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Modeling of Structural Breakdown During Rapid Compression of Semi-Solid Alloy Slugs

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ABSTRACT

Under normal thixoforming conditions, the semi-solid slugs experience a rapid compression before flowing into the die cavity. During a very short time interval, they experience intense shear thinning and their flow behaviour changes from one resembling a solid to that of a viscous liquid.

In this paper, a technique of rapid compression testing is outlined, carried out under conditions similar to normal thixoforming. Experimental results are combined with modelling the behaviour of these slurries in *FLOW-3D*, in order to derive the flow parameters. The special properties of semi-solid metals are described using a thixotropic rheological model in which viscosity is a function of shear rate, solid fraction and time.

INTRODUCTION

The economic benefits of being able to numerically model the filling of dies in semi-solid processing to ensure defect-free products and to avoid the costly and time-consuming trial and error approach, are self-evident. To carry this out properly will eventually require both the computation of slurry flow and of heat transfer into the die. However at the present stage of progress even ignoring heat transfer, there appears to be disagreement about the appropriate rheological models to be employed in isothermal computations, which clearly must be resolved first before taking the matter further. Many of the rheological investigations on alloy slurries to date have been concerned with fraction solids less than 0.4 and with steady-state viscosities achieved after several minutes of constant shearing. Since commercial thixocasting is carried out on slugs having 0.5 fraction solid or above, and die filling takes around 0.1s so that steady-state conditions can hardly apply, the results of these studies are of limited value for industrial processing. Of more interest is the work of *Laxmanan and Flemings* [1] on the isothermal compression of Sn/Pb alloy with solid fractions (f_s) up to 0.8, and Loue et al. [2] of Al/Si alloys, although the strain rates were very low in these experiments. However using back extrusion techniques, the latter workers were able to obtain viscosity data at high shear rates (up to $10^3\ s^{-1}$) in their alloys containing f_s~0.5, and this is clearly closer to industrial conditions. Although they were able to demonstrate a dependence of viscosity on shear rate, no time dependence (i.e. thixotropic) effect was determined, and in view of the known behaviour of these materials during thixoforming, this would appear to be an important omission in the rheological data.

A number of previous attempts at computer modelling of die filling have assumed either a constant viscosity [3] or Bingham pseudoplastic flow behaviour [4], neither of which include thixotropic time-dependence. *Zavaliangos and Lawley* [5] first introduced time dependent flow by adopting the micromechanical model developed by *Brown* and co-workers [6-8] based on an internal structural parameter which changed with shear rate and time according to specified kinetics, allowing the viscosity to change accordingly. More recently, *Barkhudarov* et al. [9,10] have modified a commercial CFD program (*FLOW-3D* code, Version 7.1) to include thixotropic behaviour during flow, and this has been used in the present work to analyse the results of rapid compression tests carried out at Sheffield. These experiments were conducted on A357 aluminium alloy at fractions solid and shear rate conditions close to those experienced at the initial stages of commercial thixocasting.

EXPERIMENTAL PROCEDURE USING RAPID COMPRESSION TESTS

The present experimental work is based is based on measuring the force acting on a small cylindrical slug (42*mm* high, 36*mm* diam.) of semi-solid alloy during rapid compression at constant velocity.

An experimental chamber has been designed and constructed incorporating a load cell, which allows data collection at a rate of 2 *kHz*, during rapid compression tests. The compression velocity can be varied from 200 to 2000 *mm/s* and is carried out between plates of low thermal conductivity, allowing the assumption of isothermal conditions during the period of testing. The force acting on the slug during compression is measured in a load cell incorporated into the upper part of the chamber. This experimental set-up has been used, in conjunction with a number of thixotropic aluminium alloys, produced by a variety of routes (*MHD, RAP, Sprayforming*) to carry out a number of rapid compression tests. As a result, a number of changes have been made to the chamber (Figure 1), and a procedure for these tests has now been established and the following work has been carried out using an A357 aluminium alloy which has been warm extruded as the model material.

