EXPERIMENTAL AND NUMERICAL ASPECTS REGARDING LEAD ALLOY PLASTIC DEFORMATION

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Abstract. The aim of this paper is to present an experimental and finite element analysis (FEA) of the cold forward extrusion of lead alloy. The influence of die angle, reduction ratio and ram speed on the extrusion force during the extrusion process was investigated. In order to determine the deformation flow patterns, square grids were scribed on the meridional plane of one of the two matching halves of the splitted-lead specimens. A finite element analysis (FEA) of the cold forward extrusion process was undertaken in parallel with the experimental programme. The flow curve of lead alloy was determined by torsion tests and data were used in numerical analysis. The FEA simulation was carried out using MSC SuperForm, FEA software, specifically produced for metal forming simulation. Data obtained from the FE model included extrusion force, effective stress and strain and material deformation flow. The data obtained by numerical simulation confirm theoretical and experimental results.

Key words: plastic deformation, extrusion, die angle, finite element method.

1. INTRODUCTION

Extrusion is a bulk forming process in which the material is made to flow using high pressure. The deformation takes places mainly at room temperature in the case of cold extrusion and plate-finished workpieces with close dimensional accuracy are obtained Cold extrusion can be used with materials that has adequate coldworkability, like lead, tin, zinc, copper and alloys. Low-carbon soft annealed steel can also be cold extruded. The billets are only heated to forging temperature in hot extrusion if extreme conditions would be necessary for cold forging (high punch force, high degree of deformation, etc). Workpieces produced in this way are of low dimensional accuracy and have rough surfaces due to scaling, requiring reworking in most cases. The main advantages of cold extrusion as opposed to hot extrusion are that good mechanical properties are imparted to the workpiece due to the severe cold working, good surface finish with the use of proper lubricants and no oxidation of the workpiece.

Study of metal flow in extrusion billet is fundamental and useful to understand extrusion technology. Investigation of behavior of extrusion billet skin and microstructure of products were reported by M. Schikorra et al. [1].

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The geometrical features of the die land are a critical feature in obtaining defect free cold extruded parts. As the die land length directly influences the amount of friction at the die–billet interface, extrusion die designers use this geometrical parameter to control the metal flow from the die. A physical model capable of predicting the friction and sticking/slipping lengths in the bearing channel during unlubricated aluminium extrusion processes were developed by X. Maa et al. [2].

The influence of die angle, reduction ratio and die land on the extrusion force during the cold extrusion process were investigated by J.S. Ajiboye et al. [3], S.O. Onuh et al. [4] and P. Tiernan et al. [5]. Further investigation were developed on the deformation models and internal flow patterns of the deformed specimens by J.S. Ajiboye et al. [3] and N. Solomon et al.[6].

Finite element analysis (FEA) of the cold and hot extrusion process was undertaken in parallel with experimental programme. P. Tiernan et al. [5] reported data obtained from the FE model included die-workpiece contact pressure, effective stress and strain and material deformation velocity.

The relative influences of the semi-angle of the die, the extrusion ratio and the friction factors were examined by Dyi-Cheng Chen et al. [7]. In order to predict the temperature evolution during the extrusion of aluminium alloys were developed researches by means of 3D FEM computer simulation. Results show that ram speed has a significant influence on the temperature distribution in the billet, which continuously changes throughout the process, as a result of complex heat generation and heat loss as is shown by L. Li et al. [8].

2. AIMS OF RESEARCH

An experimental and numerical programme of forward cold extrusion was undertaken in the present investigation. The aims of the research were to analyse the effect of some geometrical variables involved in the process, namely, die angle die land diameter and ram speed on the extrusion force. The magnitude of the extrusion force was determined experimentally by means of a force transducer. Also the influence of tehnological parameters on material flow was studied. A finite element analysis of the extrusion process was carried out using MSC SuperForm software in parallel to the experimental programme.

Results from the finite element program included extrusion force, effective stress and strain, strain rates and material flow patterns.

