PORT SAID ENGINEERING RESEARCH JOURNAL
Faculty of Engineering - Port Said University
Volume 28 No. 2 pp: 110 : 118

Microstructure Characterizations and Mechanical Properties of 1050-aluminum Deformed by Equal Channel Angular Pressing

Elshafey Ahmed Gadallah[1,], Mohamed I. A. Habba[1], Eman El Shrief[2], Abdelkarim Yousif Mohamed[1], and Hossam Hemdan El-Fahhar[1]*

[1] *Mechanical Department (Production), Faculty of Technology and Education, Suez University, Suez, 43221, Egypt, email: Elshafey.Gadallah@ind.suezuni.edu.eg, Mohamed.ibrahim@suezuni.edu.eg, Abdelkarim.Mohamed@ind.suezuni.edu.eg and Hossam.Alfaghaar@suezuniv.edu.eg*

[2] *Production Engineering & Mechanical Design Department Faculty of Engineering, Port Said University, Port Said, 42523, Egypt, email: eman.ahmed@eng.psu.edu.eg*

**Corresponding author,* *DOI: 10.21608/pserj.2024.264575.1315*

Received 3-2-2024,
Revised 10-3-2024,
Accepted 13-3-2024

ABSTRACT

Equal Channel Angular Pressing (ECAP) is a promising severe plastic deformation technique that has gained significant attention for its ability to refine grain structure and enhance mechanical properties in metallic materials. This study focuses on investigating the impact of ECAP with route A and up to three passes on the mechanical properties and microstructure of 1050-aluminum. The study yielded compelling evidence of substantial enhancements in yield strength, ultimate tensile strength, and hardness. Specifically, these properties increased from 58.19 MPa, 67.06 MPa, and 23.85 HV in the annealed state to 133.02 MPa,141.21 MPa, and 38.96 HV after the third pass of the ECAP process, respectively. Furthermore, an interesting observation was made regarding the hardness ratio, which demonstrated a noticeable decrease with an increasing number of ECAP passes. This phenomenon correlated with a reduction in the size of dimples on the fracture surface. Microstructural analysis via scanning electron microscopy SEM confirms a significant reduction in grain size after ECAP passes, indicating the effectiveness of the process in inducing microstructural refinement. These findings collectively underscore the potential of ECAP with route A in enhancing the mechanical properties and microstructure of 1050-aluminum. This research contributes valuable insights into the application of ECAP with route A as a viable strategy for improving the performance of aluminum alloys.

Keywords: ECAP, 1050-aluminum, Mechanical Properties, Microstructure, Hardness

1.INTRODUCTION

In recent times, there has been a growing demand for applications that require various metals and alloys. The most used metals are ferrous alloys such as steel and cast iron. Concurrently, aluminum and its alloys have gained widespread usage owing to their low density, excellent machining capabilities, heightened corrosion resistance, and noteworthy electrical and thermal conductivity. These properties render them particularly well-suited for applications in the aerospace, automotive, and construction industries [1, 2]. Furthermore, there is a growing need for new techniques that utilize Severe Plastic Deformation (SPD), particularly those based on angular pressing methods that result in significant strength and hardness improvements [2-5]. The refinement of metals and metal alloys through SPD has been extensively studied due to their ability to enhance their mechanical and physical properties. Several methods of SPD have shown improved material properties such as high strength, good elasticity, superior plasticity, high wear resistance, improved high exertion cycle life, and favorable corrosion resistance. Among these methods are high-pressure torsion (HPT) [6, 7], accumulative roll bonding (ARB) [8], multiaxial forging (MF) [9], and equal channel angular pressing (ECAP) [10]. An area of significant promise within the realm of nanoscience and nanotechnology revolves around the application of SPD techniques for the production of ultrafine-grain (UFG) materials [1, 11-15]. However, cold plastic deformation can result in a metallographic structure made of elongated grains, which can cause the material to become hard and fragile, increasing the likelihood of breaking during new deformation. To avoid this, the hardening state achieved through annealing should be eliminated before new cold deformation. This results in a structure with proportional grains, lower hardness, and no internal tensions [14, 16-18].

The average grain size plays a pivotal role in influencing the mechanical and physical properties of materials. The strength of materials is intricately linked to the grain size, according to the Hall-Petch Eq. [1, 7].

$$\sigma_y = \sigma_o + k_y d^{-1/2} \quad (1)$$

Where, σ_y, σ_o, k_y and d are yield stress, friction stress, constant of yielding and the grain size respectively. This was also observed in the case of hardness according to the Hall-Petch relation [1, 19, 20].

$$H = H_o + K' d^{-1/2} \quad (2)$$

Where, H and d are the hardness and the grain size, respectively, and Ho and K′ represent constants in the context of this relationship [1, 19, 20].

It can be noted from equations (1) and (2) that the strength and the hardness of the material are increased with the decrease of its grain size. So, the need for producing materials with ultrafine grain size (UFG) increases because of its superior properties over traditional materials with large grain size. Ultrafine-grain (UFG) materials are defined by grain sizes typically less than ~1μm, accompanied by an equiaxed microstructure. These materials exhibit a substantial proportion of grain boundaries, often characterized by a large angle of misorientation [1, 19].

The present research has two main objectives. Firstly, it aims to assess the influence of ECAP processing on both the microstructure and mechanical properties of 1050-aluminum, employing a die with angles of 120°. Secondly, the study aims to explore the effects of employing a reduced pressing rate and a smaller ECAP die angle compared to previous applications. This approach is undertaken with the intent of producing 1050-aluminum characterized by a microstructure comprising a combination of fine and coarse grains, coupled with enhanced mechanical properties.

