Research Article

Alhassan Mohammed Hassan*, Jabbar Gattmah, and Suha K. Shihab

Evaluation of microstructure and mechanical properties of Al1050/Al_2O_3/Gr composite processed by forming operation ECAP

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Abstract: Enhancement of microstructure and mechanical features of the hybrid aluminum matrix composite (HAMC) prepared by the stir-casting process (SCP) is quite significant for failure prevention during the service. In this work, the circular rod of hybrid aluminum matrix composite reinforced with particles of alumina (Al_2O_3) 50 µm, and graphite (Gr) 40–100 µm fabricated by SCP was adopted. This Al1050/Al_2O_3/Gr composite was subjected to severe plastic deformation using equal channel angular pressing (ECAP) at room temperature to show the impact of this process on the microstructure and mechanical features of the fabricated composite. Grain refinement, strength, and hardness were evaluated at different forming passes (1P, 3P, and 5P) with two channel angles (die angles) of 120° and 135°. The results revealed that the number of ECAP cycles has a significant effect on the refinement of the grain size. The fifth pass of ECAP (5P ECAP) with a die angle of 120° gave more refinement of the grains in the range of 36–75 nm compared to other passes. On the other hand, the strength and hardness relatively augment until 5P ECAP with increasing the cycle number at two die angles of 120° and 135°. The ultrafine grain can reduce the voids of the aluminum matrix then the hardness is enhanced.

Keywords: Al composites, equal channel angular pressing, microstructure, strength, hardness

*** Corresponding author: Alhassan Mohammed Hassan,** Department of Material Engineering, College of Engineering, University of Diyala, 32001, Baqubah, Diyala, Iraq, e-mail: eng.alhassan99@gmail.com
Jabbar Gattmah: Department of Material Engineering, College of Engineering, University of Diyala, 32001, Baqubah, Diyala, Iraq, e-mail: msc_jgj_katma7@yahoo.com
Suha K. Shihab: Department of Material Engineering, College of Engineering, University of Diyala, 32001, Baqubah, Diyala, Iraq, e-mail: suhakshihab@gmail.com

