An investigation on the deformation of Al alloy during integrated Extrusion and ECAP

Ankit Sahai¹, Shanti S Sharma¹, Rahul S Sharma¹, K. HansRaj¹, Suren N. Dwivedi²

¹Faculty of Engineering, Dayalbagh Educational Institute, Dayalbagh, Agra, INDIA
²Mechanical Engineering Department, University of Louisiana, Lafayette, USA

Email: sahaiankit13@gmail.com

Abstract:

Bulk Nano Materials have number of applications in automobile, aero-space, medical and manufacturing applications. These are produced by subjecting materials to severe plastic deformation (SPD) and have widely emerged as a technique for grain refinement in Al, Cu, Ti, Mg alloys with improved mechanical properties. Equal Channel Angular Pressing (ECAP) is one such SPD technique employed to produce bulk ultra-fined grained (UFG) materials by introducing a large amount of shear strain into the materials without changing the billet shape or dimensions. FE (Finite Element) modeling of SPD processes has become an important tool for designing feasible production processes, because of its unique capability to describe the complex geometry and boundary conditions. In this proposed work, integrated SPD processes namely Extrusion + ECAP (Ex-ECAP) is proposed and the specimen is subjected to these processes in the same die set-up. The 3D finite element modelling of Al6061 was performed using metal forming software FORGE. The dies used in both the processes during the simulation of Al6061 billet include channel angle of 90° and outer corner angle fixed at 16° with simulation performed for different plunger velocities. The simulation results clearly depict the change in equivalent strain in the entire specimen on account of these processes. Evolution of strain at different considered cross-sections is analysed. Also, the variation in extrusion force and energy are studied for the considered process parameters. The FE simulations greatly help in designing the dies for various experimental conditions to produce bulk nano-materials.

Keywords: Severe Plastic Deformation, Nanomaterials, Equal Channel Angular Pressing, Extrusion, Finite Element Modeling, Ultra-Fine Grained Material

1. Introduction

Presently, engineering sectors like automotive and aerospace are focussing on aluminium alloys due to their good corrosion resistance, superior mechanical properties along with good machinability, weldability, and relatively low cost [1,2]. One of the key factors in changing the mechanical properties of polycrystalline materials is by controlling the grain size. At low temperatures, the yield strength is related to the grain size by the well known Hall–Petch relationship [3, 4], where the yield strength of material increases with decreasing grain size. A reduction in grain size can also lead to low temperature and/or high strain rate superplasticity [5].

Since last decade many deformation processes are under investigation to obtain metals and alloys with ultrafine microstructures and consequently high strength. Hence, materials with nanometer or sub micrometer grain sizes are receiving greater interest because of their unique mechanical and physical properties and high performance [6–9]. The production of
materials with ultra fine grain sizes can be achieved by subjecting coarse grained metal to severe plastic deformation to improve their mechanical and physical properties [10-14]. SPD technology has become the focus of attention of many research groups and individual researchers and an analysis was conducted by Langdon [15] to evaluate the impact of the broad publications appearing over the last decade within the discipline of material science indicating it to be the most popular research area. Many SPD techniques like equal channel angular pressing (ECAP) [8-11], high pressure torsion (HPT) [16], twist extrusion (TE) [17], etc., have been developed and analysed. ECAP is a promising process because it can produce bulk, fully dense, and contamination-free UFG materials. Moreover, one can design and predict the microstructural evolution by using different routes (route A, B, BC, and C). In recent years, numerous theoretical and experimental investigations on the ECAP process [9-15] have been conducted to demonstrate the effect of process parameters on material behaviour. Recently, Valiev et al. [18] discussed new concepts and principles in application of SPD processing to fabricate bulk nanostructured Al alloys with advanced properties. Many researchers are also working on Finite Element Modelling (FEM) [19-26] to understand the deformation behaviour of materials and to estimate the developed strain in the ECAP process. FE simulations help to understand and critically assess the existing ECAP process with a better insight into influence of different process parameters. Recently, Suo et al. [19] and Basavaraj et al. [20] have done some 3D analyses to trace the homogeneity during the ECAP processes after the first pass Xu et al. [22] and Jiang et al. [23] studied the distribution of strain in the cross-section of the sample of pure Al and CP-Ti, respectively, during the 3D FEM simulations for the multiple passes. Hans Raj, et al. [21,24] has analysed the influence of friction and channel angle in ECAP using FE analysis. Nagasekhar et al. [25] considered the effect of strain hardening and friction in the pure copper by 3D FEM and Balasundar et al. [26] analysed the effect of friction models on deformation behaviour of pure aluminium. Sabirov et al. [27] discussed the application of ECAP with parallel channels on deformation behaviour of Al alloys and Ahmadabadi et al. [28] analysed the changes in mechanical properties of Al alloy during ECAP with different heat treatments.

In this work, authors have tried to combine extrusion and ECAP (Fig. 2) in the same die setup and investigated the deformation of Al6061 during low friction conditions and for different plunger velocities.

