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Finite Element Analysis on Aluminium Alloy Subjected to Cyclic Extrusion and Compression Process

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Abstract: Severe Plastic Deformation (SPD) was developed as an effective approach to produce ultrafine grained metals and alloys [1]. A finer grain size after severe plastic deformation increases the mechanical strength, fracture toughness, ductility and fatigue characteristics of the metals and alloys. SPD processed metals and alloy are extensively used in bolts, micro bolts, piston, sport articles and in medical implants [2]. The Cyclic extrusion and compression (CEC) process is used to allow arbitrarily large strain deformation of a sample with retention of the original sample shape and the deformed are examined. In this work Rigid Plastic Finite Element Analysis is done using AFDEX software to investigate the plastic deformation behavior of an aluminum alloy 6061 billet during its axi-symmetric extrusion and compression through a conical die, of an extrusion angle of 45°, the extrusion ratio of 1.77, with the friction factor of 0.05 and frictional coefficient of 0.025.The result shows that the effective strain, effective stress and hardness values increased from 1.6, 156.24MPa, 102 to 6.08,191.33MPa and 112 respectively.

Keywords: SPD, CEC, Effective Strain, Grain Size

I. INTRODUCTION

The properties of metals and alloys are highly influenced by their microstructure which may be modified or altered by alloying elements, by heating or heat treatment or by plastic deformation. For example, metals and alloys may be hardened by plastic deformation. It would, therefore, be helpful if we look at metals at the micro level. Grain size plays an important role in deciding the peculiar properties of material like strength, toughness, hardness and corrosion [3]. A fine-grained material is harder and stronger than one that is coarse grained, because the former has a greater total grain boundary area to impede dislocation motion. For many materials, the yield strength 'σy' varies with grain size according to the equation $\sigma_y = \sigma_0 + K_y d^{-1/2}$ This expression, termed as Hall–Petch equation, where'd' is the average grain diameter, 'σ_0' and 'k_y' are constants for a particular material. Ultra-fine grained (UFG) materials may be defined as polycrystalline materials having average grain size less than ~1μm. The grain sizes of UFG materials may lie within the submicrometer (100-1000 nm) range. Severe Plastic Deformation (SPD) is one of the methods of obtaining very fine crystalline structure in different bulk metals and alloys, which possess different crystallographic structure. SPD causes the formation of micrometer and sub-micrometer sized subgrains in the initially coarse grain materials. As a result of that enhanced mechanical performance is observed. The processing of metals through the application of severe plastic deformation (SPD) has become important in materials research over the last few years. This interest has arisen because SPD processing provides an opportunity for refining the grains of conventional bulk solids to produce grain sizes within the submicrometer (100nm–1.0μm) or even the nanometer (<100 nm) range. Since many of the fundamental characteristics of polycrystalline materials are dependent upon the grain size, SPD processing has the capability of producing materials having unusual and attractive properties. Experimental techniques that are typically used for SPD includes Cyclic Extrusion Compression (CEC), Equal Channel Angular Pressing (ECAP), High Pressure Torsion (HPT), Accumulative Roll Bonding (ARB), Cyclic Closed Die Forging (CCDF), and Repetitive Corrugation and Straightening (RCS) [4]. Fig.1 shows a schematic representation of these methods.

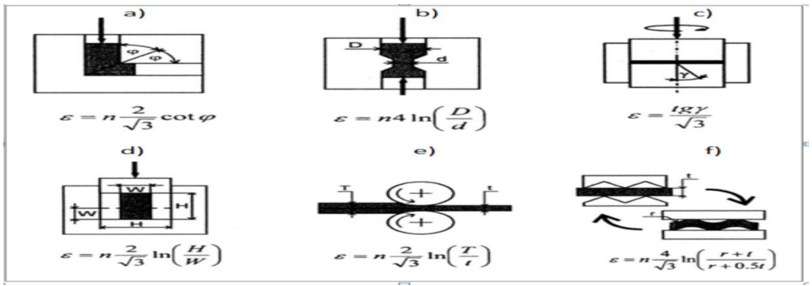


Fig.1 Severe Plastic Deformation methods
a) ECAP, b) CEC, c) HPT, d) CCDF, e) ARB and f) RCS.

