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Investigating the Effects of Severe Plastic Deformation on Aluminium Alloy Properties: A Comparative Study

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Abstract

Equal channel angular pressing is a metal forming process. It serves as a strengthening treatment through which ductile metals can be processed to refine their grain and subgrain structure. This process improves the mechanical performance of metals, including tensile strength, stress-controlled fatigue strength, and resistance to fatigue crack propagation. Equal channel angular pressing is one of the severe plastic deformation methods employed to produce ultrafine-grained materials. In this method, a large shear strain is imparted to the material without altering its cross-sectional dimensions. Aluminum alloys are promising lightweight, high-strength materials in which precipitation strengthening can be achieved. In this study, equal channel angular pressing was employed to improve the strength of the Al alloy. The ECAP process was performed using a die with an internal channel angle (Φ) of 120° and an outer arc curvature (Ψ) of 30°. Optical microscopy was employed to examine the microstructures before and after equal channel angular pressing. Microhardness testing and tensile experiments were performed to evaluate the mechanical properties. In the homogenized state, coarse grains with an average size of approximately 180 µm were observed, the grain size reduced to approximately 2 µm. The microhardness and strength of the alloy increased after ECAP processing. In the homogenized condition, the alloy exhibited a microhardness of 95 Hv. After equal channel angular pressing, the microhardness of the alloy increased to 180 Hv. In the homogenized state, the alloy exhibited an ultimate tensile strength of 120 MPa, which rose to 205 MPa following ECAP processing.

Keywords: SPD, ECAP, Al alloy, Grain Refinement, Plastic Deformation, Shear Deformation, Hydrostatic Stress.

1. Introduction

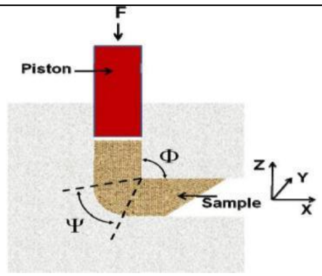
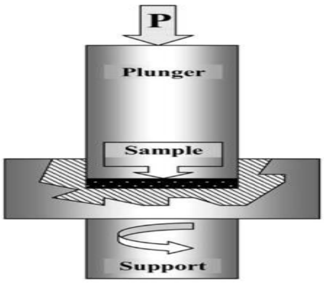
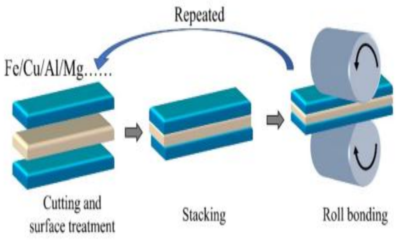
The grain size of a material has a crucial influence on its mechanical properties. According to the Hall–Petch relationship, material strength increases as the grain size decreases. Consequently, there has been growing interest in developing materials with extremely fine grain structures [1]. Because of their many advantages, considerable interest has focused on developing new techniques to fabricate ultrafine-grained (UFG) materials (grain size < 2 µm). As conventional processing methods have limitations in reducing grain size to only a few micrometers, UFG structures are achieved either through bottom-up approaches or top-down approaches [2]. Severe plastic deformation (SPD) methods are based on fundamental principles of mechanics of materials, along with process-specific equations used to evaluate the imposed strain and its influence on material properties (table 1).

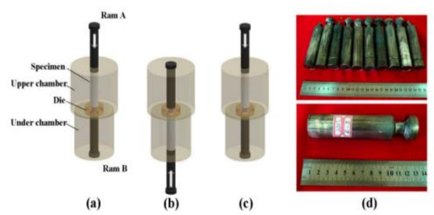
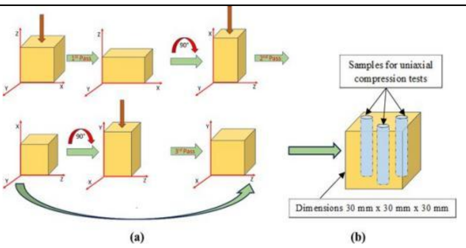
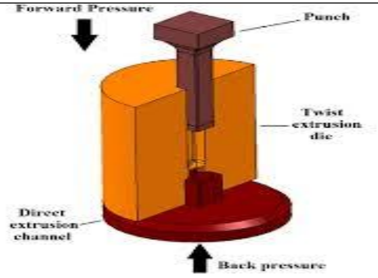
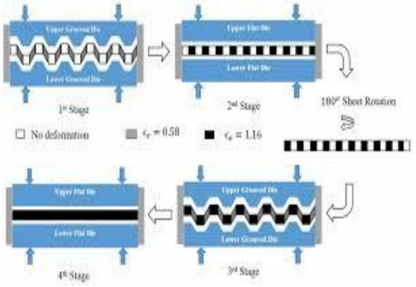
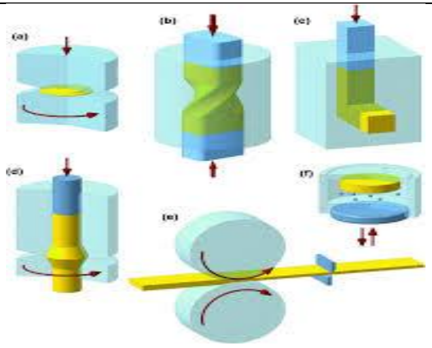
Table 1. These equations, together with advanced constitutive models employed in finite element analysis (FEA), enable engineers and researchers to analyze and predict the microstructural evolution and mechanical behavior of materials subjected to severe plastic deformation [3].

S.N.	General Constitutive Equation	Various Parameters	Techniques	Ref.
1.	$\sigma_y = \sigma_0 + k_y d^{-\frac{1}{2}}$	σ_y = Yield strength, σ_0 = Friction stress, k_y = Constant related to yielding, d= Average grain diameter, This equation serves as a fundamental principle that explains why ultrafine-grained materials processed by SPD display enhanced strength.	The correlation between yield strength and grain size is commonly expressed by the Hall–Petch equation.	[4]
2.	$\gamma = 2cot\left(\frac{\Phi + \Psi}{2}\right) + \Psi csc\left(\frac{\Phi + \Psi}{2}\right)$	The effective strain γ per pass can be estimated based on the die angle Φ and the outer arc curvature angle Ψ. The total effective strain after N passes is approximately N times the strain per pass, assuming certain processing routes.	Equal-Channel Angular Pressing	[5]
3.	$\gamma = \frac{2\pi rN}{t}$	The shear strain γ in an HPT-processed disk is not uniform and is typically a function of the radial distance r from the center, the material thickness t, and the number of revolutions N, The strain is highest at the edge and zero at the center.	High-Pressure Torsion (HPT)	[6]
4.	$\varepsilon = \frac{4\pi RN}{3\sqrt{3}H}$	The magnitude of the mean strain ε can be calculated using the specimen's radius R, length H, and the number of rotations N	Torsion Extrusion (TE)	[7]
5.	$\varepsilon = 4ln\left(\frac{D_1}{D_0}\right)$	The equivalent strain ε after a number of cycles n is related to the initial D_1 and final diameters D_0	Expansion ECAP (Exp-ECAP)	[8]

