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The Effect of Strain Rate on Electrical and Mechanical Characteristics of Pure Aluminum Using Equal Channel Angular Pressing (ECAP)

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***Abstract-* Equal-channel angular pressing (ECAP) is A new engineering technique that can localize microstructure refinement and enhance mechanical characteristics. In order to enhance the microstructure of pure Al with a rectangular cross-section, ECAP was carried out at room temperature.**

During equal-channel angular pressing (ECAP), the effect of severe plastic deformation (SPD) rate on both the electrical (electrical resistance, denoted as (R),Ω and The electrical resistivity denoted as (ρ), Ω.m) and mechanical characteristics (Ultimate Tensile Strength abbreviated as (UTS), MPa and Micro-Hardness measured in Vickers Hardness Number, abbreviated as VHN) of pure aluminum alloy are experimentally investigated.

ECAP was used to improve the pure aluminum alloy's microstructure at room temperature, which had samples with square cross sections. The findings indicate that as the rate of strain decreases from 0.3 to 0.1 s^-1, there is a gradual increase in both Ultimate Tensile Strength (UTS) and hardness, with the highest values observed at a strain rate of 0.025 s^-1.

This study empirically explored the influence of ECAP on the macrostructure, microstructure, mechanical properties, and electrical properties of pure aluminum alloy at different strain rates (s^-1) – 0, 0.025, 0.1, and 0.3. In summary, it was observed that under the optimized ECAP conditions, specifically at a strain rate of 0.025 s^-1, the ultimate tensile strength increased by approximately 266%, micro-hardness by about 210%, and electrical resistivity by roughly 250% compared to the base material. The maximum value of the ultimate tensile strength was equal to 93 MPa, while the maximum value of hardness was equal to 41 VNN, and the maximum value of electrical resistivity was equal to 1.8 Ω.m, which is equivalent to the ratios mentioned above. Additionally, there was notable fragmentation of course second-phase particles and microstructure refinement. Both macrostructure and microstructure examinations revealed locally homogeneous microstructures in the pure aluminum alloy processed via the equal-channel angular pressing (ECAP) technique.

***Keywords-* Equal channel angular pressing (ECAP), macrostructure, Pure Aluminum, macrostructure, microstructure refining, Compression rate, strain rate, Ultrafine Grained (UFG), mechanical properties, The ultimate tensile strength (UTS), Hardness, electrical resistance, The electrical resistivity and Electrical Properties.**

I. Introduction

Pure aluminum, widely used because of its abundance and favorable properties, encounters constraints in certain sectors due to its comparatively modest mechanical attributes, such as strength and hardness. [1–5].

The Mechanical properties and electrical properties are very important properties and improving them increases the applications in which the material is used. Equal Channel Angular Pressing (ECAP) technology is used for this purpose [5–7]. Therefore, this study came to demonstrate the extent of the effect of using this technology with pure aluminum to improve its mechanical and electrical properties.

In response to these challenges and to address these problems, several techniques for treating aluminum alloys have been devised, such as stir friction processing [8] and the Equal-Channel Angular Pressing (ECAP) method [5,8–11].

ECAP entails applying severe plastic deformation to the metal by compelling it to pass through intersecting channels within a die, resulting in alterations to the microstructure of the aluminum. [9,12,13].

The ECAP technique has been demonstrated to be effective in enhancing the mechanical properties of pure aluminum. Substantial plastic deformation refines the microstructure, resulting in improved strength, hardness, and ductility. Furthermore, the ECAP method can also be applied to enhance the mechanical attributes of aluminum alloys. [4,9,14,15].

This flexibility makes it a cost-effective approach for manufacturing high-quality aluminum products. By employing ECAP, manufacturers can overcome the limitations associated with pure aluminum and produce materials with improved mechanical properties. [1,11,14].

Ultrafine Grained (UFG) metals, also known as nanocrystalline or nanometals, exhibit grain sizes ranging from 0.1 to 1 µm, which are significantly smaller than the conventional metal grains that typically range from tens to hundreds of µm. [16–18], this structural modification profoundly impacts various mechanical properties of UFG metals, resulting in a notable strength enhancement of 3 to 5 times [7,18,19].

In recent decades, there has been extensive research into nanocrystalline, and ultrafine-grained (UFG) materials created through severe plastic deformation (SPD) methods [20,21].

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Among the various methods of severe plastic deformation (SPD), one standout approach is the Equal Channel Angular Pressing (ECAP). This technique offers distinct benefits, such as the capability to generate large samples [22] and its potential for practical application [23]. Initially conceived by Segal et al. [13] as a means to enhance ductility, ECAP was further developed by Valiev et al. [24,25].

In this method, as illustrated in Figure 1, a billet is subjected to pressing through a die that incorporates two intersecting channel angles and an outer curved section. This procedure results in an approximate equivalent strain of 1 [17]. An important feature of equal-channel angular extrusion (ECAE) is that it maintains a constant cross-sectional area of the material during extrusion. This property allows for repetitive deformation, facilitating the achievement of a significant total strain [26]. Additionally, materials processed in this way have applications in various fields, including ultra-high-strength materials, smart alloys, and superplastic materials.

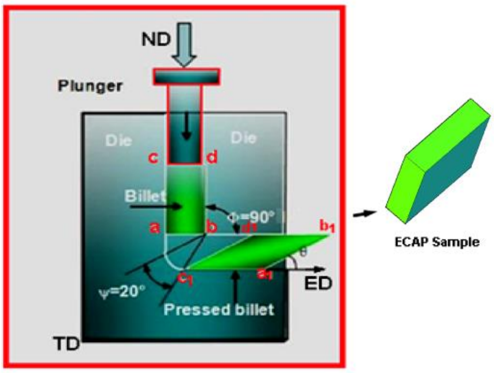

Figure 1. A schematic representation of Equal Channel Angular Pressing (ECAP) at Φ= 90° and at ψ= 20°.

