A THREE DIMENSIONAL FINITE ELEMENT ANALYSIS OF EQUAL CHANNEL ANGULAR EXTRUSION

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Abstract. *Several finite element based studies on Equal Channel Angular Extrusion (ECAE) have been conducted recently, most of them within a two-dimensional setting whereby the plane strain assumption is adopted. In this paper we present a three-dimensional finite element model to analyse a single ECAE pass of a pure aluminum billet of rectangular cross section. It is investigated the effects of contact friction and material response on the deformation behavior of the billet. In particular, the equivalent plastic strains in three orthogonal planes are obtained showing their heterogeneity. The numerical predictions compare well with analitical and experimental results, which validate the proposed model as tool to analyse ECAE*

Keywords*: ECAE, three dimensional finite elements, severe plastic deformation, ultrafine grained materials*

1. INTRODUCTION

It is now well established that ultrafine grained materials can be readily produced during processing by severe plastic deformation (SPD), whereby a very heavy plastic strain is imparted on a bulk solid in order to promote grain refinement down to the nanoscale. The success of a SPD technique in producing ultrafine grained materials depends on its ability to impart a very high and homogenous plastic deformation. These requirements are crucial for the formation of nanostrucures uniform within the volume, which is necessary for providing stable properties of the processed material (Valiev, Islamgaliev and Alexandrov, 2000).

Recently, equal-channel angular extrusion (ECAE), which was introduced by Segal and coworkers in the former Soviet Union, has emerged as one of the most promising among all SPD techniques. During ECAE, a billet is pressed in a closed die that has two channels of equal cross section intersecting at an internal angle Φ, with an additional angle Ψ representing the outer arc of curvature where the two channels intersect (Figure 1). The billet undergoes plastic deformation without substantial changes of its cross section which permits the process to be repeated as many times as necessary to achieve the desired amount of plastic strain. The plastic deformation takes place within a region in the intersection corner of the two channels called the plastic deformation zone (PDZ). The strain homogeneity obtained during ECAE depends on the characteristics of the PDZ, which are strongly influenced by processing parameters such as contact friction, channel geometry, billet shape and material response. A comprehensive review on ECAE is provided by Valiev and Langdon, 2006.

The influence of the processing parameters on the deformation behavior of the billet during ECAE has been the subject of analytical studies that are based on the slip line theory, where it is assumed that: the plastic flow is plane, uniform and steady; the material response is rigid perfectly plastic; friction is uniform (Segal (2003), Segal (2004)). Departure from these idealized conditions has led to the development of numerical studies, the majority of them based on two dimensional finite element analysis (Li et al (2004), Antunes et al (2006) and references cited therein), where it is assumed that the strain state is plane, although a 3D finite element analysis has been carried out recently (Suo et al

2006). The numerical studies were mainly concerned with the investigation of the influence of processing parameters on the strain level and heterogeneity as well as the working load in the course of a single pass ECAE.

In this paper we carry out a three dimensional finite element based study on ECAE in order to analyze the influence of contact friction and material response on the deformation behavior of a billet during a single pass ECAE. In particular, we investigate the influence of the aforementioned factors on the strain heterogeneity and working load versus displacement. It was considered a die with an intersection angle of Φ=140° and outer corner angle of Ψ=0° and a billet with rectangular cross section. The simulations included two material responses (elastically perfectly plastic and elastically strain hardening) and two friction conditions (frictionless and uniform friction).

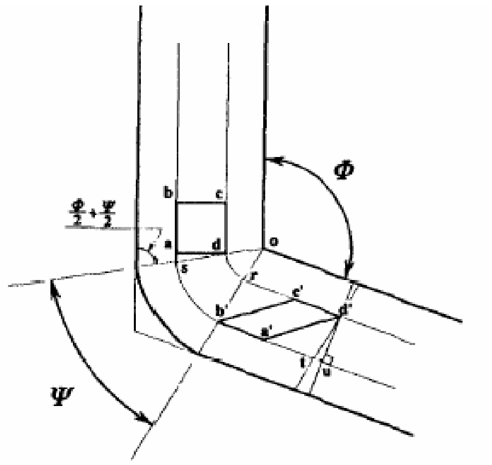

Figure 1. ECAE geometry (Iwahashi et al 1996)

