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ABSTRACT

Plastic flow during equal-channel angular pressing (ECAP) of a copper billet is analyzed in this paper using three-dimensional finite element. The influence of the outer die radius and friction coefficient on the homogeneity in the accumulated plastic strain distribution is investigated. An increase in either outer radius or friction conditions was found to decrease the size of the steady-state region and increase heterogeneity in the final strain distribution from top to bottom and from side to side.

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THREE DIMENSIONAL MODELING OF PLASTIC DEFORMATION FLOW DURING ECAP

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Abstract

Plastic flow during equal-channel angular pressing (ECAP) of a copper billet is analyzed in this paper using three-dimensional finite element. The influence of the outer die radius and friction coefficient on the homogeneity in the accumulated plastic strain distribution is investigated. An increase in either outer radius or friction conditions was found to decrease the size of the steady-state region and increase heterogeneity in the final strain distribution from top to bottom and from side to side.

Keywords: Three-dimensional FEM, ECAP, punch force, die friction, die geometry

Introduction

Recent investigations have clearly demonstrated the great potential of the severe plastic deformation (SPD) methods, particularly by means of equal-channel angular pressing (ECAP), for ultra-fine grain refinement in various metals and alloys. One of the biggest challenges faced is the fabrication of larger and larger bulk ECAP samples with a uniform desired microstructure, e.g. equiaxed ultra-fine grains, and hence outstanding mechanical properties characteristic of such SPD materials. The degree of homogeneity depends on a myriad of processing and material variables [1].

Numerical methods, such as finite elements (FE), have been an important tool in simulating the ECAP process and exploring the large ECAP parameter space, such as the pressing route and number of passes, die channel intersection angle, outer radius of the die, friction coefficient, pressing rate, material deformation response, and backpressure, e.g., [2]. Studying the effects of several factors simultaneously, however, can potentially lead to ambiguous conclusions about the regularities in the plastic flow, regularities in the material fill status, or the final distributions of accumulated total plastic strain. Thus more systematic studies using FE coupled with theoretical considerations are needed. Also, most of the FE studies [3] found in the literature are two-dimensional analyses, and therefore cannot make conclusions regarding the influence of the confined character of plastic deformation on plastic flow in ECAP.

In this work, we present preliminary results using a three dimensional (3D) FE code for simulating ECAP. The influence of the outer die radius and friction coefficient on the accumulated plastic strain in a single ECAP pass of pure Cu (99.9%) is investigated. Special attention is paid to the heterogeneity in strain along the billet length, from top to bottom, and side to side. We will also compare the simulated punch force vs displacement curve with the experimental curve to access the accuracy of the material and friction models.

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Modeling Methodology

Material Model

An elastic-viscoplastic model was used for the material deformation response. Figure 1 shows the model fit to the experimental tensile stress-strain curve at room temperature. As shown in Fig. 1, it was necessary for the model curve to extend beyond the strain range of the experimental curve. It was assumed that the material response saturated after 50% strain. For the copper material, the Young's modulus $E = 0.8\times10^5$ Mpa, Poisson's ratio $\nu = 0.34$, and the tensile yield strength $\sigma_{0.2} = 100$ MPa. For the viscoplastic component of material response, the following isotropic hardening model for flow stress, σ_y, was used [4].

$$\sigma_y = A(\varepsilon_0 + \bar{\varepsilon})^m + B\dot{\bar{\varepsilon}}^n \tag{1}$$

where $\bar{\varepsilon}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}$ is the equivalent plastic deformation rate, $\varepsilon_0 = (\sigma/A)^{(1/m-1)}$, m is the strain hardening coefficient, n is the strain rate sensitivity, and A, B are material constants.

The distribution of the accumulated plastic strain ε_i^p at a given time in the process was calculated using the following formula:

$$\varepsilon_i^p = \int \left(2/3 \cdot \dot{\varepsilon}_{kj}^p \cdot \dot{\varepsilon}_{kj}^p\right)^{1/2} dt \ , \tag{2}$$

where $\dot{\varepsilon}_{kj}^p$ is the deviator part of the strain rate tensor. Calculation of ε_i^p was performed at each node and updated at each time in the process.