2.EXPERIMENTAL WORK

The strips labeled 1050-aluminum were cut into strips with dimensions of 5 mm in thickness, 130 mm in length, and 20 mm in width of sample. The chemical composition of the annealed 1050-aluminum is shown in Table 1. The strips underwent an annealing process at 350 °C for a duration of 2 hours followed by furnace cooling at room temperature (RT) before ECAE processing and fully recrystallized starting microstructure.

Table 1. Chemical composition of 1050-aluminum (wt. %).

Si	Fe	Cu	Zn	Mn	Mg	Ti	V	Al
0.142	0.20	0.023	0.019	0.028	0.024	0.017	0.019	Bal.

The die geometry for Equal Channel Angular Pressing (ECAP) is characterized by specific parameters, including channel angles and curvature angles. In this study, the ECAP die is defined by channel angles of 120° and curvature angles (φ) of 30°. The samples were annealed and lubricated with molybdenum disulfide (MoS_2) to reduce friction during the ECAP process before being pressed into the ECAP die [10, 21]. The 1050-aluminum samples were pressed up to 3 passes at RT using a 500 KN universal testing machine (UTM) model (UH-FXh, Europe). The pressing operation was conducted at a speed of 5 mm/min, as illustrated in Fig. 1a. The figure depicts the initial shape of the unprocessed strips alongside the progressively processed samples after 1, 2, and 3 passes of ECAP, as shown in Fig. 1b. The correlation between the strain generated and the mentioned angles is expressed by Eq. (3) [10, 22].

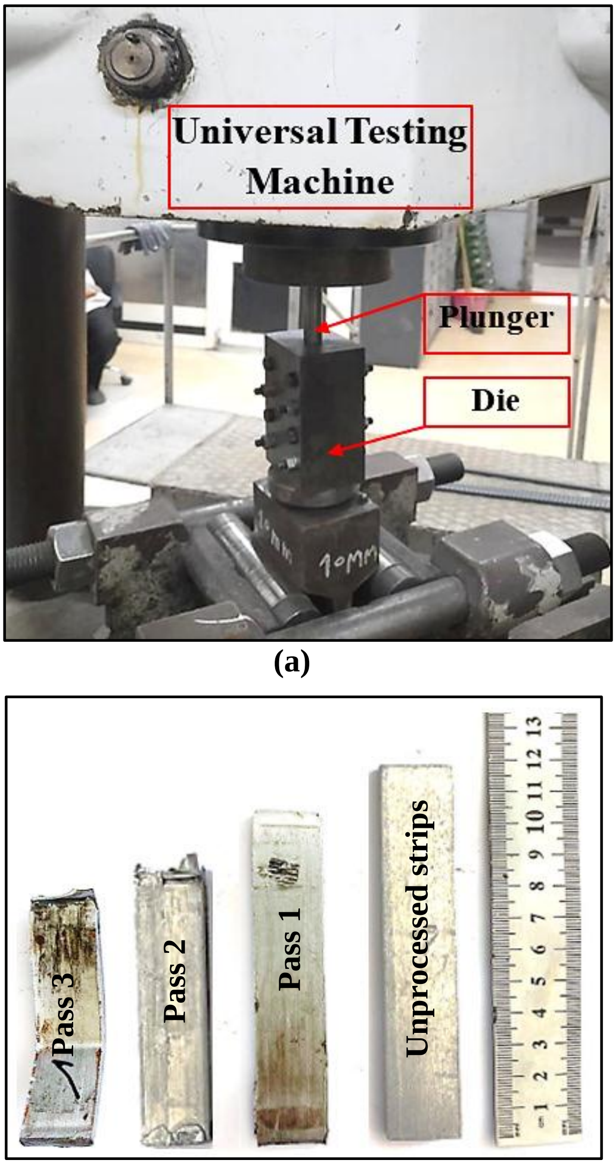
$$\bar{\varepsilon}_{ECAP} = \frac{N}{\sqrt{3}}\left[2\cot\left(\varphi/_2 + \psi/_2\right) + \psi\,\mathrm{cosec}\left(\varphi/_2 + \psi/_2\right)\right] \quad (3)$$

Where φ, ψ, and N of the ECAP, the parameters were selected to die channel angle 120°, 30°, and represent the number of passes, respectively.

The 1050-aluminum strips were processed through the ECAP up to 3 passes through route A at RT. The ECAP was carried out using a die manufactured from H13 cold work steel and hardened to 52 HRC.

The microstructure of 1050-aluminum strips was analyzed using a scanning electron microscope (model XL30SFEG, Philips, Tokyo, Japan) before and after the ECAP process. The process of preparing the 1050-aluminum involved mounting the samples, grinding them, polishing them using an alumina solution, and finally etching them using a mixture of 2.5% HBF solution and 20V for 2-5 min [23].

Tensile samples, with dimensions illustrated in Fig. 2, were tested using the universal testing machine Instron tensile test machine (model 4208-300 kN capacity, Norwood, MA, USA) at room temperature (RT). The testing was carried out until failure, employing a constant strain rate of 8.33×10^{-3} s^{-1}. For robust and reliable results, each test condition was repeated three times. Subsequently, the fracture surface morphology of the tensile samples was examined using Scanning Electron Microscopy SEM (model Quanta FEG 250, FEI Company, Hillsboro, OR USA).



(a)

(b)

Figure 1: (a) the experimental set-up for the ECAP process and (b) unprocessed and ECAP processed samples (after 1, 2 and 3 passes).

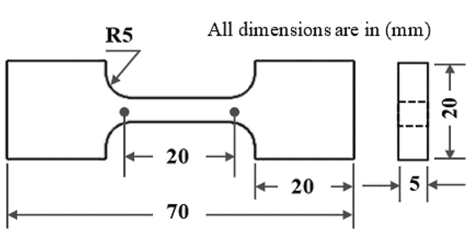


Figure 2: Complete drawing of the tensile test sample.

