Investigation of Effective Parameters in Elliptical Spiral Equal-Channel Angular Extrusion of AA6063 Alloy Utilizing the Taguchi Process for Optimal Design

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Abstract:

This research investigates the effective input parameters of the Elliptical Cross-Section Spiral Equal-Channel Angular Extrusion method and selects the optimal performance. The influential parameters in the ECSEE method are considered as input factors in the experimental design, which are expressed in three parameters: punch speed, sample annealing, and the number of extrusion passes. Subsequently, a Taguchi design of experiments table was created for each input parameter according to its variation range. After designing the experiments, the output results of forming force and plastic strain for each level were obtained using experimental tests. The novelty of this work lies in the application of a multi-response Taguchi-based optimization approach specifically to the ECSEE process, providing a robust and systematic framework for selecting optimization parameters. The optimization of the input values was investigated based on the S/N ratio criterion. The obtained results indicated that the optimal test level in the ECSEE method for achieving the minimum forming force is using a punch speed of 9 mm/min, sample annealing at 300°C for 120 minutes, and 2 extrusion passes. Furthermore, to achieve the maximum plastic strain, the optimal parameters are a punch speed of 9 mm/min, sample annealing at 200°C for 120 minutes, and 6 extrusion passes. This study conclusively demonstrates that by employing the proposed methodology, it is possible to precisely determine the optimal parameter sets for specific manufacturing goals, thereby advancing the practical application of the ECSEE technique.

Keywords:

Severe Plastic Deformation; Elliptical Cross-Section Spiral Equal Channel Extrusion; Optimization; Taguchi Experimental Design; Mechanical and Microstructural Properties

1- Introduction

In the age of advanced technologies, the need for engineering materials with exceptional strength and durability is felt more than ever before. In modern engineering, achieving materials with exceptional strength and durability is crucial. Traditional methods like electrolytic deposition, powder compaction, and mechanical alloying improve strength but face inherent limitations such as porosity, contamination, and uneven microstructures. At this point, Severe Plastic Deformation (SPD) methods, including Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE), offer a practical solution. SPD enables extreme shear deformation without altering bulk geometry, producing ultrafine-grained materials with high dislocation density and compact grain boundaries. Its incremental nature allows continuous microstructure refinement, leading to uniform grain distribution and enhanced mechanical properties at room temperature under high hydrostatic pressure. SPD methods involve applying very large shear strains to the material without causing a significant change in its overall dimensions [1-3]. Severe Plastic Deformation (SPD) methods have therefore emerged as a novel and effective paradigm to overcome limitations such as failure to achieve desired mechanical and microstructural properties.

These methods enable the fabrication of ultra-high-strength materials with refined and unique microstructures, which cannot be achieved through conventional processes such as heat treatment (Quenching & Tempering, Carburizing, Solution Treatment & Aging). To provide a clearer scientific foundation, SPD processes serve as the core modern approach for grain refinement, enabling drastic improvements in strength, ductility, and functional properties through extreme shear deformation without altering the bulk geometry of the material. SPD processes lead to the creation of a very high density of dislocations, compact grain boundaries, and ultimately, ultrafine-grained materials at the nano and submicron scales. A key feature of this process is its gradual and incremental nature, allowing for the possibility of applying further strain to the sample at each stage. This sequence results in the continuous refinement of the microstructure, reduction of grain size, and a more uniform distribution of grains [4]. SPD methods are generally performed at room temperature without a significant change in the overall dimensions of the sample. In these methods, metals are deformed under significant hydrostatic pressure so that very high strain is applied while maintaining the sample's dimensions, leading to grain refinement. The primary goal of applying this high pressure is to delay the ultimate fracture of the extruded samples [2, 5]. Numerous methods have been developed under the title of SPD, each with its own specific advantages and application areas. Among the most prominent of these methods are Equal-Channel Angular Pressing (ECAP), Twist Extrusion (TE), Accumulative Roll Bonding (ARB), High-Pressure Torsion (HPT), and Simple Shear Extrusion (SSE). Severe Plastic Deformation (SPD) encompasses a range of techniques used to process metallic materials, enabling grain refinement and enhancement of mechanical properties. To provide a clearer classification and improve readability, these techniques can generally be grouped into channel-based processes (e.g., ECAP, ECSEE), torsion-based processes (e.g., HPT, TE), and sheet or layer-based processes (e.g., ARB). This categorization highlights the diverse strain-imposition mechanisms within SPD. Wang et al. [6] introduced a new method for severe plastic deformation of metals entitled "Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE)". The main motivation for developing this method was the easier processing of cylindrical workpieces compared to prismatic samples on an industrial scale. Due to its specific deformation channel, this method is capable of extruding various alloys and improving their mechanical and microstructural properties. Compared with conventional SPD techniques, ECSEE provides a unique spiral elliptical deformation route that enhances strain accumulation, improves homogeneity, and offers greater suitability for continuous or industrial-scale processing, key motivations for further research into this process. As one of the severe plastic deformation methods, Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) is highly efficient in producing bulk nanostructured and ultrafine-grained materials. In this method, based on Transmission Electron Microscope (TEM) observations, the microstructural evolution from a coarse-grained to an ultrafine-grained state occurs through the formation of shear bands, fine grains, high-angle dislocation grain boundaries, and equiaxed structures [7]. Zhang et al. [8] demonstrated that low-temperature isothermal multidirectional forging (IMDF) enables the formation of ultrafine grains and dispersed $(Ti, Zr)_6Si_3$ nanoprecipitates in TiBw/near-α Ti composites, effectively overcoming the typical strength–ductility trade-off. Lower IMDF temperatures refine the grain size from 0.98 to 0.59 μm and drive silicide precipitation from boundaries to both α-grain interfaces and intragranular regions. Balali et al. [9] proposed a hybrid ultrasonic-assisted simple shear extrusion (USSE) method in which ultrasonic vibrations (20.332 kHz, 15–25 μm) are introduced at the entrance of the deformation zone. Their finite-element-guided horn design efficiently amplified and transmitted vibrations, producing ultrafine-grained copper with 54–65% grain-size reduction and significantly higher microhardness due to acoustic hardening. The presence of ultrasound also decreased extrusion force through acoustic softening while enhancing equivalent plastic strain along the sample. Wan et al. [10] fabricated an aluminum matrix composite reinforced with in-situ ($TiAl_3$, Al) core–shell particles via ball milling and hot-pressing sintering. To enhance mechanical properties, they investigated two deformation methods:

