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Research Article

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Study of multi pass equal channel angular pressing using 3D finite element analysis

Sanjeev Sharma[1], Ashok Kumar Raghav[2], Surendra Kumar[3]
[1]Mechanical & Automation Engineering, Amity University Haryana, India
[2] Industrial Research & Development Cell, Amity University Haryana, India
3 Mechanical Engineering Department, GLA University, Mathura, India

Abstract -

Equal Channel Angular Pressing (ECAP) has emerged as most prominent Severe Plastic Deformation (SPD) technique used to produce an ultrafine grained (UFG) structure in metals in order to improve their mechanical and physical properties. In this work Finite Element modeling of ECAP is attempted in FORGE 2007 environment. Four passes of the ECAP process of 10mm square shaped AL 6061 billet were carried out for routes A, B_A and C for different channel angles and values of coefficient of friction to investigate their influence on the billet. The models were developed assuming a range of friction conditions at the billet-die contact region considering eight distinct friction coefficient (μ) values of 0.0, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40, respectively. The simulations are carried out using three distinct situations of die channel angles (Φ), 90^o, 105^o, and 120^o respectively. Route 'B_A' emerged as a better method among the three routes studied and 90^o channel angle appeared to be optimal in terms of producing high equivalent strain.

Keywords - Equal Channel Angular Pressing, Severe Plastic Deformation, ultrafine grained (UFG) structure, equivalent strain, Finite Element Analysis.

I. INTRODUCTION

Severe Plastic Deformation (SPD) technique has emerged as a popular method for producing large volume and low cost nanostructured bulk metals. Equal Channel Angular Pressing (ECAP) is nowadays considered as one of the most promising SPD technique to produce nanostructured metals in bulk [1, 2]. In this technique a billet is forced topass into a die with two channels of identical cross-sections. The microstructure of the material is refined by the action of simple shear imposed at the channels intersection.

The strength of polycrystalline materials is related to the grain size 'd', through the Hall-Petch equation [3, 4] which states that the yield stress, σ_Y, is given by:

$$\sigma_y = \sigma_o + k_y\, d^{-½}$$

where, σ_o is friction stress and k_y is constant of yielding. It follows from this equation that the strength increases with a reduction in the grain size and this has led to an ever-increasing interest in fabricating materials with extremely small grain sizes.

The ECAP parameters, viz., amount of deformation shear strain (ε), number of passes (N), rotation angle between each repetitive pressing, the strain rate monitored by movement of punch, and the temperature in process greatly influence the final microstructure and thus the properties of the final product in ECAP [5-7]. A schematic of the process is exhibited in figure 1, where Φ and Ψ are the channel intersection angle and the arc curvature angle respectively. There are four basic processing routes in ECAP and these routes introduce significant differences in the microstructures produced by ECAP. The four different processing routes are summarized schematically in Figure 2. In route A the billet is pressed without rotation, in route B_A the billet is rotated by 90^o in alternate directions between consecutive passes, in route B_C the billet is rotated by 90^o in the same sense (either clockwise or counterclockwise) between each pass and in route C the billet is rotated by 180^o between passes.

The magnitude of Φ and Ψ along with the number of passes determines the shear strain induced into the sample. The strain increment (ε) that the material undergoes after each pass can be expressed in terms of punch pressure (P) and the flow stress of the material (σ_{fs}) and depends on the intersection angle (Φ) between two channels as follows:

Strain increment after each pass $\Delta\varepsilon = \dfrac{P}{\sigma_{fs}} = \dfrac{2}{\sqrt{3}}\cot\Phi$,

The shear strain value greatly depends on the number of passes (N) and the curvature angle at the channel intersection and can be generalized as follows:

Shear strain, $\varepsilon = \dfrac{N}{\sqrt{3}}\left[2\cot\left(\dfrac{\Phi}{2}+\dfrac{\Psi}{2}\right)+\Phi\cos es\left(\dfrac{\Phi}{2}+\dfrac{\Psi}{2}\right)\right]$

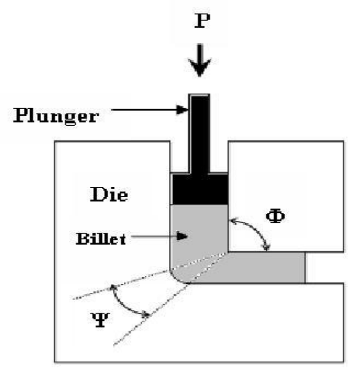

Fig. 1. Typical ECAP process, where Φ is die channel angle and Ψ is angle of curvature.