The test starts by bringing the top of the *sindanyo* pedestal in contact with the *sindanyo* insert at the top and applying a small load. Once this has been recorded, the position becomes the point of reference for all calculations (i.e. zero point). The pedestal is then is withdrawn to the heating position, which has the slugs' centre of symmetry at one millimetre below the geometrical centre of the coil in order to avoid levitation of the slug during heating, and the slug is then brought to the required temperature before being forged. Two thermocouples half way down the slug, one near the surface and one in the centre, are used to ensure that there are no variations of more than $1^{o}C$ radially.

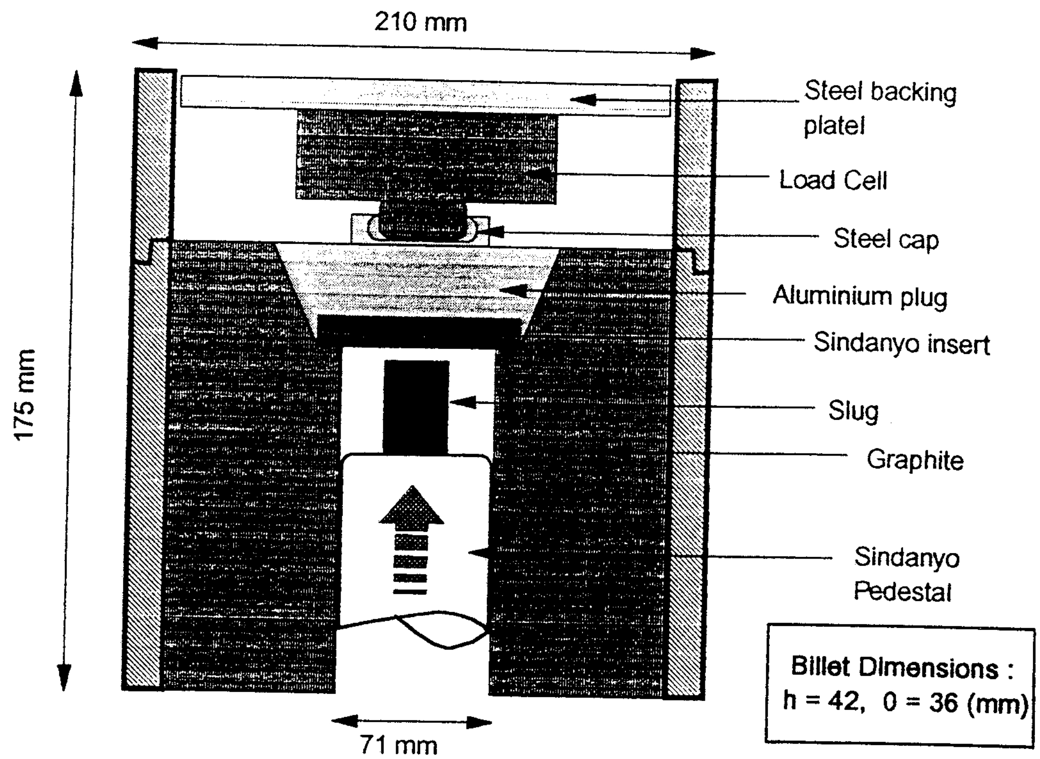


Figure 1. Experimental chamber developed for rapid compression tests.

RESULTS

Tests have been carried out at 500 *mm/s* injection velocity and at three different temperatures (572^oC, 574^oC, and 576 ^oC) and therefore different fraction solids (f_s). Figure 2 shows examples of data collected during such tests.

It is apparent from the data that there is a rise in the load sensed by the load cell when the slug first touches the sindanyo insert, followed by a drop in the load immediately after, that is during the rapid compression of the slug. It is also clear from the graphs that the initial load changes are sensitive to temperature. The microstructures of the compressed slugs appeared to be quite uniform with no apparent segregation of liquid. Figure 3 shows typical microstructures taken from the centre and the edge of a compressed slug of A357 at 576^oC. However, at the lower temperatures of 574^oC and 572^oC, there were evidence that the extruded microstructure had survived in part, during the compression of the slugs.

