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Research Paper

Deformation of Al Alloy during Integrated Extrusion and ECAP: A Simulation Research

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Abstract
Bulk nanomaterial have several applications in automobile, aerospace, 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-fine 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 modeling of Al6061 was performed using metal forming software FORGE. The dies used in both the processes during the simulation of Al6061 billet include a channel angle of 900 and outer corner angle fixed at 160 with simulation performed for different plunger velocities. The simulation results depict the change in equivalent strain in the entire specimen on account of these processes. The evolution of strain at different considered cross-sections is analyzed. 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 nanomaterial.

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

1. Introduction
Presently, engineering sectors like automotive and aerospace are focussing on aluminum alloys due to their good corrosion resistance, superior mechanical properties along 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 the 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 the 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 analysis were 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 analyzed. 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_A, B_C, 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 behavior. Recently, Valiev et al. [18] discussed new concepts and principles in the 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 behavior 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 the 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] have analyzed 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] analyzed the effect of friction models on the deformation behavior of pure aluminum. Sabirov et al. [27] discussed the application of ECAP with parallel channels on deformation behavior of Al alloys and Ahmadabadi et al. [28] analyzed the changes in mechanical properties of Al alloy during ECAP with different heat treatments.

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

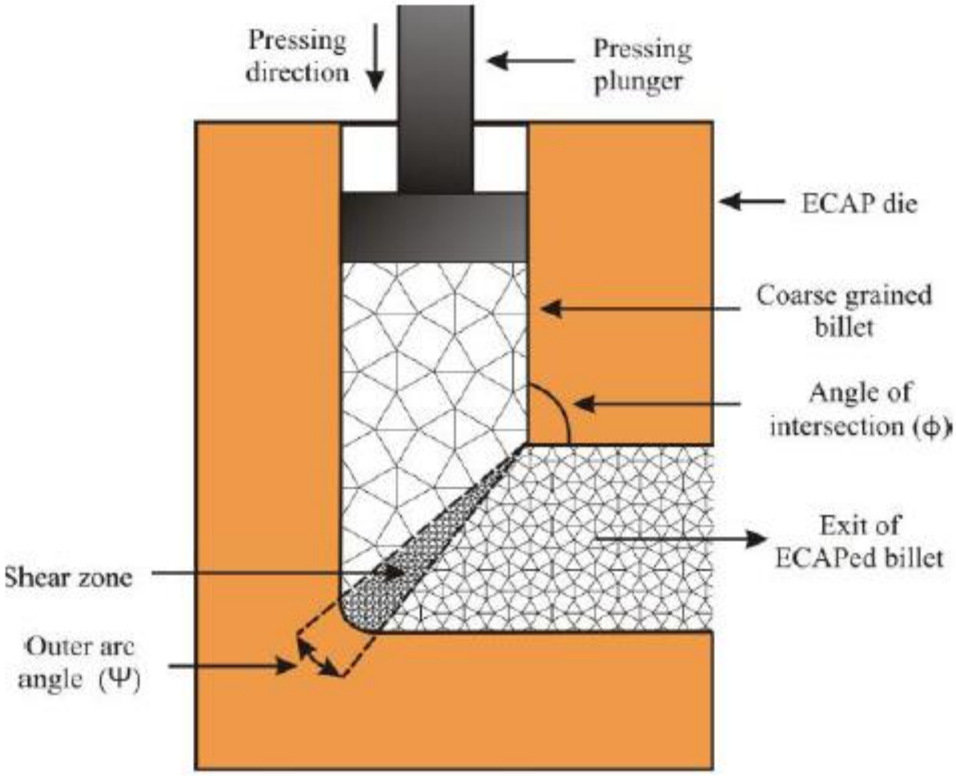


Figure 1. Schematics of ECAP process

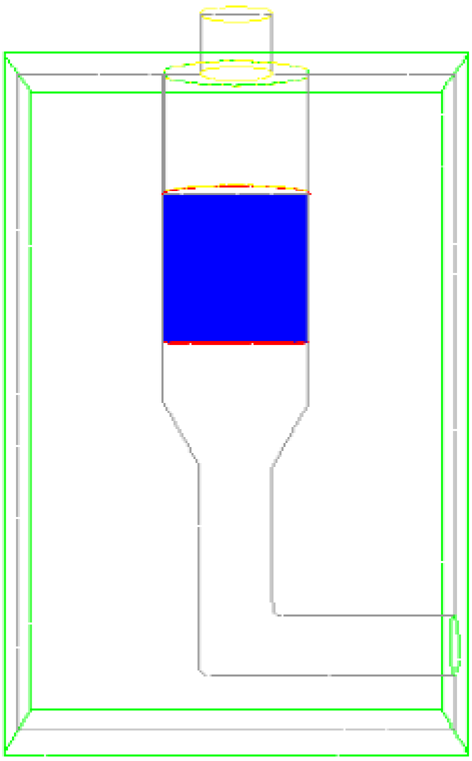


Figure 2. Extrusion-ECAP

2. Finite Element Modeling

The 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 was done in the 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 workpiece (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 ($\Phi = 90_0$ and $\psi = 16_0$) having low friction conditions ($\mu = 0.02$ and value of Tresca coefficient, *m* is kept constant at 0.05).

