Research Programs

Modeling and Simulation of SSM Rheology

Research Team:

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Introduction

All existing and future SSM technologies are based on the unique combination of solid-like and liquid-like behavior of semisolid metals whose rheological behavior is not fully understood. Mathematical modeling and simulations remain a critical issue in understanding and optimizing the process. Semisolid slurries are non-Newtonian materials that exhibit complex rheological behavior. Therefore, the way these slurries flow in cavities is very different from the way liquid in classical casting fills cavities. In fact, filling in semisolid processing is often counterintuitive.

The objectives of this work were to:

1. Employ computational and modeling studies to investigate SSM slurry constants and slurry structure breakdown, which are experimentally difficult to do;
2. Use constitutive models to identify, understand, and describe flow instabilities that occur during actual processing of slurries, and
3. Provide mechanisms to explain and control those instabilities, an important step to promote further commercialization of SSM technology.

Strategies

The research efforts and strategies pursued in this work are described below:

- The understanding of the SSM rheology from a fundamental point of view and the mathematical description of the observed macroscopic constitutive behavior. Current understanding of the rheology of SSM suspensions indicates that the slurries are characterized by a finite yield stress, and by material properties that are time and shear rate dependent. Mathematically, the observed behavior fits well a generalized time-dependent Herschel-Bulkley fluid model. The theory developed incorporated into a number of two- and three-dimensional computer codes.
- The understanding and a mapping of flow instabilities distinct to semisolid processing. During filling semisolid slurries exhibit flow behaviors not observed in liquid casting. For instance, semisolid slurries fill cavities in a preferential way i.e. filling in one direction may halt while filling proceeds in other parts of the cavity. Due to flow instabilities during filling, final parts are found to have unacceptable variability in their mechanical properties. The dominant instability responsible for this variability in the properties is known as the "toothpaste instability." In our modeling we managed to reproduce the above mentioned behavior.
- The development of a general mathematical and computational model that can describe the flow of semi-solid materials when the material is delivered as a slurry-on-demand.
- The simulation of filling of real parts. Case studies were developed in collaboration with the ACRC consortium members. Actual parts were modeled using the MPI developed program, and the results were compared to actual plant experience.

Salient Results

To understand the filling behavior of semi-solid metals and the flow instabilities encountered during commercial forming operations, we modified the constitutive model previously developed by the ACRC team. Specifically, to deal with the discontinuity in the constitutive relation, a regularized model was developed as follows:

$$\tau = \left[\eta + \tau_o \frac{1 - \exp(-\mathrm{m}\,\gamma\,)}{\gamma} \right] \dot{\gamma}$$

where τ is the shear stress, η is the effective viscosity, γ prime is the shear rate, γ is the second invariant of γ prime, and 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 can be approximated by relatively large values of m.

A complete map of filling patterns has been developed in a wide range of Reynolds and Bingham numbers experienced in semi-solid processing (see Figure 1). Specifically, five distinct flow patterns have been identified. They are: (1) **Shell**, (2) **Mound**, (3) **Disk** , (4) **Bubble**, and (5) **Transition**.

To understand flow instabilities, we analyzed the flow under a 2-D geometry (see Figure 2) using "exact" finite element simulations along with a moving mesh scheme. Figure 2 illustrates the toothpaste filling observed in commercial forming operations.

