Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 09 September-2026, Page No.- 11507- 11516
DOI: 10.47191/etj/v11i09.13, I.F. – 8.595

Performance Analysis of Equal Channel Angular Pressing (ECAP) on Al-Mg Alloy at Varied Temperatures

Omenka, Kenneth Ikoni[1], Gundu, Terfa David[2], Ashwe, Abugh[3]
[1,2,3]Department of Mechanical Engineering, Joseph Sarwuan Tarka University P.M.B. 2327, Makurdi Benue State Nigeria

ABSTRACT: The application of severe plastic deformation (SPD)techniques to refine the microstructure and enhance the mechanical properties of metallic materials presents a promising avenue for advancements in materials science. Amongst the several SPD techniques, the high pressure torsion (HPT) and the equal channel angular pressing (ECAP) are the most explored. Equal angular channel pressing (ECAP) is a severe plastic deformation technique in which billet is passed through a die at a specific rate and undergoes shear deformation before coming out. ECAP which stands out as a promising and cost-effective technique for processing various materials was performed on Al-Mg alloys at varied temperatures. In this study, Al-Mg alloy samples were ECAP processed at temperatures of 90, 100, 120, 140 and 150°C for four (4) ECAP passes. Microstructural examination and mechanical property assessment of ECAP processed billets was performed. The mechanical property assessments of the ECAPed processed billets showed a notable increase in both Ultimate tensile strength (UTS) and Yield strength (YS) of the alloy. At 90 °C temperature, the YS and UTS increased from 223 and 319 MPa to 271 and 387 MPa respectively. Similarly, an upward trend occurred at 100, 120, 140 and 150 °C. However, there was a significant reduction in percentage elongation at all temperatures with values 7.0 to 3.6 (90 °C), 7.7 to 3.3 (100 °C), 6.9 to 3.2 (120 °C), 6.7 to 3.1 (140 °C) and 6.5 to 3.0 (150 °C). The microstructure of the extruded samples revealed the presence of blow holes and the sizes of individual grains could not be clearly distinguished at the different temperatures for the first pass. However, as the number of ECAP passes increased, a notable increase in the quantity of shear bands is revealed. Also, grains displayed elongations aligning parallel to transverse directions and after 4 passes, a significant refinement occurred. ECAP was found to be a viable method for improving the mechanical properties and refining the grain size of Al-Mg alloys.

KEYWORDS: Equal Channel Angular Pressing, Al-Mg Alloy, Temperature Variation, Microstructure, Mechanical Properties

1.0 INTRODUCTION

The continual quest for advanced materials with enhanced mechanical properties has over the years given rise to the introduction of severe plastic deformation (SPD) techniques. Conventional plastic deformation methods such as rolling or extrusion fall short in producing ultra-fine grained (UFG) materials (Roberto et al., 2022). The development of the principles of SPD techniques dates back to the 1930s to the pioneering work of P.W Bridgman of Harvard university. His work focused on the effects of a combination of large hydrostatics pressures and simultaneous shear deformation acting on solids. The main objective of this process is to produce very strong and lightweight parts that would find applications in engineering practice (Jia et al., 2023; Muhammad et al., 2017). Severe plastic deformation (SPD) techniques such as high-pressure torsion (HPT) and accumulated roll bonding (ARB) have shown promise but are not without limitations. HPT is constrained to certain materials such as Cu, Ti, steel, and Mg alloys (Thiyaneshwaran and Sureshkumar, 2013). On the other hand, ARB faces challenges like material fracture and remains at an experimental stage (Snopiński et al., 2019).

Equal channel angular pressing is used to deform materials through shear deformation. Here samples are passed through a die at a specific rate and undergoes shear deformation before coming out. Equal Channel Angular Pressing (ECAP) technique has emerged as a versatile method in metalworking offering unique opportunities for the fabrication of ultra-fine-grained metals and alloys. Furthermore, its ability to enhance mechanical properties such as strength and hardness without altering the sample's cross-sectional dimensions has gained it significant attention (Tsuji et al., 2003). ECAP can be used for industrial application as a continuous flow process that results in material grain refinement thereby increasing material strength (Krajňák et al., 2020). Numerous studies have investigated the impact of ECAP on various alloys. For instance, Snopiński, et al (2019) demonstrated that ECAP enhances the mechanical properties of al alloy by refining the grain structure. However, their work primarily focused on effects of ECAP with helical die on microstructure, grain refinement, and hardness of Al-3%Mg alloy. Another study by Hajizadeh, et al, (2023) explored the effects of ECAP processing routes on the microstructural characteristics of commercial pure titanium. Their study showed that different processing routes can influence the degree of grain refinement and mechanical properties of titanium. Damavandi, E., et al (2019) investigated the effects of ECAP on microstructure and tensile properties of A390 aluminum alloy. Their study demonstrated that ECAP significantly improved the tensile strength and refined the microstructure. Thiyaneshwaran et al. (2013) noted that ECAP involves the repetitive shear deformation of the material through an angular channel leading to significant grain refinement and alteration of dislocation density. Despite these advances, most studies do not comprehensively address the role of temperature in ECAP processing. The success of this process is controlled by several factors with temperature emerging as a vital parameter influencing the outcome. The role of temperature in ECAP process cannot be overstated since it not only affects the materials ductility or formability but also influences the kinetics of microstructural evolution during plastic deformation.

Al-Mg alloys are known for their excellent corrosion resistance and favorable strength – to – weight ratio. There are widely used in aerospace, automotive and marine industries. Optimizing their mechanical properties through ECAP could lead to more efficient and high-performance components (Khelfa et al., 2021). Furthermore, Al-Mg alloy's microstructure plays a very crucial role in the determination of its mechanical properties and by subjecting it to ECAP, an unprecedented improvement in its performance is unlocked (Snopiński et al., 2019). However, the influence of processing temperature on the performance of Al-Mg alloys during ECAP is not yet fully understood. This study aims to fill this knowledge gap by analyzing the effect of varied temperatures on the mechanical properties and microstructure of Al-Mg alloys processed through ECAP.