Ultrafine-grained (UFG) materials produced through equal channel angular pressing (ECAP) offer two notable advantages: exceptional strength and the ability to exhibit super plasticity even at lower temperatures and higher strain rates [12,27]. These materials hold significant promise across various applications, particularly in the advancement of microelectronics, informatics, and micro electro-mechanical systems [12,17].

As these advantageous properties become more apparent, it is expected that additional applications will emerge. The corresponding plastic strain, denoted as N and approximately equal to 1.15 in this instance [28,29],[5], can be calculated using the following equation:

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

In this context, N signifies the number of passes. Since modifying the microstructure usually necessitates a strain level of 4–8, the billet must undergo multiple passes through the die. Additionally, during each pass of the Equal Channel Angular Pressing (ECAP), the billet has the opportunity to rotate around its axis (as showed in Figure 2). There are three primary rotation options: A (no rotation), C (180° rotation), and BC (90° rotation in the same direction)[5].

Several researches have discussed the existence of four potential processing routes for Equal Channel Angular Pressing (ECAP) [30,31]. Some researchers have proposed that route BC, which involves a 90° clockwise or anti-clockwise rotation of the billet, is the most effective for producing ultrafine-grained (UFG) materials [5,7,31]. Conversely, others have suggested that route A, which doesn't involve rotation, yields superior results [32]. One notable characteristic of the deformation behavior of these materials is the absence of strain hardening [33]. Additionally, there is evidence suggesting a reduction in hardness and strength as the number of passes during ECAP increases [27,34,35]. However, there has been limited analysis of this phenomenon. The present study aims to investigate the impact of strain rate on the evolution of microstructure and mechanical properties in ECAP materials, with a specific focus on aluminum in our investigation.

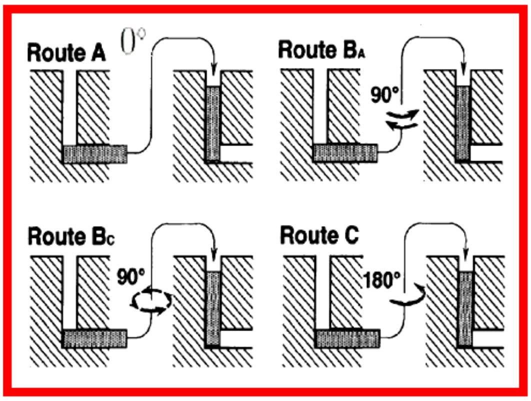

Figure 2. A schematic the processing routes followed during consecutive passes through the ECAP die.

II. EXPERIMENTAL WORK

A. Materials

The experiments involved the use of high-purity aluminum, boasting an aluminum content of 99.6%. Aluminum was chosen for its symmetrical crystal structure (FCC), which leads to consistent dislocation densities and its wide-ranging applications in engineering.

To analyze the base metal, a spectrometer was employed, specifically the "Spectromaxx™ LMX06 Arc/Spark (OES) analyzer" from Germany. This spectromaxx Arc/spark optical emission spectrometry (OES) analyzer is designed to cater to various analytical preferences by utilizing different wavelength ranges. Sample excitation is meticulously controlled digitally, ensuring precise plasma conditions and heightened analytical precision. The recently introduced Pro MAXx software by Spectro simplifies the operational process for the spark analyzer substantially. Instead of multiple dialog boxes, it offers a straightforward operator interface with distinct options accessible via dedicated toolbar buttons.

This analyzing device is located at the 99 Military Factory. The analysis results for the aluminum samples are presented

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in Table 1, showcasing the chemical composition of the materials used in this study.

The Egypt Aluminum Company located in NagaHammady provided the pure aluminum in the form of extruded rods. Subsequently, these rods were transformed into billets, each measuring 40 mm in length and possessing cross-section.

dimensions of 12 mm x 12 mm. These billets were then readied for ECAP processing.

B. ECAP Experimental Setup

The ECAP process are done under room temperature conditions, utilizing various velocities of 1, 4, and 12 mm.s^-1, which corresponded to initial strain rates of 0.025, 0.1, and 0.3 s^-1, respectively. This was accomplished using a split die featuring an internal channel with an angle of Φ = 90° and an external curvature angle of ψ = 20°.

All extrusion processes were conducted using an Instron 8505 machine, which possessed static loading capabilities of up to 120 tons and dynamic loading capabilities of up to 100 tons (as showed in Figure 3).

The die and sub-press equipment, including the punch and clamps, were fabricated from tool steel. Lubrication was applied using Molybdenum disulfide (MoS_2) and Teflon.

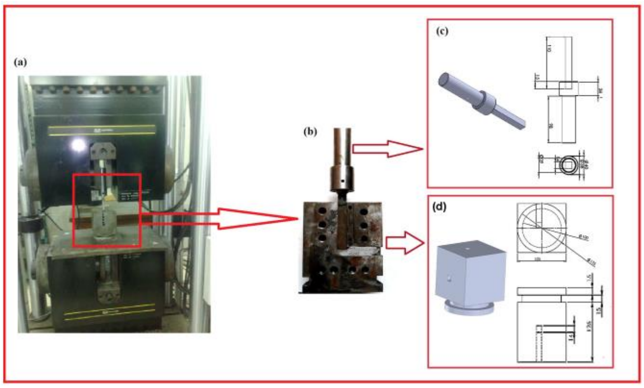

Figure 3. ECAP process (a) An Instron machine, (b) The die and the processed sample at the conclusion of the ECAP process, (c) plunger's dimensions, mounted on the Instron machine, and (d) the die's dimensions, also mounted on the Instron machine.

