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Numerical Simulations of the Squeeze Flow of Thixotropic Semisolid Slurries

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Abstract. We propose a methodology for the rheological characterization of semisolid metal slurries using experimental squeeze flow data. The material is modelled as a structural thixotropic viscoplastic material, obeying the regularized Herschel-Bulkley constitutive equation. The yield stress and the power-law exponent are assumed to vary with the structural parameter that is governed by a first-order kinetics. The squeeze flow is simulated using finite elements in a Lagrangian framework. The evolution of the sample height has been studied for all the ranges of the Bingham and Reynolds numbers, the power-law exponent as well as the kinetics parameters of the structural parameter. Systematic comparisons have been carried out with experimental data on a semisolid aluminium alloy (A356) sample, compressed from its topside at a temperature of 582 ºC under a specified load, which eventually becomes constant. Excellent agreement with the experimental data could be achieved provided that at the initial instances (up to 0.01s) of the experiment the applied load is much higher than the nominal experimental load and that the yield stress and the power-law exponent vary linearly with the structural parameter. The first requirement implies that a different model should be employed during the initial stages of the experiment. As for the second one, the evolution of the sample height can be reproduced allowing the yield stress to vary from 0 (no structure) to a maximum nominal value (full structure) and the power-law exponent from 0.2 to 1.4.

Introduction

Semisolid metal (SSM) processing or thixoforming is used for the production of complex near-net-shaped components with high quality and durability characteristics. The material is processed at such high temperatures that it becomes a rather dense suspension of specially prepared spheroidal particles lying in a state between the solidus and liquidus limits applied [1]. This suspension is viscoplastic, i.e., it behaves as a solid below and as a fluid above a yield stress, τ_y [2]. Moreover, semisolid metals exhibit thixotropic behavior, i.e., the material parameters are time dependent [1].

Let $\underline{\underline{\boldsymbol{\tau}}}$ and $\underline{\underline{\dot{\boldsymbol{\gamma}}}}$ denote the viscous stress tensor and the rate-of-strain tensor, respectively. Then, the regularized version of the Herschel-Bulkley constitutive equation reads [3,4]:

$$\underline{\underline{\boldsymbol{\tau}}} = \left\{ \frac{\tau_y \left[1-\exp(-m\dot{\gamma})\right]}{\dot{\gamma}} + k\dot{\gamma}^{n-1} \right\} \underline{\underline{\dot{\boldsymbol{\gamma}}}} \tag{1}$$

where k is the consistency index, n is the power-law exponent [3], and $\tau \equiv \sqrt{\underline{\underline{\boldsymbol{\tau}}} : \underline{\underline{\boldsymbol{\tau}}} / 2}$ and $\dot{\gamma} \equiv \sqrt{\underline{\underline{\dot{\boldsymbol{\gamma}}}} : \underline{\underline{\dot{\boldsymbol{\gamma}}}} / 2}$ are the magnitudes of the stress tensor and the shear rate. For sufficiently high values of the growth parameter m, Eq. (1) approximates the ideal Hercshel-Bulkley model. The advantage of this equation is that it applies everywhere in the flow domain and avoids the need of determining the yielded and the unyielded regions.

The squeeze or compression flow is a transient viscometric test that is very often to characterize viscoplastic materials [5]. A fixed amount of material is squeezed under constant force or velocity and information about its rheological behavior is deduced from the relation between the force and the displacement of the sample.

The main idea of the present work is to combine numerical simulations with experimental squeeze data in order to determine the material parameters of semisolid slurries at a given temperature. For this purpose, we employ the regularized Eq. (1). Some years ago, we have employed Lagrangian coordinates, a mixed-Galerkin finite element method, and the Papanastasiou regularization to numerically solve the squeeze flow of a Bingham plastic ($n = 1$)[6]. Numerical simulations were carried out considering both constant load and constant velocity and the effects of the Reynolds and Bingham number on the flow and the shape evolution were investigated. Emphasis was also given on the development of the yielded/unyielded regions during the squeeze experiment. This work was subsequently extended to include thixotropic effects by means of a structural model [7].

