



MARMARA UNIVERSITY

FACULTY OF ENGINEERING



# Mechanical Design of a New ECAP Die Considering Friction

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## GRADUATION PROJECT REPORT

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MARMARA UNIVERSITY

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**Design of a New ECAP Die Considering Friction**

by

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## **ABSTRACT**

In this study, the changes in the physical properties of the Al7075 part were investigated by three different ECAP processes. Three-dimensional finite element analysis (FEA) was performed using the elasto-plastic finite element analysis software ABAQUS/Explicit to investigate the deformation behavior of three different ECAP processes. These processes are named as Conventional Equal Channel Angular Pressing (ECAP), Multi-pass Equal Channel Angular Pressing (Three-pass) and Torsional Equal Channel Angular Pressing (T-ECAP). First, the variation of the Conventional ECAP process on the physical properties of the part was analyzed. In the Multi-Pass ECAP analysis, the effect of three different pass on the workpiece was observed in a single simulation thanks to the designed die. For the second analysis, a special die with three-pass was designed. The purpose of this design is to expose the workpiece to multiple pass in a single operation and to observe what kind of improvement in physical properties is provided by the Multi-Pass ECAP process compared to the Conventional ECAP process in the same period of time. In the third analysis, a rotational effect was applied to the newly designed die around its axis to impose an extra shear strain to the workpiece. As a result of these two different improvements on the conventional ECAP setup, important physical properties of the part such as stress and strain were compared. Comparing the load requirement to perform all three ECAP processes, it is observed that the reaction force required increases for the Conventional ECAP, Multi-Pass ECAP and T-ECAP processes, respectively. The simulation results for the strain values show that T-ECAP shows a higher magnitude and more uniform distribution than Multi-Pass ECAP, and Multi-Pass ECAP shows a higher magnitude and more uniform distribution than Conventional ECAP.

## **SYMBOLS**

**N:** Number of Pass

**$\Psi$ :** Angle of Curvature

**$\Phi$ :** Channel Angle

## **ABBREVIATIONS**

**ARB:** Accumulative Rolling-Bonding

**CCC:** Roller-Coated Compression

**CGP:** Constrained Groove Pressing

**ECAP:** Equal-Channel Angular Pressing

**FSP:** Friction Stir Processing

**HPT:** High-Pressure Torsion

**MMC:** Metal Matrix Composite

**SPD:** Severe Plastic Deformation

**T-ECAP:** Torsional Equal-Channel Angular Pressing

**UFG:** Ultra Fine Grain

# 1. INTRODUCTION

The mechanical and physical characteristics of all crystalline materials are determined by a number of factors, with the average grain size of the material being very important and often playing a dominant role.

Some thermomechanical processes are applied to reduce the grain size of commercial alloys and improve their mechanical properties. However, these processes can only reduce grain sizes to micrometer size. In order to produce materials with ultrafine grain sizes with sub-micrometer and nanometer grain sizes, studies are being carried out on new and different methods from conventional methods.

In order to transform a coarse-grained solid material into an ultrafine-grained material, it is necessary to apply an exceptionally high deformation to create a high density of dislocations, which are then rearranged to form grain boundaries. In practice, however, conventional metal processing methods such as extrusion or rolling are limited in their capacity to produce UFG structures for two important reasons. Firstly, the total deformations that can be applied by these methods are limited because the machining techniques require reductions in the cross-sectional dimensions of the workpieces. Secondly, the deformations applied during conventional machining are often insufficient to form UFG structures due to the low machinability of metal alloys at ambient and low temperatures.

Formally, a severe plastic deformation (SPD) process can be defined as the application of a very high stress to a bulk solid, without significant change in the overall dimensions of the solid, resulting in exceptional grain refinement. Therefore, the bulk solids being processed typically contain 1000 or more grains in any given cross-section.

Various SPD processing techniques have been proposed, developed and evaluated. These techniques include equal-channel angular pressing (ECAP), high-pressure torsion (HPT), multi-directional forging, auger extrusion, cyclic extrusion-compression, reciprocal extrusion, repetitive ripple and straightening, constrained groove pressing (CGP), roller-coated compression (CCC), accumulative rolling-bonding (ARB), friction stir processing (FSP) and underwater friction stir processing. All of these methods can achieve large plastic

deformation and significant microstructural refinement. Some of them, such as ECAP, HPT, multidirectional forging and ARB, are well known methods for the production of UFG materials, where the processed microstructures usually have grain sizes in the range of 70-500 nm, depending on the type of crystal structure. Other techniques are still being developed for this purpose.

Of these various procedures, ECAP is a specialized machining technique, and there are several reasons why it is so. Firstly, it can be applied to fairly large blocks, which has the potential to produce materials that can be used in a wide range of structural applications. Secondly, it is a relatively simple procedure and, apart from die construction, can be easily carried out using equipment that is widely available in many alloys processed by ECAP. Third, ECAP can be applied and developed to many materials, from alloys with different crystal structures and precipitation hardened alloys to intermediate metals and metal matrix composites. Fourth, as long as the pressing is continued to a sufficiently high deformation, reasonable homogeneity is achieved in most pressed blocks. Fifth, the process is scalable for pressing relatively large samples and there is potential for the use of ECAP in commercial metalworking procedures. These attractive features have led to many experimental studies and new developments in the ECAP process over the last decade.

In this report, a die with 3 fractures other than the traditional ECAP for Aluminum 7075 was designed and examined how the mechanical properties change by giving a rotation to this die around itself and it was observed that the properties were much better and more efficient than the Conventional ECAP. This process is called Torsional ECAP. T-ECAP is examined in detail in Section 2.3.

## 2. LITERATURE REVIEW

### 2.1 ECAP PROCESS

#### 2.1.1 Conventional ECAP Process

Principles of the ECAP process is shown in below.

The specimen, in bar or rod form, is machined to fit into the channel and the die is placed in a press of some kind so that the specimen can be passed through the die using a piston. The theoretical slip plane is shown between two adjacent elements within the specimen and

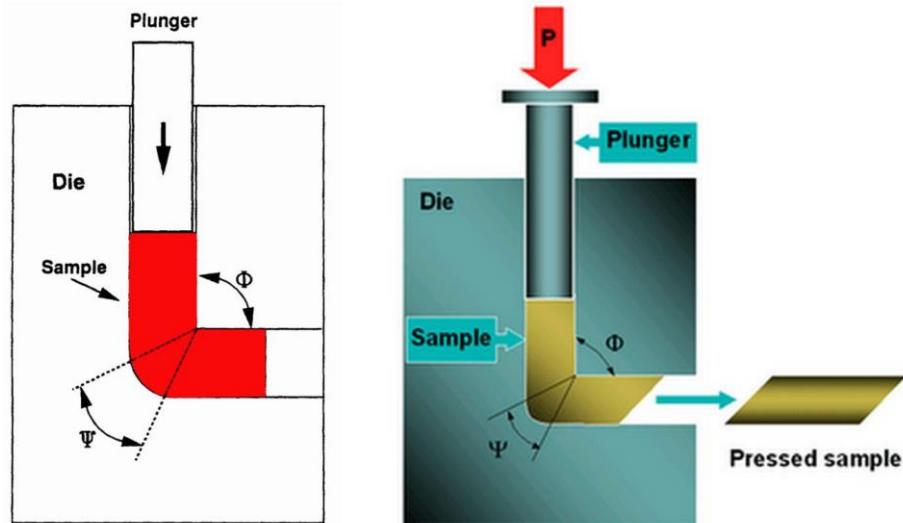
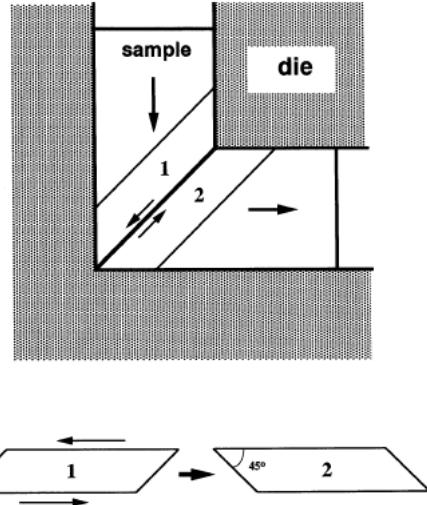


Figure 1 Schematic illustration of a typical ECAP facility

these elements are displaced by the slip as shown at the bottom of the diagram.

Maintaining the same cross-sectional area despite very large deformations being applied during the ECAP process is an important feature of the SPD process. This feature distinguishes such processes from conventional metalworking operations such as rolling, extrusion and drawing.

Since the cross-sectional area remains unchanged, the same sample can be pressed repeatedly, and exceptionally high deformations can thus be achieved. For example, repeated pressing operations provide the opportunity to introduce different sliding systems by rotating the samples in different ways with each successive pass.



*Figure 2 The lower portion of the figure illustrates the ECAP principle*

In practice, much research on ECAP involves the use of square cross-section bars and dies with square channels. For these samples, it is appropriate to develop processing paths by rotating the blocks 90° between each pass. The same processing routes can be easily applied when the samples are in the form of rods of circular cross-section. Circular channels and cylindrical samples will be used in this thesis.

### 2.1.2 Influence of the Channel Angle, $\Phi$

Die channel angle,  $\Phi$ , is the angle where the two channels intersect, and this has great impact on the production of shear strain which ultimately leads to grain refinement. The channel angle is the most important experimental factor as it determines the total strain applied in each pass and therefore has a direct influence on the pressed microstructure. However, despite the critical importance of this angle, most of the experiments reported to date use values between 90° and 120°, and no significant comparison is usually made between the results obtained using dies with different channel angles.

It should be noted that although ECAP dies with channel angles of  $\Phi = 90^\circ$  are efficient, it is experimentally easier to press billets with dies with angles greater than  $90^\circ$ . This is particularly important for very hard or low ductility materials. For example, experiments have shown that pressing commercial grade tungsten from a die with a  $90^\circ$  channel angle at a temperature of 1273 K is not possible as it causes cracking in the billets, but excellent results are obtained with dies with larger angles. Table 1 shows the channel angle and curvature angle versus strain values.

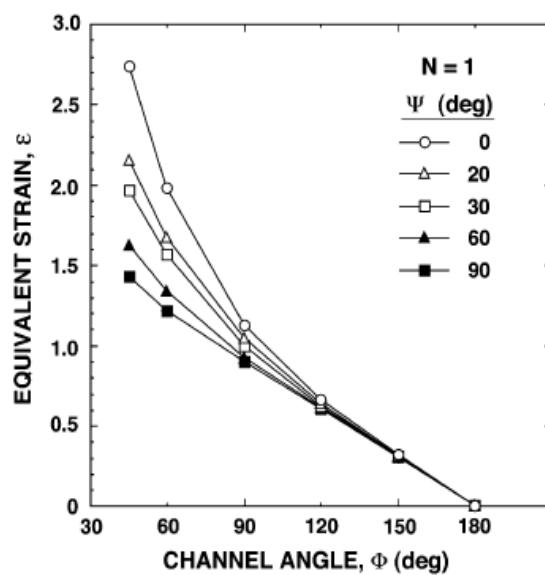


Figure 3 Variation of Equivalent Strain – Channel Angle

Table 1 Strain Values Shown According to Various Channel Angles

S. No.	Channel angle	Equivalent Shear strain for $\Psi = 0$	Equivalent Shear strain for $\Psi = 10$	Equivalent Shear strain for $\Psi = 20$
1	90	1,154	1,1	1,054
2	105	0,886	0,855	0,828
3	120	0,666	0,649	0,635
4	135	0,478	0,47	0,462
5	150	0,309	0,306	0,303

### **2.1.3 Influence of the angle of curvature, $\Psi$**

The angle of curvature,  $\Psi$ , refers to the outer arc where the two sections of the channel in the die intersect. This angle plays only a minor role in determining the strain applied to the specimen, as the equivalent strain estimates given in Fig. 3 illustrate this. Nevertheless, it is important to investigate the influence of this angle in the production of ultrafine-grained materials. In a study, three different curvature angles ( $15^\circ$ ,  $25^\circ$ ,  $35^\circ$ ) were investigated while maintaining a constant internal channel angle of  $90^\circ$ . It was found that as the angle of curvature increases, the friction between the billet and the die surface decreases, resulting in a decrease in force and temperature during the process. Aljawad,, Alamer & Karataş (2022).