The exit billets were cut perpendicular to their longitudinal axes using a wire cutting machine. They were then fixed, prepared, and finished as depicted in Figure 4.

Figure 4. The samples before undergoing ECAP, with Teflon used to secure them in a bent configuration.

Table I. Chemical composition of the materials.

Component	**Fe**	**Si**	**Cu**	**Mn**	**Mg**
by wt %	0.115	0.173	0.005	0.001	0.004
Component	**Ag**	**Ti**	**Cr**	**NI**	**Al**
by wt %	0.0002	0.01	0.001	0.003	Balance

C. Evaluation of ECAP Specimens

C.1 Visual Inspection

Samples subjected to ECAP are visually inspected to assess their quality, which encompasses an examination of the cross-sectional area. This evaluation entails slicing the samples with a manual saw and subsequently refining them with SiC emery papers up to a granularity of 600.

C.2 Mechanical Testing

C.2.1 The micro-tensile testing

A micro-tensile testing machine equipped with a 500 N load cell was employed for the tensile testing of the processed sample. Conventional tensile tests were conducted on specimens extracted from the workpiece (Figure 5) after a single ECAP pass, with their axes aligned parallel to the pressing direction. These tensile specimens featured a gauge length of 6 mm and a cross-sectional area of 1.23 mm × 1.73 mm (depth × width), as depicted in Figure 6.

In this Schematic (Figure 5), the abbreviations ED, TD, and ND specifically denote the extrusion, transverse, and normal directions, respectively.

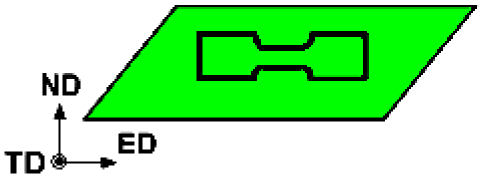

Figure 5. Schematic of the sample following the ECAP process, indicating the location from which the tensile sample was extracted.

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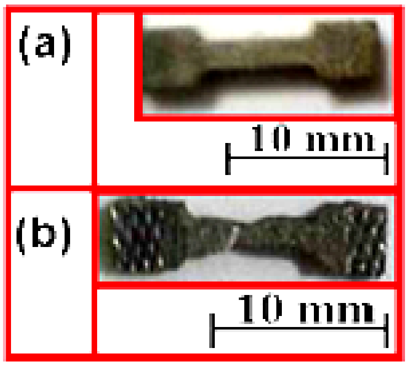

Figure 6. The micro-tensile test sample: (a) prior to the test, and (b) post-testing.

C.2.2 Micro-hardness measurements

The Vickers hardness (kg/mm²) was assessed utilizing an Instron universal hardness testing machine equipped with a 10 kg load. Several measurements were obtained from each polished section by methodically moving the Vickers indenter across the surface in a systematic grid pattern, maintaining a 3 mm interval between measurement points. The recorded values represent the Vickers hardness, denoted as Hv.

C.3 Microstructure investigation

Microstructure analysis is crucial for comparing the material deformed through ECAP with the base metal, providing insight into the ECAP process's impact on the microstructure and its ability to rectify base metal imperfections. To examine the microstructure of both pure aluminum alloy and aluminum alloy subjected to ECAP, the following procedure is employed:

- To achieve a consistent surface finish, the initial surface grinding is performed with SiC emery papers with grit sizes of 220, 400, 600, 800, 1000, and 1200. Water is used as a lubricant.
- After that, the surface is polished using colloidal silica or alumina suspension (ALU-MIK 0.3 m) for 20 to 30 seconds while being cooled with water to avoid affecting the microstructure.
- Using water as a lubricant, final polishing is accomplished with 1 µm diamond compounds for 2 or 3 minutes.

The Struers 'Knuth-Rotor2' manual grinding machine is used for grinding, while the Struers 'LaboPol,' a single-disc machine with variable rotation speed settings ranging from 50 to 500 rpm, is used for polishing.

Electrolytic polishing and etching procedures are conducted using the "Struers Polectrol" machine at 22 volts for 10 seconds at room temperature, utilizing a specialized electrolyte.

Furthermore, an Olympus optical microscope is used to carefully inspect polished surfaces.

C4 Measurement of Electrical Resistance (R)

To evaluate electrical resistance (R), we utilized a digital multi-meter device to measure it at various positions. Figure 7 visually illustrates the different points where electrical resistivity measurements were taken with the digital multi-meter device, and R represents the material's electrical resistance in ohms (Ω).

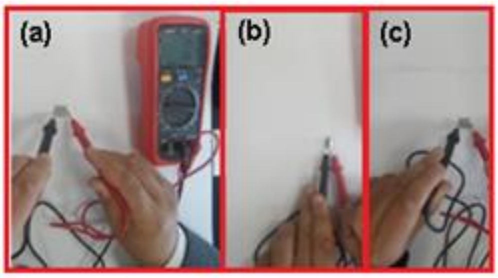

Figure 7. The locations for measuring electrical resistance: (a) the first location, (b) the second location, and (c) the third location.

III. Results and Disscusion

A. Macro- and Micro-Structural Observations

Figure 8 show the typical front and side views of the Pure AL sample following ECAP at a strain rate of 0.025 (s^-1). Additionally, Figure 9 showcases the macroscopic structure of the sample's cross-sectional area, which appears defect-free to the unaided eye. From visual inspection of all samples processed with ECAP technology, it was found that, Although the macrostructure of all samples does not exhibit visible defects, there are noticeable inclined metal edges due to the ECAP process and related stresses, the deformation primarily arises from shear, with elevated strain rates at the junction where two channels meet.

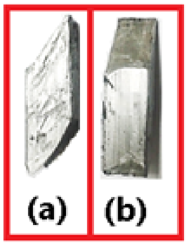

Figure 8. The Pure AL sample after undergoing ECAP at a rate of 0.025 (s^-1) (a) front view and (b) side view.

