A 2D FINITE ELEMENT MODEL FOR EQUAL CHANNEL ANGULAR EXTRUSION

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Abstract. *In this paper we present a two dimensional finite element model for the analysis of a single equal channel angular extrusion (ECAE) pass of a pure aluminum billet. It is examined the effects of contact friction and material response on both deformation behavior of the billet and working load. The numerical predictions are in good agreement with analitical and experimental results.*

Keywords: *ECAE, two 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. 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 two 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 ECAE pass. 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 (PP) and elastically strain hardening (SH), and two friction conditions (frictionless and uniform friction).

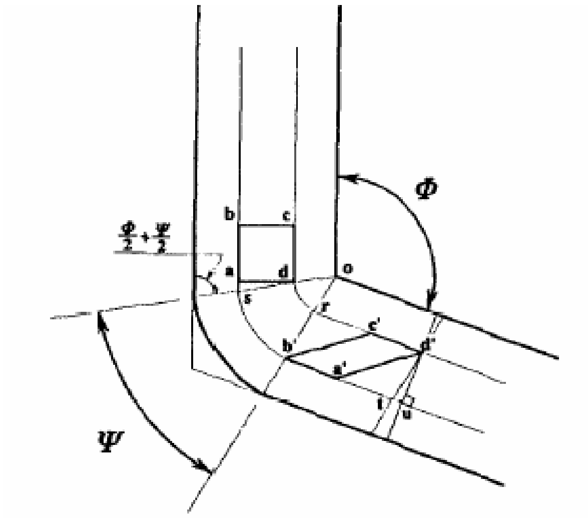

Figure 1. ECAE geometry (Iwahashi et al 1996)

2. THE 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. In all the simulations, a mesh of 6156 elements of the type CPE4R was used along with automatic remeshing.

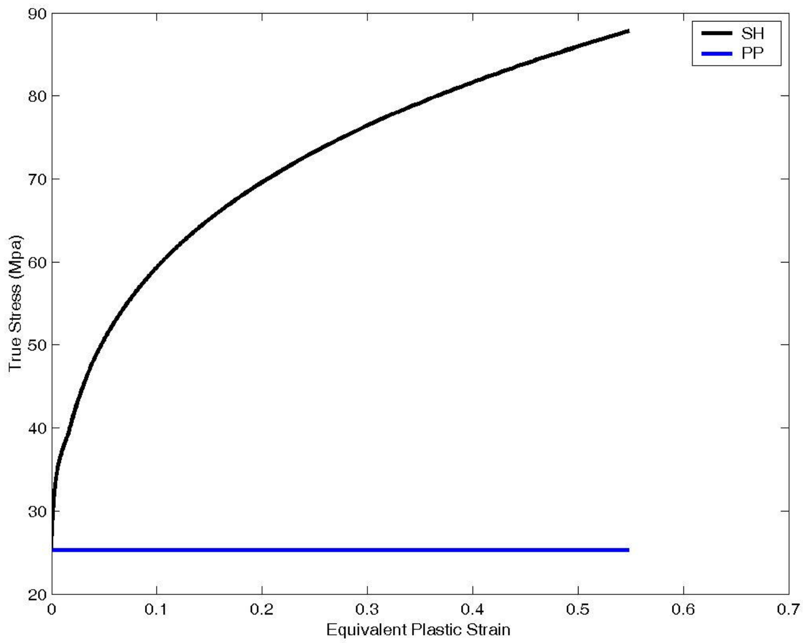

Figure 2. Flow curve of the strain hardening material

2. RESULTS AND DISCUSSION

The simulation results, labeled as indicated in Table 1, are depicted in the following figures. Equivalent plastic strains contours during a single pass are shown in Figure 3, from where it can be seen three distinct deformation regions: tail, middle and head. The deformation in the head region is very complex. In addition, the plastic deformation zone comprises a thin region around the intersection corner for the simulations PP0 and PP1. Because of the billet bending, there appear four gaps in all simulated cases. They are more pronounced for the simulations SH0 and SH1. It can be seen from the results for that friction enhances matrix filling.