### **2.1.4 Influence of the Pressing Speed**

The ECAP process is usually carried out using high capacity hydraulic presses with relatively high piston speeds. Typically, pressing speeds are in the range of 1-20 mm/s. However, it is also possible to build dies for use on conventional mechanical testing machines and this allows pressing speeds to be spread over a very wide range.

In the first study to examine the effect of pressing speed in detail, pure aluminum and Al-1%Mg alloy were pressed at piston speeds ranging from  $10^{-2}$  to 10 mm/s . Furukawa, Horita, Nemoto, Langdon (2001). This research showed that the pressing speed had no significant effect on the final size of the ultrafine grains formed by ECAP. However, these lower speeds produce more stable microstructures, as healing occurs more easily when pressing at slower speeds. Showing the lack of dependence on the pressing speed for Al-1Mg alloy, Fig. 27, the yield stress in tensile tests at room temperature using a strain rate of  $1.0 - 10^{-1} \text{ s}^{-1}$  is plotted against the pressing speed after a number of pass from 1 to 4. Furukawa, Horita, Nemoto, Langdon (2001). Results confirm that the strength of the material increases with increasing number of pass through the die, this increase reaches saturation after 4 pass and the pressing speed has no significant effect on these results.

Equivalent strain after N pass is expressed in a general form by a relationship

$$\varepsilon_N = \frac{N}{\sqrt{3}} [2 \cot\left(\frac{\phi}{2} + \frac{\psi}{2}\right) + \psi \operatorname{cosec}\left(\frac{\phi}{2} + \frac{\psi}{2}\right)] \quad \text{Eqn. 1}$$

### 2.1.5 Influence of Material Choice and Processing Parameters

Any critical evaluation of microstructures developed by the ECAP process requires separate observations in the X, Y and Z planes, depending on the number of pass through the ECAP die and the influence of the process route. Such detailed results are available for pure polycrystalline aluminum with an initial grain size of about 1.0 mm in the unpressed condition.

It is worth mentioning that the choice of the test material influences the equilibrium grain size reached after ECAP and the homogeneity of the microstructure. For example, it has been observed that the equilibrium grain size in pure Al is 1.2-1.3 micrometers and the microstructure is extremely homogeneous after pressing at room temperature. In contrast, it has been observed that the equilibrium grain size is much smaller (typically 0.27 micrometers) when pure Cu is pressed at room temperature and the microstructure is not completely homogeneous.

### 2.1.6 Advantages of ECAP Process

Equal Channel Angular Pressing (ECAP) has many advantages. Firstly, it significantly reduces the grain size of metals, which gives the material superior mechanical properties. This results in higher strength, hardness, and durability. Furthermore, materials produced by the ECAP method become more suitable for processes such as super plastic forming. This means that they can be easily formed even at high temperatures.

Another advantage of ECAP is that only the internal structure of the material is modified and improved, while retaining its original shape and dimensions. This makes it possible to process even large volumes and complex shaped parts. Finally, the ECAP process ensures microstructural homogeneity in the material Gupta,Chandrasekhar & Saxena. (2021).

### 2.1.7 Limitations of ECAP

Firstly, ECAP is a continuous machining technique where the workpiece is inserted into the channel, pushed along the channel, then removed and the process repeated. This means that the process has to be repeated over and over again to achieve maximum strain. This indicates that ECAP is an effective process for laboratory research but there are some difficulties in fully adapting it to industrial production due to its labor intensity. Secondly, the overall length of the workpiece is limited by the length of the groove and the piston movement, and there is also a critical aspect ratio to manage. Finally, a disadvantage of ECAP is that both ends of the billet have irregular surfaces due to different deformations. This leads to some cutting waste to make both ends parallel Gupta,Chandrasekhar & Saxena. (2021).

### **2.1.8 Mechanical Property Changes with Increasing Number of ECAP**

#### **Pass**

The multi-pass Equal Channel Angular Pressing (ECAP) process has significant effects on the microstructure and mechanical properties of metals and alloys. Each pass through the ECAP die imposes severe plastic deformation on the material, which increases dislocation density, strain hardening and yield stress. This results in a more uniform and increased strain distribution. Multiple pass result in a significant reduction of the grain size, often achieving ultra-fine grains of less than 1 micron. This refined microstructure increases hardness according to the Hall-Petch relationship. As a result, the strength and toughness of the material are significantly improved, tensile and yield strength are increased by grain boundary consolidation and work hardening resulting from repeated deformation cycles. Furthermore, properties such as corrosion resistance and wear resistance are also improved due to the fine grain structure and homogeneous distribution of alloying elements. Multi-pass ECAP is a powerful technique that significantly improves the mechanical properties of metals, making them suitable for a variety of advanced applications (Alateyah, Mohamed, Yasser, Abd El-Hafez, Alawad, & El-Garaihy, 2021).

## **2.2 MATERIAL**

Technological advances play an important role in the development of composite materials in all fields and especially in the field of materials science.

Composite materials are as old as human civilization, although they were commercialized after World War II. They are formed by combining two or more different materials to achieve higher physical and mechanical properties compared to individual materials in order to meet industrial needs and the demands of modern engineering applications.

Aluminum, the third most abundant element in the world, and its various alloys are widely used for a variety of new applications such as automobile and aircraft structures. Especially in the last two decades, researchers have turned to combining aluminum metal and its various alloys with innovative structures and new manufacturing methods to develop metal matrix composites.

Recently, there has been an increasing interest in MMCs (Metal Matrix Composites) due to their outstanding mechanical strength and good wear resistance. Popular matrix materials today are aluminum, magnesium and titanium. However, according to reports, Aluminum-based MMCs (AMMCs) account for about 69% of the annual mass for various industrial uses such as aerospace, automobiles, electronic devices, marine industry and space shuttle. AMMCs offer a wide range of outstanding physical and mechanical properties and the combination of these properties includes properties such as improved ductility, toughness, formability and electrical and thermal conductivity. The tribological properties of AMMCs have been improved by adding nano-reinforcements using hard particles. These hard particles include carbides (TiC, SiC, B<sub>4</sub>C), borides (TiB<sub>2</sub>, AlB<sub>2</sub>), oxides (Al<sub>2</sub>O<sub>3</sub>, MgO, ZrO<sub>2</sub>, ZrSiO<sub>4</sub>), nitrides (BN, AlN) and materials such as residual carbon nanotubes and graphene. Nano-reinforcement contributes to the improvement of wear and high temperature mechanical properties by offering properties such as high hardness, strength, high temperature resistance, low thermal expansion (Khalid, Umer & Khan, 2023).

### **2.2.1 Aluminum**

For over 80 years, various aluminum alloys have proven to be an ideal material for structural aircraft materials. Aluminum alloys have light weight and good mechanical properties among all metals and are widely used in engineering structures, especially in the aerospace industry. Due to their high strength, low density and easy processing, they are frequently used in engineering, marine vessels and military applications. Moreover, these

alloys are the driving force behind global development in making objects and devices lighter. At present, the research and development of aluminum alloys has become an important development goal for defense science and technology.

Figure 4 shows a brief classification of aluminum alloys. Aerospace structures use 80% aluminum by weight. Aluminum is always the first choice for many commercially available aircraft. Therefore, it carries more weight and offers high corrosion resistance, which ensures the safety of the aircraft and its passengers. Aluminum alloys are prone to corrosion and often require various surface treatments such as plasma electrolytic oxidation protection, anode oxidation protection and surface coatings. Engineering components are subjected to different types of loading during their lifetime, but fatigue loading is the worst of them. In fatigue, materials fail below the yield point. 7XXX alloys are the most widely used because they have the highest mechanical properties of all aluminum alloys. (Khalid, Umer & Khan,2023).

Aluminium Alloys a brief Overview			
Classifications	Alloy Component	Properties and Applications	
1XXX	Al	>>>	Cheapness, good workability, used in conventional industries
2XXX	Al-Cu	>>> Fe/Mn/Zn	High strength, used in aerospace
3XXX	Al-Mn	>>> Cu/Mg/Si	Excellent antirust function, used in airconditioning, refrigerator, car bottom
4XXX	Al-Si	>>> Fe/Cu/Mg	Good heat and wear resistance, used in welding wires
5XXX	Al-Mg	>>> Mn/Si/Fe	Low density, high elongation, used in aerospace
6XXX	Al-Mg-Si	>>> Zn/Fe/Mn	Corrosion and oxidation resistance, used in low-operation weapons and aircraft connections
7XXX	Al-Zn-Mg	>>> Cu/Si/Fe	High strength, used in aircraft industry
8XXX	Otherwise	>>>	Depending on the element

Figure 4 A comprehensive classification of Al alloys

## **2.2.2 Al7075**

7075 is an aluminum alloy with zinc as the main alloying element. It has high fatigue strength and average machinability, but exhibits poor weldability and low corrosion resistance compared to other alloys and is predominantly used in aerospace and structural applications. Among the many commonly used aluminum alloys, 7075 aluminum is notable for having the strongest quality in a variety of industrial applications. As a lightweight, easily machinable metal with adequate corrosion resistance, it provides strength similar to steel alloys and is also a lightweight metal. As with all aluminum alloys, 7075 has a specific gravity of 2.73. 7075 aluminum alloy is used in various components such as fuselage and wings due to its remarkable physical and mechanical properties, such as its high strength-to-weight ratio and excellent stress corrosion resistance for aircraft applications.

7075 aluminum alloy is used commercially in various industrial applications such as aerospace, automotive components and marine. In real-time applications, 7075 aluminum alloys inevitably face many challenges when being processed under conventional manufacturing routes such as surface nitriding and metal plating. Therefore, various heat treatment techniques cannot be effectively used on 7075 aluminum. Therefore, there is a strong push for semi-solid processing of 7075 aluminum alloys.

Aluminum for high-quality aluminum metal matrix composites (AMMC) is produced in a variety of ways using powder and liquid metallurgy techniques. Among all of these production methods, mixing and compression casting methods can produce high-quality AMMCs with the desired tribological properties.

The T6 heat treatment of 7075 aluminum alloys significantly improves its various mechanical properties due to grain refinement, solid solution hardening, dislocation hardening and precipitation hardening by solution treatment during heat treatment techniques based on artificial aging.

## **2.3 T-ECAP**

Torsion-Equal Channel Angular Pressing (T-ECAP) combines the severe plastic deformation (SPD) technique of Equal Channel Angular Pressing (ECAP) with torsional

deformation. In this process, the entire ECAP die rotates around its axis, applying additional shear stresses to the specimens. The main difference between T-ECAP and ECAP is that in T-ECAP the die rotates, while in conventional ECAP it remains stationary. T-ECAP offers a significant advance in SPD techniques by improving load requirements, strain distribution and efficiency in the production of ultra-fine grain (UFG) materials. By incorporating die rotation into the ECAP process, T-ECAP improves the mechanical properties of materials.

### **2.3.1 Advantages of T-ECAP**

**Load Reduction:** The T-ECAP process requires a lower load than the conventional ECAP process under the same conditions. This load reduction is due to the change in friction mode induced by the torsional component of T-ECAP.

**Increased Strain and Hardness Distribution:** The T-ECAP process can generate larger and more uniformly distributed strains within the material. Simulation and experimental results show that the equivalent strain in T-ECAP specimens increases by approximately 60% compared to ECAP specimens. This increased strain leads to a more uniform hardness distribution, which is beneficial for the mechanical properties of the processed material.

**Grain Refinement Efficiency:** The integration of torsion into the ECAP process accelerates grain refinement, potentially achieving finer grain structures in fewer pass. This efficiency makes T-ECAP a time-saving and cost-effective method for producing ultra-fine grain (UFG) materials (Khalid, Umer & Khan,2023).

### **2.3.2 Disadvantages of T-ECAP**

**Die Wear and Durability:** The rotary motion in the T-ECAP can increase die wear and tear. This can increase die maintenance and replacement costs.