cycling extrusion-compression (CEC) and elliptical cross-section spiral equal-channel extrusion (ECSEE). Their results showed that both techniques effectively refine coarse grains formed during sintering, with ECSEE preserving the particle shell due to dominant torsion and axial shearing. Consequently, ECSEE is particularly suitable for improving the mechanical performance of these core–shell reinforced composites. Simsek et al. [11] compare linear twist extrusion (LTE) with the improved nonlinear twist extrusion (NLTE), which modifies the die geometry to reduce strain reversal and enhance grain-refinement uniformity. Using rate-dependent CPFE simulations on single-crystal copper, the authors analyze texture evolution and stress/strain distribution under both techniques. Their results demonstrate that NLTE provides more stable texture development and more homogeneous deformation compared to the conventional LTE process. Latypov et al. [12] conducted a numerical comparison of two torsion-based severe plastic deformation processes entitled Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) and Twist Extrusion (TE). The results of finite element simulations showed that although ECSEE was developed for processing cylindrical samples and creating a more uniform strain distribution, the twist zone in both methods creates similar states of strain and stress. Machackova [13] reviewed the Twist Channel Angular Pressing (TCAP) method, an ECAP-based SPD technique that integrates channel twisting and bending within a single die to impose three independent strain paths per pass. They highlight that this complex strain route effectively accelerates substructure formation and grain refinement compared to conventional ECAP. The review also outlines the evolution of TCAP since 2010 and briefly compares it with other hybrid ECAP–TE methods developed to enhance strain homogeneity and processing efficiency. Edalati et al. [14] summarized the rapid progress of Nano SPD over the past two decades, highlighting that severe plastic deformation enables bulk ultrafine-grained and nanostructured materials with high defect densities and exceptional mechanical and functional properties. They emphasized the expansion of SPD from classical methods (HPT, ECAP, ARB, TE) to emerging continuous techniques capable of producing larger-scale samples and processing a wide range of materials from metals and alloys to ceramics, polymers, and composites. Their review shows that SPD not only enhances strength–ductility combinations but also enables unique functionalities such as superplasticity, hydrogen storage, photocatalysis, corrosion resistance, and other advanced performance characteristics. Wang et al. [15] in a study investigated the deformation characteristics and microstructure of ultrafine-grained copper produced by the Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) process. The results indicated that a high friction coefficient can improve the effective strain accumulation in the material's deformation. Furthermore, the heterogeneity of microhardness distribution on the longitudinal cross-section of the sample extruded by ECSEE corresponds to the characteristics of strain distribution and microstructure. Despite these valuable studies, previous research has not systematically examined how process parameters influence forming force and plastic strain in ECSEE, nor has it provided an integrated experimental optimization strategy for improving microstructural and mechanical outcomes. This gap highlights the need for a comprehensive evaluation of ECSEE parameters and their combined effects on extrusion performance. In the present research, the optimal ECSEE process parameters for reducing the forming force and increasing plastic strain were obtained using the Taguchi experimental design method and experimental tests. Then, by extracting the optimal values, the samples were extruded under these parameters, and their mechanical and microstructural properties were reported compared to non-optimal parameters. Accordingly, this study provides both an optimization framework and an experimental validation, offering new insight into the controllability and efficiency of the ECSEE technique. Also, by optimizing the input parameters of the ECSEE process, such as the speed of the punch advance, the annealing of the samples, and the number of extrusion passes, it was possible to achieve the lowest forming strain and the highest plastic strain.

2- Materials and Methods

2-1- Parameters Influencing the ECSEE Method

2-1-1- Punch Feed

Increasing the punch feed directly raises the applied plastic strain per pass, thereby reducing the number of passes required to achieve the desired total strain. Furthermore, as the punch feed increases, the plastic stress and the force necessary for deformation significantly rise. Consequently, the risk of workpiece or tool failure due to excessive loads becomes greater. A higher feed rate increases the strain imparted in a single pass, which can reduce the total number of passes required to achieve a target cumulative strain. The temperature of the sample in the plastic deformation zone increases due to the application of high strains. If the resulting temperature exceeds the material's recrystallization threshold, it can trigger undesirable microstructural changes, such as grain growth or abnormal recrystallization, compromising the goal of grain refinement. As a result, the uniformity of strain distribution throughout the sample may be compromised, leading to increased heterogeneous strains. In severe plastic deformation methods, excessive punch feed can degrade the die geometry and make material extrusion impossible [16, 17]. Therefore, optimizing the punch feed values is particularly important, as it helps balance process efficiency and final product quality in the Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) method.

2-1-2- Annealing the Samples

Annealing plays a fundamental role in Severe Plastic Deformation (SPD) processes, enabling the recovery and recrystallization of the material's microstructure. By relieving internal stresses and reducing dislocation density, annealing restores the material's ductility, preventing embrittlement and enabling further deformation in subsequent passes without cracking. Annealing makes it possible to increase the severe plastic deformation of the sample without cracking or fracture, while also improving the mechanical properties of the material, such as strength and toughness. The cyclic alternation between deformation and annealing leads to the accumulation of very high strains, to the extent that it enables the mass production of high-strength metallic samples. Annealing is essential in SPD methods for preserving sample integrity, thereby ensuring microstructural stability and uniformity of mechanical properties throughout the SPD processes [2, 18, 19]. By controlling annealing parameters such as temperature and time, grain size can be optimized. Ultimately, this facilitates the achievement of nanostructured microstructures and the easy extrusion of samples in the Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) process. The sample heating rate, denoted in °C/min, is defined by a specific temperature maintained for a predetermined duration

2-1-3- Number of Extrusion Passes

The number of extrusion passes is of particular importance in Severe Plastic Deformation (SPD) methods for achieving desired mechanical and microstructural properties. With an increase in the number of passes, the accumulated plastic strain in the material significantly increases. This increase in strain leads to further refinement of the crystalline structure and a reduction in grain size to the nanometric scale. Consequently, the material's strength drastically increases due to the Hall-Petch strengthening mechanism. However, this relationship is not monotonic; a saturation point is often reached beyond which further deformation yields diminishing returns or may even degrade properties due to defect saturation or the initiation of micro-cracks. The increase in the number of passes directly affects the structural stability of the material and the uniformity of the microstructure, altering the shear stress and true strain after each extrusion pass [20, 21]. Precise control over the number of extrusion passes is essential for achieving the desired properties and preventing material failure. Consequently, optimizing the number of extrusion passes is a key factor in designing the process of Elliptical Cross-Section Spiral Equal-Channel Extrusion (ECSEE) to produce high-performance nanostructured materials.

2-2- Experimental Design Using the Taguchi Method

The high coefficient of friction in most severe plastic deformation methods leads to disadvantages such as high forming force and difficult extrusion of samples. In the ECSEE method, the extrusion of high-strength alloys is accompanied by problems such as sample failure and increased forming force. Therefore, in this research, the design of experiments for parameters affecting the ECSEE process (punch speed, sample annealing, and number of extrusion passes) was carried out using the Taguchi method and experimental tests. This study aims to systematically identify and optimize the key processing parameters that influence ECSEE performance. By integrating the Taguchi design of experiments with empirical testing, this work seeks to determine the optimal conditions that minimize forming force while maximizing plastic strain. To justify the selected levels, the ranges of punch speed, annealing condition, and number of passes were determined based on preliminary pilot trials, constraints of the ECSEE setup, and deformation limits reported in previous ECAP/ECSEE studies. These levels were selected to ensure coverage of the operational window where measurable variations in strain accumulation and forming force are expected, while avoiding conditions that could lead to premature billet failure or die overloading. Moreover, to ensure consistency in sample preparation, all billets were machined from the same material batch, followed by identical surface cleaning, dimensional verification (±0.02 mm tolerance), uniform lubrication, and controlled pre-heating/temperature stabilization before ECSEE extrusion. This standardized procedure ensured that annealing was not the sole equalizing step but part of a comprehensive and repeatable preparation protocol. Table 1 shows the range of variations for the input parameters. The range selected for the punch speed (3, 6, and 9 mm/min) was determined empirically. A punch speed lower than 3 mm/min leads to an excessively slow extrusion process in the ECSEE method, which is economically inefficient due to the extended press operation time. Conversely, a punch speed higher than 9 mm/min significantly increases the risk of punch buckling and the destruction of the die channel .Constant time for annealing samples was primarily based on preliminary experiments and industry-standard practices for this specific aluminum alloy, where a time sufficient for complete recrystallization is often prioritized. The L9 orthogonal array was selected for this research primarily due to its optimal efficiency for the input parameter domain under investigation. The preliminary analysis involved three key factors, each with three levels. The L9 array is specifically designed for such a configuration (3^3) and provides statistically significant data on the main effects of each factor with only nine experimental runs. While an L27 array offers a higher resolution and enables a detailed analysis of all two-factor and three-factor interactions, it would substantially increase the experimental workload (from 9 to 27 tests). Given the costly and time-consuming nature of the ECSEE process, the L9 array provided a balanced and pragmatic approach for identifying parameters that significantly influence the forming force and plastic strain, without incurring prohibitive time and cost expenditures. Furthermore, the orthogonal experimental design for the input parameters, according to the variation range for each factor, is specified in Table 2.