II. EXPERIMENTAL PROCEDURE

A. Cyclic Extrusion Compression (CEC) Technique

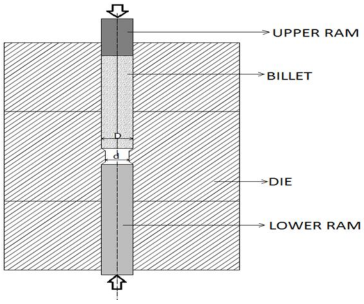


Fig.2 A schematic illustration of Cyclic Extrusion and Compression (CEC) technique

The CEC-method was invented to allow arbitrarily large strain deformation of a sample with the preservation of the original sample shape after n number of passes and the deformed Specimen is examined extensively[5]. In the CEC process, a sample is contained within a chamber and then extruded repeatedly forwards and backwards. The die extrusion angle is 45°. At first, the billet is placed in the die. As the upper ram presses the billet the extrusion process takes place. During this process the chamber diameter (D) is reduced to channel diameter (d), the lower ram compresses the extruded channel diameter (d) to chamber diameter (D) simultaneously. This completes the first cycle of CEC process. The effective strain (ϵ) induced during this cycle is 1.6. During the second cycle, the same deformed material in first cycle is used, the lower ram pushes the billet and extrusion process takes place and upper ram compresses the extruded material to the original diameter. The effective strain (ϵ) induced after second cycle is 3.1. After first cycle the effective strain induced is 1.6 and for 4 numbers of cycles the total effective strain of 6.08 is induced in the billet. By repeating this CEC process, very large amount of plastic strain can be accumulated in the sample without changing its initial dimensions and resultantly, an ultrafine grained structure can be obtained.

The accumulated effective strain is given by,

$$\epsilon = 2(n) ln \frac{D^2}{d^2} \text{...} (1)$$

Or

$$\epsilon = 4\,(n)\; ln\; \frac{D}{d}$$

Where, ‘D’ is the chamber diameter, ‘d’ is the channel diameter and ‘n’ is the number of deformation cycles.

The present study employs ‘AFDEX’ (Adviser for metal Forming Process Design Expert) for the plastic deformation behavior of an aluminum billet during its axisymmetric extrusion through a conical die. AFDEX 2D/3D allows combined 2D and 3D simulations and permits 2D results to be more vividly visualized via a powerful 3D computer graphic utility

III. BASIC EQUATIONS OF RIGID-PLASTIC FEM

This study performs rigid-plastic finite element simulations using AFDEX software. The basic equations of the rigid-plastic finite element are as follows:

A. Equilibrium Equation

$$\sigma_{ij,j} = 0 \text{...} (2)$$

Compatibility and incompressibility equations:

$$\dot{\varepsilon}_{ij} = \frac{1}{2}(u_{i,j}+u_{j,i}),\ \dot{\varepsilon}_v = u_{i,i} = 0 \text{.......................................}(3)$$

Constitutive equations:

$$\acute{\sigma}_{ij} = \frac{2\bar{\sigma}}{3\dot{\bar{\varepsilon}}}\dot{\varepsilon}_{ij},\ \bar{\sigma} = \sqrt{\frac{3}{2}}(\acute{\sigma}_{ij}\acute{\sigma}_{ij}),\ \dot{\bar{\varepsilon}} = \sqrt{\frac{2}{3}}(\dot{\varepsilon}_{ij}\,\dot{\varepsilon}_{ij}) \text{.................}(4)$$

B. Boundary Conditions:

$$\sigma_{ij}n_i = F_j \text{ on } S_F,\ u_i = U_i \text{ on } S_U \text{...................................}(5)$$

where σ_{ij} and $\dot{\varepsilon}_{ij}$ are the stress and the strain velocity respectively, $\bar{\sigma}$ and $\dot{\bar{\varepsilon}}$ are the effective stress and the effective strain velocity respectively, Fj is the force on the boundary surface of S_F, and U_i is the deformation velocity on the boundary surface of S_U.

