A Review of the Modelling of Semi-Solid Processing-from an Experimentalist's Point of View

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ABSTRACT: Semi-solid processing of metallic alloys and composites utilises the thixotropic behaviour of materials with non-dendritic microstructure in the semi-solid state. Modelling of die fill leads to more effective die design to avoid defects. Here approaches to modelling are summarised. They can be categorised as one phase or two phase and as finite difference or finite element. Although many workers have qualitatively compared their predictions with experimental results (usually obtained through interrupted filling), there is little quantitative data. There are no direct comparisons of the capabilities of various software packages to model die fill accurately. In addition, the modelling depends on rheological data. This is sparse, particularly for the increasingly complex two-phase models. Direct flow visualisation can provide useful insight and avoid the effects of inertia in interrupted filling experiments.

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

1 INTRODUCTION

At MIT in the early 1970s, Spencer at al. [1] discovered metallic alloys in the semi-solid state with a non-dendritic microstructure (i.e. spheroids of solid in a liquid matrix) behaved in a thixotropic way i.e. when sheared the material thinned but when allowed to stand it thickened again. This occurs because on shearing, the bonds between spheroids, and between agglomerates of those spheroids, are broken down and when allowed to stand they rebuild. This behaviour is the basis of a family of innovative manufacturing processes termed semi-solid processing. The technology is in use commercially in the form of:- *thixoforming*, where material gives a non-dendritic microstructure on reheating into the semi-solid state and is then forced into a die; *rheocasting*, where a liquid alloy is cooled into the semi-solid state in such a way as to give a non-dendritic microstructure, and then placed in the shot sleeve of a die casting machine; *thixomoulding* (which to date has only been applied to magnesium alloys), which is allied to injection moulding of polymers, with a continuous screw feed. In all cases, die design can be made more efficient and effective through the use of modelling. The purpose of this paper is to briefly review the approaches to modelling semi-solid processing from an experimentalist's point of view. A fuller discussion, extensive references and full details of the equations are given elsewhere [2]. Previous reviews include those by Kirkwood [3], Atkinson [4] and Alexandrou [5].

2 APPROACHES TO MODELLING

2.1 Finite Difference, One Phase

The model of Brown and co-workers [6-8] forms the basis of much of the finite difference modelling work (and indeed of some finite element). They presented a constitutive model based on the 'single internal variable' concept, where the structural parameter λ varies between 0 and 1 depending on whether the structure is fully broken down or fully built-up, respectively. Their model assumes that flow resistance is due to hydrodynamic flow of agglomerates and deformation of solid particles within the agglomerates. Some workers have also introduced a yield stress. The model predicts an increase in deformation resistance with the solid fraction f_s and this becomes rapid between 0.5 and 0.6 f_s. It is not valid at higher solid fractions.

An alternative to the Brown et al. approach is that in Barkhudarov et al. [9] and Barkhudarov and Hirt [10], which has been incorporated into the FLOW3D commercial thixotropic modelling software. Barkudarov et al. [9] use a transport equation for viscosity η rather than a transport equation for λ. The transport equation includes an advection term and a relaxation term which accounts for the thixotropy of the material. The relaxation term is based on the steady state viscosity η_e and the relaxation time, both of which may be functions of shear rate and solid fraction. No yield stress, wall slip or elastic or plastic behaviour at high solid fractions are included. The model therefore applies for fractions of solid less than about 0.6-0.7. In Barkhudarov and Hirt [10], if the local viscosity is greater than the equilibrium viscosity η_e, then the local viscosity is driven towards η_e at the thinning rate α. If the local viscosity is less than η_e, it is driven towards η_e at the thickening rate β. Modigell and Koke [11] used FLOW3D to model die fill for Sn-15%Pb (Fig.1). The results illustrate the difference between a Newtonian fluid and a thixotropic one. They assumed the fluid obeyed a Herschel-Bulkley model i.e. $\tau = \tau_y + k\dot{\gamma}^n$, where τ is the shear stress, τ_y a yield stress, k a constant related to the viscosity, $\dot{\gamma}$ the shear rate and n the shear rate exponent. Ward et al. [12] showed that there was a need for a new solver in FLOW3D to cope with the fact that viscosities change over so many orders of magnitude in such short distances and times. The new Alternating Direction Implicit (ADI) solver is now incorporated. Fig.2 shows a comparison of the modelling for a shear rate jump in a viscometer with experimental results and the results from a one dimensional spread sheet calculation.

