MARMARA UNIVERSITY

FACULTY OF ENGINEERING

INVESTIGATING THE EFFECTS OF DESIGN PARAMETERS OF A MODIFIED EQUAL CHANNEL ANGULAR DIE ON STRESS AND STRAIN DISTRIBUTION

Mert Can SERBAK 150420059

Talha YAĞLI 150420045

Abdulsamed KAYMAKCI 150421041

Arda YURTSEVER 150420050

GRADUATION PROJECT REPORT

Department of Mechanical Engineering

Supervisor

Asst. Prof Serkan ÖĞÜT

Istanbul 2025

MARMARA UNIVERSITY

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By

Mert Can SERBAK, Talha YAĞLI,

Abdulsamed KAYMAKCI, Arda YURTSEVER

June 2025, Istanbul

SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN

PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

BACHELOR OF SCIENCE AT

MARMARA UNIVERSITY

Signature of Author(s)

Mert Can SERBAK

Talha YAĞLI

Abdulsamed KAYMAKCI

Arda YURTSEVER

Certified By

Department of Mechanical Engineering
Dr. Öğr. Üyesi Serkan ÖĞÜT
Project Supervisor, Department of Mechanical Engineering

Accepted By

Prof. Dr. Bülent EKİCİ
Head of The Department of Mechanical Engineering

ACKNOWLEDGEMENT

First and foremost, we would like to express our deepest gratitude to our advisor, Asst. Prof. Serkan ÖĞÜT, for his invaluable guidance, continuous support, and patience throughout this research. His expertise and encouragement were instrumental in the completion of this thesis.

ÖZET

Bu çalışma, Eşit Kanal Açısal Presleme (ECAP) sürecinde malzeme deformasyon homojenliğini artırmak ve çekme gerilimi konsantrasyonlarını azaltmak amacıyla modifiye edilmiş bir kalıp tasarımının optimizasyonunu araştırmaktadır. Deform-3D kullanılarak yapılan sonlu elemanlar analizi (FEA) ile 5–25 mm geçiş uzunluğu ve 2°–5° eğim açısına sahip 20 farklı kalıp konfigürasyonu değerlendirilmiştir. 15 mm geçiş uzunluğu ve 5° eğim açısına sahip optimal tasarım, tamamen basınçlı gerilim durumu ve minimum deformasyon homojensizliği (indeks: 0.08174) sergilemiştir. Emniyet faktörü hesaplamaları, maksimum yükler altında punç (M2 Takım Çeliği) ve kalıbın (H13 Takım Çeliği) yapısal bütünlüğünü doğrulamıştır. Sonuçlar, bu modifiye edilmiş kalıbın endüstriyel uygulamalarda tane incelmesini ve mekanik özellikleri iyileştirme potansiyelini vurgulamaktadır.

ABSTRACT

This study investigates the optimization of a modified Equal Channel Angular Pressing (ECAP) die design to enhance material deformation homogeneity and reduce tensile stress concentrations during the process. Through finite element analysis (FEA) using Deform-3D, 20 die configurations with varying transition lengths (5–25 mm) and tilt angles (2°–5°) were evaluated. The optimal design, featuring a 15 mm transition length and 5° tilt angle, demonstrated a fully compressive stress state and minimal strain inhomogeneity (index: 0.08174). Safety factor calculations confirmed the structural integrity of critical components, including the punch (M2 Tool Steel) and die (H13 Tool Steel), under maximum loads. The results highlight the potential of this modified die to improve grain refinement and mechanical properties in industrial applications while maintaining process stability.

SYMBOLS

Φ: Abrupt Angle

Ψ: Arc of Curvature

α: Tilt Angle

mm: Millimeter

N: Newton

°: Degree Angle

n: Safety Factor

S: Yield Strength

σ: Stress

F: Force

A: Area

E: Young's Modulus

I : Moment of Inertia

L: Length

K: Boundary Conditions

ε: Strain

P: Buckling Force

ABBREVIATIONS

SPD: Severe Plastic Deformation

ECAP: Equal Channel Angular Pressing

HPT: High Pressure Torsion

TE: Twisted Extrusion

VF: Versatile Forging

RCS: Repeated Corrugation and Straightening

CGP: Constrained Groove Pressing

CCC: Cylinder Covered Compression

ARB: Accumulative Roll Bonding

FSP: Friction Stir Processing

SFSP: Submerged Friction Stir Processing

IECAP: Incremental Equal-Channel Pressing

TMCAP: Multi-Channel Angular Pressing

TWO-CAP: Thin-Walled Open-Channel Angular Pressing

EXP-ECAP: Expansion Equal Channel Angular Pressing

PTCAE: Planar Twist Channel Angular Extrusion

ANN: Artificial Neural Network

FE: Finite Element

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1. INTRODUCTION

1.1. THEORETICAL BACKGROUND

Since the industrial revolution, the development of production and forming methods continues unabated with increasing demand in various industrial areas such as automobile, aerospace, biomedical and defense sectors. In particular, the enhanced properties of materials are crucial for the requirements of future improvements in industry. At this point, SPD techniques are being examined by researchers and scientists through an extensive research process due to their serious potential in improving material properties [1].

SPD is an application technique used in material production and development processes that has proven itself with lab-scale research, especially in obtaining ultra-fine grained (UFG) and nanocrystalline materials while bringing the material properties to the desired levels. The material microstructure can be classified by examining their grain size as 4 different groups which are called as nanocrystalline, ultra-fine grained, fine grained and coarse grained. The grain size of nanocrystalline material is within the range 1 nm – 100 nm, grain size of ultra-fine grained material is in the range 100 nm – 500 nm, the grain size of fine grained is in the range 0.5 µm – 10 µm, and grain size of coarse grained is greater than 10 µm [1], [2].

The SPD process rearranges and shapes the grain structure of the material, which directly affects its mechanical properties. This can be explained by the equation called the Hall-Petch relationship. That describes the relationship between the grain size of the material and the yield strength value. The SPD process focuses on improving the mechanical properties with this approach [3], [4].

$$\sigma = \sigma_0 + \frac{k}{\sqrt{d}} \tag{1}$$

where:

$$\sigma_0 : the\ friction\ stress$$

$$k : the\ strengthening\ coefficient$$

$$d : grain\ size$$

SPD techniques allow the production of UFG and nanocrystalline materials by creating high levels of strain in the microstructure of the material and rearranging and reshaping the grain structures. During this application, no significant change in geometric dimensions of the workpiece is observed. As a result of the observed application, the characteristic properties of the material obtained are improved, while its ductility is preserved or even improved at the desired levels.

In this way, the low-ductility problem observed after the application in most plastic deformation methods used in the industry is prevented [5].

There are many studies on SPD techniques in the literature. Poojitha et al. shows that also the corrosion resistance of the material and fatigue performance are enhanced by applying this process. On the other hand, several passing may cause unexpected failure on the material structure and the limitation of some different techniques of SPD (for example the thickness limitation of HPT) can be given as disadvantages for this concept. After all, the improving technology work to overcome these difficulties and make the SPD techniques easier and beneficial for industrial usage [6].

There are many SPD techniques used in the studies whose results are published earlier. These SPD techniques are:

Equal-Channel Angular Pressing (ECAP), High-Pressure Torsion (HPT) [7], Accumulative Roll Bonding (ARB) [8], Twist Extrusion (TE) [9], Multi-Channel Spiral Twist Extrusion (MC-STE) [10], Repetitive Corrugation and Straightening (RCS) [11], [12], Cyclic Extrusion–Compression (CEC) [13], [14], Constrained Groove Pressing (CGP) [15], [16], Cylinder Covered Compression (CCC) [17].

Since the beginning of SPD techniques, the most notable techniques are ECAP and HPT methods. These methods are the first methods used in the production of physically and mechanically improved UFG and nanocrystalline materials such as alloy and metals [5]. Although HPT and ECAP are the most common SPD techniques, it should be noted that ECAP studies do not require complicated and more expensive facilities that are required by HPT studies. Therefore, ECAP is slightly more preferable than HPT technique [18], [19].

There are several reasons for focusing on ECAP techniques within the other SPD techniques. To explain these reasons briefly:

1.1.1. Repetitive Applicability and Homogeneity

The ECAP method provides a more uniform and consistent change in the microstructure of the material. In other SPD methods, especially in the HPT method, a more homogeneous microstructure is formed in areas close to the surface of the material, while the homogeneous feature may be lost in the central areas. In the ECAP method, a homogeneous distribution occurs throughout the entire cross-section of the material [1], [20].

1.1.2. Constant Cross-Sectional Area

While performing the ECAP process, high plastic deformation is achieved while the cross-sectional area is kept constant. In this way, dimensional controls are performed more easily on the parts to be processed and there is no need for any reshaping and sizing at the end of the process [20].

1.1.3. Ease of Application and Low Cost

The non-complexity of the mold geometry used in the ECAP method significantly reduces production and maintenance costs compared to other complex SPD methods. In a study conducted by Segal, it was determined that the ECAP method was 40-60% cheaper than the HPT method. It was also reported that the amount of energy required to perform the process was 20-30% lower [20].

1.1.4. Variety of applicable materials

The results obtained from the application of the ECAP method using many alloys and metal materials such as aluminum, magnesium, copper, titanium and steel are quite promising and successful [1].

The effects of ECAP method on the material can be made more concrete by mentioning some studies that helped to reach these results.

Djavanroodi et al. investigated the effects of die channel angle and outer corner angle on strain distribution uniformity in commercial pure aluminum subjected to ECAP via route A up to eight passes, combining experimental work with finite element modeling [21], [22]. They compared two metrics for strain homogeneity - inhomogeneity index (Ci) and standard deviation (S.D.) concluding that S.D. provides a more reliable quantification of strain uniformity, especially as strain heterogeneity increases with the number of passes [23], [24], [25]. Djavanroodi et al. identified optimal die geometry as a 60° channel angle with a 15° outer corner angle for improved strain uniformity in cross-section, and a 120° channel angle with either 15° or 60° outer corner angle for bulk material uniformity [21], [26]. Moreover, their experimental results demonstrated significant grain refinement and strength improvement in ECAP aluminum, highlighting the importance of die design based on strain distribution uniformity rather than solely on effective strain magnitude [27], [28], [29], [30].

Several studies have highlighted the significance of processing routes and number of ECAP passes. For instance, Gupta et al. emphasize that route BC results in the highest mechanical strength due to consistent grain fragmentation and dislocation density buildup [31].

Kumar et al. reported that ECAP processing of Al7075 alloy through route BC significantly increased microhardness from 69 HV to 139 HV and tensile strength from 245 MPa to 425 MPa after four passes. However, elongation to failure decreased substantially after the first pass and remained nearly constant thereafter [32].

Minárik et al. observed similar trends in LAE442 magnesium alloy, where tensile strength and yield strength increased up to four passes and then plateaued. Elongation improved only after the first pass [33].

In the case of AE21 magnesium alloy, Minárik et al. noted a decrease in UTS after four passes despite an initial increase in yield strength up to two passes [34].
Abioye et al. demonstrated that for Al6063 alloy, tensile strength and Young's modulus increased by 48.2% and 121.1%, respectively, from pass 0 to pass 6, but elongation decreased by approximately 11.4% [35].