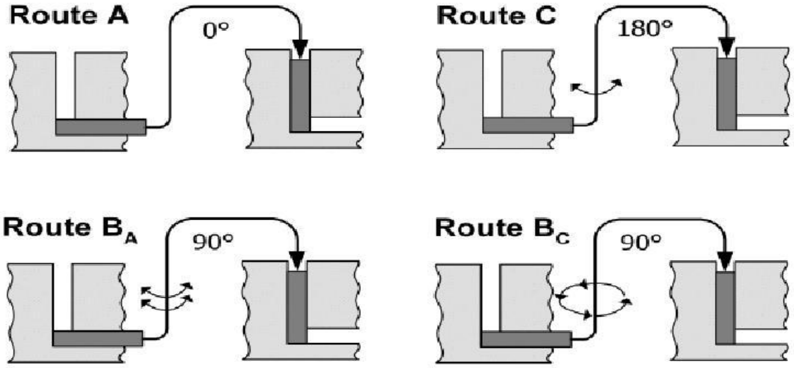

Fig.2. Four basic options for billet rotation between consecutive passes through ECAP die.

From the above equation it can be inferred that the deformed billet experiences a shear strain value of nearly equal to 1, considering the frequently practiced values of Φ and Ψ. The strain rate in ECAP depends on the diameter (for round cross-section) or width (for square cross-section) of the billet and the plunger speed during the deformation. As plastic deformation is a dynamic process governed by dislocation mobility, the strain rate in ECAP also affects the properties of final product and can be expressed by the following relationship:

$$\varepsilon = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)+\Phi\cos es\left(\frac{\Phi}{2}+\frac{\Psi}{2}\right)\right]\frac{V\sqrt{2}}{\Phi L}$$

where 'V' is the plunger speed and 'L' is the width or diameter of the billet. The optimum property evolution by ECAP technique can be envisaged by minimum contact friction, sharp corner channels, and square long or flat billet. The degree of grain refinement in ECAP method depends on various factors like processing parameters, phase composition, and initial microstructure of a material. Although stress and reaction forces are routinely available from FE simulations, only few papers mentioned these results and used them to evaluate material behavior, tool pressure, and the process force [8-12].

In this proposed work the FE modeling of ECAP process using Al6061 billet is attempted for various combination of die channel angles, friction coefficient and different processing routes, viz., Route A, Route B$_A$ and Route C. Effect of these parameters on average equivalent strain in ECAPed billet and forming energy required during ECAP process is studied using FE analysis.

II. FINITE ELEMENT MODELING OF EQUAL CHANNEL ANGULAR PRESSING (ECAP)

The modeling of ECAP process is done in FORGE 2007 environment in this study. FORGE is capable of modeling three-dimensional situations of metalforming with thermal and friction coupling for in-compressible materials with automatic mesh regeneration as reported in Hans Raj et al. [13, 14].

The material is assumed to be homogeneous, isotropic and incompressible. The material is considered to be elasto-viscoplastic. A fully automated remeshing procedure is incorporated into the analysis. The material behavior is assumed to follow that of Norton-Hoff law written in following tensorial form:

$$S = 2K(T,\bar{\varepsilon})(\sqrt{3\bar{\varepsilon}})^{m-1}\dot{\varepsilon}$$

where s = shear stress, K = material consistency, T = temperature, $\bar{\varepsilon}$ = equivalent strain, and $\dot{\varepsilon}$ = strain rate.