Following the approach of *Laxmanan & Flemings* [1] and using the experimental results obtained from the rapid compression tests, the relationship between viscosity (η) and average shear rate has been calculated and is shown in Figure 4.

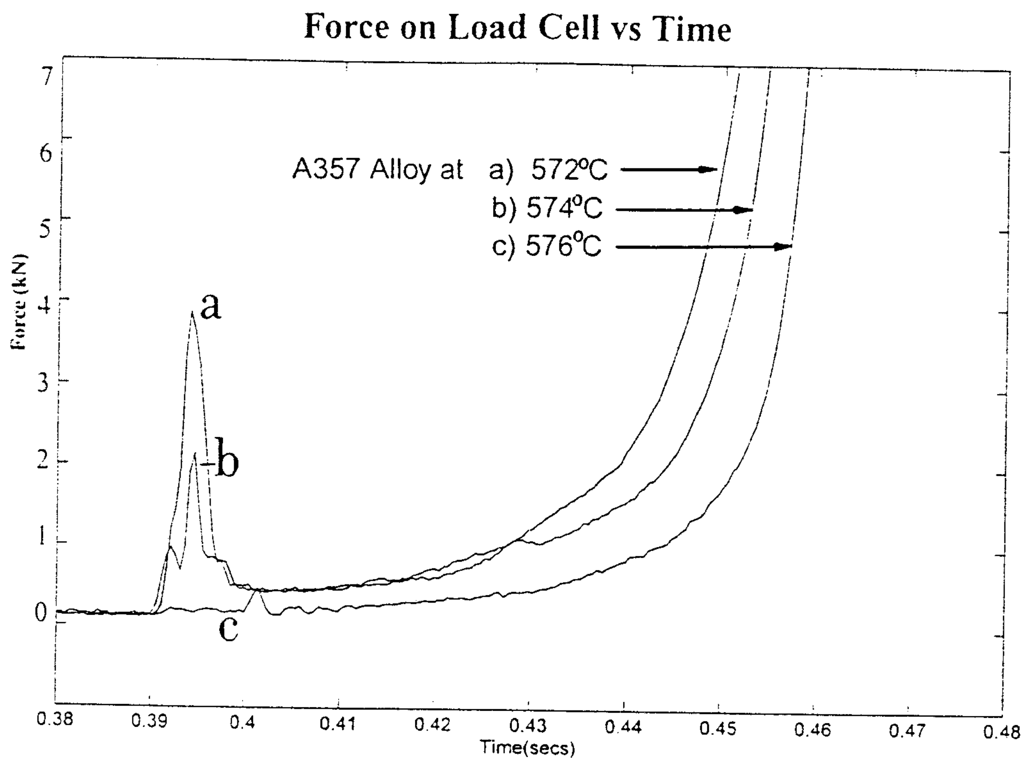
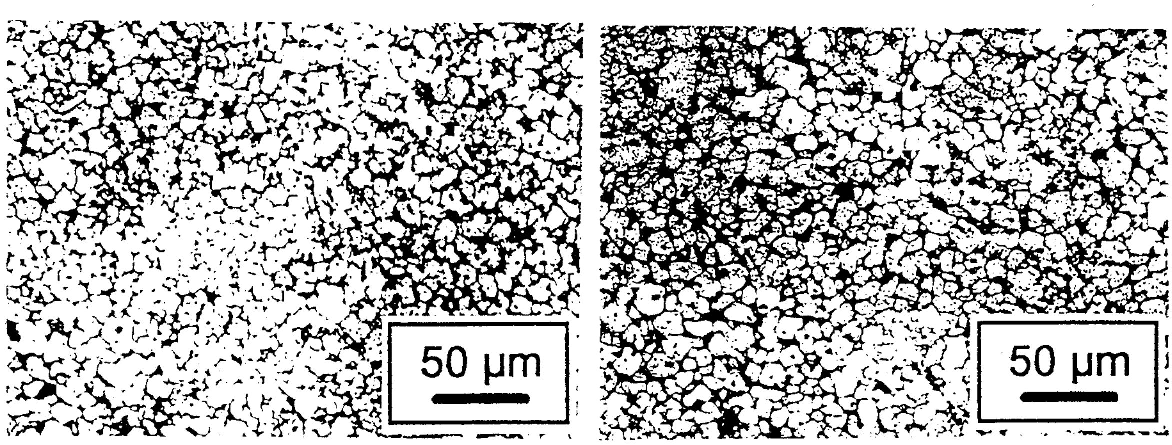


