Flow Visualisation for Semi-Solid Alloys

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ABSTRACT: A recent review of modelling of semi-solid processing has highlighted the need for appropriate methods of validation of models. Experimental details are given here of a flow visualisation method for tin/lead and aluminium alloys.

Key words: semi-solid processing, modelling, thixoforming, flow visualisation.

1 INTRODUCTION

Semi-solid processing exploits the thixotropic behaviour of metallic alloys which consist of solid spheroids in a liquid matrix in the semisolid state. Alloys with such a microstructure will flow when sheared but thicken when allowed to stand. They can therefore be handled in the semi-solid state but will flow to fill a die, giving a near net shaping capability. There are various forms of the technology including: *thixoforming,* where the material is treated beforehand in such a way that when heated into the semisolid state the non-dendritic microstructure is achieved, it is then reheated into the semisolid state for processing; *rheocasting*, where a liquid is cooled into the semisolid state in such a way as to give a non-dendritic microstructure and then forced directly into a die; *thixomoulding*, which is akin to the injection moulding of polymers. It is thixoforming which has been used for the experiments described in this paper.

Modelling can be used to make die design more efficient and effective. In the last ESAFORM Conference, a summary review was given of modelling of semi-solid processing from an experimentalist's point of view [1]. This was based on a major review which has just been published [2]. It is clear from this that there are challenges in the validation of modelling and the purpose of this paper is to review these and to give some experimental details of a flow visualisation method for aluminium alloys which can contribute to progress in this area.

2 VALIDATION OF MODELS

Virtually all the experimental validation of die filling patterns reported in [2] involves interrupted filling. The difficulty with this is that the effects of inertia compromise the results, with the materials continuing to travel even when the ram has stopped. The most appropriate way of checking the position of the flow front during die fill is with in situ observation. Petera et al. [3] (more fully reported in [4]) have carried out experiments with transparent sided dies under isothermal and non-isothermal conditions for Sn/Pb alloys. Isothermal conditions are much more difficult to achieve for aluminium alloys. In addition, the temperatures involved with aluminium alloys make the experiments very challenging if an expensive 'window' is not to be sacrificed every time a run is carried out. In the work reported here, a unique system for achieving such observation, in a reliable and low cost way, is described. A full report on the project is available on the web [5].
It is important to note that any model of semisolid

processing must not only be able to accurately simulate the flow front at a given instance under a variety of conditions, it must also be able to predict, for example, the relationship between force and time for a rapid compression test and between shear stress and time for a shear rate jump in a rheometer. There are few examples of thorough tests of models in the literature that demonstrate the applicability of the model across a range of conditions. There is a danger of 'fitting' the parameters for one set of conditions (and obtaining a reasonable match to an observed interrupted filling test) but then not testing that set of parameters against a different situation.

3 FLOW VISUALISATION FOR SN/PB AND FOR ALUMINIUM ALLOYS

3.1 Apparatus

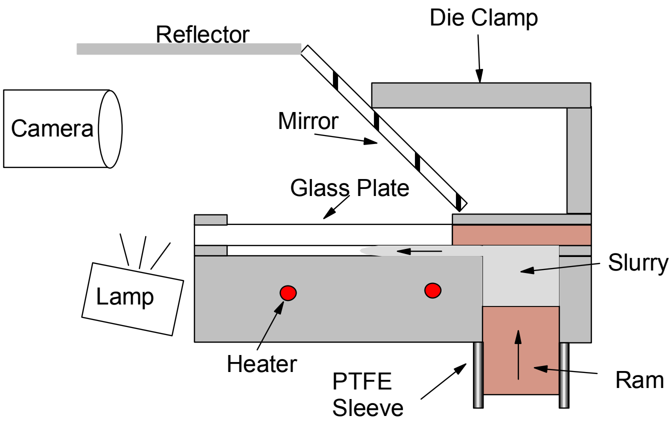

Figure 1: Apparatus used for filming die filling, mid-plane vertical section

The experiments were carried out on the thixoformer at the University of Sheffield. Figure 1 shows the set-up used for filming of die filling. For use with tin-lead, the viewing panel was a 25mm sheet of borosilicate glass, while for aluminium a quartz block was placed on top of a 6mm sheet of sacrificial window glass. The die was heated to ~190 °C, using cartridge heaters. Thus, the tin-lead shots were "near-isothermal". Loss of material from the slumping tin-lead slugs was prevented by using a PTFE sleeve, which slid down the pedestal during die filling. This meant it was possible to do shots in the fully liquid state.