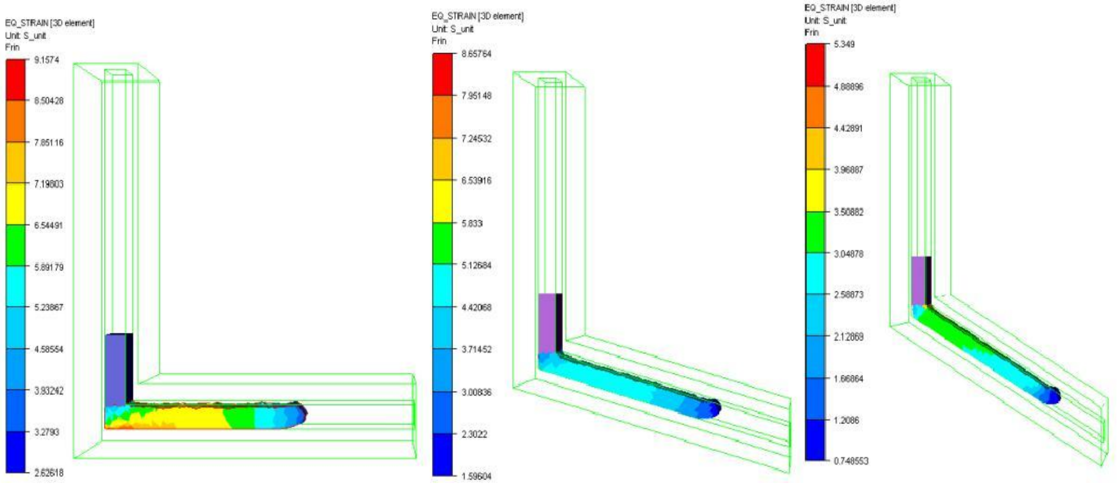

Fig. 3 The average equivalent strain contours for channel angles (Φ =90^o, 105^o and 120^o) for fourth pass of route A

Table 1

	Channel Angle (Φ) 90^o		Channel Angle (Φ) 105^o		Channel Angle (Φ) 120^o	
Friction coeff. μ	Avg. Eq. strain	Forming Energy	Avg. Eq. strain	Forming Energy	Avg. Eq. strain	Forming Energy
		(*k Joules*)		(*k Joules*)		(*k Joules*)
Route ‘A’						
0.00	6.551	1.192	4.579	1.030	2.934	0.745
0.10	6.958	1.360	4.667	1.345	3.096	1.195
0.15	7.198	1.390	4.675	1.350	3.265	1.247
0.20	7.322	1.404	4.753	1.362	3.315	1.251
0.25	7.325	1.406	5.126	1.367	3.374	1.269
0.30	7.328	1.412	5.142	1.384	3.508	1.295
0.35	7.382	1.416	5.664	1.387	3.827	1.300
0.40	7.605	1.423	6.118	1.390	4.453	1.302
Route ‘B_A’						
0.00	7.185	1.215	4.309	1.058	2.753	0.857
0.10	7.232	1.397	4.623	1.208	2.795	0.892
0.15	7.381	1.402	5.048	1.229	2.834	0.913
0.20	7.394	1.423	5.239	1.346	2.902	1.104
0.25	7.678	1.424	5.569	1.396	3.002	1.129
0.30	7.721	1.429	5.682	1.457	3.095	1.132
0.35	7.791	1.463	5.791	1.489	3.102	1.140
0.40	7.944	1.484	5.916	1.508	3.146	1.142
Route ‘C’						
0.00	6.132	1.203	4.468	1.028	2.906	0.795
0.10	6.235	1.367	4.702	1.296	3.272	1.245
0.15	6.677	1.413	4.737	1.421	3.114	1.327
0.20	6.699	1.429	4.562	1.482	3.482	1.341
0.25	6.926	1.495	4.940	1.435	3.488	1.352
0.30	7.057	1.463	5.393	1.510	3.870	1.323
0.35	7.163	1.501	5.628	1.556	3.428	1.350
0.40	7.188	1.404	5.716	1.465	3.274	1.384

FE evaluation of average equivalent strain obtained in ECAPed billet and forming energy required during the ECAP process for various Channel Angles (Φ) after fourth pass at various values of μ.

The flow stress in case of Al6061 is directly interpolated from the material data file available in FORGE software for various temperatures, strains, strain-rates. The values of K and m are not explicitly keyed in by the user in the data file for defining the rheology law.