Venkatachalam et al. showed that aged 2014 aluminum alloy samples processed through route BC achieved the highest strength of 602 MPa after three passes. They attributed this to the effective suppression of dislocation annihilation via rotational billet reorientation [36].

Murashkin et al. enhanced both mechanical strength and electrical conductivity in Al–0.6Mg–0.45Si alloy using a parallel ECAP channel. Artificially aged samples reached UTS of 310 MPa and yield strength of 295 MPa after two passes, alongside increased conductivity [37].

Additional studies on AZ31 and Mg-Al alloys affirmed that lower processing temperatures and higher pass numbers promote finer grain sizes, increased hardness, and strain hardening [38], [39].

Nevertheless, ECAP has limitations in terms of industrial scalability. Xu et al. point out issues like sample length constraints, repetitive handling, and uneven billet ends due to non-uniform deformation, which introduce material wastage [40].

Horita et al. explored the feasibility of scaling equal-channel angular pressing (ECAP) for industrial applications by investigating aluminum samples with diameters ranging from 6 to 40 mm. Their experiments demonstrated that the grain refinement and mechanical properties achieved after ECAP were essentially independent of the initial sample size [41].

Following six passes, all samples—including the largest one with a 40 mm diameter—exhibited similar ultrafine grain structures, with average grain sizes around 0.7 µm and high-angle grain boundaries, confirming uniform refinement across different sample sizes. Even across various points of the large sample cross-section, microstructural homogeneity remained intact up to 5 mm from the edges [41].

The mechanical properties also remained consistent regardless of sample size. Tensile tests revealed that ultimate tensile strength (UTS), yield stress, and elongation to failure values for the 10 mm and 40 mm samples were nearly identical, with only slight variations in ductility [41].

After review all these results from the lots of articles, the ECAP process can be more understandable and attractive concept for researchers. Unfortunately, there are also several operational limitations while processing this method as it is mentioned before. In this reason, various ECAP modification techniques are developed by researchers. Before mentioning about them, the general parameters of ECAP must be introduced and understood.

1.2. ECAP PARAMETERS

As it is mentioned before, the Equal Channel Angular Pressing (ECAP) is a Severe Plastic Deformation (SPD) technique that refines grains in bulk metals without changing the specimen's cross-sectional dimensions. The processed materials usually start to show enhanced properties such as high strength, desired level of hardness, and sometimes ductility due to the rearranged formation of ultrafine-grained (UFG) or even nanostructured microstructures [5]. The most important point to focus on in this process is that the parameters affecting these enhancements must be well adjusted in order for the improvements obtained on the material properties to reach the desired levels. These parameters which are creating a high impact on material properties, can be expressed as a list that explained below:

1.2.1. Number of Passes

The impact of the passing number can be highly effective to refine grain microstructure and achieve desired enhancement on material properties. As a proof of that, El-Garaihy et al. studied to identify impacts of ECAP on pure Mg and reported up to 111% increase in hardness value and 44.7% increase in tensile strength after process which is applied with 4 passes using route Bc with a 90° die [42].

Moreover, Lowe and Valiev reported that four to six passes are crucial settings as number of passes to obtain homogeneous UFG microstructures in materials in aluminum and titanium [5].

1.2.2. Die Angle

Generally, in industrial fields, die angles are arranged between 90 and 120 degrees. Smaller die angles are used in practice to achieve higher strain values per pass, creating greater effects to obtain finer grains and better improved properties in the workpiece.

The results reported by El-Garaihy et al. show that, as a result of the process carried out in 4 passes at a die angle of 90 degrees, a grain structure as fine as 0.88 μm was achieved, while at 120 degrees, under the same conditions, a grain structure as fine as 1.89 μm was achieved [42].

1.2.3. Processing Routes

The routes of the application determine workpiece orientation between passes.

- Route A: No rotation
- Route Bc: 90 degree rotation in the same direction
- Route C: 180 degree rotation

The most effective route setting is reported as Route Bc. The route Bc provide us to obtain more homogeneous and fined grain structure due to shear plane rotation. Valiev shows its success significantly in hard-to-deform materials such as titanium [1].

1.2.4. Processing Temperature

With rising temperatures inside the die, it becomes easier to process harder and less ductile materials, and at the same time, it helps to create a more homogeneous structure by avoiding crack formation.

1.2.5. Back Pressure

Lowe & Valiev showed that the Back Pressure which is applied during ECAP process helps to avoid cracking in less ductile materials and achieve more uniform strain distribution across the billet which has more workable characteristics.

1.2.6. Ram Speed

Edalati et al. emphasized that various values for the ram speed can affect the temperature rise, strain rate, and quality of grain refinement. Higher ram speeds cause more heat generation due to friction through die surfaces and adiabatic heating, which can help in deforming hard-to-work materials. However, speeds much higher than the maximum compliance limit at which the material can be machined can result in non-uniform deformation or surface cracking [43].

In the light of the findings found on these main parameters examined, the number of times the material processed in the ECAP process passes through the die critically affects the properties of the material. At the same time, it has been determined that the method applied with the Bc route orientation in the die with a 90-degree die angle is the most optimal option for creating a homogeneous and fine-grained structure. The parameters in other headings help to bring these developments to more extreme points [44].

1.3. MECHANICAL FUNDAMENTALS OF ECAP

The performance of ECAP in fabricating ultrafine grain (UFG) materials and improving material properties depends on critical parameters such as effective strain (ε_{eq}) and mean stress state (σ_m) . The effective strain calculated through the von Mises criterion is considered an important parameter to measure the deformation severity within the material and is directly related to the performance of the grain refinement process. The effective strain can be evaluated with Eq. (2) as it is exhibited below [45], [46]

$$\varepsilon_{eq} = \frac{N}{\sqrt{3}}\left[2\,cot\left(\frac{\Phi + \Psi}{2}\right) + \Psi\,csc\left(\frac{\Phi + \Psi}{2}\right)\right] \tag{2}$$

where:

- ε_{eq}: Effective strain (von Mises equivalent strain)
- N: Number of ECAP passes
- Φ: Die angle
- Ψ: Outer Corner Angle

The next monitored parameter for measuring the performance of ECAP is mean stress. This parameter is calculated with the simple arithmetic average formula shown in Eq. (3).

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{3}$$

where:

- σ_m: mean stress
- σ_1: The Highest Tensile Stress
- σ_2: The middle-valued stress
- σ_3: The Highest Compressive Stress

In ECAP, σ_2 is assumed “0” due to mostly 2D deformation.

In general, in typical conventional dies operating with limiting passes to 13-14 due to cracking. In this case, grain sizes could only be reduced to around 500 nm. Thanks to modified die by improved techniques allow to increase number of passing in operation. Wang et al. shows that the modified die, which is improved by various titled exit channel configuration, allows to keep mean stress in compressive stress state until 20+ passes and finer grains as 200-300nm level [47].

In summary, these two derived parameters are the most critical measurement parameters in the modification studies conducted on ECAP. In this study, performance evaluation and comparison will be measured on these two parameters.

Now, some other modification techniques developed outside the mentioned sample study can be mentioned.

1.4. ECAP MODIFICATION TECHNIQUES

In recent years, various adaptations of the foundational Equal Channel Angular Pressing (ECAP) methodology have been suggested to address its limitations and to further improve the characteristics of materials subjected to Severe Plastic Deformation (SPD). Among these adaptations are Twist Channel Angular Pressing (TCAP), Twist Multi-Channel Angular Pressing (TMCAP), Twist Variable Channel Angular Pressing (TV-CAP), and Thin-Walled Open Channel Angular Pressing (TWO-CAP). All these methods rely on the fundamental principles of ECAP, at the same time introducing new features to enhance the material's properties.

1.4.1. Twist Channel Angular Pressing (TCAP)

The TCAP process incorporates a torsional component into the ECAP process by twisting the billet during the deformation process. The modification is intended to enhance the shear deformation and optimize the grain refinement mechanism. The twisting action given to the material introduces extra shear strains, which enhances a more homogenized deformation and facilitate more uniform grain structures.

This method has shown potential in the processing of materials that are typically hard to deform with conventional ECAP, such as titanium alloys, which benefit from the additional strain path offered by the twisting action [48].

1.4.2. Twist Multi-Channel Angular Pressing (TMCAP)

Developing on the concept of TCAP, TMCAP involves the use of multiple channels subjected to twist deformation. The use of an integration of torsional and shear strains in these multiple channels significantly improves the microstructural features of the material by strengthening and standardizing the deformation process. TMCAP has proved highly effective for the development of ultrafine-grained structures in materials that are typically resistant to deformation, enabling higher strain accumulation while requiring fewer passes in processing. This multi-faceted approach minimizes the number of iterations needed to get the required grain refinement and mechanical properties [49].

1.4.3. Twist Variable Channel Angular Pressing (TV-CAP)

The TV-CAP process utilizes a changing channel angle in addition to a twisting action. By changing the channel geometry during pressing, TV-CAP enhances a more controlled strain distribution along the material. This modification results in more efficient deformation and a finer grain morphology. The change in channel angles is extremely useful for managing the strain distribution, which can be very important for the production of materials with more uniform microstructures. TV-CAP has demonstrated better formability of materials and shorter processing times than conventional ECAP, especially in alloys with complicated phase structures [50].

1.4.4. Angular Pressing of Thin-Walled Open Channels (TWO-CAP)

TWO-CAP is an adapted variation of ECAP where narrow open channels are used in material processing. This process minimizes the possibility of material fracture through an improved control over strain distribution and prevention of excessive localized deformation. Having open channels enables more distributed material flow, thereby reducing frictional forces and minimizing the opportunity for defects. The TWO-CAP process has been of immense benefit in the processing of materials that have low ductility or are susceptible to cracking when subjected to severe deformation conditions. The process has been successful in developing homogeneous ultrafine-grained microstructures in otherwise difficult-to-process materials like magnesium alloys [51].

According to these findings obtained as a result of the research, it is determined that the die angle value as 90 degrees in the design to be used in the study. The main purpose of this study is to modify the entrance of the exit path to a certain distance with a variable cross-sectional area entrance with certain angle values in order to reduce the sharp corner created by the path inside the die while changing direction and the negative results of the extremely high strain and stress values formed in the material due to this reason. Within this project, it is aimed to investigate the effects of parameters such as tilt angle and transition length on the strain distribution and failure probability of the workpiece.

1.5. REFERENCE ARTICLE

The reference article investigates a modified die design for Equal Channel Angular Pressing (ECAP) to reduce cracking and fracture tendencies in processed samples. The researchers modified a conventional die ($\psi = 16°, \Phi = 90°$) by tilting the upper surface of the exit channel by $2°$, which was validated through finite element analysis (FEM) [47].

