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Shear Strain Model for Equal Channel Angular Pressing in High Elastic Extruded Plastics

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ABSTRACT

This paper presents a novel model for plastic shear strain calculation in the Equal Channel Angular Pressing (ECAP). The model is particularly formulated to furnish for the elastic recovery after extrusion. Due to high elastic recovery after plastic deformation in polymers, the behavior of Teflon and Nylon is investigated at different temperatures as they are famous for their low coefficient of friction and wall friction effects. The main concentration is given to the basic principle of ECAP processing parameters such as strain, slip bands, and shearing patterns. In this research, a new engraved circle marking technique is used to trace the plastic deformation in the specimens. Afterwards, image analysis approach is applied to measure the deformation, strain and rotation after extrusion. The experimental results are validated with the ABAQUS based numerical simulation. A close conformity is found between them.

1. Introduction

Equal Channel Angular Processing (ECAP) is typically used to strengthen light aluminum alloys by grain refinement using severe plastic deformation technique [1-6]. It is used in extrusion dies as well as rolling. Different models have been proposed to analyze the plastic deformation and shear strain produced during the process.

To properly carry out the deformation processes, one should know the effect of die parameters and elastic recovery of the material. For these reasons, highly elastic recovery materials like Teflon and Nylon are used to carry out the experimentation at initial level and a simple model is presented, that would be later on implemented on Aluminum 6061. Most of the models in the literature [7-11] do not take into account the elastic recovery of the material once it exits the ECAP die. The new proposed model will take this into account especially if the elastic recovery phenomenon is pronounced.

To verify the models, different techniques, i. e. Cyclic Extrusion Compression (CEC), High Pressure Torsion (HPT), Accumulative Roll-Bonding (ARB), Repetitive Corrugation Straightening (RCS) and Multi-Axial Compression/Forging (MAC/F) [12] are used to track the deformation in the specimens. Equal Channel Angular Pressing method introduced by Segal in the early 1980s is the most effective and dominant technique for Severe Plastic Deformation (SPD) Valiev used ECAP as an SPD technique for generating nanostructures in bulk samples and billets. Many material strengthening techniques such as rolling, forging, extrusion, and precipitation hardening are commercially available over the decades. These strengthening techniques are based on mechanism of micro-structural refinement by severe plastic deformation [13, 14]. The ECAP method used for material strengthening and deformation, is affected by many of the parameters such as, geometry of die angles (ϕ, Ψ), temperature, nonlinearity of metallic materials, friction between the billet and die channels and the profile of plungers [15]. Another important feature is that the cross-sectional area of the specimen after passing through ECAP doesn't change. Simple shear load is the dominant mechanism of ECAP to obtain high strains in the material. The primary objective of the ECAP process is to obtain desired mechanical properties and special textures in light Al alloys by producing Ultra Fine-Grained (UFG) structure. In ECAP method, the pressing of the specimens is being done in the form of a square section bar through a channel, which is bent through an abrupt angle inside a die [16-18]. To evaluate equivalent shear strain equation 1 is suggested by Segal et al. for ECAP [19] ;

$$\gamma_{xy} = 2N\cot\frac{\emptyset}{2} \tag{1}$$

* Corresponding author

γ_{xy} = Equivalent shear strain,

N = Number of passes,

ϕ = Die angle

The equation 1 can be transformed into equation 2 and 3 for evaluating effective strain using Von Mises criterion [17, 20, 21].

$$\varepsilon_{eff} = \sqrt{\frac{2}{3}\left(\varepsilon_x^2 + \varepsilon_y^2 + \varepsilon_z^2 + \frac{\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{xz}^2}{2}\right)} \quad (2)$$

$$\varepsilon_{eq} = \frac{1}{\sqrt{3}}\gamma_{xy} = \frac{2N}{\sqrt{3}}cot\frac{\emptyset}{2} \quad (3)$$

Where ε_x, ε_y, ε_z, are the normal strain components and ε_{eq} is the total equivalent strain.

It was observed that when a billet is pressed through both of the ECAP die channels, the speed of the billet remains the same and at the intersection of both the channels a plastic zone developed which plays a vital role for the grain refinement. The pressure of the punch and load both depends upon the characteristics of the material, the friction between billet and channels of the die, the shape of the billet, die angles, and flow of materials [20]. According to Segal, the strain rate is necessary to describe the material behavior during ECAP.