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

Table 1. Identification of simulated conditions

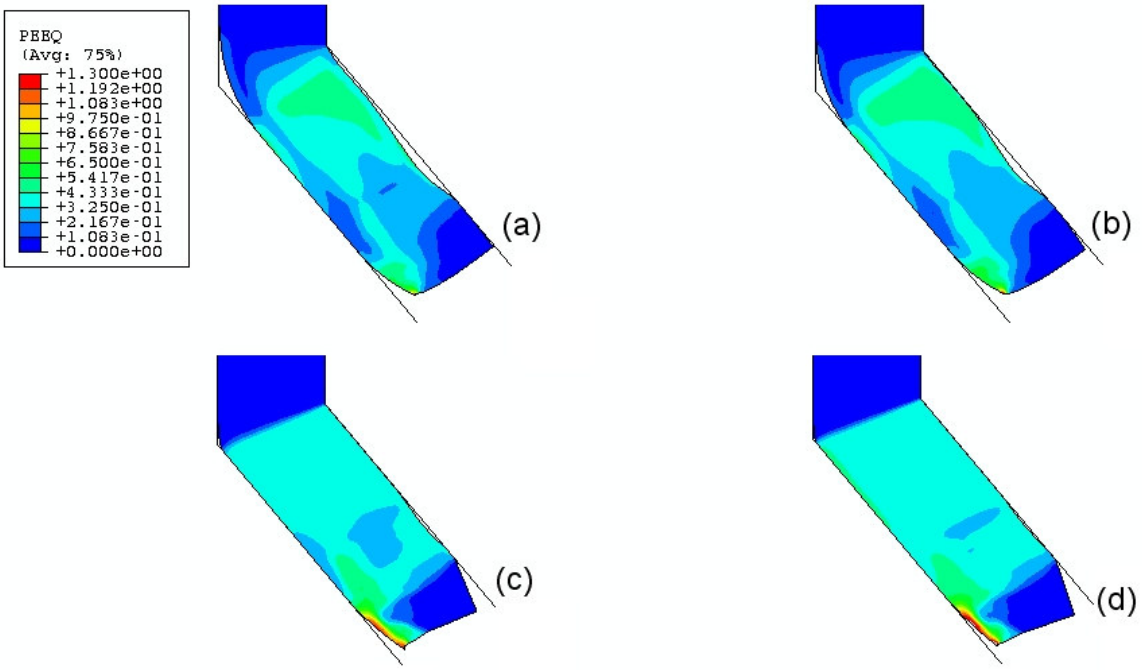

Figure 3. Equivalent plastic strain contours: (a) SH0 (b) SH1 (c) PP0; (d) PP1

In what follows, we address the issue of plastic strain homogeneity at the end of a single ECAE pass. Figures 4 and 5 depict the equivalent plastic strain contours in the undeformed and deformed configurations, respectively. They show that there exist three distinctive regions of the billet. In the central region, the strain distribution is homogeneous for the cases in which the plastic responses are perfect. In the other two outermost regions, encompassing the tail and the head, the corresponding strain distributions are highly heterogeneous mainly in the head region. The friction and strain hardening affect the plastic strain homogeneity in opposite way. The friction has a positive effect, whereas the strain hardening has a negative one, on the plastic strain homogeneity. Figure 6 shows the plastic strain distribution along the straight material line directed from the half width of the head to the half width of the tail. Again, it is shown that the plastic strains are highly heterogeneous near the billet head as well as near the tail. In addition, the central region in which the plastic strains can be considered homogeneous is large for the perfect plastic response in comparison with the strain hardening response. In their homogeneity regions, the plastic strains predicted are in good agreement with the estimative given in (Iwahashi et al, 1996). The friction coefficient chosen for the simulations does not have a significant influence on the results. Figure 7 depicts the plastic strain distribution along the straight material line crossing the billet from the half length of the outer inlet channel to the half length of the inner inlet channel. For each one of the simulated cases, there is a corresponding central region in which the plastic strain can be considered homogenous that is larger for the perfect plastic response and whose value compare well with the one obtained by Segal. The friction coefficient chosen for the simulations does not have a significant influence on the results. Figures 8 and 9 depicted both the predicted (SH0 and SH1) and experimental billet shapes after a single ECAE pass, showing that the simulated results compare very well with the experiment.

