

A Review on Characterization of Mechanical Behavior of AA5083 Through Equal Channel Angular Pressing at Different Channel Angles

Nagendra Singh^{1*}, Manoj Kumar Agrawal², Sanjeev Kumar Verma³, Ashish Kumar Tiwari⁴

Abstract

Materials that have been enhanced through traditional techniques like strain hardening, the addition of solutes, altering grain size through precipitation and refining are commonly utilized in industrial applications. However, there is a restriction on the extent of deformation that these traditional techniques can impose on a material. This research centered on examining the primary mechanical characteristics of aluminum alloys when polycrystalline materials incorporate an extremely fine grain size. By producing a high density of dislocations and then rearranging these dislocations to generate an array of grain boundaries, a high strain rate has an effect on the microstructure of aluminium alloys, converting coarse grains into ultrafine grains. Equal channel angular pressing is a manufacturing technique wherein a metal undergoes significant plastic deformation via simple shear, with no concurrent alteration in cross section of specimen with dimension. Using this technique, polycrystalline materials can contain an ultrafine grain structure. Instances are provided to illustrate the microstructural changes brought about by the ECAP process, as well as the resulting superplastic ductility achievable at extremely high strain rates. The microscopic structure and mechanical properties of an Aluminum alloy processed through ECAP, with a focus on varying channel angles like as (90⁰, 120⁰). The utilization of ECAPed to the creation of an ultrafine grain structure in A5083, enhancing its formability. This material has established its reputation as a cost-effective, durable, lightweight option that enables achieving higher speeds. The mechanical characteristics of the samples were assessed at varying channel angles, and a comparison was made between tensile strength, misorientation angle, and hardness. The findings indicate that the processed samples exhibit reduced strength when compared to different channel angles like as 90⁰ and 120⁰. ECAP was conducted using Route A, with a radius of curvature 20⁰ employed for up to four passes.

Keywords: ECAP; AA5083; microstructure; ultra fine grains; die geometry

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INTRODUCTION

Solid materials change from one state to another via a phenomenon known as deformity. Solid metals have the capacity for plastic deformation, allowing them to be reshaped into intricate forms to achieve the required shape and essential characteristics. Deformity techniques are frequently combined together various processes like casting, machining, grinding, and heat treatment. These processes take place as part of the process of converting raw materials into finished components. Deformation processes are typically categorized into two main types like bulk forming processes and

sheet forming processes [1]. Bulk forming processes typically utilize input materials in the form of billets, rods, and slabs, whereas sheet forming processes primarily involve input materials in the form of sheet blanks. Deformation processes function by subjecting metal to enough stress to induce plastic flow, resulting in the required shape. Additionally, these procedures modify the grain sizes of the materials and introduce plastic deformations. Among the deformity technique commonly employed are rolling, extrusion, forging, and wire drawing. The focus of this study is directed toward the extrusion process. Superplasticity refers to the capacity of a metals to elongate significantly under extend without experiencing necking [2]. Superplasticity is typically associated together sizes of fine grain within the range of 1 to 10 micrometers. Experiments have successfully achieved even finer grain sizes, nanometer range in aluminum based alloys through the application of intensive plastic straining techniques like equal channel angular pressing.

Conventional processing conditions do not enable the attainment of superplastic characteristics in aluminum alloys. Superplasticity is defined as the capacity of a material to go through a lot, uniform, neck-free tensile deformity, often exceeding elongation, before failing at a temperature far lower than its melting point (T_m) [3]. The mechanisms of deformation are within the range of grain boundary sliding, necessitating a size of fine grain $10\ \mu\text{m}$, elevated operating temperatures ($0.9\ T_m$), and a less strain rate for certain aluminum alloy materials.

The alloy composition involves a significant addition of zirconium, resulting in the dispersion of exceptionally fine Al3Zr particles. These components help to stabilize the wrought structure that both hot rolling and cold rolling produce, effectively inhibiting recrystallization until the initiation of the superplastic forming process. The automotive sector is placing a growing emphasis on the utilization of aluminum alloys to reduce weight, thus enhancing both performance and fuel efficiency [4]. Nevertheless, when contrasted with steel, aluminum alloy sheets exhibit reduced formability during cold stamping procedures. Certain aluminum alloys provide an alternative method where they can undergo significant deformation at elevated temperatures through a process known as superplastic forming. While it is possible to attain a fine grain size in aluminum alloys through extensive thermomechanical processes, this approach is characterized by high costs, and longer forming times are caused by the low deformity rate of strain. In Figure 1 showed all ECAP method is frequently used to promote the reduction of grain size at the sub-micrometer or nanoscale scale.