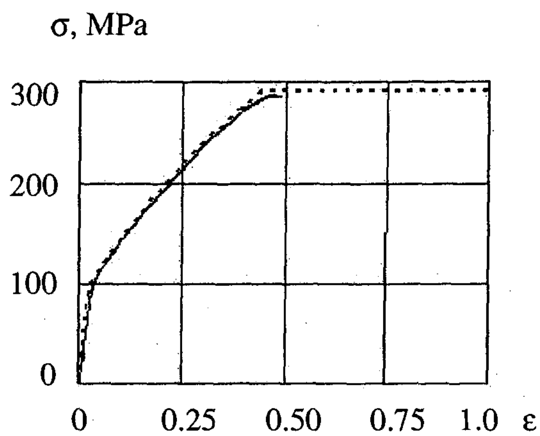


Figure. 1. Tensile stress-strain experimental curve (—) and model curve used in the calculations (- - -) at T=20 °C; and displacement rate V=6 mm/sec.

Finite Element Modeling

Finite element modeling (3D FEM) of the ECAP process was performed using SuperForm [4]. The use of this application in modeling deformation processes is wide-spread. In the FE model, as well as in the actual laboratory process, the die angle Φ was 90° and the width of the inlet and outlet square cross-section channels was 8 mm, and the length was 60 mm. The inner radius was 0.5 mm. Two absolutely hard surfaces, which form upper and lower walls of the channel, were chosen as boundary conditions. The model assumed symmetry about the x-y plane of the die (See Fig. 2). Pressure was applied to the upper part of the billet and the rate of the punch travel was 6 mm/s. In the experiment, a hydraulic press with a maximum force $P_{max} = 100.0$ kN was chosen to apply the effort. The length of the billet is 60 mm.

The FE model also considered the effects of friction between the material and die surfaces. The following model for Coulomb friction was applied [4]:

$$\sigma_{tr} \le f\sigma_n \frac{2}{\pi}\operatorname{arctg}\left(\frac{v_r}{v_0}\right), \tag{3}$$

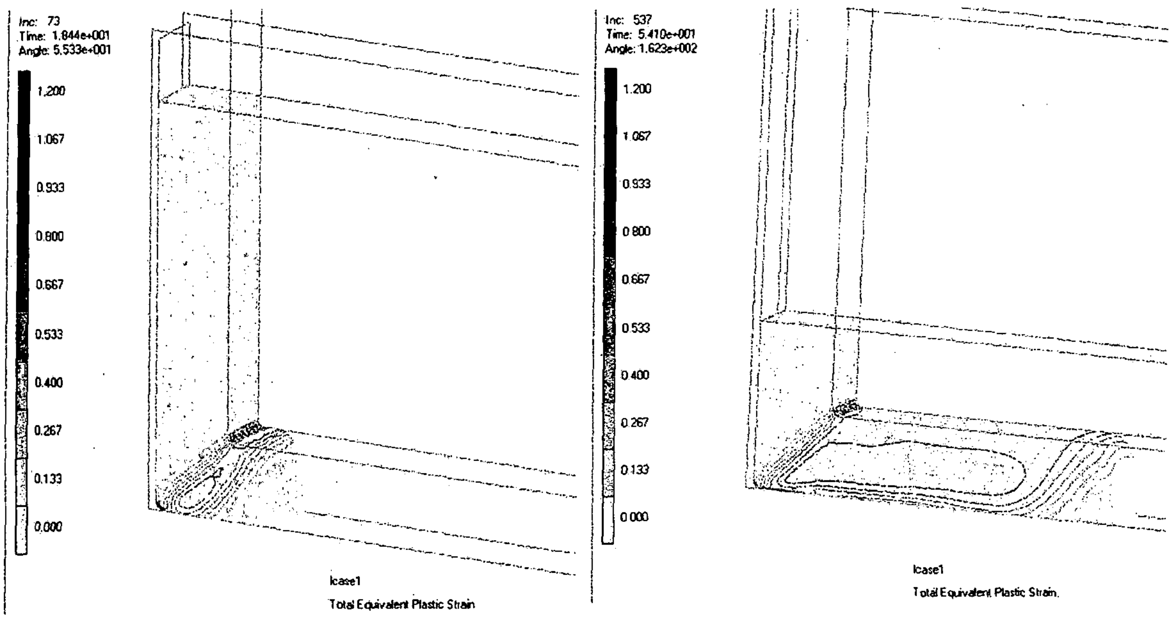
where f is the friction coefficient; σ_{tr} is the tangential (friction) stress; σ_n is the normal contact pressure, v_r is the slip rate, and v_0 is the value of the slip rate when sliding occurs. The FE analysis was conducted for two different values of the outer radius of the die r, $r = 0.5$ mm and

4 mm, and two different values of f, $f = 0.01$ and 0.12. The former coefficient represents nearly frictionless conditions, while 0.12 is a typical value for graphite lubricant.