2. THE 3D FINITE ELEMENT MODEL

The simulations of a single ECAE pass were carried out using the FE software ABAQUS (ABAQUS, 2006). It was considered a die with an intersection angle of Φ=140° and outer corner angle of Ψ=0°, and a billet with rectangular cross section with dimensions 12.8 x 12.5 x 60 mm. Both die and punch were considered rigid, whereas the billet material response was assumed to be either elastic perfectly plastic (PP) or elastic strain hardening plastic (SH). In both cases, the elastic properties were given by the Young's modulus E=70 GPa and by the Poisson's ratio ν=0.33, whereas the plastic responses are depicted in Figure 2. These properties were obtained from a tensile test of a commercially pure aluminum. The uniform friction conditions corresponding to μ=0 (frictionless) and μ=0.05, where μ is the friction coefficient, were adopted. A punch velocity of 55 mm/min was prescribed. Four simulations, labeled as indicated in Table 1, were carried using a mesh of 9600 elements of the type hexaedric along with automatic remeshing. The last simulation corresponds to the experimental situation described in Antunes et al (2006). Only one half of the billet was considered thanks to symmetry.

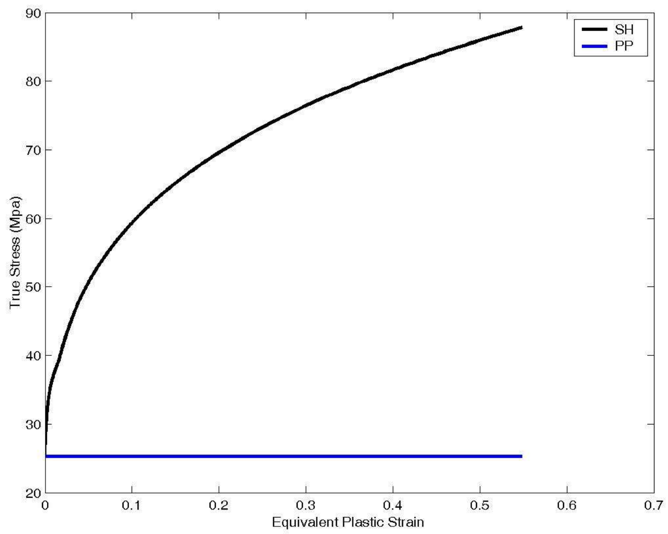

Figure 2. Stress strain diagrams adopted

Deformation behavior	Friction conditions	
	μ=0	μ=0.05
perfect plastic	PP0	PP1
strain hardening	SH0	SH1

Table 1. Identification of simulated conditions

2. RESULTS AND DISCUSSION

Equivalent plastic strain contours, on the middle plane parallel to the flow plane, during a single pass are shown in Figure 2, from where it can be seen three distinct deformation regions: tail, middle and head. In the middle region the equivalent plastic strain is higher as compared to the other regions, modulo a very small zone on the head corresponding to the initial contact region between the billet and the outer channel corner. Also, the deformation in the head region is very complex. The plastic deformation zone comprises a sharp region around the intersection only for the simulation PP0, otherwise it is diffuse. Because of the billet bending, there appear four gaps in all simulated cases. They are more pronounced for the SH hardening cases, whereas friction improves matrix filling. Both results are in qualitative agreement with the slip line analyses carried out by Segal (Segal, (2003)).