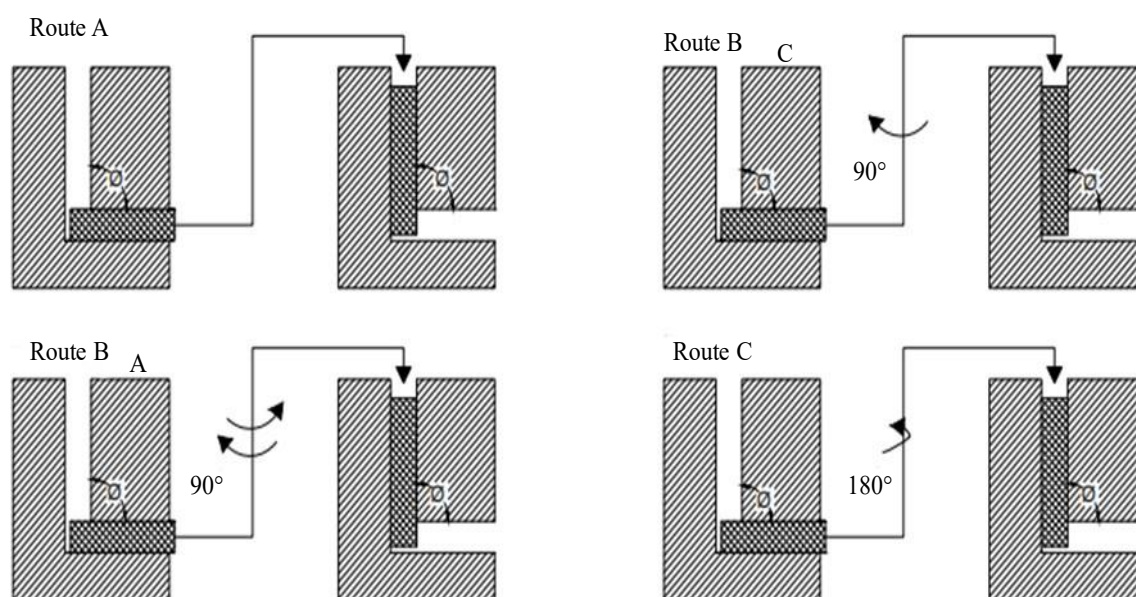


Figure 1. Schematic illustration of different routes [5].

Table 1. Different ECAP Routes [6].

S n.	Various passes	Explanation of different processes
1	Route – A	The billet remains stationary without rotation.
2	Route – B _A	The billet undergoes a counter-clockwise 90 ⁰ rotation on even number of passes and a clockwise 90 ⁰ rotation on odd number passes.
3	Route – B _C	It is rotated 90 ⁰ anticlockwise direction after every passes.
4	Route – C	It is rotated 180 ⁰ after every passes.

Table 2. Provided information on the AA5083 chemical composition [8].

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Sn	Ti	Ca	Al
Wt%	0.08	0.24	0.01	0.73	4.44	0.11	0.018	0.00	0.007	0.014	Balance

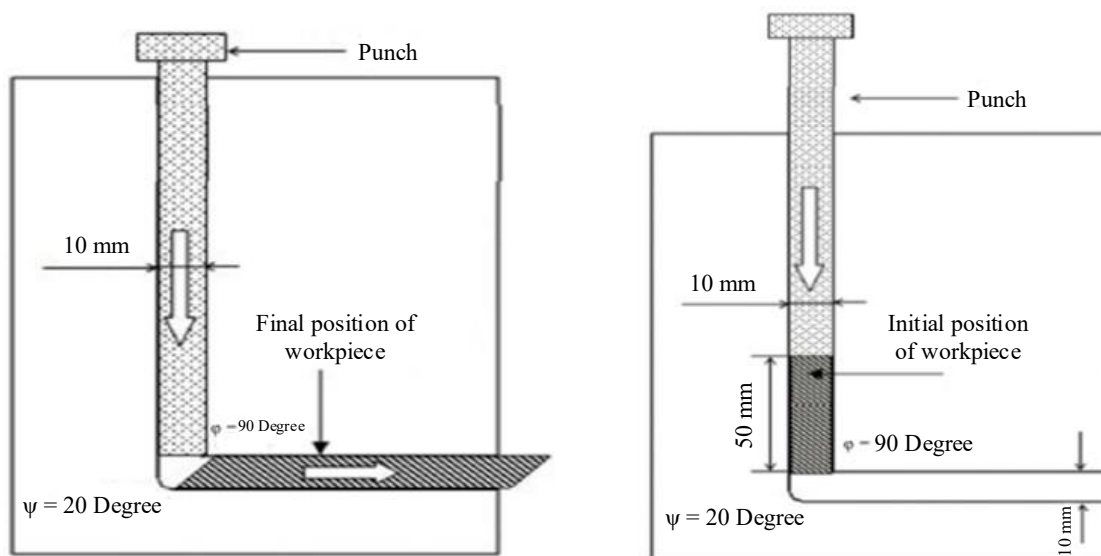


Figure 2. The final arrangement of the ECAP setup and initial configuration of the billet after processing with the die [9].

Superplasticity has been employed in shaping complex components from sheet metal due to its significant elongation capabilities mentioned in table 1. This interest is a result of experimental results showing that decreasing grain size can increase the superplastic strain rate and decrease the superplastic temperature. Materials that undergo processing by ECAP have the capacity for superplastic behavior, particularly at extremely high strain rates and in cold environments [7]. A specimen with 50 mm in length and 10 mm in diameter describe an alloy of aluminium 5083 mentioned in table 2, underwent ECAP for a total of four passes using Route A. The aluminum alloy originally arrived in plate form, which was subsequently cut into 50 mm lengths. Further machining of the plate yielded 10 mm rods with a length of 50 mm.

Prior to the ECA procedure, the specimens were subjected to annealing at a temperature of 450 °C and employed molybdenum disulfide as a lubricant. The lubricant was behaviour to minimize friction during the process, being utilised on the punch, billet, and channels. For the ECAP experiment, split dies featuring a channel width of 12 mm, a radius of curvature of 20⁰ and an inner angle of corner 90⁰ & 120⁰ were applied. The experiment was carried out using a UTM with a more capacity of 60 tons. The sample underwent pressing for a total of four passes as route A. The sample remains stationary not any rotation between passes. Tensile testing was conducted on the pressed sample after each pass along route A using a tensometer with a capacity of 2 tons [10]. The preparation of the tensile sample adhered to the ASTM E8 standard. The sample was extracted from the central portion of the sample, oriented along its length. A 200 kV Philips microscope was used to analyse the precipitate and matrix's Selected

Area Diffraction pattern. The centre of the pressed billet's cross-sectional plane was used to create samples for transmission electron microscopy. The billet was then polished, and its thickness was manually decreased to about 100 microns, utilizing disc polishers in conjunction with wet polishing papers ranging from 80 to 1800 grades. Using a dual jet polisher, the polished sample was further thinned until perforation was obtained, employing an electrolyte made of 33% nitric acid combined with methanol at a temperature of $-40\text{ }^{\circ}\text{C}$. The ECAP process, in order to learn more about the distribution of grain orientations, samples were analysed using SEM and TEM [11]. On the cross-sectional area of the pressed sample, measurements and evaluations of the pressed billet's deformation characteristics were made. TEM examinations were also used to look at the evolution of the substructure inside the grain.