The weak form of rigid-plastic FEM can be determined by applying the variational method to Eqs. (2) – (5), i.e.

$$\int \frac{(2\bar{\sigma})}{(3\dot{\bar{\varepsilon}})} \dot{\varepsilon}_{ij}\delta\, \dot{\varepsilon}_{ij}dV + \int K\, \dot{\varepsilon}_{kk}\delta\dot{\varepsilon}_{ii}dV - \int_{SF} Fi\delta ui\, dS = 0 \;..\; (6)$$

Where V and S are the volume and the surface area of the material, respectively and K is the penalty constant. The Newton–Raphson iteration method is applied to obtain the solution of the equations.

The frictional boundary condition is given by the vector form:

$$f = -\frac{2}{\pi} mk \tan^{-1}\frac{|Vs|}{u_0} t\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(7)$$

Here m is the friction factor, k is the local flow stress in shear and u_0 is a very small positive number compared to $|Vs|$, in which Vs is the velocity vector of the work piece relative to the die and t is the unit vector in the direction of Vs [6].

IV. ASSUMPTIONS CONSIDERED FOR CEC SIMULATION

The present analyses adopt the following assumptions:

1) The Die is considered as rigid body.
2) The extrusion billet is a rigid-plastic material
3) The friction factors between the extrusion billet, ram, and die are constant i.e., 0.025.
4) The simulations consider the extrusion and compression of aluminum A6061.

V. ANALYSIS AND EXPERIMENTATION

The cylindrical die and workpiece can be simplified to an axisymmetric case. Fig. 3 shows the axisymmetric FEM model for the simulation of the CEC processing. In the present study, D is 20 mm, d is 15 mm and the extrusion angle θ is 45°. The effects of process parameters on the strain were investigated after 4-cycles of CEC. The imported model in Fig. 4 shows the axisymmetric FEM model for the simulation of the CEC processing. It consists of Billet, Die and Upper/lower ram.