The die shape was a 60mm square plate 7.5mm thick, tapered to a triangular overflow, with either a parallel entrance or a splayed one that was designed to ensure the slurry remained attached to the walls as it crossed the die. Over 40 experiments were conducted under various conditions. Four obstacles were used in the die, circles of 30 and 20 mm diameter and two spider profiles used in the manufacture of PVC pipe [6]. The obstacles could be placed symmetrically in the die or offset. Ram velocities of 0.25-2ms^{-1} were used. The tests were conducted without any final consolidation force, thereby safeguarding the viewing plate. Filming was done using a Kodak EM digital system. Collection rates were adjusted to suit the ram speed, resulting in ~40 images during filling. The very confined space made lighting difficult. This, and the multiple glass surfaces, led to extraneous reflections. This needs more attention in future.

3.2 Experimental Results

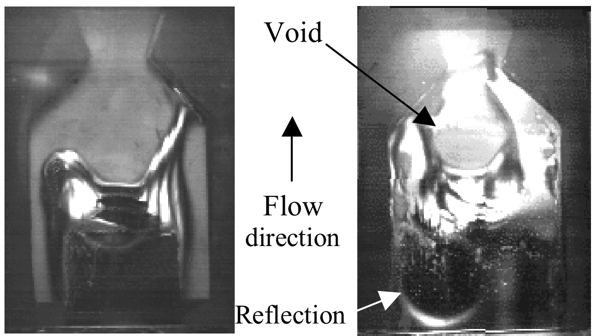

Figure 2: Die filling, SnPb alloy. At 0.25 ms^{-1} ram speed, parallel entrance (left), the central region catches up and good filling is obtained, while at 1 ms^{-1}, splayed entrance (right), a void forms.

With the tin-lead alloys, there was a marked difference in behaviour of the alloys with ram speed. Figure 2 shows that at 0.25ms^{-1}, with both the splayed and parallel entrances, the alloy flowed through the die without breaking up. However, at 1ms^{-1}, the slurry was sufficiently thinned to break up. With the splayed entrance, this happened towards the end of filling, despite the fact that the slurry had initially followed the die entrance shape. This illustrates the extreme sensitivity of the alloy viscosity to shearing as the slurry is pushed through the die entrance. At low ram speeds, the presence of a large obstacle improved the filling pattern (figure 3), as the slurry was pushed more rapidly into the "shoulder" near the parallel entrance. The slurry rejoined soon after the obstacle, the spider profiles being more effective in this respect than the circular inserts. Rejoining was also very sensitive to ram velocity and the filling pattern was very poor with all obstacles at 1ms^{-1}, as shown in figure 3.