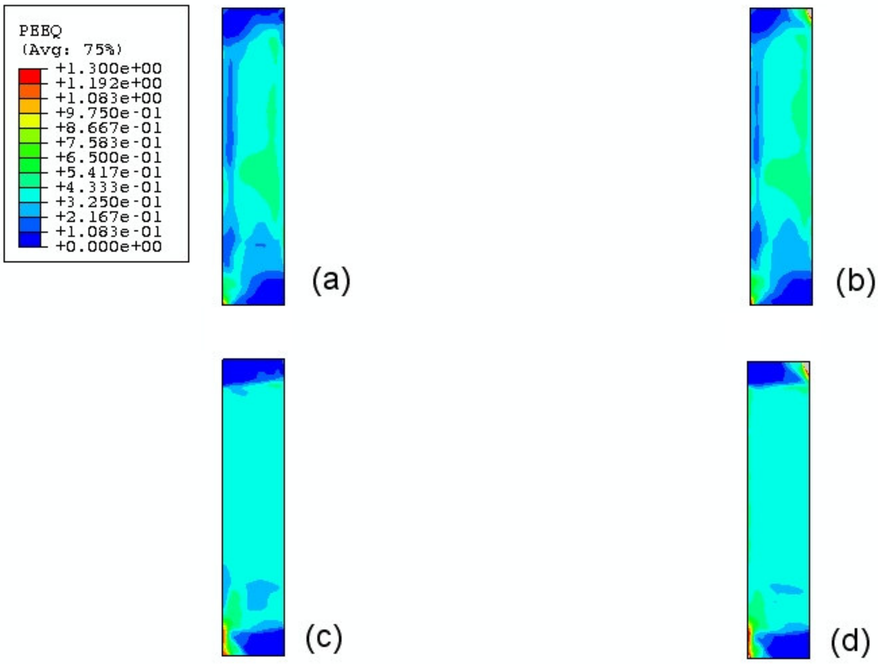

Figure 4. Plastic strain contours plotted on the undeformed configuration:
(a) SH0; (b) SH1; (c) PP0; (d) PP1

