Comparative Analysis of Mechanical Properties of AL6061/E-Glass Fibre Composites before and After Severe Plastic Deformation (ECAP)

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Abstract: This study focuses on characterizing and examining the mechanical properties of Al6061 Metal Matrix Composites (MMCs) reinforced with E-glass fibres before and after undergoing Equal Channel Angular Pressing (ECAP). Al6061 alloy is renowned for its exceptional mechanical properties and resistance to corrosion, making it highly suitable for various industrial applications. The addition of E-glass fibres enhances the composite's strength and provides the flexibility to customize material properties for specific uses. The fabrication process involved stir casting to ensure a well-dispersed and uniform material. ECAP was employed to induce grain refinement and investigate the composites' mechanical behaviour. Microstructural analysis was conducted to study the distribution of reinforcement particles and matrix phases. Density and porosity measurements were acquired using Archimedes' principle, revealing trends in the compactness of the composites. Rockwell hardness tests demonstrated an increase in hardness after ECAP, attributable to improved load-bearing capabilities. Tensile tests showed higher ultimate tensile strength (UTS) and reduced percentage elongation (PE) with an increase in E-glass fibre content and after ECAP. These findings offer valuable insights into the mechanical behaviour of Al6061 MMCs reinforced with E-glass fibres, showcasing the potential for tailoring properties to fulfil specific industrial requirements.

Keywords: Al6061 Metal Matrix Composites, E-glass fibres, Equal Channel Angular Pressing (ECAP), Mechanical Characterization, Tensile Strength, Hardness, Microstructure Analysis.

1. Introduction

Aluminium alloys have become widely utilized in various applications due to their desirable characteristics, and the advancement of composites has further boosted their performance. Metal Matrix Composites (MMCs), particularly Aluminium Matrix Composites (AMCs), have garnered significant attention for their outstanding mechanical, thermal, and tribological properties. AA 6061, a popular alloy in the aviation and automotive sectors, emerges as a prominent matrix material for AMCs. The addition of diverse reinforcement materials, such as particles, whiskers, and fibres, has demonstrated a positive impact on the tensile and compressive strength, impact resistance, hardness, and wear resistance of AMCs. Stir casting is a widely adopted fabrication method for AMCs, known for its simplicity, versatility, and cost-effectiveness, making it ideal for large-scale production. Ensuring a uniform dispersion of reinforcement particles during the stir-casting process is crucial to fully harness the potential of AMCs for a wide range of engineering applications across various industries [1-3].

Over the past decade, there have been significant advancements in Metal Matrix Composites (MMCs) production, with various manufacturing methods influencing mechanical properties and production expenses. These methods can be categorized into solid-state and liquid-state processing. Among them, stir casting has emerged as a widely adopted technique due to its cost-effectiveness and uniform distribution of reinforcements within the matrix. The process involves using electrical energy to heat the matrix material while preheating the reinforcements to facilitate better mixing. The stirring mechanism plays a pivotal role in achieving a consistent dispersion of reinforcements, and several process parameters, such as reinforcement size, stirring speed, stirring time, and melt temperature, significantly influence the properties of the resulting composites. Studies have shown the importance of smaller reinforcement particles in improving mechanical properties, and researchers generally prefer moderate ranges of process variables to optimize properties. Moreover, the design and coating of the stirrer blade are crucial for successfully producing high-quality MMCs. By strategically controlling and optimizing these parameters, researchers and manufacturers can fully unleash the potential of stir casting and create MMCs with outstanding performance characteristics [4-6].

Glass fibres, such as E-glass, have been extensively researched as reinforcement materials in composite fabrication due to their cost-effectiveness and less brittle nature [7]. Investigations have revealed that the addition of E-glass fibres to composites like Al6061 alloy and Al7075 alloy leads to a substantial increase in tensile strength, compressive strength, and hardness of the resulting materials [8-10]. However, achieving the desired mechanical properties requires careful optimization of the weight percentage of E-glass fibres since an excessive amount can lead to reduced elongation and wear resistance [9,10]. Furthermore, heat treatment has been found to influence the mechanical properties, with non-heat-treated specimens exhibiting improved wear resistance [12]. E-glass fibres have also been successfully used in hybrid composites with other reinforcement materials like fly ash, silicon carbide, and carbon nanotubes, resulting in enhanced properties [9,13,11]. The wear resistance of these composites is also affected by the aging duration [14]. Overall, these studies underscore the valuable role of E-glass fibres in enhancing the performance of metal matrix composites for various engineering applications.

SPD techniques, such as ECAP, have proven highly effective in refining microstructures and enhancing mechanical properties of materials, as evidenced in research on aluminium composites [15, 16]. The incorporation of graphene into Al4032 alloy through stir casting and ECAP has yielded significant improvements in hardness and tensile properties, opening up possibilities for advanced materials with enhanced strength and performance [17]. Moreover, the synthesis of ultrahigh-strength SiCp/Al composite via spray deposition, hot extrusion, and ECAP has resulted in exceptional mechanical properties, holding great promise for high-performance applications [18].