The hardness of the 1050-aluminum was measured both before and after the ECAP process. The strips were carefully prepared by grinding and polishing them in the longitudinal direction of the width. The Vickers hardness (HV) of the samples was determined at 21 distinct points utilizing a hardness tester machine. A load of 300 g was applied, and the dwell time was set at 15 s. The testing procedure involved assessing the sample along three different lines in the longitudinal direction of the width, and seven lines in the vertical direction for pressing. The measurement locations were spaced 5 mm apart. The average hardness value was obtained for each sample at each position and used to show the hardness distribution. The comprehensive hardness value for each case was represented by calculating the average of all the measured hardness points. The average values are depicted in Fig. 3.

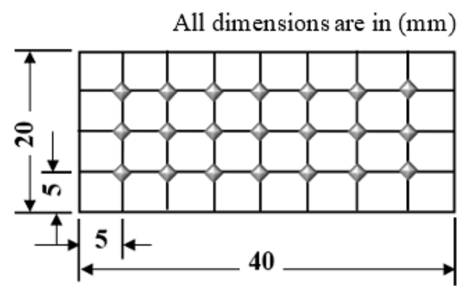


Figure 3: Schematic diagram showing the longitudinal direction in width for indentation locations of hardness for the annealed 1050-aluminum sample before and after ECAP process.

3.RESULTS AND DISCUSSION

3.1 Microstructure Characterizations

In Fig. 4a, the microstructure of the annealed 1050 aluminum exhibited homogeneity in grain size, characterized by a mean grain size of 0.9285 µm. Following the refinement of the 1050-aluminum sample microstructure through Equal Channel Angular Pressing (ECAP), the mean grain size progressively decreased to 0.7651 µm, 0.6588 µm, and 0.4766 µm after 1, 2, and 3 passes, respectively, as illustrated in Fig. 4b-d.

This observed reduction in grain size signifies the efficacy of the ECAP process in achieving finer microstructures with each successive pass. The microstructures of the 1050-aluminum grains underwent further refinement, with the observed limitation in deformation indicating increased brittleness. This phenomenon was particularly evident, as substantial deformation could only be accomplished after 3 passes, consistent with findings reported in prior research [24].

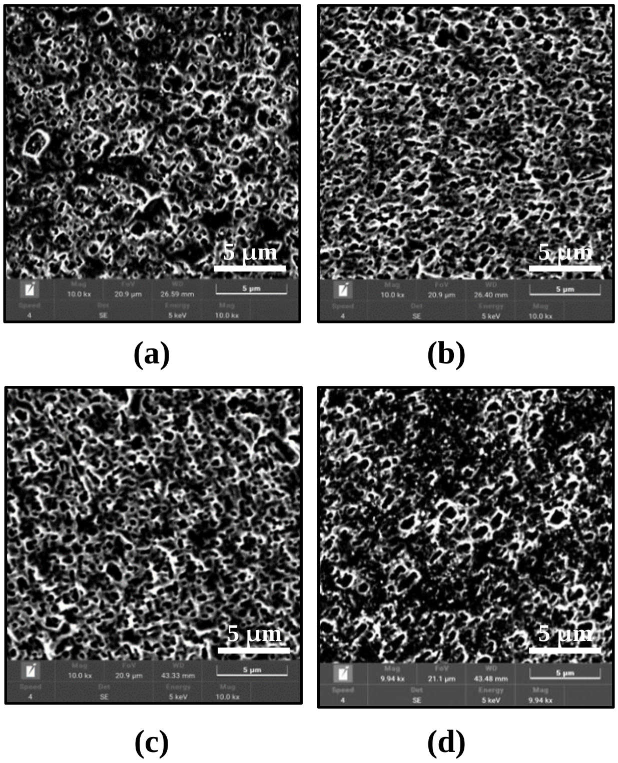


Figure 4: The scanning electron microscopy (SEM) observations: (a) before ECAP, (b) after the first pass, (c) after the second pass and (d) after the third pass of ECAP process.

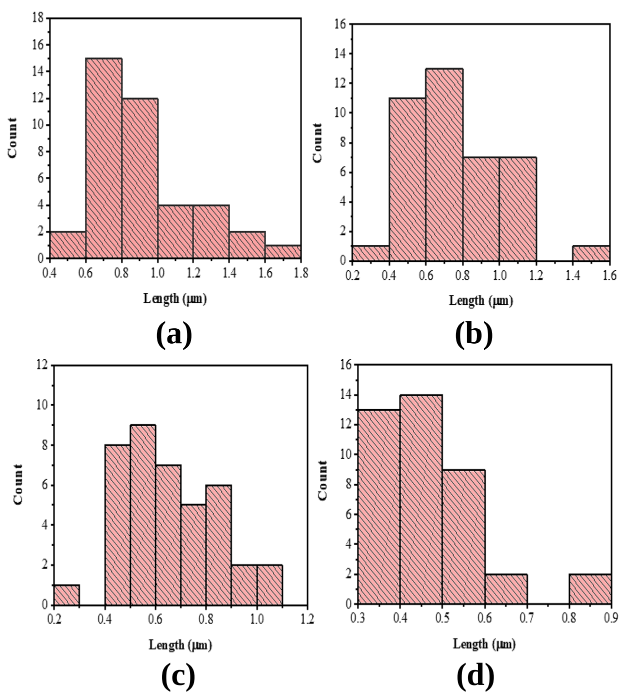


Figure 5: Distribution of grain size; (a) unprocessed before ECAP, and (b) 1 pass, (c) 2 passes, (d) 3 passes of ECAP processed samples.