In the bottom-up approach, bulk materials are formed by consolidating individual atoms or molecules, as in processes such as inert gas consolidation, electro-deposition, and hot isostatic pressing. In contrast, the top-down approach involves refining solid materials typically with a coarse-grained (CG) structure into fine-grained structures. The top-down approach can be achieved through conventional processing methods as well as severe plastic deformation (SPD) techniques. Conventional processes, such as cold rolling, lead to grain refinement [9]. However, the structures produced by conventional processing methods typically contain low-angle grain boundaries. In contrast, SPD techniques produce a much higher level of grain refinement accompanied by the formation of high-angle grain boundaries. They also result in the accumulation of substantial plastic strain within the material. A high proportion of high-angle grain boundaries is essential for achieving considerable enhancement in mechanical properties. SPD is a metal forming process in which extremely large plastic strain is applied to the material without causing any significant change in its overall dimensions. Several techniques have been developed for processing materials by severe plastic deformation [10]. These include High Pressure Torsion (HPT), Equal Channel Angular Pressing (ECAP), cyclic extrusion and compression (CEC), Accumulative Roll Bonding (ARB), Repetitive Corrugation and Straightening (RCS), Constrained Groove Pressing (CGP), and Multi-Directional Forging (MDF). Among these methods, Equal Channel Angular Pressing (ECAP) is particularly effective due to its simplicity. In ECAP, the attainable strain is virtually unlimited, whereas most conventional techniques typically require a change in shape or reduction in dimensions to achieve high levels of plastic strain [11].

Table 2. Summarizing different parameters of Severe Plastic Deformation (SPD) techniques: for various techniques [12].

SPD Technique	Process Description	Advantages	Limitations	Schematic Illustration	Ref.
ECAP (Equal Channel Angular Pressing)	Pressing through a die with two intersecting channels	Simple, scalable, bulk samples	Limited sample size, friction issues		[13]
HPT (High-Pressure Torsion)	Torsional straining under high pressure	Ultra-fine grains, high strain	Small sample size, complex setup		[14]
ARB (Accumulative Roll Bonding)	Repeated rolling and bonding cycles	Large sheet production, industrial scalability	Limited to sheet form, bonding issues		[15]

CEC (Cyclic Extrusion Compression)	Repeated extrusion and compression	Bulk samples, simple setup	Limited strain range, material flow issues		
MAF (Multi-Axial Forging)	Repeated forging in different directions	Bulk samples, simple setup	Limited strain range, shape control issues		[16]
TE (Twist Extrusion)	Twist deformation through a die	High strain, complex shapes	Complex setup, limited scalability		[17]
CGP (Constrained Groove Pressing)	Pressing through a grooved die	Simple setup, sheet processing	Limited strain range, shape distortion		[18]
RSPD (Repetitive Severe Plastic Deformation)	Repeated deformation cycles	Flexible, high strain	Complex setup, scalability issues		[19]

Therefore, materials processed by ECAP exhibit high dislocation densities, resulting in significantly greater hardness and strength compared to materials processed using other conventional techniques (table 2). In addition, ECAP processing produces a significant level of grain refinement along with the development of high-angle grain boundaries. Although the strength of a material can be enhanced through methods such as heat treatment, the addition of alloying and rare-earth elements, and coating techniques, these approaches have several limitations [20]. For example, heat treatment does not improve every property of all materials. Likewise, incorporating alloying and rare-earth elements modifies the composition and phase structure of the alloy system, and coating techniques enhance only the surface characteristics of the material. These properties are significantly influenced by the material's microstructure, which is determined by the alloy composition and the processing methods applied [21].

Therefore, severe plastic deformation techniques, such as high-pressure torsion and equal-channel angular pressing, have gained considerable attention as processing methods because of their ability to enhance the properties and performance of magnesium-based implants through grain refinement and structural homogenization [22]. These aspects are demonstrated through the processing–structure–properties–performance relationships, as presented in Fig. 1.

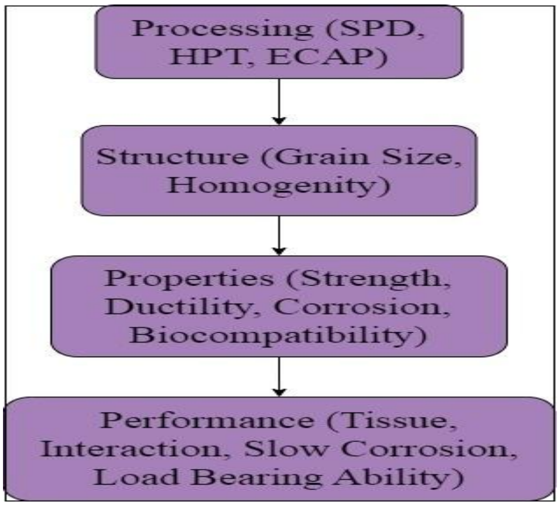


Fig. 1. Overview of the interrelationship among processing, structure, properties, and performance of magnesium for biomedical applications [23].

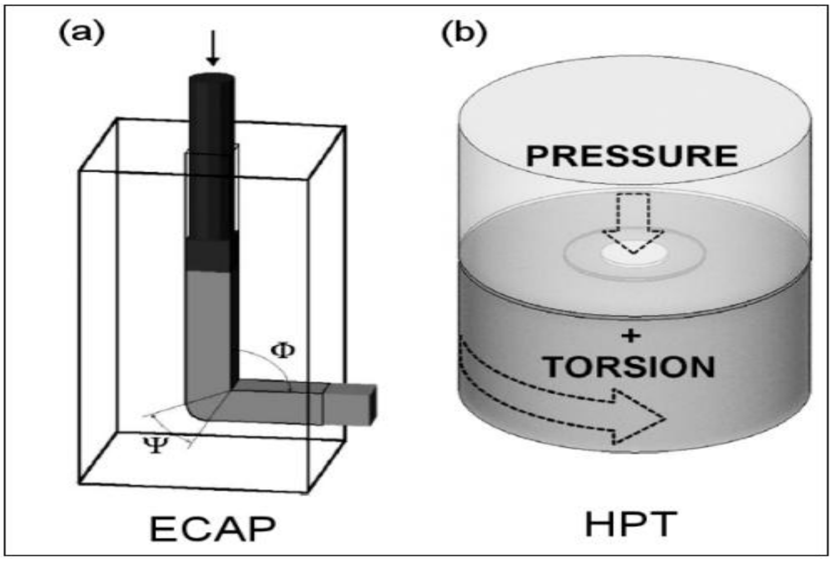


Fig. 2. Schematic representation of the principles of (a) ECAP and (b) HPT [24].