All the simulations are done at 20°C under a pressing velocity of 1, 5, and 10 mm/s, and the material rheological behavior is assumed to be elastoplastic.

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

$$\sigma_f = Aexp^{m_1 T} T^{m_9} \varepsilon^{m_2} exp^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5 T} exp^{m_7 \varepsilon} \varepsilon^{m_3} \varepsilon^{m_g T} \qquad (1)$$

Where ε is the equivalent strain, ε is the equivalent strain rate, T is temperature, and A, m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_9 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 in Table 1.

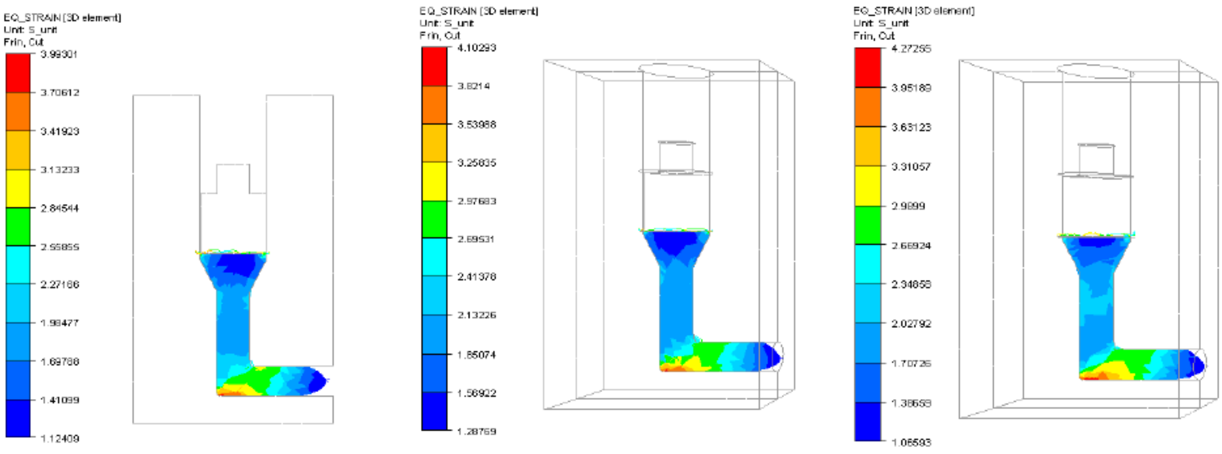
Table 1. The FE evaluation of equivalent strain, forging force, and energy during Extrusion-ECAP for $\phi = 90^\circ$ for different plunger velocities

Plunger Velocity (mm/s)	Equivalent Strain		Extrusion Force (Tons)	Energy (KJ)
	Extrusion Zone	ECAP Zone		
1	2.22	3.1	43.37	5.53
5	2.33	3.23	44.97	5.56
10	2.66	3.34	45.1	5.72

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 the billet experiences severe plastic deformation by simple shear at the region where two channels intersect. The equivalent strain contours for different plunger velocities after 1st pass are depicted in Figure 3. The schematic end billet for the process is depicted in Figure 4. The variation of equivalent strain along the billet length at the middle (BB') is also evaluated and shown in Figure 5. It can be seen that equivalent strain increases rapidly after ECAP (after 50 mm), reaching to the maximum value of around 3, and then starts declining once billet slides on the exit channel.