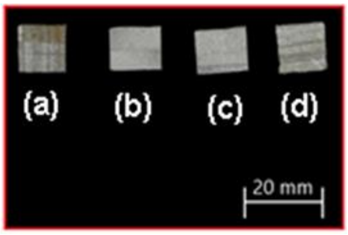

Figure 9. Macrostructure generated (a) base metal (0.0 (s^-1)) Pure AL, (b) Pure AL by ECAP at 0.025 (s^-1), (c) Pure AL by ECAP at 0.1 (s^-1) and (d) Pure AL by ECAP at 0.3 (s^-1).

Figure 10 presents optical microscopic images of the microstructures in the central cross-sectional region of pure aluminum alloy samples processed through ECAP at different strain rates (0.0 (s^-1), 0.025 (s^-1), and 0.3 (s^-1)). In general, it was observed that the microstructure in the regions

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subjected to ECAP processing was finer compared to the base metal regions, as shown in Figure 10.

The microstructure of the pure aluminum alloy base metal, as seen in Figure 9(a), exhibited larger grain sizes when compared to the materials processed using ECAP. When examining various strain rates, it was noted that the microstructure at a strain rate of 0.03 (s^-1), as shown in Figure 10(c), displayed a finer structure than that of the pure aluminum alloy base metal. Furthermore, under the same conditions of a strain rate of 0.03 (s^-1), this microstructure was the largest among all samples processed through ECAP. Meanwhile, for a strain rate of 0.025 (s^-1) as show in Figure 10(b), the microstructure was found to be the finest among all the samples processed through ECAP at that specific strain rate.

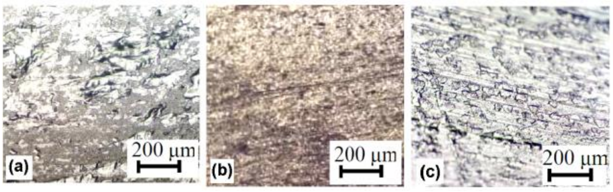

Figure 10. Optical microscopic images of the microstructures within the central cross-sectional areas of pure aluminum alloy at varying strain rates: (a) 0.0 (base metal), (b) 0.025 and (c) 0.3 (s^-1).

The microstructures illustrated in Figure 10 indicate that ECAP-induced deformation leads to grain size reduction. While this study did not include measurements of grain mis-orientation, it is widely recognized that higher strain levels result in an increased proportion of high-angle grain boundaries. As a result, the ECAP process offers a promising approach to achieving grain sizes within the range of 200–300 nm for bulk pure aluminum materials.

The aforementioned optical observations clearly showcase a significant refinement of grains with increasing deformation during ECAP. It's important to note that the microstructure transformation of the workpiece can vary depending on the chosen processing routes. Nevertheless, optical observations alone, as indicated in references [10,11,36,37], are insufficient for detecting dislocations and sub-grain boundaries in the samples. For a more detailed examination of these features, higher-resolution imaging through Scanning Electron Microscopy is necessary.

In the context of multi-pass ECAP, during the initial pass of the ECAP process, the rate at which dislocations multiply significantly surpasses the rate of dislocation annihilation due to the initially low dislocation density. This results in a notable refinement of the material's grains. As subsequent pressing passes are conducted, grain refinement continues because both dislocation density and internal energy rise. Nevertheless, the escalation in internal energy triggers phenomena like crystalline recovery and recrystallization, gradually diminishing the level of grain refinement after several pressing passes. It's worth emphasizing that the evolution of grain refinement within the workpiece varies depending on the chosen pressing routes, such as routes A and C. The accumulation and equilibrium of dislocations also differ for these routes. Through a comprehensive analysis of deformation and dislocation evolution, it becomes evident that the ECAP process can yield materials with a nanostructure. This grain refinement process can be characterized as a continuous dynamic interplay between dislocation generation and annihilation. From a microstructure perspective, it involves managing the dynamic equilibrium between these processes, while from a macro deformation standpoint, it entails determining the most favorable processing routes [15,38–40].

ECAP, when applied to particular aluminum alloys like Zn-Al alloys, produces impressive results, as documented in reference [41]. This entails a distinct phenomenon where both strength and ductility show simultaneous enhancements, even after just one pass through the die. This accomplishment represents a notable departure from traditional strengthening methods, which usually involve plastic deformation, resulting in strain hardening that increases strength but inevitably diminishes the material's ductility [5,9,26,40].

B. Mechanical Properties of ECAP Specimens

B.1 The micro-tensile results

Figure 11 presents a representation of the connection between the Ultimate Tensile Strength (UTS) of materials that have undergone Equal Channel Angular Pressing (ECAP) and the UTS of the original base metal. This relationship is examined in relation to different strain rates, expressed as (s^-1). The chart displays the tensile properties of ECAP samples processed at various strain rates (s^-1) - 0, 0.025, 0.1, and 0.3.

It becomes evident that specimens processed at a strain rate of 0.025 (s^-1) exhibit the highest UTS and ductility. Moreover, a reduction in the strain rate corresponds to an increase in the ultimate tensile stress.

Furthermore, Figure 11 serves to illustrate that the ECAP process boosts the ultimate tensile stress for all applied strain rate values. This enhancement can likely be attributed to the fragmentation of grains during the ECAP process. However, it's important to note that the degree of improvement in both properties is less pronounced when higher strain rates are applied.