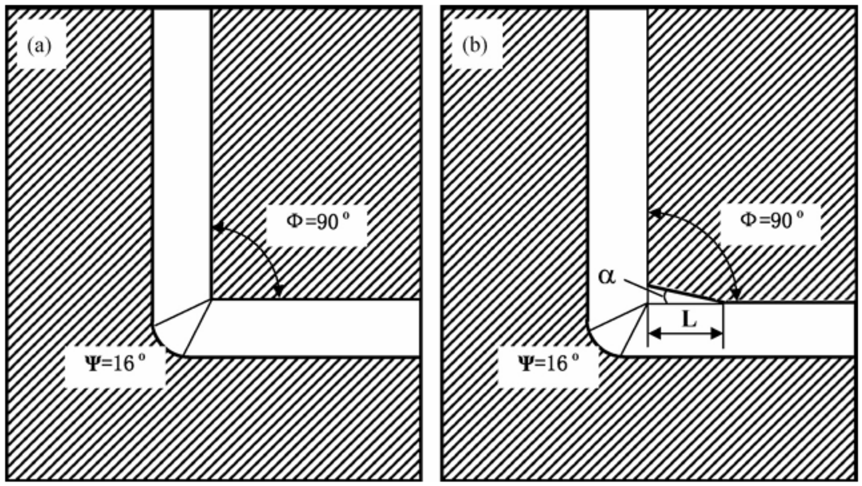

Figure 1 The ECAP dies used in the simulations: (a) conventional die; (b) modified die [47]

Results showed that while the conventional die induced tensile stress on the sample's upper surface (Figure 2a), the modified die eliminated this tension and created strong compressive stress instead (Figure 2b). Notably, the modified die proved more effective at generating compressive stress than applying 200MPa backpressure in conventional dies (Figure 2c) [47].

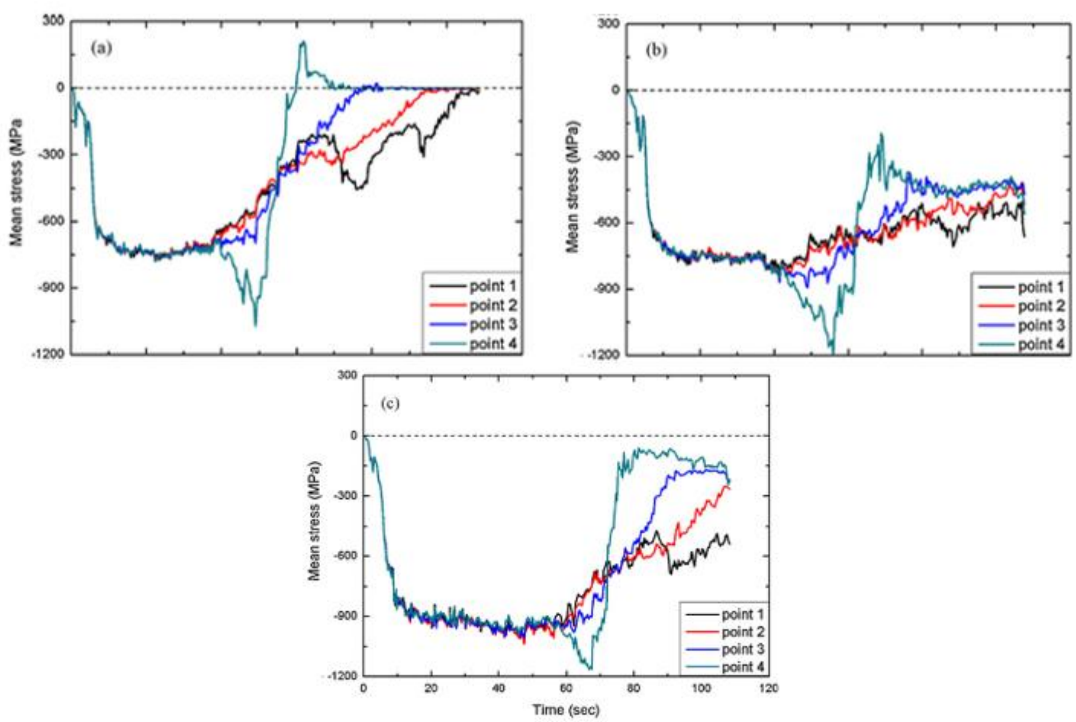

Figure 2 The mean-stress of the workpiece during extrusion in: (a) conventional die; (b) modified die; (c) conventional die with backpressure of 200MPa [47]

Deformation analysis confirmed that shear deformation patterns remained similar, though punch load slightly increased (Figure3). Experimental tests with commercial pure aluminum (99.5%) demonstrated the modified die's superiority - enabling 20 successful passes without surface defects compared to just 13-14 passes with conventional dies [47].

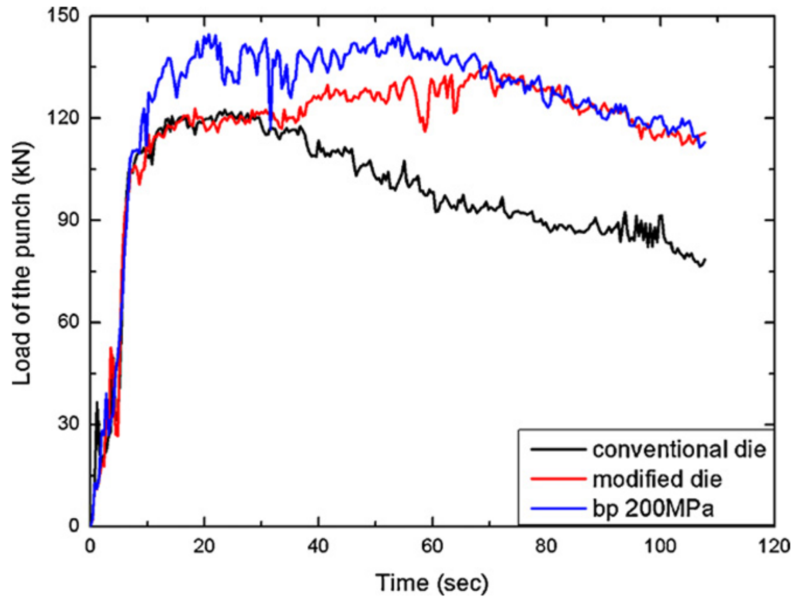

Figure 3 The load of the punches in the three ECAP conditions [47]

Furthermore, grain refinement improved significantly, with average grain sizes of 200-300nm achieved using the modified die (Figure 4b) versus ~500nm with conventional dies (Figure 4a). The modified die's simple yet effective design offers practical advantages for enhancing ECAP processing efficiency and material properties [47].

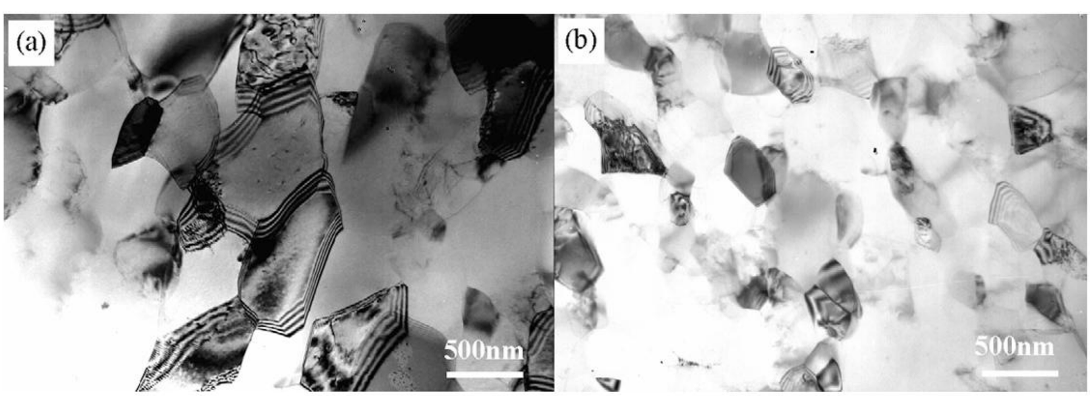

Figure 4 TEM images of pure aluminum pressed in the two dies for different passes: (a) conventional die, 12 passes; (b) modified die, 20 passes [47]

Another important point required to be focused is avoiding tensile stress. Because tensile stress occurring during the Equal Channel Angular Pressing (ECAP) process causes negative effects on material integrity and process efficiency. As shown in the study by Wang et al., the tensile stress concentrated in the regions close to the top surface of the workpiece significantly increases the tendency for crack formation and fracture and limits the number of successful ECAP passes. In conventional dies (ψ = 16° and Φ = 90°), commercially pure aluminum samples could only withstand up to 13-14 passes due to the concentration of tensile stress in the severe plastic deformation region. This stress condition not only promotes premature cracking but also leads to heterogeneous grain refinement, resulting in a coarser average grain size (~500 nm). To solve this problem, a modified die design with a 2° inclination on the top surface of the exit channel was presented in the study. This modification effectively eliminated the tensile stress by converting it into compressive stress. Finite element analysis confirmed the elimination of tensile stress and improved stress distribution, allowing 20 seamless passes and resulting in a finer (200-300 nm) and homogeneous microstructure. These findings highlight the critical role of compressive stress in suppressing crack formation, increasing deformation uniformity, and facilitating the production of ultra-fine grained materials with ECAP.

Finally considering also the relationship between material properties especially hardness and deformation homogeneity during ECAP process, optimal die parameters that will not cause tensile stress and provide a homogeneous strain distribution were investigated. It has been shown in the literature that strain distribution directly affects the mechanical properties of materials such as hardness and material strength. In this context, two critical die parameters were investigated to obtain a homogeneous strain distribution and minimize tensile stress, first on is tilt angle (α) which is also emphasized in the reference study, and second one is transition length (L) which expresses the length of the inclined transition region in the channel. The role of tilt angle (α = 2°) in converting tensile stress on the upper surface of the sample into compressive stress was proven experimentally and numerically. Transition length (L = 15 mm) provided a gradual transfer of deformation, thus reducing stress/strain concentrations and contributing to obtaining a more homogeneous microstructure. Optimization of these parameters prevented crack formation in multiple ECAP passes and increased the efficiency of grain refinement. In conclusion, this study reveals the critical importance of tilt angle and transition length parameters in ECAP mold design in terms of both mechanical properties and deformation homogeneity.

After all of the preparations for the project, the main purpose of the corresponding topic can be expressed as examination to modify the entrance of the exit path to a certain distance with a variable cross-sectional area entrance with certain angle values in order to reduce the sharp corner created by the path inside the die while changing direction and the negative results of the extremely high strain and stress values formed in the material due to this reason. It is aimed to analyze this process at different angles and examine the effects of this modification on the workpiece. It is expected that the modification method, which is applied, will prevent uncontrolled stress regions within the workpiece and perform a homogeneous grain refinement process with a uniform strain distribution. Later, the results will be compared with certain parameters and determined the best design parameters.

2. METHODOLOGY

This study investigates the optimization of a modified Equal Channel Angular Pressing (ECAP) die design through finite element analysis (FEA) to improve material deformation homogeneity and reduce tensile stress concentrations. The die configurations, incorporating varying transition lengths and tilt angles, were analyzed using DEFORM-3D. The main parameters monitored during the simulations include effective strain, mean stress, and strain inhomogeneity. The goal is to determine the most effective die geometry that minimizes tensile stress and achieves a uniform distribution of strain, leading to improved material properties and process efficiency.