ECAP has been employed to achieve refinement of the grain and improvements in mechanical properties in various materials, including aluminium alloys and Al-Zn-Mg alloys [19]. In-situ metal matrix composites, such as Al6061-5wt. %TiB2, have also benefited from ECAP, demonstrating enhanced strength and Vickers hardness [18]. Furthermore, ECAP processing in Al-Zn-Mg alloys with varying zinc content has led to increased strength and ductility, indicating their potential as high-performance materials for engineering applications [19]. Additionally, SPD techniques like ECAP have shown promise in manipulating second phase particles in aluminium alloys, offering possibilities for enhancing material properties [20]. Overall, these research endeavours highlight the significant role of SPD and ECAP in the development of advanced materials with improved mechanical properties for diverse industrial applications. In another work, Al6061 hybrid composites reinforced with TiB2 and CeO2 particles were fabricated using stir casting and hot rolling techniques. Hot rolling at 500ºC with a 50% reduction through 12 passes resulted in uniform dispersion and good interfacial bonding of both reinforcements. The hybrid composite containing 2.5% TiB2 and 2.5% CeO2 exhibited higher microhardness, yield strength, and tensile strength compared to Al6061 and other hybrid composites. This enhancement was attributed to the well-dispersed particles and strong bonding with the Al6061 matrix. Fracture analysis revealed ductile fracture for Al6061 and mixed ductile-brittle fracture characteristics for the hybrid composites [21].

This research aims to investigate the mechanical properties of AL6061 aluminium alloy composites reinforced with glass fibres after subjecting them to SPD using the ECAP process. The study seeks to fill the existing knowledge gap by comprehensively analysing how the incorporation of glass fibres impacts the microstructure and mechanical behaviour of the composites, both before and after SPD. The novelty of this work lies in its holistic approach, examining the effects of glass fibres as reinforcements and employing ECAP for microstructural evolution. The combination of multiple characterization techniques further enhances the uniqueness of this study.

Ultimately, the findings will contribute valuable insights to optimize processing conditions and develop advanced materials with improved performance for various engineering applications.

2. Experimental Procedures

2.1 Materials and Processes

AL6061 (fig.1a) is a highly versatile aluminium alloy known for its exceptional strength, formability, and resistance to corrosion, making it ideal for industrial applications. Reinforced with glass fibres, it becomes an excellent choice for composite materials. Extensive existing research on AL6061 alloy provides a solid foundation for investigating the effects of SPD through Equal Channel Angular Pressing (ECAP) on its properties. The alloy used in this study is sourced from METLINE Industries, Bangalore, ensuring reliable experimental work. E-glass fibre (fig.1b) is a widely used reinforcement material in composite manufacturing, offering high tensile strength, chemical resistance, and electrical insulation properties. Its incorporation in AL6061 composites enhances mechanical strength and allows for tailoring the material to meet specific application requirements. The E-glass fibres used in this study (180 mm and the diameter of 12µm) were sourced from Sanjay Impex, Bangalore, ensuring reliability and standardization. The stir casting technique used to fabricate the MMCs involves melting Aluminium 6061 at 900ºC, preheating the reinforcement (glass fibre) at 300ºC, followed by gradual introduction (2%, 4%, 6%, 8% and 10%) and stirring in the molten aluminium for 30 minutes. After removing byproducts, the composite is cast in preheated moulds and allowed to solidify, resulting in a well-dispersed and homogeneous material with tailored properties for various industrial applications (fig.1c and 1d).

Figure 1 (a) Matrix (Al6061), (b) Reinforcement (E-glass fibres), (c) adding reinforcement and (d) pouring molten metal in to the moulds

2.2 ECAP Process

The ECAP process involved using EN-31 steel for die (fig.2a) construction, followed by machining, manual polishing, heat treatment, and nitriding to achieve optimal hardness and surface smoothness. The plunger, made of EN-32 steel, was precisely machined and heat-treated. Aluminium-E-glass composites were subjected to 4 passes of ECAP at room temperature using route Bc on a UTM at a rate of 0.05mm/sec and load of 65KN (fig.2b). This process allowed for grain refinement and investigation of the composites' mechanical properties (fig.2c).