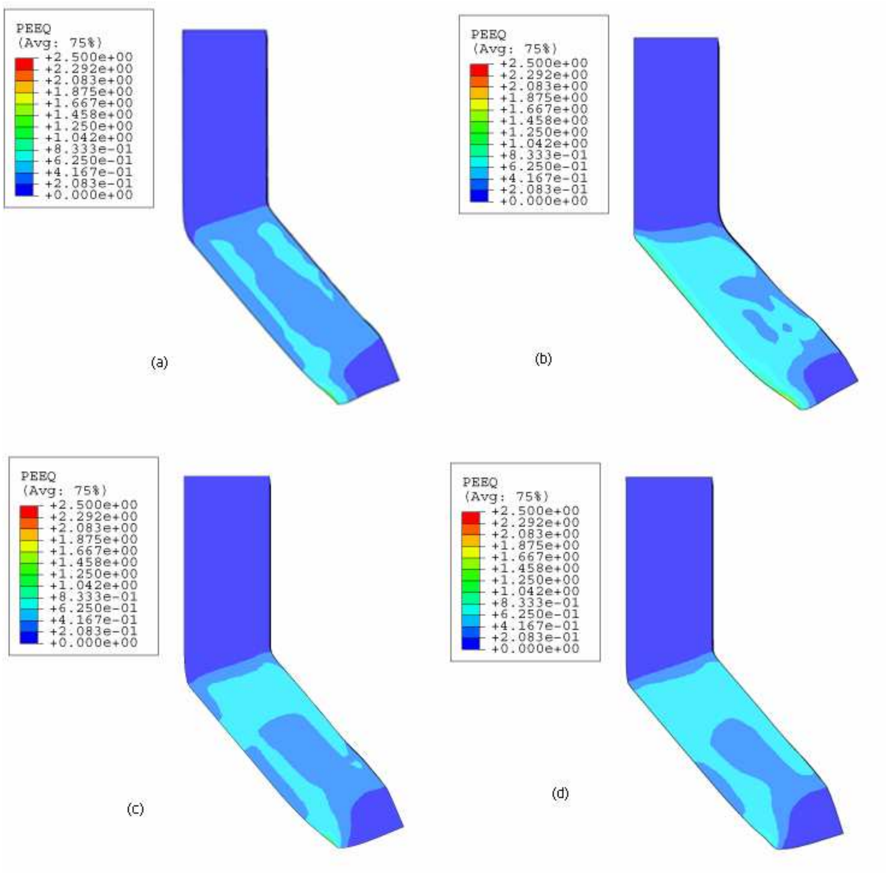

Figure 2. Equivalent plastic strain contours on the middle plane parallel to the flow plane: (a) PP0; (b) PP1; (c) SH0; (d) SH1

To analyze the homogeneity and the level of the equivalent plastic strain attained after the single ECAE pass we consider its representation on the undeformed configuration of billet, wherein it is introduced a cartesian coordinate system, the origin of which is located at the billet center of mass and the corresponding coordinate axes are defined by the longitudinal direction (X), the transverse direction normal to the flow plane (Y) and the direction orthogonal to both X and Y. Figures 3, 4 and 5 depict the equivalent plastic strain contours in the planes Y=0, Z=0 and X=0, respectively. For all the simulations, the plastic strain distributions are heterogeneous.

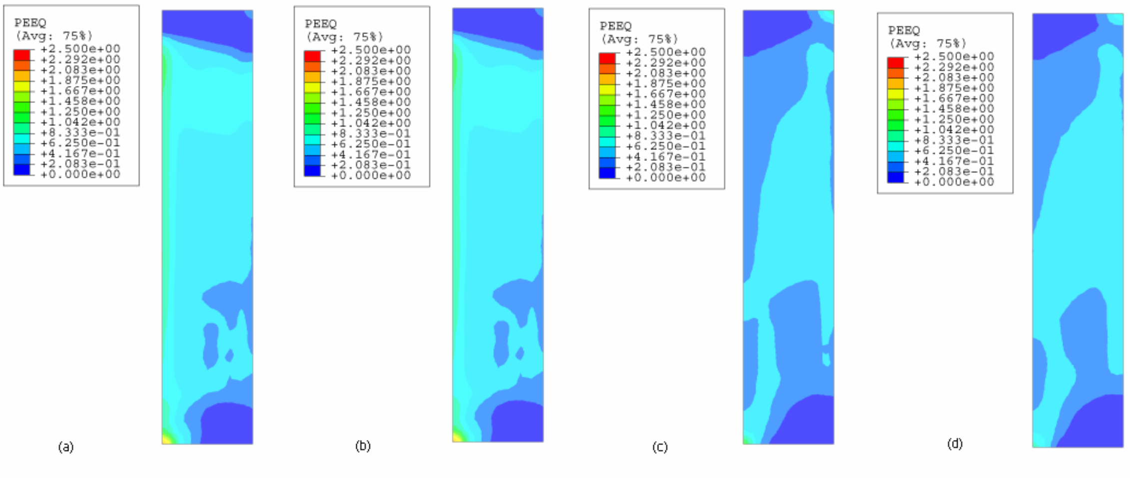

Figure 3. Plastic strain contours on the plane Y=0: (a) PP0; (b) PP1; (c) SH0; (d) SH1

