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FINITE ELEMENT ANALYSIS OF EQUAL CHANNEL ANGULAR EXTRUSION (ECAE) PROCESS

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ABSTRACT

Equal channel angular extrusion (ECAE) is a severe plastic deformation (SPD) method for obtaining bulk nanostructured materials. The ECAE die consists of two equal channels that intersect at an angle, usually between 90^o and 135^o . In the present study, the plastic deformation behaviour of the material during the ECAE process with 120^o die was investigated. Finite element modelling was included in order to analyse the deformation behaviuor as the material passes through the die. In order to perform the FEM simulations the physical properties of the commercial purity copper have been selected.

Keywords: Finite Element Analysis, Equal Channel Angular Extrusion, Copper.

1. INTRODUCTION

A severe plastic deformation technique called equal channel angular extrusion (ECAE), first developed by Segal in 1981 in the former Soviet Union [1, 2] is an innovative technique that allows the improvement of mechanical behaviour in materials by grain refinement. Novel properties like superplastic behaviour can be attained in some materials [3, 4]. In ECAE, the cross-sectional area of the workpiece is not modified, in contrast with traditional deformation methods. The ECAE method consists of two equal channels that intersect an angle, usually between 90 and 135°. A billet is then extruded through the channels, and the deformation is produced by simple shear, as the specimen crosses the shear plane. Repetitive passages through the dies are necessary and, since deformation is accumulative, it is possible to achieve high deformations in the specimen.

Different routes may be employed in order to process the material; Route A: in which the orientation of specimen remains unchanged in successive passages; Route B: in which the specimen is rotated 90° about its longitudinal axis, between consecutive passages; Route C: in which the specimen is rotated 180° about its longitudinal axis. Depending on the processing route, microstructural characteristics will differ from one route to another. The theoretical analysis of Segal states that for billets large enough and supposing idealized frictionless conditions, the material experiences simple shear producing a stationary plastic flow in the shear plane. The shear deformation is given by equation (1):

$$\gamma = \tan\chi = 2\cot\phi \tag{1}$$

. where $\chi$is the inclination angle of an element of distorted material in relation to the non-deformed element and ϕ the half angle between the extrusion channels.

The effective deformation per pass according to the Von Misses criterion is given by equation (2):

$$\varepsilon = \frac{2}{\sqrt{3}} \cot \phi \quad (2)$$

The ECAE process is influenced by several factors such as the pressing speed [5], normally between 10^{-2} and 10 mms^{-1}, and the friction conditions [6]. However, the former does not affect the final grain size. The adiabatic heating of an extruded specimen has been studied [7] and this heating is important for high pressing speeds and alloys with enhanced tensile strength. Friction conditions deeply affect the deformation region. Finite element modelling (FEM) [8–10] shows that high friction conditions and back pressure [11] assure a complete filling of the lower corner of the die providing a concentrated shear in a very narrow zone, so that the deformation is larger. On the other hand, low friction conditions carry out to a partial filling, creating a “dead zone” in the lower corner. Therefore, the deformation results in an arc and the specimen is bent rather than sheared.

2. EXPERIMENTAL PROCEDURE

The starting material was commercial purity copper (99.8 %) annealed at 700 ^{o}C for 2 hr. The samples were 108 mm in length with a cross section of 15x15 mm. The die was designed and fabricated with ϕ=120^{o} and ψ= 0. The ECAE process was performed on well lubricated (MoS_2) copper samples at a speed of approximately 50 mm/min at room temperature. The experiments were conducted using Route A, without rotation of the specimens between consecutive passes. Afterwards, specimens were cut in the extrusion axis direction (longitudinal) and transverse directions. Vickers microhardness was measured with a load of 3 kg applied for 15 seconds (hardness values are not shown here). Figure 1(a) shows the schematic diagram of equal channel angular extrusion and Figure 1(b) shows the flow curve of the copper used in the simulation.