Segal presented a slip line theory that the billet advances gradually through both of the channels with the same speed, *V*, and the plastic zone developed at the crossing plane of the channels. Punch pressure and load depends on material characteristics, friction, die design and billet shape. According to Segal, the strain rate is necessary to describe the material behavior during ECAP.

The equation 4 is used to determine the value of shear strain after each ECAP pass.

$$\frac{P}{Y} = \Delta\varepsilon_i = {}^{2}\!/_{\sqrt{3}}\, cot\left({}^{\emptyset}\!/_{2}\right) \quad (4)$$

P = Pressure, Y = Flow stress of the deformed material.

The pressure can be calculated by considering the friction between the material and die channel by using equation 5 [22]:

$$P = \tau_0(1+m)\left[2cot\left(\frac{\emptyset+\psi}{2}\right) + \Psi\right] + 4m\tau_0\left(\frac{l_i+l_o}{2}\right) \quad (5)$$

To understand the material deformation, orientation and behavior when processed through ECAP, a lot of researchers performed computer based simulation techniques. Prangnell et al [21], presented a simplified finite element model, which had been used to investigate the ECAP process. Bowen et al. [22], studied the deformation of ECAPed billet under various conditions by both finite element analysis and experiments.

1.1 Role of Die Corner Angle and Evaluation Techniques

For any given die angle (ϕ), the minimum and maximum values for die corner angle Ψ can be between 0 to (π-ϕ). The die corner angle (Ψ) can be modeled by specifying an equivalent fillet radius in the main deformation zone. The die corner angle and fillet radius play vital role in the grain refinement. The equation 8 shows the relationship between the die corner angle (Ψ) and the fillet radius (r) for any ECAP channel with a die angle (ϕ) and width (L) as shown in Fig. 1 [23].

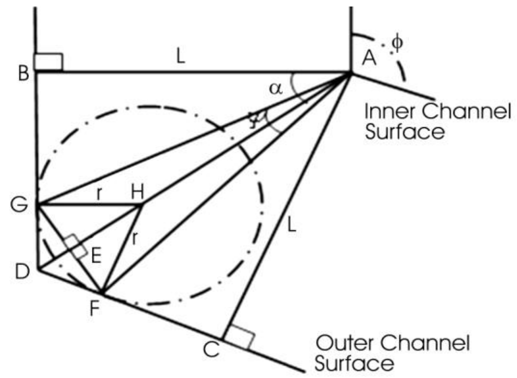

Fig 1: Relation between corner angle (Ψ) and fillet radius (r) for any channel angle (ϕ) [23]

$$\psi = 2Tan^{-1}\left[\frac{rcos\left(\frac{\phi}{2}\right)\sin\left(\frac{\phi}{2}\right)}{L - rcos^2\left(\frac{\phi}{2}\right)}\right] \text{----} \quad (6)$$

Different techniques are being employed to understand the material deformation behavior during ECAP process. One technique is the engraved surface that was aligned with the symmetric plane of the die and observed the rotation of axis. Other researchers used engraved square shape, line patterns, slip lines technique in the specimen but in this research the engraved circular cross-section, filled with lead balls, was used to observe the rotation of axis when billets were pressed through the ECAP die. The model follows the work by Xia and Wang [1] and is a modification of the model described by them.

1.2 Engineering Shear Strain in ECAP

1.2.1 Mathematical modeling

In general the flow of material through die under process is shown in Fig. 2a schematically.

If V_1 is considered to be equal to V_2 as the material is incompressible, any line parallel to Oo will remain parallel to Oo after passing through the section as shown in Fig. 2b.

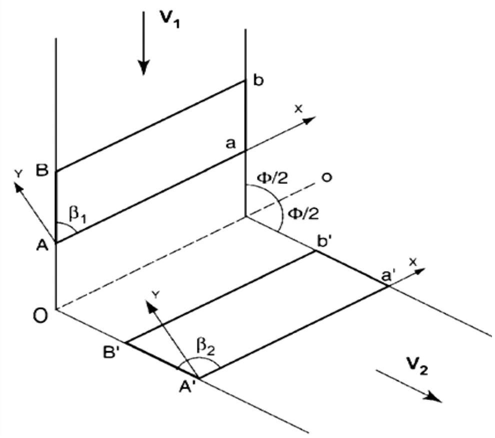

Fig. 2a: Flow of material through ECAP die [1]