Structural thixotropic models employ a time-dependent structure parameter, λ, which is unity when the matrix of the suspension is fully built up and zero when structure is fully destroyed [8]. The rate of change of λ is governed by a kinetics model and is essentially the difference of built-up and breakdown terms. Alexandrou et al. [7] assumed that the structure parameter follows a first order kinetics

$$\frac{D\lambda}{Dt} = a(1-\lambda) - b\lambda\dot{\gamma}e^{c\dot{\gamma}} \tag{2}$$

where t denotes time, a is the structure built-up parameter, and b and c are structure breakdown parameters, and that the yield stress varies linearly with λ, $\tau_y(t) = \tau_0\lambda(t)$, where τ_0 is the yield stress when the structure is completely built-up; the plastic viscosity of the material was assumed to be constant. Alexandrou et al. [7] reported that, under constant force the structure may be destroyed at the early stages of the compression, but, at a later time, it re-builds steadily till the cessation of the flow experiment. No attempts to make comparisons with experimental observations were made.

In this paper, we propose a methodology for the rheological characterization of semisolid metal slurries from squeeze flow experiments using numerical simulations. To this end, we extend the structural thixotropic model in [7] by employing the regularized Herschel-Bulkley constitutive equation in Eq. (1). Moreover, the power-law exponent is assumed to vary linearly with the structural parameter, $n(\lambda(t)) = n_{\min} + (n_{\max} - n_{\min})\lambda(t)$, where $n_{\min}$ and $n_{\max}$ are the minimum and maximum values of power-law exponent. The proposed methodology is tested against experimental data on a semisolid aluminum A356 alloy obtained applying a nominal load on the top of a cylindrical sample. We carry out systematic numerical simulations of the squeeze test imposing the experimental load on the semisolid sample and varying material and flow parameters. As discussed below, these simulations show that it is possible to reproduce the experiments only if thixotropy is taken in to account and both the yield stress and the power-law exponent vary with the structural parameter and the applied load during the very early moments of the experiment is much higher than the nominal one.

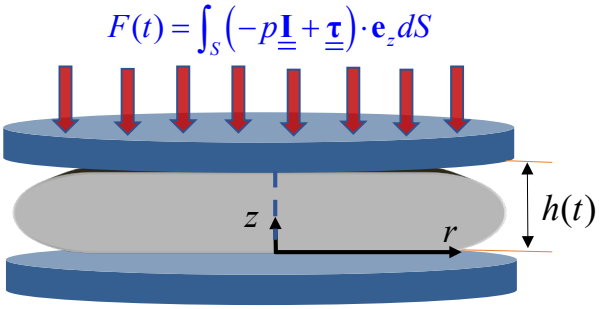

Figure 1. Illustration of the squeeze experiment. The sample is compressed from the topside.

Geometry and Experimental Data

A cylindrical sample of an aluminum alloy A356 was prepared and heated up to the semisolid state, i.e., at 582 °C, as explained in [9]. The sample of height $H_0 = 30.5\text{mm}$ and radius $R = 15\text{mm}$ was compressed from the topside at a specified strain of 80%. The geometry of the experiment is illustrated in Fig. 1. More details about the material composition, the experimental set-up, and the microstructure analysis are provided in Refs. [9,10]. The evolution of the applied load $F(t)$ is plotted in Fig. 2. This increases rapidly for the first 0.25s of the experiment until it reaches the nominal final force $F_\infty \approx 9\text{kN}$. As shown in Fig. 3, the height $h(t)$ of the sample decreases from $H_0 = 30.5\text{mm}$ to 6.23mm.

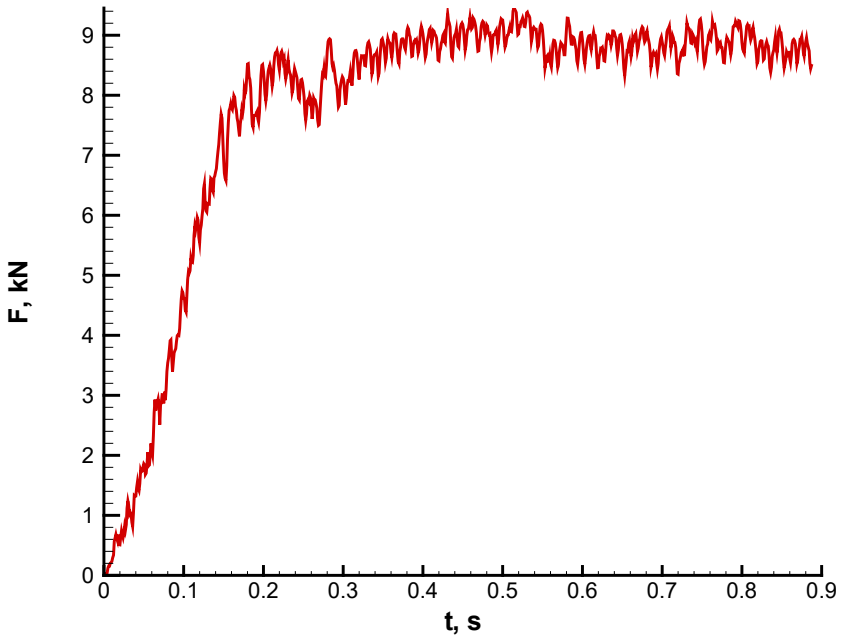

Figure 2. Experimental load during compression of an A356 alloy at 582 °C (semisolid state). The sample is compressed from the topside.

