Modelling of semi-liquid aluminium flow in extrusion

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Summary
Experimental modeling using substitute materials is usually a simply way to obtain satisfied results. This kind of experiment is characterizing by low cost. The significant results may be quickly applying using theory of probability. The way of modelling the deformation mechanisms during extrusion of aluminium alloys in semi-liquid phase, the way of preparing samples and experimental technique has been analysed in the following work. On the ground of received results (i.e. registrations of consecutive process steps) the grid of the flow velocity vectors on a flat sample surface was done. It allowed to draw conclusions which one of the basic deformation mechanisms is dominant in particular stage of the process. The technique of measurement has been shown as well. Experiments are made using plasticine and rape oil as a substitute materials. Some kind of different variants have been investigated. To ensure that such model experiments provide useful information it is essential to select model materials and prepare samples that would exhibit (preferably at room temperature) similar behaviour and similar deformation mechanisms as those present during the actual deformation process of aluminium alloys in a semi-liquid state. In particular the FLS, SS and PDS mechanisms should be adequately reproduced.

Keywords: Innovative materials and foundry technologies, thixoforming, experimental modelling, semi-liquid alloys, extrusion

1. Introduction
Thixoforming extrusion and injection (die casting) is a most complication technology. The material is deformed at the semi-solid temperature due to the heat generation caused by plastic deformation [7, 8, 9]. The billet is heated to obtain a semi-solid state, and then transferred to the dies and formed. To attain sufficient fluidity of the semi-solid material filling into the die cavity, the volume fraction of solid phase should be low [6, 7].

Many technical parameters must be still control with high accuracy. On the other hand the complex-shape can be formed. Moreover, the mechanical properties of semi-liquid material are much better than those of cast one. Some problems of physical and numerical modeling of thixoforming processes are described in [11, 12].

During semi-liquid deformation of aluminium alloys in extrusion one can identify four basic deformation mechanisms as follows [1, 3, 4, 5]:
   a) Liquid flow (LF),
   b) Flow of liquid incorporating solid particles (FLS),
   c) Sliding between solid particles (SS),
   d) Plastic deformation of solid particles (PDS).

For low levels of solid fraction the first two of the above prevail. As the solid fraction and the deformation rate increase, the SS and PDS mechanisms become more dominant.

The basic objective of the present work has been to investigate by means of model experiments interaction between the four deformation mechanisms mentioned above and the dependence of material flow on different process parameters. It seems to be practically impossible to set up an experiment that would give a direct insight into the deformation.
Many investigations and researches were made choosing substitute materials in modelling of semi-solid aluminium extrusion and injection. Experiments are made using plasticine, silicone with hardener and some kinds of water solution of gelatin. The results, especially velocity and displacement distributions on the contact surface has been confirmed that the described substitute materials have very similar properties to aluminium alloys in elevated temperatures. They may be used in modelling of plastic flow in symmetric or non-symmetric extrusion process, e.g. of formerly divided streams [13, 14, 15].

2. Preparation of the samples and experimental technique

Special samples have been designed to reproduce the three mechanisms that dominate the deformation of aluminium alloys in the semi-liquid state, namely the FLS, SS and PDS mechanisms. Plasticine and rape oil have been used to represent respectively the solid and the liquid phases.

The samples have been prepared in a shape of a parallelepiped made out of homogeneous plasticine with transversal holes filled with oil, the outer dimensions of the samples being 200mm×80mm×20mm as length, width and thickness respectively. Square grids with 5mm×5mm spacing have been inserted on the faces of the samples using plasticine of contrast colour. The transversal holes have been made circular or rectangular in cross section with diameter or side length being either 5mm or 10mm. The holes have been arranged uniformly within the sample volume, the ratio of their total area to the sample face area giving the mean liquid volume fraction $V_L$.

A number of samples have been prepared with the following values of the mean liquid volume fraction: 0.0, 0.073, 0.074, 0.084, 0.084, 0.139, 0.193, 0.209, 0.224, 0.244, 0.332.

The so prepared samples with the transversal holes filled with rape oil have been extruded using a special test device simulating plane-strain conditions [15]. Experimental stand has been shown in Fig. 1. Equipment has been presented in Fig. 2.

Since, the force requirements for the model tests have been small, one container wall has been made of transparent plastic so that the material flow and the deformation progress could be observed during the tests. All the tests have been carried out at room temperature using standard Instron 1112 machine. The deformation of the grid has been photographed at a number of deformation steps (that is for several positions of the extrusion punch) and registered using a video camera.

3. Discussion of the test results

The deformed grid patterns given in Fig.3. illustrate the material flow during solid-state extrusion (i.e. for the mean liquid volume fraction $V_L = 0.0$) through the flat die.

In the die container corner a „dead zone” develops where no material flow takes place. All the permanent deformation results from the PDS mechanism which is the only deformation mechanism present during solid-state processing.

Figures 4 and 5 illustrate the material flow during semi-liquid extrusion for two different configurations of holes with oil and different values of liquid volume fraction $V_L$ ($V_L = 0.073$ in the first case and $V_L = 0.133$ in the second). One can clearly observe significant qualitative differences when comparing Figures 4 and 5 with the flow pattern prevailing during solid-state extrusion as shown in Fig.3.