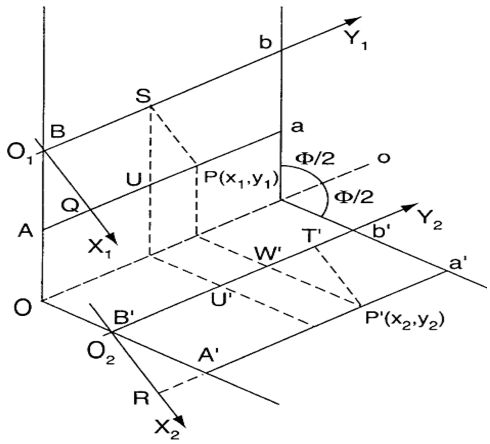

Fig. 2b: The ECAP process showing material flow direction and coordinate transformation [1]

The shear strain is defined as γ = Tan ϕ. By using ECAP method, two channels in the die are intersecting at an angle of "ϕ" as shown in Fig. 2a, then the shear produced inside will be equal to $\gamma = 2\cot(\phi/2)$, where ϕ is the die angle.

The principal strains and rotations can be evaluated using the equation 9 through 13:

$$\varepsilon 1 = \ln[(Sin\phi/2)/(1 - cos\phi/2)] \qquad (7)$$

$$\varepsilon 2 = \ln[(Sin\phi/2)/(1 + cos\phi/2)] \qquad (8)$$

$$\text{Tan}\alpha = [(1 + \cos\phi/2)/\text{Sin}\phi/2] \qquad (9)$$

$$\xi = \left(\frac{\pi}{2} - \frac{\phi}{2}\right) \qquad (10)$$

Considering Fig. 2 (a) & (b)

$$\text{Tan}\,\alpha = [1 + \text{Cos}(\phi/2)]/\,\text{Sin}(\phi/2) \qquad (11)$$

1.2.2 Evaluating major and minor axis of the ellipse formed during ECAP process

When a circle with plane placed parallel to the loading axis in the ECAP die and after passing through the die channels transforms into an ellipse as shown in Figs. 5a and 5b. Equations 14 and 15 are used for evaluation of the major axis (R_1) and minor axis (R_2) of the so formed ellipse.

$$R_1 = (R_o\, Sin(\phi/2))/(1 - Cos(\phi/2)) \qquad (12)$$

$$R_2 = R_o Sin(\phi/2)/(1 + Cos(\phi/2))R_2 \qquad (13)$$

Now if $\phi = \pi/2$

$\alpha = 67.5^o$

$\xi = \pi/2 - \alpha = 22.5^o$

2. New Proposed Model to Evaluate Shear Strains and Effects of Recovery Angle

The models presented in the literature review above do not take into account the elastic recovery phenomenon in materials like Teflon and Nylon. The model proposed by Xia and Wang [1] is modified and a factor taking into account the elastic recovery is added. This model is then experimentally verified by carrying out ECAP tests on Teflon and Nylon at different temperatures. The experiments conducted are witnessed of a high elastic recovery. Hence if no plastic deformation or rotation takes place then $\xi = 90^o$. For complete shear stress it will be 22.5^o. Thus any recovery will be greater than the value of 22.5^o . This recovery is termed as $\Re$, thus if angle $\xi' = 35^o$, then recovery $\Re$ and shear strains are evaluated using equations 16 through 16.

$$\acute{\xi} = \xi - \Re = \alpha - \left(\pi/_2 - \Phi/_2\right) - \Re \qquad (14)$$

$$\epsilon_1 = \ln\left[\frac{Sin\left(\frac{\Phi}{2}+\Re\right)}{1-Cos\left(\frac{\Phi}{2}+\Re\right)}\right] \qquad (15)$$

$$\epsilon_2 = \ln\left[\frac{Sin\left(\frac{\Phi}{2}+\Re\right)}{1+Cos\left(\frac{\Phi}{2}+\Re\right)}\right] \qquad (16)$$

The ECAP of Teflon and Nylon is carried out at different temperatures to check the behavior, deformation, orientation, and elastic recovery of the materials [24, 25]. A process of following the deformation in the material is described and analyzed using image processing analysis technique. A billet of cross-section 20x20x120 mm^3 were pressed through the ECAP die and there is an abrupt change in the path of the billet known as pressing regimes that deformed the billet and increases the mechanical strength without adding alloying elements.