Numerical Model

We prefer to work with the dimensionless equations. To this end, we scale lengths by the initial sample height, H_0, the velocity vector by $(F_\infty/(kH_0^2))^{1/n_{\max}} H_0$, the pressure and stress components by F_∞/H_0^2, the time by $(kH_0^2/F_\infty)^{1/n_{\max}}$, and the load by F_∞. With these scalings, one obtains three dimensional numbers in the equations of motion and the constitutive equation, i.e., the Reynolds

number, $Re \equiv \dfrac{\rho F_\infty^{2/n_{\max}-1}}{k^{2/n_{\max}} H_0^{4(1/n_{\max}-1)}}$, the Bingham number, $Bn \equiv \dfrac{\tau_0 H_0^2}{F_\infty}$, and the regularization number, $M \equiv m\left(\dfrac{F_\infty}{kH_0^2}\right)^{1/n_{\max}}$, where ρ is the constant density of the slurry.

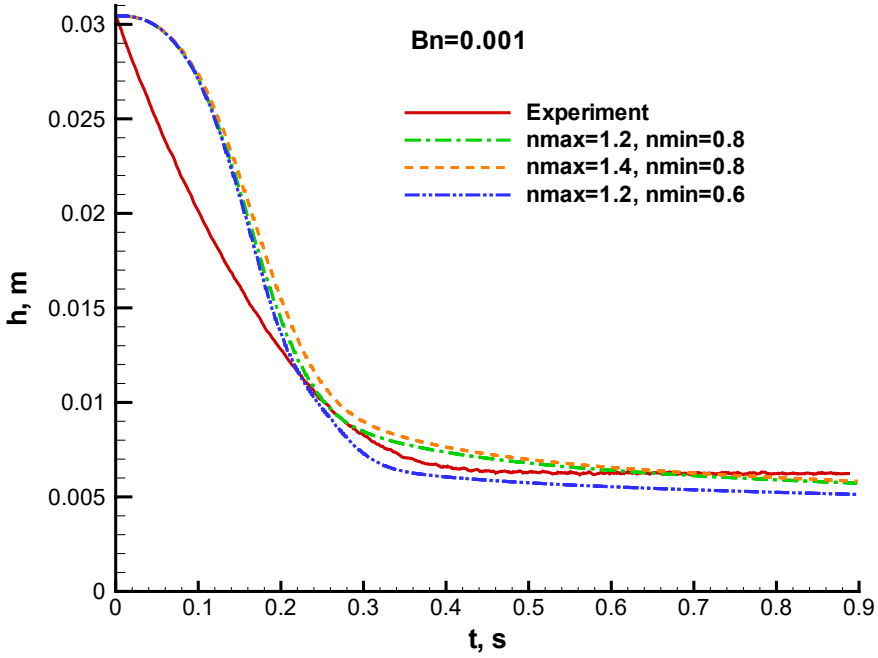

Figure 3. Results with variable power-law index for $Re = 1$, $Bn = 0.001$ and $a = b = 1$. The experimental load distribution is imposed.

Under the assumption of incompressible flow, the dimensionless forms of the continuity and momentum equation read:

$$\nabla \cdot \mathbf{u} = 0 \quad \text{and} \quad Re\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u}\right) = -\nabla p + \nabla \cdot \boldsymbol{\tau} \tag{3}$$

Note that we keep the same symbols for the dimensionless variables, for the sake of simplicity. Thus, the dimensionless form of the constitutive equation is

$$\underline{\underline{\boldsymbol{\tau}}} = \left\{\frac{Bn\lambda\left[1-\exp(-M\dot{\gamma})\right]}{\dot{\gamma}} + K(\lambda)\dot{\gamma}^{n-1}\right\}\underline{\underline{\dot{\boldsymbol{\gamma}}}} \quad \text{where} \quad K(\lambda) \equiv \left(\frac{F_\infty}{kH_0^2}\right)^{n(\lambda)/n_{\max}-1} \tag{4}$$

