[Journal of Engineering Research](https://digitalcommons.aaru.edu.jo/erjeng)

Volume 7 | Issue 2 Article 18

2023

Improvement of Mechanical Properties and Electrical Conductivity of 7075 Al Alloy using ECAP Process

Nour Eldeen Megahed,

Journal of Engineering Research (ERJ)
Vol. 7 – No. 2, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Improvement of Mechanical Properties and Electrical Conductivity of 7075 Al Alloy using ECAP Process

Nour Eldeen Megahed[1], A.M.El-Kassas[2], Maher Rashad[2,3,*]

[1]Master's student, Department of Production Engineering and Mechanical Design, Faculty of Engineering, Tanta University.
[2]Production Engineering and Mechanical Design Department, Faculty of Engineering, Tanta, 31527, Egypt.
[3]Head of Mechatronics Department, Faculty of Engineering, Horus University, New Damietta, Egypt
[*]Corresponding author email: Dr.maherrashad@f-eng.tanta.edu.eg

***Abstract*-The equal channel angular pressing (ECAP) method is used in this work to treat the Al-Zn-Mg-Cu alloy. As the most promising severe plastic deformation (SPD) technique, equal channel angular pressing (ECAP) has received extensive research in recent years. Hardness test, compression test, electrical conductivity, and surface studies were used to look into how an ultra-fine grained (UFG) industrial aluminum alloy that was made by equal channel angular pressing (ECAP) for one pass strengthened its mechanical characteristics and electrical conductivity. The product has been annealed for three hours at 415^{0}C; Experimental research is done to determine how aluminum alloy 7075's electrical conductivity and material characteristics are impacted by the rate of severe plastic deformation (SPD) during equal channel angular pressing (ECAP). According to the results, the ECAP will increase compressive strength from 145 to 295.5 N/mm^2 at the same strain in 0.016 seconds after one pass, Hardness increases progressively until 295.5 N/mm^2 is reached as its highest value, then it gradually decreases. The percentage increase in hardness was 50.9% at a strain rate of 0.016s^{-1}. ECAP method is frequently used to raise the yield strength of the aluminum alloy 7075 by 204 % while simultaneously reducing the rate of strain at a compressive strength of 145 N/mm^2 from 0.016 to 0.008s^{-1}. With just one pass, IACS of the alloy as received and after Escaping both showed an improvement in electrical conductivity from 30.8% to 43.5%., ECAP increases electrical conductivity by 29.2% with a strain rate of 0.016s^{-1}.**

Keywords-* Equal Channel Angular Pressing (ECAP), Aluminum alloy 7075, Scanning electron microscope, Hardness, Strain rate, Electrical conductivity IACS.

I- INTRODUCTION

Equal channel angular pressing (ECAP) is a process for severe plastic deformation of metals which can significantly improve their mechanical properties. In the case of AA-7075 aluminum alloy, one pass of ECAP can lead to significant improvements in its strength, ductility, and wear resistance. During ECAP, the aluminum alloy is subjected to severe plastic deformation as it is pressed through a die with two channels that intersect at an angle. The material is subjected to high strain rates and large deformations, which cause significant microstructural changes. These changes can be attributed to several mechanisms:

1- Grain refinement: ECAP can refine the grain size of the aluminum alloy, resulting in a higher density of grain boundaries. This increases the strength of the material by increasing the resistance of dislocation movement.
2- Dislocation density: The high amount of plastic deformation that occurs during ECAP creates a high density of dislocations in the material, which act as barriers to dislocation movement and contribute to strengthening.
3- Texture modification: ECAP can also modify the texture of the material, resulting in an orientation of the crystals that enhances the strength and ductility of the material.
4- Precipitation hardening: The high dislocation density and grain refinement that occur during ECAP can also lead to the formation of precipitates, which contribute to the strengthening and hardening of the material.

The combination of these mechanisms can lead to significant improvements in the mechanical properties of AA-7075 aluminum alloy after one pass of ECAP. In particular, the material can exhibit a significant increase in strength and hardness, while maintaining or even improving its ductility. Wear resistance can also be improved due to the combination of increased strength and hardness.

To further enhance the strengthening and hardness of AA-7075 after ECAP, several approaches can be used, including:

1- Increasing the number of ECAP passes: Studies have shown that increasing the number of ECAP passes can lead to a further refinement of the microstructure and an increase in the strength and hardness of the material.
2- Optimizing the ECAP processing conditions: The processing conditions used during ECAP, such as the temperature, strain rate, and channel angle, can have a significant impact on the resulting microstructure and mechanical properties. By optimizing these parameters, it may be possible to achieve a more desirable combination of strength and ductility.
3- Post-ECAP heat treatments: Heat treatments, such as annealing or aging, can be used to further enhance the strength and hardness of the material after ECAP. These treatments can help to stabilize the microstructure and promote the formation of strengthening precipitates.

Overall, ECAP is a promising technique for improving the strength and hardness of AA-7075, and further research into optimizing the processing parameters and post-ECAP treatments could lead to even greater improvements in the mechanical properties of the material.

The aerospace sectors have paid particular attention to the 7000-series alloys, since they offer the greatest resilience of any aluminum alloy. This group of alloys contains zinc and

DOI: 10.21608/ERJENG.2023.208328.1176

Journal of Engineering Research (ERJ)
Vol. 7 – No. 2, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

magnesium to facilitate the creation of the (ZnMg) phase, which hardens precipitation. Copper helps these metals be more resistant to stress-corrosion cracking. To regulate recrystallization, additional trace amounts of chromium, zirconium, titanium, or manganese are also present. Additionally, zirconium increases the metals' strength and toughness and lessens their quench sensitivity. Additionally, according to the small size of the grain.