3. EXPERIMENTAL EQUIPMENT

The lead (Pb99,5) samples were used to study the influence of geometrical parameters of the process on the extrusion force and material flow pattern. The cast lead alloys of dimensions 60 mm in diameter produced were machined into smaller lead alloy specimens of dimensions 30 mm in diameter and 20 mm in height.

The billets were subjected to upsetting tests on Heckert type hydraulic press with maximum force of 200 kN (Fig. 1). The ram speed during the tests were 0,5 mm/s, 2 mm/s, 5 mm/s. No lubricants were used so the friction coefficient was considered to be 0,3.

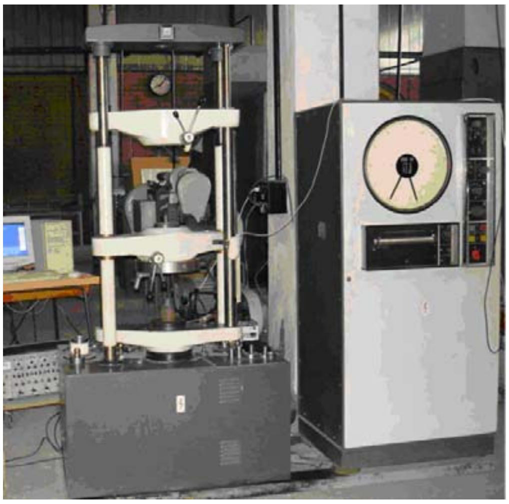


Fig. 1 – Experimental equipment.

During the experiments, the ram displacement, the time and the upsetting force were recorded simultaneously using a specific data acquisition system.

In order to study the influence of geometrical parameters (die angle, die land diameter) on extrusion force was used the following assembly ram-die-workpiece. The extrusion rig was carefully assembled together and centralized on the hydraulic press (Fig. 2).

The extrusion load, F, using a modified upper bound equation is given by the following expression [11]:

$$F_d = 2k\left[4\mu\left(\frac{H}{D}+\frac{h}{d}\right)+\left(\frac{\mu}{\sin\alpha}+1\right)\ln\frac{D^2}{d^2}\right]\frac{\pi D^2}{4} \tag{1}$$

where μ is the coefficient of friction at die/billet interface, D the billet diameter (mm), d the die land diameter (mm), h the Die land height (mm), α the die half angle (°), H the billet height (mm) and k is the maximum tangential stress at die–billet interface (N/mm^2).

The extrusion pressure is determined by:

$$p_d = \frac{F_d}{A}, \tag{2}$$

with F_d the extrusion load and A the original cross-sectional area of the work-piece.

Fig. 2 – Assembly ram-die-workpiece.

The extrusion ratio is:

$$R = \frac{A_0}{A_1}. \tag{3}$$

where A_0 is the original cross-sectional area of the work-piece and A_1 is the final cros-sectional area of the extruded product.

The area reduction is:

$$r = \frac{1}{1-R}. \tag{4}$$

The experimental program undertaken is outlined in Table 1. The three parameters varied during the experimental work were the die exit diameter *d*, the die angle α and the ram speed (0,5 mm/s, 2 mm/s, 4 mm/s). The die geometry is shown in Fig. 3.

Table 1

Experiment number	1	2	3	4	5	6	7	8	9	10	11	12
D [mm]	30	30	30	30	30	30	30	30	30	30	30	30
d [mm]	12	15	20	12	15	20	12	15	20	12	15	20
α [°]	60	60	60	70	70	70	80	80	80	90	90	90

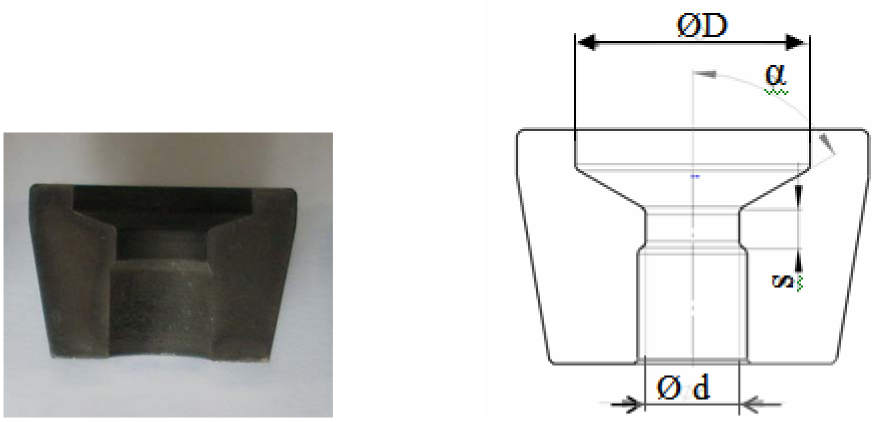


Fig. 3 – Die geometry.