3. FINITE ELEMENT MODELLING

Deformation behavior of the workpiece during ECAE was simulated using the commercial finite element analysis software ABAQUS/Standard. The die angles considered in this study were ϕ=120^{o} and ψ= 0, because these are the typical die angles adopted for the processes. The sample was meshed with four nodded first order plane strain continuum (CPE4R) element with reduced integration [12]. A two-dimensional problem was considered, since the process satisfies the plane-strain condition. Fillet radius of 2 mm was used at all sharp corners in experimental as well as in finite element simulations. In this present study the simulations were carried out at two different frictional conditions, μ = 0.08 (low friction) and μ = 0.15 (high friction). In order to develop the simulations a deformable billet was used, in which the properties for commercial purity copper (stress-strain relationship, $\sigma = 359\ \varepsilon^{0.3144}$) have been taken into account. The material properties like, Young’s modulus 69 GPa and Poisson’s ratio 0.34 are incorporated in the FEM simulation. Heat generated due to the plastic deformation was not considered. The die and punch were assumed as rigid bodies in the modeling. The displacement of 80 mm was given to the punch in extrusion direction.

4. RESULTS AND DISCUSSION

Figure 2(a) shows Von Mises stress distribution in the sample at 80% extrusion using low friction conditions. It can be observed that a complete filling of the die was not attained near the outer corner and there is no contact with the inner channel wall. In addition, there is a noticeable empty zone in the outer edge. Therefore, the corner is not filled at all during the process. The same simulation has been performed with considering of high friction condition and a good filling of the die was observed in Figure 2(b). As can be observed, deformations are very similar in the whole extruded material except in the zone of contact with the outer part of the die. As will be shown, the higher deformation values are attained near to the inner channel of the die. Figure 3(a) and Figure 3(b) shows the plastic equivalent strain plots for low friction and high friction conditions respectively. Here it can be observed that the filling of the die was not attained in low friction condition (Figure 3(a)). In high friction conditions good filling of die was observed (Figure 3(b)). For high friction conditions, FEM leads to a total filling of the outer edge.

Figure 4 shows the initial billet to study the deformation along the length of the billet. Five numbered nodes were marked onto the billet representing different locations in deformation [6]. The node 2 and node 4 represents the inner and outer edge of the billet respectively. Node 1 is top, node 3 in the middle and node 5 in the bottom of the billet. The purpose was to show an overall view of the material flow and confirm the results obtained using FEM. The selected positions as well as the frictional conditions will be critical factors in the effective strain.

Figures 5(a) and (b) shows the effective plastic strain versus time (min). Figure 5 (a) shows a noticeable effective plastic strain of 0.65 for low friction conditions. The effective strain of 0.66 appears as the maximum value with high friction conditions of μ=0.15. It can be observed that the FEM simulation and theoretically (the equivalent true strain imparted to the sample per pass is 0.67) calculated plastic strain values are similar. Luis et al. [6] have simulated ECAE with 120^o channel angle for very low friction (μ = 0.01) and high friction (μ = 0.14) conditions and have obtained similar results. However, μ = 0.01 is not a realistic value. Higher values of μ are usually prevalent during extrusion. Node 3 followed by node 2 undergoes the highest effective strain in low friction conditions. Node 4 achieved lowest strain because it is on the outer corner of the die. For this simulations node 1 has not entered deformation region and hence show practically zero strain. For high friction, the values of Nodes 2 and 3 are similar and the deformation becomes more homogeneous along the billet. Node 5 which is in bottom of the billet has an effective strain of about 0.5 and node 4 it is in outer edge of the billet has lowest strain of about 0.4. The variation in strains between node 4 and node 5 is more in high friction condition than in low friction conditions. However, slightly larger values are reached for the high friction condition.

Figure 6 shows a comparison between values obtained by FEM and experimental values for extrusion load. As can be observed, there is a considerable difference between low friction and high friction conditions. It can also be observed that the experimental values are closer to FEM models of the low friction conditions, as shown in Table 1.

5. CONCLUSIONS

A finite element analysis was carried out in order to investigate the plastic deformation behavior of the workpiece during the ECAE process. The experimental results were in good agreement with low friction condition of FEM simulation. Force verses displacement curves obtained with μ= 0.08 closely match experimentally recorded data. However low values of μ do not result in complete die filling at the outer corner of the die. The deformation across the billet is not homogeneous. The inner edge of the billet shows more strain than outer edge of the billet in both low and high friction conditions.