Generalized coulomb friction law is used in the current analysis given by:

$$\tau = \mu\sigma_n \quad \text{if} \quad \mu\sigma_n \langle \bar{m}\frac{\sigma_0}{\sqrt{3}} \qquad \text{and} \qquad \tau = \bar{m}\frac{\sigma_0}{\sqrt{3}}\frac{\Delta V}{V} \quad \text{if} \quad \mu\sigma_n \rangle \bar{m}\frac{\sigma_0}{\sqrt{3}}$$

where τ = friction stress tangential to the surface, μ = coefficient of friction σ_n = compressive stress normal to the surface (contact pressure), $\bar{m}$ = Tresca coefficient

The 3D models for the ECAP dies were developed in Solidworks software with three channel intersection angles (Φ) and the angle of curvature (Ψ) for all models is taken to be 0°. The dies are assumed to be rigid pieces and the dimension of the plunger is 10mm (width) x 10mm (height). The three dimensional billet made of Al 6061 material of 10 mm (width) x 10 mm (breadth) and 80 mm (height) is considered to perform FE analysis. In the proposed study, value of Tresca coefficient (m) is kept constant at 0.05. FE simulations are carried for above mentioned three channel intersect on angles and a range of values of coefficient of friction (0.0, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40) during fourth pass in different routes A, B_A and C and are shown in Table 1. FE simulations are performed for ECAP process in cold conditions i.e. at constant temperature of 20^oC under constant plunger velocity of 5 mm/s. The average equivalent strain contours for various channel intersection angles are shown in Figure 3 for fourth pass of ECAP process.

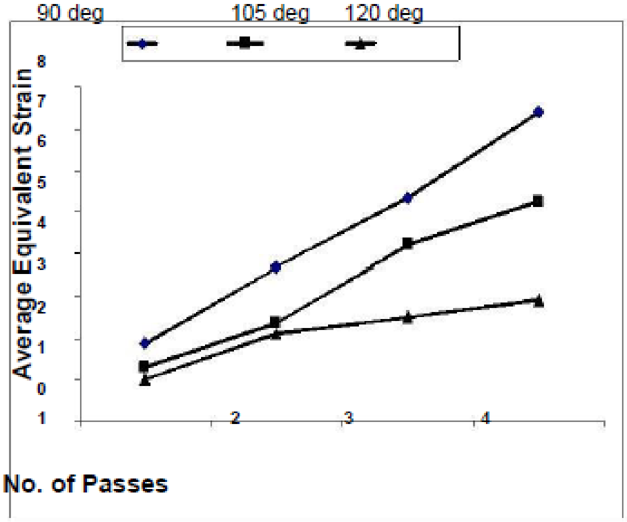

Fig. 4. The average equivalent strain v/s no. of passes for route B_A and μ = 0.2

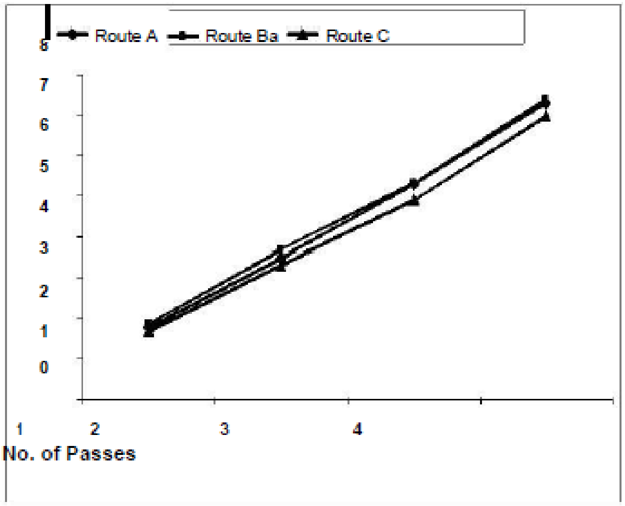

Fig. 5. The average equivalent strain v/s no of passes for channel angle 90° and μ = 0.2

III. RESULTS AND DISCUSSION

The average equivalent strain imparted during ECAP is influenced mainly by die channel angle (Φ). Channel angle of 90^o imparts higher average equivalent strain in comparison with those of 105^o and 120^o as shown in figure 4. Subsequently the forming energy for $\Phi = 90^o$ is more than that for 105^o and 120^o. Figure 5 shows that route A and B_A imposes high average equivalent strain for all channel angles in comparison with route C.

IV. CONCLUSIONS

In this work a brief review of ECAP process is attempted. Finite Element modeling and simulation of ECAP process in FORGE 2007 environment is presented. Effect of various channel intersection angles (Φ), co-efficient of friction (μ) and different processing routes namely A, B_A and C are studied for ECAP of Al6061 pre-form. Channel angle of 90^o imposes higher average equivalent plastic strain as compared to other angles. Among the three routes considered, route C develops lesser strain in comparison with route A and route B_A in the generation of UFG materials. ECAP offers a practical way of producing UFG materials from bulk metals.

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