2.0 MATERIALS AND METHOD

2.1 Material collection and preparation

The Al-Mg alloy was prepared using sand casting method and machined into rods with dimensions 19.5 x 19.5 x 70 mm. The full characteristics of the Al-mg alloy was determined using optical emission spectroscopy (OES) machine with model number MAXx LMF14 (see table 1). H13 Tool steel was machined to match the dimensions shown in Figure 1 to produce the ECAP rig. The ECAP die had a diameter of 20mm rectangular cross section with an inner channel angle (ϕ) of 90° and a twist or outer channel angle (ψ) of 20°. The die was polished for final smooth surface finishing. The plunger was machined to dimension 19.5x19.5x170 mm. The thermocouple (DTC XMTD-2301M) and heating elements (immersion cartridge heating rods) were connected to a digital temperature controller. The entire set up was assembled as illustrated in Figure 2 and 3.

Table1: Chemical Composition of produced billet

Elements	Si	Ag	Cr	Pb	Zr	Be	Bi	Fe	Cu	Mn
% Composition	0.4	0.0028	0.031	<0.0010	0.00070	0.0029	0.0029	0.4	0.0.109	0.070
	Zn	Ti	Cr	Mg	Al					
	0.050	0.037	0.07	4.61l	Bal					

2.2 Lab extrusion process

The ECAP die had an internal channel angle of 90° with an outer radius of curvature of 20°. Billets were subjected to four passes using route Bc (90° rotation between consecutive passes). ECAP was conducted at temperatures 90 °C, 100 °C, 120 °C, 140 °C and 150 °C. The temperature range was selected based on a thorough review of literature and preliminary experiments. Furthermore, a pressing speed of 2mm/s was maintained during the extrusion process. Molybdenum disulfide was used as lubricant to reduce the friction between the billet and the walls of the die.

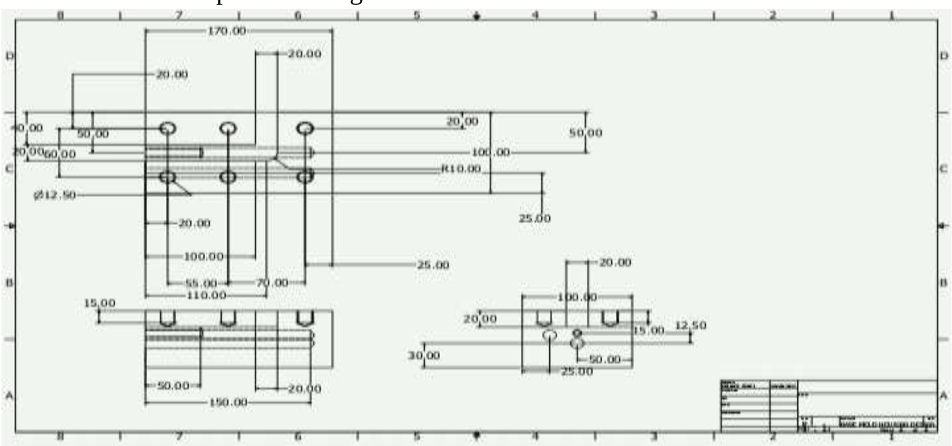


Figure 1: Schematic Diagram of ECAP Extrusion Rig.

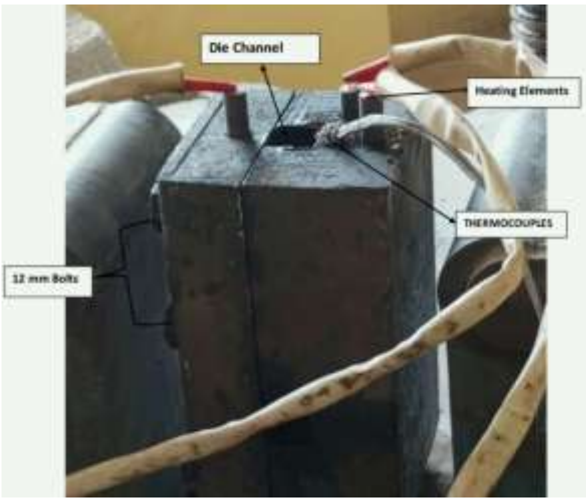


Figure 2: Assembly of ECAP Extrusion Rig

Microstructural examination was conducted on the ECAP processed billets using an optical microscope with model number MM039BOOM in accordance to the ASTM F410 standard. Also, Vickers hardness measurements was performed on the ECAPed samples to ascertain the resistance of the material to plastic deformation. Tensile tests were conducted using a universal testing machine (WA-1000) to evaluate the alloys mechanical strength and deformation behavior under varying temperatures.

Figure 3: Experimental set up for extrusion of billets

3.0 RESULTS

3.1 Hardness Test

Variation of the evolution of hardness for Al-Mg alloy at different processing temperature after each ECAP pass is shown in Figure 4 (a and b). The results showed that ECAP processing temperature have significant influence on the hardness of the extrudes. However, this influence changes with the applied temperature.