The most popular alloy in this series, Alloy 7075, offers a decent balance of strength, ductility, and toughness. In the peak-aged state, the stress-corrosion cracking resistance of the 7000-series alloys is inferior. Al–Zn–Mg–Cu alloy have a variety of uses, including the aerospace, marine, automotive, and aviation sectors. Some studies attempted to decrease the grain size utilizing equal channel angular pressing (ECAP) in order to improve their mechanical characteristics [8- 10]. The process description principle is schematically illustrated in Fig. 1 by a die with a channel bent at a direct 90-degree angle. A sample is pressed through the die using a plunger after it has been machined to fit into the channel. [2].

Angles of the channel's two sides are φ = 90° and, to a lesser extent, ψ= 20°, The two elements that have the biggest an impact on the strain put on the sample during each passing through N the die are depicted here as the intersection of the outermost arcs of curvature of the two channels. For ideal outcomes, a die with a 90-degree channel angle is frequently used for ECAP [4]. A reliable method for determining the total strain [16]. When utilizing the ECAP die, the strain equivalent is determined by:

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

The corresponding plastic strain ε_N in this case is around 1.15 [4, 18]. It can be calculated using the equation.

N is the specific kind of route chosen using the die. UFG and, therefore, the goal of the current work is to assess with a focus on the features acquired by bringing the materials up to the spherical morphology scale, findings on aluminum alloy 7075 that were distorted by angle pressing inside the angle pressing mold will be reviewed.

The purpose of this study is to increase the alloy 7075's electrical and mechanical qualities using (ECAP). ECAP is applied to refining grain size with the same cross section at room temperature.

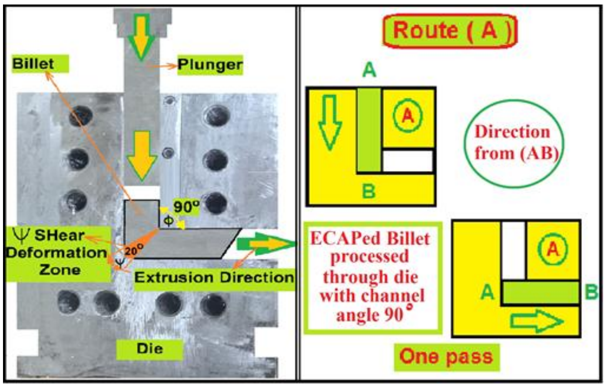

Fig. 1. ECAP and shape of die from the inside.

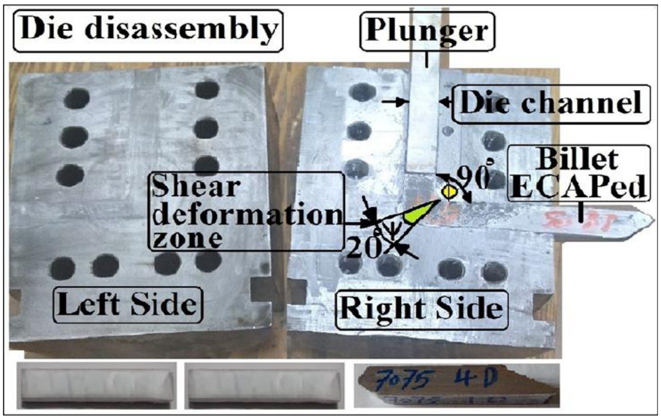

Fig. 2. The die and disassembly of sample to expose the die from the inside and billet before and after ECAP

To obtain the optimal condition, the effects of strain rate on the electrical and mechanical properties of Al-7075 following ECAP processing are examined.

II- EXPERIMENTAL PROCEDURE

In order to increase the workability of an alloy 7075 used in commercial products, different types of internal stress were eliminated using annealing heat treatment. The evolution of its traits and material behavior were evaluated after one ECAP pass. Aluminum alloy 7075 square-section pieces underwent ECAP at room temperature to improve the grain structure.

The investigations were completed utilizing an aluminum alloy whose composition is listed in (Table 1). The Wild-Barfield Electric Furnace is used for annealing aluminum alloy 7075 to reduce internal tensions. the samples inside the furnace for three hours, then turn off the power and let it cool until it reaches room temperature. [28].

The aluminum alloy 7075 are supplied by Egypt Aluminum Company in Naga Hamady and was made into sheets that measured 160 mm by 210 mm and billets that were 13.8 mm x 13.8 mm in dimension and 70 mm in length. At room temperature, the material was treated by pushing with identical channel angles at ram speeds of 10, 15, 100, and 150 mm/min. We have selected a split die with an internal channel that is 90° in angle and an outer curvature of 20° [15].

For the entire extrusion process, a compressive universal testing equipment with a 500 N loading capability was utilized (ECAP). Hardened steel was used in the construction of both the Angular press stamp and the sub-compression equipment [20]. Teflon is used to lubricate the interface between the surface of the extruded billet and the interior of the die. as depicted in Figures 2 , 3 and 4.

By using a wire cutting machine, the exit billets were sectioned perpendicular to their longitudinal axes before being mounted and finished and are recorded in a regular grid with a 3 mm gap between each individual measurement.

The Rockwell test is used to determine the hardness values for aluminum alloy 7075 by striking it with a modest force at first, then a large force, and comparing the two penetration depths directly from the hardness reading obtained from the HR 15 T scale, as shown in Fig. 5 [32].

DOI: 10.21608/ERJENG.2023.208328.1176

Journal of Engineering Research (ERJ)
Vol. 7 – No. 2, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Table 1. Chemical composition of the Al alloy used in this work.