Figure 2 (a) ECAP split dies (Φ = 135° and Ψ = 30º), (b) ECAP die mounted on UTM bed and (c) specimen pre and post ECAP process

2.3 Experimentation Procedures

The microstructure analysis of Al6061/E-glass MMCs involved meticulous surface preparation, including rough polishing, fine polishing, alumina polishing, and diamond polishing. Keller's etchant was then applied to reveal the microstructure, followed by examination using optical microscope and SEM, providing valuable insights into the distribution of reinforcement particles and matrix phases in the composites (fig.3a). Density and porosity analysis of the composites pre and post ECAP was performed using a digital density tester based on Archimedes' principle. The specimens (fig.3a) were weighed in water and air mediums to accurately determine their density, providing insights into material characteristics and changes resulting from fabrication. Rockwell hardness tests were conducted on the composites (fig.3b) pre and post ECAP following ASTM E18 standard, evaluating their resistance to plastic deformation and overall hardness. Tensile strength tests were performed on the specimens (fig.3c) using a Universal Testing Machine (UTM) as per ASTM E8 standard, determining their ability to withstand pulling forces until failure occurs, and providing crucial data on mechanical performance and deformation behaviour.

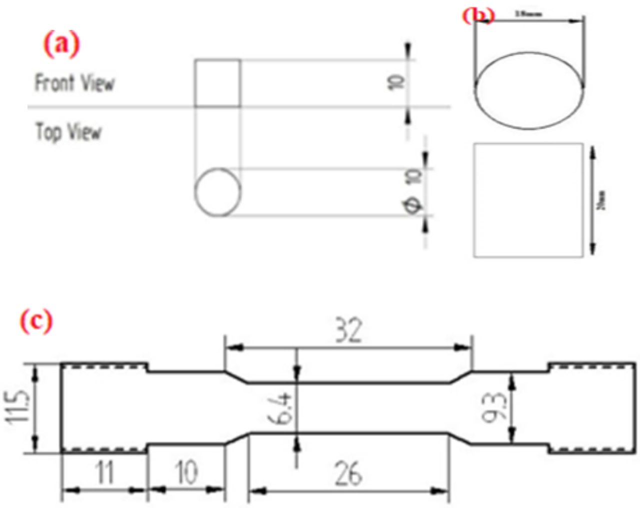

Figure. 3 Specimens for (a) microstructure, (b) hardness and (c) tensile property evaluation

3. Results and Discussion

3.1 SEM and XRD Analysis of the Composites

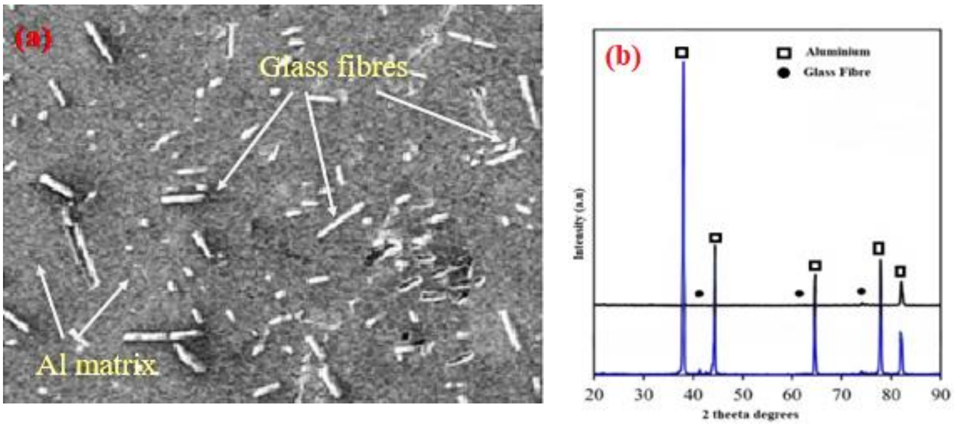

Figure. 4 (a) SEM image of AL6061 MMC reinforced with short fibres randomly oriented and (b) XRD pattern before ECAP (black) and after ECAP (blue)

The SEM micrograph in Fig. 4a reveals the composite fabricated using the stir casting technique. Upon observation, it is evident that the reinforcements, which were initially in long fibre form, have now become fragmented, indicating their breakage during the stirring process. The random distribution of fibres within the material is attributed to the nature of the stirring process. This random distribution enhances the material's isotropic properties, making its properties consistent in all directions. In these composites, the fibres play a crucial role in carrying the applied load, thereby increasing the overall strength. Similar to particulate MMCs, dispersion strengthening occurs in random short fibres-reinforced composites, where the matrix undergoes work hardening due to larger strains than the fibres experience. Notably, some E-glass fibres are transformed into particles during the stirring process, acting as barriers against dislocation movement and contributing to increased yield strength. The XRD analysis of composites before and after ECAP (Fig. 4b) reveals characteristic peaks related to E-glass fibres, confirming their presence in the composite structure. Additionally, the XRD patterns exhibit characteristic peaks of aluminium, indicating the matrix's presence. Notably, there are no new peaks in the XRD patterns, suggesting the absence of any reactions between the matrix and the reinforcement. By applying the Williamson-Hall formula, the size (crystallite) of the aluminium matrix was determined at different passes. The crystallite sizes at the first, second, third, and fourth passes were 630 nm, 510 nm, 360 nm, and 240 nm, respectively as per the measurements.