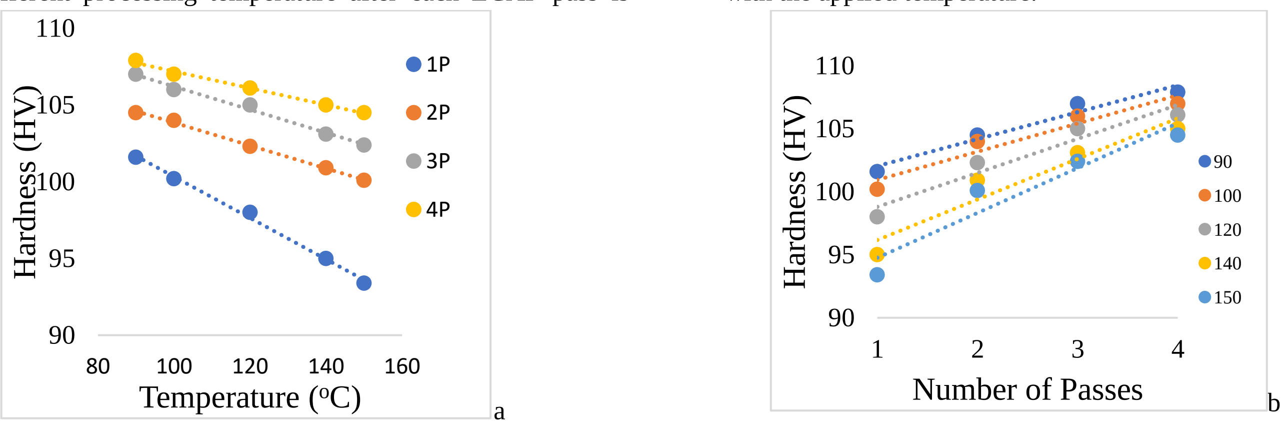


Figure 4: a: Plot of microhardness against extrusion temperature; b: Plot of microhardness against number of Passes.

The result (Figure 4a) showed that reducing the processing temperature increased the hardness of the ECAPed billet. At 90 ºC processing temperature, the processed samples revealed a notable increase in HV values from the as-cast value (76HV) to 101.6HV (1P), 104.5HV (2P), 107HV (3P), and 107.9HV (4P) respectively. Similarly, HV values increased with increase in the number of passes for 100 ºC, 120 ºC, 140 ºC and 150°C processing temperatures. This is because increase in temperature leads to an increase in thermal energy which aids dislocation movement and reduces resistance to deformation (Gupta et al., 2022). Furthermore, the cumulative effects of plastic deformation and strain hardening during each ECAP pass increases the hardness of the material (Gupta et al., 2022; Afifi et al., 2018). The optimum HV value for processed samples was obtained at 90 ºC temperature(107.9HV) after 4P. This phenomenon is in agreement with studies by Snopiński et al., (2019) who noted at lower ECAP temperature and 4 number of passes, high microhardness of processed alloy can be obtained whereas at higher extrusion temperatures, the microhardness of Al-Mg alloy could be affected. This is because higher deformation temperature and lower strain rate leads to formation of coarse grains resulting in lower material hardness (Snopiński et al., 2019)

The result (Figure 4a) is negatively linear and is related by the equation Y = - m(x)+b where Y represents the independent variable (hardness), x represents the independent variable (temperature), m is the slope of the line which is the rate of change of (Y) with respect to (x) and b is the y-intercept, indicating the value of (y) when (x) is zero. This is because elevated temperatures can promote grain growth which may result in decreased hardness since larger grain sizes are generally associated with lower strength and hardness (Dhankne et al., 2022). Also, the result (Figure 4b) is positively linear. This is because as the number of ECAP passes is increased, its hardness tends to increase. This trend can be used to predict the material behavior during the ECAP process relative to the number of passes and temperature.

3.2 Tensile Test

Yield strength, ultimate tensile strength and percentage elongation for ECAPed Al-Mg alloy are shown in Figures 5 to 7 respectively.

The result of yield strength and ultimate tensile strength (Figure 5 and 6) showed that processing temperature influences the strength of the extrude. However, this varies with the number of passes employed. The result (Figure 5a & 6a) showed increasing the processing temperature leads to reduction in strength for the extrudes. This is attributed to several factors such as low deformation, accumulated strain and work hardening. Figure 5b & 6b showed that across all temperatures explored, an increase in the number of passes increased the yield strength and ultimate tensile strength of the ECAPed al-mg alloy. This further confirms the findings of a study by Damavandi et al, (2019) which investigated the effect of ECAP on the microstructure and tensile properties of A390 aluminium alloy. Their study noted that ECAP significantly improved the tensile strength of the extrudes and refined the microstructure. Thiyanshwaran and Sureshkumar (2013) also found that enhanced tensile strength and wear resistance is achieved through ECAP extrusion process.

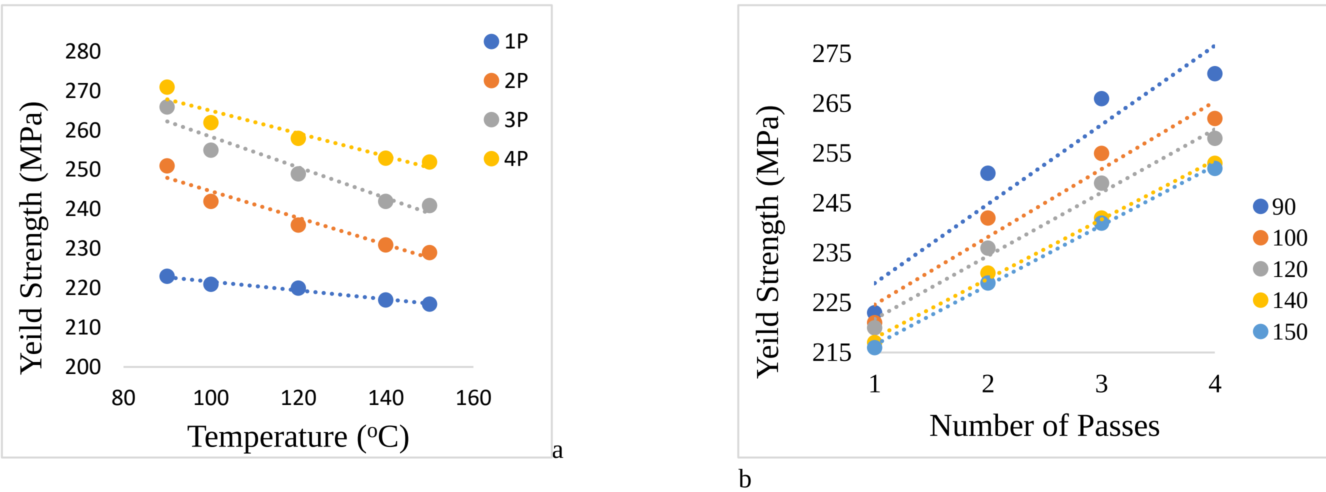


Figure 5: a: Plot of yield strength against temperature; b: Plot of yield strength against number of passes.