**Complexity and Equipment Cost:** T-ECAP requires more complex and expensive equipment than conventional ECAP. The design and manufacture of the rotary die system can impose higher costs and technical challenges.

**Process Control:** Proper control and synchronization of the rotary die is critical for successful implementation. Inadequate process management can lead to undesirable results

and a reduction in product quality.

Scalability: While T-ECAP has shown promising results in laboratory and small-scale applications, scaling the process to industrial use can be difficult and costly.

Material Limitations: T-ECAP may not be effective for all material types. Some materials may be less resistant to high torsional stresses, which may prevent the desired properties from being achieved (Khalid, Umer & Khan,2023).

A simulation was designed using the Torsional ECAP, where the designed three-pass die was used. A performance comparison with conventional ECAP and Multi-Pass ECAP is made.

### 3. SIMULATION SETUP

This analysis was conducted using the ABAQUS CAE software. The primary reason for selecting ABAQUS is its high computational capacity for explicit analyses. The material chosen for the workpiece was Al-7075. An optimal mesh count of 8750 was determined for the workpiece. During the analysis, the ALE (Arbitrary Lagrangian-Eulerian) adaptive mesh domain tool was utilized. This tool allows the highly deformed workpiece to be remeshed periodically during the simulation. Consequently, the post-simulation geometry of the workpiece was more representative of real-life conditions, contributing to more accurate results. Three different analyses were performed using two different die designs. Figure 5 and Figure 6 shows the different die designs for our report.

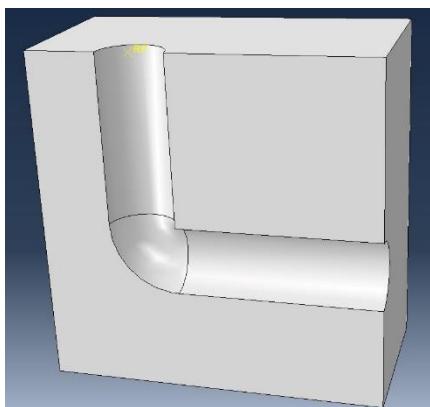


Figure 5 Die Design of Conventional ECAP Process

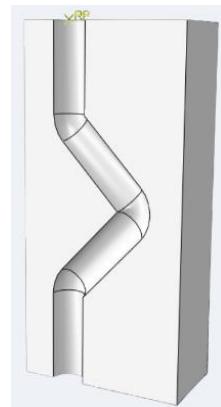


Figure 6 Die Design for Multi-Pass and T-ECAP Processes

The first analysis was completed with a single-pass die featuring a 90-degree turning angle. For the second and third analyses, the die was designed to complete three-pass of the workpiece, with angles of 135-90-135 degrees. In the third analysis, the die was additionally given a rotational speed to study its impact on the process. In the simulation, the upper surface of the workpiece was fixed, and an upward velocity was applied to the die. This setup aimed to successfully carry out the three-pass ECAP (Equal Channel Angular Pressing) analysis. The simulation time was set to one second. For the single-pass analysis with a 90-degree angle, an upward velocity of 50 mm/s was applied to the die. For the second and third analyses, this velocity was set to 150 mm/s. The mass scaling factor was set to 50 to accelerate the computation with no significant changes observed in the results. The friction coefficient between the die and the workpiece surfaces was taken as 0.14, a value selected based on typical conditions found in the literature for similar processes.

## 4. RESULTS

In order to improve the results obtained from the conventional ECAP process, a design change was made to the die. The material properties remained the same in the three different analyses and the material used was Al-7075. The first analysis was done to observe the effect of the conventional ECAP process on the part. In the second analysis, the design change in the die was aimed to obtain higher strain values in a single press operation. In the last analysis, the torsional-equal channel angular pressing T-ECAP process, the die was given a rotational speed around its axis. In this way, it was aimed to analyze the effect of extra shear stress on the workpiece.

### 4.1 One Pass Conventional ECAP – 90 Degrees

In the conventional ECAP (Equal Channel Angular Pressing) process, the intended improvement is to enhance the mechanical properties of the material by refining its microstructure. Significant improvements in stress and strain characteristics are expected as a result of these enhanced mechanical properties.

#### 4.1.1 Visual Results of Conventional ECAP Process

Figure 7 shows the sample before the simulation starts.

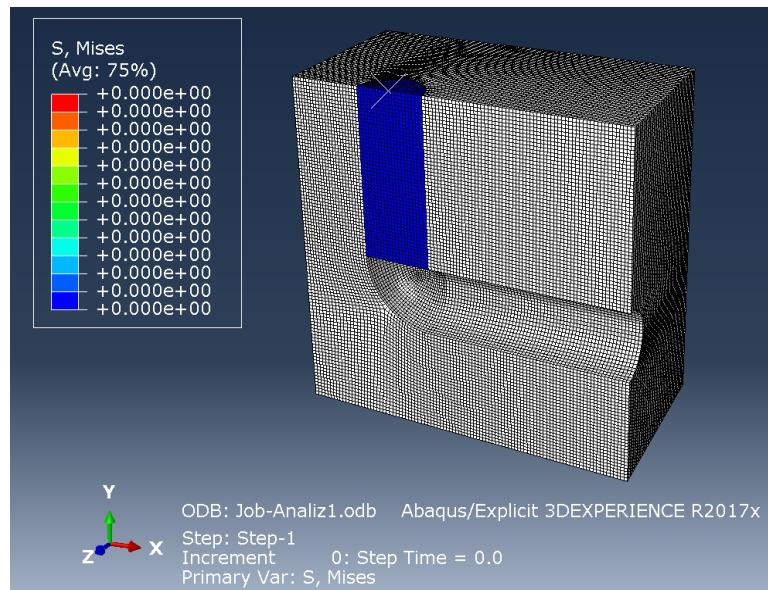


Figure 7 Initial Sample

Figure 8 shows the sample stresses in the middle of the simulation.

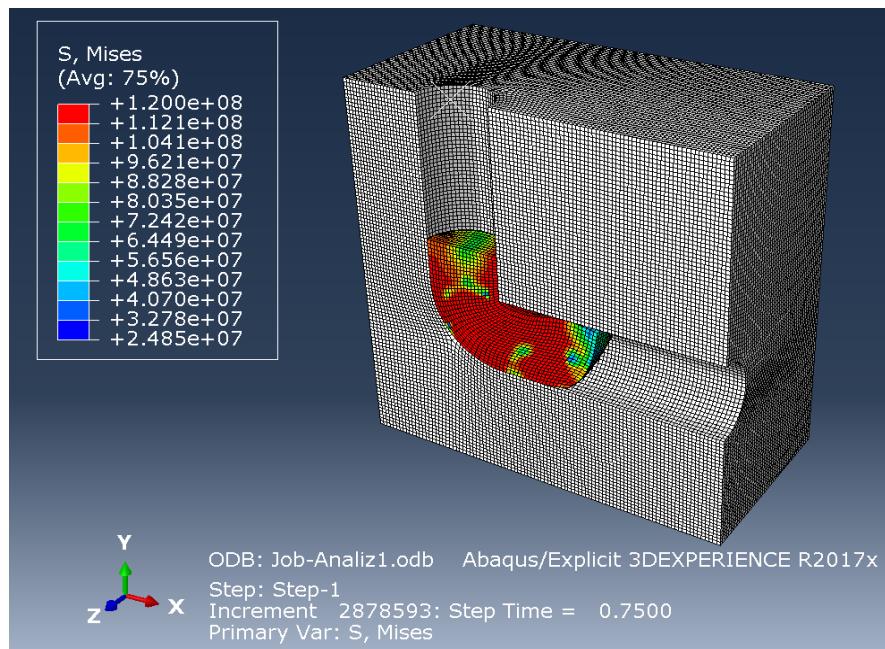
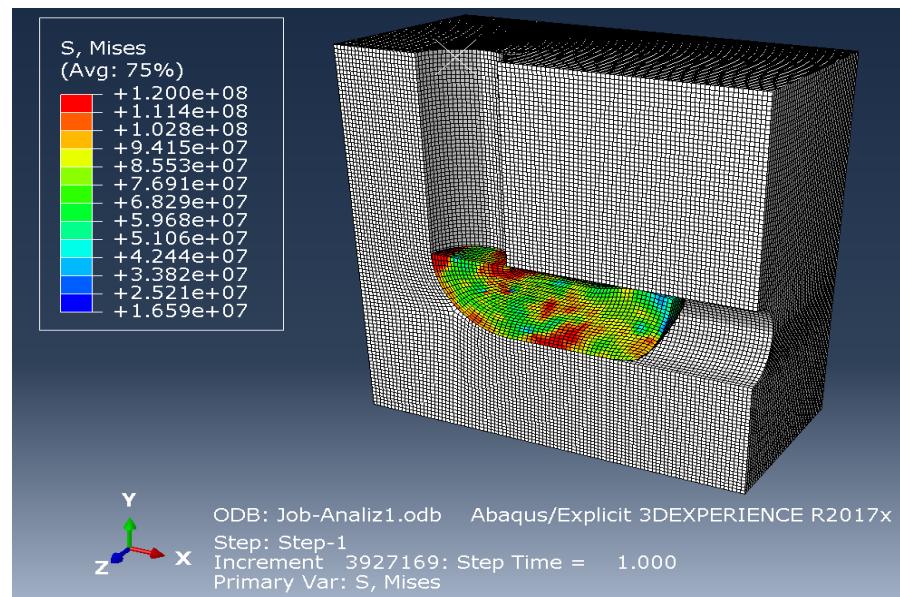


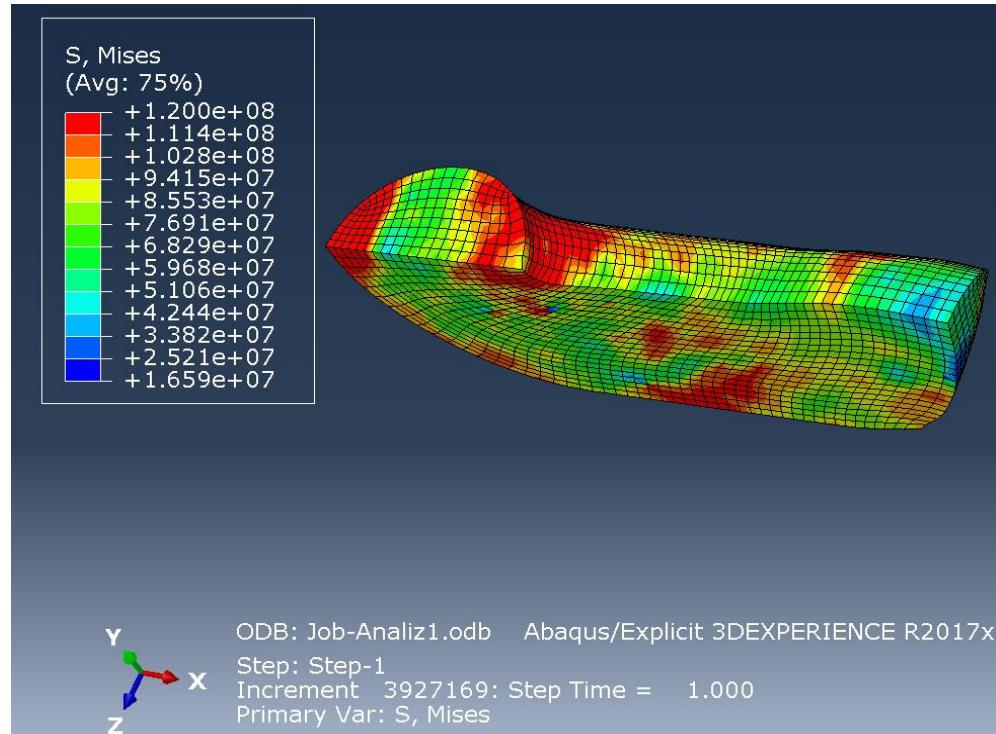
Figure 8 Middle of the Simulation Step Time: 0.75

Figure 9 shows the sample at the end of the simulation



*Figure 9 End of the Simulation*

Figure 10 and 11 show the results of the sample after simulation ends.