Deformation Processes

The Hall-Petch relation demonstrates that the yielding strength rises with an increase in the grain size refinement. This suggests that the metallic properties of a material will vary depending on alterations in its grain size. To enhance the properties of a metal, it is crucial to employ techniques that can modify its grain size. Limitations have been documented in traditional metallurgical processes like rolling, forging, drawing, and extrusion, because they cannot make metals with grain sizes that are substantially smaller than the dimensions of engineering micro-components. In non traditional metal forming operations, the extent of plastic strain generated is frequently restricted. Currently, there is considerable interest in materials characterized by structures of grain in at the nanoscale range. Nanostructural materials are intriguing in the engineering industry because they can lower the physical dimensions of various mechanical devices [12]. Effective techniques for shaping nanocomponents in engineering are essential for constructing devices at the nanoscale. Integrating the production of nano metals with significant challenges, particularly in terms of the cost associated with creating numerous raw components for functional nanomaterials. The duration needed to complete any engineering task at the nano scale is also a notable challenge. These difficulties frequently lead to diminished mechanical and electrical properties, as well as resulting in spatial distortions and suboptimal thermal performance, all of which compromise the overall system's efficiency. An alternative approach involves employing the top-down method, wherein bulk materials are transformed into nanoscale structures through conventional shaping techniques during micro and nanoscale systems and devices. Severe plastic deformation processes have been demonstrated as a significant method for producing bulk nanostructured samples and billets from various alloys [13]. The initial advancements into nanostructured materials produced through Severe plastic deformation techniques were conducted by Valiev and his colleagues more than a decade ago.

Severe Plastic Deformation

The various application of plastic straining under large applied pressure was described as Severe plastic deformation. Severe plastic deformation techniques are utilized to convert metals and alloys characterized by coarse grain structures into materials that exhibit ultrafine grain structures. The ultrafine-grained materials obtained exhibit enhanced Characteristics related to both mechanical and physical aspects., rendering them suitable for a broad area of commercial applications. Severe plastic deformation represents an innovative technique of metal forming capable of inducing material plastic deformation without significantly altering the geometry of the billet [14]. This strategy covers all metal forming techniques that depend on repeated reversed straining and simple shear, with the aim of retaining the billet's original shape. There is significant ongoing interest in the production of metals featuring ultrafine grain sizes. This interest stems from two key factors. It is feasible to enhance a material's strength at lower temperatures based on the established Hall-Petch relationship. This relationship suggests that the square root of grain size has an inverse with strength. Maintaining an ultrafine grain size at elevated temperatures, particularly in the range where diffusion-controlled mechanisms come into play, offers the chance to achieve a superplastic forming capacity at high strain rates. This is due to the fact that in superplastic deformation, The square of the grain size has an inverse relationship with the flow rate. Numerous techniques are currently accessible for achieving metals characterized by exceedingly minute grain sizes, usually falling within the range of nanometers [15].

Nevertheless, up to this point, these processes have not been advanced to a level where they can generate substantial bulk samples of any residual porosity. Due to these constraints, focus has shifted towards alternative techniques such as ECAP and HPT. These methods involve the introduction of ultrafine grains into a material through rigorous plastic straining. In practical applications, ECAP seems to offer more versatility compared to HPT. This is due to the potential to upscale the process for industrial use, involves the development of multiple pass facilities that can pass the ECAP die once while achieving high stresses. The fundamental concept behind ECAP is that a metal undergoes deformation via a simple shear process, wherein the shearing occurs without any simultaneous alteration in measuring the specimen cross-sectional area. This paper investigates the fundamental principles of the ECAP process, specifically focusing on the deformations that occur when a sample passes through a standard ECAP die with a single shearing plane, as well as any distortions brought on by rotating the sample at any point during each pass [16]. It was advised to adopt the acronym ECAP for denoting this process, and in this report, it will be employed exclusively.

Geometry of Various Die Angles

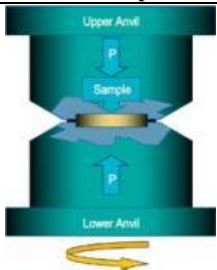
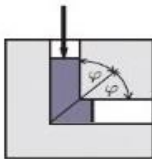
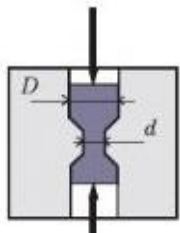
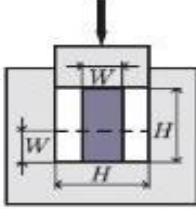
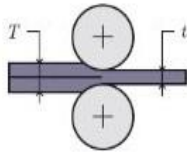
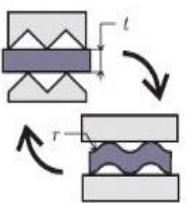
This research revolved around the impact of simultaneous shear deformation and significant hydrostatic pressures on solids, applications of these principles include the high-pressure torsion method, which was introduced in the mid-1980s, and the technique known as equal channel angular pressing. The latter was developed by V.M. Segal and his colleagues in Minsk during the early 1980s. A shift occurred in the 1990s when publications and summaries started to emerge, detailing the possibility of employing ECAP to generate metals characterized by ultrafine grains and sub-micrometer dimensions [17]. These publications sparked a robust and continuous interest in the scientific exploration, advancement, and eventual industrial application of the ECAP process. Thorough experiments have unveiled two significant characteristics linked to materials that undergo ECAP. ECAP initially creates a series of closely packed subgrain bands, but as the deformation progresses, this arrangement evolves into an array of extremely fine equiaxed grains, separated by boundaries with significant misorientation angles. The specific microstructure created by ECAP is contingent upon the processing routes chosen. Thermal stability is a crucial characteristic for materials that have undergone severe plastic deformation. A refined microstructure should retain a reasonably refined form even when subjected to heating, at a minimum up to a certain temperature $0.5 T_m$. Numerous investigations have documented the occurrence of superplastic behavior in Al alloys subjected to ECAP [18]. This paper primarily focuses on the microstructure and mechanical characterization examinations of samples subjected to ECAP pressing via a specific route A at 90° , 120° . This paper primarily focuses on the examination of microstructure and mechanical properties of samples that have undergone ECAP processing via Route A Route A at 90° , 120° at specific conditions.