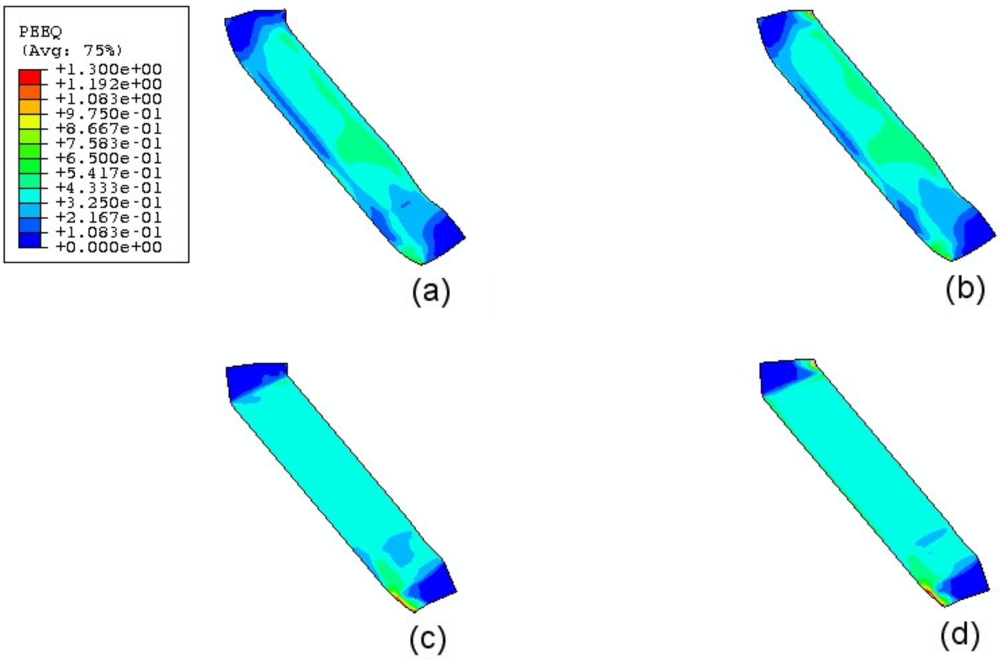

Figure 5. Plastic strain contours: (a) PP0; (b) PP1; (c) SH0; (d) SH1

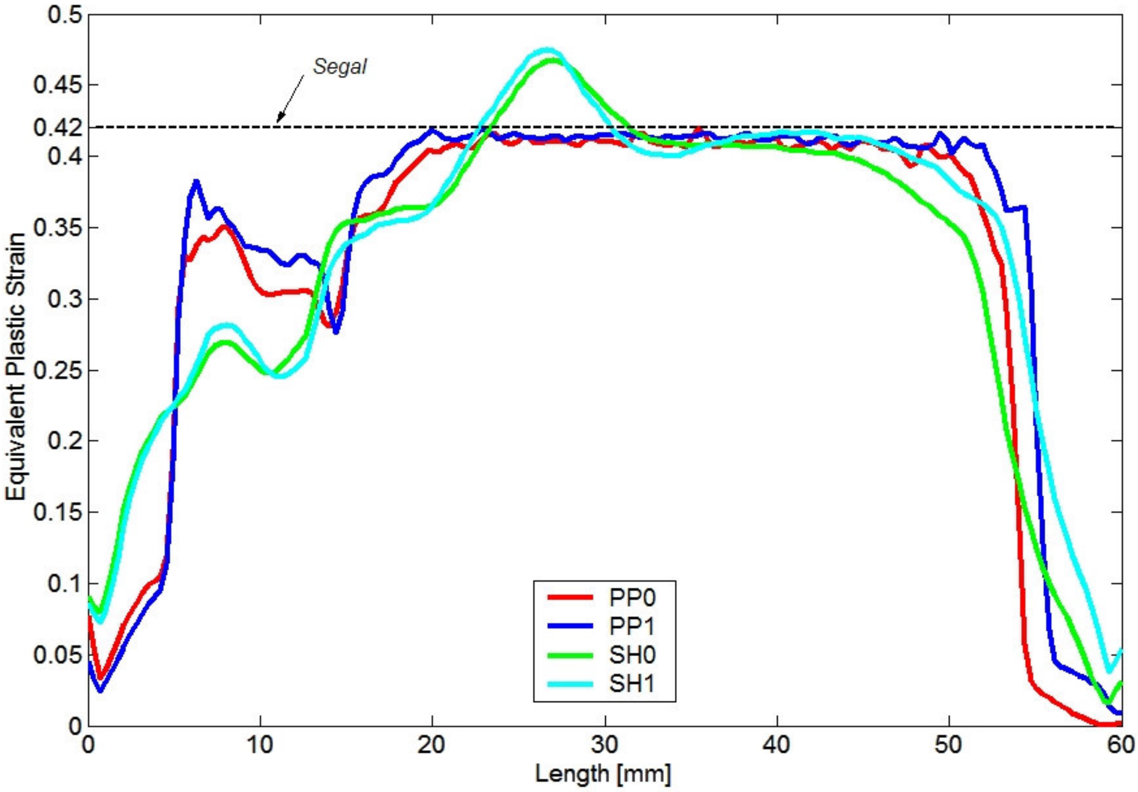