Fig. 2. In ECAP, a billet is forced through a die consisting of two intersecting channels with equal cross-sections. Shear deformation occurs at the channel intersection, and its magnitude depends on the die geometry. In comparison with these methods, strengthening through grain refinement using SPD techniques is more advantageous due to several benefits, such as operational simplicity, cost-effectiveness, and the formation of a homogeneous structure and uniform properties throughout the material. Aluminium and its alloys are regarded as reliable materials for engineering applications. Among the various aluminium alloy families, Al–Zn–Mg alloys are recognized as the strongest and hardest. Al–Zn–Mg alloys exhibit excellent strength and toughness. They are widely used in the manufacturing of engineering equipment where a high strength-to-weight ratio is a key requirement. These alloys are primarily used in aerospace, military equipment, and lightweight structural applications [25]. Al–Zn–Mg alloys demonstrate good tensile properties, dimensional stability, and machinability, and they are suitable for service at elevated temperatures. The strength of Al–Zn–Mg alloys can be improved through various severe plastic deformation (SPD) techniques. Nanostructured materials fabricated by SPD are fully dense, free from contamination, and large enough for practical use in

commercial structural applications. These materials exhibit high strength, good ductility, excellent superplasticity, a low coefficient of friction, high wear resistance, improved high-cycle fatigue life, and good corrosion resistance [26]. Equal Channel Angular Pressing (ECAP), recognized as one of the most promising material processing techniques, involves severe plastic deformation. Unlike rolling, drawing, and extrusion, the primary objective of ECAP is to impose large plastic strain on the material without reducing the cross-sectional area of the workpiece.

Equal Channel Angular Pressing (ECAP) is associated with the development of stresses in different layers of the deforming material. The magnitude of the surface stress reflects the extent of hardening in the surface layer of the pressed material. Significant attention has been devoted to assessing the potential of severe plastic deformation (SPD) to enhance the performance of magnesium for biomedical applications [27]. However, varying properties and trends, including certain inconsistencies, have been reported. The present study provides a critical review of the microstructural characteristics, mechanical properties, corrosion behavior, and biological response of magnesium and its alloys processed through severe plastic deformation, with particular focus on equal-channel angular pressing (ECAP) and high-pressure torsion (HPT). The distinctive grain refinement mechanism in magnesium processed by ECAP leads to significant variability in the resulting microstructure, and these differences can influence the material properties and make it challenging to establish consistent trends [28]. Nevertheless, recent progress in ECAP processing, along with the growing body of data from samples fabricated by HPT, indicates that grain refinement can effectively enhance mechanical properties and corrosion resistance without adversely affecting the biological response. It has been demonstrated that processing through severe plastic deformation (SPD) offers significant potential to enhance the performance of magnesium for biomedical applications.

In this review, severe plastic deformation (SPD) is regarded as a materials processing technique. The mode of deformation is the key feature that distinguishes SPD methods from conventional forming operations. At large plastic strains, the deformation mode is determined by the distribution of strain rates along continuum slip lines and may range from pure shear to simple shear. A scalar, invariant, and dimensionless parameter of deformation mode is defined as the normalized rate of rigid body rotation. Based on this, simple shear is considered the most effective mode for structural modification and grain refinement, while pure shear is regarded as the “ideal” mode for forming processes. Dedicated experiments and practical SPD applications support this conclusion [29]. Different severe plastic deformation techniques are categorized and explained based on how simple shear is achieved or approximated. It is demonstrated that accurate evaluation of processing mechanics and technological parameters is crucial for comparing SPD techniques and for developing efficient industrial applications. Grain size is a key microstructural parameter in polycrystalline materials, influencing the material’s strength and its capacity to exhibit superplastic forming behavior. Grain refinement is particularly significant because finer grains enhance material strength and increase the potential for achieving superplastic flow. Traditionally, grain size was controlled using different thermomechanical treatments; however, this approach had a major limitation, as it was not feasible to obtain grain sizes below a few micrometers [30]. Over the past four decades, this situation has changed with the discovery that significantly finer grain sizes can be achieved through severe plastic deformation (SPD), in which large strains are applied without substantially altering the overall dimensions of the specimen. This report outlines the fundamental principles of the primary SPD processing methods and highlights the importance of achieving submicrometer grain sizes.

2. Literature Review

In recent years, the production of ultrafine-grained (UFG) materials using SPD techniques has gained considerable attention from researchers. Grain sizes ranging from 0.5 to 2 μm are classified as belonging to the UFG microstructure category [31]. Examination of Fig. 3 indicates that, in contrast to the bars and rods discussed in the previous section, the number of allowable rotations between passes is now restricted. Therefore, in the vertical configuration, the sample can be rotated in several alternative ways. First, the sample may be rotated by 180° about the X axis, which is equivalent to route C and is designated as route C_X, where C indicates a 180° rotation and the subscript X specifies rotation about the X axis. Second, it may be rotated by 180° about the Z axis, referred to as route C_Z.

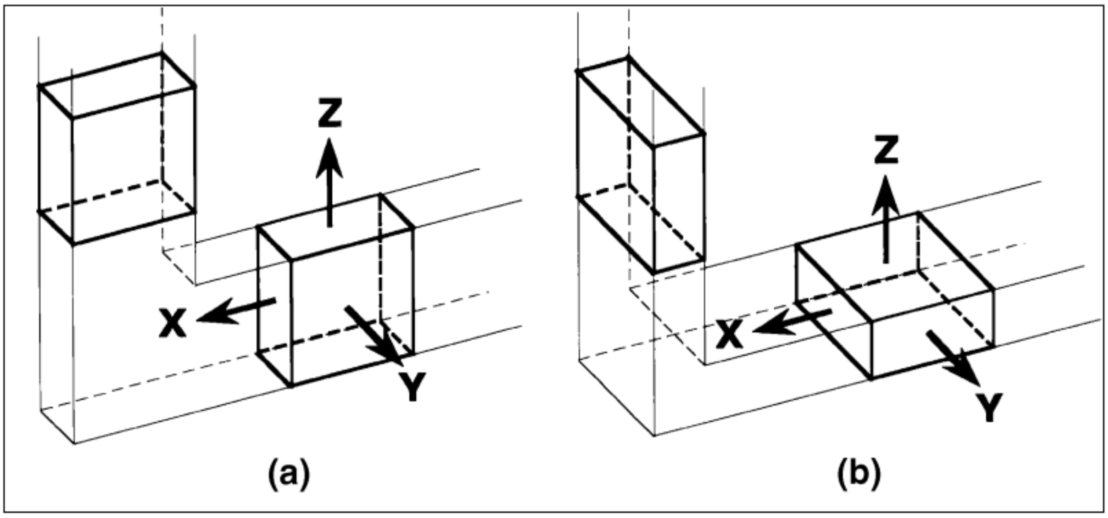


Fig. 3. Implementation of ECAP on plate samples: (a) vertical arrangement and (b) horizontal arrangement [32].