4. EXPERIMENTAL RESULTS

In order to determine the flow curve for lead alloy, torsion tests were carried out, using samples of 9 mm in diameter and 30 mm in length. Test were carried out at stain rates between 0,02 [1/s] and 6,6 [1/s]. In torsion testing, unlike tension testing and compression testing, large strains can be applied before plastic instability occurs and complications due to friction between the test specimen and dies do not arise.

Fig. 4 shows the true stress-strain curve for lead. The obtained values are in accordance to data given by Laue and Stenger [12].

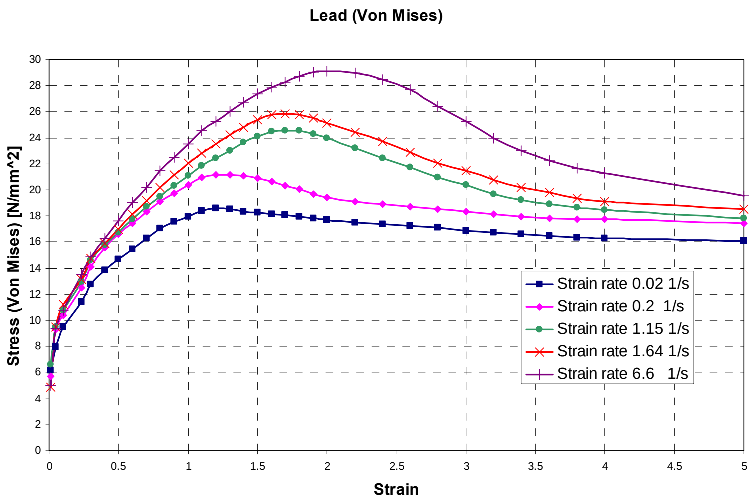


Fig. 4 – Stress-strain curves for lead samples tested at different strain rates.

The relationships of effective stresses and strains to shear stresses and strains are [13]:

$$\bar{\sigma} = \sqrt{3}\tau \text{ for Von Mises theory;} \qquad \bar{\varepsilon} = \frac{2}{3\gamma}.$$

The experimental results obtained for various process parameters are presented in Figures 5, 6, 7.

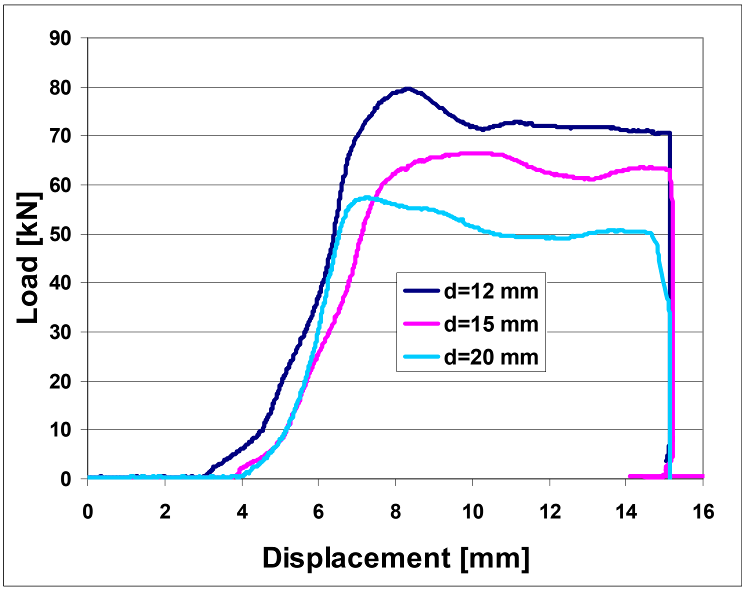


Fig. 5 – Load versus ram displacement for various die land diameters, die angle of 60^0, ram speed 0,5 mm/s.