2.1. CAD

In this study, a modified ECAP die which is considered in reference article was designed (Figure 5) using SolidWorks, a parametric 3D modeling software. The geometric design was created based on conventional ECAP principles, in which two channels of equal cross-section intersect at a specific die angle ($\Phi = 90°$). However, unlike the classical sharp-cornered die geometry, the upper wall of the exit channel was modified to include a gradual transition region with a defined tilt angle. This change was applied to avoid unexpected stress concentrations occurring at the intersection point and to achieve a more homogeneous strain distribution within the workpiece.

The model was created parametrically to improve flexibility for future changes in die geometry, including channel width, corner angle (Ψ), and transition length. The corner angle is determined as a specific angle for all die configurations ($\Psi = 16°$). The final geometry was exported in STEP format for subsequent use in finite element analysis.

The aim of this CAD modeling process is to evaluate how geometric modifications, specifically the introduction of a sloped exit channel wall, affect material flow and stress distribution during ECAP. This methodology follows the approaches described in recent literature, including Wang et al. where similar geometric adjustments were shown to reduce tensile stresses and improve processing stability [47].

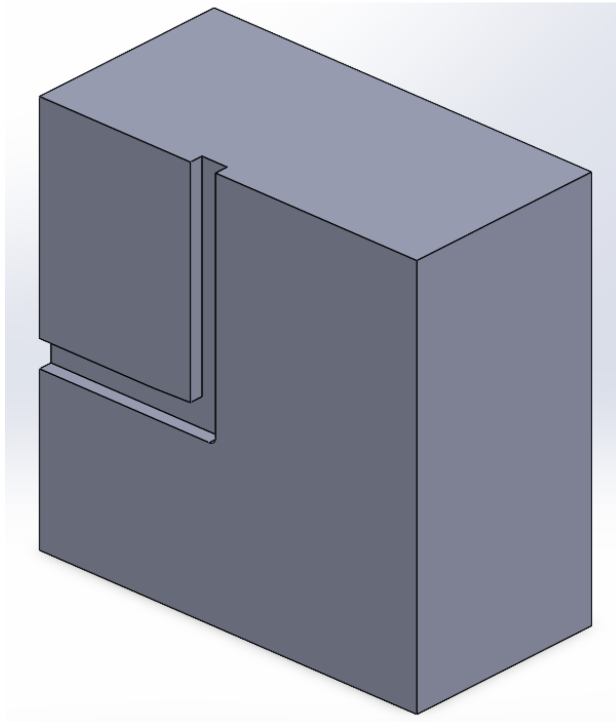

Figure 5 Modified ECA

2.2. FEM

To investigate the mechanical behavior of the workpiece during Equal Channel Angular Pressing (ECAP), numerical simulations were operated by using DEFORM-3D which is used for finite element software which is specialized in for bulk metal forming processes. The objective was to estimate how the modification of the die geometry which includes modification as a tilted surface at the exit channel, affects stress distribution, strain homogeneity, and the failure mechanism during deformation.

2.2.1. Model Setup and Simulation Conditions

The ECAP process was simulated under static, isothermal conditions, with the following parameters. These parameters were kept similar with those used in the reference study [47] for validation purposes:

- **Workpiece material:** 5083 aluminum (99.5% purity), modeled as isotropic.
- **Workpiece size:** 75 mm × 10 mm × 10 mm
- **Mesh density:** Approximately 5,000 tetrahedral elements
- **Die and punch:** H13 Tool Steel (Die) & M2 Tool Steel (Punch)

- **Punch velocity:** 0.5 mm/s
- **Friction coefficient:** 0.15 (workpiece–die interface, Coulomb model)
- **Initial temperature:** 20 °C (room temperature)

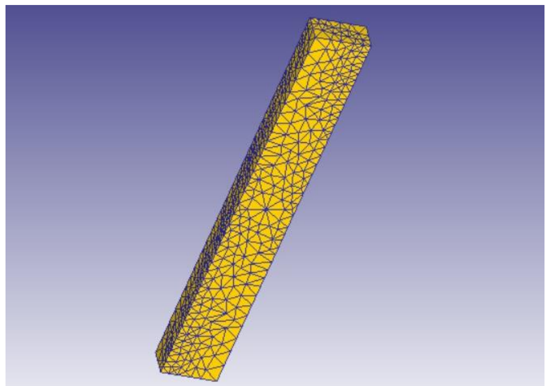

Figure 6 Mesh Density of Workpiece

A displacement-controlled loading condition was applied, and no thermal coupling or backpressure was used in the baseline analysis. Additional runs can be conducted to compare with the backpressure-assisted ECAP process if needed.

2.2.2. Evaluation Criteria and Monitored Parameters

The performance of the die geometries was assessed by tracking and comparing several key physical quantities:

- **Effective strain ($\bar{\varepsilon}$):** To evaluate the intensity and uniformity of plastic deformation.

- **Mean stress (σm):** With a focus on surface tensile stress concentrations that are prone to crack initiation.

To obtain localized stress–strain data, four control points were placed along the billet cross-section (from outer surface to core), following the method used by Wang et al. These points allowed detailed analysis of how the modified geometry affects strain gradients and surface behavior [47].

2.2.3. Objective of the Analysis

The main objective of the analysis was to examine the effect of applying the modification by implementing a tilted exit channel in the ECAP die design on the overall strain distribution within the workpiece. In this case, the homogeneous strain distribution is critical situation to achieving great enhancement on the material properties in the ECAP process.

Specifically, the study attempts to determine whether this geometric modification could effectively reduce undesirable surface tensile stresses and instead provide a more favorable compressive stress environment throughout the entire shear zone. Achieving a compressive stress state is particularly important in enhancing the mechanical properties and fatigue resistance of the processed material.

3. RESULTS

This section presents the findings obtained from the analyses and simulations conducted. The effects of different die geometries, transition lengths, and tilt angles on stress distribution, deformation homogeneity, and mechanical properties of the material are examined.

3.1. VALIDATION OF FINITE ELEMENT MODEL

In this study, the numerical model of the modified ECAP die was validated by comparing the simulated punch load–time response with experimental data reported in the literature. As shown in Figure X, the maximum punch load obtained from our simulation was approximately 140 kN. This closely aligns with the peak value of around 135–136 kN reported by Wang et al. for the modified die, with only a slight deviation. Such a difference can be attributed to minor variations in mesh density, friction assumptions, or the material model used during the finite element analysis [47].

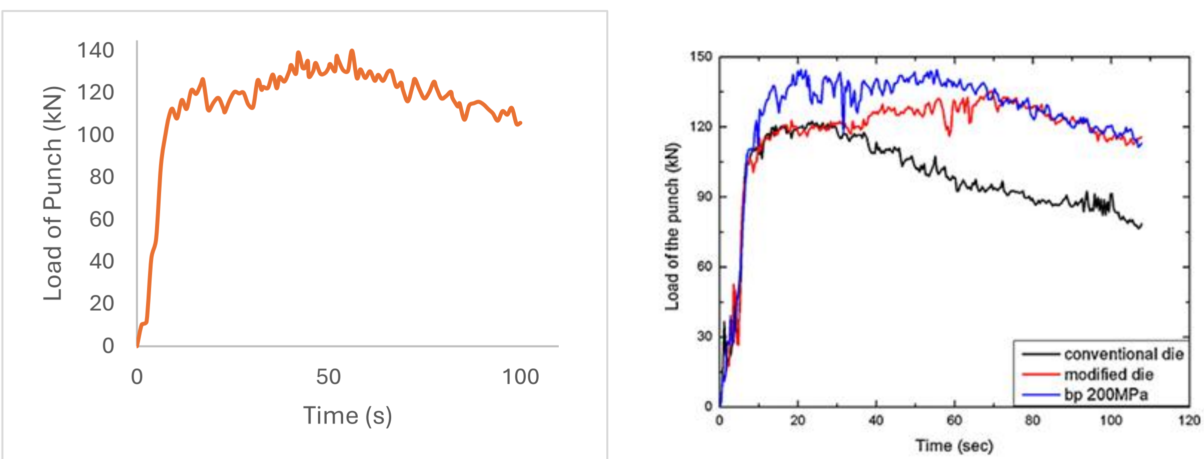

Figure 7 Comparison of the punch load with reference article [47]

In particular, the die geometry used in our simulation was designed with a tilted upper surface segment of $L = 15$ mm at an angle of $\alpha = 2°$, which matches the specific die modification parameters employed in the reference study. This geometric alteration is crucial for inducing compressive stress in the critical deformation zone, thereby enhancing process stability and increasing the number of successful ECAP passes.

Both curves exhibit a similar overall trend: a sharp initial increase in punch load due to the onset of plastic deformation, followed by a relatively stable plateau indicating steady-state flow. The slight fluctuations observed in both results suggest localized deformation effects, which further supports the similarity between the simulation and the experimental setup. This consistency in curve shape and magnitude confirms that the numerical model successfully captures the mechanical response of the ECAP process with the modified die geometry.

Beyond just validating the punch load, we also looked at how the mean stress changed over time at four key points inside the material during the ECAP process. In Figure X, you can see the stress-time curve from our simulation using the modified die design, which includes a 15 mm tilted surface angled at 2°. For comparison, Figure Y shows the same type of data from the experimental study by Wang et al. [47].

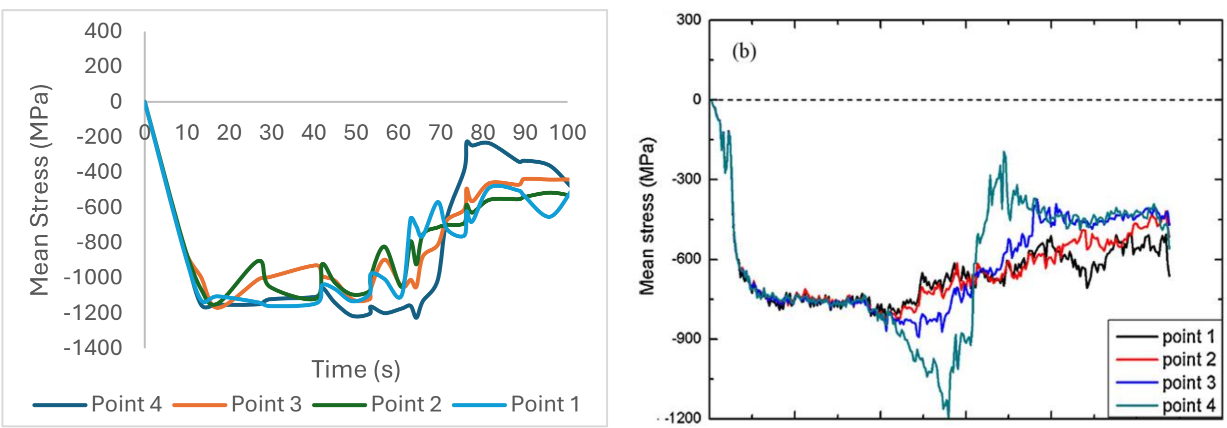

Figure 8 Comparison of mean stresses with modified die on referance article [47]

In our case, the stress at certain points drops sharply into the compressive range, reaching about −1200 MPa around 10 to 20 seconds, almost matching the −1100 MPa peak seen in the reference study. What is more important, though, is that all four points in both studies stayed in the compressive zone throughout the process. This is especially significant for Point 4, which normally tends to experience tensile stress and cracking in traditional ECAP setups.