a. OM Analysis

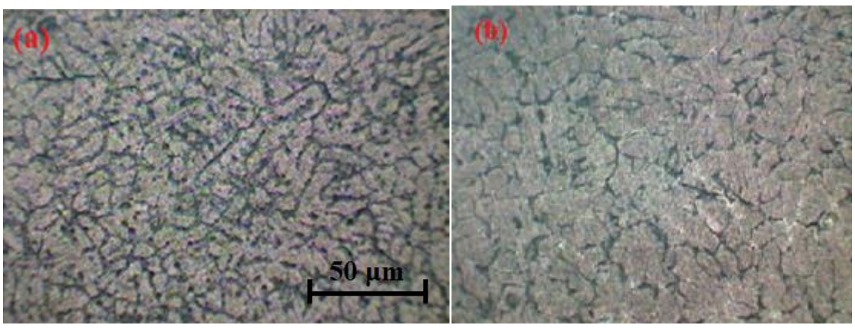

Figure. 5 OM photographs of (a) 0% E-glass fibre Al MMC (b) 6% E-glass fibre Al MMC

The image of 0% E-glass fibre Al6061 MMC (Fig.5a) shows well-defined grain boundaries, indicating distinct crystal grains of the Al6061 alloy. The grains are separated by boundaries that appear clear and distinguishable. The microstructure exhibits a dendritic network type, suggesting the solidification pattern of the Al6061 alloy during its casting process. The dendritic arms extend outward from nucleation sites, forming a branched pattern. In this image, there are visible intermetallic compounds present within the Al6061 matrix. These compounds are likely Al-Si intermetallics, which form during the solidification process, enhancing the material's strength and hardness. The gray regions present in the solid solution indicate the presence of the Al-Si eutectic phase. This eutectic phase consists of a mixture of Aluminium and silicon, contributing to the material's overall properties. Similar to the 0% E-glass fibre MMC, the 6% E-glass fibre MMC (Fig.5b) also exhibits well-defined grain boundaries. The dendritic network type is still visible, indicating the casting process's solidification pattern. In this image, we can observe the presence of E-glass fibres dispersed within the Al6061 matrix. These fibres appear as dark elongated structures, providing reinforcement to the composite material and enhancing its mechanical properties. The gray regions in the solid solution represent both the Al-Si eutectic and Al-Mg2Al3 eutectic phases. The Al-Si eutectic remains present, similar to the 0% E-glass fibre MMC, while the Al-Mg2Al3 eutectic phase indicates the presence of magnesium in the solid solution, further influencing the composite's properties.

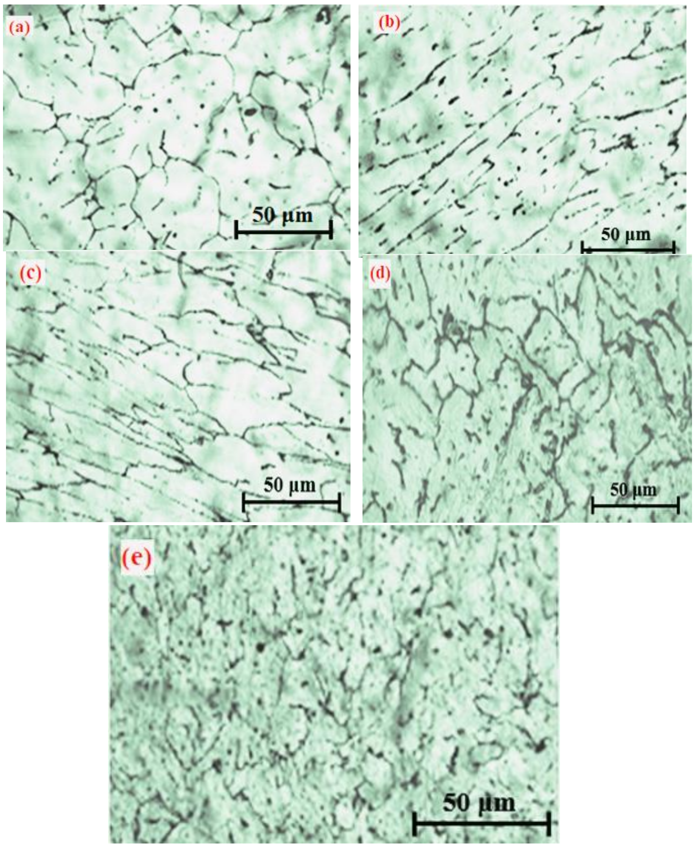

Figure. 5 OM photographs of 6% E-glass fibre Al MMC (a) pre ECAP (a) first pass (post ECAP) (b) second pass (post ECAP) (c) third pass (post ECAP) and (d) fourth pass (post ECAP)