MAGMAsoft commercial software also has a Thixotropic Module which has been used by a

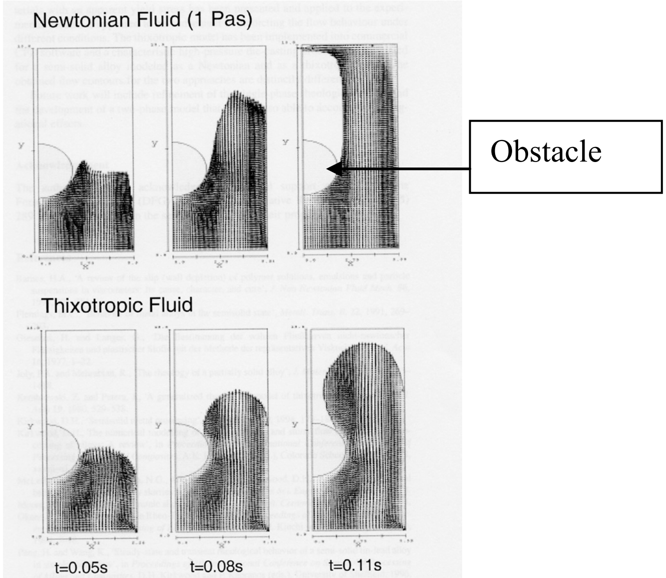

Fig.1 Comparison between simulation of flow into a cavity with a round obstacle assuming Newtonian behaviour and assuming thixotropic behaviour [11].

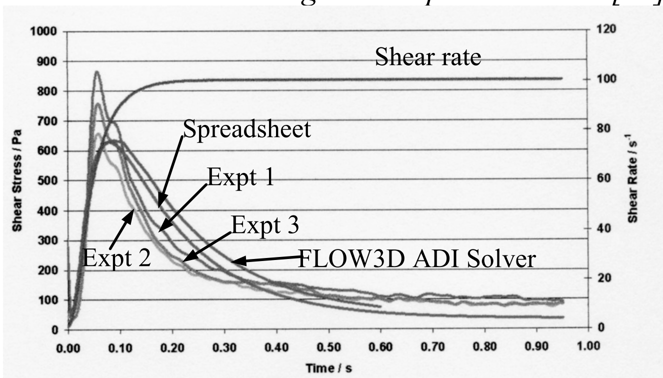

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Fig.2 Shear rate jump from 1-100 s^{-1} in SnPb alloy ($f_s = 0.36$), showing repeats of the same experiment and modelled fits using a spreadsheet and FLOW-3D [12].

number of workers. For example, Kim and Kang [13] and Seo and Kang [14] have found reasonable qualitative agreement between modelled results and interrupted filling tests assuming the Ostwald-de-Waele power law applies (i.e. $\tau = k\dot{\gamma}^n$).

2.2 Finite Difference, Two Phase

In Ilegbusi et al. [15], the single phase equations are solved for the whole filling phase. Trajectories of a given number of particles are computed, assuming they will disappear when they hit a wall or are trapped in a recirculation zone. A measure of segregation is obtained by comparing the number of particles at a given distance from the inlet with the total number of injected particles.

2.3 Finite Element, One Phase

Zavaliangos and Lawley [16] use the Brown et al. model [6-8] without a yield stress. The analysis is for Sn-15%Pb and, for fractions solid less than about 0.5, it is predicted that a free standing billet will collapse. No experimental validation is given. Backer [17] programmed various rheological models into WRAFTS software including a Herschel-Bulkley model and a model with one term dependent on $\dot{\gamma}$ and one dependent on $\dot{\gamma}^n$. Results are presented but again no experimental validation.

Alexandrou et al. [18] used PAMCASTSIMULOR to compare Newtonian and Bingham ($\tau = \tau_y + k\dot{\gamma}$) filling of a three-dimensional cavity with a core. They use a continuous Bingham law to avoid the discontinuity at the yield stress. In pipe flow, due to the finite yield stress, the Bingham case shows a large unyielded area where the material in the centre flows like a solid. For a three dimensional cavity with a cylindrical core, in the Newtonian case the velocity vectors at the rewelding front (i.e. where the flow fronts must remerge beyond the core) point towards the core, whereas in the Bingham case, they point away from the core, allowing oxide skins to be transported into overflows.

