stress and it represents the simplest possible rheology of semisolid suspensions. Instabilities that appear as unpredictable events during processing are due to the characteristic rheology of the semisolid slurries and the process conditions. Therefore, by appropriately adjusting the process and slurry conditions, the instabilities can be avoided.

References

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