The OM photographs of the 6% E-glass fibre AMMC pre and post ECAP for each pass reveal notable microstructural changes and evolution of the material. After the first pass of ECAP, the microstructure of the composite shows some initial changes. The E-glass fibres are observed to be dispersed randomly throughout the Al matrix, indicating the effectiveness of the stirring process during composite fabrication. The grain size appears to have undergone slight refinement, and grain boundaries are distinguishable. Some elongation of grains can be observed, which is typical during the ECAP process as the material undergoes severe plastic deformation. However, the presence of defects is relatively minimal at this stage. As the ECAP process progresses to the 2nd pass, significant improvements in the microstructure are evident. The dispersion of E-glass fibres becomes more uniform, with some clustering observed. The grain size continues to refine compared to the previous pass, and the grain boundaries become more refined and well-defined. The grain elongation is further pronounced, indicating the ongoing plastic deformation and grain reorientation. Fewer defects are present, indicating the material's increasing homogeneity and enhanced structural integrity. Upon reaching the 3rd pass of ECAP, the microstructure of the composite exhibits notable refinement. The E-glass fibres exhibit a more uniform distribution, and clustering is further minimized. The grain size continues to decrease, and the grain boundaries become even more well-defined and regular. The grain elongation is prominently evident, signifying the continued plastic deformation and grain reorientation during the ECAP process. The number of defects appears to be significantly reduced, indicating the material's continuous improvement in quality and homogeneity. After the fourth pass of ECAP, the microstructure of the composite shows remarkable progress. The dispersion of E-glass fibres is highly uniform, with minimal clustering observed. The size of the grains undergoes further refinement, and the grain boundaries appear highly refined and uniform throughout the material. The grain elongation is at its peak, indicating the extensive grain reorientation resulting from the severe plastic deformation during the ECAP process. Defects are minimal, suggesting that the material has achieved a high level of homogeneity and structural integrity.

3.4 Density Measurements

Density and porosity measurements were performed on Al6061 composites reinforced with 2%, 4%, 6%, 8%, and 10% E-glass fibres refer Fig.6. The theoretical density values were calculated using the rule of mixture formula, considering the densities of Al6061 alloy (2.70 g/cm^3) and E-glass fibres (2.58 g/cm^3). For the experimental density measurements, a density tester based on Archimedes' principle was utilized. The porosity values were then calculated using the experimental and theoretical density values, providing insights into the composite's densification and void content.

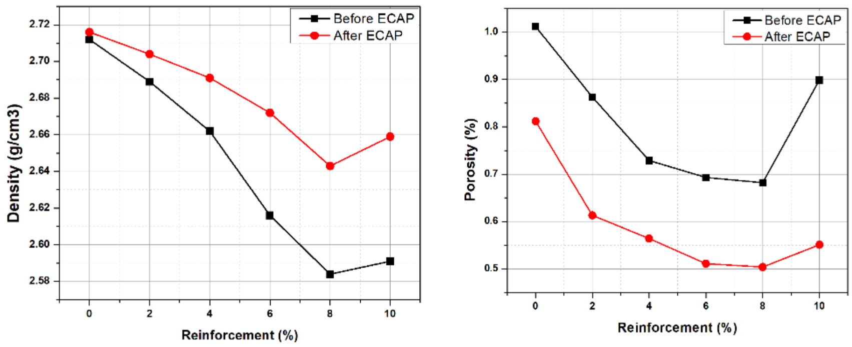

Figure. 6 Variation of density and porosity before and after ECAP for AMMCs

The results obtained for the density and porosity values of the AMMCs reinforced with E-glass fibres reveal interesting trends. Before the ECAP process, the densities of the AMMCs generally show a minor decrease with increasing E-glass fibre percentage. This decrease can be credited to the lower density of E-glass fibres (2.58 g/cm^3) compared to the Al6061 matrix (2.70 g/cm3). As the percentage of E-glass fibres increases, the overall density of the composite decreases due to the lighter weight of the reinforcing phase. However, after undergoing ECAP for 4 passes, the values of density of the composites show a different trend. With ECAP, the densities tend to increase for all reinforcement percentages compared to their initial values before ECAP. This increase in density can be attributed to the severe plastic deformation and refinement of the grains that occurs during ECAP. The reduction in grain size and the removal of voids and porosity lead to a more compact and denser microstructure, contributing to the higher density values after ECAP. Regarding porosity, the values generally decrease for all composites after undergoing ECAP. This reduction in porosity is consistent with the increased density, as the elimination of voids and interparticle spaces during ECAP leads to a more densely packed material. The decrease in porosity is more pronounced for composites with higher E-glass fibre percentages, indicating that the reinforcement plays a significant role in the porosity reduction process. However, the situation changes after 6% inclusion of reinforcement. At this point, the trend is reversed. The density of the composites starts to increase with higher E-glass fibre content, and the porosity values show a slight increase. This reversal in trend is because of achieved optimal packing above 6% and further addition of E-glass fibres might cause more spaces between them, contributing to increased porosity and density. Also, the distribution and dispersion of E-glass fibres become more challenging as their content increases beyond 6%. Uneven dispersion can lead to increased porosity and higher density due to non-uniform packing. Overall, the decrease in density due to increase in the E-glass fibre percentage is expected and consistent with the principles of composite materials. It is one of the advantages of using lightweight reinforcements like E-glass fibres to enhance the mechanical properties of composites without significantly increasing their weight.

