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Comparison between numerical simulation of semisolid flow into a die using FORGE© and *in situ* visualization using a transparent sided die

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ABSTRACT

Semi-solid processing is a promising forming process for shaping metallic alloys in one shot. Numerical simulations are of great interest for optimizing the process. Generally, numerical simulation results are compared with interrupted flow experiments but these do not fully reflect the progress of material into the die because of the inertia of the flowing material which continues to move after the interruption to the shot. Results are available for *in situ* visualization of flow using transparent sided dies. Here die filling with a 90° change of flow path was simulated using the FORGE© finite element code and a constitutive equation based on a micro-macro modelling approach. The predicted flow behaviour was compared to the *in situ* visualization images obtained with a transparent glass sided die and reported in the literature. The impact of the presence of an obstacle, ram speed and friction coefficients on the material flow front is discussed. The initial solid skeleton is broken as soon as the material is deformed. The effect of the ram speed on the flow front is successfully represented by keeping the same parameters for the constitutive laws but requires a change in the friction coefficients. Friction modelling using the Coulomb law limited by Tresca cannot represent the ram speed effect on experimental friction conditions for the *in situ* visualisation tests used for the comparison here. However, the effect of an obstacle within the die on the material flow front is predicted well.

1. Introduction

Semi-solid processing uses metallic alloys in the semi-solid state reached when alloys are heated to between the solidus and the liquidus. It exploits the thixotropic behaviour of such materials obtained when the solid phase has a spheroidal structure and firstly discovered at MIT by Flemings and co-workers (Spencer et al., 1972). Ito et al. (1992) observed that the solid particles can agglomerate even for moderate solid fractions. Flemings (1991) described that this agglomeration results in a more or less connected skeleton while the liquid phase may be entrapped in the solid phase or spatially continuous and free to flow. Deagglomeration of the solid phase and the induced change in spatial liquid-solid distribution during deformation are responsible for shear thinning and time-dependent behaviour.

The focus of this background literature survey is those more recent studies where simulation has been compared with experiment. Studies before 2005 are summarized in the review by Atkinson (2005). Numerical simulations require validation experiments. Conventionally for semi-solid processing this has been done with interrupted filling to check the intermediate position of the flow fronts (Atkinson, 2005). Comparisons also involve scrutiny of the load evolution during the process and of the solid fraction via the image analysis of the quenched microstructure. Hufschmidt et al. (2006) demonstrated the relevancy of two-phase constitutive models to reproduce the pressure evolution during filling of a T-shaped die with tin-lead alloy. They also showed that the experimental flow front is well reproduced for three piston velocities with a single set of parameters for two-phase simulations. However, the model parameters for one-phase simulation had to be readjusted to achieve satisfactory results for different piston velocities. Maciol (2009) simulated the same experiment by Hufschmidt

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et al. (2006) using their own CFD code including the Internal Variable Convection methodology which is efficient for history dependent materials. A qualitative agreement between the experimental and computed flow front was found but the modelling requires further development. Solek et al. (2005) suggested that the discrepancies between the predicted and experimental load evolution during thixocasting of Al-Si alloy were due to the fact that the transient behaviour was ignored. Koeune and Ponthot (2014) simulated thixoextrusion and predicted load evolution with three different constitutive equations. The kinematics of the deformation were compared to the experimental results, including interrupted tests. The results also revealed the effectiveness of including transient and non-isothermal behaviour in the constitutive equations so achieving a better match between experiments and simulations. Kang et al. (2008) compared the predicted and experimental filling rates of a specifically designed die providing a gradual decrease of the piece thickness. The simulations were performed using the MAGMAsoft thixo-module. They showed that the gate width had a strong effect. Very recently, Jorstad et al. (2014) explained why semi-solid slurries can fill thin sections at seemingly unlimited flow velocity thanks to comparisons between experimental and computed filling of thin cast sections.

As reported by Atkinson (2005), *in situ* observation is the most appropriate way of checking the position of the flow front during die filling but generally dies are closed and opaque. The main recent work with transparent glass-sided dies enabling die filling to be filmed is that of Hufschmidt et al. (2006) and that reported by Atkinson et al. (2002) and published in Atkinson and Ward (2006). Hufschmidt et al. (2006) used a T-shaped die covered with a glass plate on one side and carried out isothermal experiments with Sn-12%Pb. Atkinson and Ward (2006) designed a set-up which can be used with both SnPb and aluminium alloys. In the latter case, experiments are not isothermal because of the experimental challenges of these higher temperatures. However, the die is heated, the speed is fast and the die section is relatively thick minimizing the tendency for solidification. Various obstacle shapes were placed in the path of the flowing material to observe flow fronts splitting and remerging.