Figure 6. Plastic strain distributions along the length

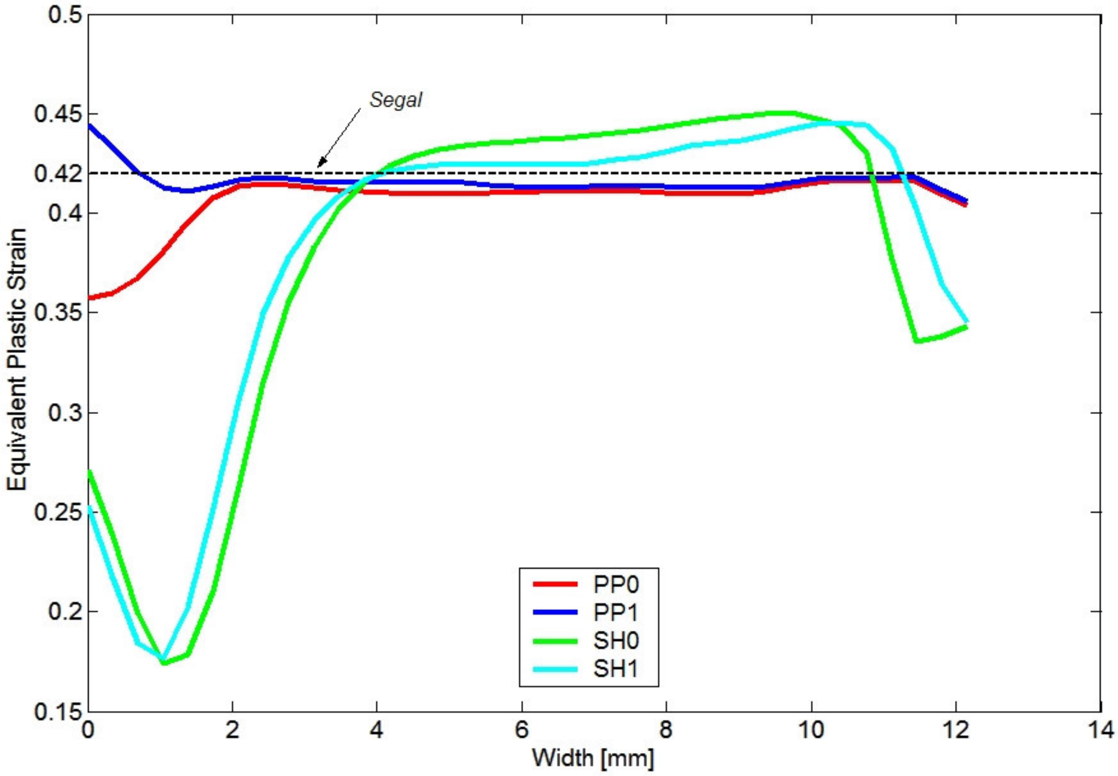

Figure 7. Plastic strain distributions along the width

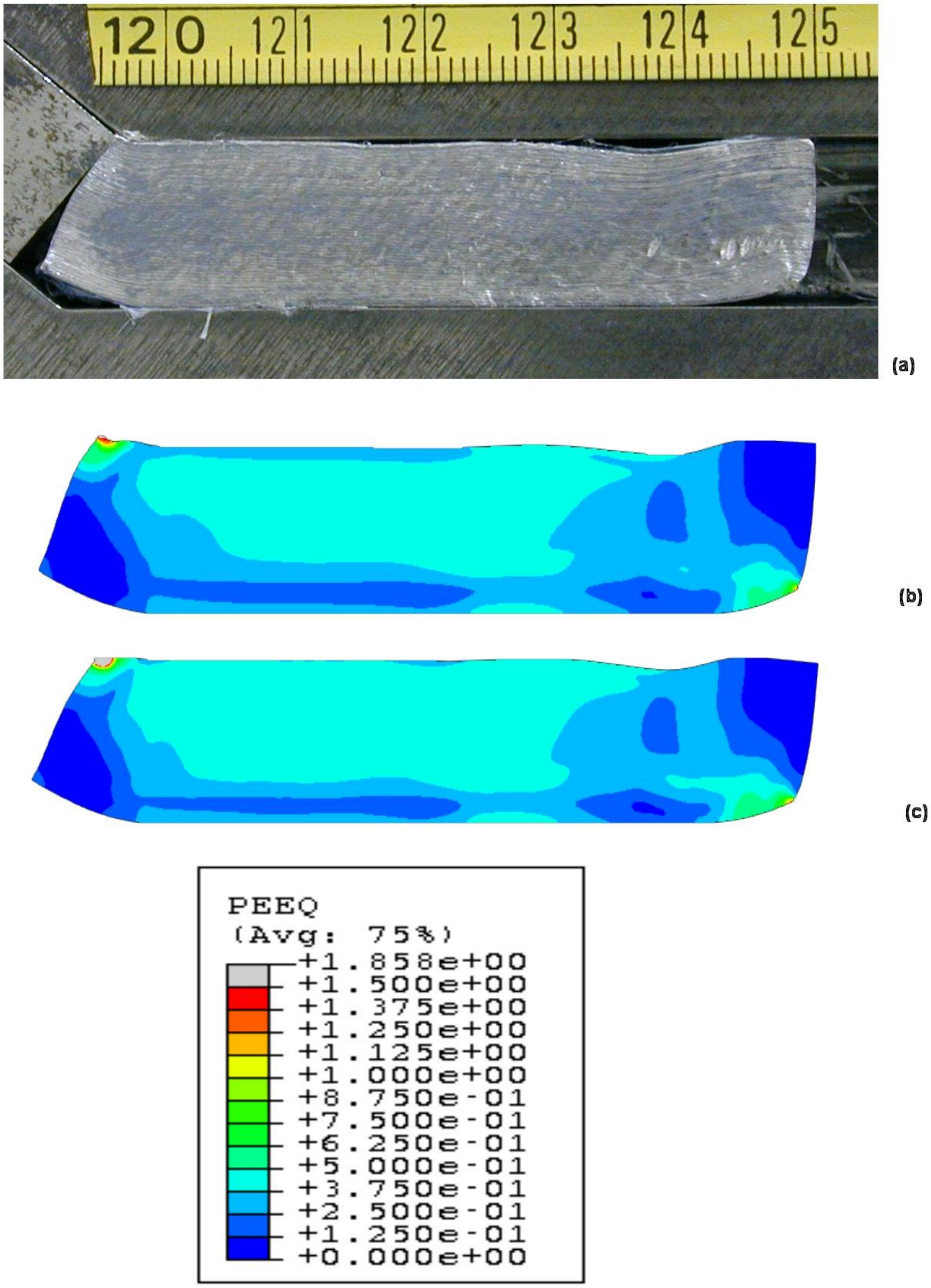

Figure 8. Final shape of the aluminum billet after a single ECAE pass: a) Experimental result; b) Numerical simulation SH0; Numerical simulation SH1