3.5 Hardness Measurements

The experiments on the AMMCs involved hardness testing using a Rockwell hardness tester. The Rockwell hardness values were obtained for the as-cast MMCs and MMCs subjected to ECAP for different passes. The tests provided valuable insights into the material's resistance to plastic deformation and helped assess the effect of ECAP on the hardness and mechanical properties of the composites. Fig. 7 shows the hardness values for AMMCs.

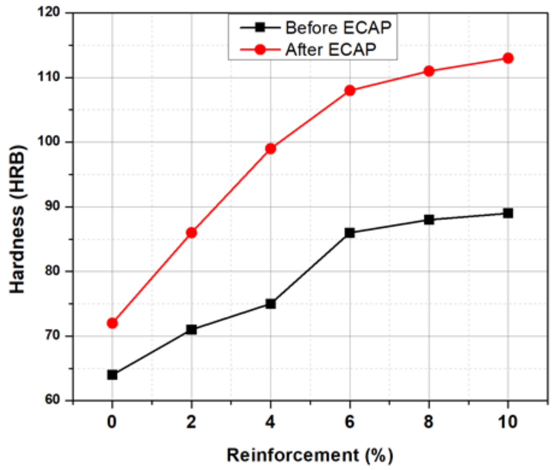

Figure. 7 Hardness values for AMMCs

The hardness values obtained for the composites using the Rockwell hardness tester demonstrate a notable improvement in hardness after subjecting the materials to ECAP. As the percentage of E-glass fibre reinforcement increased, the hardness of the composites also increased both before and after ECAP. This enhancement in hardness can be attributed to the efficient dispersion of the reinforcing phase within the aluminium matrix, resulting in improved load-bearing capabilities and increased resistance to plastic deformation. The impact of ECAP on composite hardness becomes evident as each pass leads to a significant increase in hardness values. The process induces severe plastic deformation, causing grain refinement and improved microstructural homogeneity. Consequently, the dislocation density rises, resulting in greater hardness due to the work-hardening effect. Moreover, the reduction in porosity following ECAP also plays a role in hardness improvement, as it leads to fewer voids and enhances material strength. The relationship between density, porosity, and hardness values in Al6061 Metal Matrix Composites (MMCs) is evident. With an increase in E-glass fibre reinforcement, the composites' density decreases, while porosity reduces. This trend indicates that adding E-glass fibres results in a more compact and denser microstructure with fewer voids, thereby enhancing material strength. Furthermore, a direct correlation exists between decreased porosity and increased hardness values after ECAP. The reduction in porosity during ECAP fosters a more homogeneous and defect-free microstructure, contributing to enhanced hardness. Reduced porosity means fewer voids and imperfections within the material, hindering dislocation movement and overall improving the composites' strength and hardness. The data also reveals that higher E-glass fibre reinforcement leads to increased hardness in both pre- and post-ECAP stages. This phenomenon occurs because E-glass fibres act as effective reinforcements, enhancing the load-bearing capacity of the composites and improving their hardness.

3.6 Tensile Measurements

The tensile test is a crucial mechanical evaluation conducted on the Al6061 Metal Matrix Composites (MMCs) to assess their ability to withstand tensile forces until failure occurs. The specimens, prepared with specific dimensions, are precisely gripped in a Universal Testing Machine (UTM), and a gradually increasing load is applied until the material fractures. The UTM records the applied load and the corresponding elongation,

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providing valuable data on the composites' UTS and percentage of elongation before and after the ECAP process. These measurements offer critical insights into the materials' deformation behaviour and mechanical performance.