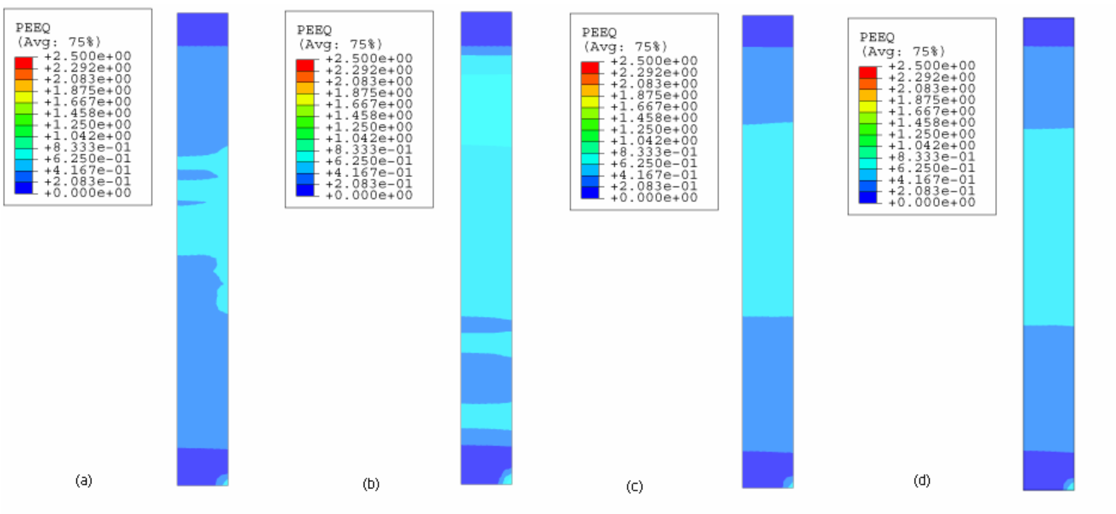

Figure 4. Plastic strain contours on the plane Z=0: (a) PP0; (b) PP1; (c) SH0; (d) SH1

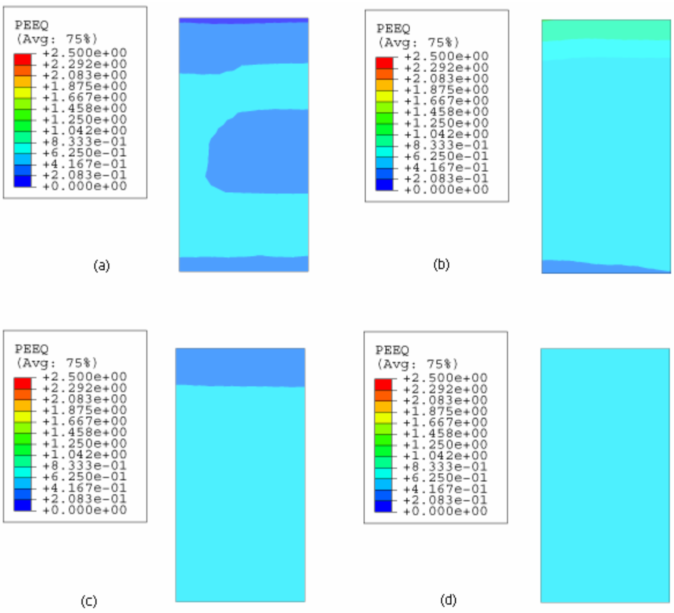

Figure 5. Plastic strain contours on the plane X=0: (a) PP0; (b) PP1; (c) SH0; (d) SH1

The plastic strain distributions along the directions X, Y and Z are depicted in Figure 6, on which the horizontal line represents the equivalent plastic strain for the rigid perfect plastic response according to Segal, (2003). In all simulated cases there exist three distinctive regions of the billet, the central and the outmost regions. For the simulation PP0, the plastic strain is homogenous in the central region and its value compares very well with the one predicted by using slip line theory (Segal, 2003).