Composition	Fe	Cr	Mg	Ti	Si	Cu	Mn	Zn	Al
Wt %	0.09	0.21	2.65	0.02	0.07	1.50	0.04	5.70	Balance

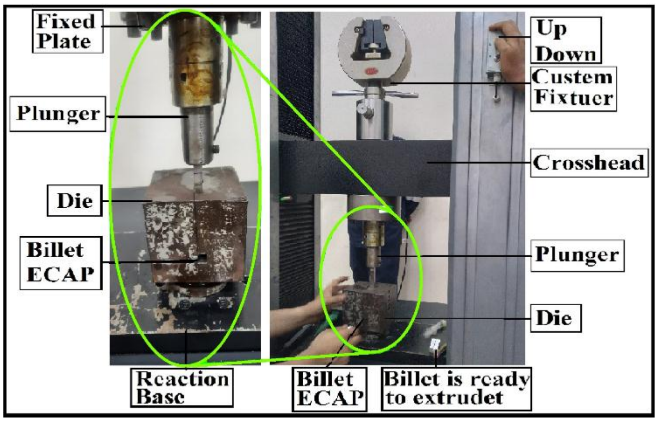

Fig. 3. The die mounting on a universal testing machine

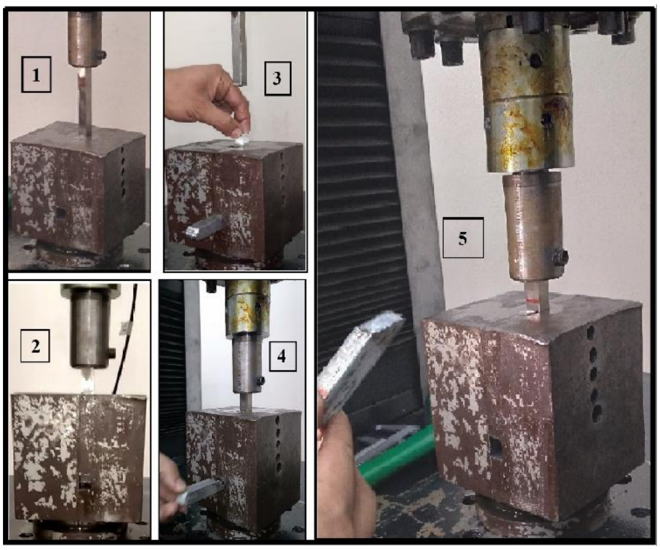

Fig. 4 The billet during ECAP

Fig. 5. Diagram of Cross-Sectional View of Indenter Tip of Rockwell during test the hardness

Using a compression testing device with a 500 KN testing machine, the treated sample's strength was assessed. The bars underwent a compression test to ascertain their compressive qualities after a single passage into an angle press mould.

According to the requirements for compression testing, the bars must be cut to a length greater than twice the cross-sectional area in order to complete this test. As can be seen in Fig. 6, the bars were cut perpendicular to the direction of the angular pressing die, with dimensions of (30 x 13.8 x 13.8 mm).

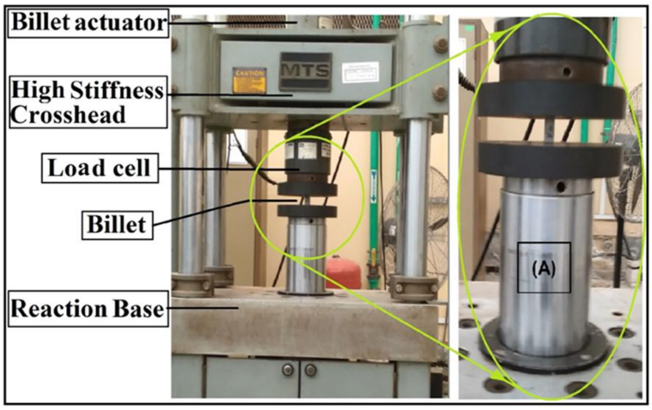

Fig. 6. The MTS compression testing device used to test the compression of AA-7075

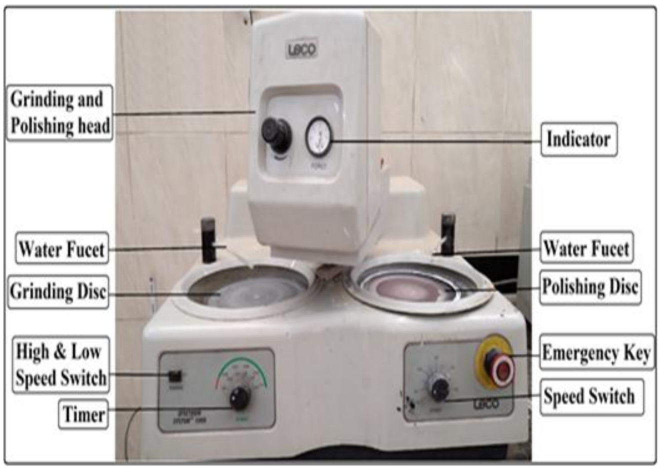

Fig. 7. Spectrum System 1000 (SS-1000) Grinder/Polisher machine

In order to study the microstructure, grinding and polishing are important steps in preparing a sample for microstructure examination:

1- Cut the samples that have been pressed inside the angular pressure mold of the equal channel into pieces with dimensions (15 x 13.8 x 13.8 mm) using wire cut so that the pieces are perpendicular to the direction of pressure (extrusion).
2- Used the spectrum system 1000 (SS-1000) grinded machine grinds samples one by one using a series of progressively coarse to fine abrasive papers to remove any imperfections or surface damage and create a flat surface for polishing.
3- Used the spectrum system 1000 (SS-1000) polished machine is used. After the grinding process, the sample is polished using Leco Abrasive Solution (P/N: 810-832).
4- Cleaned the samples with a solvent (ethanol/acetone) to remove any debris or polishing compounds that may be present.
5- Etching is the most important point in preparing samples for imaging, where the sample is excavated to reveal the microstructure by immersing it in a solution made by mixing the following components:

DOI: 10.21608/ERJENG.2023.208328.1176

Journal of Engineering Research (ERJ)
Vol. 7 – No. 2, 2023
©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

a- Nitric acid (HNO3) (5 ml).
b- Hydrochloric acid (HCl) (3 ml).
c- Hydrofluoric acid (HF) (2 ml).
d- Distilled water (H2O) (190 ml).
Then the samples are immersed in the mixture for a period of 20 to 30 seconds, then dried with cold air, and then sent to the optical microscopy device [22,29,32].

6- Optical microscopy was used on the samples of aluminum alloy 7075 by the Meiji Techno high-quality Japanese microscope shown in Fig. 8.

Using optical and scanning electron microscopes, the average grain size of the material compressed inside the angle press mold is determined.

After undergoing the ECAP technique, samples of the aluminum alloy 7075 are tested for electrical conductivity using eddy currents and the electrical conductivity of the metal using the Nortec 2000 device (Fig. 9). This test depends on a number of factors, including the chemical makeup of the metal and the stress state of its crystalline structure.

In order to lessen the impacts of material thickness, aluminum alloy 7075 samples were utilized when evaluating resistance or conductivity with a thickness larger than three times the depth of penetration.

$$t \geq 3\delta$$

where:

t = material thickness

δ = standard depth of penetration

The conductivity must be converted to Siemens/meter because it is stated as %IACS [30]. To convert IACS to Siemens/meter, the following formula can be used:

$$conductivity\ \left(\frac{simenens}{meter}\right) = \left(\frac{IACS}{100}\right) \times 5.69 \times 10^{7}$$

where: 5.96×10^{7} is the conductivity of annealed copper in Siemens/meter.

IACS (International Annealed Copper Standard) and Siemens/meter are units used to measure the electrical conductivity of materials. While IACS is a relative measure of conductivity, Siemens/meter is an absolute measure of conductivity.

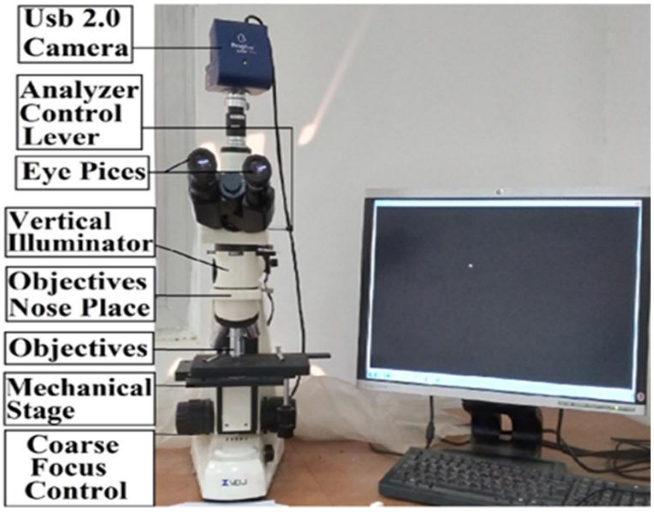

Fig. 8. MEIJI Optical Microscope

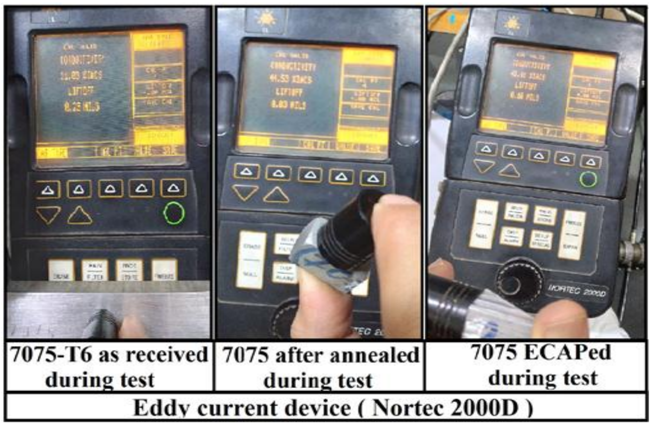

Fig. 9. Nortec 2000 device used to evaluate the electrical conductivity

III- RESULTS AND DISCUSSION

A. Strength

The stress-strain curve obtained from the compression test shows the relationship between the applied load and the resulting deformation of the material. The curve typically consists of several distinct regions, including the elastic region, the yield point, the plastic region, and the failure point.

Before ECAP, the 7075-material had strength of 145 N/mm^2 and a strain rate of 0.016s^{-1}. This means that when a load was applied to the material, it began to deform elastically up to a certain point, after which it began to deform plastically.

The point at which plastic deformation begins is known as the yield point, and it corresponds to the yield strength of the material. In this case, the yield strength of the 7075 material was 145 N/mm^2.

After ECAP, the material's strength increased significantly to 295.5 N/mm^2 at the same strain rate of 0.016s^{-1}. The ECAP process caused the material to undergo severe plastic deformation, resulting in a significant increase in its strength. The stress-strain curve obtained from the compression test of ECAP processed material shows a higher yield strength and a steeper slope in the plastic region, indicating that the material is more resistant to deformation and has a higher modulus of elasticity.