6. REFERENCES

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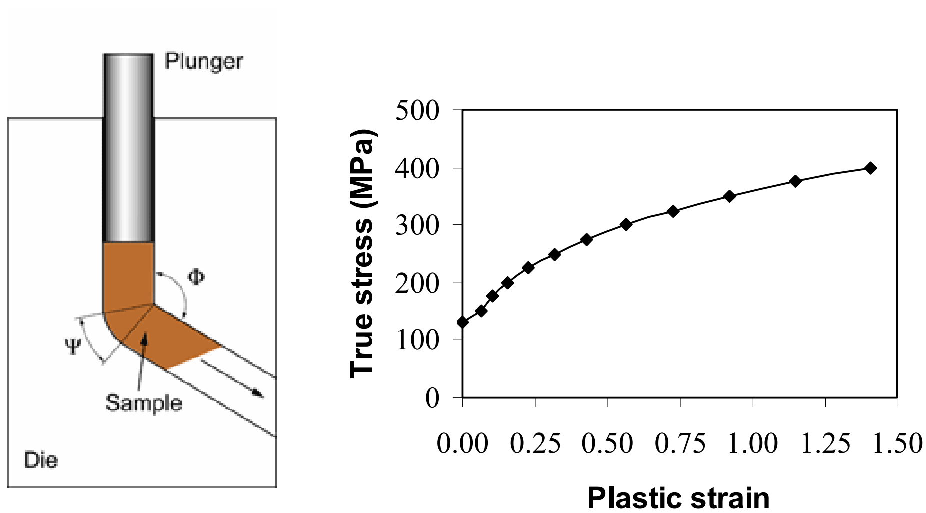
TABLES

Table1. Comparison of maximum extrusion pressures for ECAE.