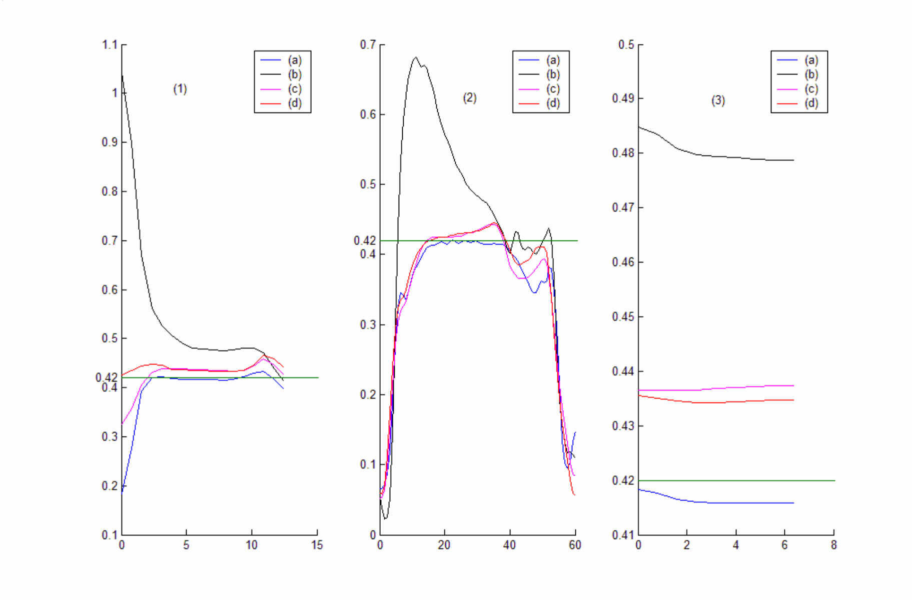

Figure 6. Plastic strain distributions along the directions X, Z and Y
(1) From the outer to the inner walls; (2) From the head to the tail; (3) From the top to the center

The Figure 7 shows the isometric of half billet after the single ECAE pass for the simulation SH1.

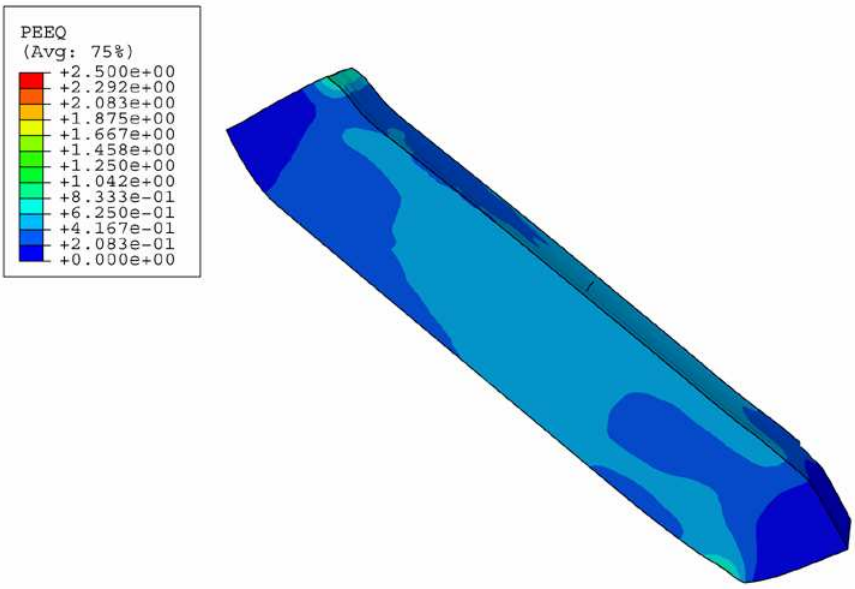

Figure 7. Isometric view of half-billet after a single ECAE pass

4. CONCLUSIONS

A three dimensional finite element model for a single ECAE pass of a pure aluminum billet of rectangular cross section for a die with an intersection angle of Φ=140° and outer corner angle of Ψ=0° by using the commercial software ABAQUS was presented in this paper. Four simulations were carried out including two material responses for the billet, elastically perfectly plastic (PP) and elastically strain hardening (SH), and two friction conditions (frictionless and uniform friction) for the billet/die interface. The die was considered rigid. The plastic strain homogeneity on three orthogonal planes after a single ECAE pass was investigated. The results predicted by the PP and SH simulations were in good agreement with analytical and experimental results, respectively, which validate the proposed three dimensional finite element model as tool to analyze Equal Channel Angular Extrusion.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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