International Journal of Mechanical Engineering and Technology (IJMET)
Volume 8, Issue 12, December 2017, pp. 264–273, Article ID: IJMET_08_12_026
Available online at http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=12
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

 Scopus Indexed

NUMERICAL SIMULATION OF OUTER DIE ANGLE OF EQUAL CHANNEL ANGULAR EXTRUSION PROCESS

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ABSTRACT

The study of the simulation of effect of outer die angle in Equal Channel Angular Extrusion (ECAE) process was investigated. The simulation was carried out on 6063 aluminium alloy with a view to achieve ultra-fine grain structures. ADINA user interphase Version 8.6 (900 modes) was used for the simulation. The unextruded parameters of the 6063 aluminium alloy were used as input codes and some basic assumptions were made in designing the model on 2-Dimensional scale. The billet was meshed by dividing the vertical and horizontal geometry into 30 and 4 elements respectively. The die angle was varied from 0^o to 90^o and the simulation results were displayed. The results showed that the force of $27.5X10^6$ N, $27.5X10^6$ N, $27.6X10^6$ N and $31.2\ X10^6$ N was required to deform when the outer die angle was 0^o, 22.5^o, 45^o and 90^o respectively. Also, the strains achieved were 0.61, 0.62, 0.66 and 0.69 respectively. Thus, highest force is required at 90^o and the strain achieved at 0^o is the lowest. Based on the results, it was recommended that it is more economical to extrude at an outer angle between 22.5^o and 45^o as a relatively higher effective strain will be induced.

Keywords: ADINA software, nanostructured materials, ultra-fine grains, simulation, deformation, stress, strain, mechanical properties.

Cite this Article: Abioye O. P, Abioye, A. A, Atanda P. O, Osinkolu G. A and Folayan A. J, Numerical Simulation of Outer Die Angle of Equal Channel Angular Extrusion Process, International Journal of Mechanical Engineering and Technology 8(12), 2017, pp. 264–273.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=8&IType=12

1. INTRODUCTION

A great increase in scientific, engineering and industrial interests in the production of ultra-fine grained and nanocrystalline materials has been observed in the last decades due to the attractive and unique properties of these materials [1]. Some major mechanical properties of ultra-fine grained and nanocrystalline materials are extremely high yield strength, high hardness, improved toughness and ductility with increasing cummulative strain rate [1-4].

Nanomaterials can be fabricated using two fundamental approaches which are (i) the "bottom up approach" as well as (ii) the "top down approach". The bottom-up approach signifies the theory of building a nanomaterial from basic building block like the atoms or molecules. The other approach is the top- down approach which comprises reformation of a bulk material so as to produce a nanostructure. The most significant method out of the two approaches is the "top-down" approach. The top-down approach is the origin of severe plastic deformation (SPD) [5].

Severe plastic deformation (SPD) processes are the processes which allows very high deformations to be introduced into a material without the cross-section getting modified [6]. The mechanical properties of processed parts can be improved by SPD processes; this is done by having the metallographic grain size of the materials reduced. This process can also be used to introduce a lot of plastic strains in the processed part. The more the deformation introduced in the part, the more the density of dislocations and therefore, the grain size reduces. Thus, improved mechanical properties are achieved [7].

Many traditional methods of SPD, which includes rolling, drawing or extrusion cannot meet the requirements of forming nanostructured materials. Nanostructures formation in bulk samples is quite challenging and sometimes not possible except through the application of special mechanical method of deformation provided that large deformations at comparatively low temperatures as well as in short of determination of optimal regimes of processing the material.

Equal channel angular extrusion (ECAE) is one of the most commonly used SPD processes. In Equal Channel Angular Extrusion process, the material is extruded through two channels (entrance and exit) that intersect at an angle. The cross section of the two channels have approximately the same dimension. The ECAE process can be used to introduce severe plastic deformation (SPD) within a part in so as to reduce the grain size and thus, improve the mechanical properties of the processed material. This technique can be applied to commercial pure metals and metal alloys [8].