1 Introduction

In recent years, aluminum matrix composites have been used in aeronautics and shipping applications due to a combination of high mechanical features and lightweight which can improve the performance of these materials during the service. Although these composites are well-admired materials, there are requirements to enhance the microstructure state and mechanical strength [1]. Many researchers have investigated the effect of equal channel angular pressing (ECAP) on the microstructure, mechanical properties, porosity, and wear mechanism of various materials. Lokesh and Mallik applied stir casting process to fabricate an Al6061/Gr/SiC hybrid composite. ECAP to enhance microstructure characterizations and mechanical features was used. They found an important reduction in the grain size of the matrix as well as a significant change in both the hardness and ultimate strength (UT) [2]. Chegini and Shaeri studied the impact of ECAP on the microstructure, mechanical features, and wear states. They demonstrated that there was ultrafine-grained of the microstructure and augmenting in the hardness, shear, and tensile stress with a reduction in coefficient of friction because of the increase in ECAP passes [3]. Hernández-Martínez *et al.* adopted the cold-compacted process based on the aluminum tube to manufacture AA7075 – ZrO_2 composite. ECAP under temperature conditions was utilized to show minimum pore% and hardness [4]. The stir casting method was conducted to create Al2618-E-Glass-SiC hybrid composites as well as study the impact of severe plastic deformation (SPD) based on ECAP on the composite characterization [5]. Bongale and Kumar VC formed aluminum 6061 and nanoparticles of SiCnp using ECAP to determine wear features and hardness value. They revealed that the increase in silicon carbide nanoparticles and the number of cycles during ECAP leads to the rise in the hardness while the augment in load and speed can increase the wear rate [6]. Xu *et al.* evaluated the matrix grain, hardness, and wear mechanism for the composite of SiCp/Al-Si which was extruded by ECAP. The results referred to significant changes in the size of the matrix grain and the close of the prose with improved hardness and wear resistance at the eighth cycle of the ECAP [7]. Another study focused on the improvement of the coating formation employing ECAP of Al–11Si alloy. The results showed there is an ability to obtain a coating with thicker, compact, and uniform [8]. Rezaei *et al.* selected Al–Cu–Ti glass particles as a composite metallic formed by ECAP to develop ultrafine grain structure and yield strength (YS). The microstructure and mechanical results were obtained by X-ray diffraction, transmission electron microscopy, electron backscatter diffraction, and uniaxial compression tests [9]. ECAP with 4, 8, and 16 passes was conducted under temperature conditions (250°C) to determine the microstructure characterizations and mechanical features of SiCp/AZ91 composites [10]. Sureshkumar *et al.* assessed the impact of the cycle increases for ECAP on the properties of microstructure, mechanical, corrosion, and tribological for the composite of metallic and ceramic reinforced by a hybrid of Al-alloy. They found that there was an important augment in both the mechanical and tribological properties while the corrosion resistance was reduced [11]. Al6061 and AA7075 alloy was formed by ECAP and HPT to deform the grains to nanosize that can raise tensile and fracture strength as well as increase hardness and wear resistance [12]. ECAP also was performed at room temperature to determine the microstructure, texture, and mechanical of the Al–Zn–Mg–Cu alloy. At 2P ECAP, the mechanical properties were strongly improved in addition to the high impact on the texture found at the first pass [13]. Traditional ECAP based on the rotary die was used to process various materials such as AZ91 and Al–Mg–Zn alloys to illustrate wear behavior [14,15]. Snopiński *et al.* conducted ECAP under heat treatment for the AlSi10 Mg alloys prepared by selective laser melting to check both the microstructure and mechanical features [16]. The YS, ductility, and hardness of the AlSi10Mg alloy were improved by employing ECAP with one and two cycles. SEM and TEM tests were applied to the analysis to evaluate the microstructure in terms of grain refinement and boundaries [17]. Alam *et al.* illustrated the fatigue behavior and mechanical properties of the Al2024 formed by the ECAP at an angle of 100° with 400°C. They showed that both the fatigue life and strength increase with the low and high cycles compared to the initial samples (non-formed) [18]. ECAP processed super alloy and a composite of Al-SiC to estimate the microstructure and mechanical behaviors [19]. Hot ECAP was adopted to extrude Al6061 and B4C composite at various volumetric fractions with different numbers of cycles. The microstructure and mechanical characterizations can be improved with the augmenting of the ECAP passes [20]. Alateyah *et al.* made a study in the investigation of microstructure and mechanical features of pure magnesium due to the ECAP effects at four cycles at two die angles of 90° and 120° with a temperature of 225°C. They also used ANOVA to determine the impact of the ECAP parameters on the grain size, hardness, and tensile responses [21]. Another research showed the effect of the ECAP and heat treatment on the microstructure fields, hardness property, tensile features, and tribological behavior for the Al–Si–Mg alloy. The mixed impact of the ECAP and heat treatment based on T6 can increase the mechanical performance and improve the wear rate of the composite [22].

The parts produced by stir casting need rehabilitation in terms of the microstructure behavior and mechanical properties because of the high-temperature effect due to the manufacturing process. In this recent research, a rod of Al1050/Al_2O_3/Gr composite is extruded by the ECAP at room conditions to undergo the composites to the SPD with different forming passes (1P, 3P, and 5P) at two profile types of channel angles of 120° and 135°. Then, the grain refinement, strength, and hardness are determined based on the profile angle and number of forming passes.

2 Materials and method

In the current article, the material received in the form of a rod represents an Al1050/Al_2O_3/Gr composite that was obtained by stir casting method. The ratio composite contains 95% aluminum alloy (Al1050) which was selected as the base matrix, 3% alumina (Al_2O_3) represents a hard and brittle material, and 2% graphite (Gr) which is very soft with low specific gravity material. The chemical composition of the aluminum matrix composite is reported in Table 1. On the other hand, reinforcement materials in terms of Al_2O_3 particles represented 50 μm and 270 mesh while the Gr powder was 40–100 μm, 0.4% ash, and 99+%.