Equal Channel Angular Pressing Process

Equal channel angular pressing has been employed for the production of materials with ultrafine-grained structures. ECAP is a convenient forming method for extruding materials using specially designed channel dies, all while preserving the material's geometry with minimal alteration. Utilizing the ECAP method for extrusion allows for the acquisition of a fine-grained structure in larger quantities. Significant progress has been made in the evolution of ECAP, which has transformed from a conventional metal processing technique into a well-established method for achieving ultrafine grain refinement. The process of achieving ultrafine grain refinement has resulted in improvements in the strength and toughness of alloys [19]. Currently, Among all the methods for severe plastic deformation processing, ECAP is the most advanced and well-established. Processing bulk materials through ECAP holds substantial industrial importance. The metal deformation and modifications in microstructure, can be utilized to create valuable tools for advancing both severe plastic deformation techniques and the enhancement of existing ones. Numerous factors affect the mechanical and physical properties of all crystalline materials, the methods for severe plastic deformation processing, ECAP is the most advanced and well-established. To alter the workpiece during the deformation process, ECAP requires considerable plastic deformation [20]. The workpiece must pass through two intersecting channels, typically at an angle of either 90° or 120° both having identical cross sections in a die, as depicted in Figure 2. ECAP is an effective method for inducing significant simple shear deformation in a material

by maneuvering it around a corner created by the intersection of two channels with the same cross-sectional shape, as depicted in Figure 3. The material can undergo the same process multiple times by being passed through the same die repeatedly, thereby accumulating greater plastic deformation. Segal used the method of ECAP to alter the texture of processed metals. Microstructural analysis conducted on materials subjected to this process revealed that the grain size was to the nanoscale level of refinement. During the ECAP procedure, different strain rates were used to examine how the microstructure of the material changed over time mentioned in Table 3 [21]. The orientation of the crystal grains in the microstructure is affected by the combination of shearing and bending deformations that occur during ECAP. In addition to the grain crystal orientation, the presence of low-angular boundaries and the critical angle for dividing grains also exert a notable influence on the flow of stress during ECAP.

Table 3. Various Severe Plastic Deformation Techniques for Grain Refinement [22].

S.N.	Process name	Schematic representation	Equivalent plastic strain
1.	HPT, by Valiev, 1997		$\epsilon = \frac{tgy}{\sqrt{3}}$
2.	ECAP by Segal, 1977		$\epsilon = n \frac{2}{\sqrt{3}} \cot \phi$
3.	CEC by J. and M. Richert, Zasadzinski Korbel, 1978		$\epsilon = 44 \ln \left(\frac{D}{d} \right)$
4.	MF by, Ghosh, 1988		$\epsilon = n \frac{2}{\sqrt{3}} \ln \left(\frac{H}{W} \right) W$
5.	ARB by, Saito, Tsuji, Utsunomiya, Sakai, 1998		$\epsilon = n \frac{2}{\sqrt{3}} \ln \left(\frac{T}{t} \right)$
6.	RCS by, Zhu, Lowe, Jiang Huang, 2001		$\epsilon = n \frac{4}{\sqrt{3}} \ln \left(\frac{r+t}{r+0.5t} \right)$

The characteristics of materials that have undergone ECAP are the behaviour of plastic deformation is closely related that occurs during pressing [23]. The properties of these materials are primarily controlled by factors like the inner die angle φ , the outer die angle ψ , material characteristics like strength and hardening behaviour, and process variables like lubrication and deformation speed all play a major role in determining how these materials behave. Since the billet travels in the vertical channel as a single piece, all deformation is confined to a limited region near the intersection point of the channels. The metal experiences a basic shearing strain under relatively low pressure, which is in contrast to the higher pressures typically seen in traditional extrusion processes. In the process of ECAP, the cross-sectional area of the workpiece remains constant, ensuring that the process can be repeated until the desired grain size level is achieved [24].

METHOD OF IMPOSING AN INTENSE PLASTIC STRAIN IN ECAP Equal Channel Angular Pressing Technique

There are several established techniques for applying strain to metallic samples, such as non traditional technique like rolling or extrusion. However, all of these methods require altering the physical dimensions of the sample. In contrast, ECAP distinguishes itself from these traditional methods because during the straining process, it does not change the sample's cross-sectional dimensions. The three-dimensional illustration displayed in Figure 3 graphically conveys the fundamental idea of ECAP. Inside the ECAP die, the die's centre, two channels with identical cross sections come together [26]. The specimen for testing is prepared to match the dimensions of these channels, and then it is pushed through the die using a plunger. The deformation experienced by the sample while passing through the die is shown in a simplified manner in Figure 4, assuming that the two channels' angle of intersection is 90° . As a result, a straightforward shear is applied at the interface between the two neighboring sections labeled 1 and 2 in Figure 4. Three planes may be seen in the sample at the point where it leaves the die. Plane x is at a right angle to the longitudinal axis of the sample, while planes y and z align with the side and top faces, respectively [27].