The grain size distributions depicted in Fig. 5a-d reveal a notable decrease in the range of grain sizes following ECAP processing. Specifically, the grain size diminishes from 0 < d ≤ 1.8 µm in the annealed state to 0 < d ≤ 1.6 µm, 0 < d ≤ 1.2 µm, and 0 < d ≤ 0.9 µm after 1, 2, and 3 passes of ECAP processing, respectively. Additionally, the grain size distribution becomes more uniform, contributing to an overall enhancement in mechanical properties. It is noteworthy that the microstructure of the 1050 aluminum after ECAP processing exhibits UFG sizes, a characteristic known to improve mechanical properties such as tensile strength and hardness while preserving a reasonable degree of ductility. This phenomenon aligns with observations made in other materials subjected to severe deformation processes [19, 25].

3.2 Mechanical Properties

3.2.1 Tensile properties

In Fig. 6, the engineering stress-strain curves of 1050 aluminum depict the impact of the ECAP process on strength and elongation. Notably, the ultimate tensile strength (UTS) and yield strength (σ_y) of 1050-aluminum exhibit enhancement from 67.06 and 58.19 MPa in the annealed state to (102.98 and 94.58 MPa), (121.02 and 112.88 MPa), and (141.21 and 133.02 MPa) after the ECAP processing up to the first, second, and third passes, respectively, as illustrated in Figs. 6 and 7. This consistent trend indicates a positive correlation between the number of ECAP passes and the observed increases in UTS and σ_y values, underscoring the strengthening effect of successive ECAP processing. Moreover, a similar trend in the difference between the UTS values in the case of the ECAP process for route A was also noted in the context of an aluminum alloy, as reported in previous studies [12, 26].

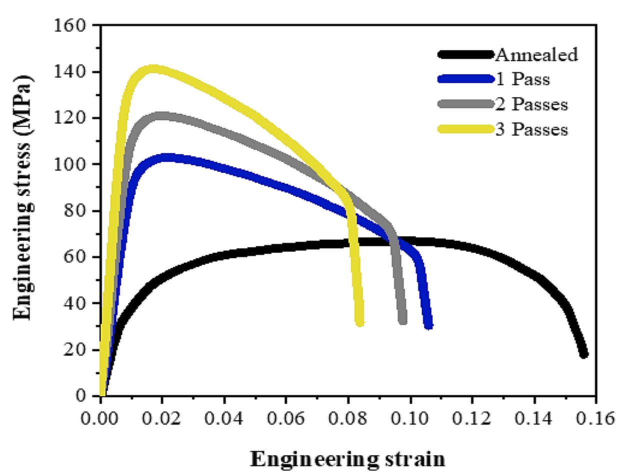


Figure 6: Engineering stress-strain curve of 1050-aluminum of before and after the ECAP processed samples.

The elongation % noted of the ECAP processes decreased drastically with the increased number of passes of the 1050-aluminum processed by route A (Fig. 7). It can be noted that the elongation % is observed to decrease from 15.59 % before the ECAP process to 10.58, 9.76 and 8.37 % after the ECAP up to 1, 2 and 3 passes, respectively (Fig. 7).

It was noted that the elongation percentage exhibited a continuous decrease, albeit at a slower rate, with the progressive increase in the number of passes during the ECAP process, extending up to three passes. The elongation % decrease after the ECAP is due to the grain size decrease, grain refinements, and strain hardening during the cold deformation of 1050-aluminum samples. Similar trends of elongation decrease were also documented in the case of aluminum processed ECAP and continuous close die forging (CCDF) [27, 28]. The concurrent increase in both UTS and σ_y can be attributed to the grain refinement resulting from the ECAP process, aligning with the Hall-Petch relationship [29, 30]. The UTS and σ_y can be obtained depending on the grain size through equation (1) [1, 29, 30].

Using the SPD (Equal Channel Angular Pressing) process, 1050-aluminum has shown improved tensile strength when compared to aluminum bulk and sheet samples that were deformed using different methods [31-35]. These observations suggest that grain refinement achieved by SPD processing is an effective technique to enhance tensile strength in 1050-aluminum using various methods [24, 36, 37].

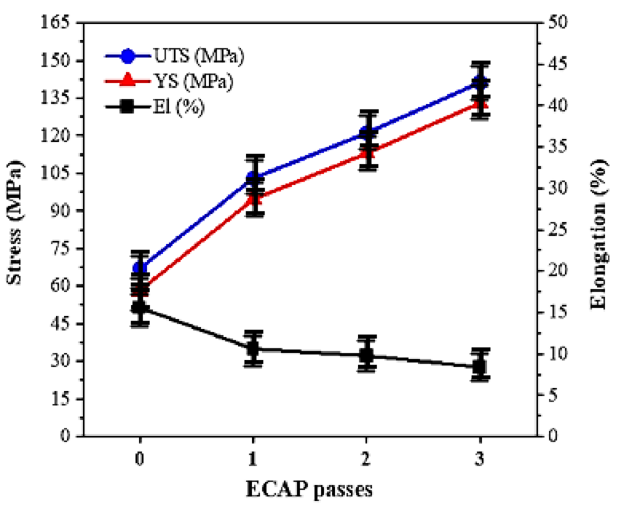


Figure 7: Tensile properties of 1050-aluminum before and after ECAP processed samples.