*Figure 10 Latest Appearance of the Sample -I*

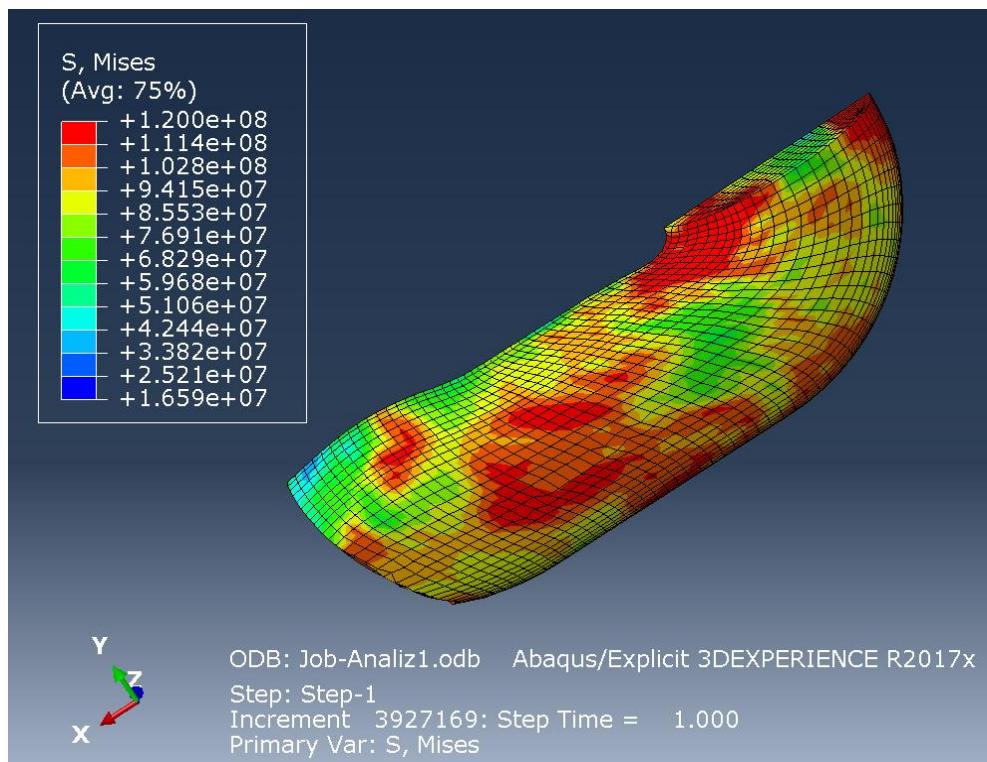
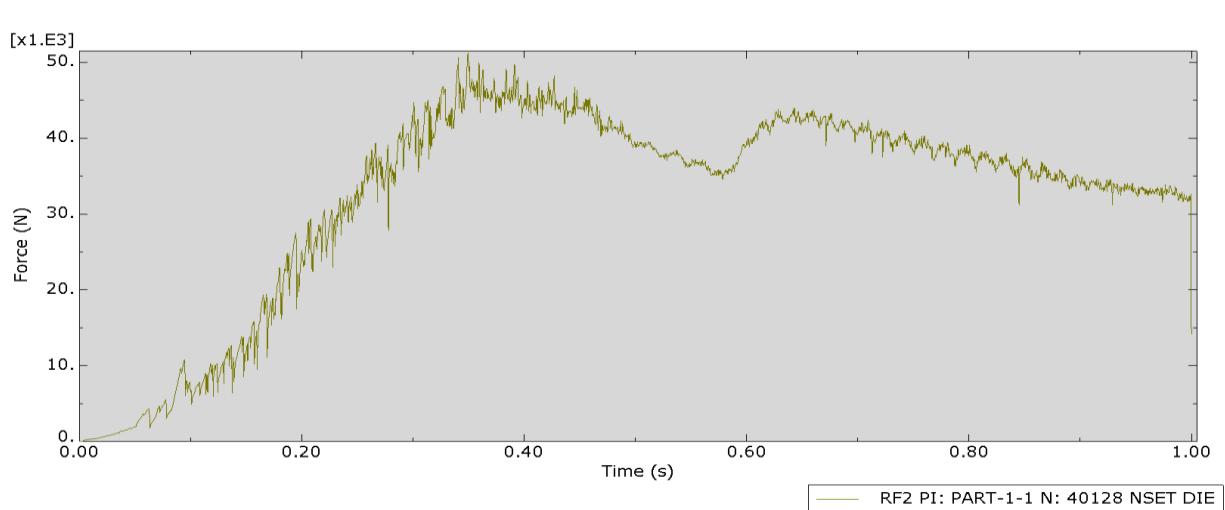
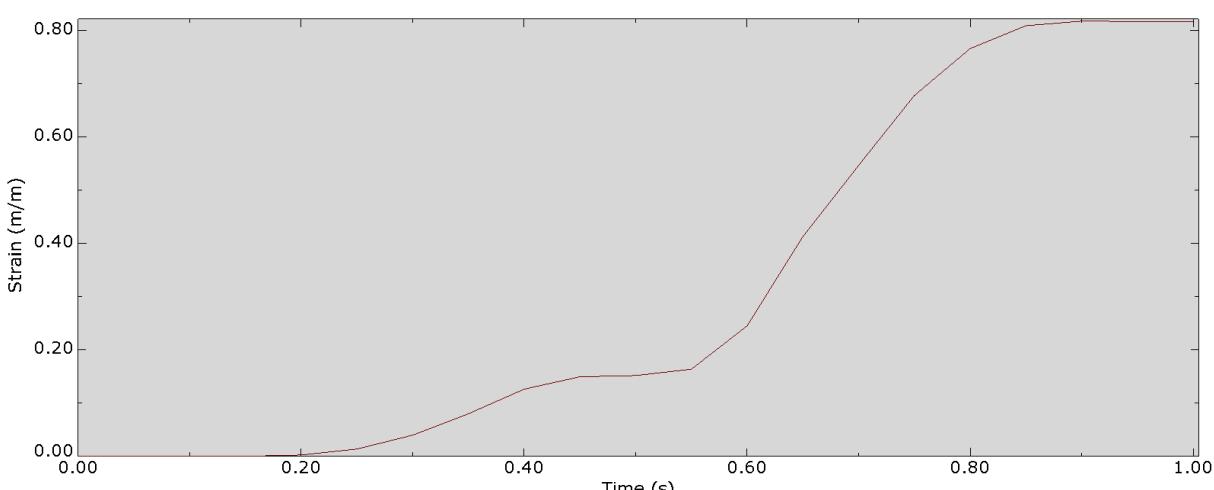
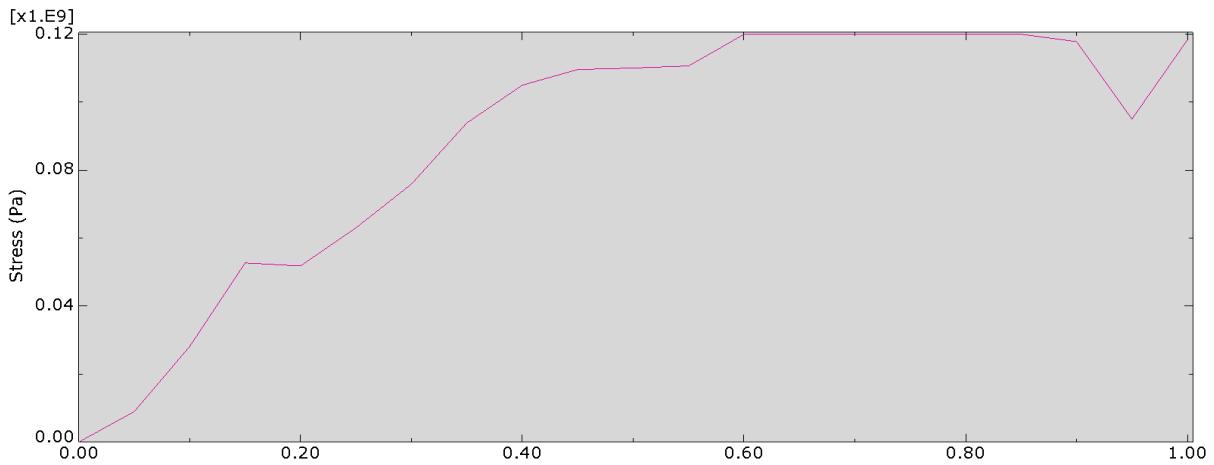


Figure 11 Latest Appearance of the Sample-2

## 4.2 Stress- Strain- Reaction Force Changes Over Time

Figure 12,13 and 14 show how the stress, strain and force change over time.



## 4.3 Three-pass ECAP- 135-90-135 Degrees

### 4.3.1 Visual Results of 3 Pass ECAP Process

Figure 15 shows the sample before the simulation starts.

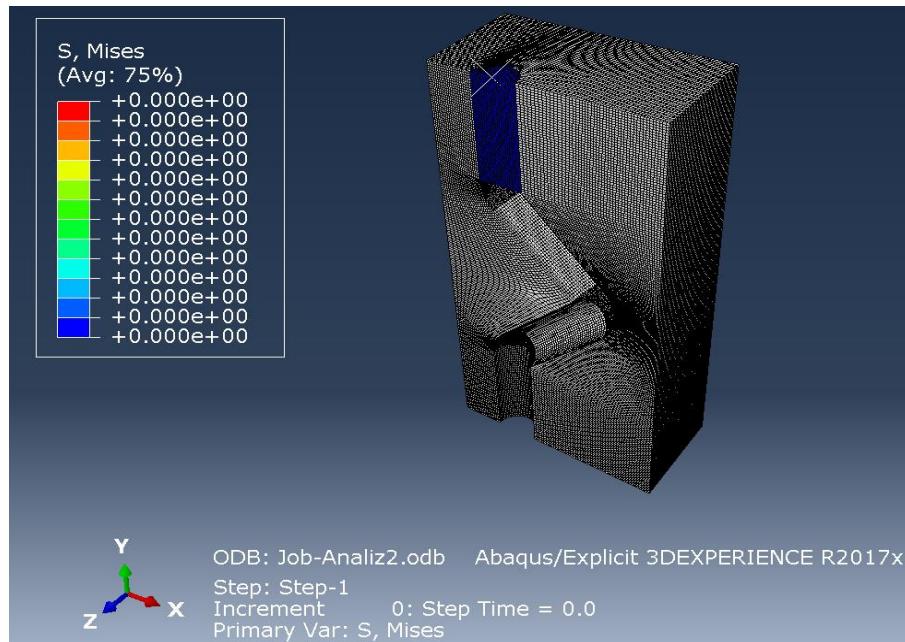


Figure 15 Undeformed Sample

Figure 16,17 and 18 show the deformation of the sample during the simulation.