Based on the received rods, the dimensions were 12 mm in diameter and 120 mm in length. The die of

Table 1: Chemical composition of Al1050 alloy

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Al1050 wt%	0.064	0.155	0.004	0.004	0.004	0.004	0.02	99.6

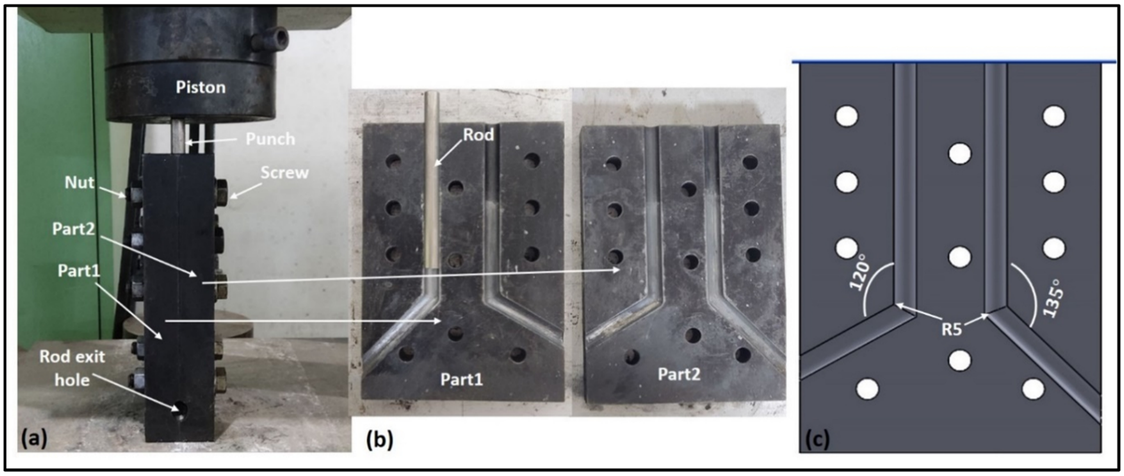

Figure 1: (a) ECAP procedure including (a) setup process, (b) die, and (c) channels angle.

ECAP was made of tool steel in two parts that were assembled and fixed by screws as presented in Figure 1. Severe plastic deformation (SPD) is considered one of the significant metal-forming techniques to obtain ultrafine-grained. The ECAP was conducted at room temperature with die angles of 120° and 135° to obtain SPD. Different passes of ECAP (1P, 3P, and 5P) were applied to process rod composite by compression device which has a maximum capacity of 1,000 kN. During the ECAP experiments, there is hard contact between the inner surface of the channel and the outer surface of the casted rod. So, the frictional force must be taken into consideration during the process [23]. To reduce the friction between the die and rod surfaces, lubrication for the steel was used as well as press velocity of 0.51 mm/s was adopted for all experiments. Eighteen samples were processed as total rods, 9 of them extruded with a channel angle of 120° and the other with a channel angle of 135°.

Field emission scanning electron microscope (FE-SEM) was applied to examine the microstructure and to determine the grain refinements for the rods manufactured based on one pass 1P, three passes 3P, and five passes 5P. For sample preparation, the rods were cut off the middle, and then 10 mm as a height was sectioned. All samples were cleaned of dust and then the stuck greases were removed. Finally, they were polished and coated with a solution called single target plasma. In this work, the analytical device of FE-SEM (Inspect TM F50) up to 200 nA was used to check the grain refinements after the different cycles of the ECAP process as shown in Figure 2.