3. Experimental Setup

The Teflon and Nylon specimens with 120 mm in length and 20 x 20 mm^2 in cross-section are used, the shear deformation behavior of the materials when pressed through ECAP die is shown in Fig. 3, using die angle Φ = 90 degree and corner angle ψ = 22 degree for a single pass is evaluated. The deformation is in the formation of an ellipse that is due to the shearing of the material when passed through the ECAP die. Normal strain, and shear strain is evaluated, along with this, the major axis and the minor axis, due to the formation of the ellipse are determined.

3.1 Tensile Tests of the Materials

The tensile tests of the materials are performed at room temperature as per ASTM E8M standard. The basic results are shown in the Table 1.

Table 1: Material Properties at 25^0C

Sr. No.	Name of Material	Yield (MPa)	UTS(MPa)
TF-1	Teflon	6.82	17.82
TF-2	Teflon	6.58	16.99
TF-3	Teflon	6.75	17.56
NY-1	Nylon	13.48	30.79
NY-2	Nylon	13.60	30.08
NY-3	Nylon	13.55	30.54

3.2 Preparation of ECAP Specimen

The specimens of Teflon and Nylon having cross-section 20 × 20 × 120 mm^3 (HWL) were prepared in two parts with cross-section 10 × 20 × 120 mm^3, and then multiple circular slots were machined in the specimens to insert lead balls as shown in Fig. 3.

Fig. 3: Un-deformed specimen filled with lead balls

3.3 Deformed ECAP Specimen

Behavior of the circles after passing through ECAP die can be observed in Figs. 5a and 5b. The dimensions of the deformed ellipse are shown in Fig. 4 graphically.

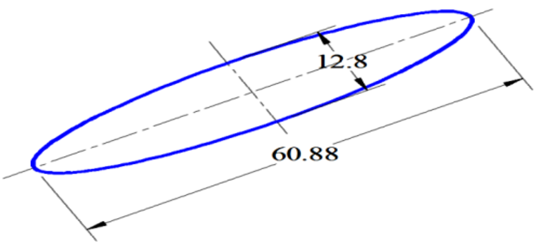

Fig. 4: Graphical Ellipse

The deformed circles were then used to estimate the strains and rotations produced in the specimens after passing through ECAP die. Due to the transformation of circle into an ellipse, the length of the major and minor axis of the ellipse, the rotation in the axis of the ellipse, was determined using different techniques, such as image analysis using paint software. To do this the coordinate system is determined according to which the rotation angle is measured. Then the distance formula is applied to determine the lengths of the minor and major axis as shown in Figs. 5a & 5b.

The distance 'D' between the points (X_1, Y_1) and (X_2, Y_2) is given by:

$$D = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2} \tag{17}$$

Lengths of deformed and un-deformed specimens were calculated from Fig. 8 by image processing technique and then the lengths of major and minor axis were evaluated with the help of distance formula which is presented in equation 17.

3.3 Measurement of Rotation of Axis

After ECAP process, shearing as well as rotation is produced in the specimens. In order to find out the rotation angle, the JPG file of deformed specimens of Nylon and Teflon were imported into AutoCAD software. Arcs were drawn at the tangent of the contour of the specimen at the both sides (above and below) and passing the minor and major axis as shown in Fig. 5a and 5b, the rotation angle was determined.