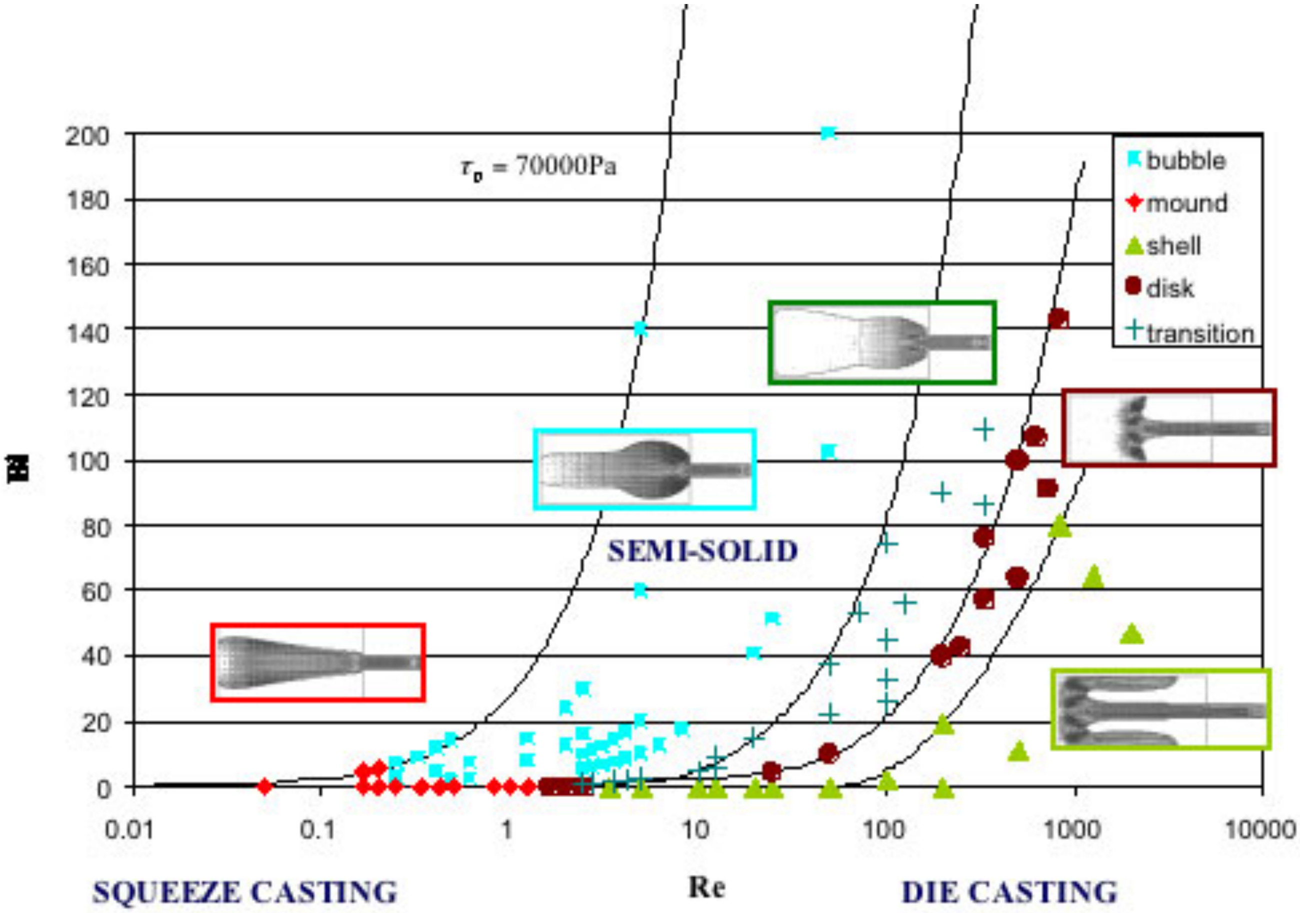

Figure 1: Flow patterns as a function of Bingham number, Bi and Reynolds number, Re. The figure illustrates five distinct filling patterns (bubble, mound, shell, disk and transition) in semi-solid casting.