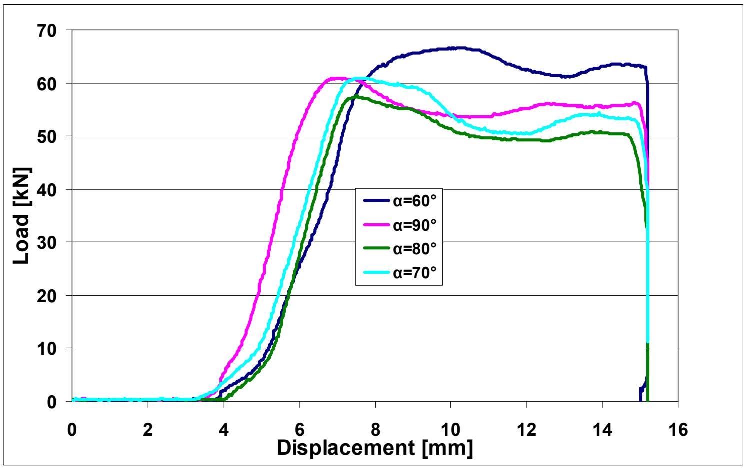


Fig. 6 – Load versus ram displacement for various die angles, die angle, ram speed 0,5 mm/s.

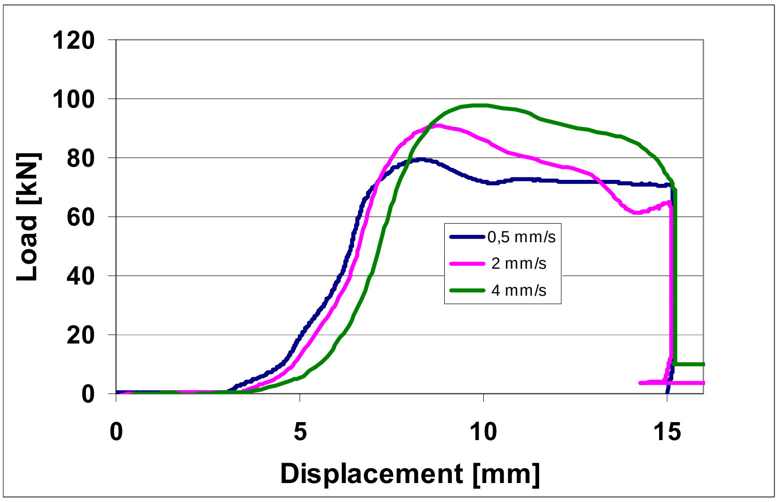


Fig. 7 – Load versus ram displacement for various ram speed, die angle 60º.

In order to determine the deformation flow patterns, square grids of 2mm×2mm were scribed on the plane of one of the two matching halves of the initial specimens. The two halves were cemented together and then extruded to the desired dimensions. After extrusion the solid halves were removed and split to reveal the deformation flow patterns as it can be seen in Figure 8.