Traditional metal forming operations cause dimensional changes in the processed material, which restricts the level of strain that can be introduced. As a result, these methods impose a lower limit on the grain size that can be attained. A high-pressure torsion straining technique can be employed to produce disk-shaped samples (Fig. 3(a & b)). In this method, an ingot is placed between anvils and subjected to torsional deformation under an applied pressure (P) of several GPa [33]. The lower holder rotates, and frictional forces at the surface impose shear deformation on the ingot. Owing to the sample's specific geometry, most of the material is deformed under quasi-hydrostatic compression resulting from the applied pressure and the pressure exerted by the outer layers of the sample. Consequently, despite the imposition of very high strain levels, the deformed sample does not fail. The high-pressure torsion straining method can be utilized to produce disk-shaped specimens (Fig. 4(a & b)), in which an ingot is positioned between anvils and subjected to torsional deformation under an applied pressure (P) of several GPa. The lower holder rotates, and shear deformation of the ingot occurs due to frictional forces at the contact surfaces [34]. Because of the sample's specific geometry, the bulk of the material is deformed under quasi-hydrostatic compression generated by the applied pressure and the constraint from the outer layers of the specimen. Consequently, despite the application of very high strain levels, the deformed specimen does not fracture. Various relationships have been employed to determine the strain values during torsion.

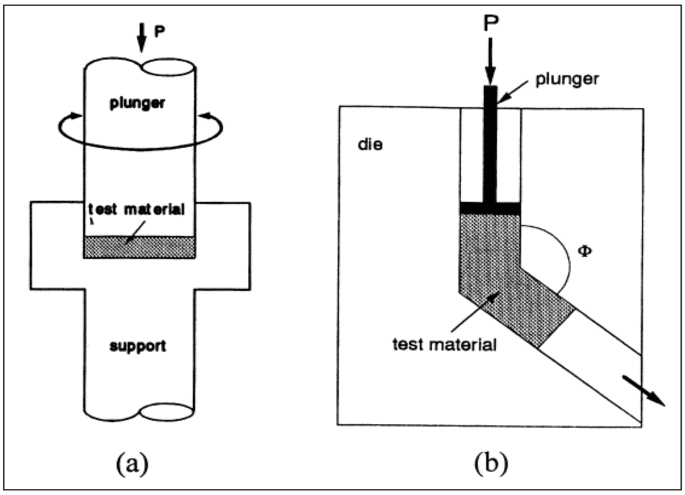


Fig. 4. Fundamentals of SPD techniques: (a) high-pressure torsion and (b) equal-channel angular pressing [35].

Moreover, the strain generated in these processes is frequently non-uniform. However, SPD techniques preserve the overall dimensions of the material, thereby eliminating the restriction on achieving large strains that arises from dimensional changes. In comparison with traditional metal forming methods, the mechanical properties achieved through SPD techniques are more uniform and often superior. Severe plastic deformation (SPD) encompasses experimental metal forming processes designed to apply extremely high strains to materials, resulting in significant grain refinement. A distinctive characteristic of SPD processing is that very high strain is introduced without causing any substantial alteration in the overall dimensions of the workpiece [36]. Materials processed through SPD develop high-angle grain boundaries as a result of the large strains applied under high pressure at relatively low temperatures, while the overall dimensions of the product remain essentially unchanged. SPD techniques offer several advantages over other bottom-up approaches. They help eliminate issues such as porosity in compacted samples and contamination arising from the consolidation of ball-milled materials. The production of bulk nanostructured materials through SPD techniques serves as an alternative to conventional nano-powder compaction methods. Among the different SPD methods, ECAP is particularly appealing due to its operational simplicity, suitability for processing large samples, and ability to produce homogeneous materials. Since then, it has become the most extensively utilized experimental method among SPD techniques.

ECAP is an advanced severe plastic deformation process capable of imparting large plastic strains to polycrystalline materials. The terms ECAP and ECAE (equal channel angular extrusion) are often used interchangeably in scientific literature. However, since the process does not involve any decrease in the billet's cross-sectional area, the term ECAP is more commonly preferred [37]. In the ECAP process, deformation occurs through pure shear. The arrangement includes a die with two channels of identical cross-section that intersect at a specific angle. A specimen with a uniform cross-section, either circular or square, is forced through these channels. A substantial shear strain is introduced into the sample as it moves through the intersection plane of the two channels, which consequently leads to a significant refinement of the grain size. A key characteristic of ECAP is that the sample dimensions remain unchanged during deformation; therefore, the same material can be processed repeatedly to impose very high strains and achieve an ultrafine-grained (UFG) structure. To achieve an optimal microstructure characterized by uniform, equiaxed grains bounded by high-angle grain boundaries, the following conditions must be satisfied: (i) Formation of slip traces over wide angular ranges on each of the three mutually perpendicular planes. (ii) Consistent and periodic restoration of the equiaxed structure during successive passes. (iii) Deformation occurring on all three orthogonal planes. This condition is satisfied when route BC is applied with a 90° die [38]. However, in a 120° die, route BC is less effective than route A. Nevertheless, route BC is still regarded as the optimal processing method. The channel angle, Φ, is a critical experimental parameter because it determines the magnitude of strain imposed in each pass. A large number of ultrafine equiaxed grains, along with a grain structure containing a high fraction of high-angle grain boundaries, can be readily obtained when the sample undergoes severe plastic deformation using a die with a 90° channel angle. As the die angle increases, the resulting grain structure contains a higher proportion of low-angle grain boundaries. It is important to note that, in practice, pressing samples through dies with angles greater than 90° is easier, especially for hard materials and those with limited ductility.

A key point is that the resulting microstructure is independent of the total accumulated strain, and it is recommended to apply a very high strain rate in each individual pass to promote a high fraction of high-angle grain boundaries and achieve finer grain refinement. High-quality microstructures can be achieved using a die with $\Phi = 60°$, and the resulting average grain size is slightly smaller than that obtained with a die having $\Phi = 90°$. The curvature angle, ψ, represents the outer arc formed at the intersection of the two channel segments within the die. This angle has only a limited influence on the magnitude of strain applied to the sample and exerts an even smaller effect when the channel angle Φ exceeds 90°. Nevertheless, understanding its role is important in the fabrication of ultrafine-grained (UFG) materials. As the sample passes through the die, a corner gap or dead zone develops at the outer corner, causing the sample to lose contact with the die walls in that region [39]. The angle formed by the corner gap is influenced by the material's strain-hardening rate. Although a corner angle can also be introduced on the inner surface at the intersection of the two channel segments, it is generally not recommended due to practical challenges. It is advisable to design a die with an outer curvature angle (ψ) in the range of 15° to 20° to obtain optimal processing conditions. Pressing speed is another variable parameter in the ECAP process. Reported results indicate that pressing speed does not significantly affect the equilibrium grain size of the ultrafine structure produced by ECAP. However, recovery processes occur more readily at lower pressing speeds, leading to more stable and equilibrated microstructures. In contrast, processing at higher speeds can cause sudden heating of the samples.