Let us point out that the dimensionless parameter $K(\lambda)$ does not imply that the consistency index varies with the structural parameter. This results from the dedimensionalization of the shear rate which is based on the maximum value $n_{\max}$ of the power-law exponent; given that the power-law exponent varies with λ, $K(\lambda)$ is defined so that the relevant term remains dimensionless. Finally, in the dimensionless version of Eq. (2), the parameters a, b, c are dimensionless numbers defined by $a \equiv a\left(\dfrac{kH_0^2}{F_\infty}\right)^{1/n_{\max}}$, $b = b$, and $c \equiv c\left(\dfrac{kH_0^2}{F_\infty}\right)^{1/n_{\max}}$.

The problem is closed by initial and boundary conditions. The material is initially at rest. Along the lower plate (Fig. 1) the velocity vanishes. Along the upper plate, the radial velocity is zero and the total load is equal to the specified load, $F(t) = \int_S \left(-p\underline{\underline{\mathbf{I}}} + \underline{\underline{\boldsymbol{\tau}}}\right) \cdot \mathbf{e}_z dS$. Along the axis of symmetry, symmetry conditions are imposed. Finally, along the free surface of the sample, $\left(-p\underline{\underline{\mathbf{I}}} + \underline{\underline{\boldsymbol{\tau}}}\right) \cdot \mathbf{e}_r = \mathbf{0}$.

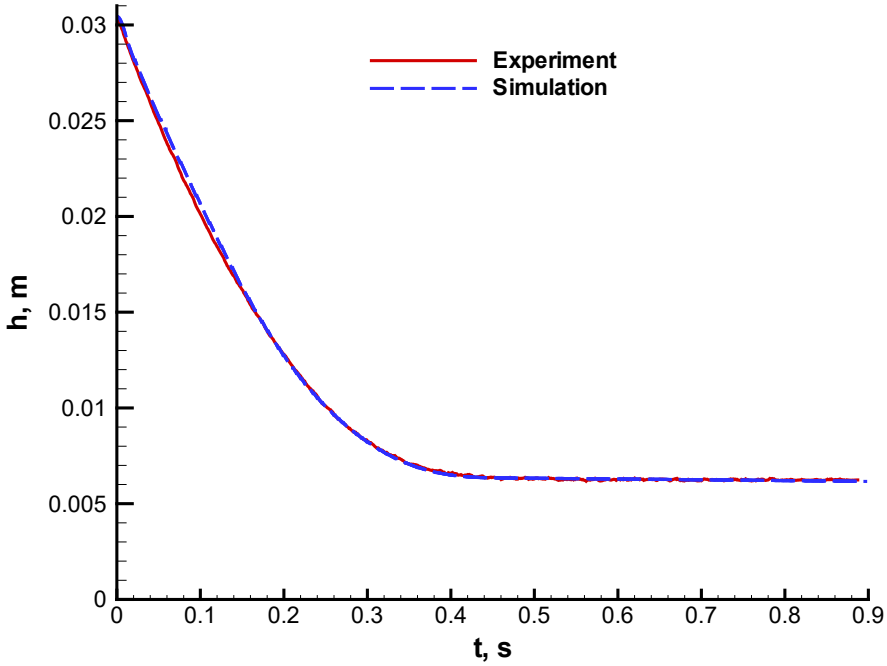

Figure 4. Experimental data are reproduced when the load in the initial 0.01s of the experiment is 10 times the nominal maximum experimental load and the power-law index varies from 0.2 to 1.4. The optimal values of the dimensionless parameters are $Re = 0.9$, $Bn = 0.000235$, and $a = b = 0.95$.

The Arbitrary Eulerian-Lagrangian formulation has been used for the numerical simulations. More details for the method are provided in [6,7].

Results and Discussion

The first step in our effort to reproduce the experimental squeeze data of Fig. 3 was to carry out numerical simulations of the flow using the experimental load (Fig. 2) and taking the power-law exponent as constant (that is independent of the structural parameter λ, $n = n_{\min} = n_{\max}$). Wide ranges of all relevant parameters have been covered in order to get results similar to the experimental data. We observed that the simulations were very slow initially and became similar to the experiments only in the final stages of the experiment. We thus decided to relax the assumption for a constant power-law exponent. Fig. 3 shows results for $Re = 1$, $Bn = 0.001$ and three different ranges of the power-law exponent. Note that in all subsequent results the values of the dimensionless parameters related to the kinetics of the structural parameter (Eq. (2)) are the 'optimal' ones: $a = b = 1$ and $c = 0.0001$. When $n_{\min}$ is reduced, compression becomes faster and the evolution of the height in the final stages of the experiment is better described. Our simulations also revealed that when the minimum value of the power-law exponent is reduced to $n_{\min} = 0.2$ and the Bingham number to $Bn = 0.00025$ the final stage of the compression is very accurately simulated.