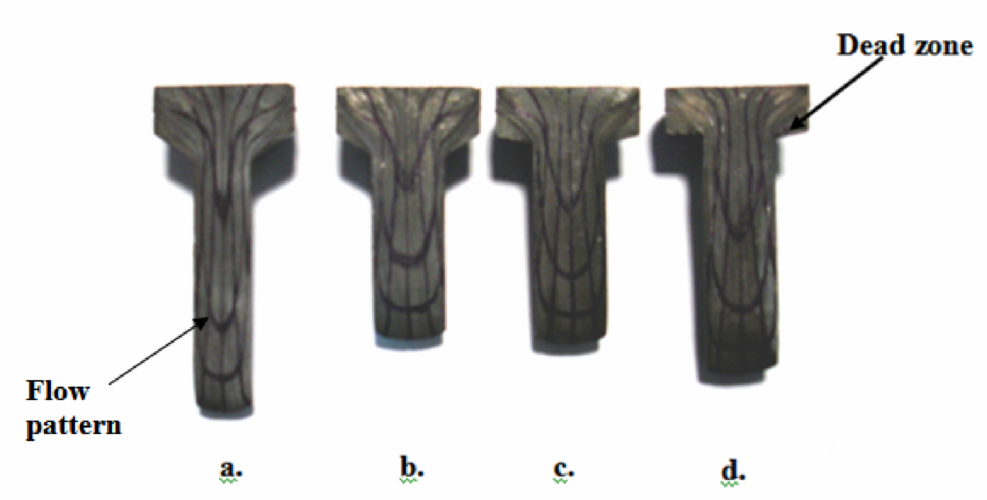
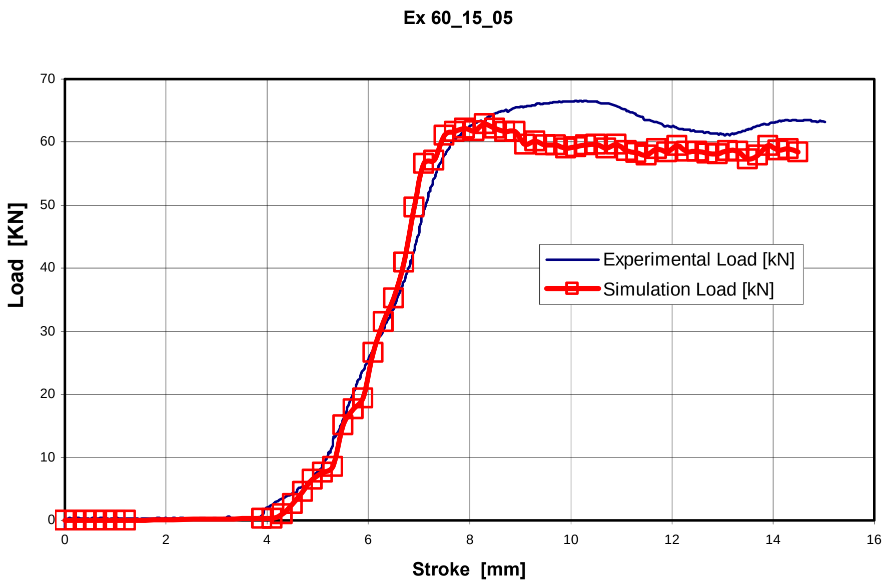
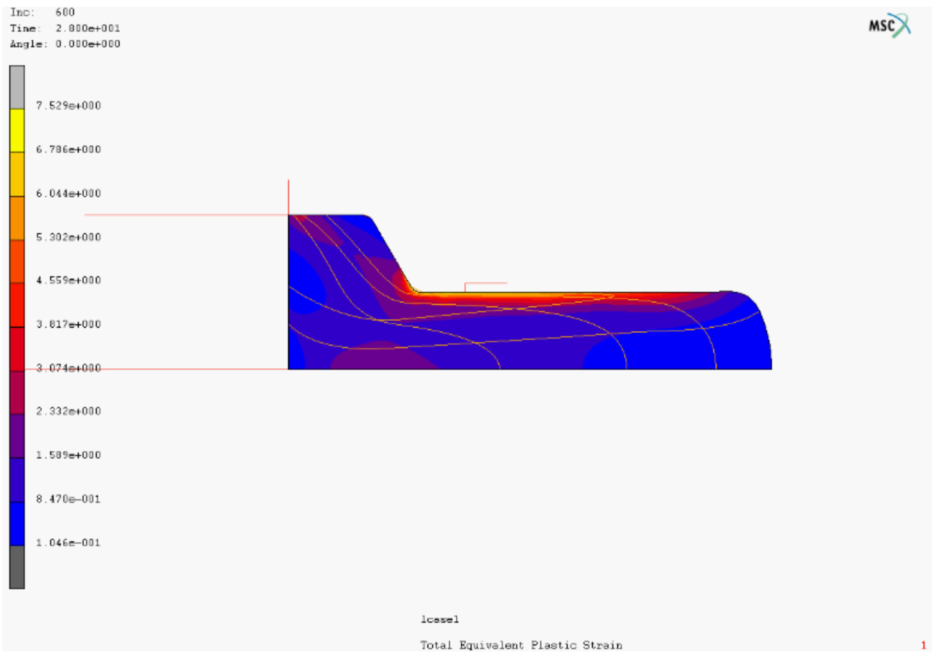


Fig. 8 – Deformation flow pattern for different die angle: a) 60º; b) 70º; c) 80º; d) 90º.