The processing temperature has a significant influence on the ECAP process, as it directly impacts the grain size obtained. Numerous investigations have been carried out to examine the effect of processing temperature on ECAP [40]. The proportion of low-angle grain boundaries rises with increasing processing temperature because the accelerated recovery rate enhances dislocation annihilation within the grains, resulting in a reduced dislocation density in the sub-grains. Optimal ultrafine-grained (UFG) microstructures are achieved when processing is carried out at the lowest feasible temperature, provided that no significant cracking occurs in the samples during deformation. Greater strength is achieved when processing is conducted at lower temperatures, whereas increasing the processing temperature leads to a reduction in strength. Maintaining a low processing temperature enables the attainment of the finest possible grain size along with the highest fraction of high-angle grain boundaries. The finer grain size and elevated dislocation density produced by ECAP result in significantly increased strength and hardness compared to coarse-grained materials. However, materials processed by ECAP typically exhibit reduced ductility [41]. In comparison with conventional metal forming processes, the reduction in ductility of ECAP-processed samples is relatively smaller. There are also reports in the literature indicating that both strength and ductility can increase after ECAP processing. A simultaneous improvement in both strength and ductility was reported in copper processed up to sixteen passes. This enhancement has been attributed to the increased fraction of high-angle grain boundaries with increasing strain. Furthermore, the changes in deformation mechanisms resulting from ECAP are associated with an increased tendency for grain boundary sliding and grain rotation. Applying an ageing treatment after ECAP significantly influences both the strength and ductility of the material.

It can be concluded that grain refinement achieved through ECAP results in a unique combination of strength and ductility. A study in which commercially pure aluminum was processed by ECAP at room temperature using both conventional and ultrasonic vibration methods to examine the effect of ultrasonic waves on the pressing load and the mechanical properties of the deformed specimens. The findings indicated that superimposing ultrasonic vibration during the ECAP process not only reduces the required punch load but also enhances the mechanical properties of the material compared to the conventional process. A study in which the ECAP method was applied for surface plating. Previously fabricated ECAP dies based on a split-die design were utilized [42]. Strips of 5083 aluminum and Ms 58 brass alloys with thicknesses of 2 mm and 4 mm were positioned side by side within the ECAP die and processed through single and double passes to simulate metallic plating under cold pressure welding conditions. No complete and sound bonding was achieved between the strips, although partial bonding was observed in some areas. A study reporting the results of both experimental investigations and finite element analysis of the ECAP process. The effects of die geometry and friction conditions on the non-uniformity of the shear strain field across the billet cross-section, and consequently on the distribution of mechanical properties, were examined. It was demonstrated that ECAP is inherently associated with an uneven shear strain distribution.

It was observed that the degree of strain irregularity can be minimized depending on the die geometry and friction conditions. Three-dimensional contour graphs of a surface stress model for Ti–6Al–4V alloy subjected to equal channel angular pressing, derived from the N (normal resultant) and M (moment resultant), and analyzed over different regions of the deforming material [43]. It concluded that St3 steel was processed using equal channel angular pressing, and its microstructure and properties were evaluated after two passes. It was found that different processing routes (Bc and C) led to distinct microstructural evolution during ECAP. It has been demonstrated that equal channel angular pressing is an effective technique for producing materials with enhanced mechanical properties. The tensile strength, elongation, static toughness, and fracture behavior of cast Al–0.63 wt.% Cu and Al–3.9 wt.% Cu alloys after processing by ECAP. It was observed that, after four ECAP passes, the grain sizes of both alloys were refined to the submicron scale. Furthermore, the θ precipitate phase located along the grain boundaries in the Al–3.9 wt.% Cu alloy was fragmented following ECAP processing. The tensile fracture strength of both Al–Cu alloys rises with an increasing number of ECAP passes, while the elongation remains nearly constant regardless of the pass number. As a result, the static toughness of the Al–Cu alloys improves at higher ECAP passes. The Al–0.63 wt.% Cu alloy fails through necking and shear fracture, whereas the Al–3.9 wt.% Cu alloy exhibits normal fracture along with shear fracture at varying shear angles. Based on these observations, the tensile properties and failure modes of the Al–Cu alloys are analyzed under cold pressure welding conditions [44]. No fully successful joints were formed between the strips, although some partial joints were observed. It reported experimental results along with finite element analysis findings from an ECAP study. The effect of die geometry and friction conditions on the unevenness of the shear strain field across the billet's cross section, and consequently on the distribution of mechanical properties, was investigated. It was found that ECAP consistently exhibits an irregular shear strain distribution.

The irregularity can be minimized depending on the die geometry and friction conditions. Three-dimensional contour graphs of a surface stress model made of Ti–6Al–4V alloy subjected to equal channel angular pressing, illustrating the effects of the normal resultant force (N) and the moment resultant (M) acting on different regions of the deformable material. It reported that St3 steel was processed using equal channel angular pressing. The microstructure and properties of the steel were evaluated after two ECAP passes [45]. It was found that different processing routes (Bc and C) led to distinct microstructural evolution during equal channel angular pressing. It has been demonstrated that equal channel angular pressing is an effective technique for producing materials with enhanced mechanical properties. The tensile strength, elongation, static toughness, and fracture behavior of cast Al–0.63 wt.% Cu and Al–3.9 wt.% Cu alloys subjected to ECAP. It was observed that, after four ECAP passes, the grains of both alloys were refined to the submicron scale. Moreover, the θ precipitate phase located along the grain boundaries in the Al–3.9 wt.% Cu alloy was fragmented following ECAP processing. For both Al–Cu alloys, the tensile fracture strength increases as the number of ECAP passes rises, whereas the elongation remains nearly unaffected by the pass number. As a result, the static toughness of the Al–Cu alloys improves at higher ECAP passes [46]. The Al–0.63 wt.% Cu alloy exhibits failure through necking and shear fracture, whereas the Al–3.9 wt.% Cu alloy shows normal fracture along with shear fracture at varying shear angles. Based on these findings, the tensile properties and failure mechanisms of the Al–Cu alloys are discussed.