Additionally Fig. 4 shows consecutive stages of the extrusion process through the cone die and Fig. 5 through the rectangular one. In the first case $V_L = 0.073$, in the second one $V_L = 0.133$.
All the tests have been carried out for every \( V_L \) mentioned in part 2. Figures 4 and 5 were chosen as a representative ones.

Comparing 4 and 5 one can also infer an influence of a die on the running flow process in the semi-liquid phase ("dead zone" field).

Fig. 3. The images of plastic flow for homogeneous material (plasticine – flat die) – \( V_L = 0 \)

Fig. 4. Material flow during semi-liquid extrusion (cone die) - \( V_L = 0.073 \)

Observation of consecutive stages of deformation reveals occurrence of considerable flow nonuniformity as a result of nonuniform distribution of material properties. High degree of distortion of the volume elements surrounding the holes with liquid phase can be observed even at early stages.
As the liquid volume fraction \( V_L \) increases the FLS mechanism and subsequently the SS mechanism occur apart from the basic PDS mechanism and become more important for the global deformation picture. The above can be most clearly seen by inspecting the regions directly under the punch and in the vicinity of the die opening. Interaction between different deformation mechanisms is most complex.

Comparison of the flow patterns obtained for the flat and wedge-shaped dies reveals that the die shape does not influence in an essential way the kind of deformation mechanisms occurring for particular value of the liquid volume fraction.

### 4. Flow velocity distribution

For a given deformation stage the distribution of the flow velocities within the solid-phase volume (that is plasticine) can be evaluated by comparing two grid patterns obtained for two consecutive punch positions. The distributions of the flow velocity computed for twelve different cases characterised by the liquid volume fractions \( V_L = 0.0 \div 0.332 \) have been plotted respectively in figures 6 \& 8. Considerable flow nonuniformity can be observed in all the above cases. The flow nonuniformity increases for increasing values of the liquid volume fraction.

![Fig. 6. Distribution of the flow velocities within the solid phase volume (flat die)](image)

![Fig. 7. Distribution of the flow velocities within the solid phase volume (cone die)](image)

Determination of the distributions of the flow velocity is the final stage in modelling processes. These are essential for building maps of the flow mechanisms. Although the process is very
complicated (4 basic mechanisms can be identified) one can identify and establish their participation in a whole process i.e. when and in which geometrical parts they appear. What is more we can also infer from the distributions of velocity vectors, which mechanism is dominating at present time.

\[ V_L = 0.133 \]

\[ V_0 = 1 \]

![Distribution of the flow velocities within the solid phase volume (flat die)](image)

The distribution of the flow velocity confirm occurrence of the PDS, FLS and SS mechanisms as well as the fact that the PDS mechanism dominates and the role of the other two increases for increasing liquid volume fraction. Moreover, the LF mechanism manifests locally in the vicinity of the die opening for high values of the liquid volume fraction.

5. Concluding remarks

The results of the modelling experiments presented above prove the complex nature of the phenomena taking place during extrusion of aluminium alloys in the semi-liquid state. While the PDS mechanism is the only one occurring during solid-state extrusion, the other mechanisms appeared as the liquid volume fraction increased.

The PDS mechanism dominated material deformation in all tests, but the role of the FLS and SS mechanisms increased for increasing values of the liquid value fraction. Moreover, the LF mechanism occurred locally in the vicinity of the die opening for high values of the liquid volume fraction. Thus, the overall deformation picture during extrusion in the semi-liquid state is much different from the one observed during extrusion of homogeneous material in the solid state.

It seems to be almost impossible to set an experiment that would give a direct insight into the deformation process of the actual aluminium alloy in a semi-liquid state under the actual technological conditions (that is an aluminium alloy in a semi-liquid state). Therefore, special model experiments using substitute material have been designed and carried out.

To ensure that such model experiments provide useful information it is essential to select model materials and prepare samples that would exhibit (preferably at room temperature) similar behaviour and similar deformation mechanisms as those present during the actual deformation process of aluminium alloys in a semi-liquid state. In particular the FLS, SS and PDS mechanisms should be adequately reproduced.

Among the multitude of different process parameters influencing the material flow during extrusion of semi-liquid aluminium alloys the following can be mentioned as the most important:

a) Initial liquid fraction \( V_L \),

b) Reduction ratio \( R \),

c) Shape of the die and shape of the extrusion punch,

d) Initial shape of the workpiece,

e) Extrusion rate or the velocity of the punch,

f) Process temperature and its distribution within the workpiece.

Liquid volume fraction \( V_L \) is defined as follows:

\[ V_L = \frac{DV_L}{DV} \]

where \( DV_L \) is the part of the volume element occupied by the liquid phase.

To investigate the effect of the pre-processing parameters on the deformation of aluminium alloys in a semi-liquid state a special experimental stand has been designed and built as described in [4].

The present work is mainly concerned with the effect of the die shape and the reduction ratio on the deformation pattern during extrusion of semi-liquid aluminium alloys. The other basic parameters have been discussed in [4, 5, 7, 8, 9, 10].

6. References