The result also showed that at processing temperature 90 ºC, a gradual increase in the values of σ_y and σ_{ult} (223 MPa and 319 MPa) occurred for the first ECAP pass. The values of σ_y and σ_{ult} continued to increase up until the 4th pass (271MPa and 387MPa). This is because, the material becomes harder and more resistant to plastic deformation with each successive ECAP pass. Furthermore, the rise in yield strength shows significant strengthening effects and changes in the materials microstructure induced by severe plastic deformation (Snopiński et al., 2019).

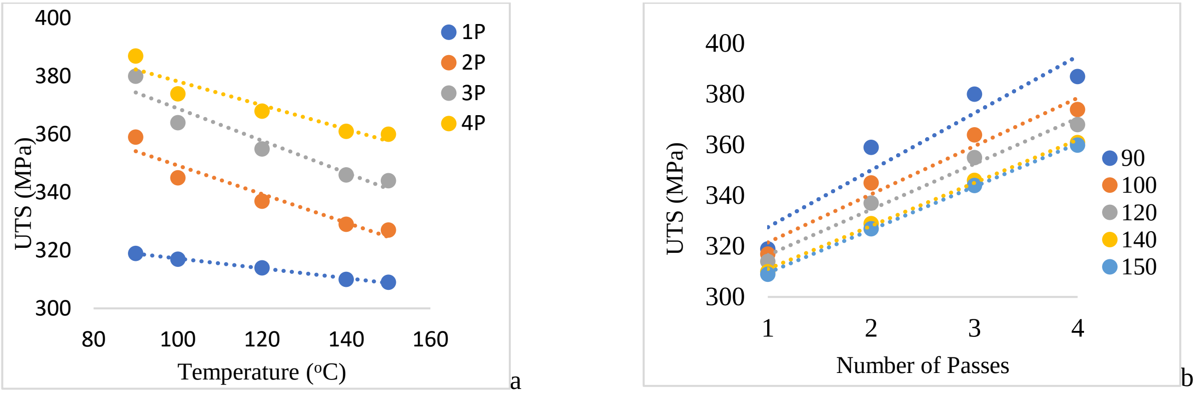


Figure 6: a: Plot of ultimate tensile strength against temperature; b: Plot of ultimate tensile strength against number of passes.

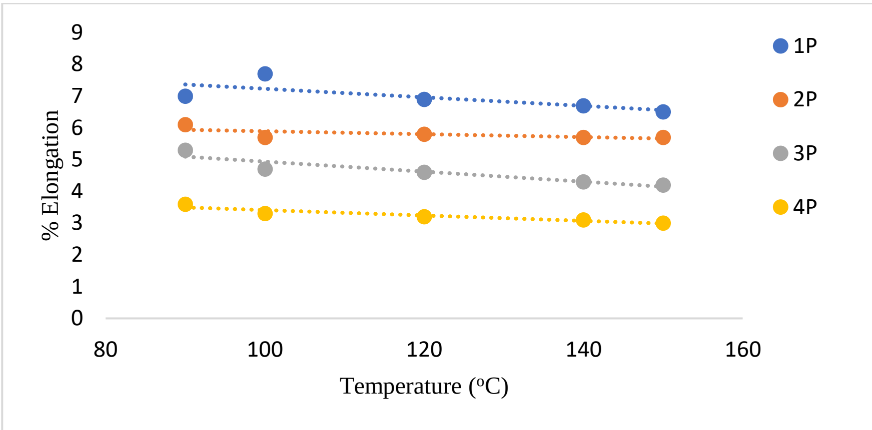


Figure 7: Plot of % Elongation against temperature

Yield strength and ultimate tensile strength tends to vary with temperature (see Figure 5a &6a). this indicates that elevated temperatures influence the yield strength and ultimate tensile strength of extrude. The result agrees with the findings of the study by Injor, (2023) who noted that significant improvement in the tensile properties of extrudes is achieved using ECAP. A decrease in percentage elongations was seen (see Figure 7) across all temperatures employed with 150 ºC after 4 ECAP passes possessing the lowest percentage elongation value of 3.0%. Generally, the mechanical properties, that is yield strength, ultimate tensile strength, and percent elongation, exhibit temperature-dependent characteristics with increasing strength and decreasing ductility with higher temperatures and more extrusion passes. The tensile test results are reasonably in good agreement with microhardness data as described by Shaeri *et al.*, (2016).

Negative linear trend for yield strength ultimate tensile strength and % elongation against temperature as shown in figures 5a, 6a and 7 respectively. This trend revealed that material behaviors is influenced by temperature variations. The trend is characterized by the equation Y = -m(x) + b where Y represents the independent variable (pressing pressure), x represents the independent variable (temperature), m is the slope of the line which is the rate of change of (Y) with respect to (x) and b is the y-intercept, indicating the value of (y) when (x) is zero. Also, Figure 5b and 6b is characterized by a positive linear trend indicating an increase in material mechanical property with increase in number of passes.

3.3 Microstructure

The microstructure of the extrude at varied temperatures for 4 ECAP passes obtained using the optical microscope are shown in Figures 8,9,10 and 11.