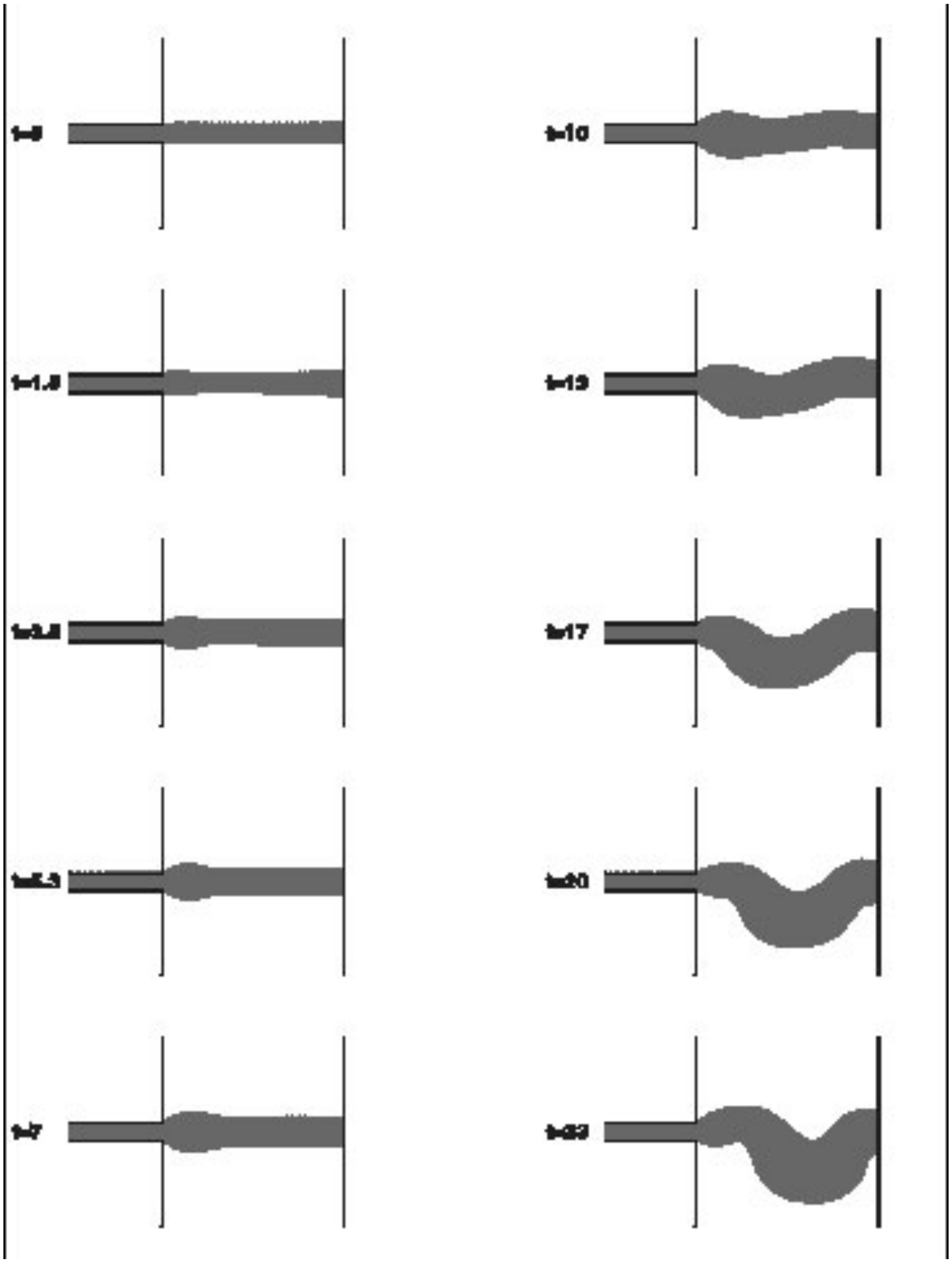

Figure 2: Toothpaste behavior: Re =1, Bi =3 and L =10. The disturbance is imposed from t=0 until t=1.5.

Figure 3 gives a stability map, which can be used to guide semi-solid processing. Depending on Re and Bi values considered, there are two distinct regions defined as "stable" and "unstable." It can be seen that a bubble pattern usually leads to unstable jet behavior, whereas shell, disk, mound, and most of transition patterns remain stable. It is quite clear that the instabilities are indeed the results of the finite yield stress and the way yielded and unyielded regions interact with each other. From a processing point of view, the above simulations indicate that instabilities can be avoided by properly selecting operating conditions from the stability map.