Deformation in ECAE is quite complicated, thus Finite Element Analysis is a key enabler in understanding the deformation process. Finite element method is one of the important approaches to understand the deformation occurring in the ECAE process [9]. Some FEA-based analyses have been done by several researchers so as to understand how the materials behave during deformation and to assess the strain developed in the ECAE process. The parameters investigated by the researchers earlier include the influence of material model, the effect of friction on material flow, the effect of the channel angle on the deformation of work-piece and the effect of back pressure on the strain [10-13]. Although some researchers [13] acknowledged that radius of outer corner of the die affect the deformation, more details is required on how and why this is so. An FEA analysis with a more precise software is helpful in achieving this aim.

FEA provides direct information on the evolution of plastic deformation during the ECAE and also, enables the simulation of the deformation of materials which are subjected to single or multi-pass ECAE [14].

2. EXPERIMENTAL PROCEDURE

The simulation of Equal Channel Angular Extrusion was carried out varying the outer die angle so as to have a good understanding how the outer die geometry impacts the ECAE process. The simulation was done using the Automatic Dynamic Incremental Nonlinear Analysis (ADINA®) software. The ADINA® software makes use of Finite Element Analysis (FEA) for its analysis.

2.1. Preprocessing

The ADINA® user interphase (AUI) version 8.6 (900 nodes) was opened on the personal computer so as create the ADINA® environment. The program module chosen was ADINA® structure. A heading was given to the simulation.

The following assumptions were made during the simulation process:

1. The material was initially homogeneous
2. The material is bilinear elastoplastic
3. There is no friction between the surface of the material and the die wall due to the use of lubricant in the Equal Channel Angular Extrusion process
4. Von Mises flow rule is used to construct the constitutive relation.

The model was designed based on a 2-dimensional (2-D) scale. The geometry of the die and billet used for the ECAE experiment was plotted on an X-Y scale graph so as to obtain the points and lines needed for the model. The geometry of these points and lines which made up the die and billet were defined in the AUI. The model was then developed.

The mechanical properties (Young Modulus, Initial yield stress) of the unextruded aluminum 6063 were recorded. The Poisson’s ratio was obtained from literature. These properties were then fed into the model so as to use them in defining the properties of the billet in the model. The Young’s Modulus is 4.70426598E+09 pa, Poisson ratio is 0.33, yield stress is 9.20044E+07 Pa and the strain hardening modulus of 1.768521045E+09 Pa. The die was defined as a rigid material.

Meshing was done so as to divide the model into little sub problems that can be formulated easily. After which the problem can be carefully combined and analyzed. The billet was meshed by dividing the vertical and horizontal geometry into 30 and 4 elements respectively. A total of 120 elements were used. The contact planes were also meshed with 3 nodes per segment. The total number of nodes used was 579. Size of the mesh fineness chosen was such that distortion or divergence in elements during simulation was avoided. The meshing was done in such a way that the mesh density is not too low or too high. An optimal meshing density was thus chosen according to the geometry and size of object.

Load was applied on the billet in the die in form of displacement downwards in the vertical direction. A constant ram speed of 0.02 mm/s was imposed.

2.2. Analysis

The data earlier inputed in the preprocessing stage was now used as the input code for ADINA® processor. The ADINA® processor then solved the nonlinear problem at every node during the deformation process. The analysis was done by the ADINA® software. Effective strains (ε_N) were calculated using Equation 1; where N is the number of ECAE passes, $\emptyset$ is the inner die angle and ψ is the outer die angle.