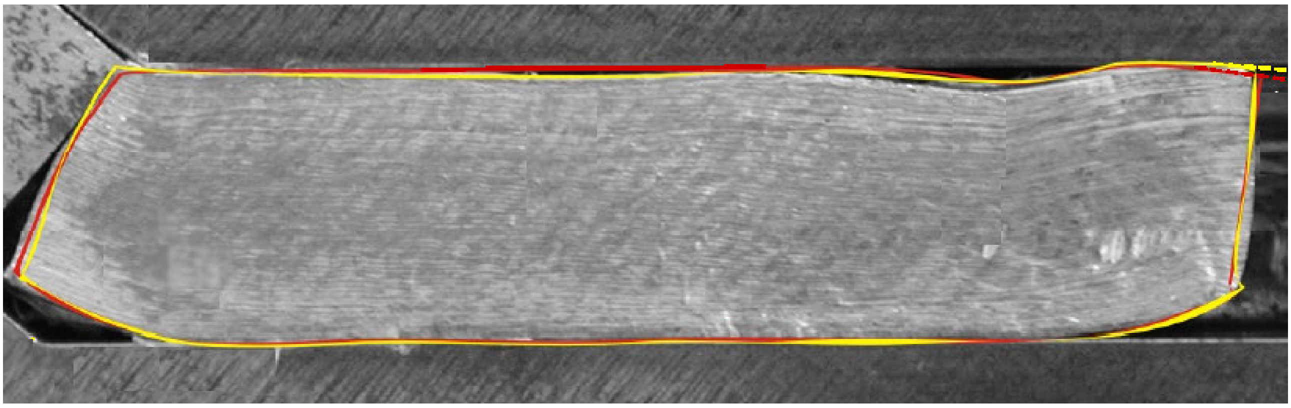

Figure 9. Billet experimental shape after a single ECAE pass and simulated contours: yellow (SH0) and red (SH1).

Figure 10 displays the load-displacement curves for all the simulations, from where we can see that material response and friction control the working load displacement curves. In all considered cases, the load increases linearly until a maximum. For the perfect plastic response (PP0 and PP1), the load is maintained almost constant in the next stage until the end of the single pass. For the strain hardening response (SH0 and SH1), the load drops to a minimum, then it increases to a local maximum and drops again. The predicted responses for simulations S1 and S2 are in good agreement with the load obtained according to the analysis by (Segal, 2003), which holds for frictionless condition and rigid perfect plastic response.