Figure 2. Forces recorded by the load cell during rapid compression of semi-solid slugs of A357 at three different fraction solids.



(a) (b)

Figure 3. Microstructures of a compressed slug of A357 at 576°C : (a) centre and (b) edge.

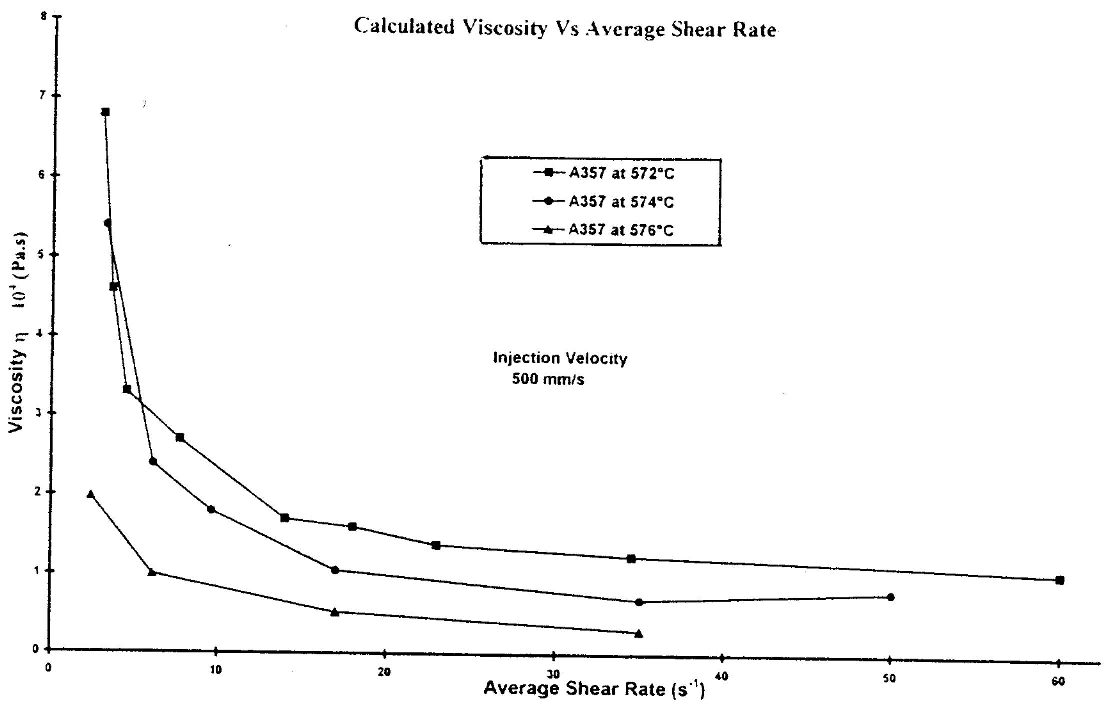


Figure 4. Plot of calculated viscosity against average shear rate

NUMERICAL MODELLING OF COMPRESSION TESTS

The thixotropic model in the *FLOW-3D* code, Version 7.1 [9] is described by a single transport equation for the apparent dynamic viscosity μ: $\quad d\mu/dt = (1/\lambda)(\mu_0-\mu)$ ..... **(1)** where **t** is time, λ the relaxation time and μ_0 $(f_s,\dot{\gamma})$ is the steady-state apparent viscosity, which is a function of solid fraction, f_s, and shear rate $\dot{\gamma}$ [10]. The relaxation time is different for flow thickening regime, i.e., when $\mu < \mu_0$, and for flow thinning, when $\mu > \mu_0$. In *FLOW-3D*, we use the thinning rate, $\beta = 1/\lambda$, instead of the relaxation time.

