SEMISOLID MATERIAL CHARACTERIZATION USING COMPUTATIONAL RHEOLOGY

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Summary

The advantages of semisolid processing derive from the characteristic rheology of the material whose state lies between that of a pure solid and that of a pure liquid. As a solid, the material maintains its structural integrity, and, as a liquid, it flows with relative ease. To successfully produce parts using this process, it is important to consider the rheology of the slurries as they fill dies in a manner very different from that of liquid metals. Therefore, the rheological characterization of the slurries is critical. Unfortunately, due to the two-phase nature of semisolid slurries at high temperature, testing and determination of material constants at these conditions is quite difficult, if not impossible, to achieve with high degree of accuracy. In this work, we demonstrate the use of accurate finite-element simulations in a classical compression experiment as a means to determine the rheological constants of semisolid materials. The same approach can be used in other standard experiments currently being used to simulate semisolid metal slurries.

Keywords: semisolid metal processing, computational rheology, 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 than in squeeze casting and have mechanical properties independent of the local cooling rate. The process can also be used to produce components with complicated forms and close dimensional tolerances, reducing the need for mechanical machining.

During processing of metal alloys in their mushy state, the raw material is melted and allowed to cool and solidify. During solidification, the dendrites are broken using mechanical or electromagnetic means. The resultant slurry has an equiaxed microstructure made up of round, rosette like crystals mixed in eutectic liquid. The specially prepared material is injected into a die (rheocasting) or solidified in billet form for later processing (thixoforming). In thixoforming, the billets are heated to a temperature in the liquid-solid range. The slug in the semisolid state is then injected into a die (thixocasting) or subjected to a forming process by means of forging (thixoforging) to obtain the desired form.

Despite the attractive features of the semisolid metal process, its implementation to industrial applications is hampered by technical problems primarily due to the complex rheology of the material [1,2]. The effect of the process variables on the filling of dies is not well understood and makes the process difficult to control. In the actual process, the material is injected at high speed into a mold cavity. Hence, the filling is very fast, lasting only fractions of a second. Therefore, due to the shear-induced evolution of the microstructure, the transient material response is very important for the understanding of the process, its further development, and its commercial viability.

2 Rheological Behavior of Semisolid Metal Suspensions

In the mushy state the mixture is a dense suspension made-up of liquid and solid particles. The average solid volume fraction is a function of the bulk temperature of the suspension which, as the temperature varies from the liquidus to the solidus limits, changes from zero to unity. Correspondingly, in the same range, the viscosity of the suspension changes significantly. However, even at constant temperature, the internal microstructure is not permanent but changes continuously. During processing, the applied forces are transmitted throughout the bulk of the mixture, thus squeezing liquid out of the solid matrix. While the liquid is squeezed out, the local volume fraction changes and the viscosity of the mixture varies. At the fully packed limit, since the mixture behaves effectively as a solid, the viscosity is not as important. Particles that remain attached for sufficiently long time can be "welded" together due to thermal diffusion, thus altering permanently the microstructure.

Despite the diversity of experiments used to determine the rheology of semisolid suspensions, it can be stated with almost certainty that semisolid materials behave as Herschel-Bulkley fluids with time- and temperature-dependent material constants. Consequently, the material exhibits phenomena associated with a finite yield stress (τ_o) [3]. Below this finite stress level, the slurry behaves and reacts as a solid. Above this level, it exhibits fluid behavior and can be characterized by rheological properties. 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 Determination of Material Constants Using Computational Rheology

Computational rheology refers to the approach were computational fluid mechanics is used simultaneously with actual experiments in order to determine the rheology of a fluid. This approach is particularly effective in rheologically complex fluids and in cases where classical experiments are not possible to perform, due to various physical limitations. Therefore, this approach can be quite effective in modeling semisolid slurries, since their complex behavior at high temperature limits the use of classical experimentation techniques.

The approach advocated here will be demonstrated using a typical compression test (Fig. 1), where a cylindrical sample is compressed either at a constant velocity or at a constant force, Fig. 1. In the actual experiment, one measures the force or the velocity of the press in order to determine the material constants. These constants are commonly evaluated based on simplifying assumptions about the flow induced by the compression. In the test shown here, one typically makes an assumption on the magnitude of the rate of strain based on the original dimension of the sample and the force, or the velocity of the press. An effective viscosity is then evaluated using measured bulk quantities that are not fixed *a priori*.