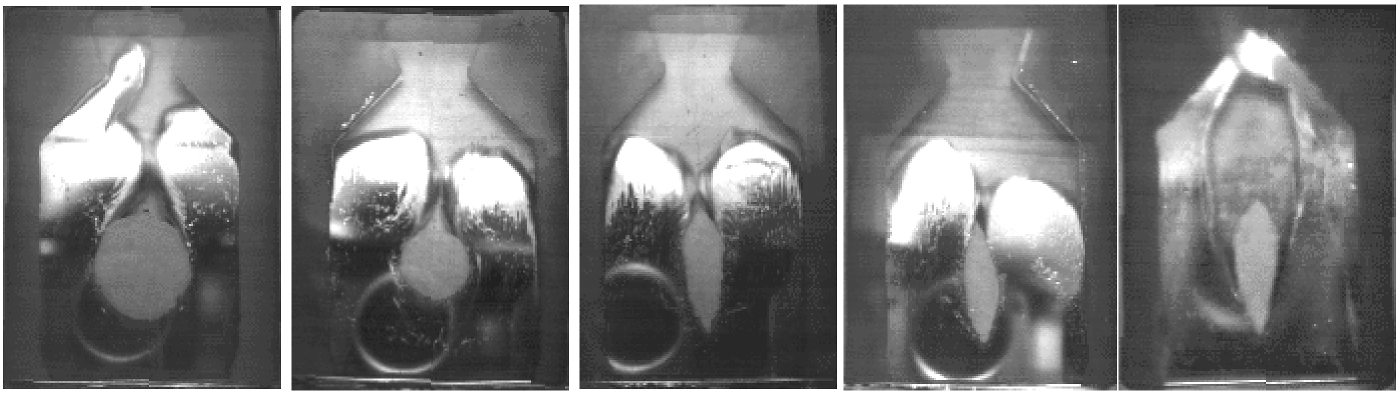

Figure 3: Effect of obstacle size and shape on meeting of split flow fronts, tin lead 189°C, 0.25 ms^{-1}, splayed die entrance (left to right): 30mm diameter, 20 mm diameter, experimental &, standard spiders for extruding PVC pipes. Note how broader obstacle leads to flow fronts meeting with die more full. Far right: experimental spider at 1 ms^{-1}.

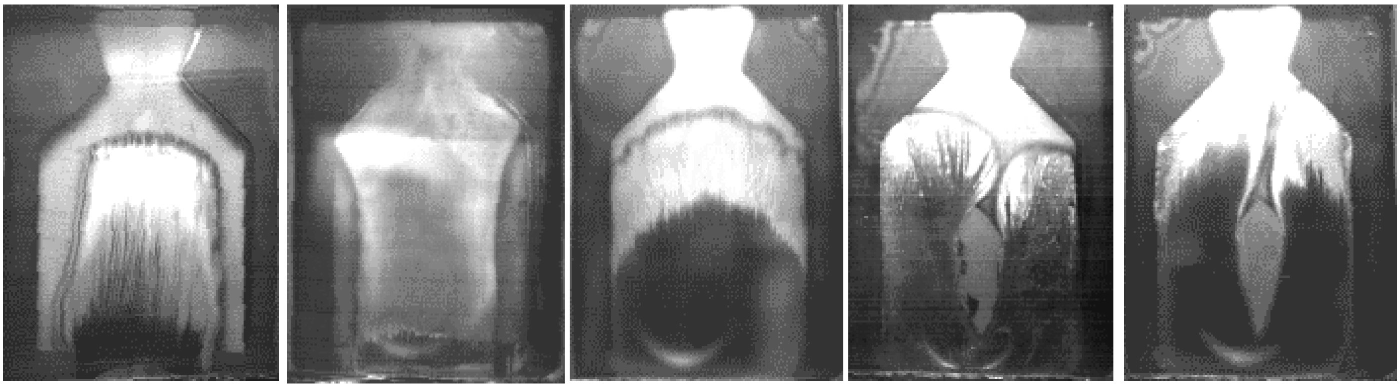

Figure 4: Shots from filmed die filling with Al A357;(left to right) 576°C, 0.25 ms^{-1}, parallel entrance; 576°C 1ms^{-1}, parallel entrance; 1ms^{-1}splayed entrance, 0.25 ms-1 splayed entrance with the experimental spider and the same at 1ms^{-1}, all at 577°C

The aluminium alloy behaved differently. Figure 4 shows that under all conditions in these experiments, the flow front remained coherent, although the die filling with the parallel entrance still resulted in insufficiently early "die swell", or spreading of the slurry, to fill the "shoulders" before the slurry had reached the end of the die. This was particularly apparent at 1ms^{-1}. The splayed entrance led to very smooth filling, consistent with previous studies which have shown that for thixoforming the die entrance must extend to nearly the full width of the component [7]. The obstacles also have a less disruptive effect on filling pattern than with tin-lead. The differences between the two alloys need to be investigated further. The higher density of tin-lead means that turbulence onset will occur at a lower slurry velocity, while cooling of the aluminium alloy during filling may contribute to better flow behaviour. In both alloys, the late swelling was unexpected. It may be indicative of plug flow, where the slurry thins markedly due to shear near the die wall, while the body of the material remains very viscous. Alternatively, the cause could be very low friction between the die surfaces and the slurry, or even plug flow on the ceramic-washed metal surface and slip at the glass surface. If plug flow is present, it would suggest that recovery times could also be short, as the slurry experiences considerable shear through its bulk as it turns through right angles to enter the die.