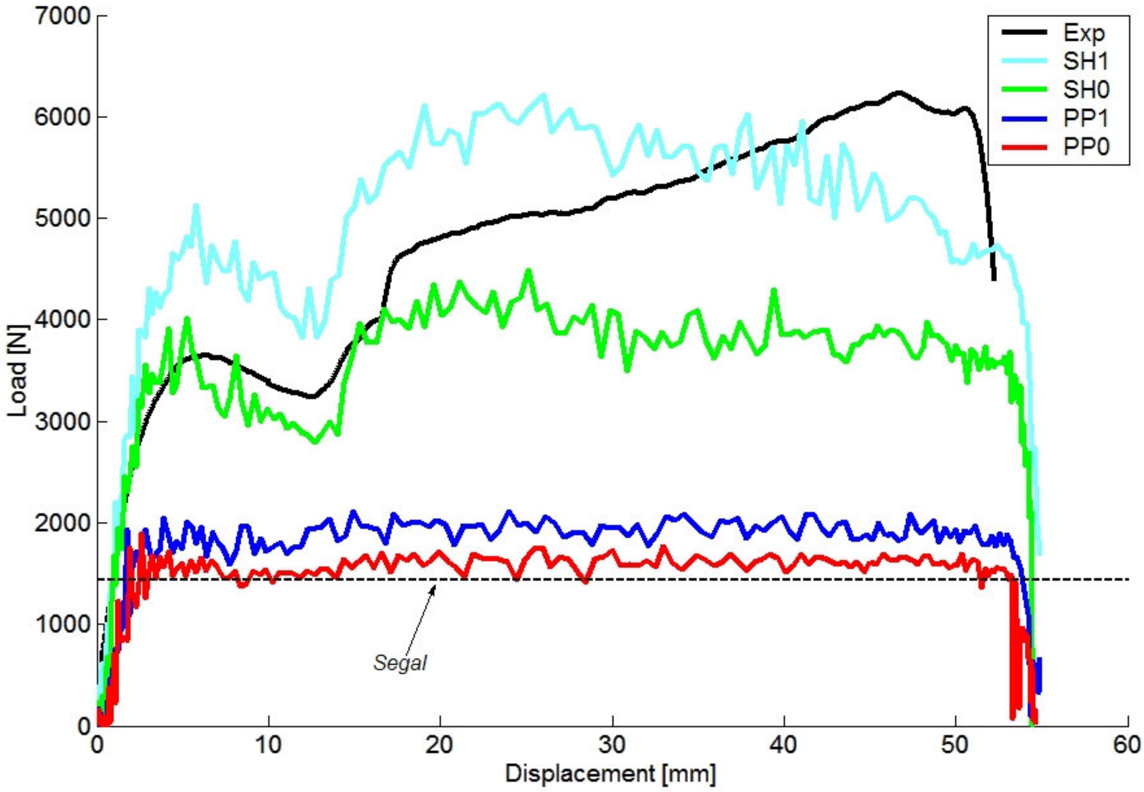

Figure 10. Working load-ram displacement curves

3. CONCLUSIONS

In this paper it was presented a two 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. 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 results predicted by the PP and SH simulations were in good agreement with analytical and experimental results, respectively, which validate the proposed model as tool to analyze Equal Channel Angular Extrusion.

3. ACKNOWLEDGEMENTS

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4. REFERENCES

ABAQUS User's Manual, 2006, Version 6.6, Hibbit, Karlsson & Sorensen, Inc.

Antunes, B.R., Duda, F.P., Garcia de Blas. J.C. and Pereira, L.C., 2006, Análise por Método dos Elementos Finitos do Processo de Extrusão Angular em Canal do Alumínio de Pureza Comercial, 17 Congresso Brasileiro de Ciência e Engenharia dos Materiais (17 CBECIMAT), Foz do Iguaçu, Brasil

Iwahashi, Y., Wang, J., Horita, Z., Nemoto, M. and Langdon, T.G., 1996, "Principle of Equal-Channel Angular Pressing for the Processing of Ultra-Fine Grained Materials", Scripta Materialia, Vol 35 (2), pp. 143-146

Li, S., Bourke, M.A.M, Beyerlein, I.J., Alexander, D.J. and Clausen, B., 2004, "Finite Element Analysis of the Plastic Deformation Zone and Working Load in Equal Channel Angular Extrusion", Materials Science and Engineering A, Vol. 382, pp. 217-236

Segal, V.M., 2003, "Slip Line Solutions, Deformation Mode and Loading History During Equal Channel Angular Extrusion", Materials Science and Engineering A, Vol. 345, pp. 36-46

Segal, V.M., 2004, "Engineering and Commercialization of Equal Channel Angular Extrusion (ECAE)", Materials Science and Engineering A, Vol. 386, pp. 269-276

Suo, T., Li, Y., Guo, Y. and Liu, Y., 2006, "Simulation of Deformation Distribution During ECAP Using 3D Finite Element Method", Materials Science and Engineering A, Vol. 432, pp. 269-274

Valiev, R.Z., Islamgaliev and R.K., Alexandrov, I.V., 2000, "Bulk Nanostructured Materials from Severe Plastic Deformation", Progress in Materials Science, Vol. 45, pp. 103-189

Valiev, R.Z. and Langdon, T.G., 2006, "Principles of Equal-Channel Angular Pressing as a Processing Tool for Grain Refinement", Progress in Materials Science, Vol. 51, pp. 881-981

Segal, V.M., 2003, "Slip Line Solutions, Deformation Mode and Loading History During Equal Channel Angular Extrusion", Materials Science and Engineering A, Vol. 345, pp. 36-46

Segal, V.M., 2004, "Engineering and Commercialization of Equal Channel Angular Extrusion (ECAE)", Materials Science and Engineering A, Vol. 386, pp. 269-276

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