3.2.1.1 Fracture surface

In Fig. 8, the fracture surface analysis of tensile 1050 aluminum samples is depicted before and after ECAP processing up to three passes. The samples prior to the ECAP pass (Fig. 8a) exhibited larger dimples in the fracture zone, aligning with the grain size measurements. Following the first ECAP pass, the dimples in the fracture zone became predominantly large (Fig. 8b), with some small dimples also evident. The distribution of dimples underwent slight changes with each additional ECAP pass. As the specimens underwent ECAP processing up to the second pass (Fig. 8c), the dimples became shallower and were distributed more uniformly, a trend that became even more pronounced in the third pass (Fig. 8d). An important observation is the significant decrease in the ductility of materials after ECAP, leading to a low uniform elongation. This reduction in ductility implies that there is insufficient time for the dimples to grow and coalesce with other dimples around them during the fracture process. As a consequence, the dimples on the fracture surface become shallower, reflecting the altered deformation behavior of the material due to ECAP processing.

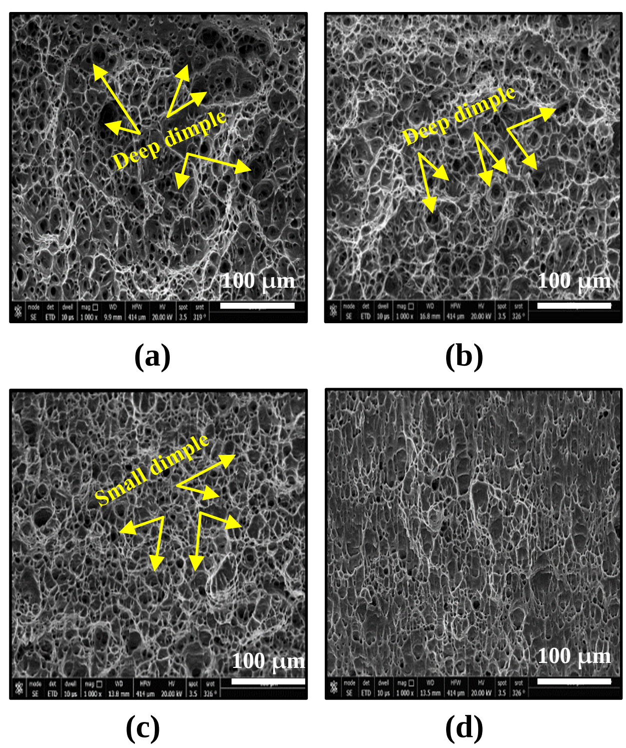


Figure 8: Tensile fractured surfaces of 1050-aluminum before and after the ECAP process: (a) 0 pass, (b) 1 pass, (c) 2 passes and (d) 3 passes.

3.2.2 Hardness results

In Fig. 9, the impact of ECAP processing on the hardness behavior of 1050-aluminum is depicted. The hardness (HV) measurements were performed in the longitudinal direction of width, with equal spacing of

5 mm between measurement locations along the length and width, as indicated in Fig. 3, both before and after the ECAP process. Hardness (HV) measurements were conducted on the UFG samples to assess the influence of the ECAP process and the number of passes on the hardness behavior of 1050-aluminum. The results revealed a significant increase in the hardness value of the extruded 1050-aluminum after the first pass of the ECAP process, rising from 23.85 HV to 31.16 HV. The trend of increasing hardness persisted gradually with each successive pass, culminating in values of 34.18 HV and 38.96 HV after the second and third passes, respectively. Consequently, it can be inferred that there is an approximate 30.65% increase in the hardness magnitude after one pass compared to the un-ECAPed condition. Additionally, there is a close to 43.31% and 63.35% increase in the microhardness value after the second and third pass, respectively, compared to the un-ECAPed condition, as shown in Figs. 9, 10. Therefore, the first pass configuration is primarily responsible for the significant increment in the hardness value.

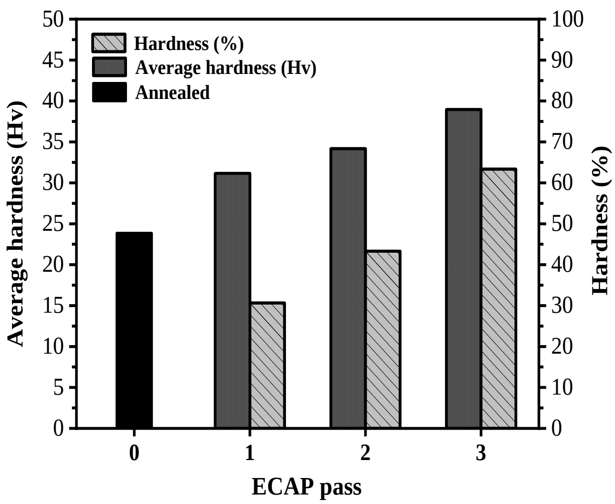


Figure 9: Hardness and hardness percentage in the longitudinal direction of width before and ECAP passes of 1050-aluminum samples.

Experimental findings reveal that the hardness of an aluminum alloy exhibits a more pronounced rate of increase following the initial pass of ECAP. However, it is observed that this rate of increase diminishes over subsequent passes. This diminishing effect can be attributed to various factors such as grain refinement reaching saturation levels or the onset of dislocation annihilation mechanisms, which gradually reduce the efficacy of further processing in enhancing hardness [7, 38, 39]. It is also apparent from (Fig. 9a,b and Fig.10) of the ECAP passes respectively, that the hardness values in the longitudinal direction of thickness further increase after one, two, and three passes. Still, thereafter the hardness remains essentially lower rate of increase up to 3 passes. Additionally, the hardness values of the 1050-aluminum samples were observed to be homogeneously distributed along the longitudinal thickness and transverse width after a total of 3 passes through the Equal Channel Angular Pressing (ECAP) processes. Additionally, it was observed that the error bars were low before ECAP compared with the passes of ECAP. Whereas error bars increased after the first passes followed by decreasing with the increasing number of passes. as depicted in Fig. 10. Moreover, the observed increase in the hardness of 1050-aluminum samples aligns with the tensile results and microstructure observations. The enhancement in hardness is attributed to grain refinement, in accordance with the Hall-Petch relationship [40].