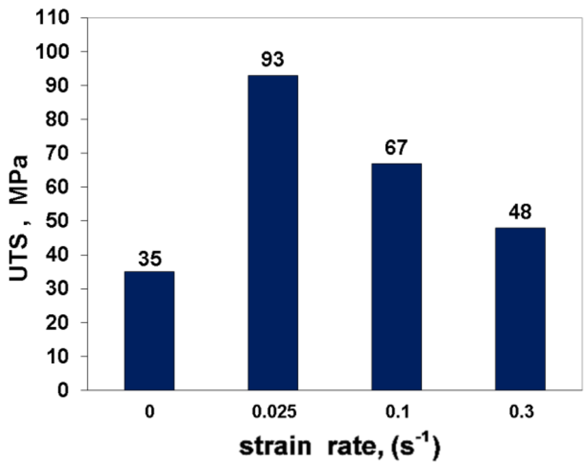

Figure 11. The ultimate tensile strength (UTS) of both the base metal (0) and specimens processed through ECAP.

B.2 Micro-hardness measurements results

Figure 12 presents the percentage change in the average microhardness of both the base metal and the specimens processed through ECAP. Notably, the specimens that underwent a single processing pass using ECAP at a strain rate of 0.025 (s^-1) display the highest microhardness values. As a general pattern, both tensile properties and microhardness values show a slight decrease with increasing strain rates.

Furthermore, Figure 12 clearly shows that the ECAP process consistently elevates microhardness values across all tested compression rates. Interestingly, there is a noticeable connection where microhardness increases as the strain rate decreases.

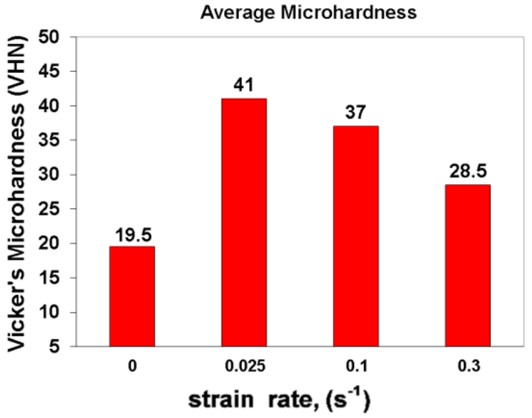

Figure 12. The hardness of BM (0) and ECAPed specimens.

As Figure 13 shows The Microhardness map of cross-sections for base metal Pure AL and Pure AL by ECAP at strain rate 0.025 (s^-1)

It is also clear from the hardness maps displayed in this way that the hardness values increase after the treatment process for pure aluminum using the ECAP technique, and the hardness is homogeneous for the cross-sectional area of the processed sample.

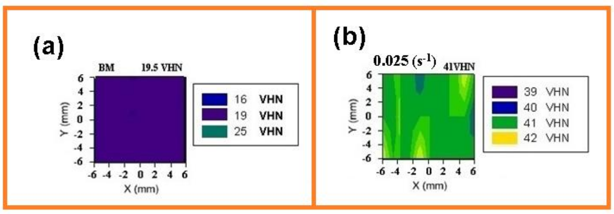

Figure 13. The Microhardness map of cross-sections for (a) base metal Pure AL and (b) Pure AL by ECAP at strain rate 0.025 (s^-1).

C. The electrical resistance (R) and The electrical resistivity(ρ) of ECAP Specimens of ECAP Specimens

Figure 14 displays the alterations in electrical resistivity (ρ) values, measured in ohm-meters (Ω·m), for both the base metal (BM) and the ECAP-processed specimens at various strain rates (s^-1). It's important to note that specimens subjected to a strain rate of 0.025 (s^-1) exhibit higher electrical resistance (R) values, whereas those processed at a strain rate of 0.3 (s^-1) demonstrate lower electrical resistance (R) values. Additionally, there's a direct correlation between an increase in strain rate and an increase in electrical resistance (R).

Furthermore, Figure 14 and Figure 15 clearly illustrates that the ECAP process consistently enhances the electrical resistance (R) values across all the examined strain rates. Consequently, this leads to an increase in electrical resistivity (ρ) values for these samples.

Figure 15 and Table 2. displays the percentage changes in mechanical properties (UTS, elongation, VHN hardness), electrical resistance (R) and the electrical resistivity(ρ) for ECAP- processed specimens processed at various strain rates (s^-1) – 0, 0.025, 0.1, and 0.3, relative to the corresponding values of the base metal.

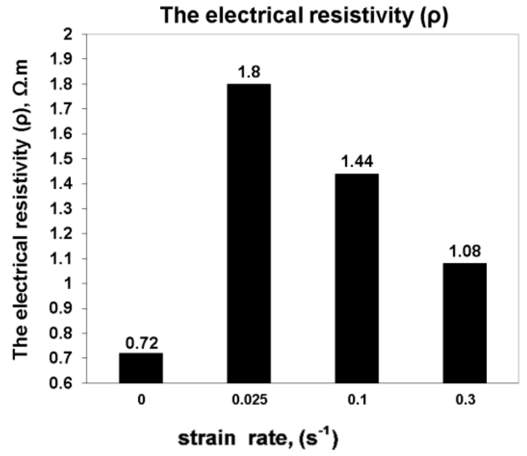

Figure 14 The electrical resistivity of BM (0) and ECAPed specimens.

For a more straightforward presentation of the impact of ECAP- processed on the mechanical properties of ECAP-treated pure aluminum alloy specimens, we have tabulated the measured UTS, hardness, electrical resistance (R) and the electrical resistivity(ρ) values in Table 2. The ratios between these property values and the equivalent base metal values are also included in this table. Additionally, it relates if each value is the greatest or the lowest among all findings that relate to it.