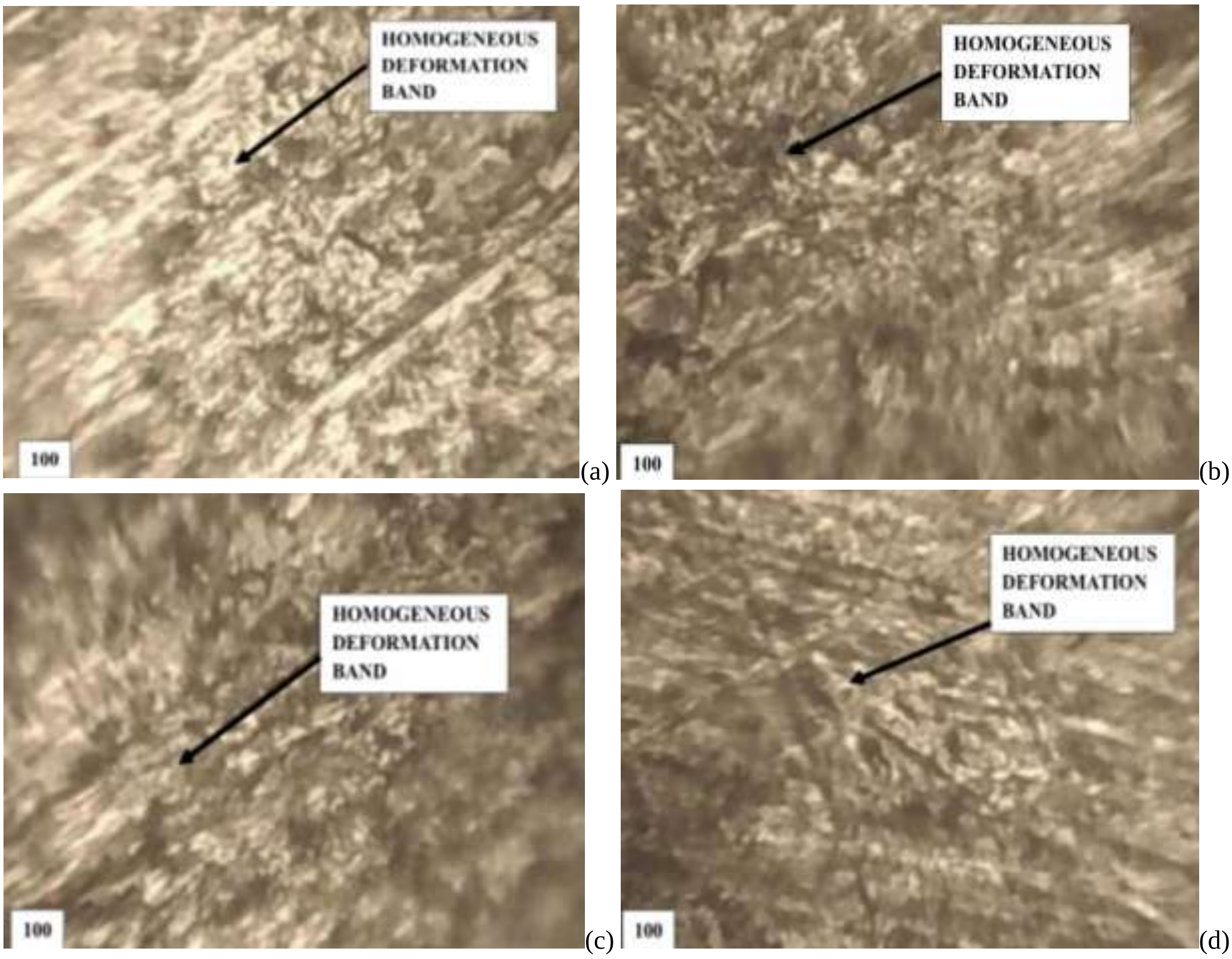
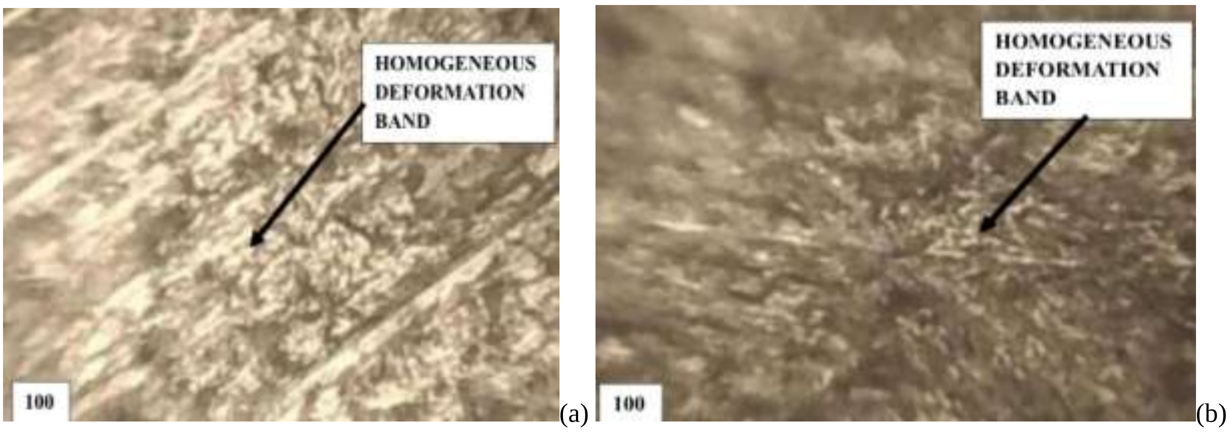


Figure 8: Optical micrograph of Al-Mg alloy ECAPed at 90ºC for (a) 1 pass (b) 2 pass (c) 3 Pass and (d) 4 Pass

Processing of the As-cast al-Mg alloy by ECAP for 4 passes across all processing temperatures resulted in a gradual microstructural grain refinement. No coarsening was observed across all processing temperature employed. The result (Figure 7) showed that for the first ECAP pass at 90ºC, change in the grain structure of the material was noticed and the size of individual grains cannot be clearly distinguished. Similar trend was revealed for 100ºC, 120ºC and 150ºC after the first pass. This can be attributed to the presence of slip, shear and micro shear bands thereby forming a band-like microstructure. However, as the number of ECAP passes increased, there was a noticeable reduction in grain size, indicative of grain refinement. This is in agreement with Injor (2023) who noted that reduction in grain sizes occurs with increase in the number of ECAP passes. The quantity of shear bands increased as the number of passes increased indicating a change in the original coarse grain structure of the As-cast billet.