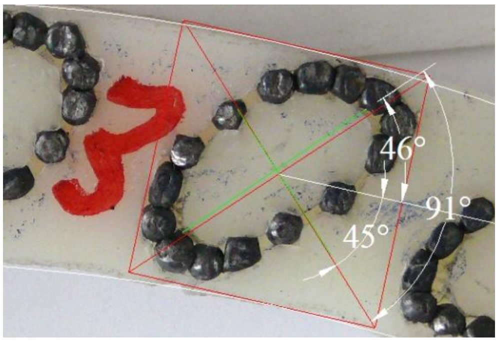

Fig. 5a: Rotation of axis produced in nylon

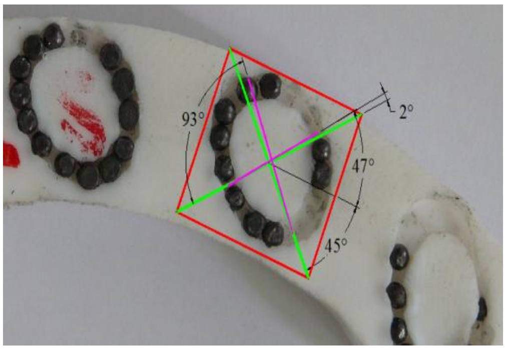

Fig 5b: Rotation of axis produced in teflon specimens

4. Finite Element Analysis

The ECAP process has been modeled and simulated using ABAQUS/Explicit^{TM}. The ECAP specimen having a circular ring is shown in Fig. 6a. Detailed finite element analysis is performed on a 3D rigid model specimen, having a volume of 20x20x120 mm^3 using ABAQUS/ Explicit^{TM} [20]. All the degrees of freedom of die are constrained whereas the plunger has been given a velocity v_2 = -0.5 m/sec in y-direction. The billet has been meshed with linear hexahedral element type C3D8R having 15977 number of elements, total nodes of 18522, an 8-node linear brick, reduced integration, hourglass control element with approximate size of 0.1 mm.

Die has been meshed with discrete rigid element R3D3 with 0.5 mm element size, a 3-node 3-D rigid triangular facet. The boundary conditions for die are encaster. The plunger has been meshed with discrete rigid element R3D4, A 4-node 3-D bilinear rigid quadrilateral just to increase the computation speed. The plunger has been given a boundary condition with velocity of -0.5 m/sec in y-direction. When specimen pressed through ECAP die, the change in shape and formation of ellipse that is due to the rotation of axis can be seen in Fig. 6b.

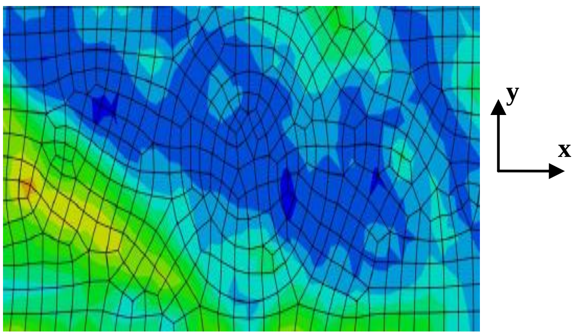

Fig. 6a: Un-deformed specimen modeled using ABAQUS

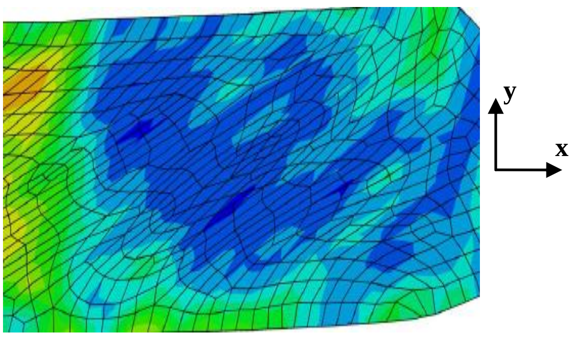

Fig. 6b: Deformed specimen during simulations performed using ABAQUS

4.1 Tensile tests

Engineering stress and strain graph of Nylon and Teflon materials as per tensile tests are shown in the Fig. 7a for Teflon and Fig. 7b for Nylon. Both materials show very high deformation in tensile tests.

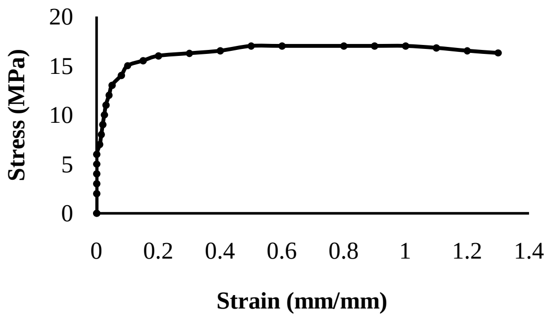

Fig. 7a: Engineering stress -strain curve for teflon

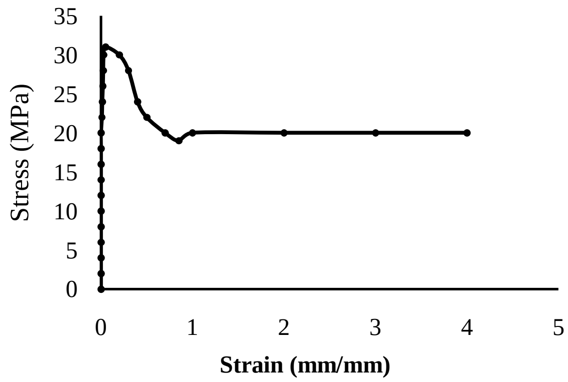

Fig. 7b: Engineering stress -strain diagram for nylon

4.2 Rotations of the Sheared Material

The rotations of the ellipses measured in degrees are shown in the Table 2.