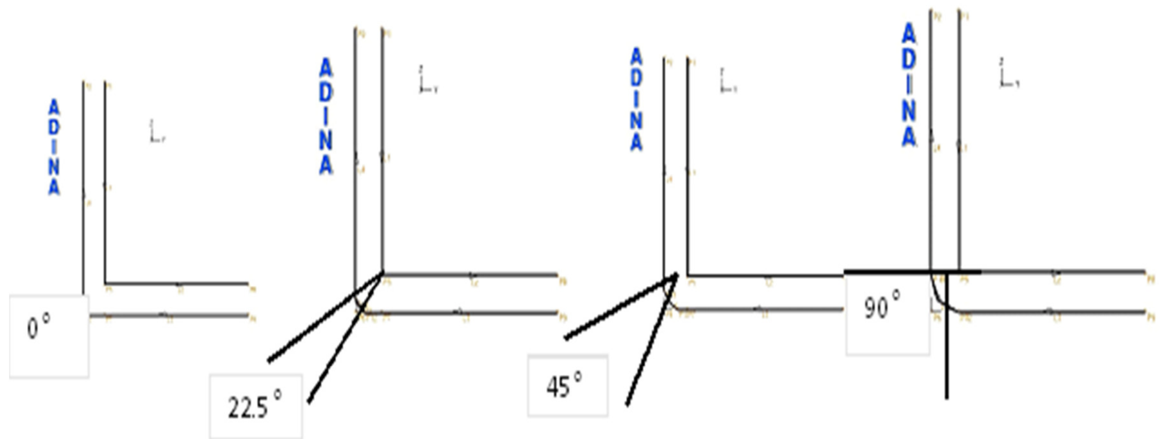
$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right) + \psi\csc\left(\frac{\emptyset}{2} + \frac{\psi}{2}\right)\right] \quad (1)$$

2.3. Post processing

The program module was then changed to postprocessing module whereby the ECAE process was played and the final extrusion result was displayed on the screen. A snapshot was done and this was saved accordingly. The billets properties at the different nodes in the inner (billet part close to the inner sharp corner of the die), middle (billet part in the middle of the billet) and outer part (billet part close to the outer corner of the die) of the billets were recorded and studied for further analysis and inferences.

2.4. Varying outer die angle

All the processes in the simulation process as discussed earlier were repeated in other simulations whereby the outer die angle was varied. The simulation was done when the outer die angle ψ= 0°, 22.5 °, 45 ° and 90 ° as shown in Fig. 1 (a,b,c and d).



(a) (b) (c) (d)

Figure 1 Geometry of the die when the outer die angle
(a) y = 0° (b) at y = 22.5° (C) at y = 45° (d) at y = 90°

3. RESULTS AND DISCUSSION

Results from ADINA® showing the distributions of equivalent plastic deformation (stresses and strains) after the ECAE are presented in the Fig. 2 (a, b, c and d).