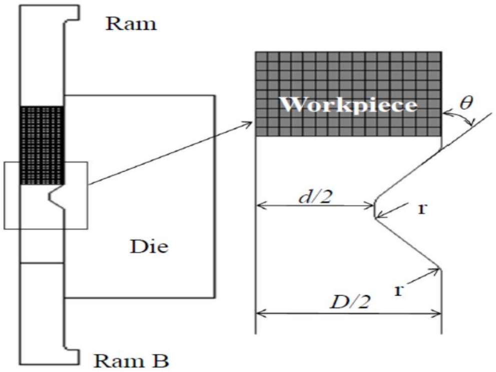


Fig.3 The axisymmetric FEM model for the CEC

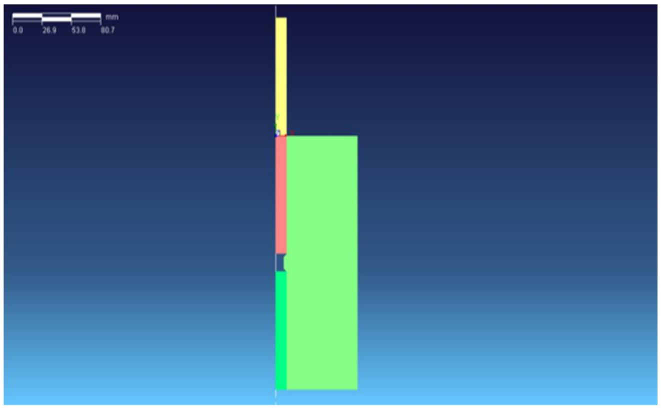
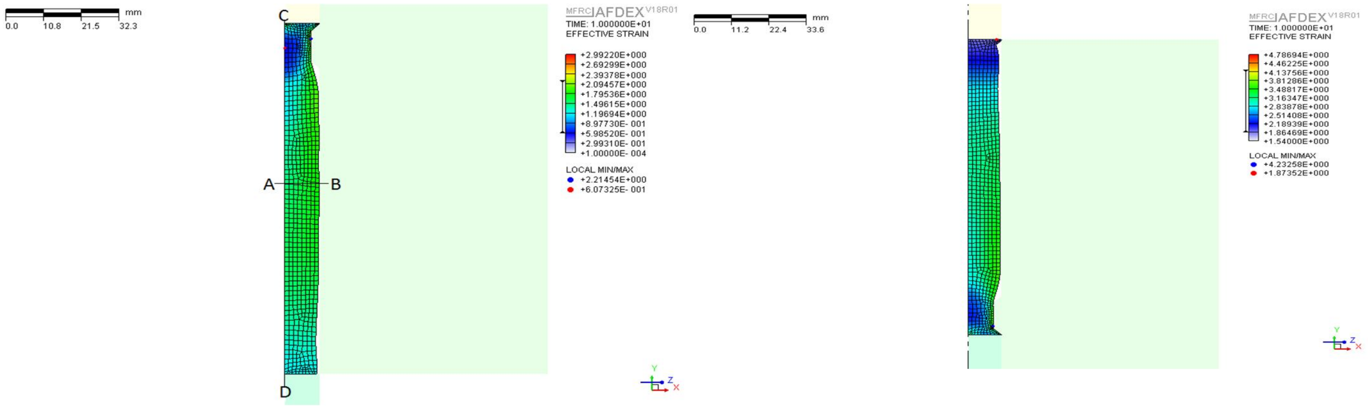