Both Table 2 and Figure 13 unmistakably reveal that the utilization of ECAP for processing pure aluminum alloy leads to an increase in UTS, hardness, electrical resistance (R), and electrical resistivity (ρ) in all processed specimens across various strain rates (s^-1) - 0, 0.025, 0.1, and 0.3. This finding aligns well with prior research results [4,5,7,9,11,18,26,40,42] this phenomenon can be attributed to grain fragmentation and microstructure refinement resulting from the deformation caused by ECAP. The most significant improvements in ultimate tensile strength, hardness, electrical resistance (R), and electrical resistivity (ρ) are observed when ECAP is conducted in a single pass at a strain rate of 0.025 (s^-1). Specifically, under these processing conditions, ECAP increases UTS by approximately 266%, average micro-hardness by about 210%, and electrical resistance (R) and electrical resistivity (ρ) by roughly 250% compared to the base material. At a strain rate of 0.1 (s^-1), UTS increases by about 191%, average micro-hardness by 190%, and electrical resistance (R) and electrical resistivity (ρ) by 200% relative to the base material. Finally, at a strain rate of 0.3 (s^-1), UTS

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increases by approximately 137%, average micro-hardness by 146%, and both electrical resistance (R) and electrical resistivity (ρ) by 150% in comparison to the base material.

It's important to clarify that the term "pressing speed" typically refers to the ram speed of the press and is presumed to have an impact on the effects of ECAP because it is directly tied to the material's deformation rate. Additionally, there is an observable increase in temperature during ECAP at higher ram speeds, which could potentially result in an uneven temperature distribution within the sample. This temperature elevation might induce dynamic recrystallization, leading to a decrease in tensile properties, micro-hardness, electrical resistance (R), and electrical resistivity (ρ). However, further investigation is required to delve into this aspect.

Table 2. Electrical and Mechanical Characteristics of Base Metal (pure aluminum) and Pure Aluminum Processed via ECAP at different Strain Rates - 0.025, 0.1, and 0.3 (s^-1).

Strain Rate, (s^-1)	UTS, MPa (UTS ECAP /UTS0) x100=100 %	Hardness, VHN (VHNECAP /VHN0) x100=100 %	electrical resistance(R), Ω (RECAP/R0) x100=100 %	The electrical resistivity(ρ), Ω.m (ρ ECAP/ ρ 0) x100=100 %
0 (BM)	35	19.5	0.2	0.72
0.025	93MPa 266% Max	41 VHN 210% Max	0.5 Ω 250 % Max	1.8 Ω.m 250 % Max
0.1	67 MPa 191 % ---	37 VHN 190% ---	0.4 Ω 200 % ---	1.44 Ω.m 200 % ---
0.3	48 MPa 137% Min	28.5 VHN 146% Min	0.3 Ω 150 % Min	1.08 Ω.m 150 % Min

The outcomes of this research hold importance across diverse industries, including aerospace, automotive, and manufacturing, particularly in applications where the mechanical properties of materials are of paramount importance.

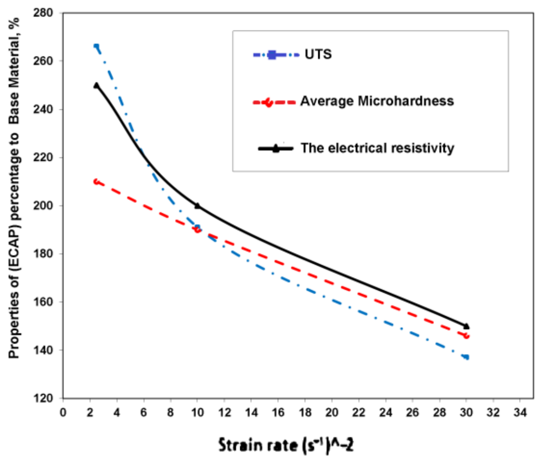

Figure 15. Relation between UTS, (MPa), Average micro-hardness, (VHN) and the electrical resistivity(ρ) of ECAPed to those of BM with Strain rate, (s^-1).

IV. CONCLUSIONS

Equal Channel Angular Pressing (ECAP) possesses the capacity to produce bulk materials with ultrafine grains, leading to improved material characteristics. This method shows great promise for widespread industrial applications due to its scalability. In this study, we investigated the impact of ECAP processing on various industrially significant aluminum alloys and findings the following:

1- Lower Strain Rate result in a more uniform microstructure forming more rapidly than higher pressing speeds.

2- Increasing the Strain Rate raises the temperature, leading to dynamic recrystallization, which subsequently leads to a reduction in ultimate tensile strength and hardness.

3- Generally, the tensile properties, micro-hardness, electrical resistance (R) and the electrical resistivity(ρ) decrease as the Strain Rate increases, but the magnitude of improvement in these properties for ECAP-processed specimens exceeds that of the base material.

4- At a Strain Rate of 0.025 (s^-1), the highest mechanical properties and electrical properties can be achieved with a single pass of ECAP.

5-Specifically, at a Strain Rate of 0.025 (s^-1) and with a single pass, ECAP increases the ultimate tensile strength by 266%, average micro-hardness by 210%, and both electrical resistance (R) and electrical resistivity (ρ) by 250% compared to the base material.

6- The hardness maps clearly show an increase in hardness values after ECAP treatment of pure aluminum, with a uniform hardness distribution across the cross-sectional area of the processed sample.

7- ECAP proves to be an efficient method for processing pure aluminum alloys, resulting in a homogeneous microstructure with high mechanical and electrical properties.

V. CONCLUSIONS

[1] J. Zhang, B. Song, Q. Wei, D. Bourell, and Y. Shi, "Journal of Materials Science & Technology A review of selective laser melting of aluminum alloys : Processing , microstructure , property and developing trends," J. Mater. Sci. Technol., vol. 35, no. 2, pp. 270–284, 2019, doi: 10.1016/j.jmst.2018.09.004.