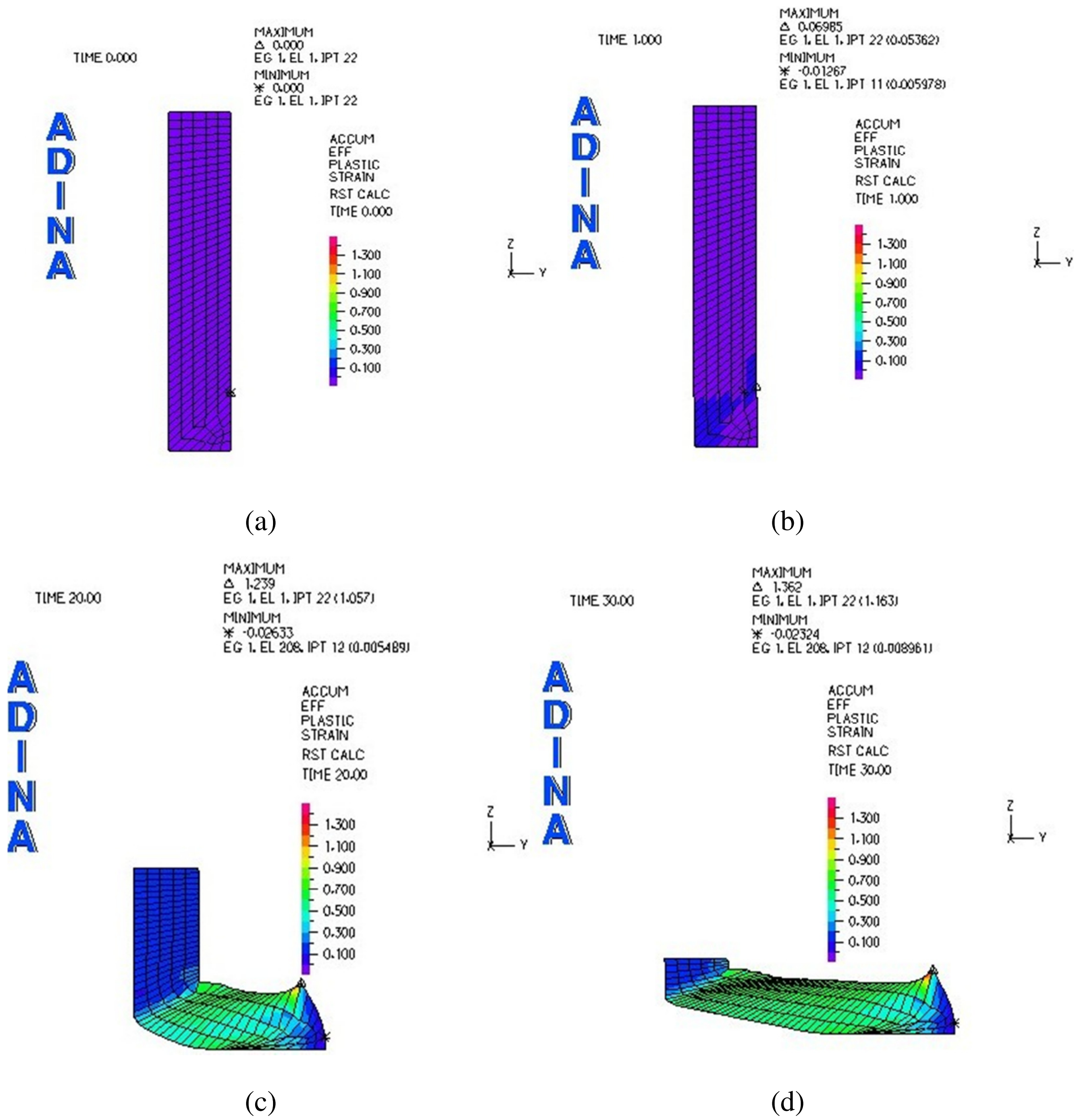


Figure 2 Distribution of accumulated effective plastic strain at different times (a)Initial stage (b) after 1 second (c) after 20 seconds (d) after 30 seconds

It was observed that plastic deformation is non-uniformly distributed along the cross-section and also the length of specimen.

Effect of the outer corner angle on the pressing force

From the graph in Fig. 3 showing the force against time, it was observed that during the ECAP process, the force increases and reached a peak towards the end of the experiment which dropped a little at the completion of the experiment.

From the ECAP at 90^{o} done at different outer die angles (that is 0^{o}, 22.5^{o}, 45^{o} and 90^{o}), Table 1 shows the pressing force that deformed the billet at each conditions. It was observed that more force was used in pressing the billet when the outer angle was 90^{o}. Also, the Maximum deforming force at outer angles 0 ^{o}, 22.5 ^{o} and 45 ^{o} are approximately the same.

This could be said to be as a result of the reduced channel dimension at the angle which therefore enabled the billet to make a very close contact with the die thus making it difficult for the billet to go through the die (as shown in Fig. 4).