According to the numerical simulations, the optimal range of the power-law exponent is 0.2-1.4. The effect of the Reynolds number was found to be important only in the intermediate stage of the experiment, the duration of which grows as the Bingham number is reduced. In order to obtain the final experimental height for a lower Bingham number, the value of the Reynolds number should be around unity and the minimum value of the power-law exponent needs to be reduced to $n_{\min} = 0.2$.

The numerical simulations with the experimental load distribution predict a rather slow compression initially for all the ranges of the flow parameters. We thus tested a modified imposed load, assuming that for a short period of time, Δt, the value F_0 of the load is much higher than the nominal load F_∞. Different scenarios for the values of the ratio $f_r = F_0 / F_\infty$ and Δt have been

investigated, which revealed that the optimal values are $f_r = 10$ and $\Delta t = 0.01\text{s}$. The 'optimal' values of all the other parameters were used: $Re = 0.95$, $Bn = 0.00025$, $n_{\min} = 0.2$, $n_{\max} = 1.4$, $a = b = 0.95$, and $c = 0.0001$. Fig. 4 shows that with these values the agreement between the model and the experiments is excellent. These optimal values have been scrutinized by systematically varying the values of the flow parameters aiming at diminishing the differences between simulation and experiments.

Conclusions

A method for determining the material parameters of semisolid metals from squeeze flow data has been proposed. The Herschel-Bulkley constitutive equation is employed allowing the yield stress and the power-law index to vary with a structural parameter that follows first-order kinetics. Finite elements are used in a Lagrangian framework to simulate squeeze constant-load data on a semisolid aluminium alloy A356. Our systematic runs for wide ranges of the material and flow parameters showed that excellent agreement with the experimental data of the height evolution could be achieved under two assumptions: (a) initially, for times up to 0.01s, the applied load should be 10 times higher than the nominal experimental load, which indicates that a different constitutive model, e.g., an elastoviscoplastic constitutive equation is necessary at the initial stages of the experiment; (b) both the yield stress and the power-law exponent vary linearly with the structural parameter.

References

[1] A.N. Alexandrou, Y. Pan, D. Apelian, G. Georgiou, Semisolid material characterization using computational rheology, in: Y. Tsutsui, M. Kiuchi and K. Ichikawa (Eds.), Proceedings of the 7th International Conference on Semi-Solid Processing of Alloys and Composites, Tsukuba, Japan, 2002, pp. 417-422.

[2] R.R. Huilgol, G.C. Georgiou, Fluid Mechanics of Viscoplasticity, 2nd ed., Springer International Publishing (Verlag), Berlin, Heidelberg, 2022.

[3] W. Herschel, R. Bulkley, Measurement of consistency as applied to rubber-benzene solutions, Proc. Am. Soc. Test Mater. 26 (1926) 621- 633.

[4] T.C. Papanastasiou, Flow of materials with yield, J. Rheol. 31 (1987)385-404 (1987).

[5] P. Coussot, Yield stress fluid flows: are view of experimental data, J. non-Newton. Fluid Mech. 211 (2014) 31–49.

[6] G.C. Florides, A.N. Alexandrou and G. Georgiou, Flow development in compression of a finite amount of a Herchel-Bulkley fluid, J. non-Newton. Fluid Mech. 143 (2007) 38-47.

[7] A.N. Alexandrou, G.C. Florides, G.C. Georgiou, Squeeze flow of semi-solid slurries, J. non-Newton. Fluid Mech. 193 (2013) 103-115.

[8] J. Mewis, N. Wagner, Thixotropy. In Colloidal Suspension Rheology, Cambridge Series in Chemical Engineering, Cambridge University Press, Cambridge, 2011, pp. 228-251.

[9] L.V. Torres, E.J. Zoqui, Microstructural stability and rheological behavior of Al-Si-Cu Alloys in the semi-solid state, Metal. Mat. Trans. B 53B (2022) 3229-3245.

[10] C.T.W. Proni, E.J. Zoqui, The effect of heating rate on the microstructural breakdown required for thixoformability, Int. J. Mater. Res. 108 (2017) 228-236.