A numerical simulation of the extrusion process was performed using the finite element software. The two dimensional CAD model was meshed and material properties and boundary conditions were added. Stress–strain data for the lead alloy was obtained from torsion tests results presented in Figure 4. Extrusion force, effective stress, strain and material flow patterns are presented in Figures 9 and 10 for different process conditions. The magnitude of the extrusion force obtained from the FE simulation was compared to experimental values.





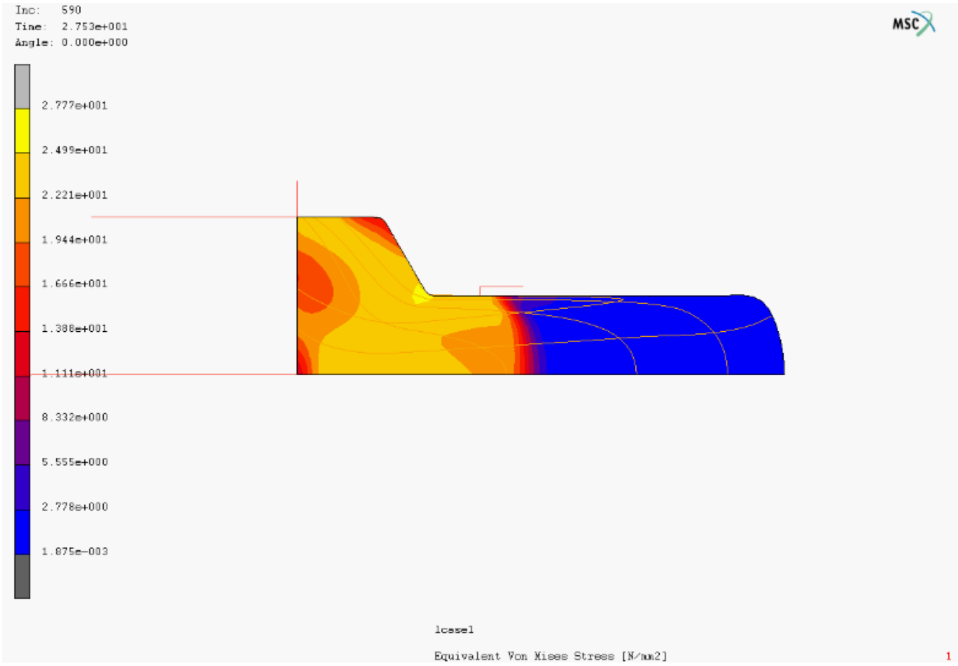
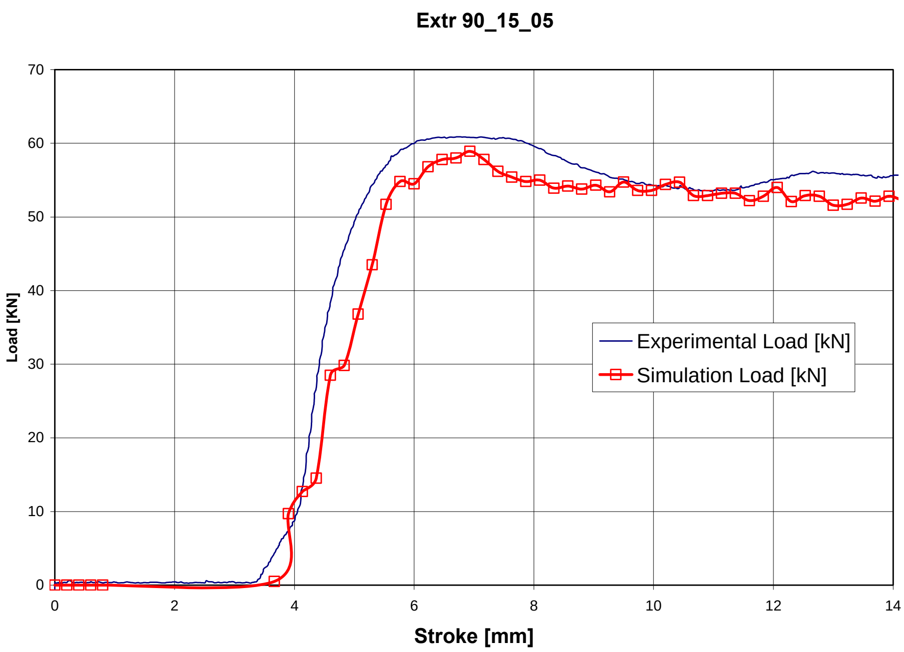