Due to time constraints, it was not possible to model (using FLOW3D from FLOWSCIENCE with a thixotropic module) the die filling extensively. However, it was found that the flow patterns found in Al with a parallel entrance (first two photos in figure 4) could not be reproduced using thixotropic properties from rapid compression tests [5]. With full wall shear, filling of the "shoulders" was almost immediate, even when modelling with Newtonian conditions and a viscosity as low as 0.1Pa.s. Without wall shear and even with rapid thixotropic recovery, no die swell occurred, as shown in figure 5. Eliminating wall shear only on the glass surface gave a similar result to that with shear on both surfaces. Using finite friction coefficients on these surfaces gave one of the two behaviours in figure 5, but not the delayed swell shown in figures 2 and 4. Further experiments and modelling, for example looking in more detail at the effects of temperature (liquid fraction) and ram velocity on die swell, will clarify the slurry behaviour.

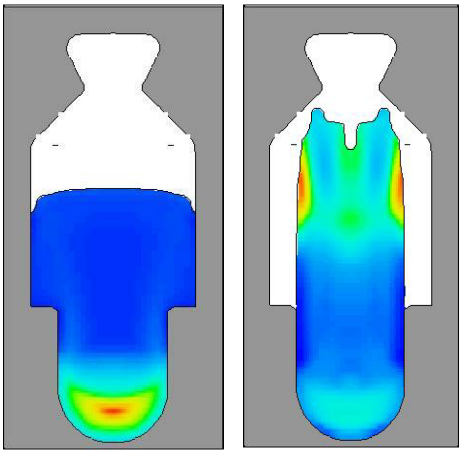

Figure 5: Modelled filling of Al alloy, ram speed 0.25ms^{-1} parallel entrance, rheological properties as for compression test in Table I with (left) and without wall shear but with a rapid recovery rate term (right). Viscosities ~100 Pa.s (blue) to 1500 Pa.s (red)

4 CONCLUSIONS

A low cost, reliable method of filming semisolid die filling with aluminium alloys has been developed. This provides a means of flow visualisation which can be used as part of the validation of models of semisolid processing.

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REFERENCES

1. H.V. Atkinson, A Review of the Modelling of Semi-Solid Processing-from an Experimentalist's Point of View, In: *Proc. ESAFORM 2004*, ed, S. Stören, Trondheim, Norway (2004) 405-408, ISBN 82-92499-02-04.
2. H.V. Atkinson, Modelling the Semisolid Processing of Metallic Alloys. *Progress in Materials Science* 50 (2005) 341-412.
3. J. Petera, M. Modigell and M. Hufschmid, Comparison of Two-Phase Finite Element Simulation with Experiments on Isothermal Die Filling of Semi-Solid Tin-Lead, In: *Proc. 5th Int. ESAFORM Conference on Material Forming*, eds, M. Pietrzyk, Z. Mitura, J. Kaczmar, Kraków, Poland (2002) 675-8. Publ. Akademia Górniczo-Hutnicza.
4. M. Modigell, M. Hufschmidt and J. Petera, Two-Phase Simulations as a Development Tool for Thixoforming Processes, *Steel Research International* 75 (2004) 513-518.
5. P.J. Ward, H.V. Atkinson, D.H. Kirkwood and S.B. Chin, Final Report of EPSRC Project 'Modelling Thixotropic Flow of Metal Alloys into a Die' Available: http://www.le.ac.uk/engineering/staff/atkinson_files/modelling_final_report.pdf.
6. Y. Huang et al, Analysis and Improvement of Die Design for the Processing of Extruded Plastic Pipes. *Materials and Design* 21 (2000) 465-475.
7. P.J. Ward, H.V. Atkinson and D.H. Kirkwood, Flow modelling and die design in the thixoforming of aluminium alloy demonstrators, In: *Proc 5th Int. Conf. Semi-Solid Processing of Alloys and Composites*, eds, A.K. BHasin, J.J. Morre, K.P. Young and S.P. Midson, Golden, Colorado (1998) 115-122.