Table 1. Input Parameters and Process Levels of ECSEE

Process Levels	Punch Speed (mm/min)	Annealing the Samples (°C/min)	Number of Extrusion Passes
Level 1	3	200 **°C**-120 min	2
Level 2	6	250 **°C**-120 min	4
Level 3	9	300 **°C**-120 min	6

Table 2. Design of Experiments Table Using the Taguchi Method with L9 Orthogonal Arrays

Experiment Number	Test Factors		
	Punch Feed (mm/min)	Sample Annealing (°C-min)	Number of Extrusion Passes
1	3	200-120	2
2	3	250-120	4
3	3	300-120	6
4	6	200-120	4
5	6	250-120	6
6	6	300-120	2
7	9	200-120	6
8	9	250-120	2
9	9	300-120	4

The loss function in the Taguchi method is a measure of deviation from the desired quality, which leads to the optimization of output parameters. The loss function is categorized into three main categories: "smaller-the-better," "larger-the-better," and "nominal-the-best," expressed by Eqs. (1), (2), and (3), respectively [22].

$$NB = 1/n\sum(y_i - y_0)^2 \quad (1)$$

$$LB = 1/n\sum(1/y_i)^2 \quad (2)$$

$$NB = 1/n\sum(y_i - y_0)^2 \quad (3)$$

According to the equations stated in the previous section, 'n' represents the number of iterations, and y represents the measured outputs. In this study, the Taguchi method utilizes experimentally obtained maximum and minimum output values to determine the optimal response for each parameter. The primary objective of this research is to reduce the forming force and increase the plastic strain in the process of Equal Channel Angular Extrusion (ECAE) of spiral channels with an elliptical cross-section. Therefore, the "smaller-the-better" loss function is applied to forming force, while the "larger-the-better" loss function is used to evaluate the plastic strain. After calculating the loss function value for each output, the total signal-to-noise ratio is computed, as expressed in Eq. (4).

$$SN = -10log(1/n\sum_{(i=1)}^{n} y_i^2) \tag{4}$$

2-3- Experimental Tests of the ECSEE Process

For experimental testing, a die was designed and manufactured considering the criteria of effective strain and its distribution uniformity. The initial design of the ECSEE die was performed in CATIA software, and then the process was simulated in Abaqus software to analyze the effect of geometrical parameters on strain and forming force. The final die was designed as a symmetrical truncated cone model, and MO40 steel was selected as the die material. Finally, the die was manufactured using milling and EDM machines, and its hardness was increased to 54 HRC via heat treatment to provide sufficient wear resistance and durability under the high-pressure ECSEE conditions. The material processed by the ECSEE method was AA 6063 aluminum alloy, prepared as billets with a circular cross-section of 14 mm diameter and a length of 55 mm. Table 3 shows the chemical composition of the AA 6063 aluminum alloy raw material. Before testing, the billets were lubricated to minimize friction and to ensure stable material flow during extrusion. A 60-ton hydraulic press was used to extrude the samples inside the ECSEE die. The device is equipped with a data monitoring system that not only regulates the punch speed at various setpoints but also directly displays the variations in the forming force. Upon entering the die channel, the billets possess an initial circular cross-section. As they progress into the plastic deformation zone, this cross-section is progressively altered into an elliptical shape. Within this critical region, the material undergoes a significant torsional strain; the top surface rotates relative to the bottom surface by a specific angle, φ. Finally, the billet reconsolidates into a cylindrical form upon exiting the outlet channel. To mitigate the high frictional forces at the billet-die interface, which contribute substantially to the required forming load, a molybdenum disulfide (MoS_2) lubricant was employed. This lubrication was essential for effectively reducing the friction between the billets and the internal channel of the ECSEE die.

The tests were conducted at room temperature according to the experimental design input variables (punch speed, sample annealing, and number of extrusion passes). The overall extrusion process is illustrated in Fig. 1. Finally, to validate the optimal and non-optimal values, the extruded samples underwent metallography, impact, and microhardness tests. Also, the flowchart of the ECSEE process under experimental and optimization operations is shown in Fig. 2.

Table 3. Physical and Mechanical Properties of Aluminum Alloy 6063

Sample Material	Density (g/cm³)	Yield Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio
Aluminum Alloy 6063	2.70	74	69	0.33