Fig. 9 – Distribution of process parameters for die angle 60º, area reduction 17%, ram speed 5 mm/s



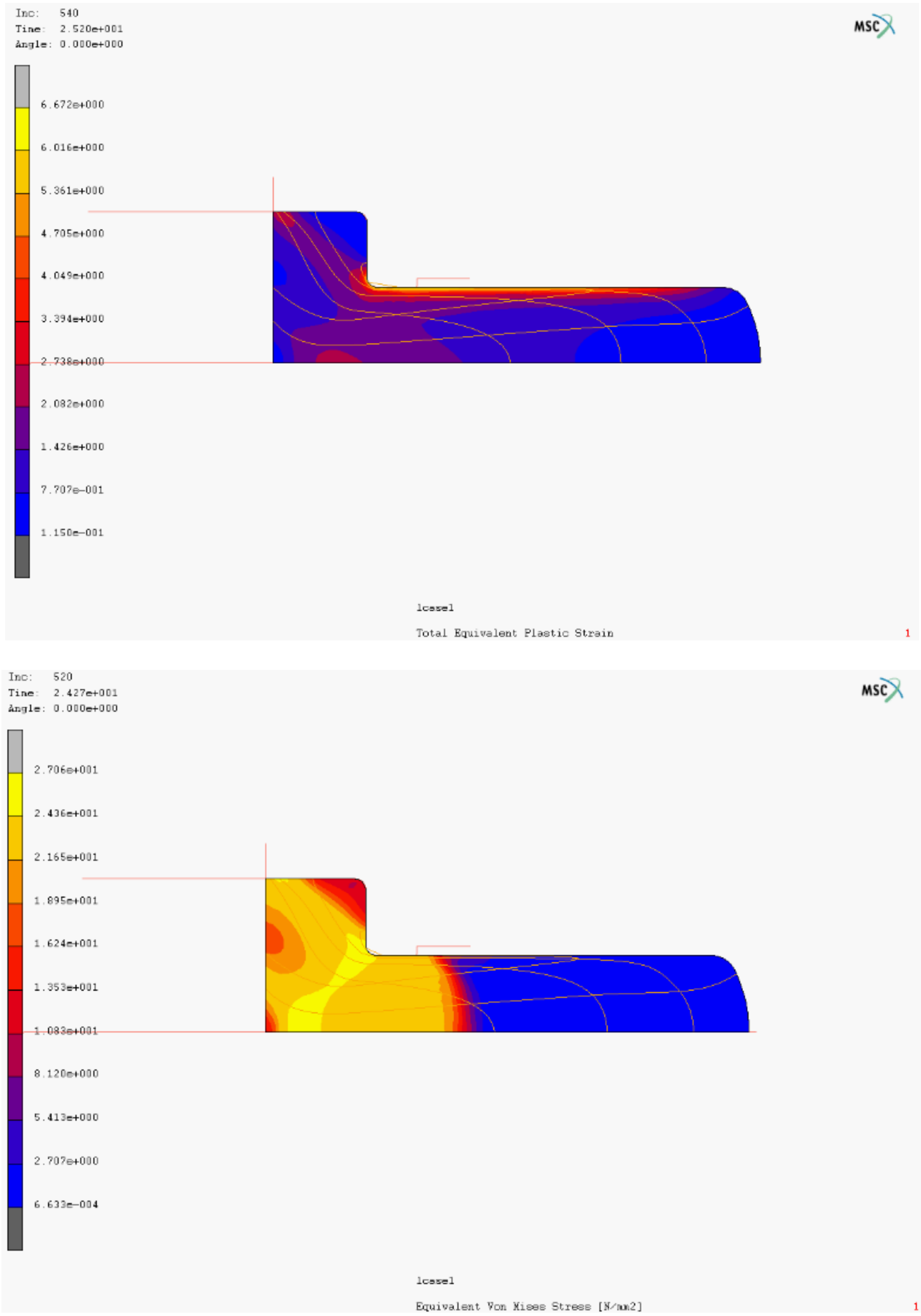


Fig. 10 – Distribution of process parameters for die angle 90º, area reduction 17%, ram speed 5 mm/s

5. DISCUSSIONS

Figure 4 shows the true stress–strain curve, named the flow curve that gives the stress required to cause the metal flow plastically. In case of lead alloy the stain rate has an important influence on true stress.

Figures 5, 6, 7 presents the experimental results obtained for extrusion load versus displacement for different process conditions. The curves indicate the three stages of extrusion: compression, steady and unsteady stages. Figure 5 shows that by increasing the die land diameter from 12 mm to 20 mm (decreasing the reduction of area from 26% to 13%) the extrusion load decrease.

The results indicate that as the die angle is reduced to 60º, larger extrusion forces are required to extrude lead alloy (Fig. 6). This is due to the increased contact length between the die and the work piece leading to high friction power losses. The aim of future research is to establish an optimum die angle for the process.

Experimental results shows that ram speed has a significant influence on the extrusion load, which continuously changes throughout the process as is shown in Figure 7. The higher value of extrusion load to a ram speed of 4 mm/s can be explained as a result of the important influence that strain rate has on flow stress (Fig. 4). An important aspect is the temperature inhomogeneity on the cross-section of the workpiece that is more pronounced when ram speed is higher. The thermal effects result in characteristic variation of extrusion load. At a lower ram speed, the decrease of extrusion load is faster during the steady-state extrusion, due to more heat generation (heat generation due to deformation, heat generation due to friction and shear at the billet–die interfaces, heat generation due to friction at the extrudate–die interface), and thus decreased flow stress, as the process proceeds.