For the compression modelling below we assumed that flow thickening is negligible during the short time of the experiment, especially as that the shear rates in the fluid are mostly increasing. Numerical tests confirmed the validity of this assumption. In addition, we assumed that the rate for flow thinning is independent of the shear rate and β is therefore constant.

The expression for the steady-state apparent viscosity is taken from *Quaak et al.* [11]. For the range of shear rates during the experiments we assume that :

$$\mu_0 = 9.0 \exp(9.5 f_s)\, \dot{\gamma}^{-1.3} \quad \text{.........(2)}$$

Simulations were carried out for the compression velocity of 500 *mm/sec*, and for three different temperatures: *572°C, 574°C* and *576°C*. In each case the total force acting on the stationary top surface of the compression chamber was calculated as a function of time and compared with the results of the measurements.

Only two free parameters were used to match the numerical results to the experimental measurements: the initial viscosity, μ_i, and the thinning rate β. The initial viscosity was found solely to control the magnitude of the initial force peak, when the slug first came into contact with the top surface of the chamber. The relaxation time, together with the steady-state viscosity function, governs the subsequent evolution of the force.

SIMULATION AT *572ºC*

A number of numerical tests were carried out for this temperature:

1. Constant viscosity Newtonian fluid, $\mu = \mu_i$.
2. Non-Newtonian fluid with shear-dependent viscosity, but no time dependence. Viscosity is defined by Eq. (2).
3. Thixotropic fluid. A few runs were made with different thinning rates.

The same initial viscosity of 3.2 x 10^4 *Pa s* was used in all these tests since this produced the same initial force magnitude (about 4 *kN*).

Figure 5 shows a comparison between calculated forces for the three cases (the thinning rate of $\beta = 20.0\ s^{-1}$ was used for the thixotropic fluid). The curves are plotted to the time of 0.055 *sec*, at which point the slug is compressed to about 36% of its original height. It is clear that without time-dependence, the force values after the initial peak are far from the experiment (curve b): the peak is very narrow and the forces at later times are too small. This is the result of very fast changes in shear rates and, therefore, viscosity, since the latter follows the changes in shear rates instantaneously. The steady state viscosity, μ_0, drops with shear rate very quickly resulting in very small flow resistance (and force) during the compression.