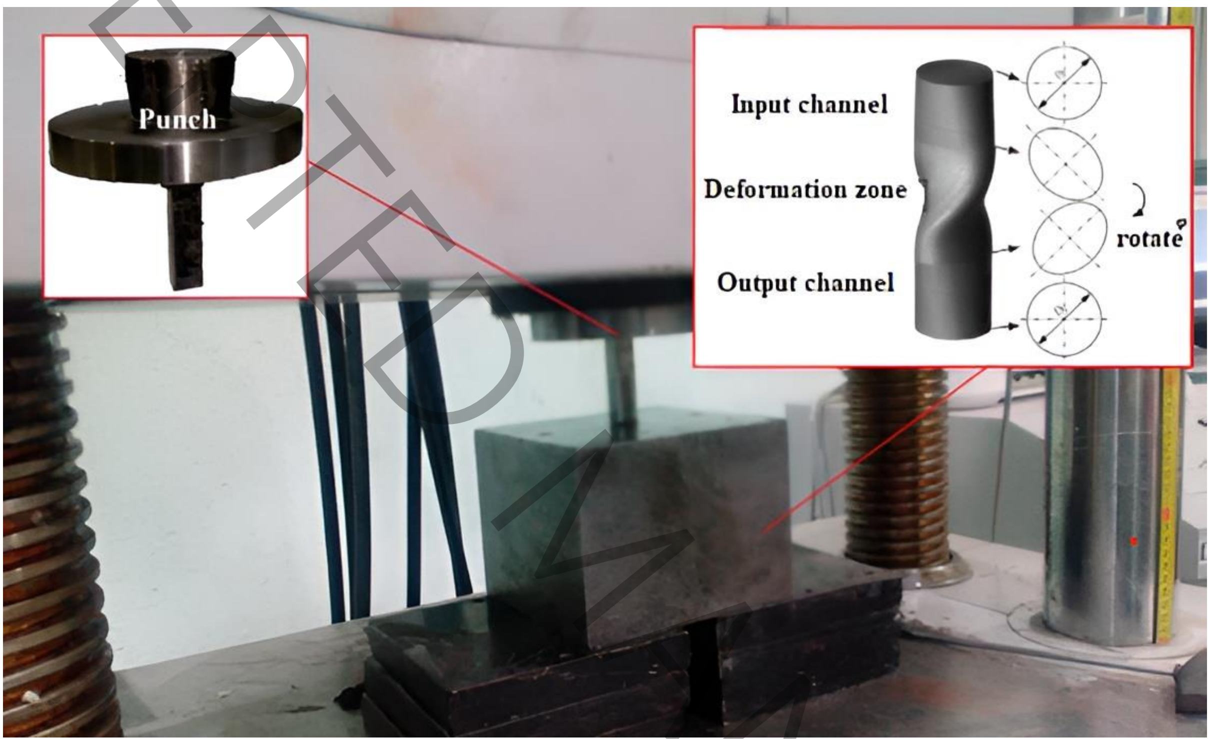

Fig. 1. The overall process of sample extrusion using the ECSEE method

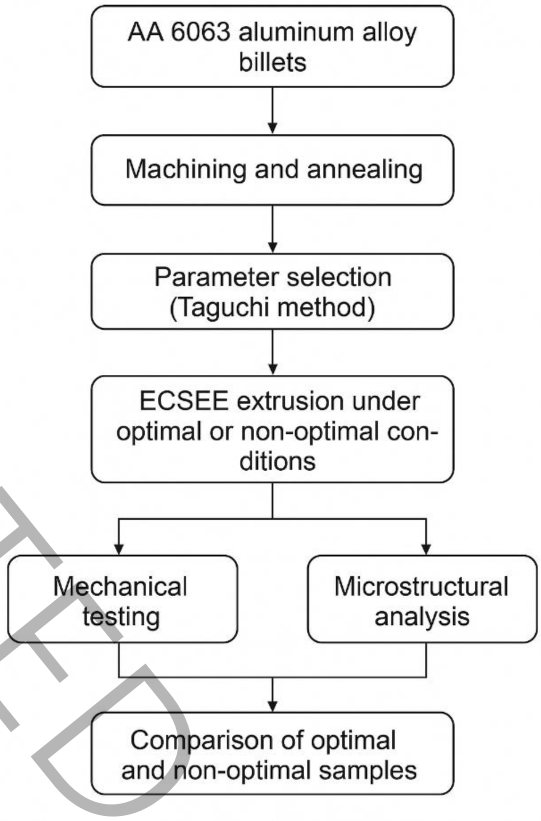

Fig. 2. Flowchart of the evolution of the ECSEE process under experimental and optimization operations

3- Results and Discussion

3-1- Optimization

Using the input parameters from the experimental design and through experimental tests, the output values (forming force and plastic strain) were obtained. The methodology for conducting these experiments was clarified to ensure reproducibility and improve transparency. The optimal levels for the output parameters were determined based on the "smaller is better" criterion for the forming force and the "larger is better" criterion for the plastic strain. Accordingly, all measurements were normalized before calculating the performance metrics to enhance the reliability of the comparative analysis. Finally, the calculated S/N ratios for each experiment are reported in Table 4. The signal-to-noise ratio method indicates the sensitivity of the studied quality characteristic to the factors affecting the output. Furthermore, this method allows for the simultaneous determination of the optimal parameter levels and the degree of influence of each parameter. In the signal-to-noise ratio analysis plot, the level with the highest mean signal-to-noise ratio is selected as the optimal choice for the corresponding parameter. Ultimately, the optimal levels for each factor, aimed at minimizing the forming force and maximizing the plastic strain, are presented in Figs. 3 and 4, respectively. These optimized parameter levels provide a more reliable basis for improving the forming process performance.

Table 4. Experimental Design Results with Output Values and S/N Ratios

Number of tests	Test Factors			The output values of the tests			
	Punch Feed (mm/min)	Sample Annealing (°C-min)	Number of Extrusion Passes	Forming Force (N)	Plastic Strain	S/N values of forming force	S/N values of Plastic strain
1	3	200-120	2	9321	1.704	-80.9913	4.6294
2	3	250-120	4	9814	2.943	-79.8369	9.3758
3	3	300-120	6	11209	3.323	-79.3893	10.4306
4	6	200-120	4	10426	3.104	-79.5654	9.8384
5	6	250-120	6	11929	4.227	-79.0024	12.5206
6	6	300-120	2	8742	1.563	-82.0624	3.8792
7	9	200-120	6	12680	4.852	-78.8322	13.7184
8	9	250-120	2	8915	1.612	-81.5321	4.1473
9	9	300-120	4	9512	2.747	-80.3624	8.7772