The exact von Mises equivalent strain experienced by the sample during its passage through the die is contingent on the specific values of the two angles, denoted as φ and ψ . Since the cross-sectional dimensions of the sample remain unchanged after a single pass through the die, it is feasible to pass the sample through the die repeatedly to accumulate a significant total strain [29]. It can be demonstrated through fundamental principles that the total accumulated strain, denoted as ε_N total, resulting from a series of repetitive pressings is determined by the following relationship by (1) and (2) equation [30].

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

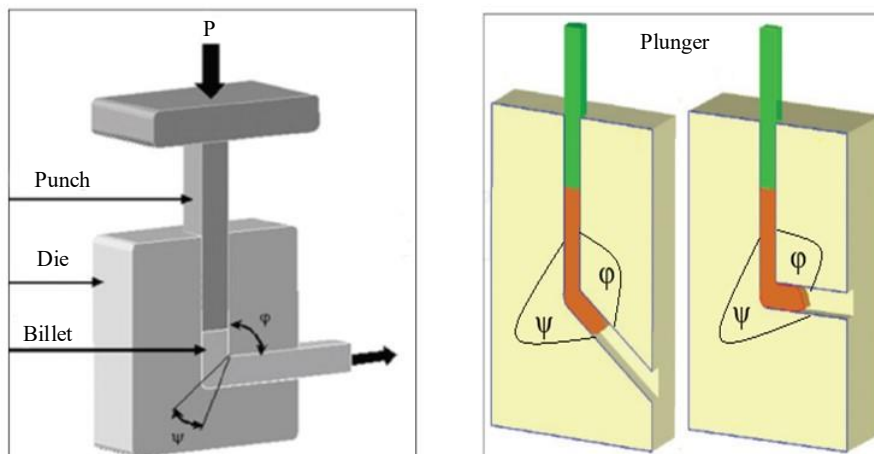


Figure 3. Schematic diagram of an ECAP die and ECAP principles (channel intersecting at 120° and 90°) [25].

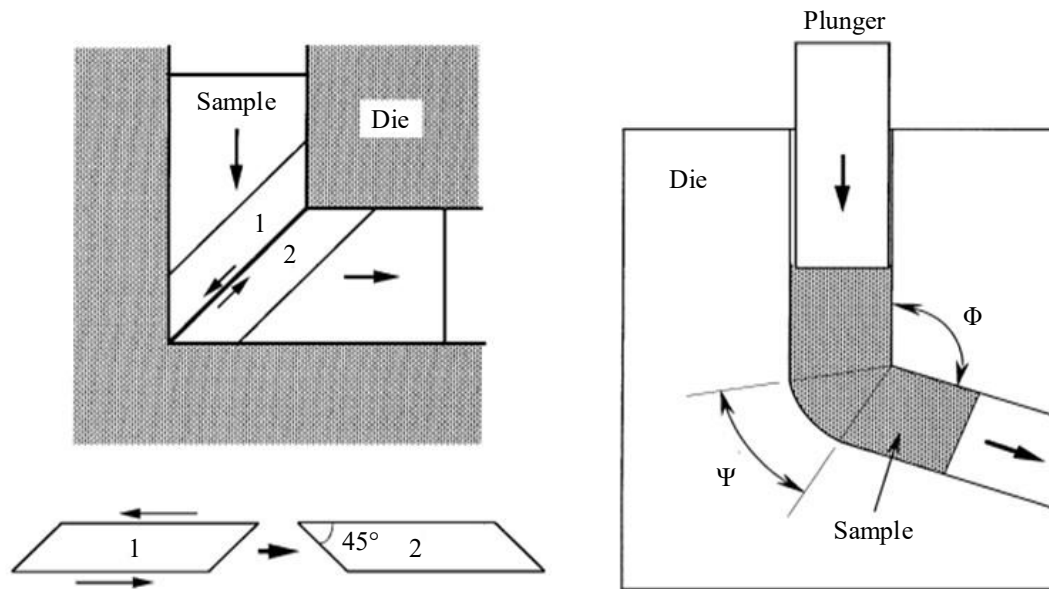


Figure 4. The concept of inducing shear between elements 1 and 2 in the ECAP process, along with a cross-sectional view of an ECAP die illustrating the two internal angles ϕ and ψ [28].

In Equation 1, N denotes the cumulative count of passes through the die. Practical experiments utilizing plexiglass dies and layers of colored plasticine have substantiated the accuracy of this equation, with the exception of regions immediately near the die walls where frictional effects may come into play. Furthermore, this relationship has found substantial support through experiments involving samples featuring grid patterns. Additionally, two-dimensional finite element modeling has confirmed its validity, except in the vicinity of the sample edges [31].

Recently, an alternative expression was suggested for ϵ_N , which is now given as

$$\epsilon_N = \frac{N}{\sqrt{3}} \left[2 \cot \left(\frac{\phi + \psi}{2} \right) + \psi \right] \quad (2)$$

Nevertheless, it can be demonstrated through calculations that Equations 1 and 2 yield the same values for ϵ at the extreme limits of the arc angle, and their disparities are less than 5% for all other situations at any angle of $\phi \geq 90^\circ$ [32]. A similar approach has been developed for determining the strain when the two channels in the die have different cross-sectional dimensions. A comparable method has also been devised for estimating the strain when the two channels of the die possess varying cross-sectional dimensions. Finite element modeling has been employed to assess the importance of any potential space that might emerge between the sample and the die wall at the outer curve where the two channels intersect.