3.2. RESULTS OF FINITE ELEMENT ANALYSIS

In this section, the results obtained from the finite element analysis (FEA) of the modified ECAP die configurations are presented. The analysis focused on evaluating the effects of varying transition lengths (L = 5, 10, 15, 20, 25 mm) and tilt angles (α = 2°, 3°, 4°, 5°) on stress distribution, strain homogeneity, and deformation behavior. The simulations were operated by using DEFORM-

3D, with key parameters such as effective strain, mean stress, and strain inhomogeneity index monitored across four tracking points (Figure 9) within the workpiece.

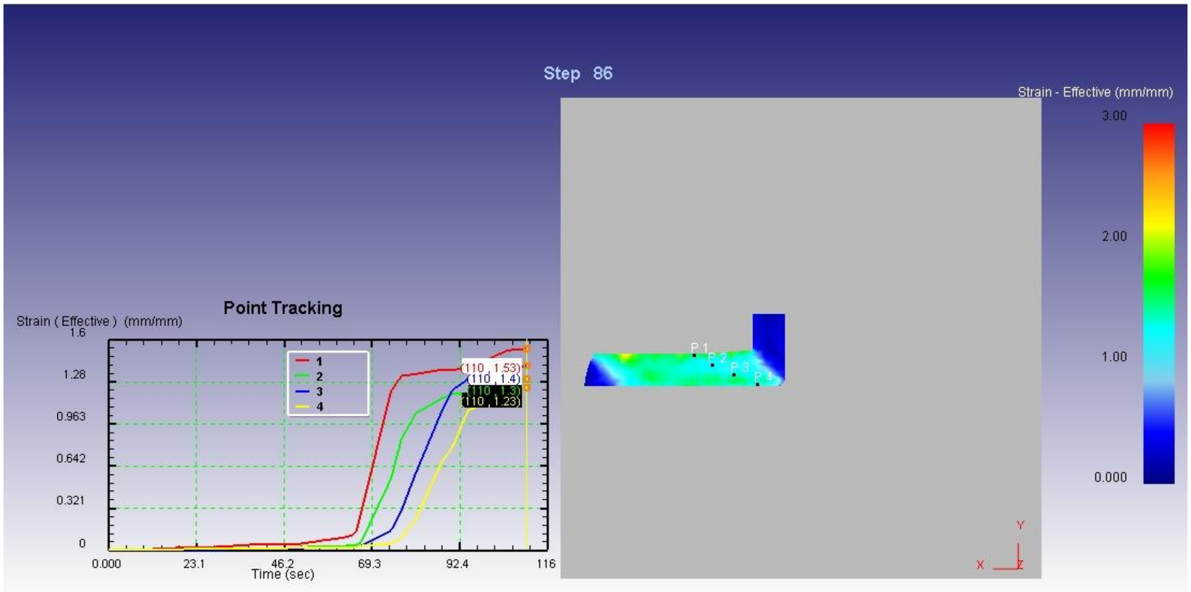

Figure 9 Point Tracking Method

The aim was to identify the optimal die geometry that minimizes tensile stress concentrations and ensures uniform strain distribution, thereby enhancing the material's mechanical properties and process efficiency. The following figures and table summarize the findings for each configuration, providing a comprehensive comparison of their performance.