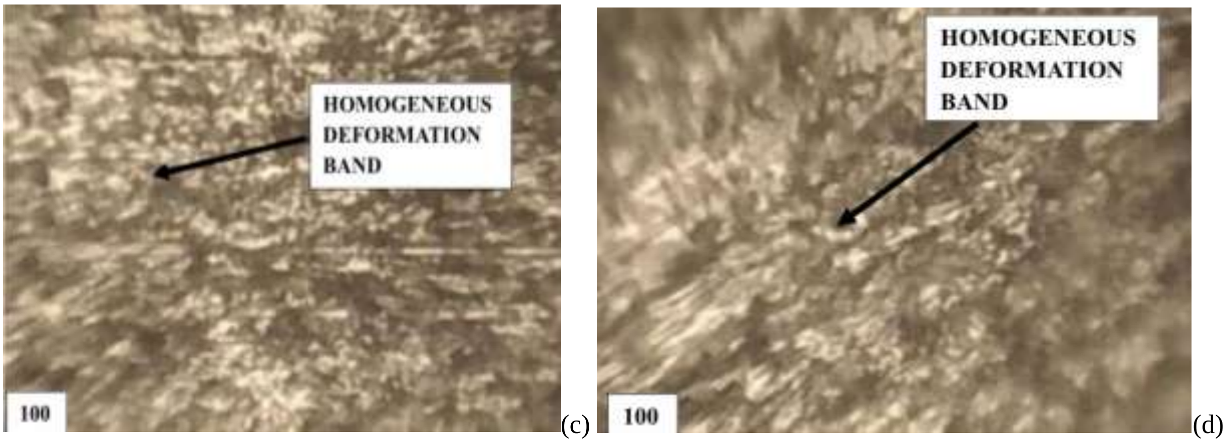


Figure 9: Optical micrograph of Al-Mg alloy ECAPed at 100ºC for (a) 1 pass (b) 2 pass (c) 3 Pass and (d) 4 Pass

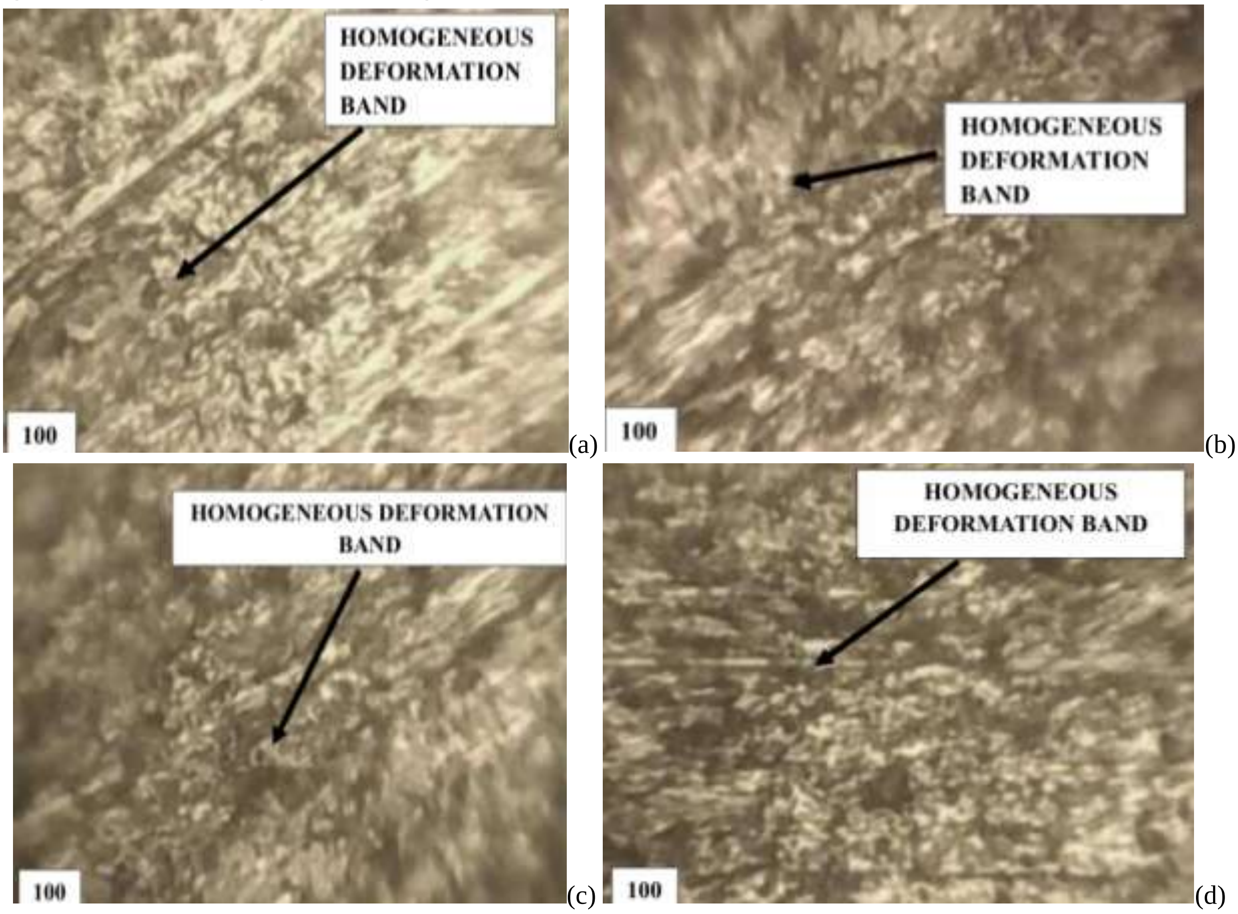
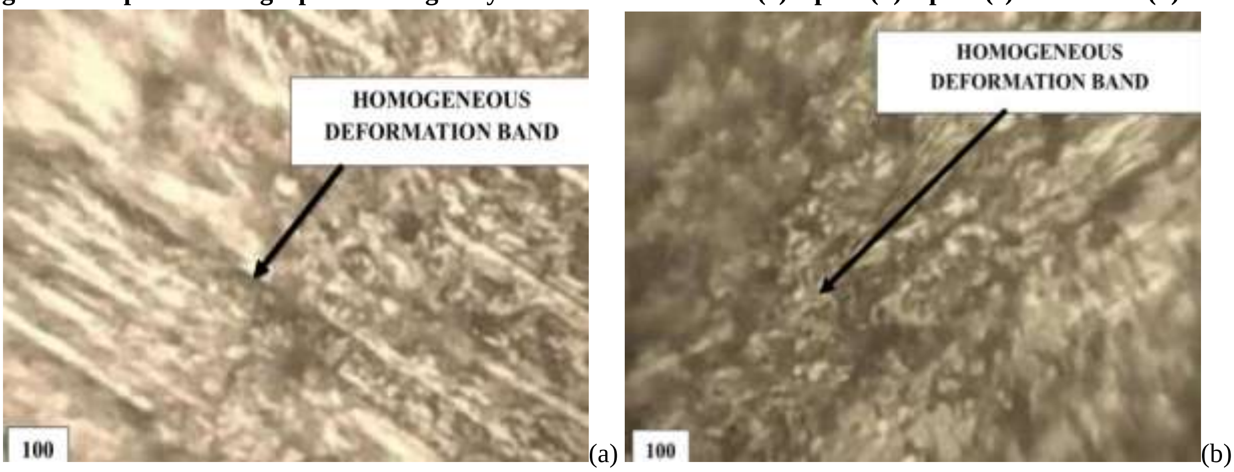
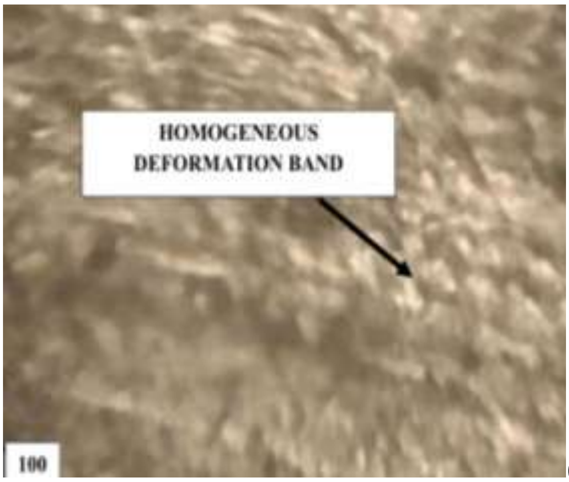
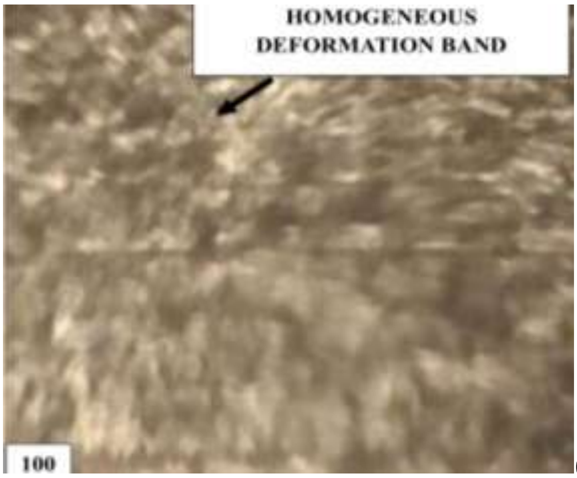