Implication of Angle of Channel ϕ

A comprehensive set of experiments conducted on pure aluminum, using dies with a range of angle ϕ values from 90° to 157.5° , revealed that the formation of an ultrafine microstructure characterized by nearly grain boundaries separating equiaxed grains with significant misorientation angles was most effectively achieved when applying an extremely high plastic strain, with the amount of approaching ϕ very nearly to 90° [33]. When ϕ takes on a value of $\phi = 90^\circ$, according to equation (1), it becomes evident that the strain put on the die during a single pass is nearly equal to 1, regardless of the specific value of ψ . As a result, after the die has been through multiple times, the strain approaches $\sim N$. Findings from finite element modeling indicate a potential issue with dies featuring both $\phi = 90^\circ$ and $\psi = 0^\circ$ and due to the emergence of a small "dead zone" at the sharp outer corner where the two channels meet, which remains void of material.

Effect of Sample Rotation Between Repetitive Pressings

It has been acknowledged that the repeated pressing of a sample through an ECAP die can alter the overall shearing behavior within the crystalline sample when the sample is rotated between each pressing. The concepts behind these four distinct routes are depicted in a diagram in Fig. 4. The cubic element within the left channel traverses the theoretical shear plane, which is depicted in shaded form at the lower left and undergoes shearing, morphing into a rhombohedral shape, as seen in the die's exit channel [34]. Which includes macroscopic grain elongation and the corresponding shearing planes within the individual grains, for each of the three sectioning planes (x, y, and z) as outlined in Fig. 4. Experimental support for the conclusions drawn from Fig. 4. is provided by direct experiments conducted with pure aluminum samples that underwent ECAP, using optical microscopy.

CHARACTERISTICS AFTER EQUAL CHANNEL ANGULAR PRESSING

Microstructural characteristics

Numerous experiments have been carried out to explore the features of microstructures formed in polycrystalline materials when subjected to ECAP, examining how the rotation of the sample affects them using various processing routes. The primary outcome of ECAP is a significant reduction in the average grain size, even after just one pass through the die. Moreover, this grain size reduction seems to be largely unaffected by the pressing speed employed. It is currently widely accepted that the specific microstructural features resulting from ECAP are influenced by the chosen processing route [35]. In practical terms, when the internal angle 90° of the die is set at φ , it has been observed that the most effective pressing condition is achieved through route B_C , wherein the microstructure, as pressed, undergoes the most rapid transformation into a configuration consisting of equiaxed grains divided by grain boundaries featuring high angles of misorientation. Moreover, there is supporting evidence indicating that when employing a die with an angle of $\varphi = 120^\circ$, route A could potentially be more efficient. One potential explanation for this variation has been put forward by studying how the shearing plane interacts with the deformation texture and the crystal structure [36]. Two essential attributes are linked to the establishment of a uniform microstructure through the ECAP process. These properties are associated with the eventual stable grain size obtained through the pressing procedure and the quantity of passes required to achieve a consistent microstructure. Broadly speaking, metals with low recovery rates seem to be particularly suitable for creating exceptionally small grain sizes. However, it may require more passes to obtain uniform arrays of grains in such materials. As an illustration, research has demonstrated that when materials are subjected to ECAP at room temperature using route B_C , the ultimate stable grain sizes are approximately $1.3 \mu\text{m}$, $0.45 \mu\text{m}$, and $0.27 \mu\text{m}$ for pure aluminum, an Al-1% Mg alloy, and an Al-3% Mg alloy, respectively. However, achieving a uniform microstructure necessitates passing these materials through 4, 6, and 8 passes, respectively. The extremely fine microstructure generated in pure aluminum after undergoing 4 passes through an ECAP die at room temperature, following processing route B_C . These planes correspond to the x, y, and z planes as previously defined in Figure 5 [37]. Under these specific conditions, the average grain size following ECAP is approximately $1.3 \mu\text{m}$. This is in contrast to the initial grain size before ECAP, which is approximately 1.0 mm after annealing but before undergoing the ECAP process.

Mechanical Characteristics

Comprehensive experiments have verified that ECAP can be employed to achieve significant superplastic elongations at exceptionally fast strain rates, given the presence of particles, as seen in numerous commercial alloys. These particles play a crucial role in limiting the growth of the ultrafine grains required for superplastic flow at the elevated temperatures necessary for the process [38]. Recent accounts have frequently documented the occurrence of high-strain-rate superplasticity in materials subjected to ECAP processing. This refers to a commercially available Russian alloy known as Al-1420, which demonstrates moderate superplastic elongations following suitable thermomechanical processing. The three lines in the lower left part of the graph represent typical outcomes after the most effective thermomechanical treatment aimed at achieving a grain size of approximately $8 \mu\text{m}$.

Subsequently, tension tests were conducted at temperatures ranging from 768 to 793 K. The remaining data points on the graph demonstrate the remarkable enhancements in ductility that are attained through the process of ECAP, resulting in a reduction of grain size to approximately 1.2 μm . The lower data points at 603 K correspond to samples that underwent pressing at a temperature of 673 K for 4 passes, resulting in a total strain of ~ 4 . On the other hand, the two sets of data on the right in Fig. 5, pertaining to temperatures of 573 K and 623 K, resulting in a total strain of around 12 [39]. The data presented clearly demonstrates a significant enhancement in ductility at higher strain rates of ECAP. Moreover, the superplastic effect is intensified with the application of ECAP to greater total strains. The increase in superplasticity at higher total strains is explained by the requirement for the grain boundaries in the ultrafine-grained material to reach high angles of misorientation.

MICROSTRUCTURE CHARACTERISTICS OF ECAP

Microstructure Before ECAP

The original microstructure of annealed aluminum 5083 is illustrated in Fig. 5 using secondary electron and backscattered mode images respectively [40]. The Linear Intercept technique is employed for the measurement and computation of grain size, resulting in a determined grain size ranging from 80 μm to 90 μm .