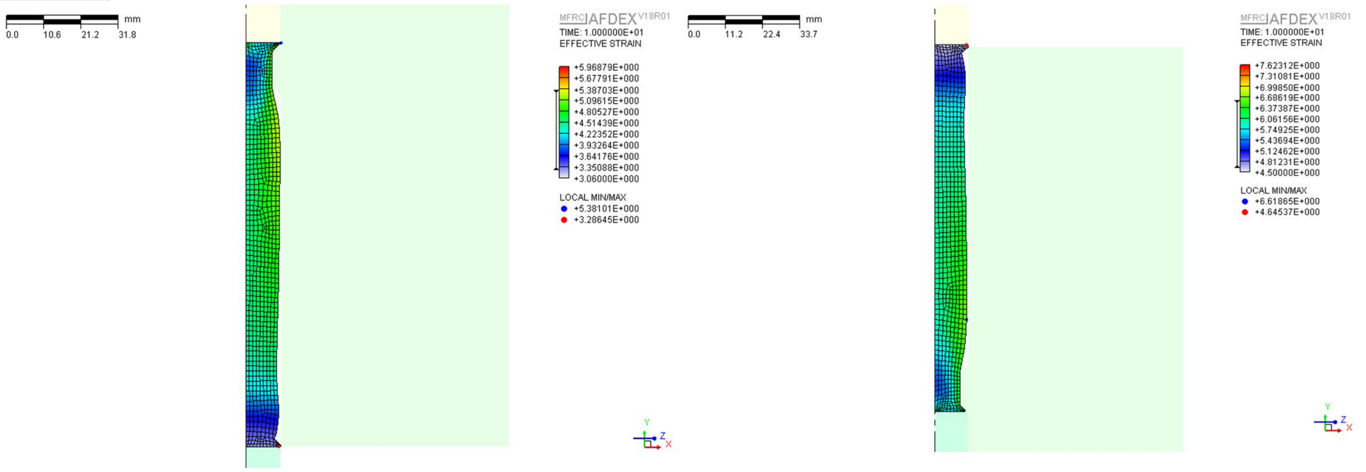
Fig.4 The axi-symmetric FEM model

VI. RESULTS AND DISCUSSIONS

A. Effective Strain

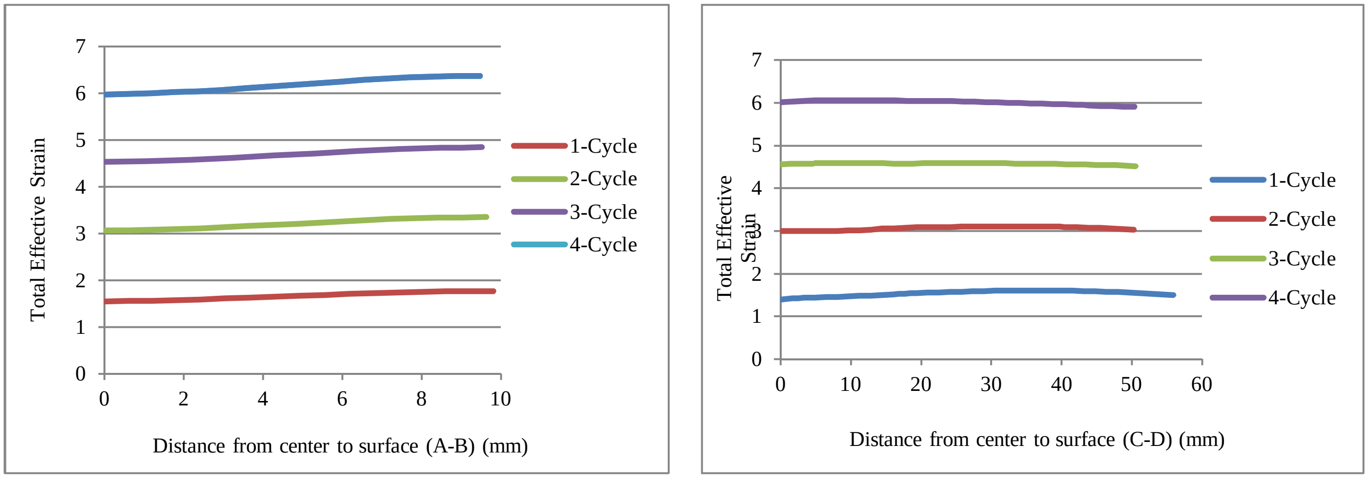


(a) (b)



(c) (d)

Fig.5 Distribution of the effective strain in the workpiece after (a) 1 - Cycle (b) 2 – Cycle (c) 3- Cycle (d) 4- Cycle