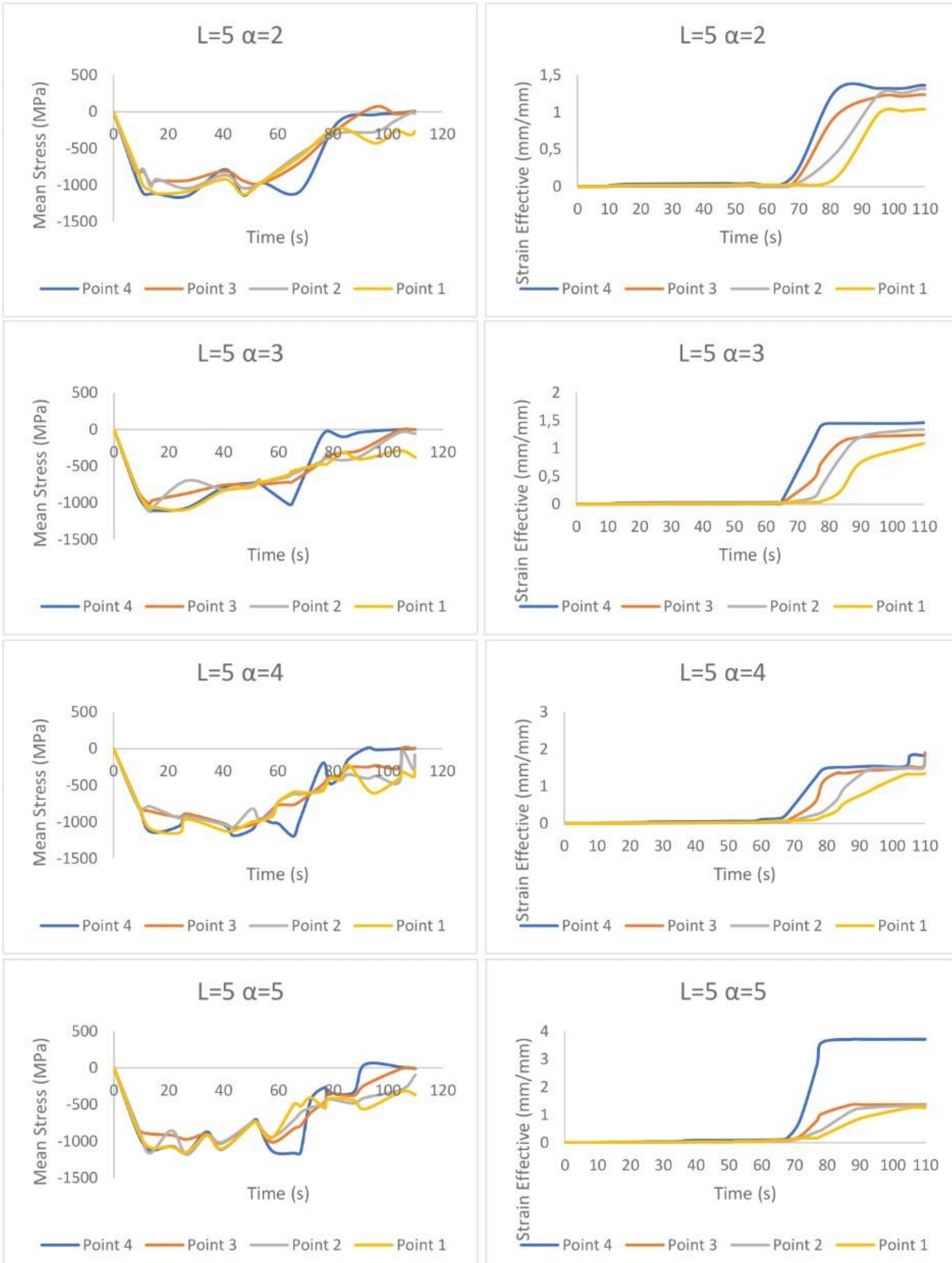

Figure 10 The results of the configuration L=5mm and α= 2-5°

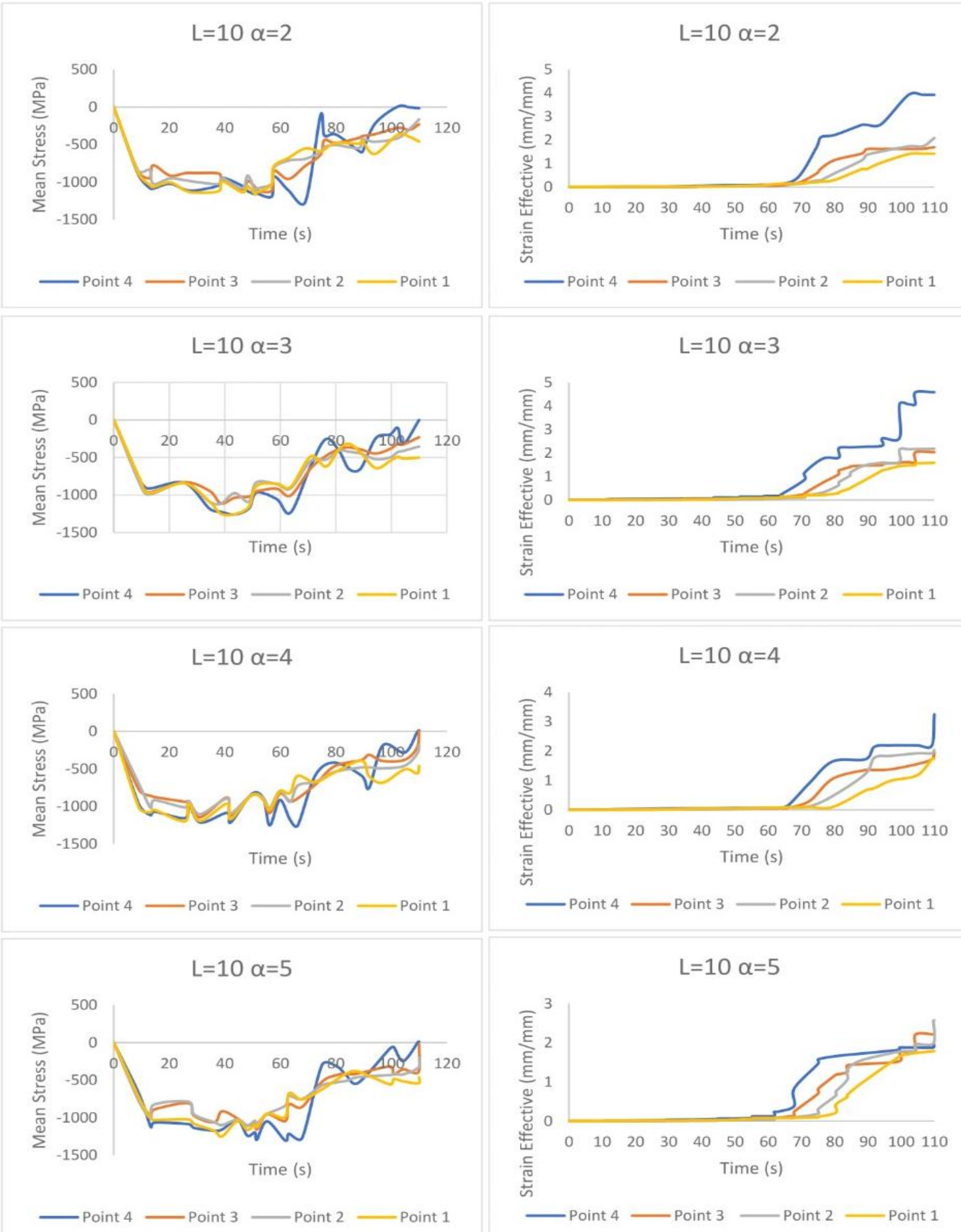

Figure 11 The results of the configuration L=10mm and α= 2-5°

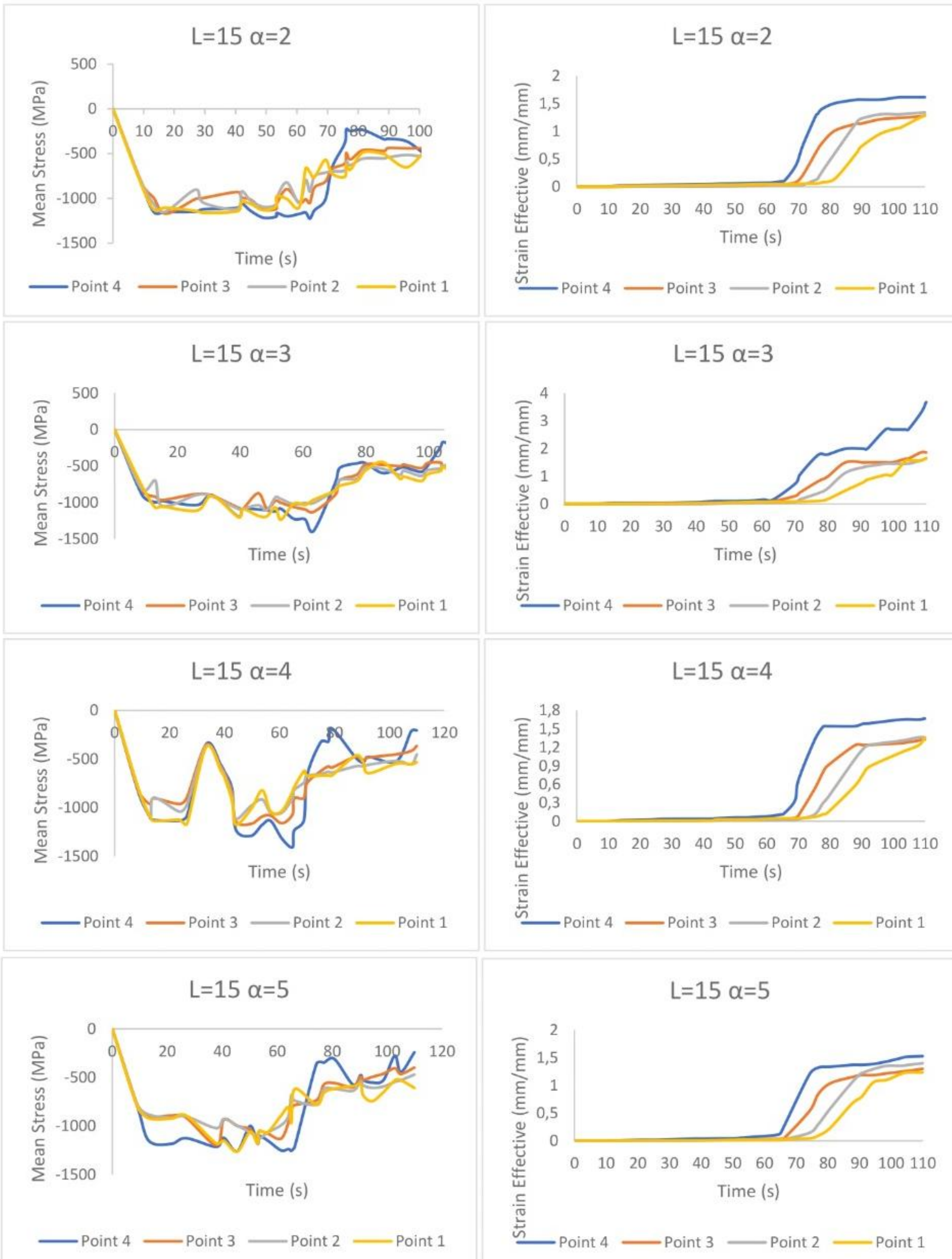

Figure 12 The results of the configuration L=15mm and α= 2-5°

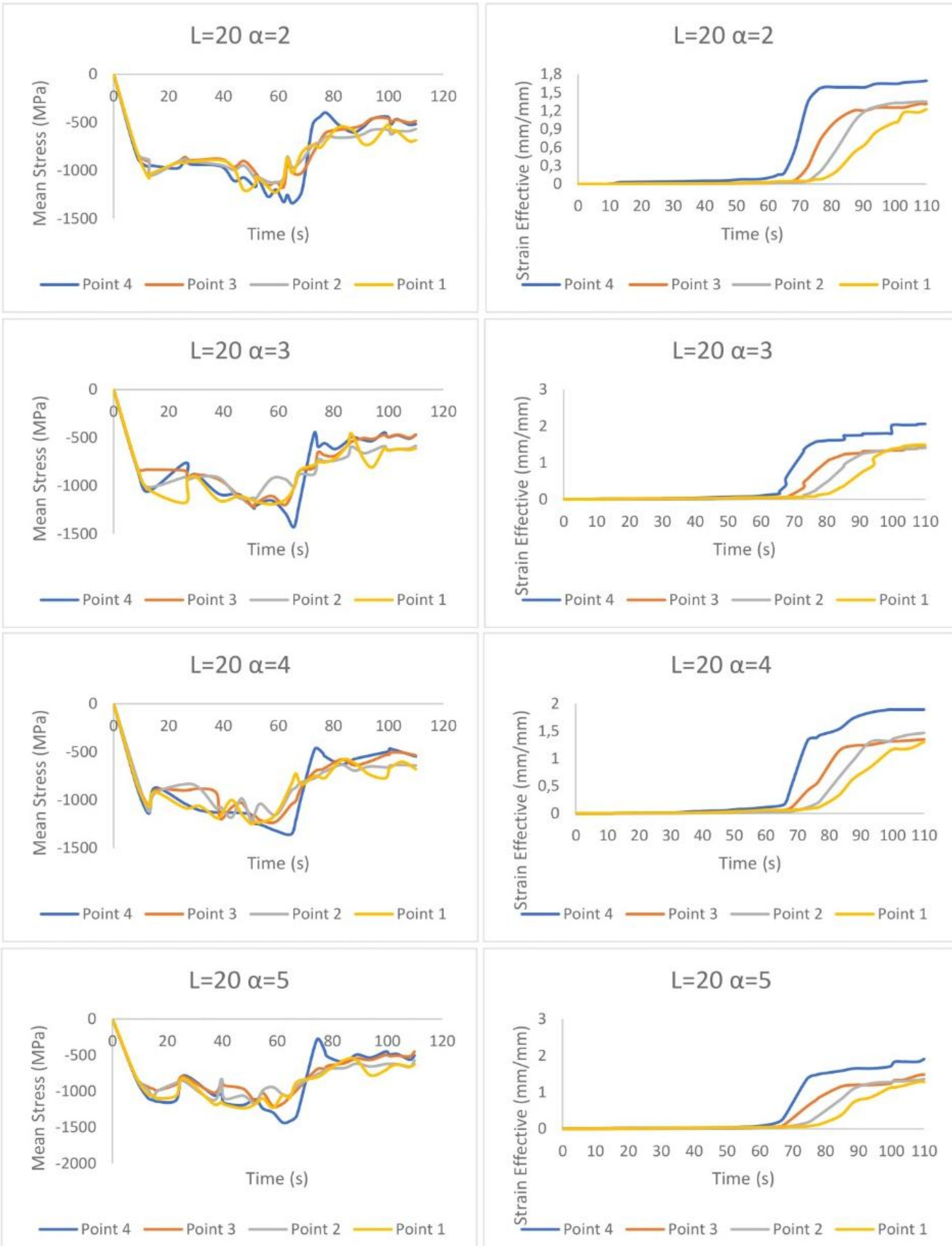

Figure 13 The results of the configuration L=20mm and α= 2-5°

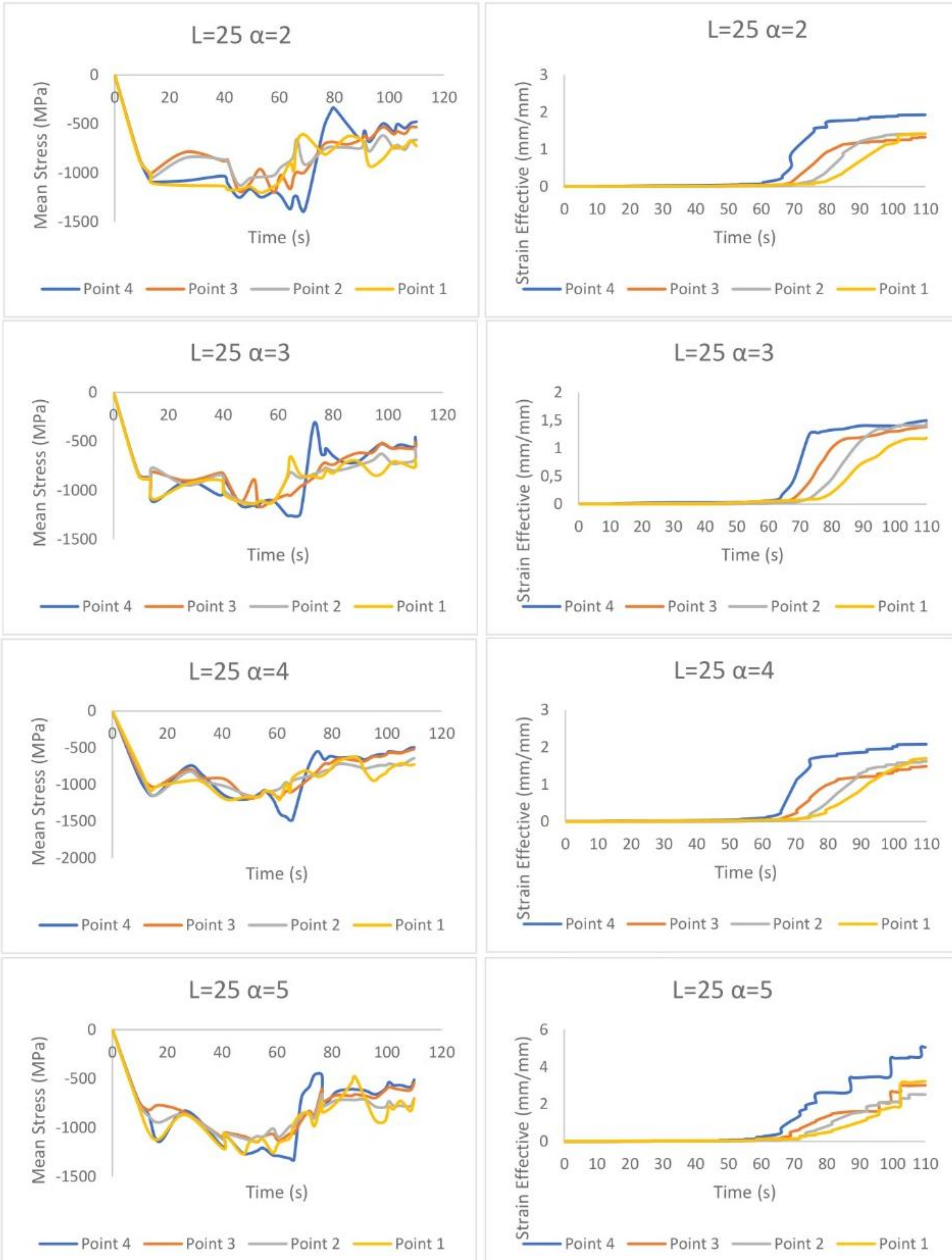

Figure 14 The results of the configuration L=25mm and α= 2-5°

Table 1 Maximum Stress and Strain Inhomogeneity Index

CFG	Max Stress (Mpa)	Index
5_2	6,929364	0,099218
5_3	-1,352839	0,105868
5_4	9,034876	0,12554
5_5	45,847299	0,539712
10_2	6,371273	0,428058
10_3	1,496257	0,449926
10_4	15,927481	0,262999
10_5	13,593227	0,139398
15_2	271,20322	0,099649
15_3	63,377214	0,385138
15_4	-186,3558	0,097036
15_5	-240,3089	0,081739
20_2	-402,2642	0,127886
20_3	-445,6618	0,170508
20_4	-467,2765	0,154799
20_5	-291,7182	0,160361
25_2	-337,3913	0,155593
25_3	-337,3913	0,084564
25_4	-337,3913	0,128527
25_5	-337,3913	0,2783

As it can be seen at Table-1, 20 different modified ECAP die geometries were designed using SolidWorks 2024, with the goal of optimizing internal stress distribution and minimizing strain inhomogeneity during SPD. Each die geometry is denoted as "X_y", where "X" represents the length of the tilted surface ($L = 5, 10, 15, 20, 25\ (mm)$) and y denotes the tilt angle ($\alpha = 2°, 3°, 4°, 5°$).