The relative importance of the inertial, viscous and yield stress effects on the filling profile in a two-dimensional cavity with a Bingham fluid is examined in [19]. The results identify five different flow patterns (Fig.3): shell (large Reynolds numbers but small Bingham numbers), 'mound' (low Reynolds and Bingham numbers), 'bubble' (larger Bingham numbers), 'disk' (occurs between shell and bubble filling) and 'transition'. Fig.4 shows the helpful resulting schematic for the different types of behaviour. This is important in identifying processing conditions with particular vulnerability to defects. Transition flow occupies a narrow region between the disk and the bubble patterns. This region may be prone to instabilities. In [20], Alexandrou et al. have analysed two-dimensional jets of Bingham and Herschel-Bulkley fluids fluids impacting on a vertical surface at a distance from the

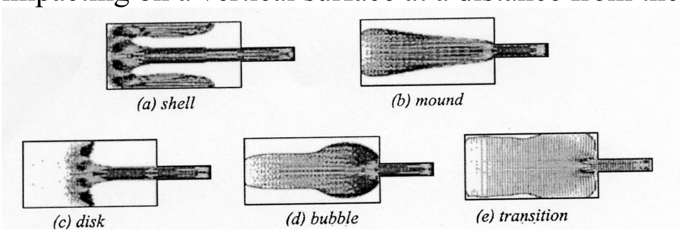

Fig.3 Flow patterns found by modelling [19].

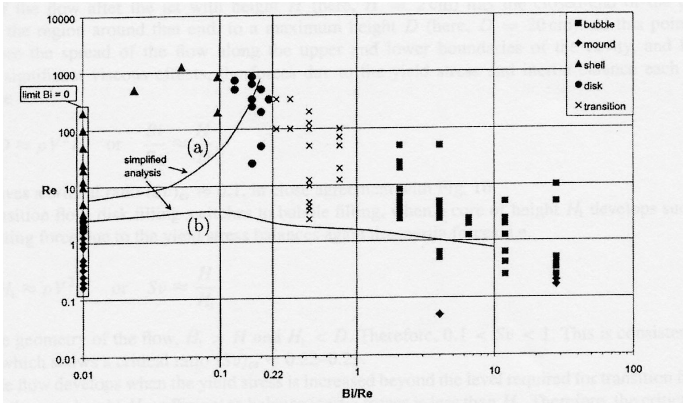

Fig.4 Map showing flow patterns in Fig.3 as a function of Reynolds number Re and the ratio of the Bingham number to the Reynolds number (Bi/Re) [19]. Curves (a) and (b) represent simplified analyses.

die entrance. This has enabled the conditions under which the 'toothpaste' instability, which is observed in thixoforming, occur.

Some workers have used viscoplastic constitutive models e.g. [21] but in [21] there is no time dependence and this therefore essentially seems to be a forging simulation.

Jahajeeah et al. [22] and Orgeas et al. [23] have both used the Power Law Cut Off (PLCO) model in Procast commercial software. In this model, shear thinning only occurs if a cut-off value is exceeded. This can be set at different values in different parts of the component. Orgeas et al. model 'ratchet-type' behaviour i.e. an increase of $\dot{\gamma}$ beyond the largest shear rate $\dot{\gamma}_0$ experienced so far will lead to a decrease in viscosity (and modify the maximum shear rate $\dot{\gamma}_0$). A decrease of $\dot{\gamma}$ below $\dot{\gamma}_0$ will not modify the viscosity (and leaves $\dot{\gamma}_0$ unchanged).

2.4 Finite Element, Two Phase

Orgeas et al. have reviewed the two-phase approaches [23]. The semi-solid material is considered as a saturated two-phase medium i.e. made of the liquid and solid phases. Each phase has its own behaviour, which can be influenced by the presence of the other phase via interfacial contributions. The conservation equations can be written in a mixture theory background and the solid phase (solid skeleton) can be modelled as a purely viscous and compressive medium. Momentum exchanges between the solid and the Newtonian liquid are handled through a Darcy-type term appearing in the momentum equations. The models are able to predict phase separation but the determination of the rheological parameters required is not straightforward. Two-phase models usually require the simultaneous calculation of a solid fraction field, a pressure field, two velocity fields (for the liquid and the solid) and a temperature field (although in most cases the simulation is isothermal). The computation time therefore tends to be very long.

A number of workers have used two-phase approaches. An example of the usefulness of such an approach is given in Modigell et al. [24]. All the non-Newtonian properties of the material are shifted to the solid phase and the liquid is treated as Newtonian. Two-dimensional contour maps showing

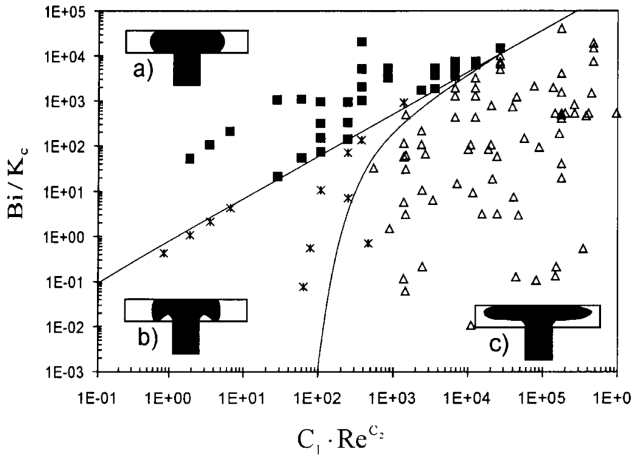

Fig.5 Map of types of flow [24]. a) Laminar, b) Transient, c) Turbulent. Bi is the Bingham number, K_c a rheological number, C_1 , C_2 geometric constant and Re the Reynolds number. K_c, C_1 and C_2 are not specified in the paper.

the transitions between laminar, transient and turbulent filling can be plotted e.g. Fig. 5.