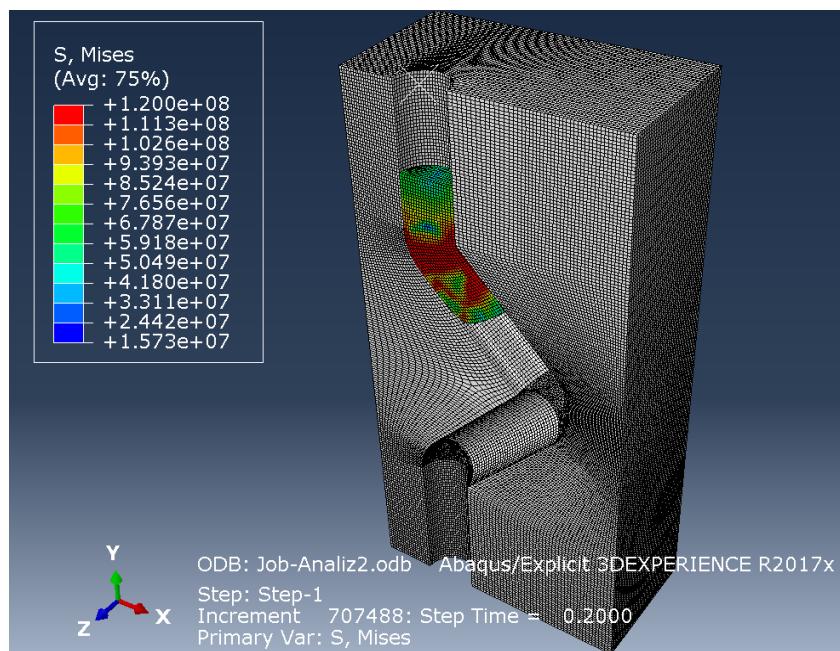


Figure 16 First Pass

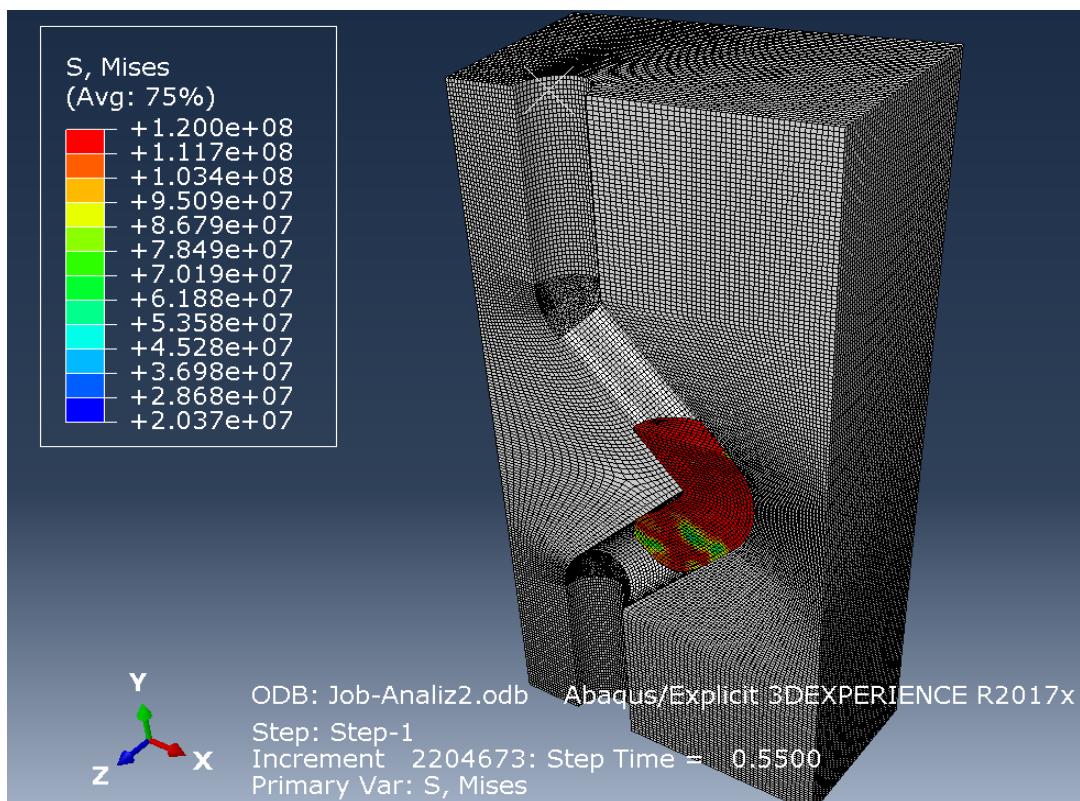


Figure 17 Second Pass

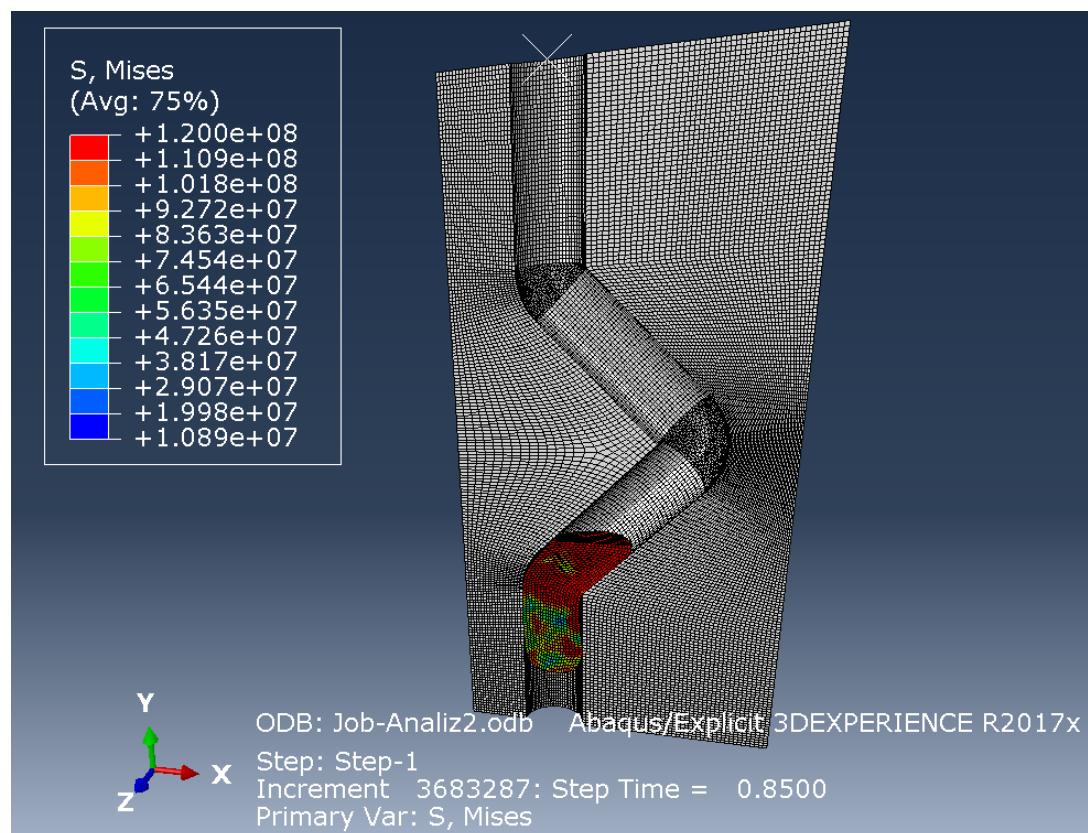


Figure 18 Third Pass

Figure 19 shows the sample with die at the end of the simulation.

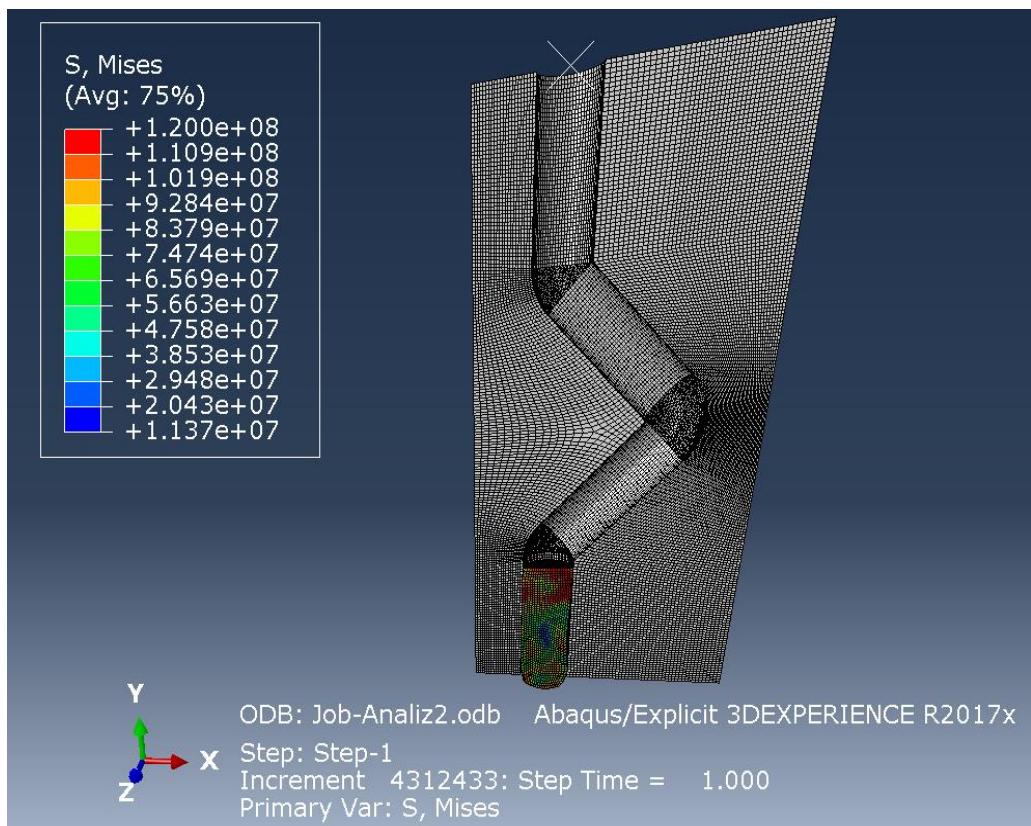


Figure 19 End of the Simulation

Figure 20 and 21 show how the sample is deformed at the end of the simulation.