All designed models were analyzed using Deform-3D finite element simulation software. For consistency and direct comparison with the reference literature, four tracking points (Points 1–4) were defined within each billet to examine varying strain and stress distributions during ECAP in different regions.

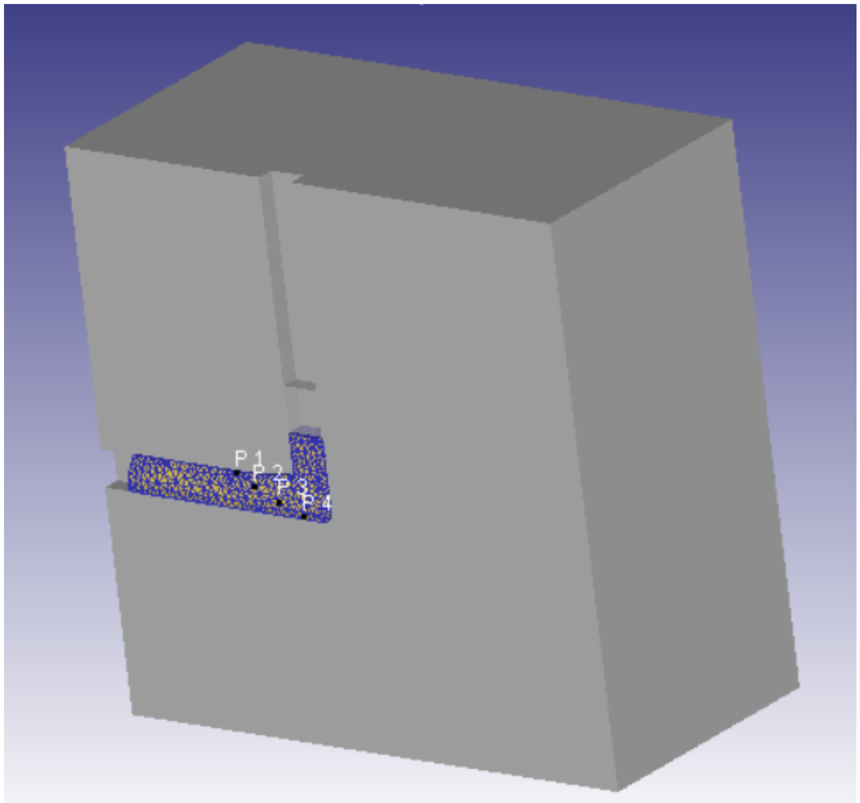

Figure 15 Four Point Representation on FEA

To evaluate the strain inhomogeneity for each design, a specified index value which is called as strain inhomogeneity index was calculated as the ratio of the standard deviation to the mean strain value Eq. (4). Additionally, maximum mean stress and effective strain values for each design were expressed (Table-1) to assess whether the die configuration effectively prevented high level of tensile stress within the workpiece. For any case that showed a positive maximum stress was considered non-viable, as tensile stress is known to cause surface cracking in ECAP-processed samples.

$$straininhomogeneityindex = \frac{Standard\ Deviation}{Mean} \quad (4)$$

Among the remaining viable candidates, the design labeled as 15_5 ($\mathrm{L} = 15\ \mathrm{mm}, \alpha = 5°$) yielded the lowest strain in homogeneity index of 0.081739, while also maintaining a fully compressive stress state measured as -240.31 MPa. Based on these two key criteria “compressive stress” and “minimum inhomogeneity”, the 15_5 labeled configuration was selected as the optimal die geometry for further investigation and validation.

3.3. CALCULATIONS FOR FINAL DESIGN OF THE DIE AND THE PUNCH

This section presents the calculations performed to ensure the structural integrity and reliability of the die and punch used in the ECAP process. The maximum forces acting on both components are analyzed, and safety factors are calculated to verify that the punch and die can withstand the applied loads without failure.

3.3.1. Punch

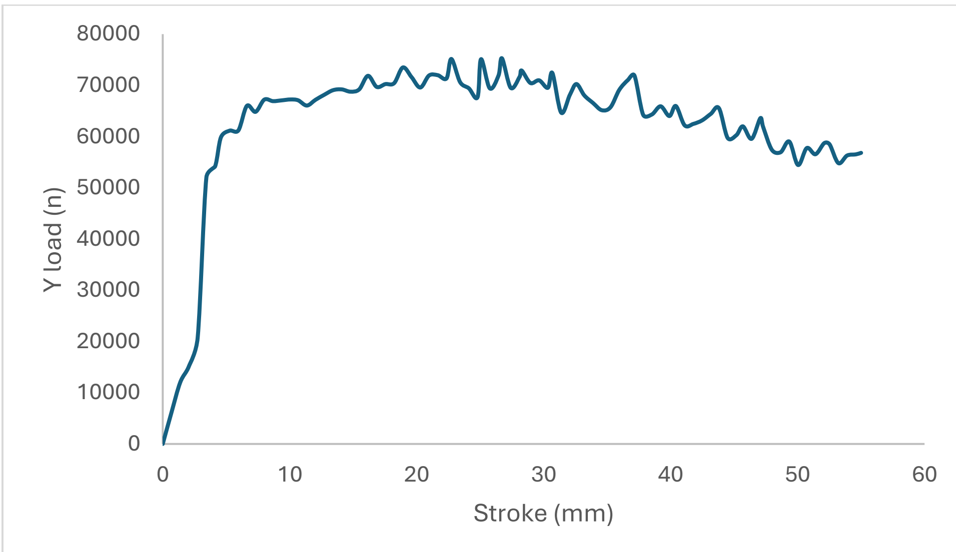

Figure 16 Load Prediction of Punch

In order to ensure the structural integrity and reliability of the punch used in the ECAP process, a safety factor calculation was conducted. From the load prediction graph obtained via Deform 3D simulation, the maximum force acting in the Y-direction on the punch was determined to be 75,278 N. Given that the cross-sectional area of the punch is 10 mm × 10 mm, the resulting applied stress on the punch was calculated using the fundamental stress formula:

$$\sigma = \frac{F}{A} = \frac{75278\ N}{10 \times 10\ mm^2} = 752.8\ \text{MPa}$$

The punch was modeled using M2 Tool Steel, a high-performance material known for its excellent strength and hardness properties. According to material datasheets, the yield strength of M2 Tool

Steel is approximately 3250 MPa. Using the ratio of yield strength to applied stress, the safety factor was calculated as:

$$n = \frac{S}{\sigma} = \frac{3250\,MPa}{752.8\,\mathrm{MPa}} = 4.32$$

This value confirms that the punch operates well within safe limits under the applied load, with a safety margin exceeding four times the yield threshold. Thus, failure due to yielding is not expected during the process.

To ensure the buckling resistance of the plunger under axial compressive loading, an Euler buckling analysis was performed. The plunger was assumed to have fixed-fixed boundary conditions, corresponding to an effective length factor of K = 2. The material selected was M2 Tool Steel, with an elastic modulus of E = 200,000 MPa. The unsupported length of the plunger was taken as L = 67.5 mm, and the area moment of inertia was calculated as I = 833.333 mm4.

The critical buckling load was computed using Euler's formula:

$$P = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2 \cdot 200000 \cdot \left(\frac{10 \cdot 10^3}{12}\right)}{(2 \cdot 67.5)^2} = 28730\,\mathrm{N}$$

Given a cross-sectional area of $A = 100\,mm^2$ the compressive stress under this critical load becomes:

$$\sigma = \frac{P}{A} = \frac{28730\,\mathrm{N}}{10 \times 10\,mm^2} = 287.3\,\mathrm{MPa}$$

Using the yield strength of M2 Tool Steel, $S = 3250\,MPa$, the safety factor against buckling is:

$$n = \frac{S}{\sigma} = \frac{3250\,MPa}{287.3\,\mathrm{MPa}} = 11.3$$

By using safety factor formula, it is found to be 11.3 and ensured that the plunger will not fail against buckling.

3.3.2. Bolts and Nuts

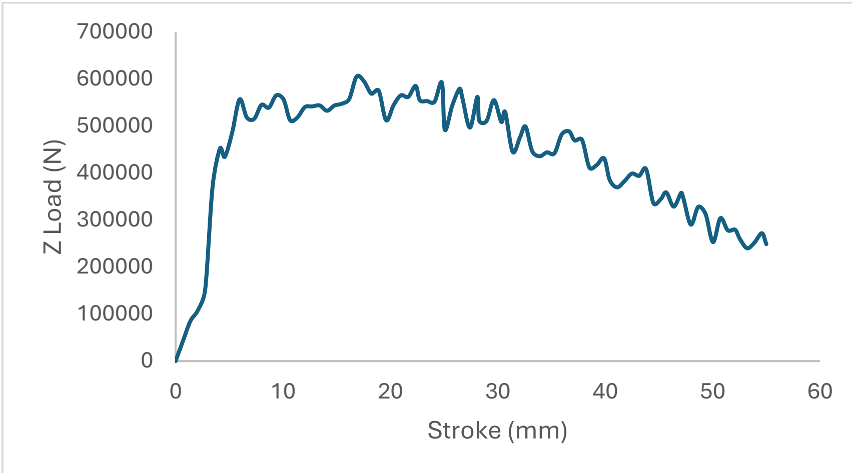

Figure 17 Load Prediction of Bolts

To ensure the mechanical integrity of the assembly under extreme loading, safety calculations were also performed for the bolts used in securing the die and the aluminum workpiece. For this assessment, the maximum force in the Z-direction acting on the Aluminum 5083 workpiece was determined from the Deform 3D simulation results as 604670 N. This total force was assumed to be evenly distributed across 10 bolts, leading to an individual bolt load of:

$$F = \frac{604670 \text{ N}}{10} = 60467 \text{ N}$$

In the design, a safety factor of 2 was assumed for each bolt to ensure adequate resistance under unexpected dynamic loads or misalignments. Using the basic stress formula and rearranging for area:

$$\sigma = \frac{F}{A} = \frac{60467 \text{ N}}{\pi r^2}$$

$$2 = \frac{S}{\sigma}$$

$$2 = \frac{1080 \; MPa}{\frac{60467 \text{ N}}{\pi r^2}}$$

$$r = \sqrt{35.64} = 5.97\,\text{mm} \approx 6\text{ mm}$$

$$D = 11.94\,\text{mm} \approx 12\text{ mm}$$

From this required area, the minimum bolt diameter was calculated, and standard bolt tables were referenced to determine the proper size. Based on the computed required cross-sectional area, M12 DIN912 grade 12.9 hex socket screw bolts were selected, which provides a sufficient load-bearing area and meets the required safety margin under the maximum Z-direction loading conditions.