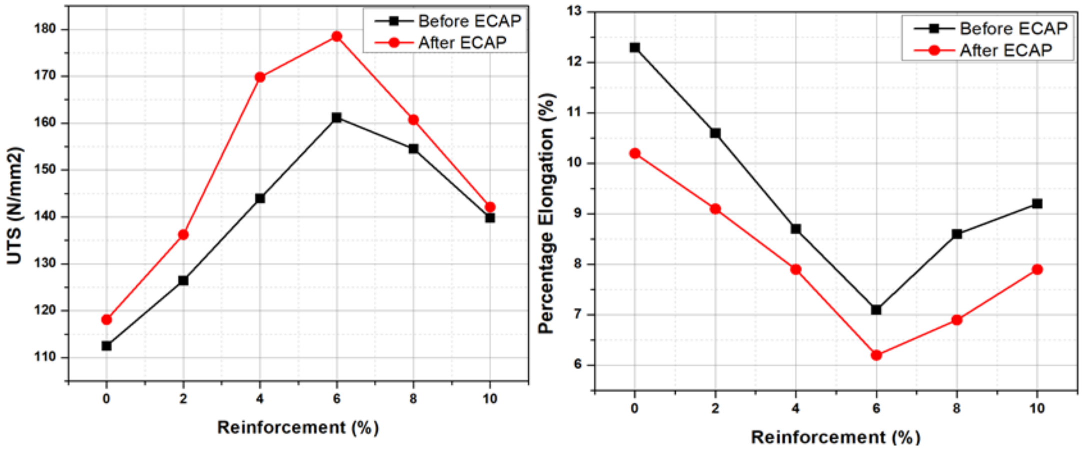

Figure 8 UTS and Elongation percentage for different composition of AMMCs before and after ECAP

The tensile test results of composites with varying E-glass reinforcement percentages reveal noteworthy findings. As the reinforcement percentage increases, there is a substantial rise in both pre- and post- ECAP ultimate tensile strength (UTS). This outcome was expected, given that E-glass fibres act as robust reinforcements, enhancing the overall strength of the composite material. The UTS after ECAP surpasses the pre-ECAP values, indicating that the severe plastic deformation process during ECAP further improves the material's strength. Conversely, as the reinforcement content increases and ECAP is applied, the percentage elongation (PE) of the composites decreases. This decline in PE can be attributed to the presence of E-glass fibres, which impede plastic deformation and elongation of the material. A higher reinforcement content introduces more obstacles (fibres) that hinder the movement of dislocations, thus reducing the material's ability to deform plastically and elongate before fracture. Of particular note is the significant drop in both ultimate tensile strength (UTS) and PE observed after introducing 6% E-glass reinforcement. This could be attributed to factors like fibre packing and dislocation density. At this level of reinforcement, the fibre content might have reached an optimal point, facilitating effective load transfer between the matrix and the fibres, leading to a peak UTS value before ECAP. However, during ECAP, the severe plastic deformation further aligns the fibres, enhancing the material's strength and causing the UTS to increase after ECAP. Simultaneously, the decrease in PE after 6% reinforcement could be attributed to the increased fibre density, which restricts the material's plastic deformation and reduces its ability to elongate before fracture. Moreover, the severe plastic deformation during ECAP could lead to grain refinement, resulting in a decrease in grain size and grain boundaries. The reduction in grain size could lead to improved mechanical properties and contribute to the increase in UTS while decreasing PE.

4. Conclusion

In conclusion, the study focused on Al6061 Metal Matrix Composites (MMCs) reinforced with E-glass fibres and the effects of ECAP on their properties. The combination of Al6061 alloy and E-glass fibres resulted in a versatile and high-performance composite material with enhanced mechanical strength and tailored properties for various industrial applications.

The fabrication process involved stir casting and meticulous surface preparation, leading to a well-dispersed and homogeneous material. ECAP further improved the material's properties by inducing grain refinement and increasing hardness through severe plastic deformation. Microstructural analysis revealed the distribution of reinforcement particles and intermetallic compounds.

Density and porosity measurements provided insights into material characteristics and changes resulting from fabrication and ECAP. The Rockwell hardness tests demonstrated increased hardness values after ECAP, indicating improved load-bearing capabilities. Tensile tests revealed higher ultimate tensile strength (UTS) and reduced percentage elongation (PE) with increased E-glass fibre content. Notably, a decrease in UTS and PE after 6% E-glass reinforcement suggested optimal packing and improved material strength. Overall, the study showcases the potential of Al6061 MMCs reinforced with E-glass fibres and the significant impact of ECAP on enhancing their mechanical properties and microstructure.

References

[1] Abdudeen A., Mourad A.-H.I., Qudeiri J.A., Ziout A. Evaluation of Characteristics of A390-SiC p Squeeze Cast and Gravity Cast Composites; Proceedings of the 2020 Advances in Science and Engineering Technology International Conferences (ASET); Dubai, UAE. 26 March–10 April 2019; Piscataway, NJ, USA: IEEE; 2019. pp. 1–6.

[2] Kumar Sharma A., Bhandari R., Aherwar A., Rimašauskienė R., Pinca-Bretotean C. A study of advancement in application opportunities of Aluminium metal matrix composites. Mater. Today Proc. 2020.

[3] Huda D., El Baradie M.A., Hashmi M.S.J. Metal-matrix composites: Materials aspects. Part II. J. Mater. Process. Technol. 1993.