The equal-channel angular pressing (ECAP) method is frequently used to raise the yield strength of the aluminum alloy 7075 by 204 % while simultaneously reducing the rate of strain at a compressive strength of 145 N/mm^2 from 0.016 to 0.008s^{-1}. With just one pass, the compressive strength of AA-7075 increases from 145 to 295.5 N/mm^2 at the same strain in 0.016s^{-1}, as shown by the stress-strain curves of the material in Fig. 10.

B. Hardness

The relative hardness of the material following equal channel angular pressing (ECAP) with one pass at various speeds is indicated by the Rockwell hardness values. This shows that the microstructure of the sample is more homogeneous in the cross-section obtained following ECAP, as illustrated in Fig. 15. According to the results, the improvements in hardness are around 15.10%, 17.69%, 18.68%, and 21.54%. The outcomes demonstrated the best performance of ECAP at 150 mm/min, as illustrated in Fig. 11. [22], [23].

DOI: 10.21608/ERJENG.2023.208328.1176

©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

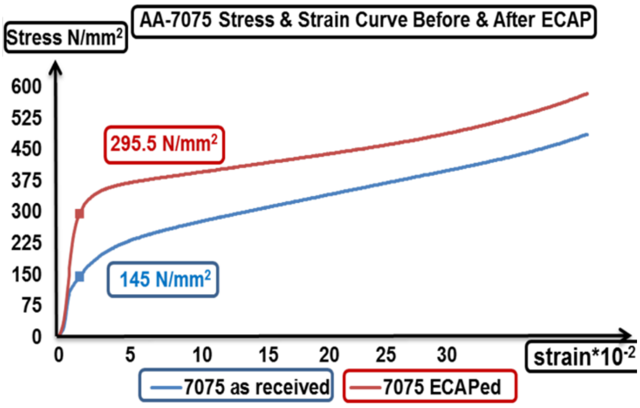

Fig. 10. The true stress strain curve of AA-7075 before and after ECAP

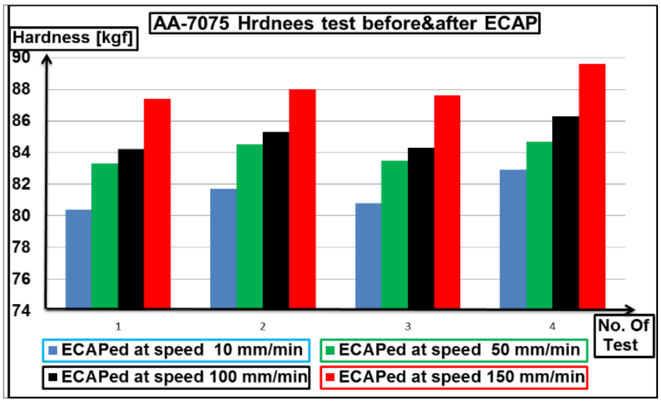

Fig. 11. The hardness of AA-7075 after ECAP with different speeds

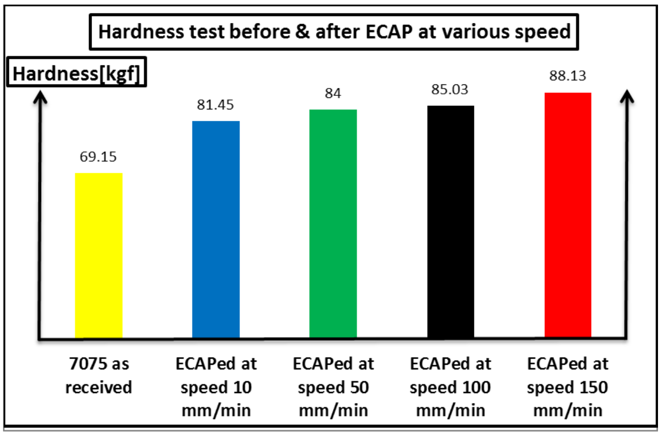

Fig. 12. The hardness of AA-7075 before and after ECAP

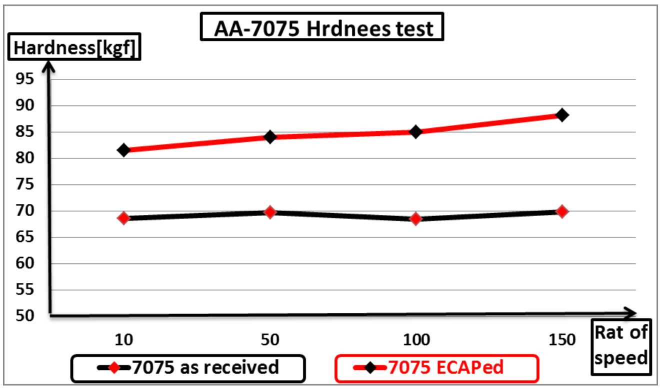

Fig. 13. The hardness testing outcomes of AA-7075 Before & After ECAP

The hardness value 69.15 kg represent the initial hardness value of the material before ECAP. Following to the application of the ECAP process with a single pass, the hardness value increase as the speed of ECAP process increases, with the highest value of 88.13 kg obtained at a speed of 150 mm/min. This increase in hardness is due to the plastic deformation that occurs during ECAP, this increase in hardness suggests that the ECAP process caused the material to become stronger or more resistant to deformation, as shown in Fig. 12.

C. Grain Refinement and Microstructure

Fig. 16 (a) and (b) show the microstructure of the aluminum alloy 7075 before and after ECAP at various press rates using scanning electron microscopy. During ECAP, significant plastic deformation occurs near the intersection of the two channels, in the restricted region (shear zone), altering the grain size and microstructure.

The ram speed, die angle, total strain, temperature, and other extrusion factors have an impact on the resultant microstructure, which is exceedingly accurate. Every ram speed results in the expected polished grain structure. However, statistics indicate that refined grain diameter grows along with an increase in compression speed. This has quantifiable supporting evidence. Measurements are used to support this.