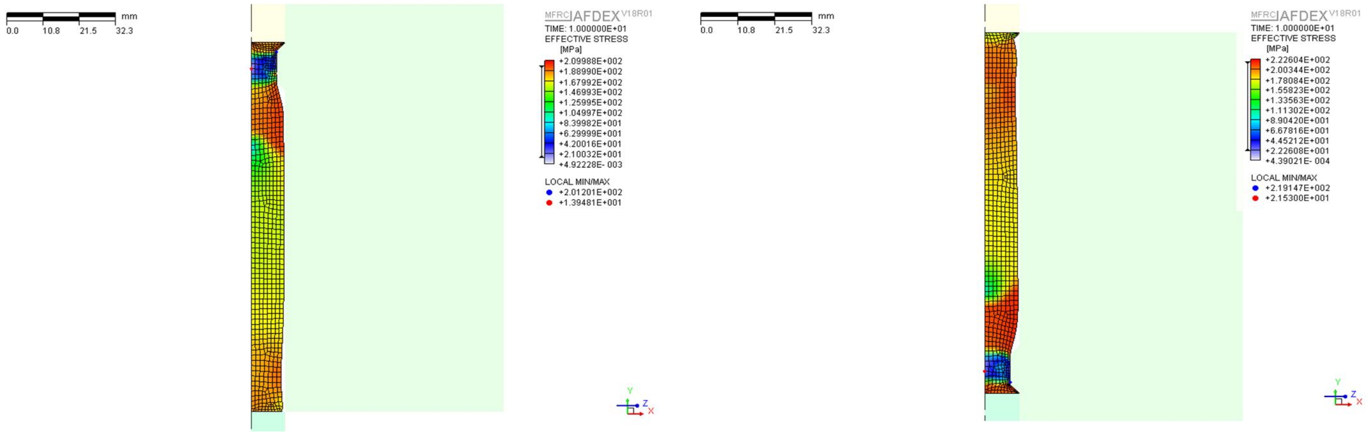


(a) (b)

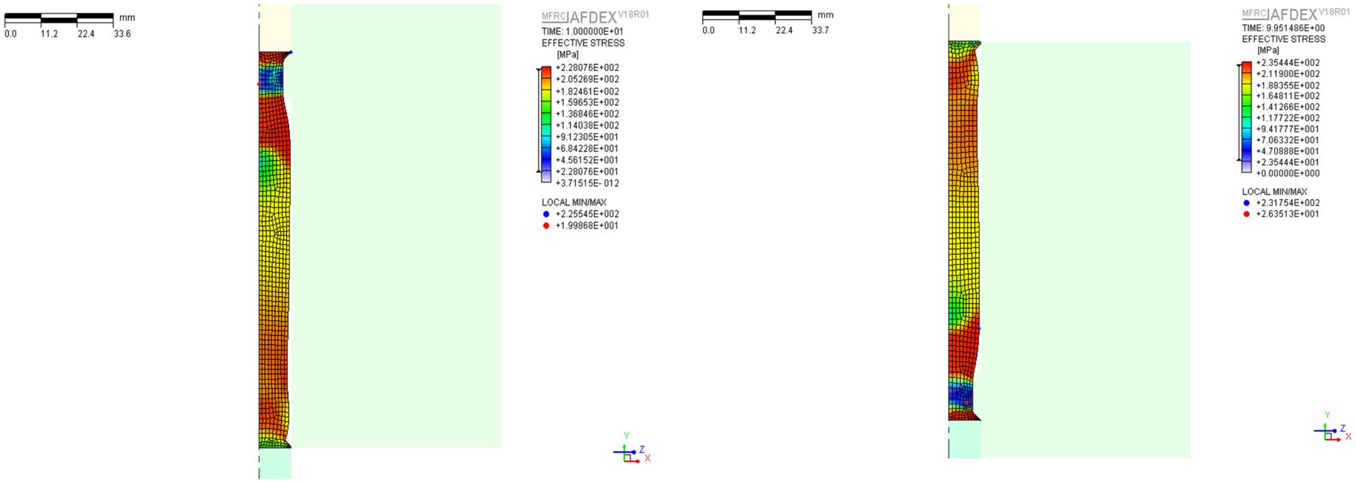
Fig.6 Effective strain distribution of different CEC cycles in x-axis (a) and Y-axis (b)

From the Fig. 5 and 6 it can be seen that the effective strain induced in the material is gradually increased after every cycle. The total effective strain induced after four cycles of CEC process is 6.07