![Figure 1: Schematics of ECAP process](image1.png)

![Figure 2: Extrusion-ECAP](image2.png)
2. Finite Element Modeling

Finite Element Method (FEM) is one of the important approaches to understand the deformation occurring in the Equal Channel Angular Pressing (ECAP) process.

In this work, the FE modeling of Extrusion-ECAP is done in FORGE environment, which is capable of modeling 3-D situations of metal forming (including thermal and friction effects) with automatic mesh regeneration. The material is assumed to be homogeneous, isotropic and incompressible. The dies are assumed to be rigid. The dimension of the plunger is 20mm (width) x 20mm (breadth). The three dimensional work piece (billet) considered has the dimensions of 20 mm (width) x 20mm (breadth) and 105 mm (height). The material of the billet is Al6061. FE simulations are carried out for ECAP (Φ = 90° and ψ = 16°) having low friction conditions (μ = 0.02 and value of Tresca coefficient, m is kept constant at 0.05). All the simulations are done at 20°C under pressing velocity of 1, 5 and 10 mm/s and the material rheological behaviour is assumed to be elastoplastic.

The Hansel – Spittel equation, Eq. 1, is used to describe the behavior of the material during the deformation which is defined as:

\[ \sigma_f = A \exp \left( m_1 \cdot T \cdot \varepsilon \right) \cdot m_2 \cdot \exp \left( \frac{m_3}{\varepsilon} \cdot \left( 1 + \varepsilon \right) + \frac{m_4}{\varepsilon} \right) \cdot \exp \left( \frac{m_5}{\varepsilon} \right) \cdot \exp \left( \frac{m_6}{\varepsilon} \right) \cdot \exp \left( \frac{m_7}{\varepsilon} \right) \cdot \exp \left( \frac{m_8}{\varepsilon} \right) \cdot \exp \left( \frac{m_9}{\varepsilon} \right) \]  

(1)

Where \( \varepsilon \) is the equivalent strain, \( \dot{\varepsilon} \) is equivalent strain rate, T is temperature and A, m1, m2, m3, m4, m5, m6, m7, m8, m9 are regression coefficients.

The variation of energy required and equivalent strain in the end product with different plunger velocities for low friction conditions are obtained, Table 1.

Table 1: The FE evaluation of equivalent strain, forging force and energy during Extrusion-ECAP for Φ = 90° for different plunger velocities

<table>
<thead>
<tr>
<th>Plunger Velocity (mm/s)</th>
<th>Equivalent Strain Extrad Zone</th>
<th>Extrusion Force (Tons)</th>
<th>Energy (KJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.22</td>
<td>43.37</td>
<td>5.53</td>
</tr>
<tr>
<td>5</td>
<td>2.33</td>
<td>44.97</td>
<td>5.56</td>
</tr>
<tr>
<td>10</td>
<td>2.66</td>
<td>45.1</td>
<td>5.72</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1 Evolution of Equivalent Strain

In this process, Extrusion-ECAP, deformation occurs twice, first during extrusion and then during ECAP where billet experiences severe plastic deformation by simple shear at the region where two channels intersects. The equivalent strain contours for different plunger velocities after 1st pass are depicted in Fig. 3. The schematic end billet for the process is depicted in Fig. 4. The variation of equivalent strain along the billet length at the middle (B-B’) is also evaluated and shown in Fig. 5. It can be seen that equivalent strain increases rapidly after ECAP (after 50 mm), reaching to maximum value around 3 and then starts declining once billet slides on the exit channel.
Figure 3: Equivalent Strain Contours during Extrusion-ECAP for plunger velocities (a) 1mm/s, (b) 5 mm/s and (c) 10 mm/sec

Figure 4: Schematic representation of billet after 1st Pass

Figure 5: Strain distribution in the billet mid surface in Extrusion-ECAP for $\Phi = 90^\circ$ at $\mu = 0.02$ for different plunger velocities.

3.2 Variation of Extrusion Force

Fig. 6 depicts the variation of extrusion force during 1st pass for $\Phi = 90^\circ$ at low friction condition. During the initial stages of deformation, the billet enters the deformation zone...
during extrusion and force increases to a certain limit. During further deformation, as the punch moves in the downward direction, the billet is compressed in the main deformation shear zone (ECAP) where force attains its peak value. On further pressing, billet slides on the die surface which causes shear deformation and hence the extrusion force drops. It can be seen that more extrusion force is required for plunger velocities 5 and 10 mm/sec as compared to 1 mm/sec.

![Figure 6: Variation of extrusion force during the deformation process for different plunger velocities](image)

3.3 Variation of Energy

The variation of energy during Extrusion-ECAP is predicted in Fig. 7. It can be seen that energy is constantly increases once the deformation starts during extrusion and then decreases sharply after the end of the process. Also, plunger velocity of 10 mm/s exhibits higher values of energy as compared to other plunger velocities.

![Figure 7: Variation of energy during Extrusion-ECAP for different plunger velocities](image)

Conclusions

Severe plastic deformation (SPD) is an important process for creating bulk ultra fine grained materials. Three dimensional FE modelling of Extrusion-ECAP was carried out to study the
evolution of equivalent strain on Al6061 alloy for different plunger velocities at low friction conditions.