[2] W. Xue, J. Zhou, Y. Shen, W. Zhang, and Z. Liu, "Micromechanical behavior of a fine-grained China low activation martensitic (CLAM) steel," J. Mater. Sci. Technol., vol. 35, no. 9, pp. 1869–1876, 2019, doi: 10.1016/j.jmst.2019.05.005.
[3] A. M. Mavlyutov, T. A. Latynina, M. Y. Murashkin, R. Z. Valiev, and T. S. Orlova, "The Impact of Severe Plastic Deformation on the Microstructure and Physicomechanical Properties of Al–0.4 Zr," Inorg. Mater. Appl. Res., vol. 10, no. 1, pp. 5–11, 2019, doi: 10.1134/S2075113319010210.
[4] A. N. Abood, N. K. Abid Alsahib, S. G. Hussien, N. K. A. Alsahib, and S. G. Hussien, "Enhancement of the Mechanical Properties of Al-Pb Alloy using an Equal Channel Angular Pressing Process," in IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2018, p. 12055. doi: 10.1088/1757-899X/433/1/012055.
[5] M. R. Mohamed and C. A. E. R. Saleh, "The effect of compression rate on hardness for pure Al, Al-5083, and Al-1050 with equal channel angular pressing," Automot. Ind., vol. 16, p. 17, 2014.
[6] N. E. Megahed, M. Rashad, A. Elkassas, and M. R. Mohamed Salem, "Improvement of Mechanical Properties and Electrical Conductivity of 7075 Al Alloy using ECAP Process," J. Eng. Res., vol. 7, no. 2, pp. 161–168, 2023, doi: 10.21608/ERJENG.2023.208328.1176.
[7] maher Mohamed, N. Nabil Zaafarani, A. E. Kabeel, and A. E Kabeel, "The Effect of the Rate of Strain on the Thermal and Mechanical Properties of Al-6030 Processed by ECAP.," MEJ. Mansoura Eng. J., vol. 46, no. 4, pp. 1–6, 2021, doi: 10.21608/bfemu.2021.208215.
[8] Y. Jiang, X. Yang, H. Miura, and T. Sakai, "Nano-SiO2 particles reinforced magnesium alloy produced by friction stir processing," Rev. Adv. Mater. Sci., vol. 33, no. 1, pp. 29–32, 2013.
[9] A. I. Alateyah, M. Alharbi, H. A. El-Hafez, and W. H. El-Garaihy, "The Effect of Equal-Channel Angular Pressing Processing on Microstructural Evolution, Hardness Homogeneity, and Mechanical Properties of Pure Aluminum," SAE Int. J. Mater. Manuf., vol. 14, no. 2, pp. 113–125, 2020, doi: 10.4271/05-14-02-0009.
[10] C. Rochet et al., "Influence of equal-channel angular pressing on the microstructure and corrosion behaviour of a 6xxx aluminium alloy for automotive conductors," Corros. Sci., vol. 166, no. December 2019, p. 108453, 2020, doi: 10.1016/j.corsci.2020.108453.
[11] P. Vishnu et al., "A review on processing of aluminium and its alloys through Equal Channel Angular Pressing die," Mater. Today Proc., vol. 21, no. xxxx, pp. 212–222, 2020, doi: 10.1016/j.matpr.2019.04.223.
[12] R. Z. Valiev and T. G. Langdon, "Principles of equal-channel angular pressing as a processing tool for grain refinement," Prog. Mater. Sci., vol. 51, no. 7, pp. 881–981, 2006.
[13] R. Lachhab et al., "Study of the microstructure and texture heterogeneities of Fe–48wt% Ni alloy severely deformed by equal channel angular pressing," J. Mater. Sci., vol. 54, no. 5, pp. 4354–4365, 2019, doi: 10.1007/s10853-018-3114-6.
[14] R. Z. Valiev et al., "Developing nanostructured Ti alloys for innovative implantable medical devices," Materials (Basel)., vol. 13, no. 4, p. 967, 2020.
[15] A. Rezaei, R. Mahmudi, C. Cayron, and R. E. Logé, "Simple shear extrusion versus equal channel angular pressing: A comparative study on the microstructure and mechanical properties of an Mg alloy," J. Magnes. Alloy., vol. 11, no. 5, pp. 1769–1790, 2023, doi: 10.1016/j.jma.2023.05.006.
[16] K. Edalati et al., "Nanomaterials by severe plastic deformation: Review of historical developments and recent advances," Mater. Res. Lett., vol. 10, no. 4, pp. 163–256, 2022, doi: 10.1080/21663831.2022.2029779.
[17] R. Z. Valiev, R. K. Islamgaliev, and I. V Alexandrov, "Bulk nanostructured materials from severe plastic deformation," Prog. Mater. Sci., vol. 45, no. 2, pp. 103–189, 2000.
[18] E. V. Bobruk, V. U. Kazykhanov, M. Yu. Murashkin, and M. Y. Murashkin, "Influence of deformation at elevated temperatures on stability of microstructure and mechanical properties of UFG aluminum alloy," Mater. Lett., vol. 301, no. June, p. 130328, 2021, doi: 10.1016/j.matlet.2021.130328.
[19] R. B. Figueiredo and T. G. Langdon, "Fabricating ultrafine-grained materials through the application of severe plastic deformation: a review of developments in brazil," J. Mater. Res. Technol., vol. 1, no. 1, pp. 55–62, 2012, doi: 10.1016/S2238-7854(12)70010-8.
[20] Z. Zhang et al., "A novel method for preparing bulk ultrafine-grained material: Three dimensional severe plastic deformation," Mater. Lett., vol. 276, p. 128209, 2020.
[21] F. Flory, L. Escoubas, and G. Berginc, "Optical properties of nanostructured materials: a review," J. Nanophotonics, vol. 5, no. 1, p. 52502, 2011, doi: 10.1117/1.3609266.