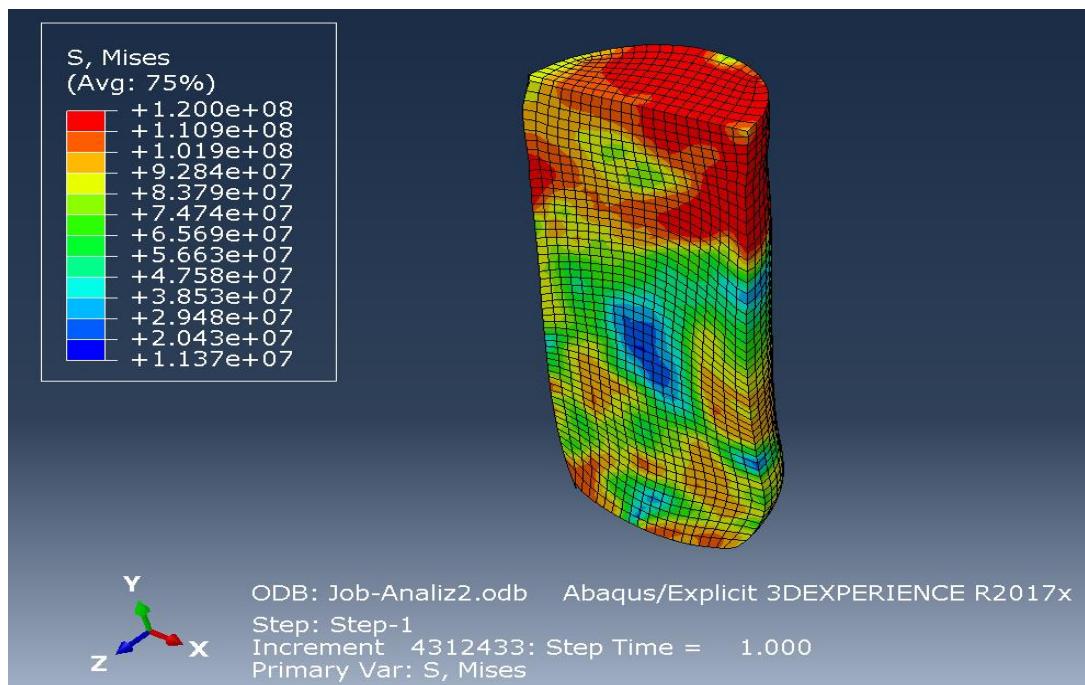


Figure 20 Sample Deformation-1

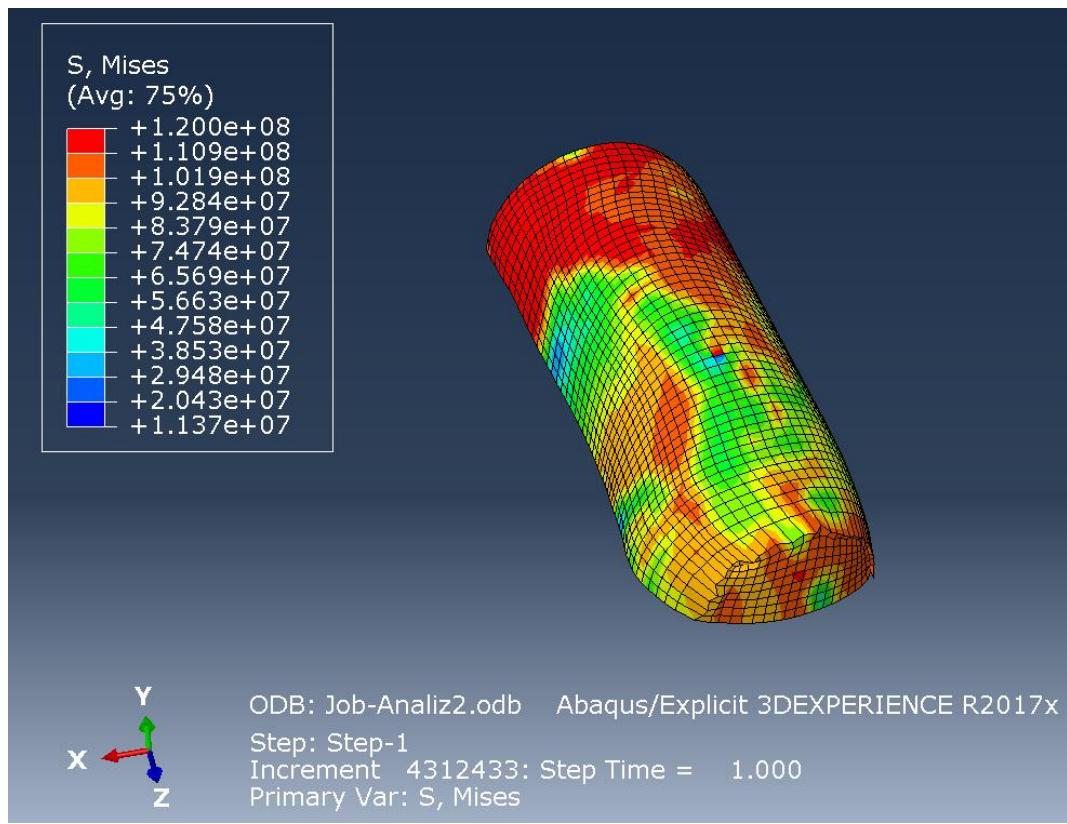


Figure 21 Sample Deformation - 2

#### 4.3.2 Stress- Strain- Reaction Force Changes Over Time

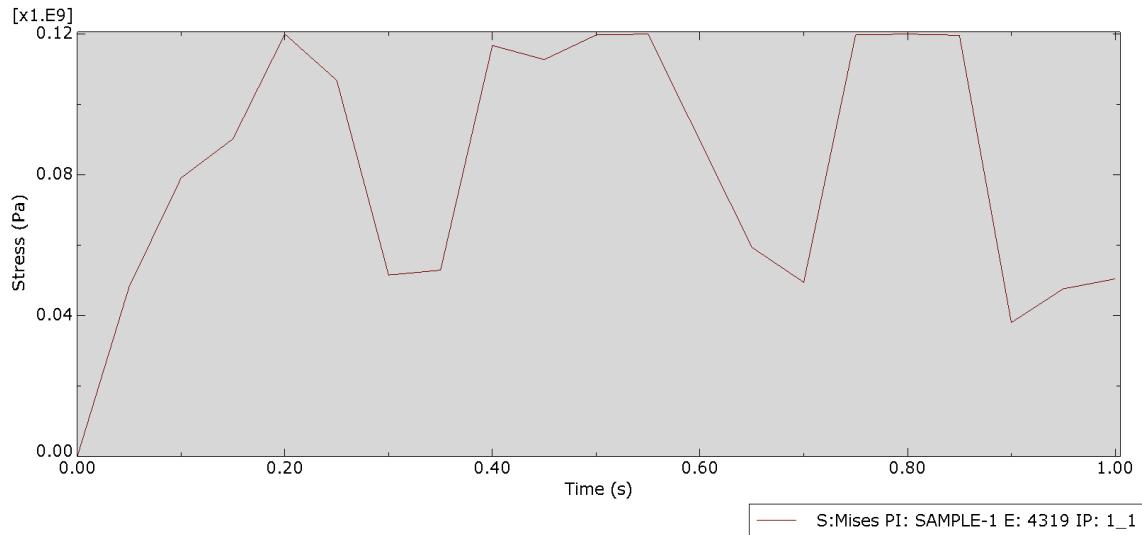


Figure 22 Stress vs Time Graph for Multi-Pass ECAP

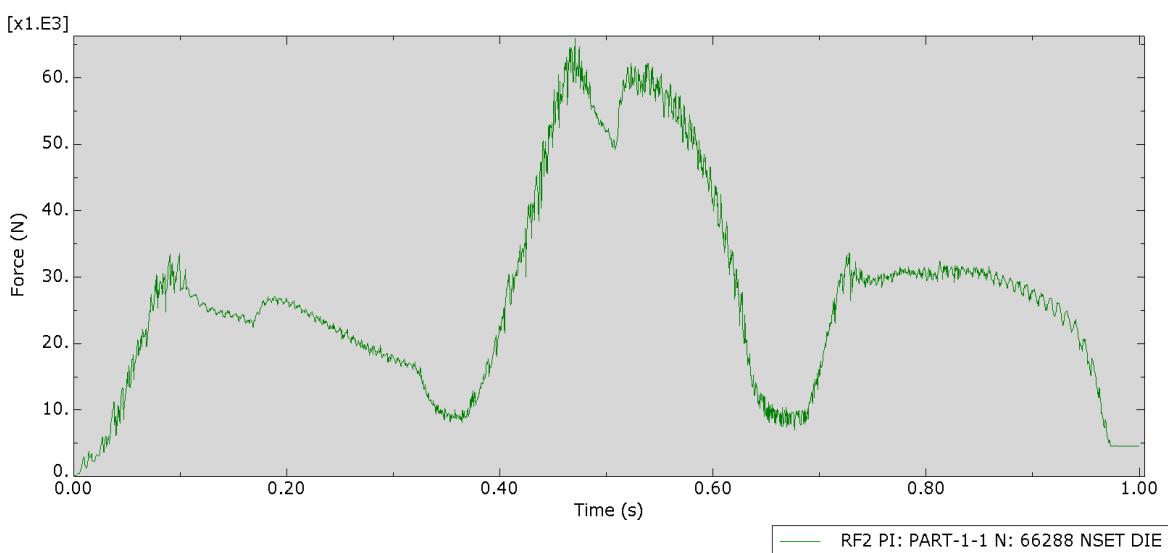
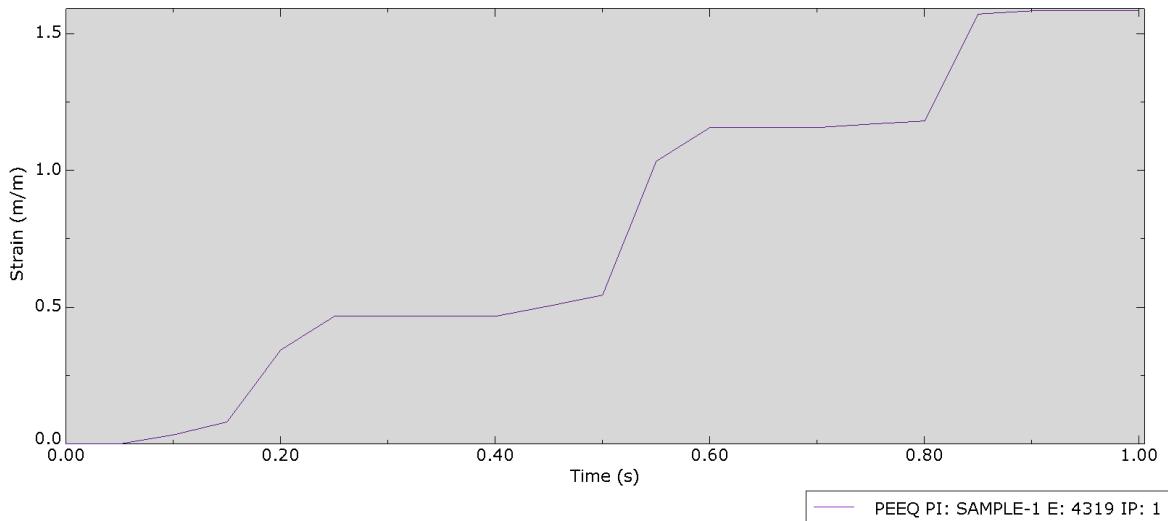


Figure 24 Reaction Force vs Time Graph for Multi-Pass ECAP

## 4.4 Three-pass T-ECAP 135-90-135

### 4.4.1 Visual Results of 3 Pass ECAP Process

In this section, the rotational effect applied to the die has not resulted in any changes in the visuals. The primary impact on the part is shown in the reaction forces, strain, and stress curves section. In this section, differently, the visual change in the part after the T-ECAP process can be seen in its complete form.

Figure 25 and 26 shows the deformed sample after the Multi-Pass T- ECAP Simulation.