(a) (b) (c)

Figure 3. Equivalent Strain Contours during Extrusion-ECAP for plunger velocities (a) 1mm/s, (b) 5 mm/s and (c) 10 mm/sec

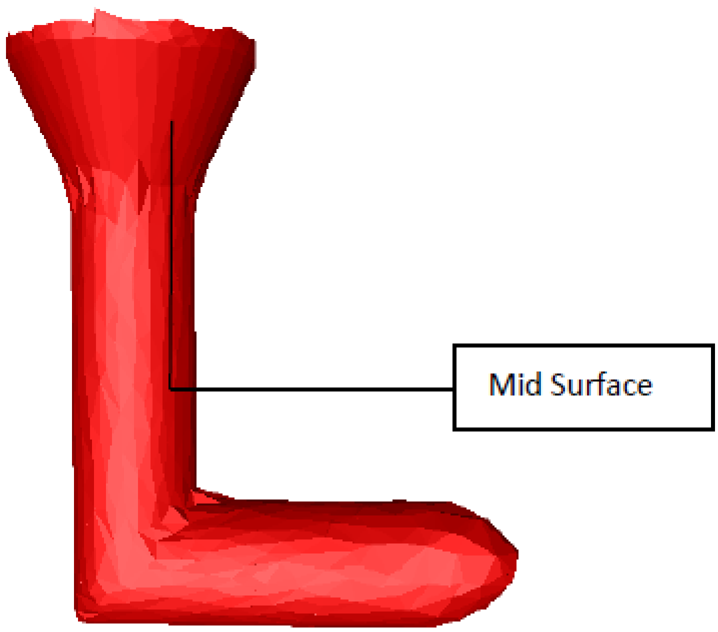


Figure 4. Schematic representation of billet after 1st Pass

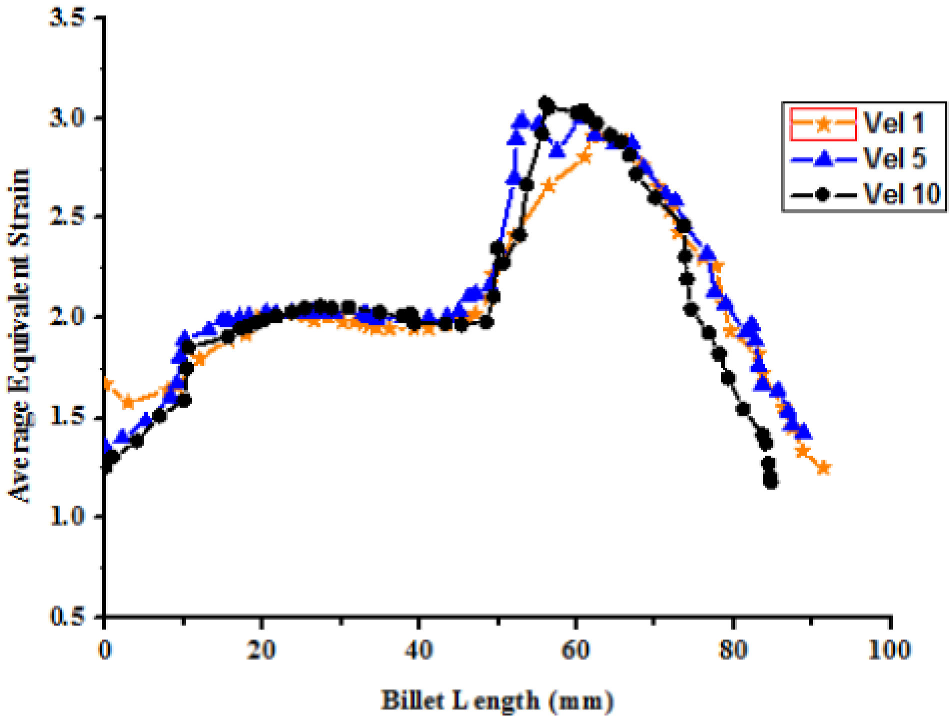


Figure 5. Strain distribution in the billet mid surface in Extrusion-ECAP for Φ = 90° at μ = 0.02 for different plunger velocities

3.2 Variation of Extrusion Force

Figure 6 depicts the variation of extrusion force during 1st pass for Φ = 90° at low friction conditions. 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 cause 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.