Figure 10: Optical micrograph of Al-Mg alloy ECAPed at 120ºC for (a) 1 pass (b) 2 pass (c) 3 Pass and (d) 4 Pass





(c)



(d)

Figure 11: Optical micrograph of Al-Mg alloy ECAPed at 150ºC for (a) 1 pass (b) 2 pass (c) 3 Pass and (d) 4 Pass

Furthermore, grains were observed to be elongated and parallel to transverse direction and after the fourth pass, a greater grain refinement was observed. Though optical microscopy may not directly visualize dislocations, the changes in the grain structure and morphology indirectly shows the accumulation of dislocations within the extruded samples. Microstructural features observed under the optical microscope are consistent with previous studies on ECAP-processed materials performed by Snopiński, (2019), Krajňák *et al*., (2020), Damavandi *et al*., (2021) and Jia *et al.*, (2023), which have reported similar trends of grain refinement and microstructural homogenization.

It can also be concluded that the extrusion temperature inadvertently affects the grain size and refinement. At elevated temperature of 150 ºC, a significant increment was noticed following the simple grain growth rule whereas at 90 ºC, finer and more refined grain structures are observed

4.0 CONCLUSION

The performance analysis of ECAP on Al-Mg alloy at varied temperatures showed several factors are responsible for efficient and successful use of ECAP for refining Al-Mg alloy. The analysis revealed increasing the processing temperature reduces the hardness of the extrude since increase in temperature promotes grain growth. The optimum HV value for the processed sample was obtained at 90 ºC temperature (107.9HV) after 4P. However, regardless of the temperature employed, an increase in the number of ECAP passes leads to improved material hardness. Same trend was obtained for tensile properties (yield strength and ultimate tensile strength) with optimum values (271 and 387 MPa) been obtained at 90 ºC temperature after 4P. Microstructural examination showed reduced grain sizes at lower temperature resulting in an increase in grain refinement of the alloy.

Generally, ECAP was found to be reliable in the grain refinement and mechanical property enhancement of Al-Mg alloy. Furthermore, the predictive trend relation between temperature and tensile properties and number of passes can be obtained linearly using the equations Y = -m(x) + b and Y = m(x) + b respectively.

5.0 LIST OF ABBREVIATIONS

Abbreviations	Full Meanings
Al-Mg	Aluminum-magnesium
ARB	Accumulative roll bonding
ASTM	American Society of Testing and Materials
ECAP	equal channel angular pressing
HPT	high pressure torsion
MPa	Mega Pascal
OES	optical emission spectroscopy
OM	Optical Microscopy
SPD	severe plastic deformation
UFG	ultra-fine grain
UTS	Ultimate Tensile Strength
YS	Yield Strength

6.0 DECLARATION

6.1 Availability of data and materials

We the authors hereby declare that the datasets used and/or analyzed during the current study will be made available on reasonable request.

6.2 Competing Interest

We declare that we have no competing interests. All authors read and approved the final manuscript.