3.4. FINAL DESIGN

The final design of the ECAP process included M12 DIN912 Grade 12.9 hex socket screw bolts and matching nuts. The die was made from H13 Tool Steel for its high strength and wear resistance, while the punch was crafted from M2 Tool Steel for durability. The chosen die configuration, with a 15 mm transition length and 5° tilt angle, ensures compressive stress and uniform strain distribution, optimizing the process for better material properties and mechanical stability.

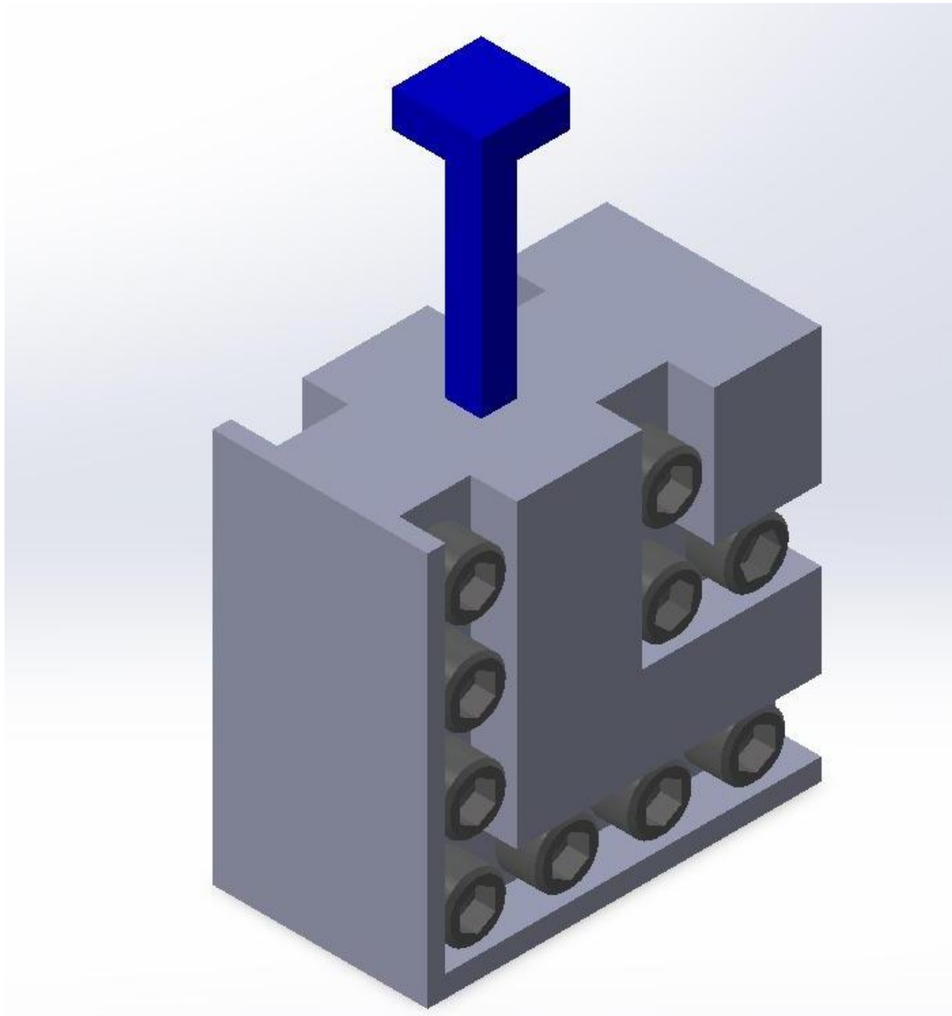

Figure 18 Final Design 1

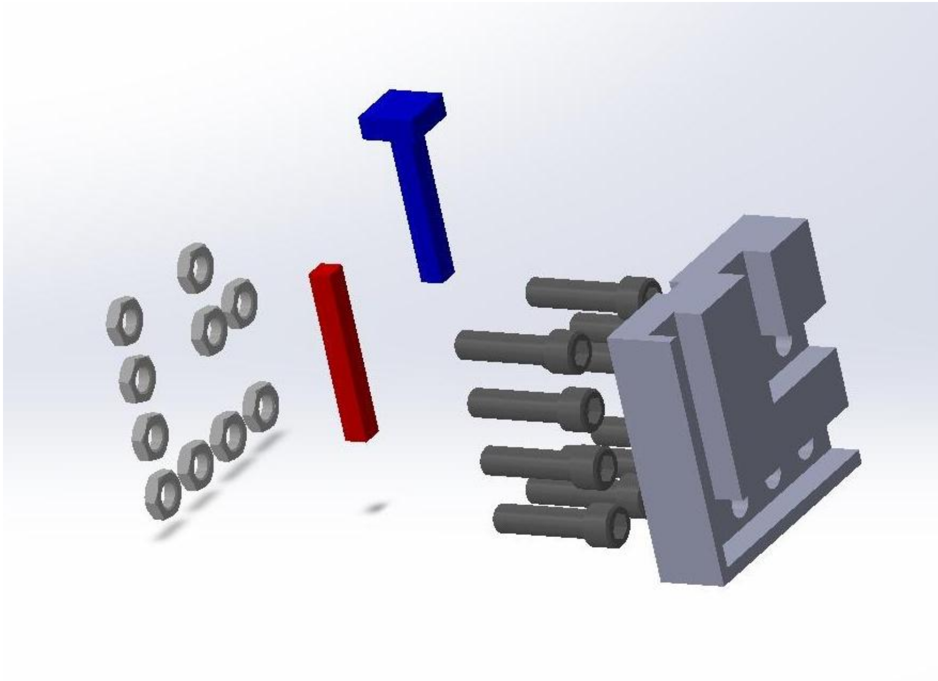

Figure 19 Final Design 2

3.5. COST ANALYSIS

The materials used in the project, along with their corresponding costs, are presented in Table-2. These costs include both raw and processed materials and parts. Online supplier websites and direct customer services were searched and used to gather more precise data.

Table 2 Cost Analysis

Material	Unit and production cost	Number of Amount	Cost
M12 DIN912 Grade 12.9 Bolts	9.70 TL	10	**97 TL**
M12 DIN 934 Nuts	1.70 TL	10	**17 TL**
Die	10,000 TL	1	**15,000 TL**
Punch	4,000 TL	1	**4,000 TL**
TOTAL			**19,114 TL**

For standard components like bolts and nuts, several alternatives from online suppliers were compared based on length, amount, strength, and compatibility. The selections were made with cost-effectiveness and functionality.

When the die and punch parts started to investigate, the machining was also included in the cost analysis. Because the process was more complex, their costs were higher than the basic parts. These parts were designed with specific geometries that required CNC machining, and in some cases, post-processing like grinding and welding. The costs for these were determined by consulting machine workshops, considering both material prices, respectively, H13 and M2 steel for the die and punch.

For the workpiece, a simpler method was followed. Once the type of Aluminum (5083) was selected, its cost per kilogram was taken from market sources, and the total price was calculated based on the part's volume and density.

This cost analysis helped in finding which parts had the highest effect on the costs. It also allowed for better planning of resources and materials during the design and manufacturing processes.

4. CONCLUSION

In this study, determining of the optimal modified design for Equal Channel Angular Pressing (ECAP) process was carried out through finite element analysis (FEA) by using Deform 3D software. A total of 20 different die configurations were evaluated by systematically varying two key design parameters: the transition length (L) of the exit channel, with values of 5, 10, 15, 20, and 25 mm, and the tilt angle (α), with values of 2°, 3°, 4°, and 5°. These parameters were selected to investigate their effects on the overall material deformation and stress distribution during the ECAP process.

For each configuration, maximum mean stress values were extracted to determine whether the stress state remained in compression. Because tensile stresses can lead to surface cracking and failure. Only the geometries that exhibited entirely negative mean stress values were considered viable, as tensile stress is known to significantly increase the risk of material fracture. Among these design configurations, further evaluation was examined based on the strain inhomogeneity index, which measures the non-uniformity level of strain distributions within the material. The configuration has the lowest strain inhomogeneity index was identified as the optimal design.

The initial plan is that using Artificial Neural Network approach for determining the optimal configuration. But the configuration parameters do not exhibit logical analytic relation on FEA results. So that, the optimal result of FEA is selected by their comparison among them. In this case, according to all of results of the FEAs, the configuration which has die geometry of 15 mm transition length and 5° tilt angle was selected as the optimum die design configuration. This geometry provided both a compressive stress state and an extremely homogeneous strain distribution which is represented with corresponding index as 0.08174, which should improve the mechanical stability of the material during the ECAP process. The reduction of strain inhomogeneity and the general compressive stress state mean that this structure minimizes the chances of localized failure and optimizes the mechanical properties of the material, including grain refinement and strength enhancement.

In addition to the die optimization, safety factor calculations were carried out for all critical components involved in the ECAP process, including the punch, die, and bolts. The punch, made from M2 Tool Steel, and the die, made from H13 Tool Steel, were both confirmed to operate well within safe stress limits under the maximum simulated load. The safety factor for both the punch and die was found to be significantly high, ensuring their structural integrity during the process.

The workpiece material was selected as aluminum, and the simulations were operated accordingly, confirming the material's ability to withstand the process without failure. To further ensure the mechanical stability of the entire system, the bolt and nut components were carefully selected. The maximum lateral force acting on the workpiece was calculated to be 604,670 N, and this force was distributed evenly across the 10 bolts securing the die and the workpiece. The safety factor for each bolt was accepted to be 2 from practical applications in industry, ensuring that the bolts would remain secure under the maximum expected load.

For the bolt selection, the M12 DIN912 Grade 12.9 hex socket screw bolts were chosen based on the calculated load distribution and safety factor requirements. The nut selection was aligned with the same specifications, ensuring the full system would maintain its integrity under extreme loading conditions.

To sum up, this study presents an effective and comprehensive approach to finding the optimal specialized modification configuration ECAP die design, integrating both finite element analysis and safety factor assessments. The results indicate that the 15 mm transition length and 5° tilt angle provide the best balance of deformation uniformity, stress management, and safety, making this die design highly suitable for future industrial applications. Additionally, the safety and durability of critical components such as the punch, die, and bolts were thoroughly evaluated, confirming their performance and reliability throughout the ECAP process.

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