ECAP was applied to Al-7075 square cross-section samples at room temperature to refine grain size. The studies show that after one pass at the same strain of 0.016s-1, ECAP raises the rate of compressive strength from 145 to 295.5 N/mm2, also, improvement The rate of compressive strength of 295.5 N/mm2 marks the highest value at which the hardness gradually increases, improvement The rate of compressive strength of 295.5 N/mm2 marks the highest value at which the hardness gradually increases. and after reaching its maximum potency, progressively declines. Due to the reduction in grain size following ECAP, the hardness enhancement is approximately 50.9% at a strain rate of 0.016s-1.

To determine the usual grain size of the material both before and after ECAP, as seen in Fig.16 (b) and Fig.17 (b) of the Aluminum Alloy Sample 7075 following ECAP, wherein ECAP causes the grain size to decrease and the distorted plastic's microstructure to evolve, in contrast to Fig. 16 (a) and Fig. 17 (b) of sample 7075 before ECAP, the shape and size of the grains are larger. As the result, understanding these changes in grain size is necessary to comprehend the grain size and changes in the mechanical and electrical properties.

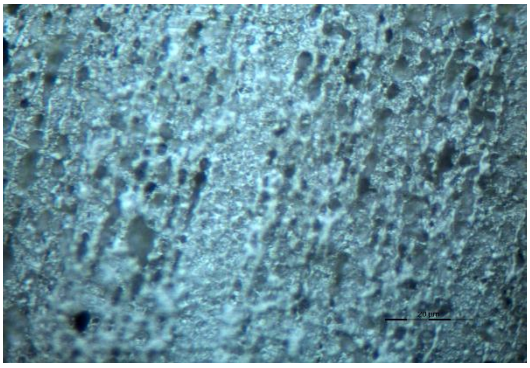

Fig. 14 Optical microstructures of Al-7075 prior to ECAP

DOI: 10.21608/ERJENG.2023.208328.1176

D. *Electrical Conductivity*

The varying readings in each of the three scenarios, as determined by measurements made on samples of aluminum alloy, are shown in Figure 18.

1- The original ingot sample of 7075-T6 aluminum.
2- The second instance of the 7075-grade annealed aluminum ingot sample.
3- The third instance of an aluminum ingot 7075 sample following ECAP.

The electrical conductivity of the alloy rises from 30.8% to 43.5% IACS when it was received and after the ECAP procedure, improving by 29.2% at a strain rate of 0.016 s^{-1}.