Experimental (MPa)	FEM (MPa)	
	μ=0.08	μ=0.15
258	267	600

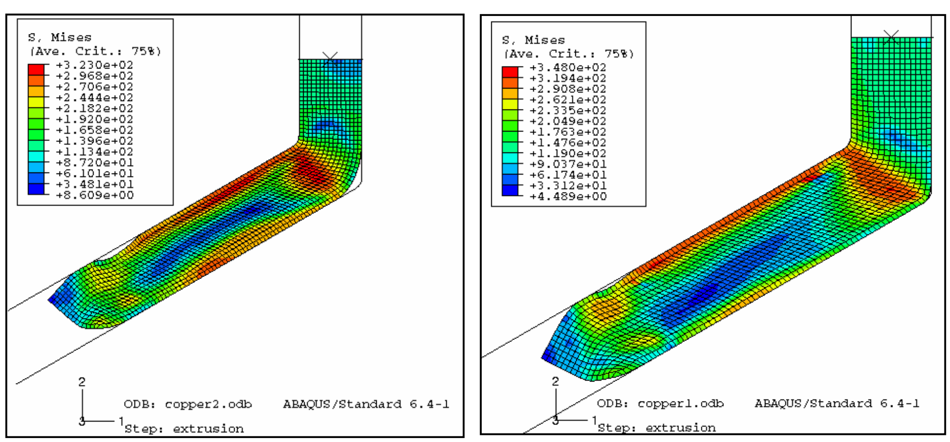
FIGURES



(a) **(b)**

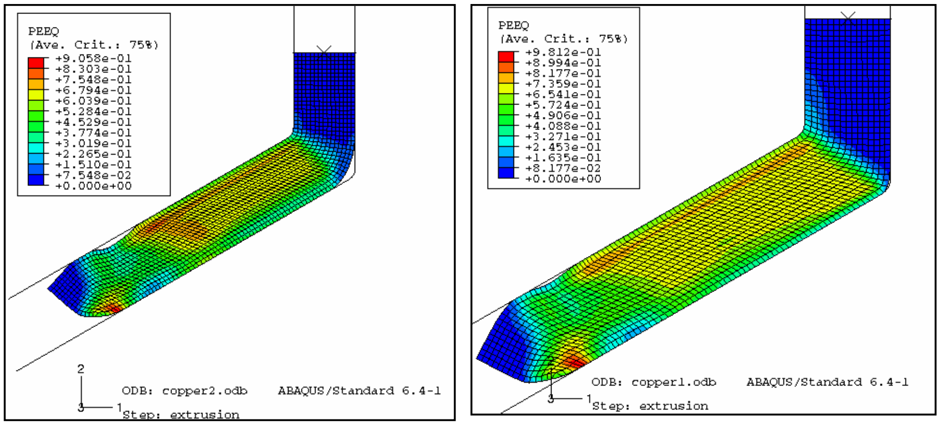
Figure 1 (a) Schematic diagram of equal channel angular extrusion (ECAE) process.

(b) Flow curve of the modelling material (copper) used in the FE simulation.



(a) **(b)**

'igure 2 Von Mises stress distribution of the samples simulated with $\phi = 120°$ and $\psi = 0°$
(a) Low friction condition (b) High friction condition.



(a) **(b)**

Figure 3 Plastic equivalent strain distribution of the samples simulated with $\phi = 120°$ and $\psi = 0°$ (a) Low friction condition (b) High friction condition.

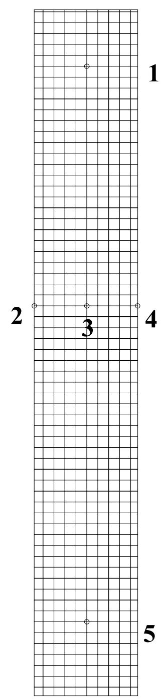
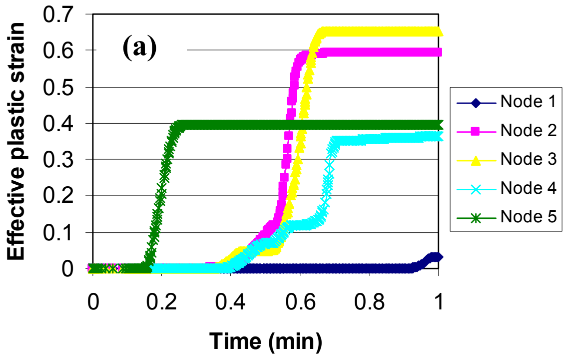


Fig. 4 Initial billet with the nodes of the study (node 1 is top and node 5 is bottom)



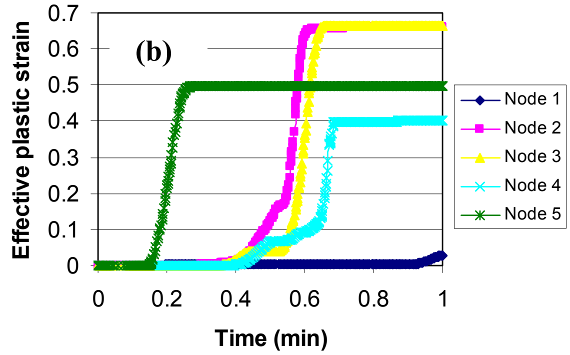


Figure 5 Effective plastic strain Vs deformation time (a) Low friction conditions (b) High friction conditions

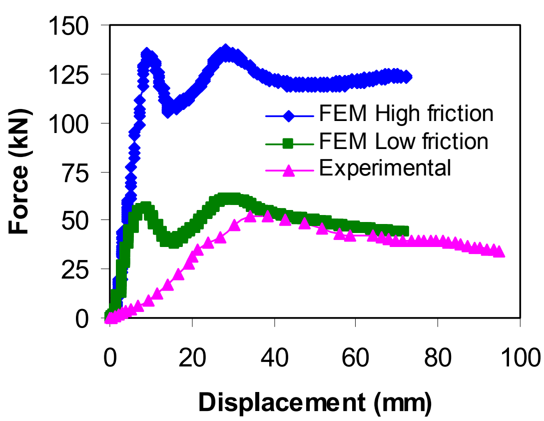


Figure 6 Force–displacement curves obtained during ECAE (experimental and finite element simulation with $\phi = 120°$ and $\psi = 0°$).