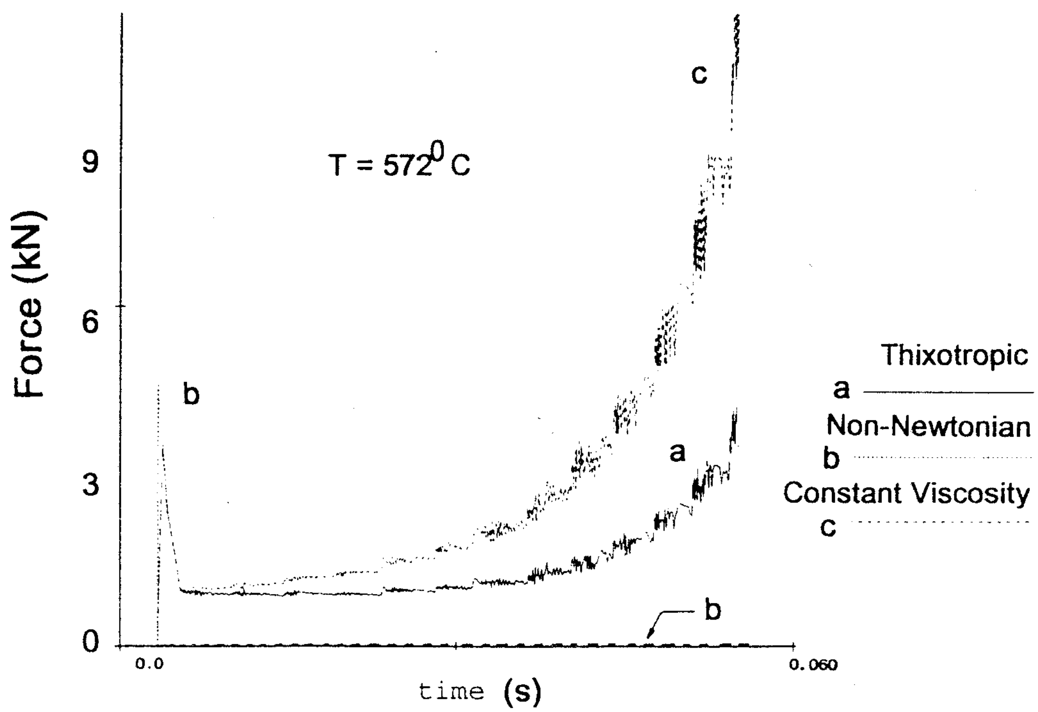


Figure 5. Plots of computed force versus time for a slug of A357 at 572ºC, assuming: (a) Thixotropic, (b) non-Newtonian and (c) Constant viscosity, behaviour.

Surprisingly, the constant viscosity model produces a force evolution not too far from the experimental one, and at least it exhibits the right trends: the initial peak, its magnitude and width, subsequent decrease in force, and its gradual increase at later stages (curve c). However, since viscosity remains at the high initial value during the compression, the force after the initial peak is overestimated at least by a factor of two. The thixotropic model result shows force values closer to the measured ones than in either of the other two cases. However, the predicted force does not drop as low after the initial peak as in the experiment. The experiment shows a drop in the force magnitude by a factor of ten, while the numerical model predicts a factor of 3.5.

Different thinning rates, from 5.0 to 100.0 s^{-1}, produce results in the range between those given by the constant viscosity model and the non-Newtonian, time-independent model. The larger the thinning rate the closer the results are to those of the non-Newtonian model. It seems like the thinning rate of 20.0 s^{-1} (*relaxation* time of 0.05 *sec*) produces the best results. For example, the force magnitude increases to the value of the initial peak about half way through the compression, similar to the experimental result. The same thinning rate of 20.0 s^{-1}, was used for the simulations at higher temperatures.

SIMULATION AT *574°C* AND *576°C*

The steady-state viscosity was recomputed for these temperatures according to Eq. (2), although the results are very close since the solid fraction for these temperatures vary little (from 0.513 at *576°C* to 0.538 at *572°C*). The main variable that was changed was the initial viscosity μ_i. For T = *574°C*, $\mu_i = 1.6 \times 10^4$ *Pa s*, and for T = 576°C $\mu_i = 2 \times 10^3$ *Pa s*. The criterion in selecting these values was only the magnitude of the initial force peak. Figure 6 shows the comparison of the forces at three different temperatures, at the thinning rate of 20.0 s^{-1}. Overall the results are close to the measurements. The main discrepancy in each case is in the values of the force minimum after the initial peak, which is somewhat larger than the measured values.