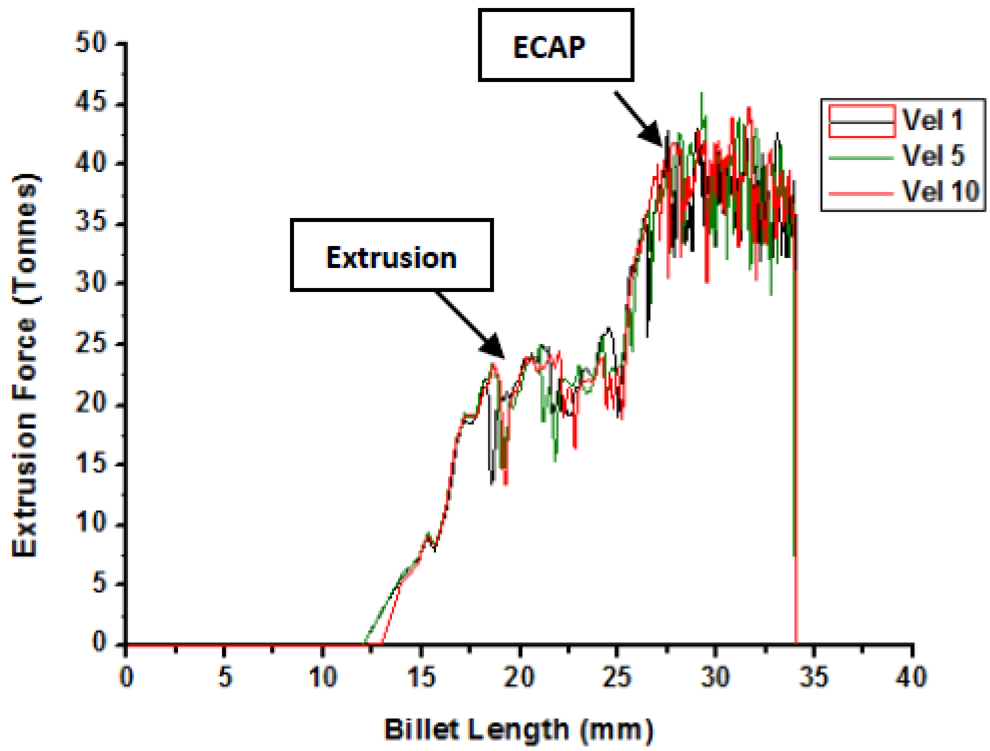


Figure 6. Variation of extrusion force during the deformation process for different plunger Velocities

3.3 Variation of Energy

The variation of energy during Extrusion-ECAP is predicted in Figure 7. It can be seen that energy is constantly increased 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.

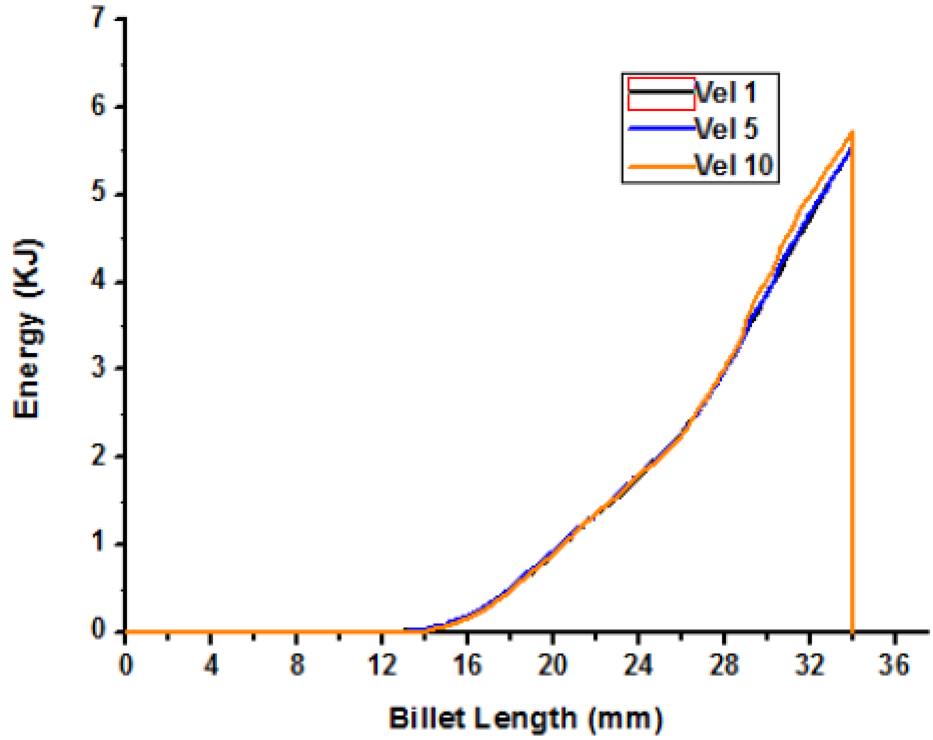


Figure 7. Variation of energy during Extrusion-ECAP for different plunger velocities

4. Conclusions

Severe plastic deformation (SPD) is an important process for creating bulk ultrafine-grained materials. Three-dimensional FE modeling 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 an increase in plunger velocity.
- Plunger velocity of 10 mm/s exhibits higher values of energy as compared to other plunger velocities.
- The front and back end of the billet exhibit less equivalent strain as these regions experience less deformation while a high value of equivalent strain is exhibited in the central part of the billet.

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