The base alloy specimens underwent annealing at 450°C for two distinct time periods, and the resulting changes in hardness along the transverse, longitudinal and cross-sectional planes. There is no substantial alteration in the hardness value between the samples annealed for 1 hour and 2 hours. In the sample from the second hour of annealing, the hardness values exhibit a decreasing trend. As a result, the annealing period for the ECAP experiment is set at one hour. The hardness values exhibit a declining pattern in the sample annealed for 2 hours. Therefore, the annealing duration for the ECAP experiment is set at 1 hour.

Characterization of Mechanical Properties After ECAP at Route A-90⁰

The Vickers microhardness was determined for each pass using the HMV 2000 instrument [42]. A 0.3 kg load was applied, and the test was conducted with a dwell time of 20 s at various locations on the sample. Measurements were conducted at the central section of the circular sample, that is oriented at a right angle to the extrusion plane. With each pass as a result of the highly deformed grain structure, the fragmentation of precipitates, and the formation of subgrains due to the significant strain imposed on the material mentioned in table 4 [43]. There is a strong correlation between strength and hardness, which is visually illustrated in Figure 6.

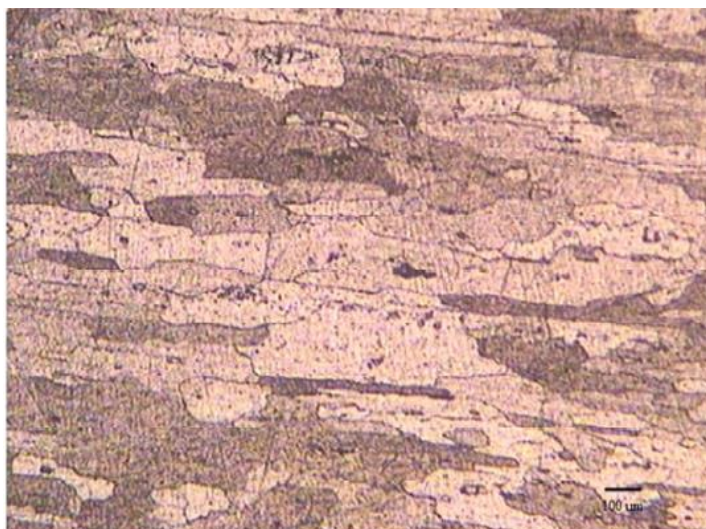


Figure 5. Annealing sample after microstructure at initial condition [41].

Characterization of Mechanical Properties After ECAP at Route A-120⁰

Characterization of microstructural grain

The fourth pass of the crushed billet produced the tiny grains and the elongated shape. Figs. 6,7 and 8 show the microstructure of each direction in the three passes, and ImageJ was used to determine the misorientation angle. Each microstructures misorientation angle is determined. According to the research, increasing the number of passes results in a decrease in the misorientation angle for each segment mentioned in table 5[48]. This demonstrates that the ECAP process causes grain deformation and alignment in a specific direction. Grain refinement occurs during the ECAP process, and due to this increased refinement, for a number of passes, it becomes more difficult to detect individual grains under an optical microscope. To attain finer grain refinement, SEM or TEM can be applied for microscopic analysis. Nevertheless, it's still possible to calculate the misorientation angle [49]. The reduction in misorientation angle following ECAP suggests that the grains are becoming textured and exhibiting a tendency to develop a specific orientation. The reduction in misorientation angle is most significant in the transverse direction, indicating that texture may be more pronounced in this orientation. Additional research on texture is needed to validate these findings [50].

Table 4. The tensile strength and hardness of the material after four ECAP passes using processing route A [44].

ECAP routes for various samples	Tensile strength N/mm ²	Mean hardness values (HV)
1 hr AA5083	308	130
1 st Pass	392	139
2 nd Pass	149	145
3 rd Pass	446	149
4 th Pass	455	154

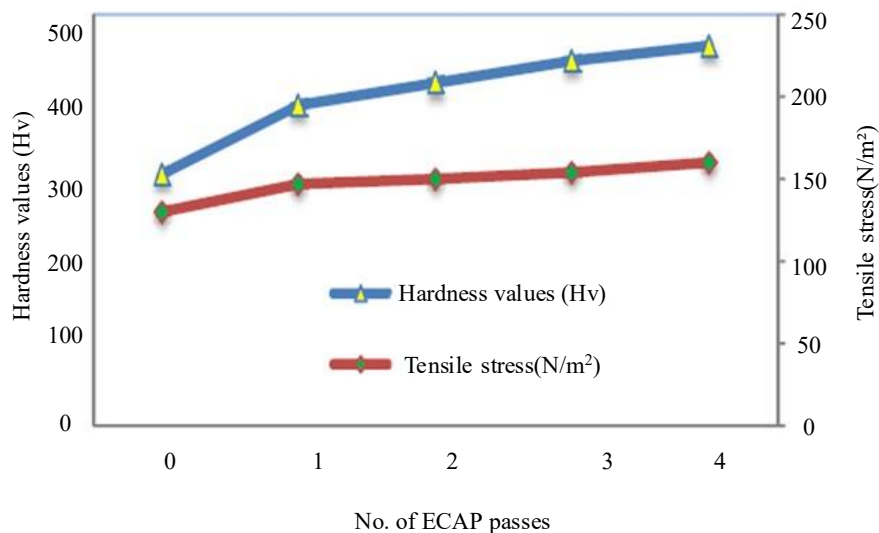


Figure 6. Graph depicting the hardness values and tensile stress for the material after undergoing four ECAP passes using Route A [45].

Table 5. The tensile strength and hardness of the material after four ECAP passes using processing route A [46].