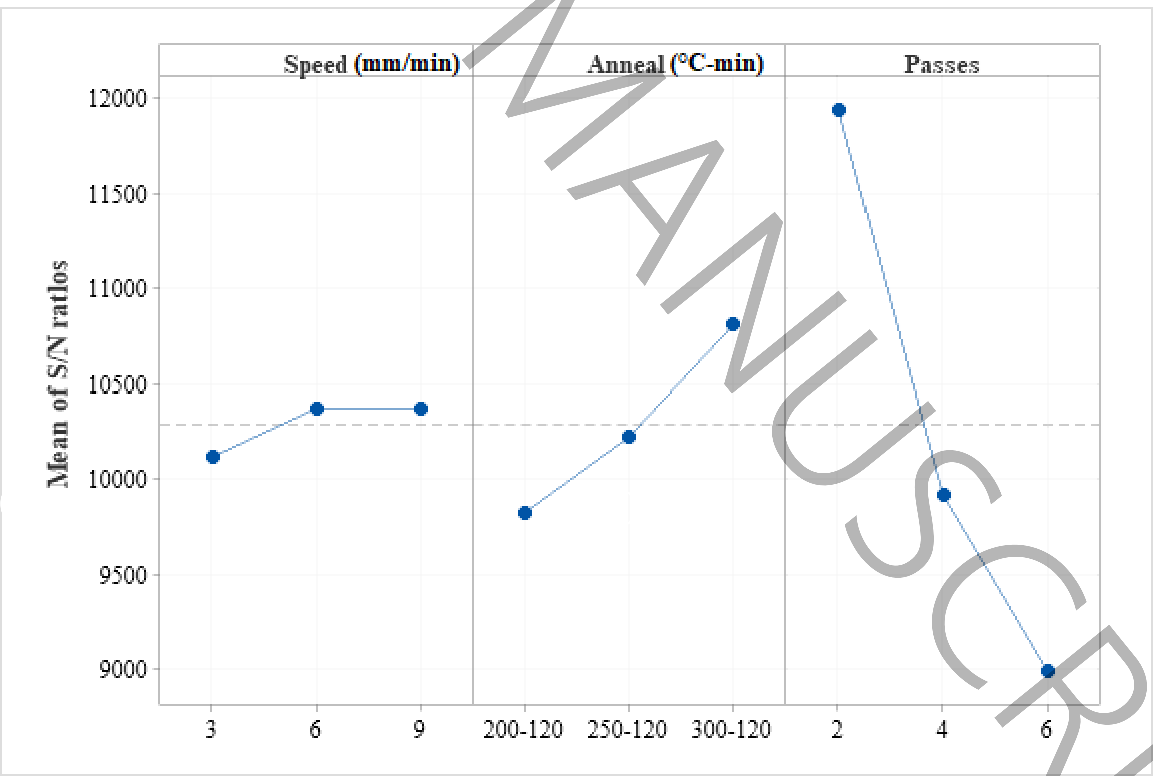

Fig. 3. Signal-to-Noise (S/N) Analysis Graphs for Forming Force

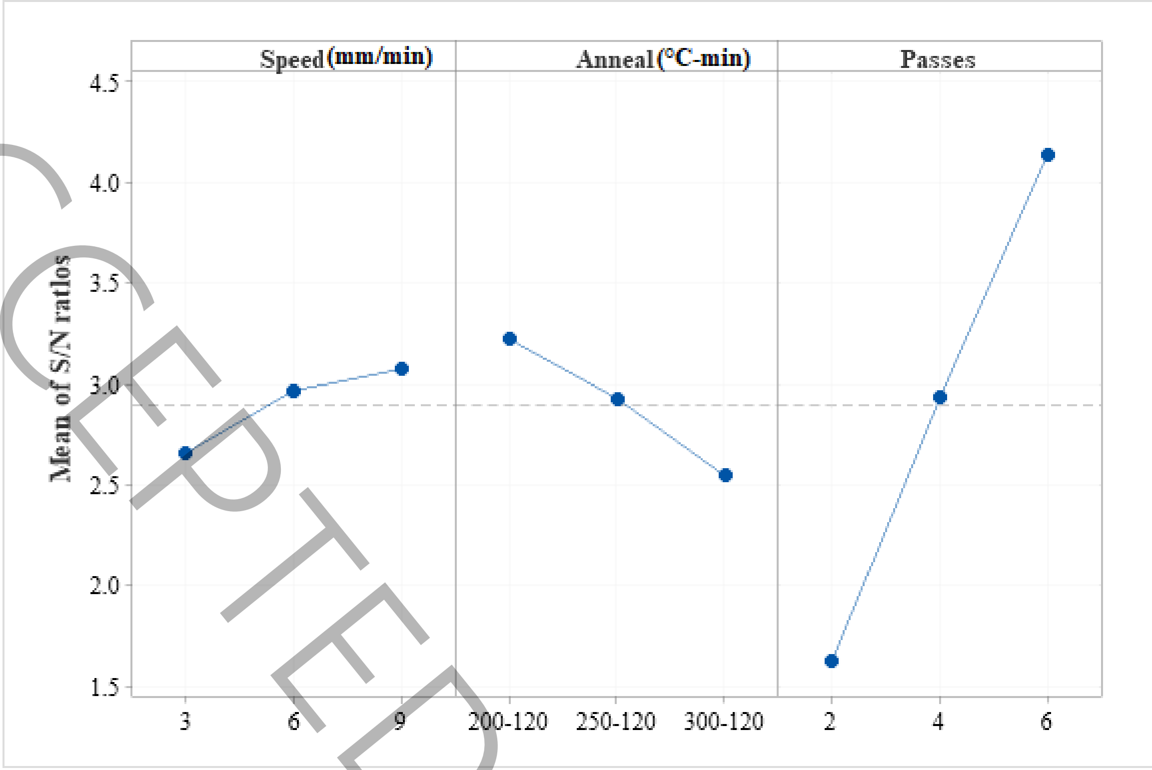

Fig. 4. Signal-to-Noise (S/N) Analysis Graphs for Plastic Strain

As evident in Figs. 3 and 4, the parameters (punch feed, sample annealing, and number of extrusion passes) are set at their high levels to reduce the forming force and increase the plastic strain. These results indicate that increasing the level of these parameters enhances material deformability while lowering the required forming load. Based on the optimal values from the S/N ratio diagram, it can be concluded that the punch feed, number of extrusion passes, and sample annealing have the greatest effect on reducing the forming force, whereas the number of extrusion passes and sample annealing play the most dominant role in enhancing the plastic strain. Table 5 shows the optimal level values of the input factors in the ECSEE method. These optimized settings provide a reliable guideline for improving process efficiency and mechanical performance in ECSEE applications.

Table 5. Optimal experimental level values for forming force and plastic strain

Experimental Factors	Optimal Plastic Strain Values	Optimal Forming Force Values
Punch Feed **(mm/min)**	9	9
Sample Annealing **(°C-min)**	200-120	300-120
Number of Extrusion Passes	6	2

An ANOVA test was employed to identify significant factors and determine the contribution percentage of input variables, as presented in Tables 6 and 7. The adequacy of the developed relationships was confirmed through ANOVA, demonstrating high adjusted coefficient of determination (R^2 adjusted) values of 98.14% and 97.82% for the forming force and plastic strain regression models, respectively. Furthermore, the predicted R^2 values for forming force and plastic strain regression models were calculated as 96.77% and 96.38%, respectively. The close agreement between these two sets of values confirms the satisfactory consistency and reliability of the regression models. According to the ANOVA results, the number of passes and sample annealing significantly influence the forming force parameter, with contribution percentages of 88.95% and 9.68%, respectively. Additionally, the number of passes exhibits an increasing effect on plastic strain, with a contribution percentage of 88.25%. To develop mathematical models for forming force and plastic strain, a second-order response surface regression analysis was implemented. The regression model analysis was performed using Minitab statistical software. Consequently, significant factors identified through ANOVA testing were used to establish mathematical modeling coefficients for the output variables (plastic strain and forming force). These are expressed as functions of the input variables (number of passes, annealing, and punch feed) in Eqs. (5), and (6).

Table 6. Results of the analysis of variance of the forming force

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	127698	0.83%	127698	63849	1.55	0.398
Anneal	2	1482520	9.68%	1482520	741260	18.03	0.047
Passes	2	13626337	88.95%	13626337	6813168	165.68	0.006
Error	2	82246	0.54%	82246	41123		
Total	8	15318801	100.00%				

Table 7. Results of the analysis of variance of the plastic strain

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0.2771	2.59%	0.2771	0.1386	0.96	0.511
Anneal	2	0.6889	6.44%	0.6889	0.3444	2.37	0.296
Passes	2	9.4378	88.25%	9.4378	4.7189	32.54	0.030
Error	2	0.2901	2.71%	0.2901	0.1450		
Total	8	10.6939	100.00%				

$$\begin{aligned} Force \;=\; & 10283.1 - 168.4\,Speed\_3 + 85.9\,Speed\_6 + 82.6\,Speed\_9 - 462.1\,Anneal\_200-120 \\ & - 63.8\,Anneal\_250-120 + 525.9\,Anneal\_300-120 + 1656.2\,Passes\_2 - 365.8\,Passes\_4 \\ & - 1290.4\,Passes\_6 \end{aligned} \tag{5}$$

$$\begin{aligned} Strain \;=\; & 2.897 - 0.241\,Speed\_3 + 0.067\,Speed\_6 + 0.173\,Speed\_9 + 0.323\,Anneal\_200-120 \\ & + 0.030\,Anneal\_250-120 - 0.353\,Anneal\_300-120 - 1.271\,Passes\_2 + 0.034\,Passes\_4 \\ & + 1.237\,Passes\_6 \end{aligned} \tag{6}$$

Fig. 5 presents the main effects plots illustrating the influence of input parameters on forming force and plastic strain. In the ECSEE process, reducing the friction coefficient between the workpiece and die channel is crucial for minimizing forming force. ANOVA results indicate that the number of passes and annealing parameters are statistically significant factors affecting forming force, while punch feed demonstrates no substantial influence. Regarding plastic strain, the number of extrusion passes emerges as the most dominant factor. Annealing at temperature T effectively reduces or eliminates residual stresses induced by cold working or improper heat treatment, facilitating the extrusion process with lower forming forces. This enables the successful processing of ECSEE samples through a higher number of passes. Furthermore, increasing the number of extrusion passes introduces greater work hardening, consequently enhancing the accumulated plastic strain. As evidenced in Fig. 5, the minimum forming force occurs at a punch feed of 3 mm/min, annealing at 200°C for 120 minutes, and 6 extrusion passes. Conversely, the maximum plastic strain is achieved under a punch feed of 9 mm/min, with the same annealing conditions (200°C for 120 minutes) and 6 passes.