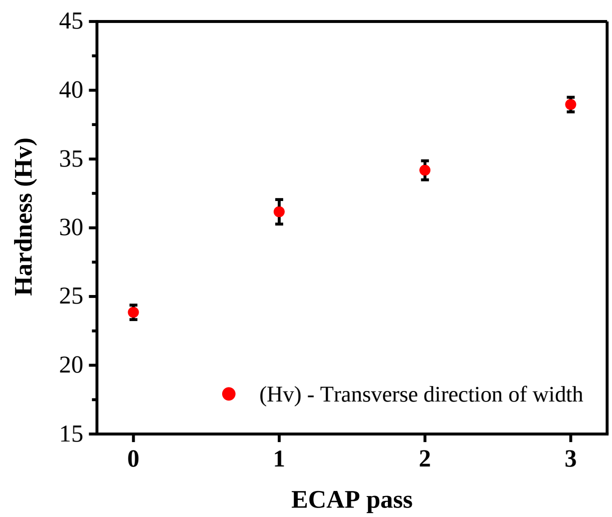


Figure 10: Average hardness and standard deviations (error bar) of 1050-aluminum samples of the annealed before and after ECAP up to 1st, 2nd, and 3rd passes.

4.CONCLUSIONS

In light of the current research, it was concluded the successful implementation of Equal Channel Angular Pressing (ECAP) on 1050-aluminum is as follows:

1. The ECAP process involved the utilization of a die with channel angles and angles curvature φ =120° and ψ =30° respectively, Additionally, a pressing rate of 5 mm/min was applied during the procedure, which was carried out through a series of up to 3 passes.
2. The research results reveal a considerable decrease in grain size, which was observed during the scanning electron microscopy (SEM) analysis of the samples that underwent the Equal Channel Angular Pressing (ECAP) process. This reduction in grain size suggests

that the ECAP treatment effectively alters the microstructure of the 1050-aluminum alloy, leading to finer grains within the material.

3. The ECAP deformation technique leads to both material strengthening and grain refinement. Following the first, second, and third passes, enhancements of approximately 53.56%, 80.47%, and 110.57% have been achieved for the ultimate tensile strength (UTS) compared to the annealed state before the ECAP process. Similarly, the yield strength (σy) increased by approximately 62.54%, 93.98%, and 128.59% after the first, second, and third passes, respectively, compared to the annealed condition. Additionally, the elongation to failure percentage decreased by approximately 32.14%, 37.39%, and 46.31% compared to the annealed condition, corresponding to the 1^{st}, 2^{nd}, and 3^{rd} passes, respectively. The enhancement level of mechanical properties is markedly notable for the initial pass and progressively rises with each successive ECAP pass.
4. In the annealed strip, a ductile fracture was identified, distinguished by a prominent necking zone and deep dimples. However, subsequent to the Equal Channel Angular Pressing (ECAP) process, a discernible change in fracture characteristics was observed. The size and depth of the dimples notably decreased, a transformation attributed to the grain refinement accomplished through ECAP. This alteration in fracture features underscores the influence of grain size on the mechanical properties and fracture behavior of the Al material.
5. A significant enhancement in the hardness of the 1050-aluminum as the number of ECAP passes increased. The hardness values progressed from 23.85 HV in the annealed state to 31.16 HV and 38.96 HV after 1 and 2 passes, respectively. Notably, this represents an impressive increase by a factor of 7.8 HV after the first pass, equivalent to a percentage rise of approximately 25.03%. These findings underscore the positive influence of the ECAP process on both the fracture behavior and mechanical properties, particularly hardness, in the examined aluminum.

Acknowledgments

The author would like to express his gratitude to the Mechanical and Civil Departments of the Faculty of Technology and Education at Suez University, Egypt, for their support in the experimental work (Heat-treatment and Pressing test). Special thanks are also due to Eng. Maher haridy, director of the central laboratories of Ezz Flat Steel, Ain Sokhna, Egypt, for his invaluable help in completing the mechanical testing (Tensile and Hardness tests).

Credit Authorship Contribution Statement

Elshafey Ahmed Gadallah (E.A.G.): Generating the idea, collecting data, Methodology & Original draft preparation, **Elshafey A. Gadallah (E.A.G.), Mohamed I. A. Habba, Abdelkarim Y. Mohamed, Hossam H. El-Fahhar, and Eman El Shrief:** Reviewing & Supervision, **Elshafey A. Gadallah (E.A.G.), Mohamed I. A. Habba, Abdelkarim Y. Mohamed, Hossam H. El-Fahhar, and Eman El Shrief:** Validation, Editing, Reviewing & Supervision. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Declaration of Funding

This research received no external funding.

5.REFERENCES

[1] R. Z. Valiev, and T. G. Langdon, "Principles of equal-channel angular pressing as a processing tool for grain refinement," *Progress in Materials Science*, vol. 51, no. 7, pp. 881-981, 2006/09/01/, 2006.

[2] A. Azushima, R. Kopp, A. Korhonen, D.Y. Yang, F. Micari, G.D. Lahoti, P. Groche, J. Yanagimoto, N. Tsuji, A. Rosochowski, and A. Yanagida, "Severe plastic deformation (SPD) processes for metals," *CIRP Annals*, vol. 57, no. 2, pp. 716-735, 2008/01/01/, 2008.

[3] R. Z. Valiev, Y. Estrin, Z. Horita, T. G. Langdon, M. J. Zehetbauer, and Y. Zhu, "Producing Bulk Ultrafine-Grained Materials by Severe Plastic Deformation: Ten Years Later," *JOM*, vol. 68, no. 4, pp. 1216-1226, 2016/04/01, 2016.