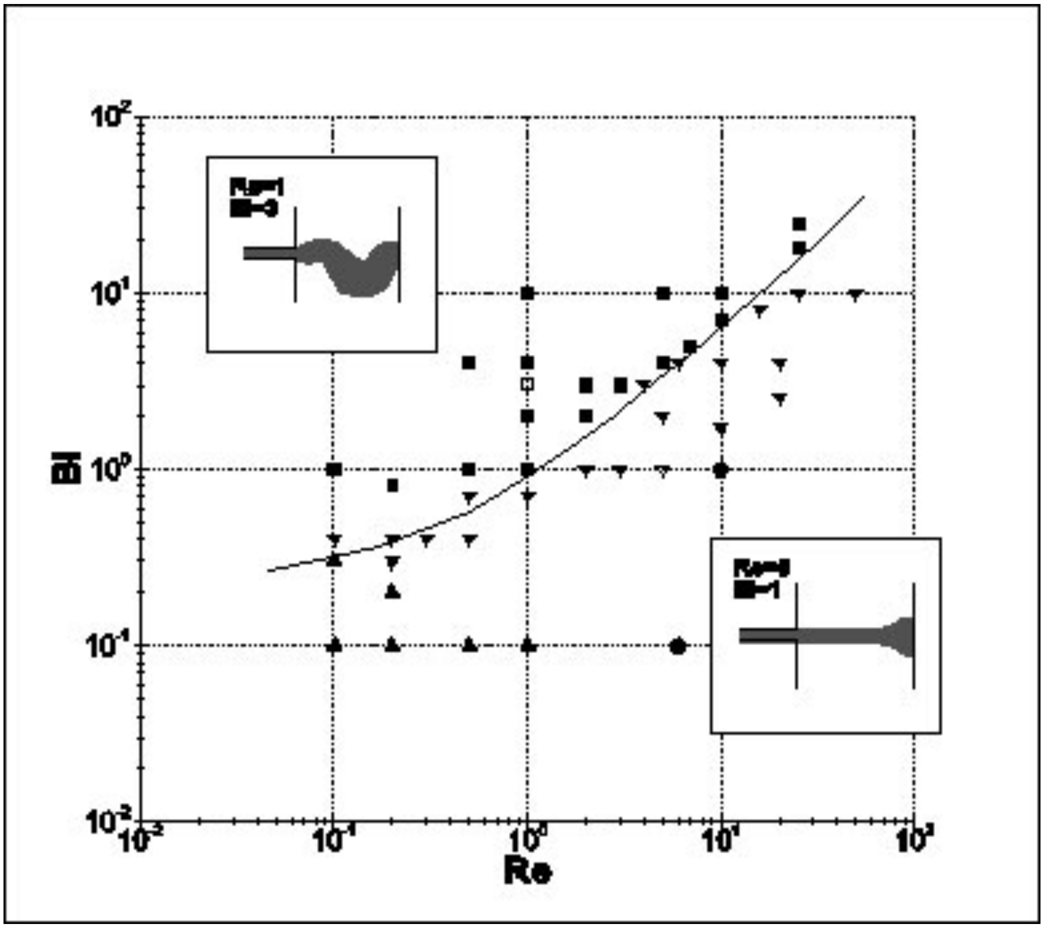

Figure 3: Stability of the jet as a function of Re and Bi. The symbols indicate various flow patterns: mound pattern (triangle pointing upwards); disk pattern (dot); bubble pattern (square); transition pattern (triangle pointing downwards).

A significant challenge encountered in our modeling efforts was the determination of some important rheological constants of semi-solid metals. To address this issue, a "reverse modeling" strategy was used, in which compression experiments (under both constant shear rate and constant stress conditions) were simulated using "exact" finite-element method. To ensure accurate measurements, a well controlled compression experimental apparatus (see Figure 4) was developed and used. Specifically, a high speed TV camera was utilized to record the flow behavior of the semi-solid sample during compression through a transparent window. Quantitative data such as shape vs. time, stress vs. time and extension vs. time of semi-solid samples under different compression conditions were determined through an advanced data acquisition system and image analysis. The experimental data and boundary conditions were then used as output and input of the predictive models for reverse modeling. Figure 5 illustrates experimentally observed flow behavior of A356 sample compressed under a constant shear rate (5.0×10-3s-1) in comparison with simulation results. The "reverse modeling" strategy has proven to be reliable to enhance our simulation tools with high degree of accuracy. Some important rheological constants such as the structure breakdown of semi-solid metals were determined.