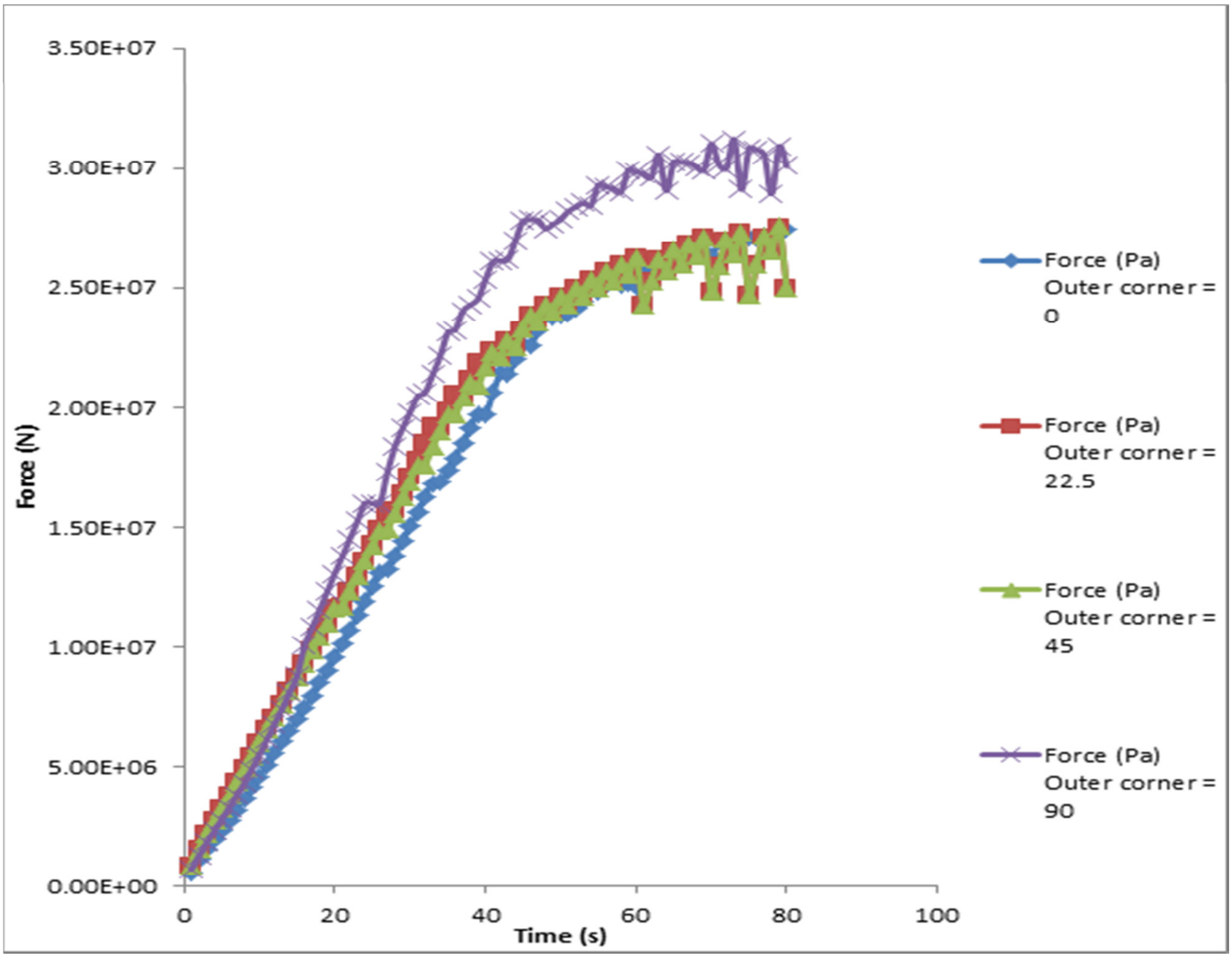
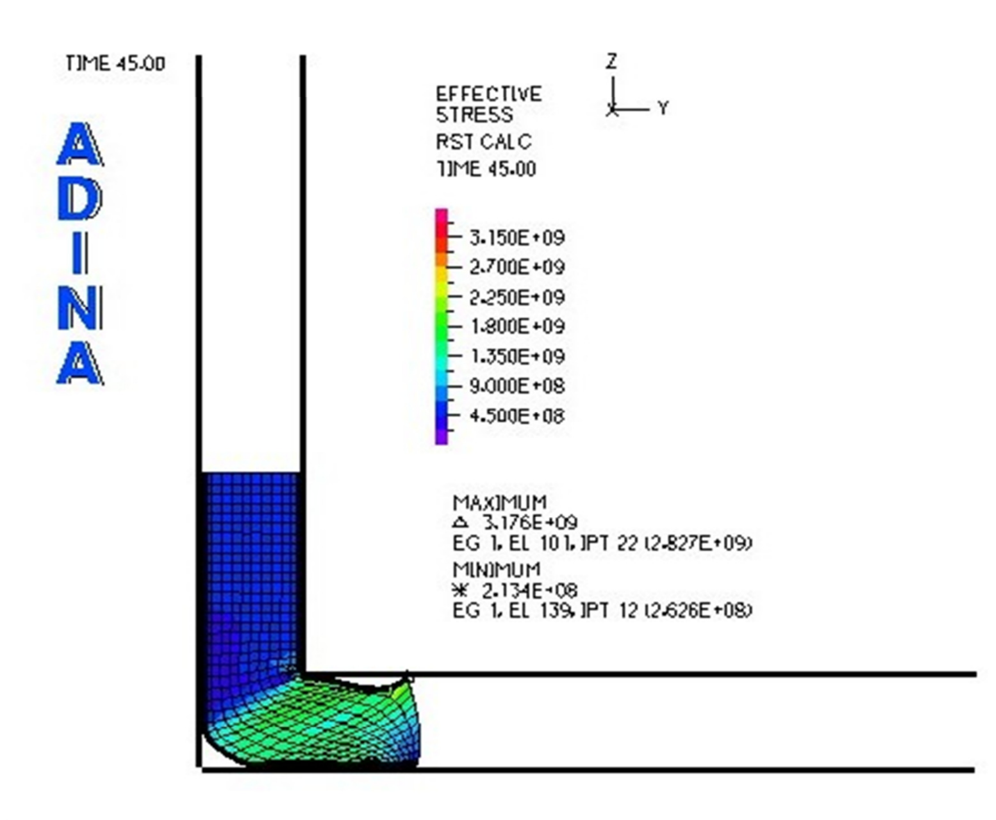