Analysis of the Results

Influence of outer radius r

First, the influence of r is considered. In this case, the process of the plastic material flow is analyzed at two different stages during billet extrusion through the die-set. Figures 2 and 3 show the distribution of the accumulated plastic strain fields under nearly frictionless conditions, $f = 0.01$, for $r = 0.5$ mm and 4 mm, respectively. In Fig. 3, the appearance of a sharp outer corner may be deceiving so the outline of the non-zero outer radius is shown by cross-hatching. Figures 2a and 3a show the deformation near the beginning of the extrusion, which involves the formation of a non-uniform head end. Figures 2b and 3b, at the end of the extrusion, show that a steady-state region forms behind the head end. Comparing the two figures shows that r significantly alters the strain distribution in the steady-state region and the size of this region, whereas the size of the non-uniformly deformed head end is similar in the two cases. As r increases from 0.5 mm to 4 mm, the steady state region reduces by approximately 23-35%. Also, comparing the frequency of the isolines in Figs. 2 and 3 suggests that variation in strain from the top to bottom surfaces within this region increases with r. A larger bottom region of relatively lower intensity forms for $r = 4$ mm than for $r = 0.5$. Consequently, the maximum accumulated plastic strain across the billet, ε^{p}_{max}, decreases are r increases, being ~1.2 for $r = 0.5$ mm and ~1.0 for $r = 4$ mm. In contrast, there is negligible variation in strain from the front face to the back face in both cases.



a b

Figure. 2. Distribution of constant levels of accumulated plastic strain in the deforming Cu billet in the beginning (a) and in the end of the first pass of ECAP (b) for $r = 0.5$ mm, $f = 0.01$.

Influence of friction

Figure 4 shows the plastic strain distribution for $r = 0.5$ and $f = 0.12$ near the end of the first pass. Comparing Figs. 2b and 4 allows evaluation of the influence of the friction coefficient f on the material plastic flow characteristics. It is revealed that alongside with the growth of the friction coefficient, there is a substantial decrease in the steady-state region, being approximately 30% of the billet width. The non-uniformly deformed head end is similar in size to the other cases studied. Also, not surprisingly due to strain hardening in the material, a corner gap is formed for $f = 0.01$ (Fig. 2b), but is reduced for $f = 0.12$. In general, the higher the strain hardening coefficient, the larger the corner gap between the die and billet. For the same material response, this corner gap reduces as r or f increases.

Comparing Fig. 2b and 4 also shows an increase in the heterogeneity of plastic strain distribution with friction. Despite the sharp corner angle, $r = 0.5$ mm, and the reduction in corner gap for $f = 0.12$, there is an increase in the variation of plastic strain from top to bottom and formation of a bottom region of low intensity deformation with increase in f. In addition, unlike the frictionless case, there is side-to-side variation in strain for $f = 0.12$. Also, the maximum strain ε^{p}_{max}, decreases with f. For $f = 0.12$ and $r = 0.5$ mm ε^{p}_{max} reaches 0.96 compared to 1.2 for $f = 0.01$ and $r = 0.5$ mm. Likewise (though not shown), for $f = 0.12$ and $r = 4.0$ mm, ε^{p}_{max} is 0.85, lower than ~1.0 for $f = 0.01$ and $r = 4.0$ mm.