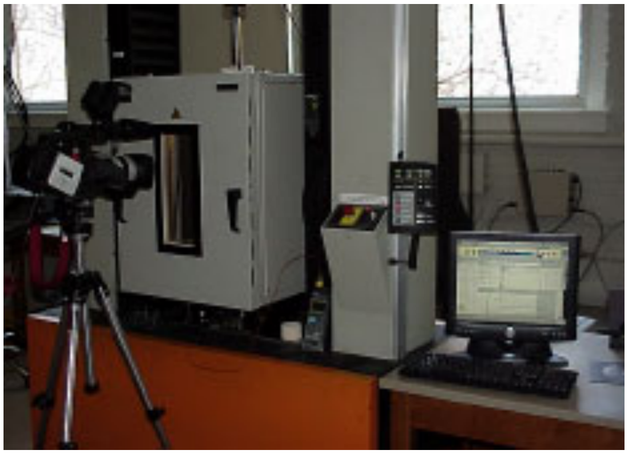

Figure 4: Well controlled compression apparatus.

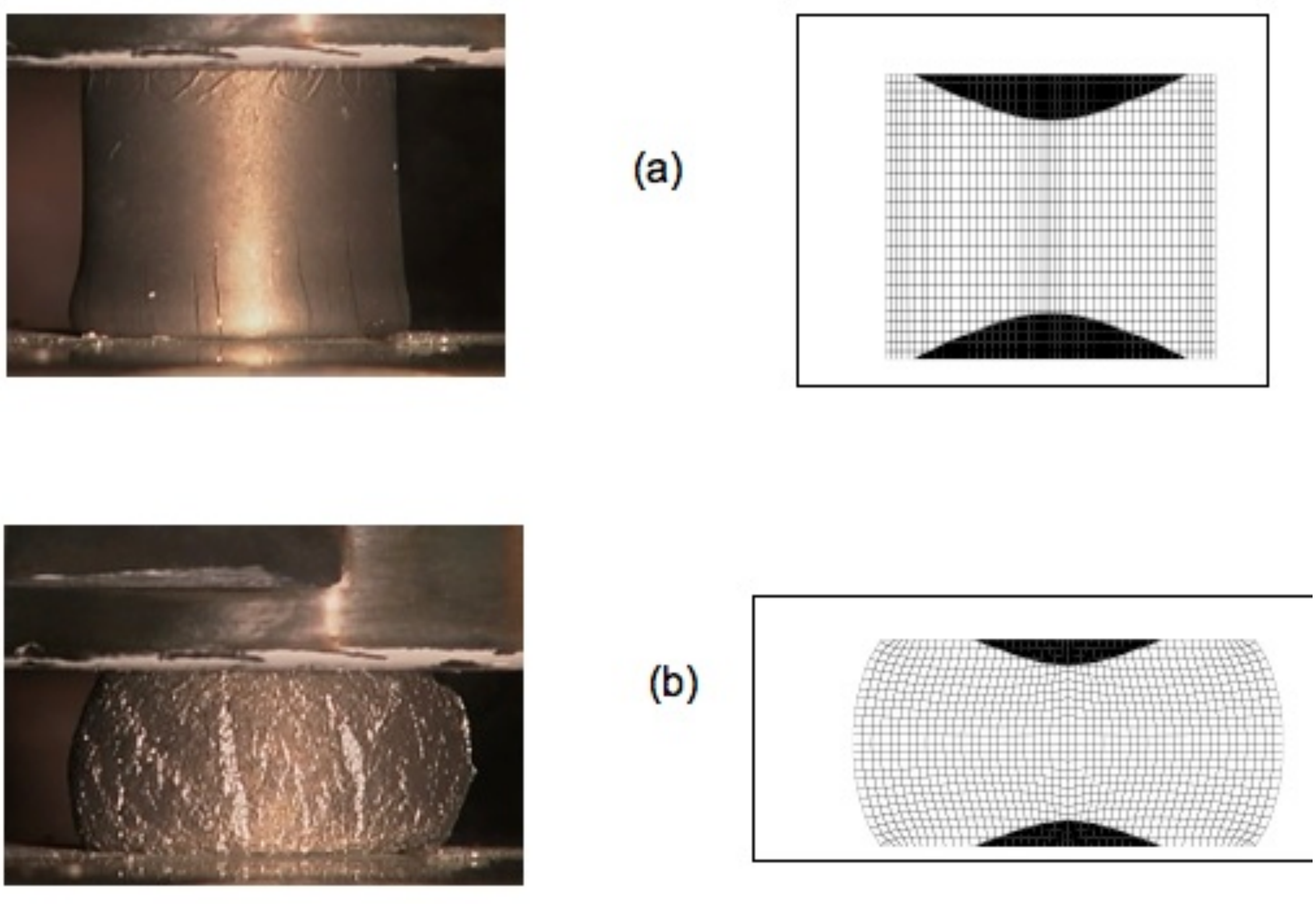

Figure 5: Flow behavior of A356 sample at different shear strains (temperature: 585°C; shear rate: 5.0x10^{-3}s^{-1}) (a) 0, (b) 31.9. The figures on the left are the experimental data and those on the right are the corresponding simulation results.

To support modeling and simulation efforts, we also established a high temperature rheological measurement system, and generated rheological data to input and validate the models developed by the research team. As illustrated in Figure 6, an advanced