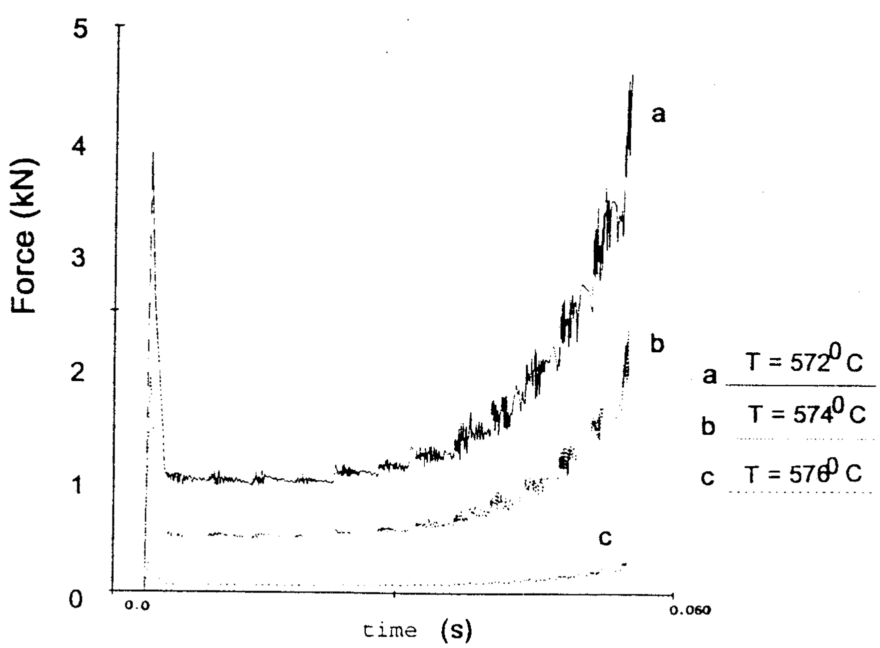


Figure 6. Plots of computed force versus time for a slug of A357 at 572°C, 574°C & 576°C.

DISCUSSION

Experimental tests for isothermal rapid compression produce semi-solid metal flow with interesting features. The overall time-scale of the experiments is in the range of characteristic times for flow thinning indicated by previous work [10,12], and this allowed us to investigate the time-dependent properties of the apparent viscosity. The shear rates and solid fraction values are well within the range of the available steady-state data for apparent viscosities of the alloy tested (A357). Finally, the force measurements are a simple and effective means of analyzing the transient rheological characteristics of the semi-solid metal which enables straight-forward comparisons with numerical predictions.

Numerical simulations showed the adequacy of the numerical approach chosen in *FLOW-3D*. The time-dependence and the shear-rate dependence of the apparent viscosity are critical in the accurate modelling of semi-solid metals. Standard non-Newtonian fluid model without time-dependence produces results far from the experimental data. However, the simplest, constant viscosity model appears to give significantly more accurate results, at least for the compression velocity of 500 *mm/sec*. This can be a consequence of the flow thinning rate being relatively low so that fluid viscosity does not have time to significantly deviate from the initial value. For example, for 572^0C, the average apparent viscosity drops from the initial value of 3.2×10^4 *Pa.s* to about 0.8×10^4 *Pa.s* towards the end of the compression, when the shear rate averages at around 200 s^{-1}. For comparison, the steady-state viscosity at that shear rate is just 1.5 *Pa.s.*

It appears that small changes in solid fraction mainly affect the initial apparent viscosity, and not so much the subsequent evolution of viscosity. This is especially obvious from the experimental results. The numerical predictions show that the initial viscosity value produces a larger effect on the subsequent viscosity during compression than indicated by the experiments, but not significantly.

The main discrepancy between the numerical and experimental results is seen in the value of the force at the minimum that occurs in all cases shortly after the initial peak in force. The experiments show a minimum force value 3 to 4 times smaller than that given by the numerical model. This may indicate that there is another relaxation time (or thinning rate) involved besides the one used in Eq. (1) which should be much shorter (at least by a factor of 10) than that used here (0.05 *sec*) or estimated elsewhere *e.g.* [12]. It might be that this time describes the process of the initial breakdown of the structure when the specimen is sheared from the condition of zero shear rate, and would allow for a very fast decrease of the viscosity at very small shear rates after which the 'normal' relaxation processes take over. Alternatively, we could introduce a yield stress, instead of a continuous change of viscosity, to describe this initial breakdown in the specimen's rigidity.

Quaak et al. [12] have indicated that at least two relaxation times can be extracted from transient rheometry measurements: a short time of order of one second or less, λ_1, and a long time, λ_2, that spans some minutes leading to the final steady state viscosity. It can be shown that in a transient flow with a characteristic time much smaller than λ_2, such as the rapid compression, the slow relaxation process can be ignored. In that case, λ in Eq. (1) is equal to λ_1 , and μ_0 is the actual steady state viscosity as measured by the experiments.

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