The study revealed the following outcomes:

- During deformation, plunger velocity of 10 mm/s exhibits higher values of equivalent strain (3.34) as compared to other velocities.
- Extrusion force increases with increase in plunger velocity.
- Plunger velocity of 10 mm/s exhibits higher values of energy as compared to other plunger velocities.
- Front and back end of the billet exhibit less equivalent strain as these regions experience less deformation while high value of equivalent strain is exhibited in central part of the billet.

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References


Biography

Ankit Sahai is an Assistant Professor in Mechanical Engineering Department, Faculty of Engineering, Dayalbagh Educational Institute, Agra, India. He did his M.Tech. in Applied Mechanics from IIT Delhi and currently pursuing Ph.D. in Mechanical Engineering from Dayalbagh Educational Institute in collaboration with IIT Delhi. His research areas include Severe Plastic Deformations, Fatigue and Fracture Analysis, Composite Materials, Finite Element Analysis. He has few papers published in conference proceedings and journals.

Shanti Swaroop Sharma is pursuing his M.Tech. from Dayalbagh Educational Institute and working as Project Associate in UGC R&D Project in Mechanical Engineering Department at Faculty of Engineering, Dayalbagh Educational Institute, Agra. His research interest includes CAD/CAM and FE simulation of Metal Forming Processes.

Rahul Swarup Sharma has received M.Tech. and PhD in Mechanical Engineering from Dayalbagh Educational Institute Agra, India. He is a faculty member since 1999 in the University Science Instrumentation Centre of Dayalbagh Educational Institute, Agra, India. He has been visiting Assistant Professor at Rensselaer Polytechnic Institute, Troy, NY, USA in 2009. His research interests are development of Bulk Nanostructured materials through Severe Plastic Deformation. He has been awarded BOYSCAST Fellowship by Government of India in year 2009 and “Institution medal” for the year 2001 of Institution of Engineers (India) for his research paper. He has 25 publications to his credit in journals and conferences. He is a member of Institution of Engineers (India), Indian Society of Mechanical Engineers, Indian Science Congress Association, Systems Society of India and Indian Society of Technical Education.

Kandikonda Hans Raj was born on 31st July 63. He has received B.Sc. Engineering in Mechanical Engineering from Agra University, M.Tech. in Mechanical Engineering from I.I.T. Roorkee and Ph.D. from Dayalbagh Educational Institute. He is a Fellow of Institution of Engineers, India (FIE). Presently he is a Professor in Mechanical Engineering at Dayalbagh Educational Institute, Dayalbagh, Agra. He is actively involved in research and teaching since 1988. Intelligent and Agile Manufacturing, Metal Forming Process Modeling and Optimization, Soft Computing Applications in Manufacturing and Quantum Evolutionary Optimization. He is a research consultant to ADRDE (DRDO), India. He has been a visiting scientist to CEMEF Laboratory, Sophia Antipolis, France, University of Kiel, Germany, Mathematics and Computer Science Department, University of Maryland, MD, Rensselaer Polytechnic Institute, NY, MIT, MA U.S.A. He has been awarded prestigious “Production Engineering Division Medal” for 1999 & 2000 and most coveted “Institution medal” for the year 2001 of Institution of Engineers (India) for his research papers. He has supervised 26 U.G. and 28 P.G. Projects and 3 Ph.D.’s. He is currently supervising 3 Ph.D. scholars. He has 126 publications to his credit in journals.
and conferences. He is a life member of International Society of Agile Manufacturing, Indian
Society for Mechanical Engineers, Indian Society for Technical Education, Indian Society for
Continuing Engineering Education, Institution of Engineers (India), Systems Society of India
and Aeronautical Society of India.

Dr. Surendra Nath Dwivedi, Board of Regents Eminent Scholar, Endowed Chair Professor and Director of the Virtual Reality and Product Realization Lab at University of Louisiana Lafayette, U.S.A. was born in Ballia, a small district in U.P. He graduated with a B.Sc. (honors) and a B.Sc. in Mechanical Engineering from the B.H.U. He has also earned an M.S. in Machine Design from the University of Roorkee; an M.A.Sc. in Mechanical Engineering from the University of British Columbia, Vancouver; and a Ph.D. in Engineering from the Birla Institute of Technology, Ranchi. In 2009, he received the honorable Louisiana Faculty Professionalism Award, and has received 33 awards for outstanding teaching, research, professional and community services. His research areas are Concurrent Engineering, Agile Manufacturing and Lean Manufacturing. He has developed and implemented programs in teaching CAD/CAM and robotics. He has taught several courses to graduate and undergraduate students. He has guided more than 100 students through their M.S. theses and their Ph.D. dissertations. He is the founding president of three professional journals: Concurrent Engineering: Research and Application (CERA), International Journal of Agile Manufacturing (IJAM) and The International Journal of Advanced Manufacturing (IJAMS). He has published more than 200 papers in reputed journals and at prestigious conferences.