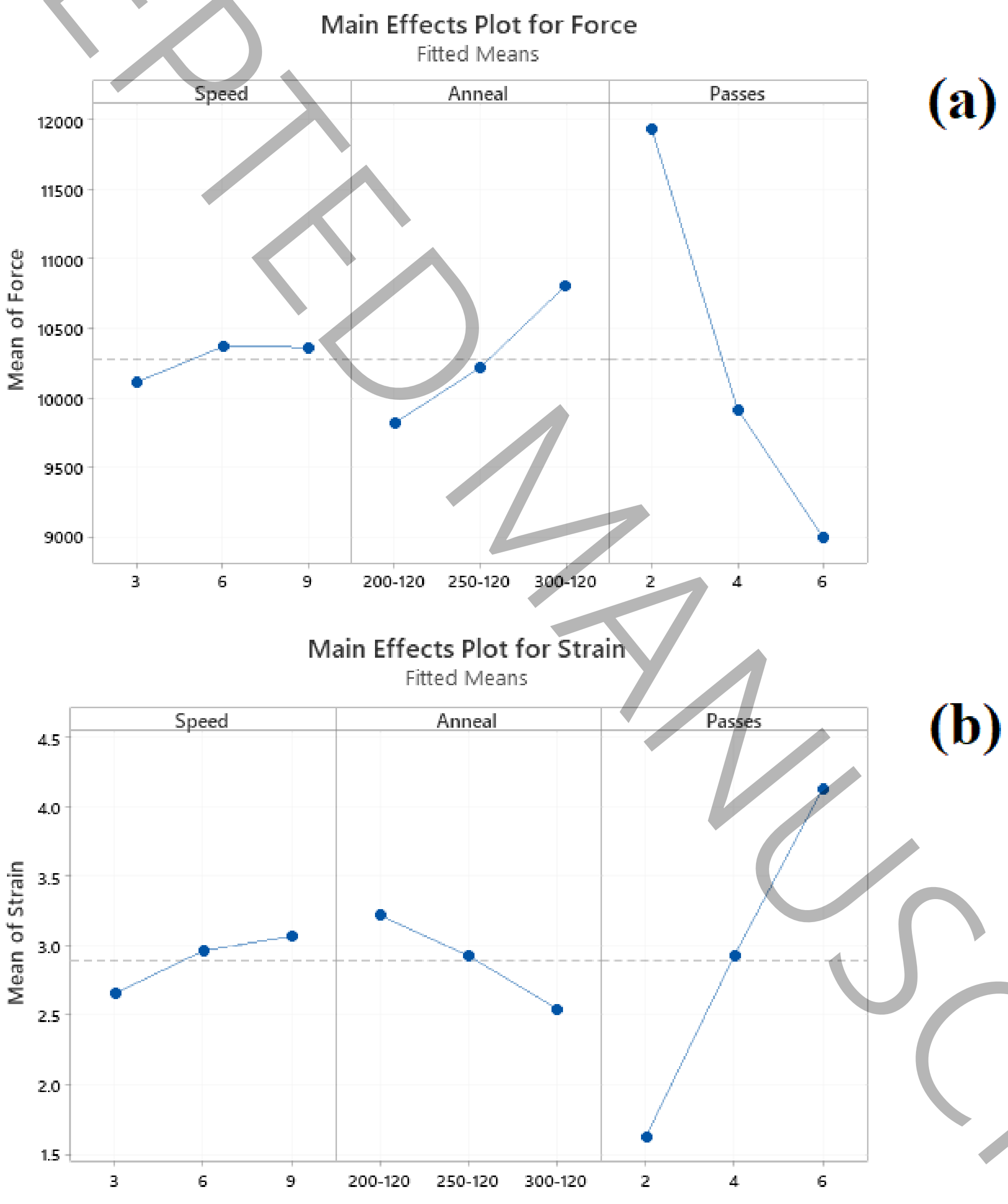

Fig. 5. Effect of input factors on forming force (a) and plastic strain (b)

Fig. 6 illustrates the influence of key input parameters in the ECSEE process on achieving optimal output values. Each process parameter exerts distinct effects on the response variables - specifically, plastic strain and forming force. Consequently, a comprehensive optimization of the ECSEE process was conducted to identify optimal parameter configurations that would yield superior performance in the output variables. The multi-objective optimization criteria were established to simultaneously maximize plastic strain while minimizing forming force. The optimal parameters were determined as follows: a punch feed of 9 mm/min, an inter-pass annealing treatment at 200°C for 120 minutes, and 6 processing passes. This optimized parameter set enables the concurrent enhancement of plastic strain accumulation and reduction of required forming force, thereby improving both the efficiency and effectiveness of the ECSEE process.

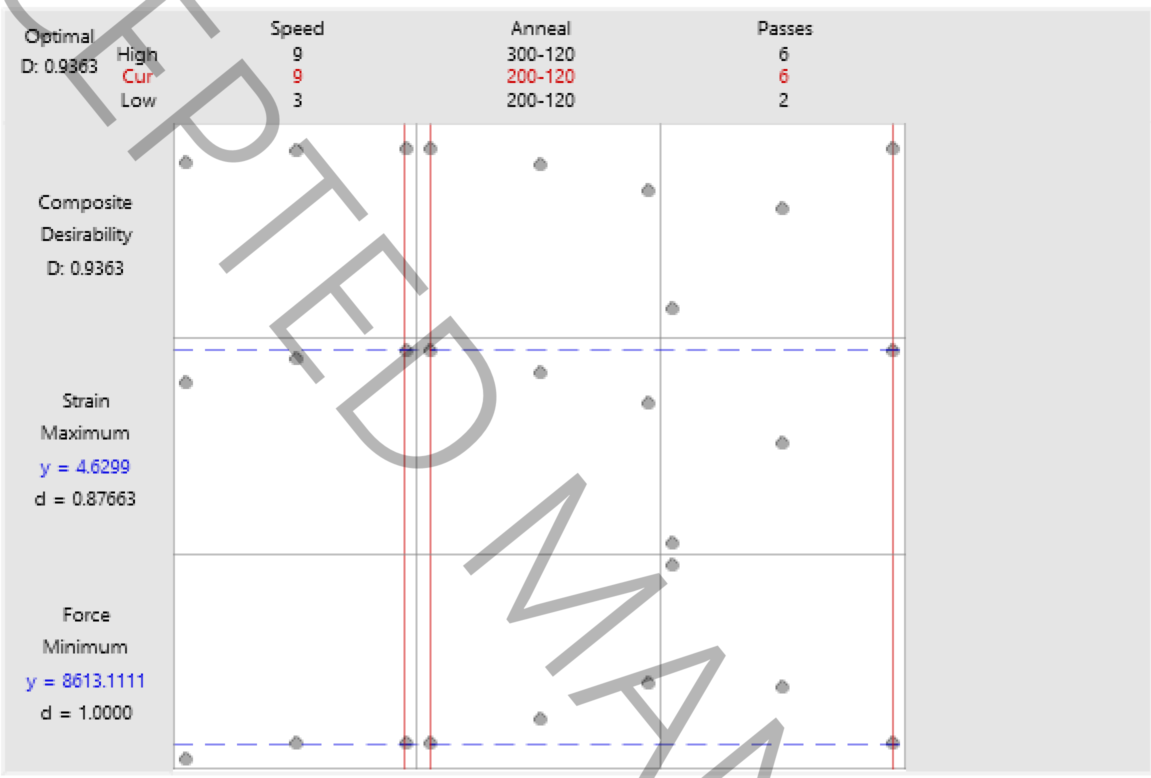

Fig. 6. Graphical image of optimization results

3-2- Microstructure

Several experiments were conducted at optimal and non-optimal levels to compare microstructural characteristics, as shown in Table 8. The microstructural results for experiments E1, E2, and E3 are presented in Fig. 7, demonstrating that grain refinement in samples produced by the optimal ECSEE process parameters is greater than that achieved with non-optimal parameters.