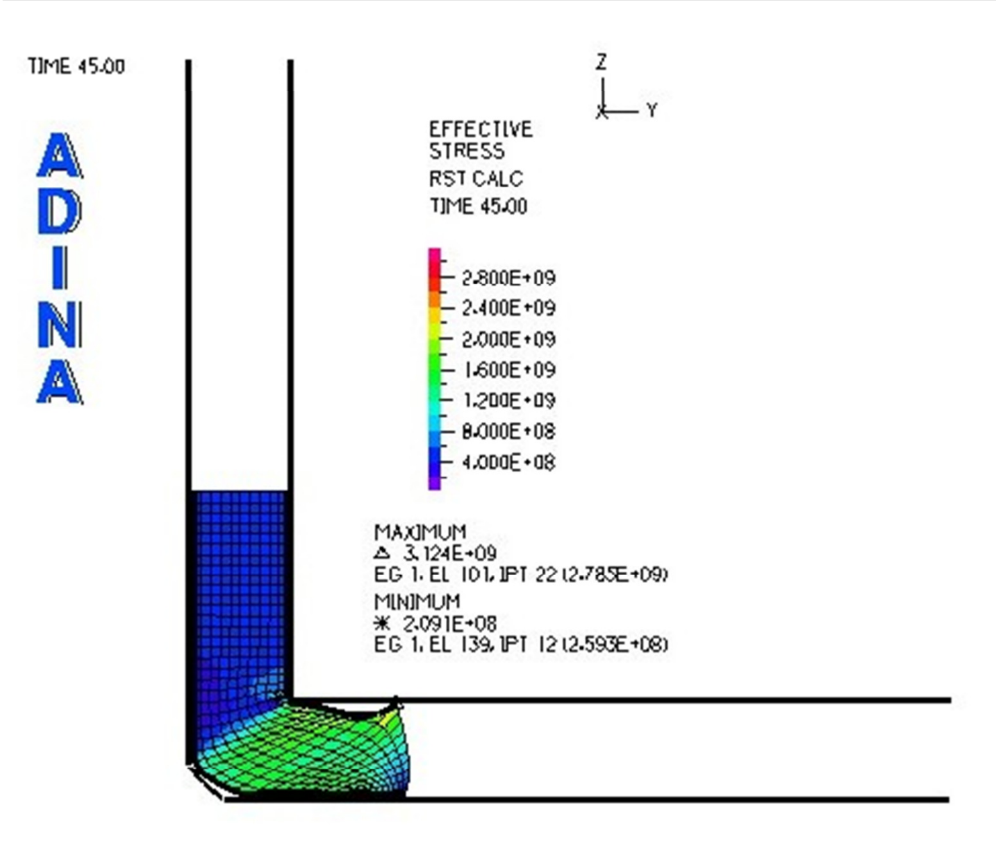
Figure 3 The graph of the pressing forces acting on the modeled workpiece for outer die angle, y = 0°, 22.5°, 45° and 90°