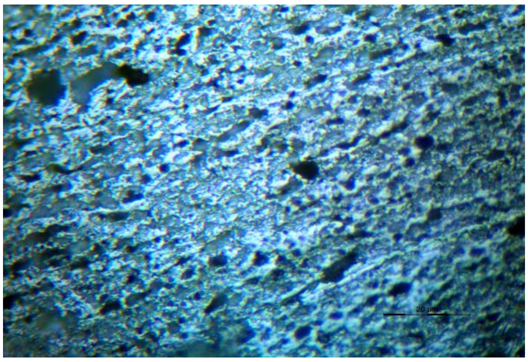

Fig. 15 Optical microstructures of Al-7075 after ECAP

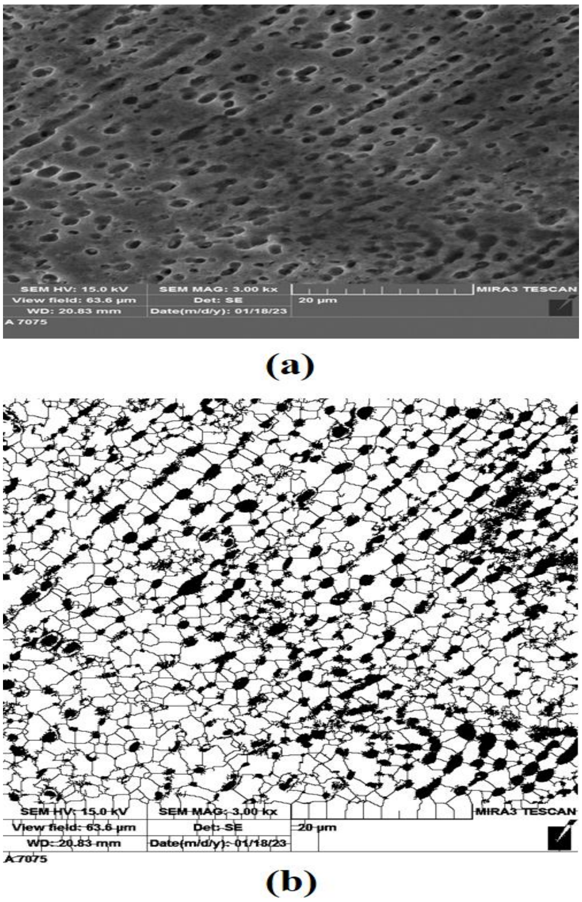

Fig. 16. Microstructures of Al-7075 as received using (a) SEM and (b) image J

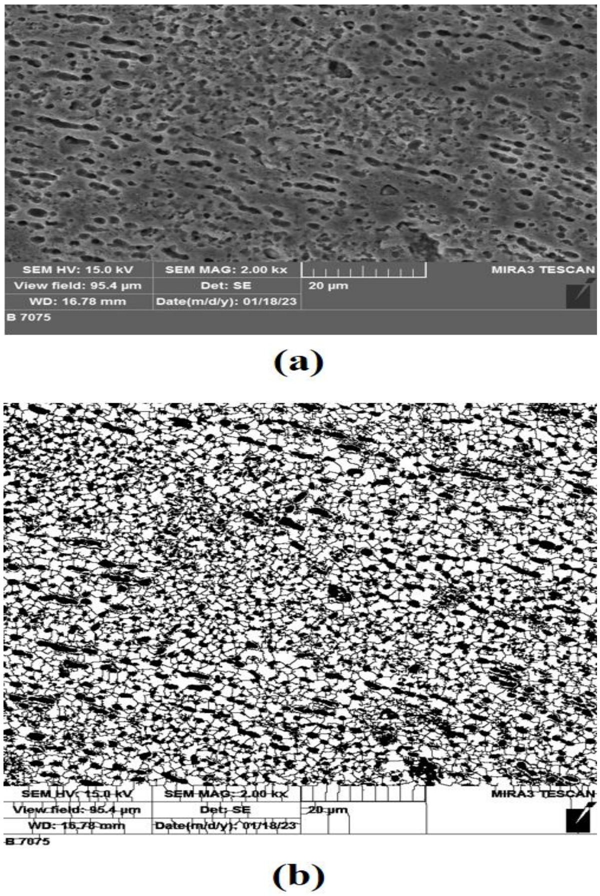

Fig. 17 Microstructures of Al-7075 after using ECAP (a) SEM and (b) image J

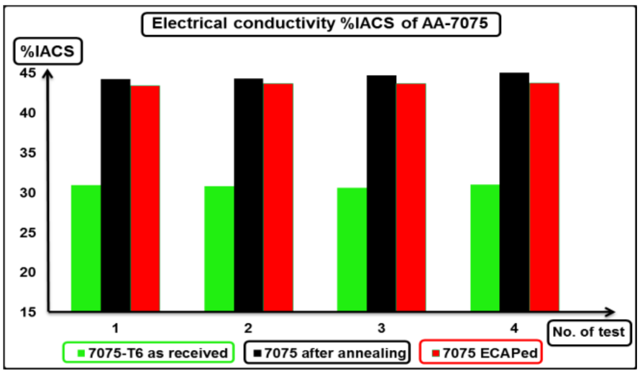

Fig. 18. Electrical conductivity %IACS of 7075 for the three cases

From the present experimental results, the optimum rate of strain is 0.016 s^{-1} which lead to the optimal electrical conductivity and mechanical properties of the AA-7075 during the ECAP processing [30].

IV- CONCLUSION

After one pass of ECAP, the microstructure of AA-7075 is refined and the material's strength and hardness are increased. During the ECAP process, the material is subjected to severe plastic deformation as it is forced through a die with two channels that intersect at a specific angle. This process causes the material to undergo significant strain hardening and deformation, resulting in changes to its microstructure.

DOI: 10.21608/ERJENG.2023.208328.1176

©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

Equal-channel angular pressing can be used to produce bulk samples of materials with ultrafine grains, which will enhance the materials' characteristics. The method's potential for scaling up for use in industrial applications makes it especially appealing. We may therefore state the following this project required research to demonstrate how the ECAP process rate affected the aluminum alloy 7075.

- After ECAP, the yield strength of the aluminum alloy 7075 is frequently raised by 204%.
- ECAP method is frequently used to reducing the rate of strain at a compressive strength of 145 N/mm2 from 0.016 to 0.008s-1. With just one pass.
- Following the application of ECAP, compressive strength rose from 145 to 295.5 N/mm2 at the same strain in 0.016s-1.
- At speeds of 10, 50, 100, and 150 mm/min, the gains in hardness are around 15.10%, 17.69%, 18.68%, and 21.54%. The outcomes showed us that the ideal speed for ECAP is 150 mm/min.
- The improvement in hardness is about 50.9%, as a result of the ECAP-induced refinement of particle size.
- As a result of ECAP, the deformed plastic's microstructure changes and its grain size reduces.
- When the AA-7075 was received and when it was ECAPed, their respective electrical conductivities increased from 30.8 % to 43.5 %IACS.
- The electrical conductivity is improved by 29.2 % with a strain rate of 0.016s-1 by the ECAP procedure.
- In general, these studies have shown that ECAPed AA-7075 has increased strength, ductility, and fatigue resistance compared to non-ECAPed material. The improvement in strength is due to the refinement of the grain structure, which reduces the size of the grains and increases the density of the grain boundaries. This results in a material that is more resistant to deformation and has a higher yield strength.

Funding: The authors should mention if this research has received any type of funding.

Conflicts of Interest: The authors should explicitly declare if there is a conflict of interest.