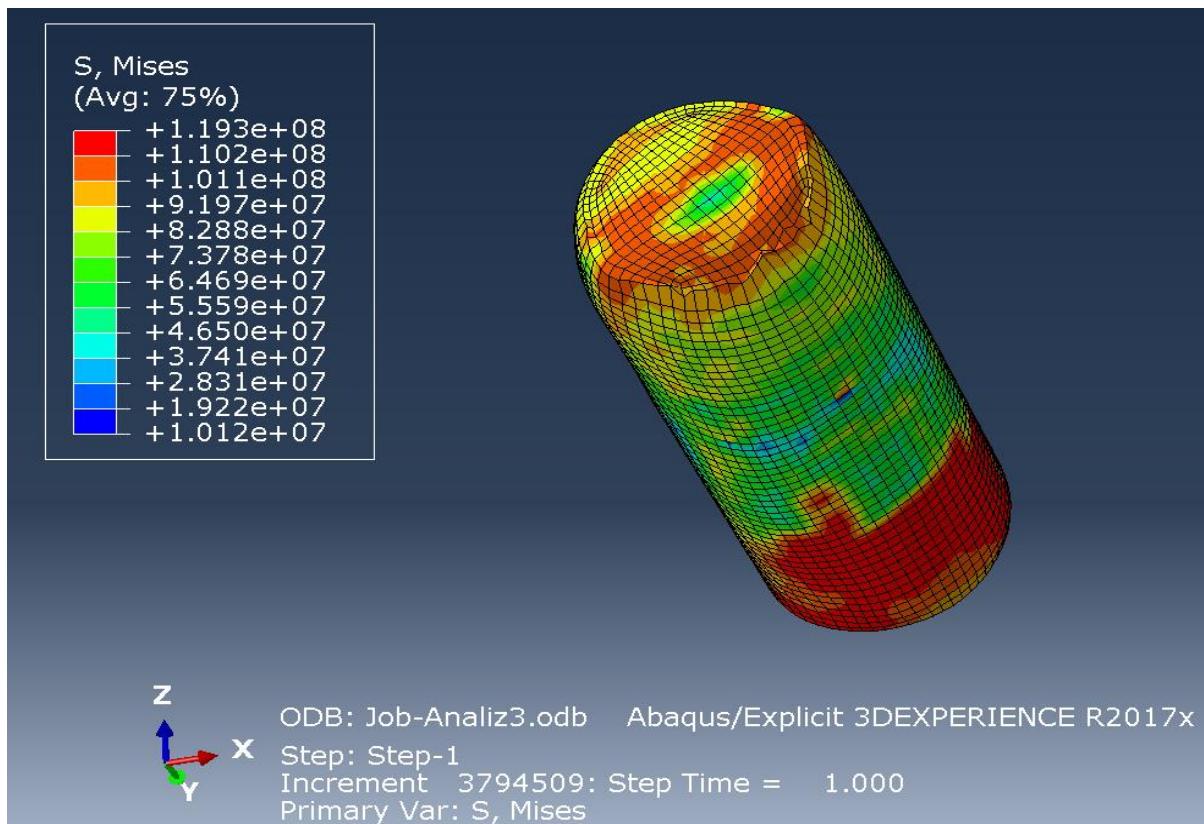


Figure 25 Deformed Sample - 1

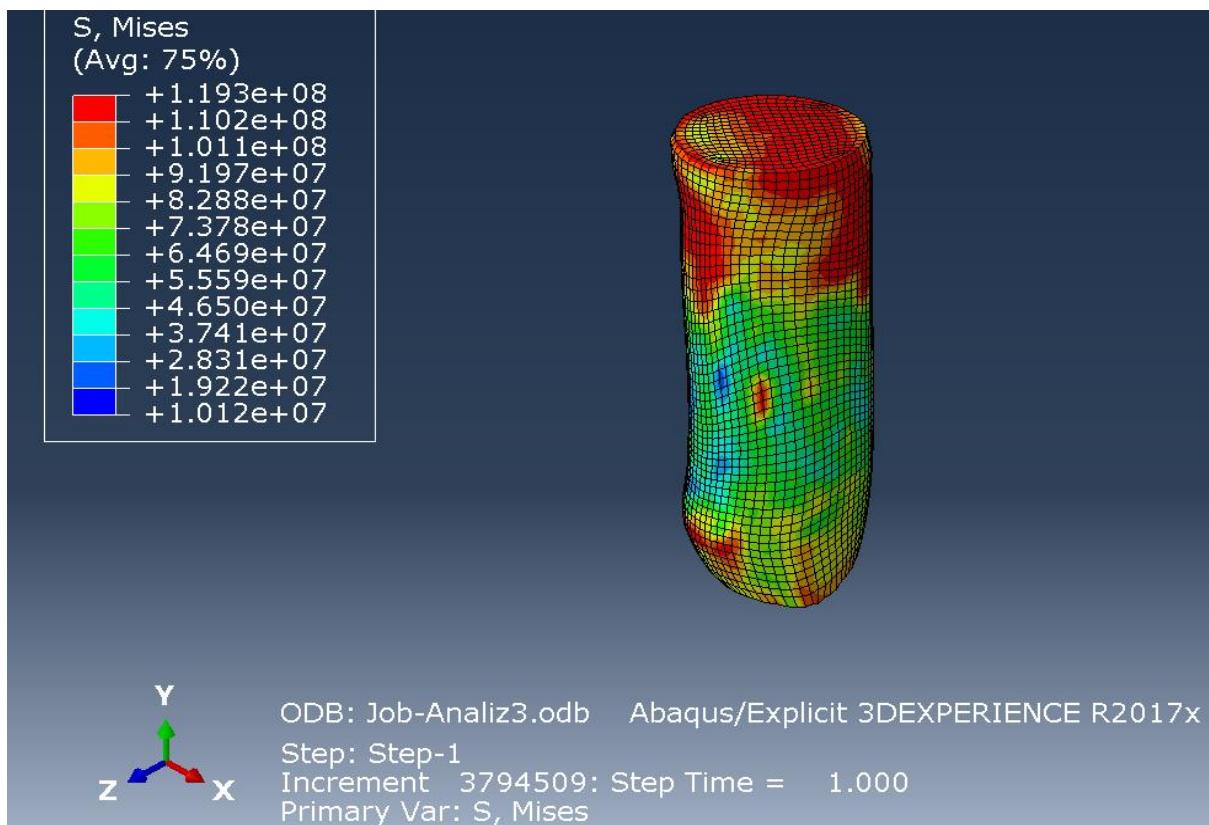
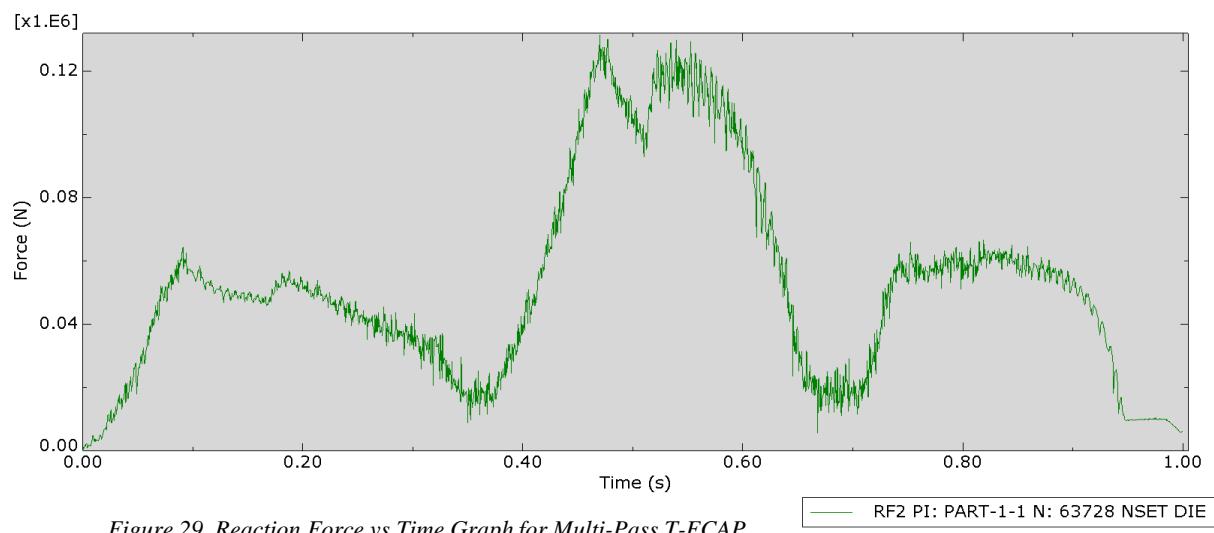
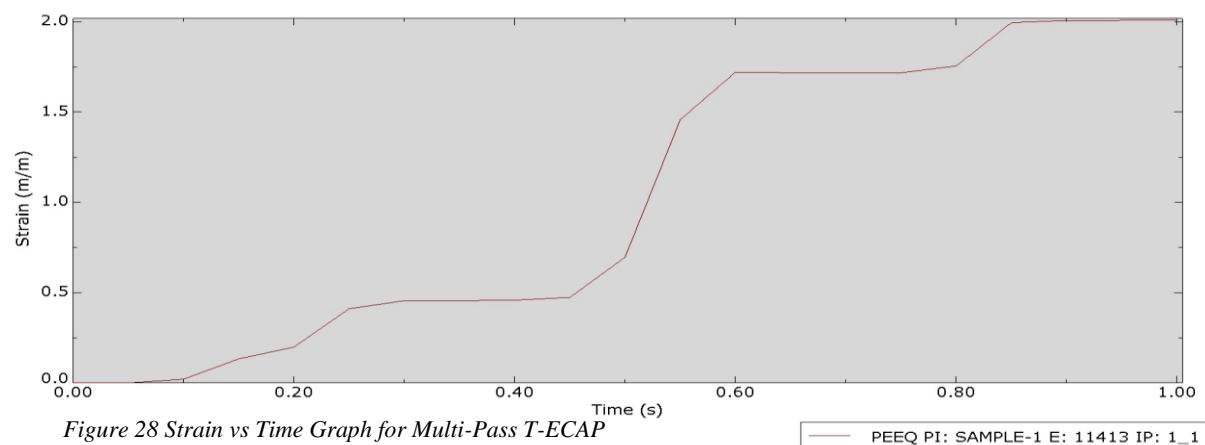
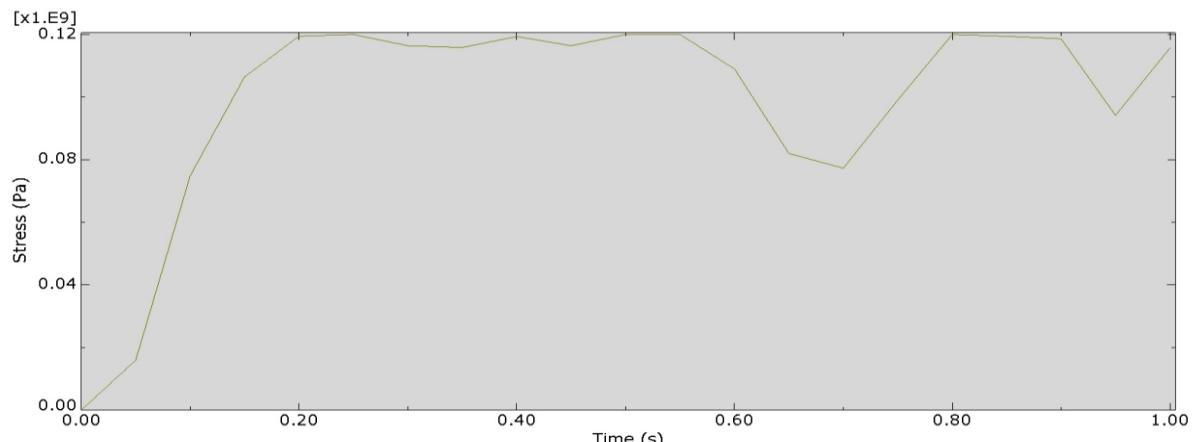


Figure 26 Deformed Sample - 2

#### 4.4.2 Stress- Strain- Reaction Force Changes Over Time



## 4.5 Cost Analysis

Firstly, in order to perform our ECAP process, we must use a press with a minimum compression force of 132 MN, which is the largest load at T-ECAP. We made a market research for suitable press Then, we calculated the power required to operate this press by multiplying the compression forces (52 MN, 66 MN, 132 MN) by the displacement velocity (50 mm/s for ECAP, 150 mm/s for Three Passes ECAP and Three Passes T-ECAP). We found electricity price for businesses as 0.14-0.15 USD per kWh.

For ECAP

$$P = F \times V_T = (52 \text{ MN}) \times \left(50 \frac{\text{mm}}{\text{s}}\right) = 2600 \text{ kW}$$

$$E = P \times t = (2600 \text{ kW}) \times 1 \text{ h} = 2600 \text{ kWh per hour working.}$$

$$\begin{aligned} \text{Price} &= E * (\text{electricity kWh price}) = (2600 \text{ kWh}) \times 0.14 \text{ USD per kWh} \\ &= 364 \text{ USD} \end{aligned}$$

For Three Passes ECAP

$$P = F \times V_T = (60 \text{ MN}) \times \left(150 \frac{\text{mm}}{\text{s}}\right) = 9000 \text{ kW}$$

$$E = P \times t = (9000 \text{ kW}) \times 1 \text{ h} = 9000 \text{ kWh per hour working.}$$

$$\begin{aligned} \text{Price} &= E * (\text{electricity kWh price}) = (9000 \text{ kWh}) \times 0.14 \text{ USD per kWh} \\ &= 1260 \text{ USD} \end{aligned}$$

For Three Passes T-ECAP

$$P = F \times V_T = (132 \text{ MN}) \times \left(150 \frac{\text{mm}}{\text{s}}\right) = 19800 \text{ kW}$$

$$E = P \times t = (19800 \text{ kW}) \times 1 \text{ h} = 19800 \text{ kWh per hour working.}$$

$$\begin{aligned} \text{Price} &= E * (\text{electricity kWh price}) = (19800 \text{ kWh}) \times 0.14 \text{ USD per kWh} \\ &= 2772 \text{ USD} \end{aligned}$$

## Investment Costs

Special die for high stress extrusion processes: 12000-15000 USD

Extrusion machine which is capable to press up to 150 MN force : 140000-160000 USD

Special plunger for rotational processes: 1500-1700 USD

Part heater for pre-processing: 2000 USD

Part cooler for post-processing: 2500 USD

Additional safety equipments: 500 USD

Quality assurance equipments: 4000-4500 USD

7075 T6 Aluminum cost for per ton: 3600-4000 USD per ton.

Special lubrication oils for extrusion processes: 30-35 USD per liter.

Machine operator cost: 1200-1400 USD per month.

## 5. DISCUSSION

Simulation results for three different ECAP processes (single-pass conventional ECAP, three-pass ECAP, and three-pass T-ECAP) provide critical information on mechanical behaviors and deformation properties under varying conditions. The analyses focused on the time-dependent changes in key parameters of stress, strain, and reaction force during the ECAP processes. In Figures 28, 29, and 30, you can see how these three variables of interest change relative to each other in these different ECAP processes.