Table 2 Effect of varying outer die angle on the deformation

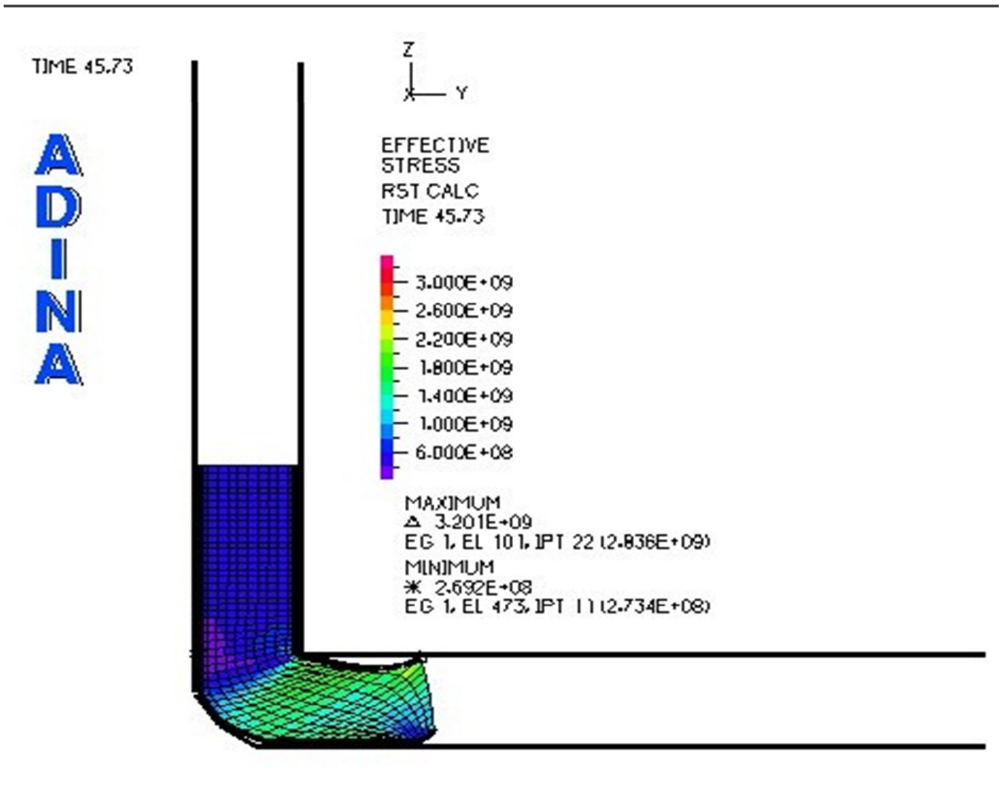
Outer Die Angle	Maximum Deforming Force (N)	Average Accumulated Effective Plastic Strain
0 °	2.75E+07	0.61
22.5 °	2.75E+07	0.62
45 °	2.76E+07	0.66
90 °	3.12E+07	0.69


TIME 45.00
ADINA
EFFECTIVE
STRESS
RST CALC
TIME 45.00
Z
Y
3.150E+09
2.700E+09
2.250E+09
1.800E+09
1.350E+09
9.000E+08
4.500E+08
MAXIMUM
△ 3.176E+09
EG 1, EL 101, IPT 22 (2.827E+09)
MINIMUM
✳ 2.134E+08
EG 1, EL 139, IPT 12 (2.626E+08)