The various external parameters associated with the ECAP processing of Cu–Al–Ni shape memory alloys using ABAQUS 6.10 software, which is widely utilized today. The parameters examined included the outer corner angle, as well as the temperatures of the die and billet. Identifying the optimal values of the influencing parameters has made this study noteworthy. Moreover, since no data were available on ECAP processing of Cu–Al–Ni shape memory alloys, future work should focus on an experimental investigation of the process [47]. The outer corner angle was selected based on achieving optimal strain homogeneity in the sample with minimal dead zone formation, while avoiding any adverse effects. Hyoung An Equal Channel Angular Pressing (ECAP) forming process that extrudes material through specially designed channel dies without significantly altering its overall geometry, while producing ultrafine-grained material by applying severe plastic deformation. Since the microstructural evolution and mechanical properties of the deformed material are closely linked to the extent of plastic deformation, understanding the mechanisms associated with strain development is crucial in the ECAP process [48]. The plastic deformation behavior during pressing is primarily controlled by the die geometry (channel dimensions, channel angle, and corner angles), material characteristics (strength and strain-hardening behavior), and process parameters (temperature, lubrication, and deformation rate). There is a requirement for modeling approaches that enable a broader investigation of the observed effects, leading to improved process control and a deeper understanding of process-related phenomena. In this work, we present a series of continuum modeling results for the ECAP process to demonstrate the applicability of the modeling approach. First, the finite element modeling results of ECAP for different geometric parameters are presented. Next, the non-uniform deformation arising from the material's strain-hardening behavior is discussed [49]. Finally, the simulation of the temperature field coupled with stress, as a representative process variable in ECAP, is described.

Equal-Channel Angular Pressing (ECAP) is an efficient processing technique for producing ultrafine-grained materials. To examine the influence of grain refinement during ECAP on the wear behavior of Al 7075 alloy, the specimens were subjected to up to four passes following route BC at room temperature. After ECAP processing, dry sliding wear tests were performed using a pin-on-disk apparatus under applied loads of 10, 20, and 30 N at a constant sliding speed of 0.23 m s^{-1}. Microstructural characterization was carried out using transmission electron microscopy (TEM), and the worn surfaces of the specimens were examined by scanning electron microscopy (SEM). The influence of applied load and the ECAP process on mass loss was analyzed in relation to the microstructure and wear mechanisms [50]. A comparison of the specimens' wear resistance indicates that ECAP significantly enhances wear resistance due to the development of ultrafine grains during processing. The influence of ECAP temperature and post-ECAP annealing on grain size, texture, and mechanical properties. The observed softening of ECAP-processed Mg alloys, despite significant grain refinement, was attributed to texture modifications occurring during ECAP. However, the strength of ECAP-processed AZ31 Mg alloys increased with decreasing grain size in accordance with the conventional Hall–Petch relationship, provided that a similar texture was maintained. From the current analysis, it can be concluded that achieving a substantial increase in the strength of Mg alloys through grain refinement using ECAP is practically difficult, as the texture-induced softening effect often outweighs the strengthening contribution from grain refinement.

This technique commonly employed to impose large plastic strains. However, experimental findings indicate that significant tensile stresses develop in the specimen during deformation, which can sometimes result in cracking in metallic alloys and pronounced curvature in polymeric materials [51]. To address these limitations, the ECAE process may be performed at elevated temperatures. However, this approach substantially reduces the amount of plastic deformation imparted to the specimen. Therefore, employing a multi-pass tool appears to be a suitable solution. In this study, a newly designed die geometry consisting of two elbows was simulated using the finite element method to gain insight into the deformation mechanisms and to identify the optimal tool geometry. The numerical findings indicate that the length and cross-sectional area of the second channel significantly influence the uniformity of plastic strain distribution. It was observed that optimal homogeneity was achieved when the second channel had the same cross section as the entrance and exit channels and a length equal to three times its width [52]. The materials using powder metallurgy with powders of different particle sizes, namely < 30 μm and > 30 μm. The composites were then processed by equal channel angular pressing (ECAP) under various conditions, and the microstructural evolution during ECAP was investigated. Particular attention was given to the influence of ECAP parameters on the distribution of SiC whiskers. This study aimed to assess the feasibility of ECAP as a post-processing technique for producing discontinuous metal matrix composites. Microstructural analysis and microhardness testing of the ECAP-processed samples indicated that the best combination of a uniform microstructure and improved mechanical properties could be achieved by (a) employing finer powders, (b) lowering the ECAP temperature, and (c) applying multiple ECAP passes.

3. Methodology

The ECAP die was manufactured using a split-type configuration, with alignment pins incorporated to ensure accurate positioning. It was machined with two channels of 16 mm diameter intersecting at an internal angle (Φ) of 120° and an արտաքին arc of curvature (Ψ) of 20°. With these angular parameters, an equivalent strain of 0.667 was imparted to the specimen in each pass. The ECAP die and punch were fabricated from H11 tool steel and subsequently heat-treated to achieve a hardness of 50 HRC. Provision was made in the ECAP die to accommodate heating coils, enabling the die to be heated to the desired processing temperature [53]. The dimensions of the ECAP die in millimeters. In this study, ECAP processing was performed using a 40-ton universal testing machine (UTM). During the process, the die blocks were secured together and properly aligned using alignment pins. The die blocks were subsequently fastened using three pairs of flat clamps, bolted securely to apply sufficient pressure. In this study, route BC was employed, as it provides a more uniform strain distribution in the material compared to other processing routes. Furthermore, route BC offers optimal processing conditions for achieving a homogeneous microstructure composed of equiaxed grains bounded by high-angle grain boundaries, thereby resulting in isotropic mechanical properties. Additionally, processing via route BC induces shearing over a wider range of angles compared to other routes. The ECAP operation was performed by pressing the specimen at a constant speed of 0.5 mm/s. To minimize friction between the die and the specimen, molybdenum disulphide (MoS_2) was applied as a lubricant. Before each pass, the die was heated to the required processing temperature, after which the specimen was placed inside and held for 15 minutes to ensure that thermal equilibrium was achieved between the sample and the die [54]. During processing, the entire die assembly was kept at the required temperature using a built-in heating system. After completion of the process, the specimen was manually extracted from the die. The procured material was homogenized at 480 °C for up to 20 hours. For ECAP processing, the homogenized material was machined to a diameter of 15.9 mm and a length of 85 mm, aligned parallel to the ingot axis (table 3).

Table 3. Comparison among severe plastic deformation techniques.