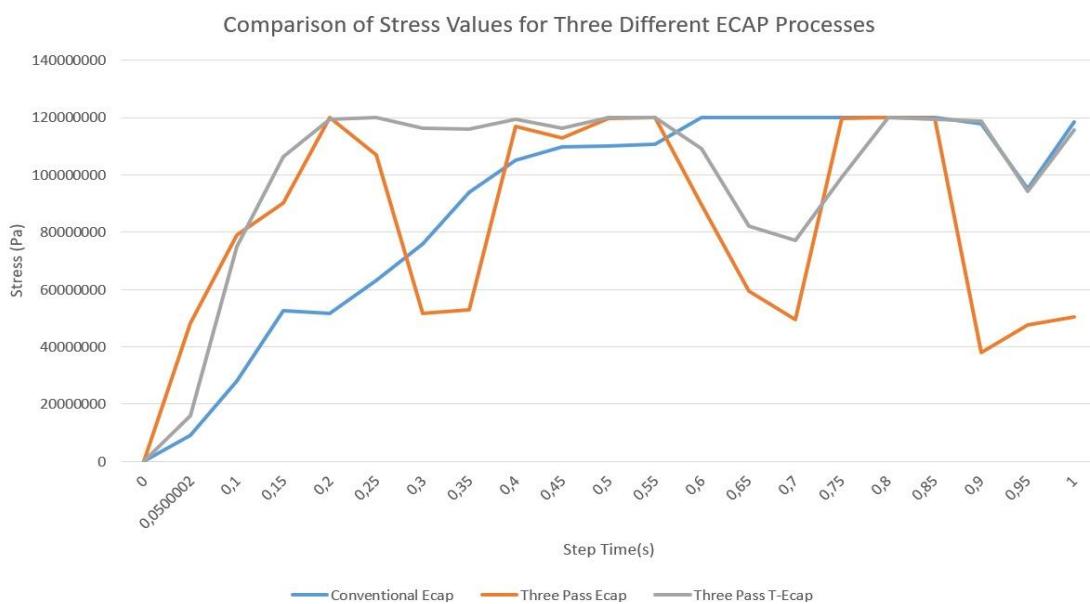


Figure 30 Stress vs Step Time Graph of Three Simulations

In the single-pass conventional ECAP process, while overall stress levels did not exhibit significant fluctuations, significant variations in stress were observed. This indicates that the traditional ECAP process maintains relatively stable stress levels during extrusion. However, in the three-pass ECAP process, approximately 50% stress reductions were recorded at step times of approximately 0.30 and 0.65 between each pass, attributed to the linear paths followed by the workpiece between passes. This results in a less uniform strain distribution. However, in the T-ECAP process, stress reductions between passes were minimized, indicating a more consistent stress applied throughout the deformation process. The introduction of rotation to the die reduces sudden stress changes, likely due to the friction effect during extrusion.

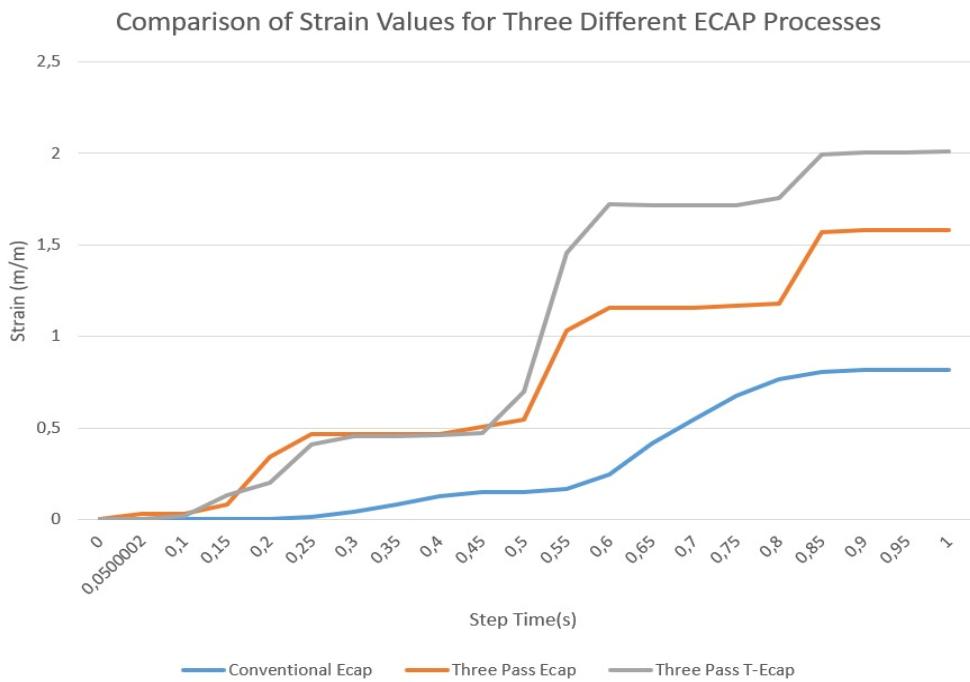
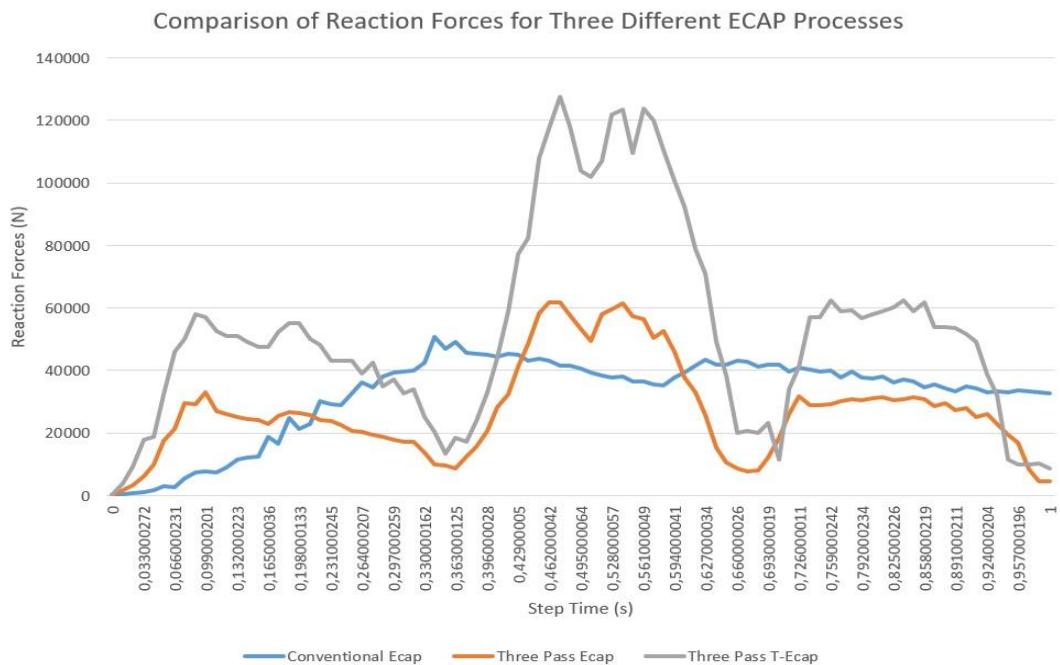


Figure 31Strain vs Step Time Graph of Three Simulations

Different maximum strain values obtained in different ECAP processes highlight where the effects of the new die design or the rotation speed imposed on the die are most evident. In single-pass conventional ECAP, strain values increased gradually, reaching up to 0.82. With the new die design, a multi-pass ECAP process performed within the same duration showed higher strain values due to the cumulative effect of repeated passes, reaching a value of 1.58, representing a 93% increase compared to traditional ECAP. Analyzing the strain increments on sample at each angle, it was observed that the increase in strain changing depending on the deformation due to angle value. Considering the angles of the designed new die are 135-90-135, the incremental values at each die can be described as follows. The first die at 135 resulted in an approximate strain increase from 0.08 to 0.46, with step times ranging from 0.15 to 0.35. In the section with the second 90-degree die, where there is more deformation, the strain value increased from 0.46 to 1.15, representing the range from 0.35 to 0.7. Finally, in the triple and last die transition region at 135 degrees, with step time changing from 0.70 to 1, the strain value increased from 1.15 to 1.58. Thus, it is evident that the impact of angle values on material deformation during transitions is quite clear. Analyzing the values for each angle, an approximate strain increases of 0.4 was observed for dies at 135 degrees, while approximately 0.75 strain increase was observed in the transition region where the deformation at 90 degrees is more significant. This confirms

the significance of the transition angle mentioned in the report.

In T-ECAP, as expected, the highest strain values were obtained among the three methods. The extra shear stress imposed on the workpiece due to the rotation speed of the die primarily from friction resulted in the achieved strain value, clearly indicating the attainment of desired fine-grained structures to improve material strength and hardness.



*Figure 32 Reaction Force vs Step Time Graph of Three Simulations*

Measured reaction forces during simulations serve as important indicators for understanding the efficiency of each process and also play a significant role in cost calculations. In single-pass conventional ECAP, reaction forces remained relatively constant due to the single pass effect. The maximum required reaction force in the traditional ECAP process was measured at 50.6 kN, with an average required reaction force of 32.3 kN. For three-pass ECAP, reaction forces varied more significantly in relation to the observed stress reductions between passes, likely due to the linear path followed by the workpiece between passes. In multi-pass ECAP, the maximum required reaction force was measured at 61.8 kN, with an average required reaction force of 27.2 kN. However, comparing average values among three-pass ECAP processes would be more appropriate since the drop in reaction forces due to the linear path followed may be misleading when compared to conventional ECAP processes. Percentagewise, compared to conventional

ECAP, the maximum reaction force increase was 20%. Delving into the reason for the 20% increase in maximum reaction forces for processes with the same die degree (90 degrees), it can be said that the AL7075 part, experiencing changes in physical properties after the first die, exhibited greater resistance in the second die.

In conclusion, T-ECAP and multi-pass ECAP methods yielded results such as smoother stress distribution, higher strain values, and higher reaction forces as expected. It was observed that in materials subjected to severe plastic deformation, better mechanical properties were achieved in the same duration compared to conventional ECAP, as a result of the new die design and the rotational effect imposed on the die. Both developments led to significant improvements on AL7075 sample.

## **6. CONCLUSION**

In this study, the deformation behavior and changes in the physical properties of Al7075 alloy are investigated using three different ECAP processes through three-dimensional finite element analysis (FEA) with ABAQUS/Explicit. The analyzed processes are Conventional ECAP, Multi-pass ECAP (Three-pass) and Torsional ECAP (T-ECAP).

A new die design was developed to enhance the conventional ECAP process. This design used for Multi-pass ECAP and T-ECAP leads to remarkable improvements in material properties. It allowed to obtain workpieces with better material properties within the same process time. The disadvantages are that the newly designed die is more expensive than the conventional ECAP and the required reaction force is higher, which has a negative impact on costs.

Experimental and simulation results showed a clear difference in strain distribution and load requirements for each process. The load requirement was observed to gradually increase from Conventional ECAP to Multi-Pass ECAP and then to T-ECAP, indicating the additional mechanical work and deformation involved in each subsequent process.

Strain distribution analysis revealed that the T-ECAP not only generated a higher strain, but also achieved a more uniform distribution compared to the Multi-Pass ECAP, which was more effective than the Conventional ECAP. The T-ECAP most improved the strain distribution and significantly increased the magnitude of the strain due to the rotational speed applied to the die. T-ECAP was concluded to be the most effective method to improve the mechanical properties of Al7075 alloy.

Finally, the die designed for Multi-Pass process demonstrates the feasibility of multiple passes in a single operation, significantly improving the properties of the material in the same process time as Conventional ECAP. Multi-pass ECAP (three pass) and T-ECAP significantly enhanced the strain uniformity and magnitude, confirming its better in improving the mechanical properties of the Al7075 alloy. Depending on the material properties using in the industry and cost concern, either of these two improved ECAP methods can easily be preferred over Conventional ECAP.

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