B. Effective Stress

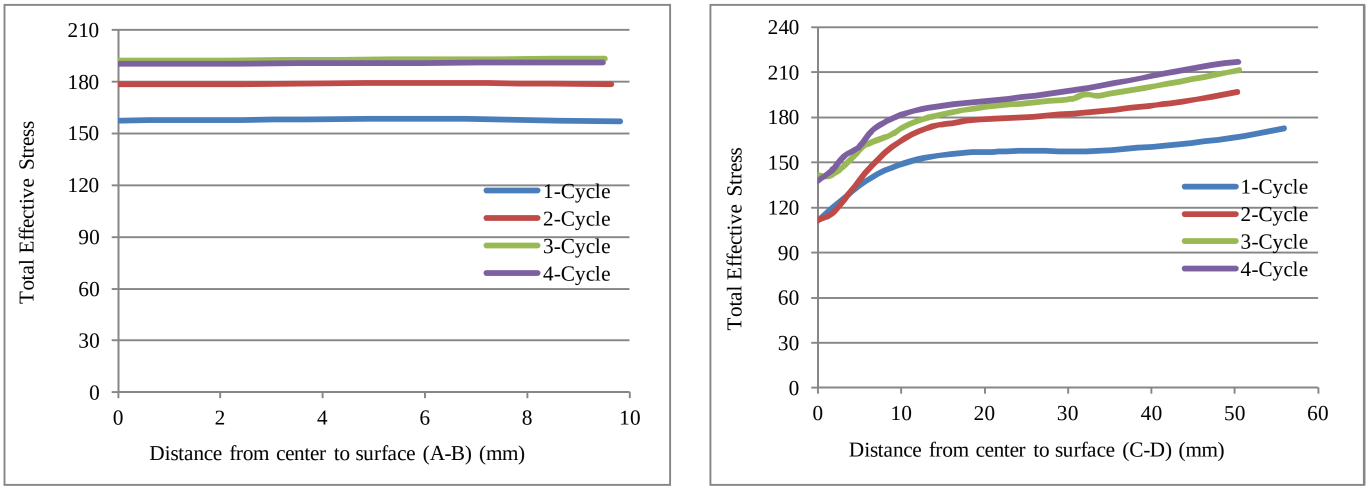


(a) (b)



(c) (d)

Fig.7 Distribution of the effective stress in the workpiece after (a) 1 - Cycle (b) 2 – Cycle (c) 3- Cycle (d) 4- Cycle



(a) (b)

Fig.8 Effective stress distribution of different CEC cycles in x-axis (a) and Y-axis (b)

From the Fig. 7 and 8, it can be seen that the effective stress induced in the material is gradually increased after every cycle. The total effective stress induced after four cycles of CEC process is 191.33MPa.

C. Brinell Hardness

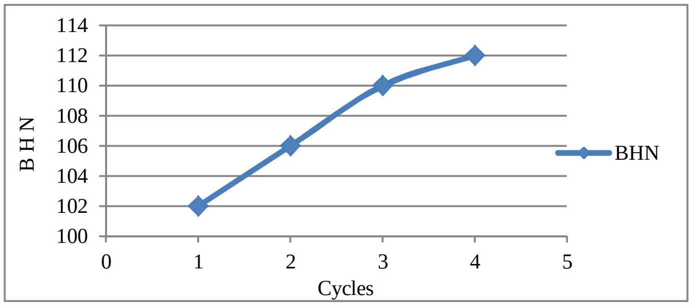


Fig.9 BHN during different CEC cycles

From the Fig. 9 it can be seen that the Brinell hardness number induced in the material is gradually increased after every cycle. The final BHN induced after four cycles of CEC process is 112.

VII. CONCLUSIONS

The following conclusions are drawn by Rigid Plastic Finite Element Analysis using AFDEX software, to investigate the plastic deformation behavior of an Aluminum Alloy 6061 billet during its axi-symmetric extrusion and compression through a conical die.

A. The effective strain has been increased in Aluminum Alloy 6061 billet after every CEC process from 1.6 to 6.08 after 4-cycles. This is because during large plastic deformation the original grain structure of metals develops a microstructure on a much smaller scale. The deformation structures are cell walls, shear bands. Extended dense dislocation walls separating regions of relatively low dislocation densities, between these regions lattice misorientations develop with increasing strain.

B. The effective stress has increased in the billet after every CEC process from 156.24MPa to 191.33MPa after 4-cycles. This is because after every CEC process there will be pre- induced stress in the material this will be added in each cycle.

C. The Brinell hardness number has been increased in the billet after every CEC process from 102 to 112 after 4–cycle. This is because after every CEC process the grain size in the billet will be reduced this leads to increase in the hardness of the material.