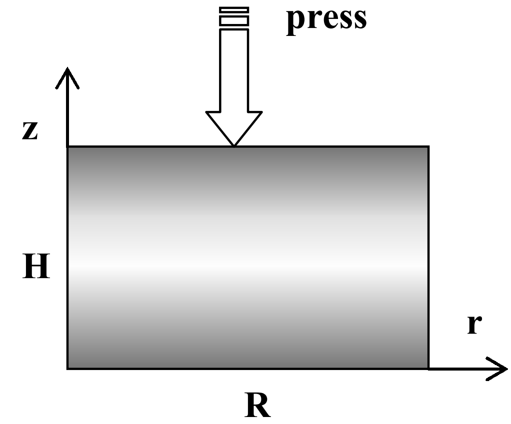

Figure 1: *Schematic of the compression test.*

Unfortunately, this procedure ignores the fact that, irrespective of its size, the sample responds to the compression in the same, complex manner as a larger sample. Therefore, given the complexity of the flow in the sample, one cannot simplify the procedure in order to determine constants characteristic of the sample. Interestingly, the procedure ignores also other useful information about the material response, such as the sample's shape during compression. From a mathematical point of view, this is equivalent to throwing away boundary conditions when solving an equation. Using computational rheology, one can first measure all pertinent quantities of the sample and, then, by using accurate computational models, can select by trial-and-error the flow model and material constants that can reproduce the measured experimental data and match the history of deformation of the sample.

In this work, we modeled the semisolid slurries as Bingham plastics, i.e. we employed the following constitutive equation

$$\dot{\gamma} = 0, \qquad \tau \le \tau_o$$
$$\tau = \tau_{\mathbf{o}} + \eta\,\dot{\gamma}, \qquad \tau \ge \tau_o \qquad (1)$$

where $\dot{\gamma}$ is the shear rate and τ is the shear stress. The two material constants in the model, i.e. the effective viscosity η and the finite yield stress τ_o, are to be determined by using the approach advocated here. The use of this model implies that the evolution of the sample's internal structure has been ignored. A more detailed model must account for the transient behavior of the slurry and the evolution of the microstructure.

4 Material and Flow Modeling

As shown in Fig. 1, the cylindrical sample characterized by a diameter D=2R (where R is the radius) and initial height H, is compressed by a press using either, constant velocity, or constant force. Due to the inherent singularity of the ideal Bingham plastic model it is difficult to implement it in computational codes. A common approach to avoid the numerical difficulties exhibited by the discontinuous Bingham plastic 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 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 ideal Bingham-plastic behavior is approximated by relatively large values of *m*. The accuracy and effectiveness of the Papanastasiou model has been demonstrated by many researchers (see [4] and references therein).

Two dimensionless numbers appear in the non-dimensionalized form of the momentum equation, the Reynolds and Bingham numbers, given by

$$\mathrm{Re} = \frac{\rho\ \mathrm{U}_0\, D}{\eta} \qquad \text{and} \qquad \mathrm{Bi} = \frac{\tau_o\, D}{\eta\, \mathrm{U}_0} \qquad (2)$$

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

The governing continuity and momentum equations in Lagrangian coordinates (the mesh is moving with the fluid velocity), together with the boundary conditions 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 step.

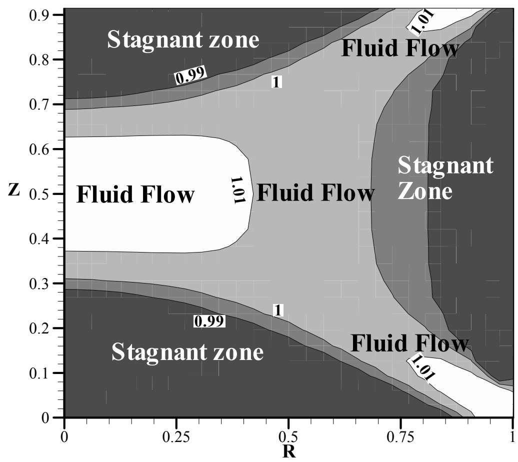

Figure 2: *Stress distribution at an early stage of the compression (Bi=5, Re=1, F=-1.)*

5 Results

Figures 2 and 3 are snapshots in time of numerical predictions during two stages of the compression experiment indicating the distribution of the second invariant of the stress tensors in a cylindrical SSM sample. As the two figures indicate, the distribution is quite complex and changes significantly during the compression. Therefore, the results support the statement made earlier that one cannot simplify the stress distribution (as it is done in practice) in order to extract a single value to be used in the evaluation of an effective viscosity that represents the sample.