[4] L. S. Toth, and C. Gu, "Ultrafine-grain metals by severe plastic deformation," *Materials Characterization*, vol. 92, pp. 1-14, 2014/06/01/, 2014.

[5] M. I. Abd El Aal, and E. A. Gadallah, "Parallel Tubular Channel Angular Pressing (PTCAP) Processing of the Cu-20.7Zn-2Al Tube," *Materials*, vol. 15, no. 4, pp. 1469, 2022.

[6] M. I. A. El Aal, H. H. El-Fahhar, A. Y. Mohamed, and E. A. Gadallah, “Influence of High-Pressure Torsion Processing on the Tribological Properties of Aluminum Metal Matrix Composites,” *Materials*, vol. 16, no. 1, pp. 216, 2023.

[7] M. I. Abd El Aal, H. H. El-Fahhar, A. Y. Mohamed, and E. A. Gadallah, “The Mechanical Properties of Aluminum Metal Matrix Composites Processed by High-Pressure Torsion and Powder Metallurgy,” *Materials*, vol. 15, no. 24, pp. 8827, 2022.

[8] Y. Saito, H. Utsunomiya, N. Tsuji, and T. Sakai, “Novel ultra-high straining process for bulk materials-development of the accumulative roll-bonding (ARB) process,” *Acta Materialia*, vol. 47, no. 2, pp. 579-583, 1999/01/15/, 1999.

[9] P. Trivedi, K. C. Nune, R. D. K. Misra, S. Goel, R. Jayganthan, and A. Srinivasan, “Grain refinement to submicron regime in multiaxial forged Mg-2Zn-2Gd alloy and relationship to mechanical properties,” *Materials Science and Engineering: A*, vol. 668, pp. 59-65, 2016/06/21/, 2016.

[10] E. A. Gadallah, M. A. Ghanem, M. Abd El-Hamid, and A. E. El-Nikhaily, “Effect of tin content and ECAP passes on the mechanical properties of Cu/Sn alloys,” *Port-Said Eng. Res. J*, vol. 18, no. 1, pp. 79-89, 2014.

[11] K. Edalati, Y. Hashiguchi, H. Iwaoka, H. Matsunaga, R. Z. Valiev, and Z. Horita, “Long-time stability of metals after severe plastic deformation: Softening and hardening by self-annealing versus thermal stability,” *Materials Science and Engineering: A*, vol. 729, pp. 340-348, 2018/06/27/, 2018.

[12] E. A. El-Danaf, M. S. Soliman, A. A. Almajid, and M. M. El-Rayes, “Enhancement of mechanical properties and grain size refinement of commercial purity aluminum 1050 processed by ECAP,” *Materials Science and Engineering: A*, vol. 458, no. 1, pp. 226-234, 2007/06/15/, 2007.

[13] Z. Horita, S. Lee, S. Ota, K. Neishi, and T. G. Langdon, “Equal-Channel Angular Pressing as a Production Tool for Superplastic Materials,” *Materials Science Forum*, vol. 357-359, pp. 471-476, 2001.

[14] J. Zhang, K.-s. Zhang, H.-C. Wu, and M.-h. Yu, “Experimental and numerical investigation on pure aluminum by ECAP,” *Transactions of Nonferrous Metals Society of China*, vol. 19, no. 5, pp. 1303-1311, 2009/10/01/, 2009.

[15] A. Alshafey, M. Abd El-Aal, R. Ramadan, and A. El-Nikhaily,“Effect of PTCAP Passes on the Mechanical Properties of Copper Tubes,” *Port-Said Engineering Research Journal*, vol. 21, no. 2, pp. 164-172, 2017.

[16] X. Wang, P. Li, and K. Xue, “Strain effect on grain refinement and thermal stability of ultrafine-grained molybdenum processed by severe plastic deformation,” *Procedia Manufacturing*, vol. 15, pp. 1487-1494, 2018/01/01/, 2018.

[17] E. A. El-Danaf, M. S. Soliman, and A. A. Almajd, “EBSD investigation of the microstructure and microtexture evolution of 1050 aluminum cross deformed from ECAP to plane strain compression,” *Journal of Materials Science*, vol. 46, no. 10, pp. 3291-3308, 2011/05/01, 2011.

[18] E. A. El-Danaf, M. S. Soliman, and A. A. Almajid, “Effect of deformation path change on plastic response and texture evolution for 1050 Al pre-deformed by ECAP and subsequently plane strain compressed,” *Materials Science and Engineering: A*, vol. 527, no. 10, pp. 2547-2558, 2010/04/25/, 2010.

[19] M. S. Soliman, E. A. El-Danaf, and A. A. Almajid, “Effect of Equal-Channel Angular Pressing Process on Properties of 1050 Al Alloy,” *Materials and Manufacturing Processes*, vol. 27, no. 7, pp. 746-750, 2012/07/01, 2012.

[20] M. I. A. E. Aal, and H. S. Kim, “Wear properties of high pressure torsion processed ultrafine grained Al–7%Si alloy,” *Materials & Design*, vol. 53, pp. 373-382, 2014/01/01/, 2014.

[21] M. I. Abd El Aal, H. H. El-Fahhar, A. Y. Mohamed, and E. A. Gadallah,“Influence of Parallel Tubular Channel Angular Pressing (PTCAP) Processing on the Microstructure Evolution and Wear Characteristics of Copper and Brass Tubes,” *Materials*, vol. 15, no. 9, 2022.

[22] M. I. Abd El Aal, H. Yong Um, E. Yoo Yoon, and H. Seop Kim,“Microstructure evolution and mechanical properties of pure aluminum deformed by equal channel angular pressing and direct extrusion in one step through an integrated die,” *Materials Science and Engineering: A*, vol. 625, pp. 252-263, 2015/02/11/, 2015.