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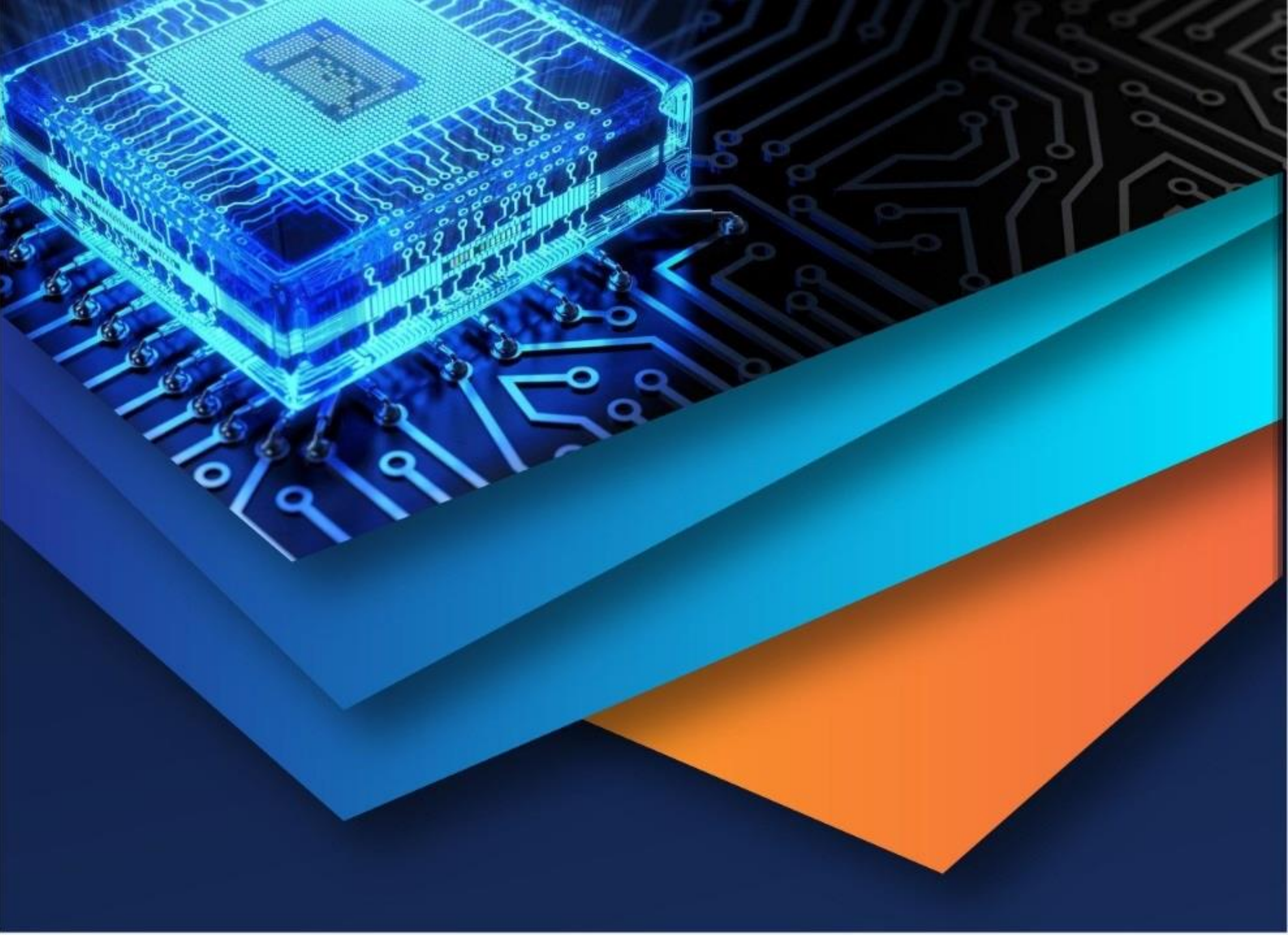

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