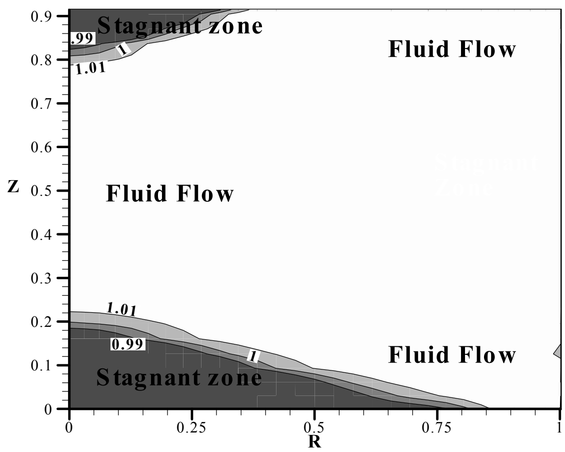

Figure 3: *Stress distribution at a later stage of the compression (Bi=5, Re=1, F=-1.)*

Figure 4 shows experimental results of the same compression experiment where an A356 sample at 585°C is pressed at a constant velocity of 6mm/min. The original height of the sample is 20 mm and the diameter 20 mm. Results are shown for different times. On the right hand side are preliminary simulation results, which are obtained using values of the effective viscosity η and the finite yield stress τ_o that reproduce closely the history of the applied force **F** as a function of time. The dark areas in the simulations of Fig. 4 indicate unyielded material regions. Fine adjustments to the magnitude of the two material constants are performed by reproducing the shape of the free surface during deformation.

6 Conclusions

The rheology of semisolid slurries is quite complex and traditional rheological experiments cannot be used to establish the material constants. The use of computational rheology can both facilitate the determination of such constants and also reveal the exact physics of the deformation and flow of these slurries. A more comprehensive constitutive model could also include the internal microstructural dynamics of the sample

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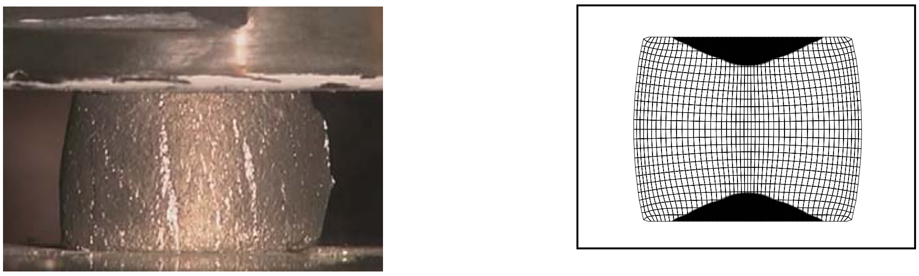
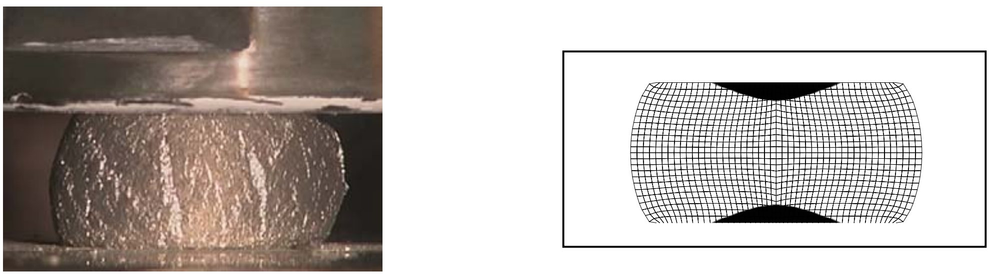
(a)



(b)



(c)

Figure 4: *Flow behavior of A356 sample at different shear strains (temperature: 585℃; shear rate: $5.0\times10^{-3}s^{-1}$) (a) 0, (b) 19.5 (c) 31.9. The figures on the left are the experimental data and those on the right are the corresponding preliminary simulation results.*