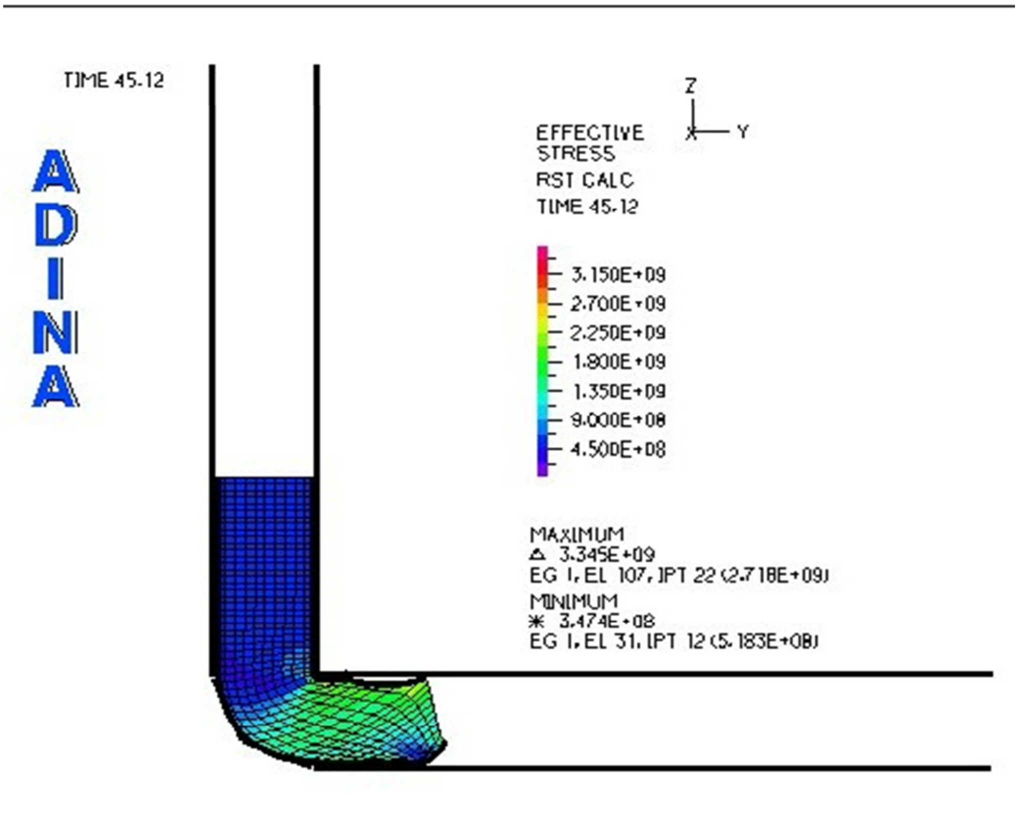
(a)


TIME 45.00
ADINA
EFFECTIVE
STRESS
RST CALC
TIME 45.00
Z
Y
2.800E+09
2.400E+09
2.000E+09
1.600E+09
1.200E+09
8.000E+08
4.000E+08
MAXIMUM
△ 3.124E+09
EG 1, EL 101, IPT 22 (2.785E+09)
MINIMUM
✳ 2.091E+08
EG 1, EL 139, IPT 12 (2.593E+08)

(b)



(c)



(d)

Figure 3 Simulation at different ψ values where at (a) y = 0 ^{o}, (b) y =22.5 ^{o}, (c) y =45 ^{o} and (d) y = 90 ^{o}

The effective strain increased as the outer angle increased.

It is thus advised that it is more economical to extrude at an outer angle between 22.5 ^{o} and 45 ^{o} in that a relatively higher effective strain will be induced in the billet.

4. CONCLUSION

A finite element analysis (FEA) has been carried out in order to investigate the plastic deformation behaviour of the work-piece during the ECAE process.

From mathematical simulations of ECAE process by FEA, it was observed that the effective plastic deformations depend largely on the outer die geometrical of ECAE die.

From the results, it was observed that more force is needed for deformation as the outer corner angle increases. Also more effective plastic strains were accumulated as the corner angle increases which thus leads to increase in dislocation introduced in the material leading to improving the mechanical properties in the material.

AKNOWLEDGEMENT

We acknowledge the financial support offered by Covenant University in actualization of this research work for publication.

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