[4] Ramanathan A., Krishnan P.K., Muraliraja R. A review on the production of metal matrix composites through stir casting—Furnace design, properties, challenges, and research opportunities. J. Manuf. Process. 2019; 42:213–245.

[5] Garg P., Jamwal A., Kumar D., Sadasivuni K.K., Hussain C.M., Gupta P. Advance research progresses in aluminium matrix composites: Manufacturing & applications. J. Mater. Res. Technol. 2019; 8:4924–4939.

[6] Kumaraswamy H.S., Bharat V., Krishna Rao T. Influence of Mechanical &tribological Behaviour of Al 2024 MMC Fabricated by Stir Casting Technique-A Review. Mater. Today Proc. 2018; 5:11962–11970.

[7] Soo-Jin Park, Min-Kang Seo, Interface Science and Technology, 2011

[8] Arun Kumar M B and R P Swamy, "Evaluation of Mechanical Properties of Al 6061, Fly Ash and E-glass fibre Reinforced Hybrid Metal Matrix Composites", ISSN 1819-6608 Asian Research Publishing Network (ARPN), Vol.6, Issue.5 May 2011

[9] M. M Sreenivasa Reddy, Dr. Soma V Chetty, Dr. Sudheer Premkumar, Reddappa H N, "Influence of reinforcements and heat treatment on mechanical and wear properties of Al 7075 based hybrid composite", Procedia Materials Science 5 (2014) 508 – 516

[10] Prasanna, Devraj, Rakeshkumar, Mr. Mahadevappa, Asst Prof. Sharanabasappa R P, "A Study on Mechanical Properties of Silicon Carbide, E-glass and Red Mud Reinforced Aluminium (LM25) Composite", IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 11, Issue 3 Ver. VIII, PP 08-19, May-Jun. 2014.

[11] Santhosh Kumar B M, Dr. Girish D. P, "Assessment of Mechanical Properties of Aluminium 7075 based Metal Matrix Composite", International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 5 Issue 02, February-2016

[12] J W Pinto, G Sujaykumar, Sushiledra R M, "Effect of Heat Treatment on Mechanical and Wear Characterization of Coconut Shell Ash and E-glass fibre reinforced aluminium hybrid composites", American Journal of Materials Science, 6(4A): 15-19.

[13] N Basavaraj, Mr. Jagadeesh C, Mr. Kiran Raj H N, Dr. H.K. Shivanand, "Studies on Characteristics and Mechanical Behaviour of Carbon Nano Tubes & E-glass fibre reinforced Al 7075 Alloy Matrix Hybrid Composites", Indian Journal of Research, ISSN - 2250-1991 | IF: 5.215| Volume: 5 | Issue: 8 | August 2016.

[14] Mahagundappa M. Benal, H. K. Shivanand, Effects of reinforcements content and ageing durations on wear characteristics of Al (6061) based hybrid composites, Wear, 262(5):759-763 February 2007.

[15] R Shobha, Dr. K.R.Suresh, Dr. H.B. Niranjan, paper entitled "Effect of 'Conventional' and Severe Plastic Deformation on 8 % TiB2 reinforced 'In-situ' Aluminium composite" International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, Volume 3, Issue 5, May 2013.

[16] Günay Bulutsuz, A., Chrominski, W. Incremental Severe Plastic Deformation Effect on Mechanical and Microstructural Characteristics of AA6063. Trans Indian Inst Met 74, 69–77 (2021).

[17] Krishnarao, R.S., Veeranna, V. & Krishna, A.G. Influence of Graphene Addition on Microstructure and Mechanical Properties of Homogenized Al4032–Graphene Composites Processed Through ECAP. J. Inst. Eng. India Ser. D 103, 203–216 (2022).

[18] Y. P Sun, J. Han, Y. Tu, Z.Bai, Y.Q He , "Microstructure and mechanical properties of a spray deposited SiCp/Al Composite processed by hot extrusion and equal channel angular pressing", Material research innovations, Vol.18, Issue-4, July 2014, pp. 220-223.

[19] Zenji Horita, Keiichiro Ohishi & Kenji Kaneko (2006) Microstructure control using severe plastic deformation, Science and Technology of Advanced Materials, 7:7, 649-654.

[20] Manjunath, G.K., Preetham Kumar, G.V. & Udaya Bhat, K. Tensile Properties and Tensile Fracture Characteristics of Cast Al–Zn–Mg Alloys Processed by Equal Channel Angular Pressing. Trans Indian Inst Met 70, 833–842 (2017).

[21] Iyengar, S. & Sethuram, D. & Shobha, R. & Koppad, Praveennath. (2021). Microstructure, microhardness, and tensile properties of hot-rolled Al6061/TiB2/CeO2 hybrid composites. Journal of the Southern African Institute of Mining and Metallurgy. 121. 1-6. 10.17159/2411-9717/1560/2021.