high temperature rheological measurement system was built here at ACRC. The system consists of a TA rheometer coupled with an optimized vane-cup geometry. Specifically, the optimized vane-cup design circumvents some critical problems encountered in traditional methods such as the wall slip effect etc. Validation experiments with various standard materials indicated that the system can be used to characterize the rheological behavior of semi-solid metals under both steady and transient shear conditions.

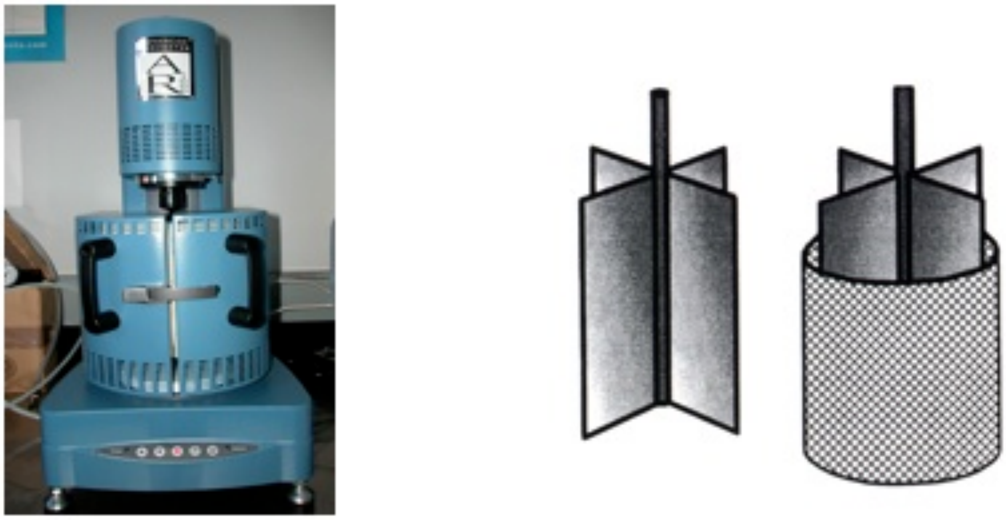

Figure 6: ACRC high temperature rheometer and the optimized vane-in-cup geometry.