[22] Z. Horita, T. Fujinami, and T. G. Langdon, "The potential for scaling ECAP: effect of sample size on grain refinement and mechanical properties," Mater. Sci. Eng. A, vol. 318, no. 1–2, pp. 34–41, 2001, doi: 10.1016/S0921-5093(01)01339-9.
[23] V. M. Segal, "Engineering and commercialization of equal channel angular extrusion (ECAE)," Mater. Sci. Eng. A, vol. 386, no. 1–2, pp. 269–276, 2004.
[24] R. Z. Valiev, N. A. Krasilnikov, and N. K. Tsenev, "Plastic deformation of alloys with submicron-grained structure," Mater. Sci. Eng. A, vol. 137, no. C, pp. 35–40, 1991, doi: 10.1016/0921-5093(91)90316-F.
[25] R. Z. Valiev, A. I. Pshenichnyuk, A. A. Nazarov, A. V Korznikov, and R. R. Mulyukov, "Structure and properties of ultrafine-grained materials produced by severe plastic deformation," Mater. Sci. Eng. A, vol. 168, no. 2, pp. 141–148, 1993, doi: 10.4028/www.scientific.net/kem.97-98.59.
[26] E. A. El-Danaf, "Mechanical properties, microstructure and texture of single pass equal channel angular pressed 1050, 5083, 6082 and 7010 aluminum alloys with different dies," Mater. Des., vol. 32, no. 7, pp. 3838–3853, 2011, doi: 10.1016/j.matdes.2011.03.006.
[27] F. Salimyanfard et al., "EBSD analysis of nano-structured copper processed by ECAP," Mater. Sci. Eng. A, vol. 528, no. 16–17, pp. 5348–5355, 2011, doi: 10.1016/j.msea.2011.03.075.
[28] Y. Iwahashi et al., "Principle of equal-channel angular pressing for the processing of ultra-fine grained materials," Scr. Mater., vol. 35, no. 2, pp. 322–324, 1996, doi: 10.1002/art.21843.
[29] I. Engineering et al., "Analytical and numerical approaches to modelling severe plastic deformation," Prog. Mater. Sci., vol. 95, pp. 172–242, 2018.
[30] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, and P. . J. Nagasekhar, A. V., Chakkingal, U., Venugopal, "The shearing characteristics associated with equal-channel angular pressing," Mater. Sci. Eng. A, vol. 257, no. 2, pp. 328–332, 1998.
[31] Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, and J. Huot, "The process of grain refinement in equal-channel angular pressing," Acta Mater., vol. 46, no. 9, pp. 3317–3331, 1998, doi: 10.1007/978-3-319-35107-0_5.
[32] A. Gholinia, P. B. Prangnell, and M. V. Markushev, "The effect of strain path on the development of deformation structures in severely deformed aluminium alloys processed by ECAE," Acta Mater., vol. 48, no. 5, pp. 1115–1130, 2000, doi: 10.1016/S1359-6454(99)00388-2.
[33] R. Z. Valiev, "Structure and mechanical properties of ultrafine-grained metals," Mater. Sci. Eng. A, vol. 234, pp. 59–66, 1997, doi: 10.1016/s0921-5093(97)00183-4.
[34] Z. Horita, M. Nemoto, and T. G. Langdon, "AN INVESTIGATION OF MICROSTRUCTURAL EVOLUTION DURING EQUAL-CHANNEL ANGULAR PRESSING," vol. 45, no. 11, 1997.
[35] W. J. Kim et al., "Enhancement of strength and superplasticity in a 6061 Al alloy processed by equal-channel-angular-pressing," Metall. Mater. Trans. A, vol. 33, no. 10, pp. 3155–3164, 2002, doi: 10.1007/s11661-002-0301-4.
[36] A. P. Zhilyaev, D. L. Swisher, K. Oh-ishi, T. G. Langdon, and T. R. McNelley, "Microtexture and microstructure evolution during processing of pure aluminum by repetitive ECAP," Mater. Sci. Eng. A, vol. 429, no. 1–2, pp. 137–148, 2006, doi: 10.1016/j.msea.2006.05.009.
[37] M. Ciemiorek, M. Lewandowska, and L. Olejnik, "Microstructure, tensile properties and formability of ultrafine-grained Al–Mn square plates processed by Incremental ECAP," Mater. Des., vol. 196, pp. 1–11, 2020, doi: 10.1016/j.matdes.2020.109125.
[38] G. Zhao et al., "Grain refinement mechanism analysis and experimental investigation of equal channel angular pressing for producing pure aluminum ultra-fine grained materials," Mater. Sci. Eng. A, vol. 13, no. 2, pp. 281–292, 2006, doi: 10.1016/j.msea.2006.07.138.
[39] A. Korchef and I. Souid, "Grain Refinement and Strengthening of an Aluminum Alloy Subjected to Severe Plastic Deformation through Equal-Channel Angular Pressing," Crystals, vol. 13, no. 8, 2023, doi: 10.3390/cryst13081160.
[40] R. Mohammed, A. Shahab, and A. Rezaei, "Effect of ECAP process on mechanical properties and microstructure of AA-6061 recycled chips," Eng. Technol. J., vol. 41, no. 7, pp. 1–16, 2023, doi: 10.30684/etj.2023.137807.1367.
[41] G. Pürçek, "Improvement of mechanical properties for Zn-Al alloys using equal-channel angular pressing," J. Mater. Process. Technol., vol. 169, no. 2, pp. 242–248, 2005, doi: 10.1016/j.jmatprotec.2005.03.012.
[42] K. Edalati, K. Imamura, T. Kiss, and Z. Horita, "Equal-channel angular pressing and high-pressure torsion of pure copper: Evolution of electrical conductivity and hardness with strain," Mater. Trans., vol. 53, no. 1, pp. 123–127, 2012, doi: 10.2320/matertrans.MD201109.