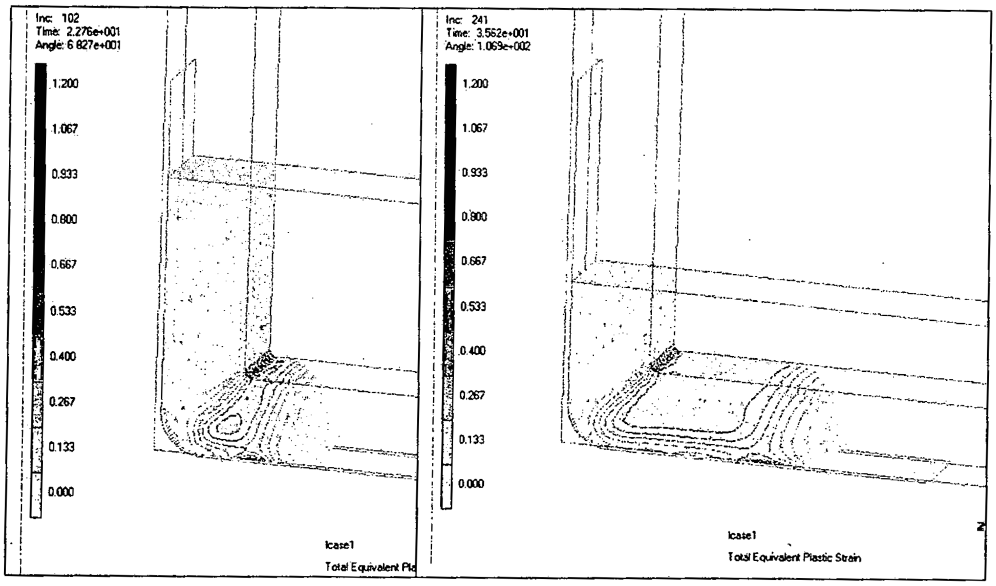


Figure. 3. Distribution of constant levels of accumulated plastic strains in the beginning (a) and in the end (b) of the ECAP pass for $r = 4$ mm, $f = 0.01$. The outer boundary radius is shown by cross-hatching, not by the visible sharp outer corner shown to emphasize the roundness of the actual outer corner.

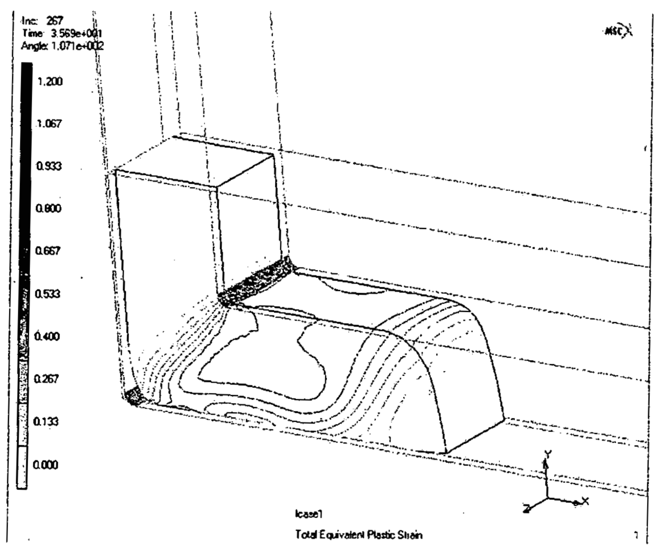


Figure. 4. Distribution of constant levels of the equivalent plastic deformation ε^{pl} in the deforming Cu billet with friction coefficient value $f = 0.12$ for outer radius $r = 0.5$ mm.

Evaluation of heterogeneity of the plastic deformation distribution

It is established that deformation during single pass ECAP is inhomogeneous. One may observe three typical zones in the vicinity of the deformed billet. Two zones, located on the tail and head ends of the billet, have a size, corresponding to its thickness. They are characterized by a significantly greater heterogeneity in accumulated strains. In the region between the head and tail end lies the steady state zone where the degree of homogeneity is higher. However, even within this steady state zone, particularly when friction is present, the strains at the contact surfaces can still differ substantially from the central portion. For instance on the top and bottom surfaces of this zone the strain values approximately differ by 30 % from the values in the central part.

Evaluating the non-uniform character of the accumulated strain distribution requires introducing a quantitative criterion. Perhaps the simplest way to quantify heterogeneity is with the ratio of the maximal value of the accumulated strain to its mean value (see Fig. 5a) with a value of unity representing homogeneous deformation. Such an evaluation can be performed along separate directions (lines), sections (squares), as well as in volumes. For instance, for $r = 0.05$, this 'heterogeneity ratio' is 1.33 for $f = 0.01$ and 1.39 for $f = 0.12$.

In this section, we take a closer look at the heterogeneity in the plastic strain deformation along the axis of the billet for $r = 4.0$ and $f = 0.01$. Figure 5a shows the variation in accumulated plastic strain ε_i^p in Eqn (2) along the billet axis at three different locations. Profiles of accumulated plastic strain in Fig. 5a correspond to the lines, located at a distance of 1.0 mm from the sample bottom and top surfaces (curves 1 and 3, respectively), and along the central billet axis (curve 2), as illustrated in Fig. 5b. These profiles expose the significant variation in strain along the length of the billet. If one defines the length of the uniformly deformed region by the concomitant uniformity in strain along all three locations, then for this case, it would be ~10 mm (from ~25 mm to ~35 mm in Fig. 5a), substantially shorter than the length of the billet 60 mm. Yet, curve 3 shows that within this uniform length, the strain is still much lower at the top than in the center and bottom.