In this work, the latter experiments (Atkinson et al., 2002; Atkinson and Ward, 2006) have been simulated using the FORGE© software. The predicted flow is compared to the experimental results in order to better understand the filling pattern. The impact of the presence of an obstacle, ram speed and friction conditions on the processing is discussed. For this purpose, a micro-macro constitutive model proposed by Cezard et al. (2005) and Favier et al. (2009) was used. Some preliminary results have been reported in Neag et al. (2014) but this paper presents a much fuller analysis.

2. Finite element simulation procedure

2.1. Geometry of the filling device

Fig. 1 shows a 3D view of the filling system used in the Atkinson et al. (2002) experiments. The cylindrical billet is 40 mm diameter and 45 mm height. The billet is first pushed into a vertical die, compressed by the upper part of the die and then turns 90° to enter into a 60 mm square Plate 7.5 mm thick. In some experiments, an obstacle was placed symmetrically in the die. Different shapes of obstacles were used (Table 1).

2.2. Mesh

In this work, the finite element code FORGE© was used to perform the numerical simulations. Only a half of the geometrical model (along the symmetrical plane) was meshed and considered for calculations as the mechanical problem is symmetric in the flow direction. Using the multi-block technique, an adaptive volume meshing for the billet was applied on the region where the billet is severely deformed. These two mesh boxes were created in order to limit the element number and to ensure calculation accuracy for forming simulation. The billet is divided into 29497 tetrahedral elements and 6356 nodes, corresponding to a 0.7 surface shape factor (automatically checked by the GLPre Forge preprocessor). Up to 60% finer and coarser meshes were tested. The selected mesh provides similar strain rate and viscosity fields to those of the finer meshes while reducing the CPU time. The other parts of the geometrical model have coarser meshes. The die and the punch were assumed to be rigid bodies. The input parameters assigned to the deformed material are the initial temperature, the punch velocity (velocity at which the material enters in the mold), the friction coefficients and the parameters of the constitutive equations. The alloy was A357 aluminum alloy and the flow takes place under isothermal conditions. The initial temperature was chosen to be that associated with 0.5 solid fraction (from Liu et al. (2005)). The filling tests were carried out considering the mechanical parameters of a hydraulic press. Two ram velocities were used, 0.25 and 1 m s^{-1} (Fig. 2).

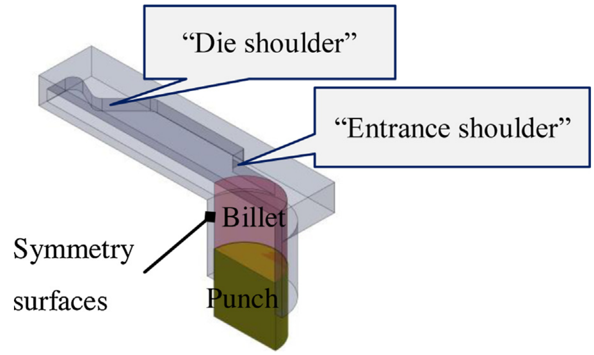

Fig. 1. Solid model of die filling system without an obstacle.

Table 1
Different shapes of obstacle used in this study (the terms 'standard spider' and 'experimental spider'originate from when obstacles with these geometries are used in polymer processing).

Circular		Standard spider	Experimental spider
Ø20 mm	Ø30 mm		

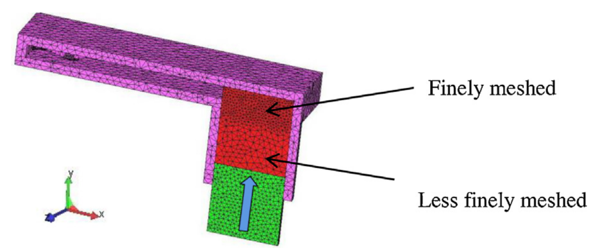

Fig. 2. The initial meshed view of the geometric model.

2.3. Modeling material behaviour and parameter identification

The constitutive equations adopted for this study are based on a micromechanical model proposed by Cezard et al. (2005) and Favier et al. (2009) which separates the role of four mechanical phases: the solid globules/agglomerates; the solid bonds between the solid globules; the free liquid; and liquid entrapped in the solid globules. The overall solid fraction is termed f^s. At rest, the solid globules tend to agglomerate leading to the formation of a 3D network. The