Table 8. Test Settings for Comparing Microstructural Properties

Experiment	Speed (mm/min)	Passes	Anneal (°C/min)
Non-Optimal (E1)	3	4	250-120
Optimal-Strain (E2)	9	6	200-120
Optimal-Force (E3)	9	2	300-120

Investigations reveal that the non-optimal sample possesses a homogeneous structure with coarser grains compared to the two optimal processes. In contrast, the sample processed with optimal forming force parameters exhibits an inhomogeneous distribution due to the imposition of heterogeneous strains in the plastic deformation zone of the die. Coarse and fine grains are situated adjacent to one another, resulting in a reduction of the average grain size to 2.67 micrometers in this condition. Quantitative results from the optimal strain parameter indicate that the average grain size in the first pass reaches approximately 1.23 micrometers, representing a reduction of 68% and 53% compared to the non-optimal sample and the optimal force sample, respectively. The mechanism behind the formation of this microstructure can be attributed to the accumulation of dislocations at grain boundaries and the transformation of low-angle grain boundaries into high-angle grain boundaries. This process ultimately leads to the formation of a uniform and stable microstructure [23]. Accordingly, it can be concluded that the optimal parameters for achieving a nanostructure demonstrate high efficiency compared to the traditional ECSEE process. The micrographs in Fig. 7(a) demonstrate a clear progression in microstructure morphology with increasing ECSEE passes. Fig. 7(b) Low Deformation: The surface reveals a mixed-mode morphology with elongated, shallow dimples aligned along the shear direction. This indicates limited ductile tearing and pronounced strain localization, consistent with insufficient grain refinement at low accumulated strain, resulting in quasi-ductile fracture behavior. Fig. 7(b) Intermediate Deformation: A transition toward a more ductile mode is evident, characterized by finer, deeper, and more uniformly distributed dimples. This reflects the onset of significant microstructural refinement, including sub-grain formation and increased dislocation density, imparted by additional ECSEE passes. Fig. 7(c) High Deformation: The surface exhibits a fully developed ductile morphology, with a high density of fine, equiaxed dimples. This signifies extensive plastic deformation and efficient energy absorption, directly correlating with the superior microstructural homogeneity and refinement achieved at the highest number of ECSEE passes. The average grain size was determined using MIP4 software by calculating the mean length and width of the grains.

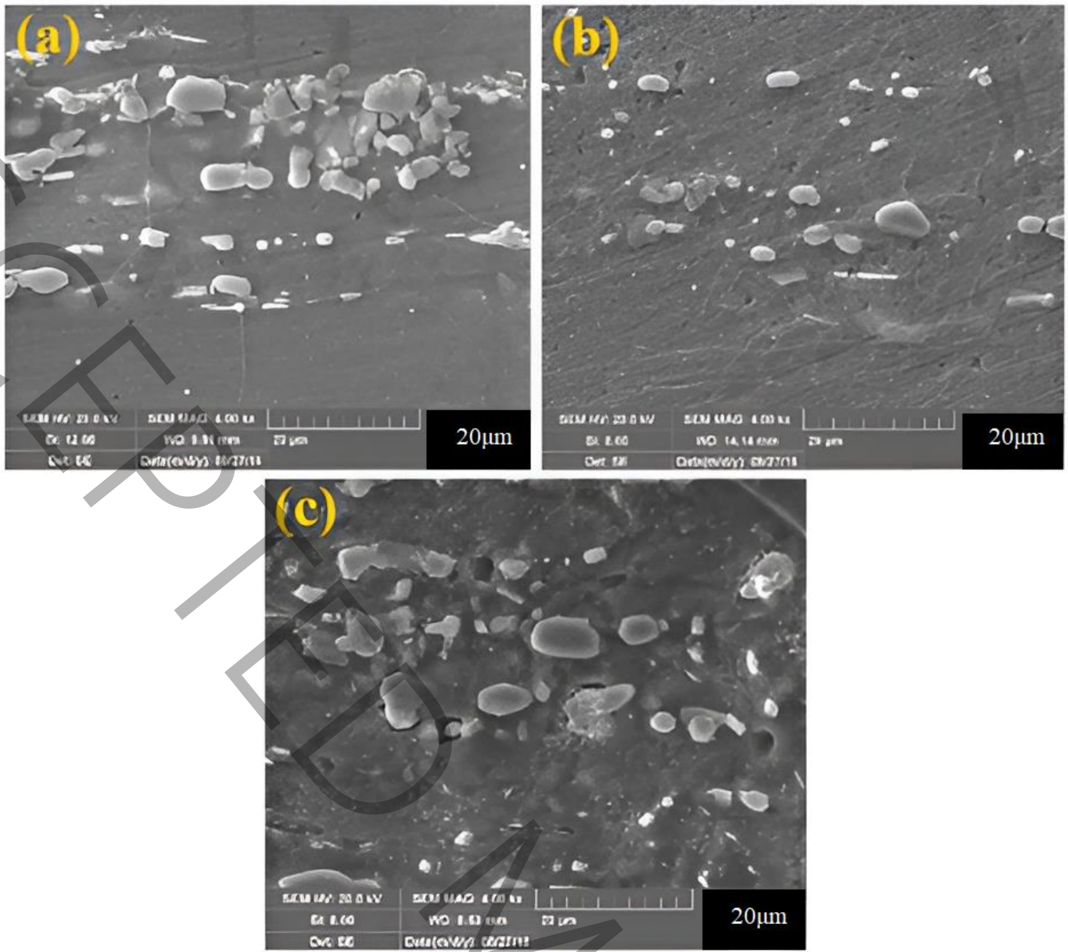

Fig. 7. (a) SEM image of non-optimized ECSEE sample (E1), (b) Optimized plastic strain ECSEE sample (E2), and (c) Optimized forming force ECSEE sample (E3)

A main feature of the ECSEE method is its ability to produce a homogeneous and uniform grain structure. This microstructural homogeneity significantly influences the resulting mechanical properties. To quantitatively evaluate the uniformity of the grains, the standard deviation of the grain size was calculated using the following equations for standard deviation and coefficient of variation [24]:

$$\bar{x} = (\sum_{(i=1)}^{N} x_i) / N \quad (7)$$

$$\sigma_x = ((\sum_{(i=1)}^{N} (x_i - \bar{x})^2) / N)^{(1/2)} \quad (8)$$

$$CV_x = \frac{\sigma_x}{\bar{x}} \quad (9)$$

The terms in the equations are defined as follows: $\bar{x}$ is the average grain size, σ_x the standard deviation, CV_x the coefficient of variation, x_i an individual grain size, and N the total number of grains measured. The analysis of grain size distribution and homogeneity was conducted by calculating the standard deviation. Based on the average grain sizes across all three parameters (two optimal and one non-optimal), the results demonstrated that the optimal parameters, with their lower standard deviation values, exhibit a more uniform grain size distribution and, consequently, a more desirable and homogeneous microstructure.

3-3- Impact Strength

Impact testing was also conducted to analyze the impact toughness of the samples after the ECSEE process under optimal and non-optimal parameters; the results of which are reported in Fig. 8. As evident in Fig. 5, the samples processed with optimal parameters recorded plastic strain and forming force with impact energies of 8 and 13 joules, respectively, indicating a significant reduction in energy compared to the non-optimal parameters. The decrease in impact energy is attributed to reduced ductility, diminished toughness, and increased material strength, such that the more brittle the sample, the less energy is required for fracture. This refinement in fracture morphology reflects a transition from mixed-mode ductile fracture toward a predominantly quasi-brittle mechanism, characterized by smaller dimple sizes and reduced dimple depth. Such microstructural evolution aligns with the SEM fractography results, which illustrate the progressive transformation from elongated dimples at low deformation levels to fine equiaxed dimples at higher ECSEE passes. These changes confirm that material behavior under impact loading is strongly controlled by the accumulated strain, grain refinement, and the distribution of dislocations introduced during the ECSEE process. Overall, the combined mechanical and microstructural evidence suggests that while the ECSEE method significantly enhances strength through grain refinement and strain hardening, it may also reduce impact toughness at high deformation levels due to increased brittleness and reduced capacity for plastic energy absorption.