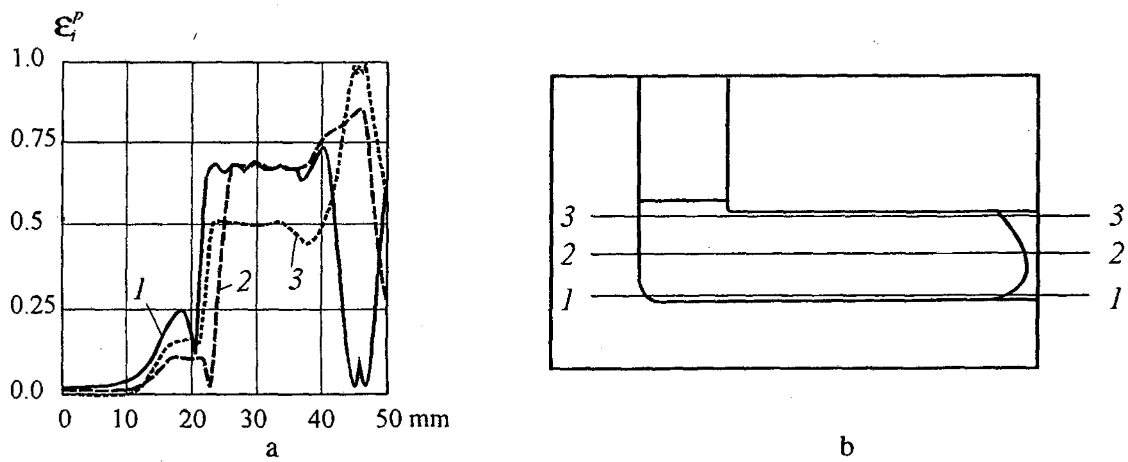


Figure. 5. a - The change of the accumulated strain (3D FEM) ε_i^p along the axis of the billet in the middle section of the billet: *1* and *3* correspond to lines, located at a distance of 1 mm from the surface of the sample; *2* – corresponds to the central axis line; b - curves 1, 2, 3 correspond to sections 1-1, 2-2, 3-3 accordingly.

Along the billet central axis (curve 2), the heterogeneity ratio changes from 1.9 at the head end to 1.1 at the tail end. The variation in deformation is more significant when traveling across the billet width (top to bottom), changing, for instance, from 1.68 at the location of curve 1 to 2.38 at the location of curve 2.

Analysis of the punch force on the tool

Punch force was determined by integrating the nodal reactions along the upper section of the billet. The evolution of the punch force with ram displacement will depend on the deformation response of the billet, die geometry such as the outer radius *r*, and friction conditions.

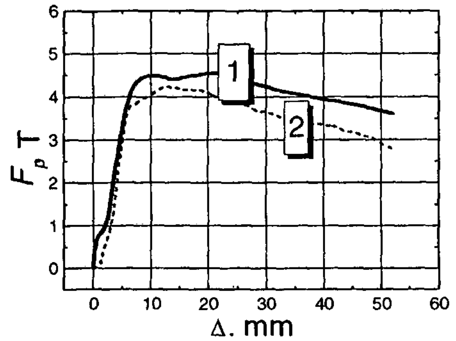


Figure. 6. Experimental (1) and FEM calculated (2) curves of the punch effort change depending on its travel in the process of ECAP.

Fig. 6 compares the evolution of the punch force with billet displacement as calculated by 3D FE model (f=0.12; r=0.5 mm) and as measured, both using the same material and die. As shown, the FE calculation underestimates the experimentally measured punch force. We suspect that the discrepancy is due either to the inadequacy in the friction model (3) or in the extrapolation of material response beyond the experimental curve, See Fig. 1.

Discussion and Conclusion

An analysis of material plastic flow of a copper billet during ECAP was conducted with the use of a 3D FE model. Consideration of the out of plane constraint on plastic deformations using 3D FE allows for more representative simulations of the ECAP process. Though not shown here, the absolute value of the accumulated plastic deformations at 3D FEM can differ from 2D FEM by 20-30%.

The influence of the outer radius *r* and friction coefficient *f* on the degree of inhomgeneity in plastic flow was explored using this 3D FE model. The highest degree of homogeneity and the largest steady-state region were achieved under nearly frictionless conditions and a small outer radius, $r = 0.5$ mm. The smallest steady state region, approximately half the length of the best case, developed in the case of a higher friction coefficient $f = 0.12$ and a more rounded outer radius $r = 4$ mm. Increasing the outer radius leads to an increase in the heterogeneity in plastic strain from top to bottom and decrease in the size of the steady state region, but with little variation from the front to back faces. Friction was found to further increase the heterogeneity in the plastic strains across the billet from the top to bottom surfaces and generate additional variation from the front to back faces. It is also revealed that growth of heterogeneity of plastic deformation is accompanied with a simultaneous decrease in the maximum values of plastic strain.

Acknowledgements

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