Table 2: Rotation produced in both specimens

Sr. No.	Specimen	Testing Temperature ˚C	Rotation (Degrees)
1	TF-1	10	91
2	TF-2	50	93
3	TF-3	100	101
4	NY-1	10	96
5	NY-2	50	97
6	NY-3	100	91

4.3 Engineering Strain Calculation

The values of strain, produced during ECAP processing for each specimen is evaluated using formulae as given below.

Engineering Strain (along Major Axis) = $(\Delta L/L_o)$ = 0.29

Engineering Strain (along Minor Axis) =$(\Delta L/L_o)$ = -0.25

Tensile and compressive strains produced in both the nylon and the Teflon materials are shown in Table 3 and Table 4.

Table 3: Engineering strain produced in nylon

Speci-men No.	Dist. Major Axis (px)	Dist. Minor Axis (px)	ΔL Major Axis (mm)	ΔL Minor Axis (mm)	Strain ε1*	Strain ε2
NY-1	666	364.8	12.304	0.294	-0.291	0.304
NY-2	630	336	11.789	0.273	-0.321	0.789
NY-3	678	302	10.709	0.385	-0.383	0.709

*negative sign represents compressive strain

The tests carried out on different specimens show close correlation and little scatter in the strain measurements. The experimental results and form of ellipse is compared with the simulation results in the case of Teflon. One can see the close proximity in the simulation versus the experimental results in the Fig. 8.

Table 4: Engineering strain produced in teflon

Speci-men No.	Dist. Major Axis (px)	Dist. Minor Axis (px)	ΔL Major Axis (mm)	ΔL Minor Axis (mm)	Strain ε1	Strain ε2
TF-1	534	530	25.735	25.542	0.482	0.471
TF-2	500	495	24.038	23.798	0.384	0.371
TF-3	528	510	20.887	20.565	0.203	0.185

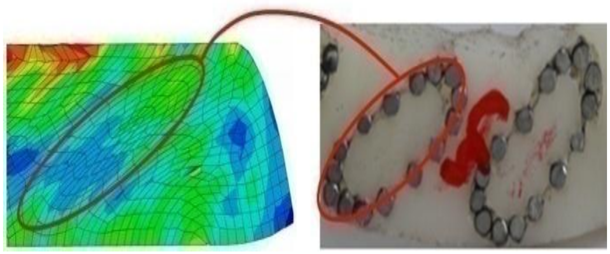

Fig. 8: Ellipse formation comparison between experimental and ABAQUS results

All the strains as measured through simulations, analytical formula of elastic recovery and the experimental solutions are compared below in Table 5.

Table 5: Comparison of engineering strains among different approaches

Speci-men No.	Formula Values (Standard)		Image Analysis		ABAQUS Analysis	
	ε_1	ε_2^*	ε_1	ε_2	ε_1^*	ε_2^*
TF-1	0.4995	-0.4995	0.4855	0.4494	0.4939	0.4922
TF-2	0.3844	-0.3844	0.3995	0.3567	-0.381	0.3856
TF-3	0.2021	-0.2021	0.2268	0.2008	-0.216	-0.192

*negative sign represents compressive strain

5. Conclusion

In the current work a new model of ECAP is proposed. The main purpose of this model is to take into account the phenomenon of elastic recovery in polymers. Polymers undergoing large plastic deformation have a high spring back that we have called "elastic recovery". The model is then experimentally verified. Experiments are performed on Nylon and Teflon polymers. A particular method of shear deformation tracking is presented called "Engraved Circle" Technique. Lead pellets are introduced in a circular path machined into the specimen. The deformation of the circle into an ellipse as well as rotation of the circle is tracked. The ECAP process has also been numerically simulated using ABAQUS software.

The experimental, analytical and numerical simulation results have been compared for the the shear and normal strains. The three methods have shown to be in good agreement, confirming the validity of the proposed ECAP model with "elastic recovery".

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