Equal Channel Angular Extrusion (ECAE/ECAP) [55]	High-Pressure Torsion (HPT) [56]	Accumulative Roll-Bonding (ARB) [57]
✓ ECAP (also called ECAE – Equal Channel Angular Extrusion) is an advanced metal processing technique used to refine grain structure.	✓ High-Pressure Torsion (HPT) is a severe plastic deformation (SPD) technique applied to metal disks.	✓ Achieves very high plastic strain without major geometric changes. Industrially viable for continuous production of

✓ It produces ultrafine-grained (UFG) or nanostructured materials. A billet is pressed through two channels of identical cross-section intersecting at an angle (usually 90°–135°). ✓ Severe shear deformation occurs at the intersection corner. Since both channels have the same cross-section, the billet's external dimensions remain unchanged. ✓ This allows multiple extrusion passes to accumulate very high plastic strain. ECAP mainly produces intense simple shear deformation. ✓ The intersection angle controls strain intensity. Multiple passes (extrusion cycles) increase total strain. Much higher strain is achieved compared to conventional rolling or forging. ✓ Formation of elongated shear bands and low-angle subgrain boundaries. Increase in dislocation density. Low-angle grain boundaries convert into high-angle grain boundaries (HABs). ✓ Ultrafine or nanometer-sized equiaxed grains. No rotation between passes; elongated grain structure remains. Produces more equiaxed grains. Promotes homogeneous microstructure quickly by activating different slip systems. ✓ Mechanical Property Improvement-Significant increase in: Hardness, Strength, Wear resistance, Fatigue resistance Often improves toughness and	✓ It subjects materials to intense compression and torsional strain to produce ultrafine-grained (UFG) structures. ✓ A small metallic disk is placed between two anvils. ✓ A high compressive force is applied. ✓ One anvil is rotated relative to the other, imposing severe torsional deformation. ✓ This generates extremely high shear strain within the material. ✓ Grains are refined to the nanometer scale. ✓ Dense dislocation networks are formed. ✓ Low-angle boundaries transform into high-angle grain boundaries. ✓ A homogeneous ultrafine-grained microstructure is achieved. ✓ Significant improvement in hardness and strength. ✓ Enhanced ductility and overall mechanical performance. ✓ Production of bulk nanostructured materials with superior properties. ✓ Consolidation of metal powders into dense UFG components without melting. ✓ Synthesis of new materials such as high-entropy alloys and metal matrix nano-composites. ✓ Development of materials for hydrogen storage, photo-catalysis, and tribological uses. ✓ Processing of magnesium alloys for potential biomedical applications.	high-strength metals and composites. ✓ Layers are bonded and reprocessed to accumulate large strain. Forms layered structures with enhanced mechanical properties. ✓ More suitable for bulk sheets compared to Equal Channel Angular Pressing (ECAP), which is better for billets. ✓ Two metal strips are: Degreased, Wire-brushed, Removes oxide layers, Increases surface roughness for strong bonding. ✓ Cleaned sheets are stacked together, Stacked sheets are rolled together, Typically ~50% thickness reduction per pass, Forms a solid bonded sheet. ✓ The bonded sheet is cut into two halves (or required lengths), Cut pieces are stacked again in original configuration. Doubles the number of layers, Adds additional plastic strain., Leads to ultra-high strain accumulation. ✓ Each rolling cycle increases plastic deformation, Produces extremely high cumulative strain, Leads to ultrafine grain formation and strengthening. ✓ Process carried out at elevated temperatures, Temperature kept below recrystallization temperature, Strong bonding, Maximum strain retention, Prevention of grain coarsening. ✓ Formation of elongated, pancake-shaped grains, High dislocation density develops, Transformation of low-angle boundaries to high-angle grain boundaries. ✓ Final structure: Sub-micron or nanometer-sized grains, Layered ultrafine-grained

ductility compared to conventional processing. ✓ Suitable for aluminum, copper, titanium, and their alloys. Can also consolidate nanopowders. Role in Severe Plastic Deformation (SPD).	✓ Industrial scalability remains a major challenge. ✓ ECAP is a leading SPD technique. Produces bulk nanostructured materials. Bridges traditional metallurgy with nanotechnology. ✓ Advanced structural materials, Aerospace and automotive components, High-strength lightweight materials.	microstructure. Dramatic increase in: Hardness, Strength, Strength may increase several times compared to initial material. ✓ May slightly reduce ductility, Enables low-temperature superplasticity. RB stands out for continuous sheet production and composite manufacturing.

Carl Zeiss optical microscopy software was used to examine the microstructure of the material before and after ECAP processing. To evaluate the mechanical properties of the alloy, mechanical tests such as microhardness measurements and tensile tests were performed on both the unprocessed and processed samples [58]. The microhardness of the samples was evaluated using a Vickers microhardness tester. The Vickers hardness values (Hv) were obtained by applying a load of 50 g for 15 seconds in accordance with the ASTM E384 standard. For each sample, 12 hardness readings were taken. The average microhardness was then determined by discarding the highest and lowest values and calculating the mean of the remaining 10 measurements. To determine the ultimate tensile strength (UTS) and elongation to failure (ductility) of both unprocessed and processed samples, tensile tests were performed at room temperature using a universal testing machine at a constant crosshead speed of 0.1 mm/min [59]. For tensile evaluation, both unprocessed and processed materials were machined into specimens in accordance with the ASTM E8 standard. The ECAP-processed specimens were prepared parallel to the processing direction. In each condition, three specimens were tested to ensure repeatability, and the average values were reported (table 4).

Table 4. ECAP Die Configuration and Processing Conditions [60].

S.N.	Parameter	Description/Value
1.	ECAP Die Design	Split type design with align pins
2.	Channel Diameter	12 mm-18 mm
3.	Internal Angle (Φ)	90º-120º
4.	Outer Arc Curvature (Ψ)	0º-20º
5.	Equivalent Strain per Pass	0.687-0.799
6.	Die Material	H11 tool steel
7.	Die Hardness	55 HRc
8.	Heating Provision	Holes for heating coils
9.	Processing Equipment	45-ton Universal Testing Machine (UTM)
10.	Die Alignment	Align pins for proper alignment

The measurement of crystallographic orientations on the surface of a material. The digitized orientation data are analyzed to identify the grain structure and are subsequently displayed as crystal orientation maps. The data analysis initially involves detecting grain boundaries, followed by the identification of individual grains [61]. Once the grain morphology is determined, the uniformity of grain size can be evaluated and structural parameters associated with the material's physical properties can be estimated.

The paper presents techniques for imaging and quantitatively characterizing the grain boundary structure in metals using data obtained from electron backscatter diffraction (EBSD). These approaches were applied to copper samples processed through equal-channel angular pressing (ECAP).