The material flow pattern is influenced by local friction conditions and die geometric shape. These aspects influenced the size of the dead zone in the material as is shown in Figure 8. In these flow patterns of the extruded lead at 90º die angle, the boundary of the dead l zone is clearly visible, as zones of intense shear. Due to friction forces between work piece and die and, the material on the inside tends to move faster than the outside.

For a die angle of 90º, nonuniform material flow is due to high friction. By reducing the die angle to 60º the deformation in the section is more uniform.

The magnitude of the extrusion force obtained from the FE simulation was compared to experimental values and as is shown in Figures 9 and 10 were in good agreement. In order to determine the deformation parameters (effective stress and strain) in finite element analysis were used the values from flow curve (Fig. 4).

The maximum level of effective von Mises stresses occurs in the work piece at the exits of the die.

The differences between the FEA and experimental results can be attributed to frictional and deformation heating of the extruded material, unstable die–billet interface conditions and measurement errors.

6. CONCLUSIONS

A successful experimental programme of cold extrusion of lead alloy was carried out. Material flow curve and extrusion forces for different process parameters were determined. The finite element results show good correlation with experimental ones, confirming the accuracy of the finite element model.

The process parameters including die geometry and ram speed has an important influence on material flow during the deformation. The material flow affects the product quality (structure and properties) and the extrusion load. In order to limit the friction force, die and ram has to be designed with appropriate dimensions.

Ram speed affects the amount of heat generation and also the amount of heat loss to the extrusion tooling and thus has a major influence on the temperature values in the remaining billet and temperature distributions. These aspects will be the subject of future research.

Received on: January 18, 2012

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