6.3 Funding

There was no external funding for this research.

6.4 Author's contribution

Omenka, Ikoni Kenneth, conceptualization, Writing - original draft, methodology and visualization, formal analysis and investigation. Gundu Terfa David, conceptualization, supervision, Writing – review and editing. Ashwe, Abugh. Supervision, Writing – review and editing.

6.5 Acknowledgements

We wish to acknowledge all the lab technologist who in one way or the other contributed to the success of this work.

REFERENCES

1. Afifi, M. A., Wang, Y. C., Pereira, P. H. R., Huang, Y., Wang, Y., Cheng, X., and Langdon, T. G. (2018). Effect of heat treatments on the microstructures and tensile properties of an ultrafine-grained Al-Zn-Mg alloy processed by ECAP. *Journal of Alloys and Compounds*, *749*, 567-574. DOI: 10.1016/j.jallcom.2018.03.206.
2. Damavandi, E., Nourouzi, S., Rabiee, S. M., Jamaati, R., and Szpunar, J. A. (2021). EBSD study of the microstructure and texture evolution in an Al–Si–Cu alloy processed by route A ECAP. *Journal of Alloys and Compounds*, *858*, 157651. https://doi.org/10.1016/j.jallcom.2020.157651
3. Dhakne, A., Jaju, S., and Shukla, S. (2022). Review on analysis of enhancing wear properties through thermo-mechanical treatment and grain size. Materials Today: Proceedings, 60, 2270-2272. https://doi.org/10.1016/j.matpr.2022.04.719.
4. Gupta, A., Saxena, K. K., Bharti, A., Lade, J., Chadha, K., and Paresi, P. R. (2022). Influence of ECAP processing temperature and number of passes on hardness and microstructure of Al-6063. Advances in Materials and Processing Technologies, 8(sup3), 1635-1646. https://doi.org/10.1080/2374068X.2021.1953917
5. Hajizadeh, K., Farhad, H., and Kurzydlowski, K. J. (2023). Effect of ECAP processing routes on the microstructural characteristics of commercial purity titanium. *Applied Physics A*, *129*(8), 583. https://doi.org/10.1007/s00339-023-06868-8
6. Injor O.M. (2023). Development of equal channel angular pressing (ECAP) for deformation of 7075 al alloy for structural application. Ph.D. thesis submitted to the department of Metallurgical and Materials Engineering, Federal University of Technology, Akure (Unpublished).
7. Jia, J., Yang, Z., Xu, B., Xie, W., Xu, Y., Luo, J., and Wang, Q. (2023). Microsturucture evolution, mechanical properties, and strengthening mechanisms of 6061 aluminum alloy processed via corrugated constrained groove pressing. Materials Science and Engineering: A, 145218. https://doi.org/10.1016/j.msea.2023.145218
8. Khelfa, T., Lachhab, R., Azzeddine, H., Chen, Z., Muñoz, J. A., Cabrera-Marrero, J. M., and Khitouni, M. (2021). Effect of ECAP and subsequent annealing on microstructure, texture, and microhardness of an AA6060 aluminum alloy. Journal of Materials Engineering and Performance, 1-18. https://doi.org/10.1007/s11665-021-06404-w
9. Krajňák, T., Minárik, P., Stráská, J., Gubicza, J., Dluhoš, L., Máthis, K., and Janeček, M. (2020). Influence of temperature of ECAP processing on the microstructure and microhardness of as-cast AX41 alloy. *Journal of Materials Science*, *55*(7), 3118-3129. https://doi.org/10.1007/s10853-019-04171-7
10. Muhammad J. Q, Giribaskar S, Andrzej R, and Sonia B, (2017) Effect of incremental equal channel angular pressing (I-ECAP) on the microstructural characteristics and mechanical behavior of commercially pure titanium, Materials & Design, Volume 122, 2017, Pages 385-402, ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2017.03.015.
11. Roberto B. F, Masayoshi F, Tadahiko F, Thierry G, Jenő G, Anton H, Zenji H, Jacques H, Yoshifumi I, Miloš J, Megumi K, Petr K, Shigeru K, Langdon G, Daniel R. Leiva, Valery I. Levitas, Andrey M, Masaki M, Hiroyuki M, Terukazu N, Reinhard P, Vladimir V.P, Elena N. P, Gencaga P, Oliver R, Ádám R, Xavier S, Vaclav S, Werner S Boris B. S, Satyam S, Laszlo S. T, Nobuhiro T, Ruslan Z. V, Gerhard W, Michael J. Z and Xinkun Zhu (2022) Nanomaterials by severe plastic deformation: review of historical developments and recent advances, Materials Research Letters, 10:4, 163-256, doi: 10.1080/21663831.2022.2029779.
12. Shaeri, M. H, Ebrahimi, M., Salehi, M. T., and Seyyedein, S. H. (2016). Effect of ECAP temperature on microstructure and mechanical properties of Al–Zn–Mg–Cu alloy. *Progress in Natural Science: Materials International*, *26*(2), 182-191. https://doi.org/10.1016/j.pnsc.2016.03.003

13. Snopiński, P., Tański, T., and Matus, K. (2019). Microstructure, grain refinement and hardness of Al-3%Mg aluminium alloy processed by ECAP with helical die. Archiv.Civ.Mech.Eng 19, 287–296 https://doi.org/10.1016/j.acme.2018.11.003
14. Thiyaneshwaran N. and Sureshkumar P. (2013). Microstructure, Mechanical and Wear Properties of Aluminum 5083 Alloy Processed by Equal Channel Angular Extrusion, International Journal of Engineering Research & Technology (IJERT), Vol. 2, Issue 5, ISSN: 2278-0181
15. Tsuji, N., Yoshihiro, S., Seong-Hee, L. and Yoritoshi, M. (2003). ARB (Accumulated Roll-Bonding) and other new Techniques to Produce Bulk Ultrafine Grained Materials, Advanced Engineering Materials, Vol 5, pp338–344. **https://doi.org/10.1002/adem.200310077**