4. Results and Discussion

Existing studies on ECAP processing suggest that optimal mechanical properties can be obtained by deforming the material at the lowest feasible temperature. Accordingly, efforts were made to process the material at the minimum possible temperature. The material was successfully processed at 200 °C for up to four passes following route BC without any failure. Processing was discontinued after four passes because, in route BC, the deformation re-establishes an equiaxed microstructure in all three planes after every four consecutive passes. In the homogenized state, uniformly sized grains were observed as a result of recrystallization, with an average grain size of about 180 µm. It was noted that ECAP processing resulted in substantial grain refinement in the alloy. Under this condition, the grain structure was refined through the formation of subgrains. The development of these new subgrains led to a more refined microstructure [62]. A significant volume of shear bands was also observed. The shear bands were oriented almost parallel to the processing direction, with a measured size of approximately 2 µm at this stage. After the fourth pass, a homogeneous and equiaxed microstructure was obtained. In this study, route BC was utilized. It should be noted that, in route BC, the deformation re-establishes an equiaxed structure in each plane after every four successive passes, with deformation occurring in all three planes. Additionally, route BC processing produces shearing over a wider range of angles compared to other processing routes. In the homogenized state, the alloy exhibited a microhardness of 95 Hv. Following ECAP processing, the microhardness increased to 180 Hv. A substantial improvement in microhardness was observed after ECAP. In the homogenized condition, the alloy had an ultimate tensile strength of 120 MPa [63]. After ECAP processing, the ultimate tensile strength increased to 205 MPa. A notable enhancement in ultimate tensile strength was observed following ECAP. The enhancement in microhardness and ultimate tensile strength after ECAP processing is attributed to the substantial reduction in grain size along with various strengthening mechanisms. These include (i) grain refinement strengthening, (ii) strain or work hardening, and (iii) precipitation strengthening.

Materials produced through SPD processing typically exhibit high dislocation densities, non-equilibrium grain boundaries, and other microstructural characteristics resulting from severe plastic deformation. The ultrafine grain sizes and elevated defect densities impart significantly greater strength compared to their coarse-grained equivalents [64]. Conversely, these microstructural characteristics can also contribute to a reduction in ductility. Materials with high strength generally tend to display lower ductility, regardless of whether the strength is obtained through compositional variations, thermo-mechanical treatments, phase transformations, or other approaches. In general, it is expected that materials processed through SPD will exhibit a similar trend. However, it should be emphasized that SPD processing decreases ductility to a lesser degree compared to conventional deformation methods such as rolling, drawing, and extrusion. Equal-channel angular pressing is carried out by repeatedly forcing an ingot through a specially designed die consisting of two channels with identical cross-sections that intersect at an angle of 120°. Each pass through the die introduces an additional effective strain of about 0.667. For materials that are difficult to deform, the process is carried out at elevated temperatures [65]. Processing at higher temperatures places specific demands on the heat resistance and durability of the die. Substantial microstructural refinement can be readily achieved in both pure metals and alloys through ECAP. However, obtaining homogeneous ultrafine-grained (UFG) nanostructures with high-angle grain boundaries necessitates careful control of the equal channel angular processing parameters.

A uniform ultrafine-grained (UFG) microstructure can be achieved in alloys after four to six passes using route BC. In this route, the billet is rotated by 90° in the same direction about its longitudinal axis between successive passes. The evaluation of shearing behavior for various processing routes shows that route BC restores the shape of an initially cubic element in the unpressed specimen after four passes through the die, resulting in a homogeneous and equiaxed microstructure [66]. Mechanical modeling of ECAP has demonstrated that contact stresses within the die play a critical role in the development of SPD processing. Studies examining the effect of friction between the deforming billet and the die walls have revealed that the shear plastic strain during ECAP may be distributed non-uniformly throughout the processed specimen. By integrating experimental work with finite element modeling (FEM), it is possible to improve microstructural uniformity and optimize friction conditions. The fundamental concept of SPD processing is that the material undergoes an extremely high strain while maintaining its overall dimensions unchanged. Therefore, SPD processing is fundamentally different from conventional methods such as extrusion, rolling, and drawing, where the applied strain is accompanied by a decrease in the cross-sectional area of the workpiece. ECAP employs relatively large billets, and the technique can be scaled up to manufacture bulk specimens appropriate for industrial use. The ECAP process subjects the material to extremely high strain, thereby generating a substantial density of dislocations within the sample [67]. Following one pass, the microstructure is composed of elongated subgrain bands bounded by low-angle misorientation boundaries. With additional passes, the structure progressively transforms into a distribution of ultrafine, nearly equiaxed grains separated by high-angle grain boundaries.

The microstructure formed during ECAP progressively develops into a fairly homogeneous distribution of equiaxed grains bounded by high-angle grain boundaries. After a single pass, a banded subgrain structure is distinctly observed, with the bands closely oriented along the shear direction. However, this structure changes rapidly, resulting in an array of nearly equiaxed grains after four passes. The shear direction becomes indistinguishable after further processing. The progression of the microstructure is also reflected in the steady increase in the proportion of high-angle grain boundaries. These observations indicate that ECAP processing offers two important advantages for producing materials with exceptional properties [68]. First, it is well recognized that ECAP produces arrays of ultrafine grains, generally within the submicrometer range. These grain sizes are significantly smaller than those obtained through conventional thermomechanical processing methods. Second, there is clear evidence that the grain boundary character distribution evolves from mainly low-angle boundaries during the early stages of ECAP to relatively high proportions of high-angle boundaries after multiple passes and the application of substantial plastic strain. Low-angle boundaries show minimal or no grain boundary sliding; therefore, superplasticity necessitates a sufficiently high fraction of high-angle boundaries. The distinctive grain refinement mechanism in magnesium processed by ECAP is linked to a heterogeneous grain structure characterized by a wide range of average grain sizes and grain size distributions. Processing through HPT is generally more efficient than other techniques in achieving grain refinement and structural homogenization, although instances of localized deformation have been reported. Grain refinement markedly enhances the mechanical properties of magnesium and its alloys [69]. Fine- and ultrafine-grained magnesium produced through SPD exhibit high strength along with remarkable ductility. There is an apparent tendency for corrosion resistance in magnesium and its alloys to improve as grain size decreases. The majority of investigations indicate enhanced corrosion resistance following SPD processing. Reports indicating reduced corrosion resistance after SPD are generally associated with ECAP-processed samples where grain refinement was insufficient and/or the microstructure remained non-uniform. Biocompatibility assessments and in vivo studies show that SPD processing does not have any adverse impact on the biological response of magnesium.

5. Conclusion

In this study, the Al alloy was processed using ECAP with a die having an internal channel angle (Φ) of 120°. The processing followed route BC. Microstructural characterization and mechanical property evaluation were conducted both before and after ECAP processing. The Al alloy was successfully processed at 200 °C for up to four passes. In the homogenized state, coarse grains with an average size of about 180 μm were observed. Following ECAP processing, marked grain refinement occurred, reducing the grain size of the alloy to approximately 2 μm. Both the microhardness and strength of the alloy increased after ECAP processing. In the homogenized condition, the alloy exhibited a microhardness of 95 Hv, which rose to 180 Hv following ECAP. Similarly, the ultimate tensile strength in the homogenized state was 120 MPa. The ultimate tensile strength of the alloy increased to 205 MPa. In this review work, the finite element method was employed to obtain valuable insights into the plastic strain distribution within the material extruded through the ECAE die. From a wider viewpoint, it is evident that deformation becomes more complex when using a two-turn 90° die compared to a conventional ECAE die.

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