ECAP routes for various sample	Tensile strength N/mm ²	Mean hardness values (HV)
1 hr AA5083	310	130
1 st Pass	392	139
2 nd Pass	402	141
3 rd Pass	417	143
4 th Pass	430	146

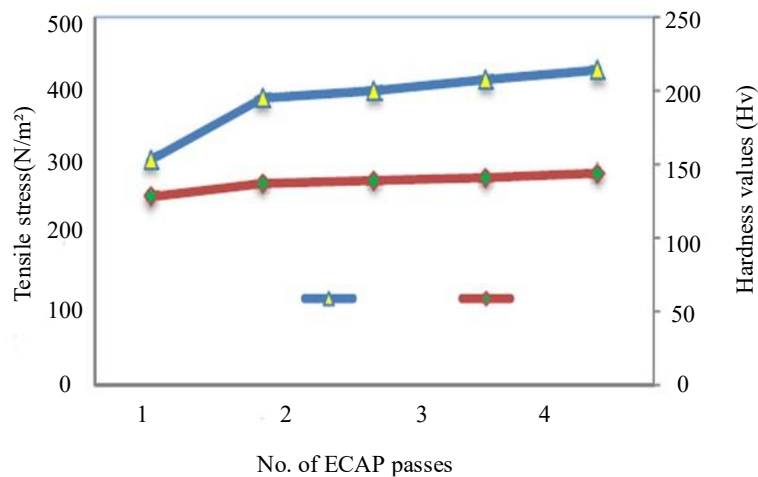


Figure 7. Graph illustrating the tensile stress and hardness values results for the four ECAP passes conducted through Route A [47].

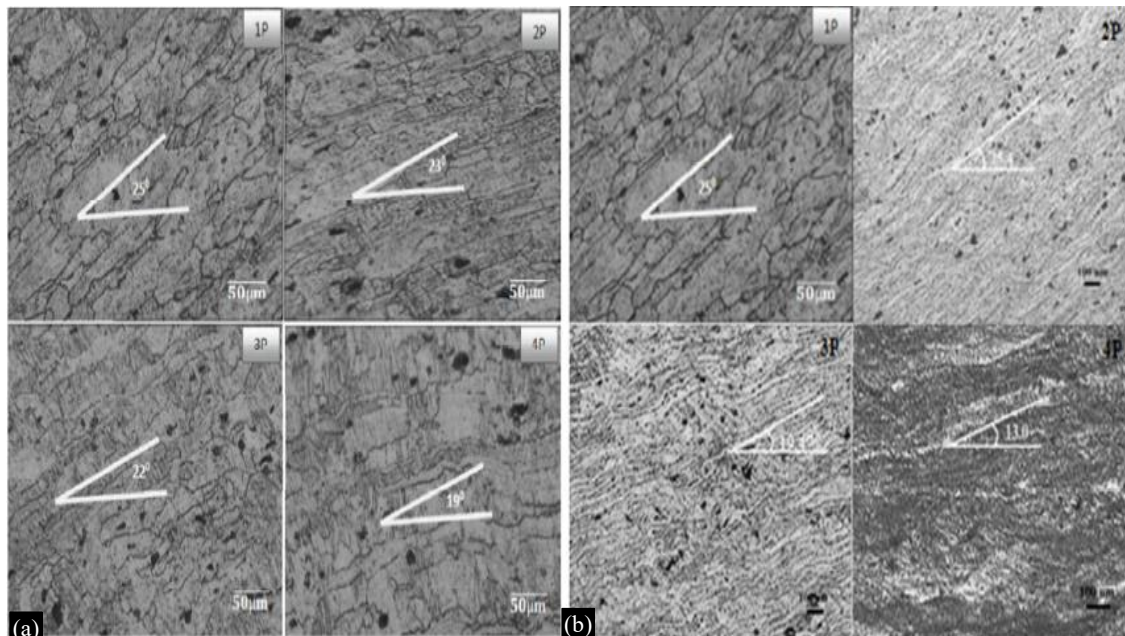


Figure 8. Microstructure after ECAP at (a) Route A-90° and (b) Route A-120° [51].

CONCLUSIONS

Based on the present review, it can be inferred that the application of severe plastic deformation by equal channel angular is a highly beneficial method for enhancing mechanical properties, accompanied by a moderate and a permissible decrease in ductility. Since the cold-worked material had already undergone a significant portion of its permissible plastic deformation via ECAP, the accumulation of dislocations and stretching of electronic bonds had sufficiently impeded dislocation motion and plastic deformation. Consequently, strain hardening diminishes ductility and enhances brittleness. The utilization of ECAP for processing resulted in refinement of grain and the formation of arrays containing ultrafine grains, which are notably smaller compared to those typically generated through conventional thermomechanical processes. ECAP is a straightforward procedure that can be easily implemented with various materials. ECAP subjects a sample to significant plastic deformation via simple shear, all while maintaining the same cross-sectional dimensions. Therefore, multiple pressing cycles can be performed to attain exceptionally large cumulative strains. The resulting microstructure brought about by ECAP is influenced by both the routes, which involves the rotation of the sample during successive pressings, 90° and 120° the angle between the two channels within the ECAP die with corner angle 20°.

Empirical observations demonstrate that the most favorable uniform microstructure, distinguished by equiaxed grains divided by grain boundaries with high angles of misorientation. The ultrafine grain sizes induced by ECAP offer the opportunity to achieve superplastic behavior at extremely fast strain rates. The fourth pass revealed a crack in the material. The samples were subjected to microstructural analysis following each pass. A favourable texture could potentially develop along Route A for both channel angles 90° and 120° given the declining tendency in misorientation angles. The mechanical strength and hardness ratings increased with each succeeding pass. Subsequently, gradual improvements in strength were observed, attributed to the grain refinement mechanism, resulting in finer and elongated grains.

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