CONCLUDING REMARKS

Approaches to modelling semi-solid processing have been reviewed. There is still considerable scope for progress particularly in validating predictions (e.g. using in situ flow visualisation) and in gathering rheological data for input into the models.

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REFERENCES

1. D.B. Spencer, R. Mehrabian, M.C. Flemings, Metall. Trans. 1972;3:1925-32.
2. H.V. Atkinson, Prog. Mat. Sci. to be published.
3. D.H. Kirkwood, Proc. 5th Int. Conf. Semi-Solid Processing of Alloys and Composites, Golden Colorado, USA., June 1998, ed. A.K. Bhasin et al., publ. Colorado Scool of Mines, p.xxxiii-xl.
4. H.V. Atkinson, Proc. Int. Conf. Synthesis of Lightweight Metals III, San Diego, 1999, ed. F.H. Froes et al.. publ. Minerals, Metals and Materials Society, p.205-12.
5. A. Alexandrou, Ch. 5 in 'Science and Technology of Semi-Solid Metal Processing', ed. A. de Figueredo, publ. North American Die Casting Association, 2001.
6. P. Kumar, C.L. Martin, S. Brown, Acta Metall. Mater. 1994;42:3595-602.
7. C.L. Martin, P. Kumar, S. Brown, Acta Metall. Mater. 1994;42:3603-14.
8. P. Kumar, C.L. Martin, S. Brown, Metall. Trans. 1993;24A:1107-16.
9. M. R. Barkhudarov, C.L. Bronisz, C.W. Hirt, Proc. 4th Int. Conf. Semi-Solid Processing of Alloys and Composites, Sheffield, UK., June 1996, ed. D.H. Kirwood and P. Kapranos, publ. University of Sheffield, 1996, p.110-14.
10. M.R. Barkhudarov, C.W. Hirt, Proc. Materials Week '96, TMS Conference, Cincinatti, Ohio, Oct. 1996, p.1-9, Paper FSI-96-00-2.
11. M. Modigell, J. Koke, Mechanics of Time Dependent Materials 1999;3:15-30.
12. P.J. Ward, H.V. Atkinson, D.H. Kirkwood, S.B. Chin, Final Report for Engineering and Physical Sciences Research Council project 'Modelling Thixotropic Flow of Metal Alloys into a Die' (GR/M17334/01) 2002, http://www.le.ac.uk/engineering/staff/atkinson_files/modelling_final_report.pdf.
13. N.S. Kim, C.G. Kang, J. Mater. Process. Technol. 2000;103:237-46.
14. P.K. Kang, C.G. Kang, Proc. 7th Int. Conf. Advanced Semi-Solid Processing of Alloys and Composites, Tsukuba, Japan, Sept. 2002, ed. Y. Tsutsui et al., publ. Nat. Inst. Adv. Sci. and Technol. and Japan Society for Technol. of Plasticity, 2002, p.515-20.
15. O.J. Ilegbusi, K.A. Quach, K.D. Mat, J. Mater. Engng. Perform. 1999;8:31-4.
16. A. Zavaliangos, A. Lawley, J. Mater. Engng. Perform. 1995;4:40-7.
17. G.P. Backer, JOM 1998; August:21-3.
18. A. Alexandrou, F. Bardinet, W. Loué, J. Mater. Process. Technol. 1999;96:59-72.
19. A. Alexandrou, E. Duc, V. Entov, J. Non-Newtonian Fluid Mech. 2001;96:383-403.
20. A. Alexandrou, P. le Menn, G. Georgiou, V. Entov, J. Non-Newtonian Fluid Mech. 2003;116:19-32.
21. A. Rassili et al. op. cit. [14] p.367-72.
22. N. Jahajeeah et al. op. cit. [14] p.533-8.
23. L. Orgeas, J-P. Gabathuler, Th. Imwinkelried, Ch. Paradies, M. Rappaz, Modelling Simul. Mater. Sci. Engng. 2003;11:553-74.
24. Modigell et al. op. cit. [14] p.77-82.