Using the measurement system, we performed systematic rheological measurements with commercial MHD A356 alloys, and generated a vast set of rheological data to enhance our simulation models. Figure 7 shows typical transient steady shear properties of MHD A 356 samples tested in a shear rate range from 4 s^{-1} to 357s^{-1}. The experiments were conducted at a constant temperature of 595°C (fraction solid: ~0.2) in an argon atmosphere. From the apparent viscosity versus time curve, one can see that the apparent viscosity decreases rapidly with time within the first 10 seconds of shear, and approaches an equilibrium value after approximately 20 seconds. It is clear that semi-solid metal slurries show time-dependent rheological properties, thus the inclusion of the time effect in constitutive models is critical in modeling semi-solid processing.

Using a structure kinetic approach, the time dependent properties of the samples tested were determined. Through the analysis of experimental data, we found that the rate of structure breakdown of the semi-solid slurry at the solid fraction of 0.2 follows a second order of the structure kinetic model in the shear rate range investigated. Moreover, the rate of structure breakdown increases by two decades when shear rate is increased from 4s^{-1} to 357s^{-1}. Using these valuable experimental data, we have been able to improve the accuracy and the capability of our simulation models to describe the flow behavior of semi-solid metals during the initial stage of die filling.

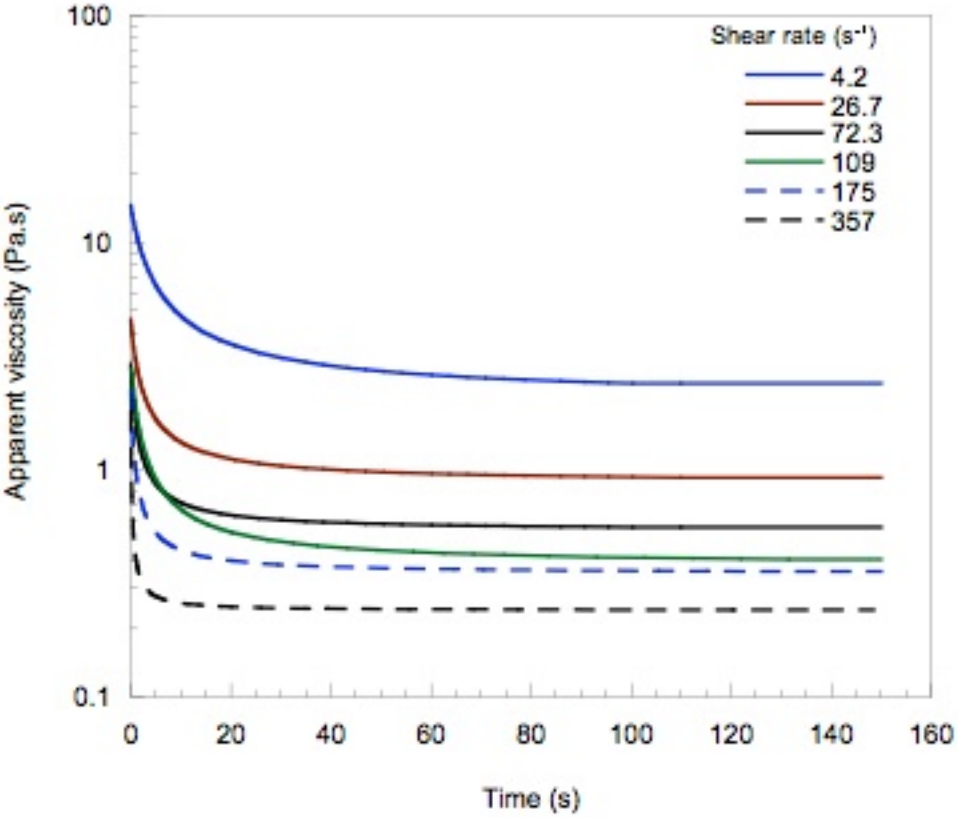

Figure 7: Transient apparent viscosity data of MHD A356 samples (fraction solid: 0.2).

SSM Related Publications (2002-Present)

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