[23] M. C. V. Vega, B. H. Piva, R. E Bolmaro, M. Ferrante, and A. M. Kliauga,“ The texture development of ECAP processed AA1050 aluminum, before and after a final anneal: effect of the initial texture,” IOP Conference Series: Materials Science and Engineering 63, no. 1, pp. 012152, 2014/04/07/, (2014).

[24] M. S. Soliman, E. A. El-Danaf, and A. A. Almajid, “Enhancement of static and fatigue strength of 1050 Al processed by equal-channel angular pressing using two routes,” *Materials Science and Engineering: A*, vol. 532, pp. 120-129, 2012/01/15/, 2012.

[25] P. Ahmadian, A. Akbarzadeh, P. Asadi, and A. K. Saxena,“Achieving an Optimal Balance of Strength and Elongation in AA 1050 Aluminum Alloy via Equal Channel Angular Pressing, Intermediate Annealing, and Post-Rolling,” *Journal of Materials Engineering and Performance*, vol. 31, no. 12, pp. 9573-9585, 2022/12/01, 2022.

[26] P. M. Keshtiban, and F. Bashirzadeh, “Experimental Investigation of Multi-pass ECMAP Process,” *Transactions of the Indian Institute of Metals,* vol. 72, no. 1, pp. 239-244, 2019/01/01, 2019.

[27] A. P. Zhilyaev, M. J. Torres, H. D. Cadena, S. L. Rodriguez, J. Calvo, and J.-M. Cabrera,“The Effect of Pre-Annealing on the Evolution of the Microstructure and Mechanical Behavior of Aluminum Processed by a Novel SPD Method,” *Materials,* vol. 13, no. 10, pp. 2361, 2020.

[28] J. Valder, M. Rijesh, and A. Surendranathan, “Forming of tubular commercial purity aluminum by ECAP,” *Materials and Manufacturing Processes,* vol. 27, no. 9, pp. 986-989, 2012.

[29] E. O. Hall, “The Deformation and Ageing of Mild Steel: III Discussion of Results,” *Proceedings of the Physical Society. Section B,* vol. 64, no. 9, pp. 747-753, 1951/09/01, 1951.

[30] S. N. Naik, and S. M. Walley, “The Hall–Petch and inverse Hall–Petch relations and the hardness of nanocrystalline metals,” *Journal of Materials Science,* vol. 55, no. 7, pp. 2661-2681, 2020/03/01, 2020.

[31] C. Illgen, B. Bohne, M. F.-X. Wagner, M. Gruber, W. Volk, and P. Frint, “Facing the Issues of Sheet Metal Equal-Channel Angular Pressing: A Modified Approach Using Stacks to Produce Ultrafine-Grained High Ductility AA5083 Sheets,” *Advanced Engineering Materials,* vol. 23, no. 9, pp. 2100244, 2021/09/01, 2021.

[32] Z. S. Zahari, D. N. Awang Sh’ri, M. A. H. Abu Hassan, and and W. S. Wan Harun, “Effect of ECAP die angle to the microstructure and mechanical properties of bulk nanostructured Al-6061,” *IOP Conference Series: Materials Science and Engineering,* vol. 469, no. 1, pp. 012054, 2019/01/01, 2019.

[33] N. Sadasivan, M. Balasubramanian, and B. R. Rameshbapu, “A comprehensive review on equal channel angular pressing of bulk metal and sheet metal process methodology and its varied applications,” *Journal of Manufacturing Processes,* vol. 59, pp. 698-726, 2020/11/01/, 2020.

[34] Z. Bézi, G. Krállics, M. El-Tahawy, P. Pekker, and J. Gubicza,“Processing of ultrafine-grained titanium with high strength and good ductility by a combination of multiple forging and rolling,” *Materials Science and Engineering: A,* vol. 688, pp. 210-217, 2017/03/14/, 2017.

[35] L. Jiang, O. A. Ruano, M. E. Kassner, and M. T. Pérez-Prado,“The fabrication of bulk ultrafine-grained zirconium by accumulative roll bonding,” *JOM,* vol. 59, no. 6, pp. 42-45, 2007/06/01, 2007.

[36] M. Salamati, S. Tamimi, S. Moturu, G. Sivaswamy, M. Qarni, and A. Rosochowski, “Microstructure and mechanical properties of Al-1050 during incremental ECAP,” *IOP Conference Series: Materials Science and Engineering,* vol. 194, no. 1, pp. 012009, 2017/05/01, 2017.

[37] D. C. C. Magalhães, O. M. Cintho, V. L. Sordi, and A. Kliauga, “Improved tensile properties in heterostructured 1050/7050 Al sheets produced by accumulative roll bonding,” *Journal of Materials Research and Technology,* vol. 17, pp. 2014-2025, 2022/03/01/, 2022.

[38] M. Wroński, K. Wierzbanowski, R. Malik, S. Wroński, D. Wojtas, A. Baczmański, and J. Tarasiuk,“Microstructure Characteristics of ECAP Processed 1050 Aluminum After Deformation and 5 Years Later,” *Metals and Materials International,* vol. 27, no. 8, pp. 2720-2731, 2021/08/01, 2021.

[39] B. Shivashankara, G. K. R, S. Pradeep, and R. R. Rao,“Investigation of mechanical properties of ECAP processed AL7068 aluminium alloy,” *IOP Conference Series: Materials Science and Engineering,* vol. 1189, pp. 012027, 10/01, 2021.

[40] S. Naik, and S. M. Walley, “The Hall–Petch and inverse Hall–Petch relations and the hardness of nanocrystalline metals,” *Journal of Materials Science,* vol. 55, 03/01, 2020.