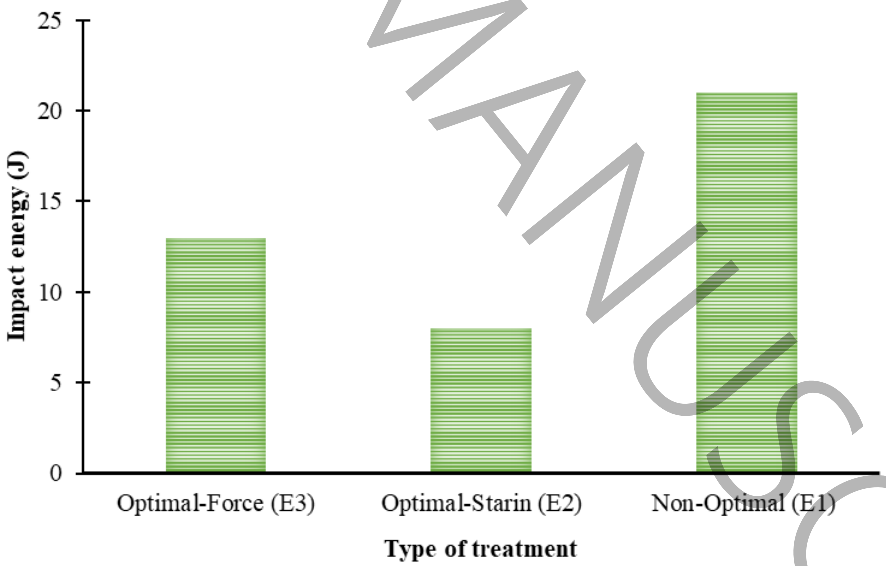

Fig. 8. Impact energy of the samples processed by different treatments

The reduction in impact energy observed in the optimized samples clearly reflects a decrease in fracture toughness, representing a known trade-off in SPD processes such as ECSEE, where substantial grain refinement increases strength but often diminishes ductility and toughness. The practical significance of this reduction, however, depends on the loading conditions of the intended application. For shock- or impact-dominated environments, or in the presence of pre-existing cracks, the lower toughness is a critical limitation and makes the optimized material less suitable. In contrast, for applications governed mainly by quasi-static tensile or compressive loading, the compromise may be acceptable, as the markedly improved yield strength and fatigue resistance become the primary design criteria. Despite the reduced impact toughness, the material can still retain sufficient uniform elongation for forming and structural stability. In summary, ECSEE shifts the material's property profile from high toughness–low strength to high strength–lower toughness, making it advantageous for applications where strength-to-weight ratio and resistance to plastic deformation are prioritized over impact resistance.

3-4- Microhardness

Microhardness and its distribution are among other factors that must be considered after the Severe Plastic Deformation (SPD) process. For this purpose, cross-sections of the deformed samples were cut, and microhardness values were measured. The microhardness test was performed at five points along the longitudinal diameter of the sample's cross-sectional face. Fig. 9 shows the microhardness distribution of materials processed by the ECSEE method with optimal and non-optimal parameters. According to Fig. 9, the microhardness values reach their maximum at the center of the sample and decrease with increasing distance from the center. This hardness distribution is perfectly aligned with the distribution of plastic strain within the sample. Due to the application of high strains at the sample's center, this region possesses higher microhardness [25]. The strain is maximum at the center of the processed sample and decreases towards the sample surface. Consequently, the hardness is highest at the sample's center. Furthermore, the results indicate that the sample processed with the optimal strain parameter in the ECSEE method has higher microhardness compared to the other two parameters. Specifically, for this sample, with a reported average microhardness of 134.562 Vickers, an increase of 12% and 41% was reported compared to the optimal forming force parameter and the non-optimal parameter, respectively. The phenomenon of increased microhardness is due to grain size reduction caused by the application of high strains and is justified according to the Hall-Petch relationship.

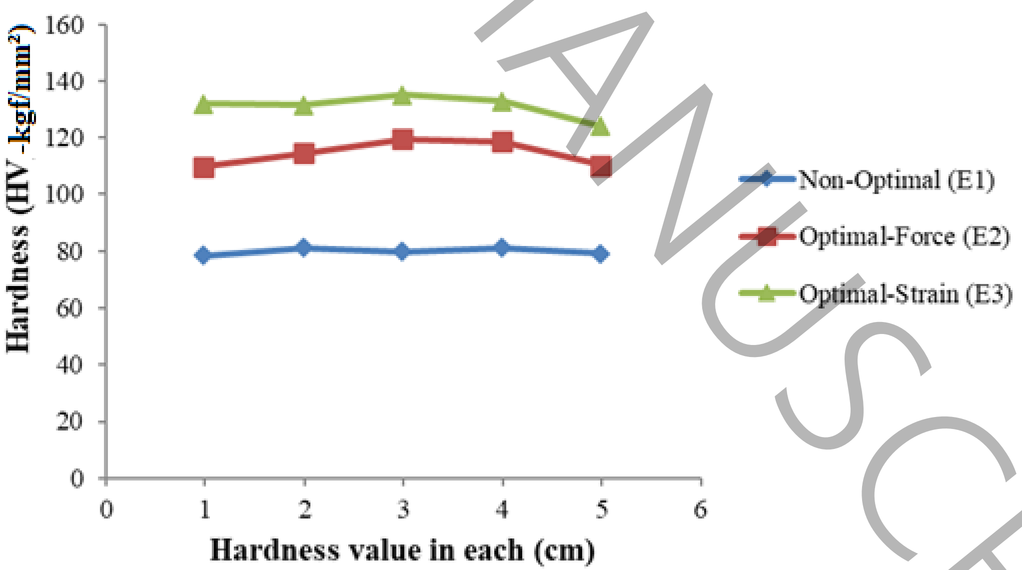

Fig. 9. Microhardness Results of Optimized and Non-Optimized Samples in the ECSEE Method

4- Conclusions

In this research, the effective parameters of the ECSEE process, such as punch feed, sample annealing, and the number of extrusion passes, were investigated to improve the forming force and plastic strain. This was done by first identifying the range of input parameter values and then creating the experiment table using the Taguchi experimental design method. The output values of forming force and plastic strain in the experimental design were obtained based on empirical tests. The optimal levels for the ECSEE process were extracted to minimize the forming force and maximize the plastic strain. Furthermore, in the ECSEE method, the mechanical and microstructural properties of the samples (impact strength, microhardness, and microstructure) were obtained for both optimal and non-optimal values and compared with each other. The results are categorized below:

- Increasing the punch feed increased the plastic strain and did not significantly affect the forming force. Increasing the number of extrusion passes in each stage also led to a higher forming force and an increase in plastic strain.
- Changing the sample annealing involved different temperatures and times, such that the softer the sample, the lower the force required for extrusion, and the plastic strain also decreased.
- The optimal values for reducing the forming force were stated as (punch feed of 9 mm/min, sample annealing at 300°C for 120 min, and 2 extrusion passes).
- The optimal values for increasing the plastic strain were stated as (punch feed of 9 mm/min, sample annealing at 200°C for 120 min, and 6 extrusion passes).
- A comparison of the microhardness values of samples extruded under optimal and non-optimal parameters showed that sample E3, with a value of 134.562 Vickers, had an increase of 12% and 41% compared to samples E2 and E1, respectively.
- The impact test values of the extruded samples processed under optimal and non-optimal parameters indicated that parameter E3, with a value of 8 Joules, required less energy than the other two parameters due to its increased microhardness.
- The grain size for the optimal parameters of forming force and plastic strain was reported as 2.67 and 1.23, respectively, showing a 42% and 53% reduction compared to the non-optimal parameter E1.

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