REFERENCES

[1] R. Z. Valiev, R.K. Islamgaliev, I.V. Alexandrov, Bulk nanostructured materials from severe plastic deformation, Prog. Mater. Sci., 45 (2000) 103–189.
[2] Z. Horita, T. Fujinami, T. G. Langdon, The potential for scaling ECAP: effect of sample size on grain refinement and mechanical properties, Mater. Sci. Eng. A, 318 (2001) 34–41.
[3] V. M. Segal, Severe Engineering and commercialization of equal channel angular extrusion (ECAE), Mater. Sci. Eng.A, 386 (2004) 269–276.
[4] V. M. Segal, V. I. Reznikov, A. E. Drobyshevski, V. I. Kopylov, Plastic working of metals by simple shear, Russ. Metall., 1 (1981) 99–105.
[5] R. Z. Valiev, N. A. Krasilnikov, N. K. Tsenev, Plastic deformation of alloys with submicron-grained structure, Mater. Sci. Eng. A, 137 (1991) 35–40.
[6] R. Z. Valiev, A. V. Korznikov, R. R. Mulyukov, Structure and properties of ultrafine-grained materials produced by severe plastic deformation", Mater. Sci. Eng., 168 (1993) 141–148.
[7] 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, Materials and Design, 32 (2011) 3838–3853.
[8] Jinfang Dong, et al, Microstructure Evolution in High Purity Aluminum Single Crystal Processed by Equal Channel Angular Pressing (ECAP), Materials, 2017; 10(1): 87
[9] R. Z. Valiev, T. G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, Prog. Mater. Sci., 51 (2006) 881–981.
[10] F. Salimyanfard, M. R. Toroghinejad, F. Ashrafizadeh, M. Jafari, EBSD analysis of nano-structured copper processed by ECAP, Materials Science and Engineering A, 528 (2011) 5348–5355.
[11] V. A. Fokine. The main directions in applied research and development of SPD nanomaterials in Russia, Nanomaterials by severe plastic deformation, NanoSPD2, Vienna, Austria, December 2002,798–803.
[12] A. Rosochowski, L. Olejnik, M. Richert, 3D-ECAP of square aluminum billets", Adv. Methods Mater Form, 10 (2007) 21–32.
[13] S. L. Semiatin, D. P. DeLo, Equal channel angular extrusion of difficult-to-work alloys, Mater Design, 21 (2000) 311–22.
[14] Krishna Mohan Agarwal1, et al, Deformation and strain analysis for grain refinement of materials processed through ECAP, Materials Today: Proceedings, 21(2020) 1513-1519.
[15] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, The shearing characteristics associated with equal-channel angular pressing, Mater. Sci. Eng. A, 257 (1998) 328–332.
[16] K. R. Gopi, et al, Microstructural Evolution and Strengthening of AM90 Magnesium Alloy Processed by ECAP, Arabian Journal for Science and Engineering, 42 (11) 2017;, 4635–4647.
[17] Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, The process of grain refinement in equal-channel angular pressing, Acta Mater., 48 (1998) 3317–3331.
[18] A. Gholinia, P. B. Prangnell, M. V. Markushev, The effect of strain path on the development of deformation structures in severely deformed aluminum alloys processed by ECAE, Acta Mater., 48 (2000) 1115–1130.
[19] R. Z. Valiev, Structure and mechanical properties of ultrafine-grained metals, Mater. Sci. Eng.A, 234 (1997) 59–66.
[20] Y. Iwahashi, Z. Horita, M. Nemoto, T. G. Langdon, An investigation of microstructure evolution during equal-channel angular pressing, Acta Mater., 45 (1997) 4733–4741.
[21] W. J. Kim, et al, Enhancement of Strength and Superplasticity in a 6061 Al Alloy Processed by Equal-Channel-Angular-Pressing, Metall. Mater. Trans., 33A (2002) 3155–3164.
[22] ASM Handbook®, Volume 8 Mechanical Testing and Evaluation states, 2000.
[23] F. Salimyanfard, et al, Investigation of texture and mechanical properties of copper processed by new route of equal channel angular pressing, Materials and Design, 44 (2013) 374–381.
[24] X. Huang, et al, Strengthening mechanisms in nanostructured aluminum, Materials Science and Engineering A, 483–484 (2008) 102–104.
[25] M. Rashad, N. Nabil Zaafarani, et al, Strain rate effect on deformation of pure Al in equal channel angular pressing, Mansoura Engineering Journal, 40 (3) September 2015.
[26] Maher Rashad Mohamed , Nader Nabil Zaafarani, et al, The effect of compression rate on hardness for pure Al, Al-5083, and Al-1050 with equal channel angular pressing, International Journal of Scientific & Engineering Research, 5 (12); 2014: 356
[27] Y. Estrin, A. Vinogradov, Extreme grain refinement by severe plastic deformation: A wealth of challenging science, Acta Materialia, Volume 61, Issue 3, February 2013, Pages 782-817 .
[28] ASM Handbook®, Volume 4 Heat Treating was published in 1991.
[29] ASM Handbook®, Volume 9 metallography was published in 1992.
[30] MANUAL SUPERSEDES, T.O. 33B-1-1/NAVAIR 01-1A-16-1/TM 1-1500-335-23, DATED 15 SEPTEMBER 2010.
[31] Snopiński P., Tański T., Sroka M., Kremzer M.: The effect of heat treatment conditions on the structure evolution and mechanical properties of two binary Al-Mg aluminum alloys. Metalurgija 56 (3-4) (2017) 329÷332.
[32] ASTM E18-2020 - PDFCOFFEE.COM
[33] Agwa M. A., Ali M. N., Al-Shorbagy A. E.: Optimum processing parameters for equal channel angular pressing. Mech. Mater. 100 (2016) 1÷11.
[34] Snopiński P., Tański T., Sroka M., Kremzer M.: The effect of heat treatment conditions on the structure evolution and mechanical properties of two binary Al-Mg aluminium alloys. Metalurgija 56 (3-4) (2017) 329÷332.

DOI: 10.21608/ERJENG.2023.208328.1176

©Tanta University, Faculty of Engineering
ISSN: 2356-9441 https://erjeng.journals.ekb.eg/ e ISSN: 2735-4873

[35] R. Abrahams, J. Mikhail, P. Fasihi, Effect of friction stir process parameters on the mechanical properties of 5005-H34 and 7075-T651 aluminum alloys, Mater. Sci. Eng. A 751 (2019) 363–373.
[36] P.V. Kumar, G.M. Reddy, K.S. Rao, Microstructure, mechanical and corrosion behavior of high strength AA7075 aluminum alloy friction stir welds – effect of post weld heat treatment, Defense Technology 11 (4) (2015) 362–369.

DOI: 10.21608/ERJENG.2023.208328.1176