The tensile test was conducted at the environment temperature to evaluate the YS and UT of the rods at various

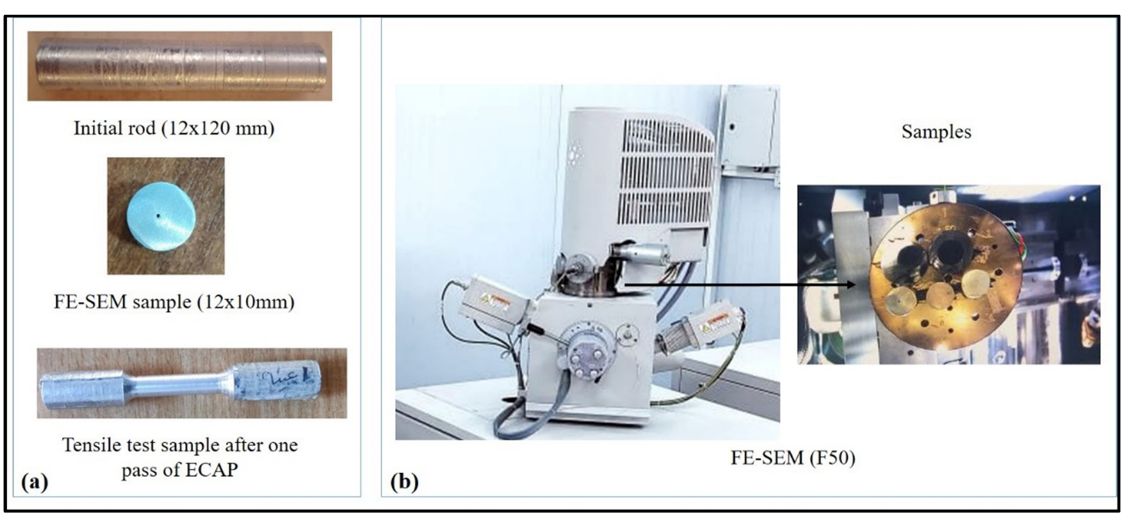

Figure 2: Shows (a) sample of FE-SEM, and tensile test, and (b) inspect F50 FE-SEM.

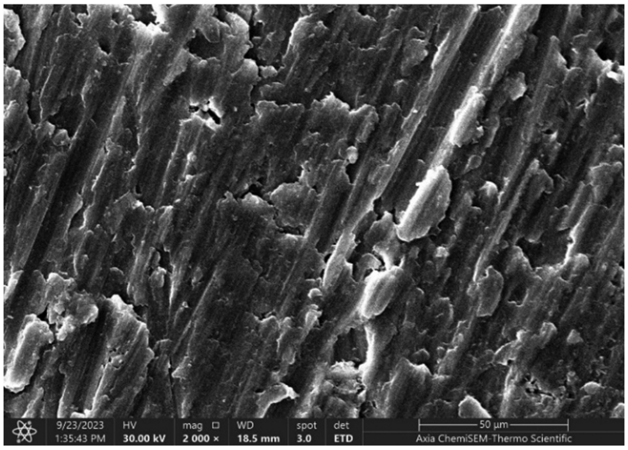

Figure 3: Surface and particle morphology with 2,000× obtained by SEM of Al1050/Al_2O_3/Gr composite.

ECAP cycles. The samples were prepared based on ASTM E8, and the tensile tests were performed by computer tester WDW-200E with a velocity of 20 mm/min. A digital micro Vickers hardness tester was utilized to measure the hardness in the middle of the rod with three different positions. Figure 2 depicts the samples for FE-SEM and tensile tests as well as inspect of F50 FE-SEM.

3 Results and discussion

3.1 Results of microstructure for the hybrid composite processed by ECAP

Figure 3 displays an image of the surface and particle morphology of the hybrid aluminum including 95% Al1050, 3% Al_2O_3, and 2% Gr. The non-uniform surface topography and particles of the composite are obviously caused by the stir casting method. In the early stage of cast Al1050, the grain boundaries are relatively large, and there are a few voids and cracks visible on the surface.

Figure 4 indicates the microstructure of the rod fabricated of the hybrid aluminum composite which is processed by different cycles of ECAP at the channel angle of 120°. Figure 4a and b refer to the grain structure of the

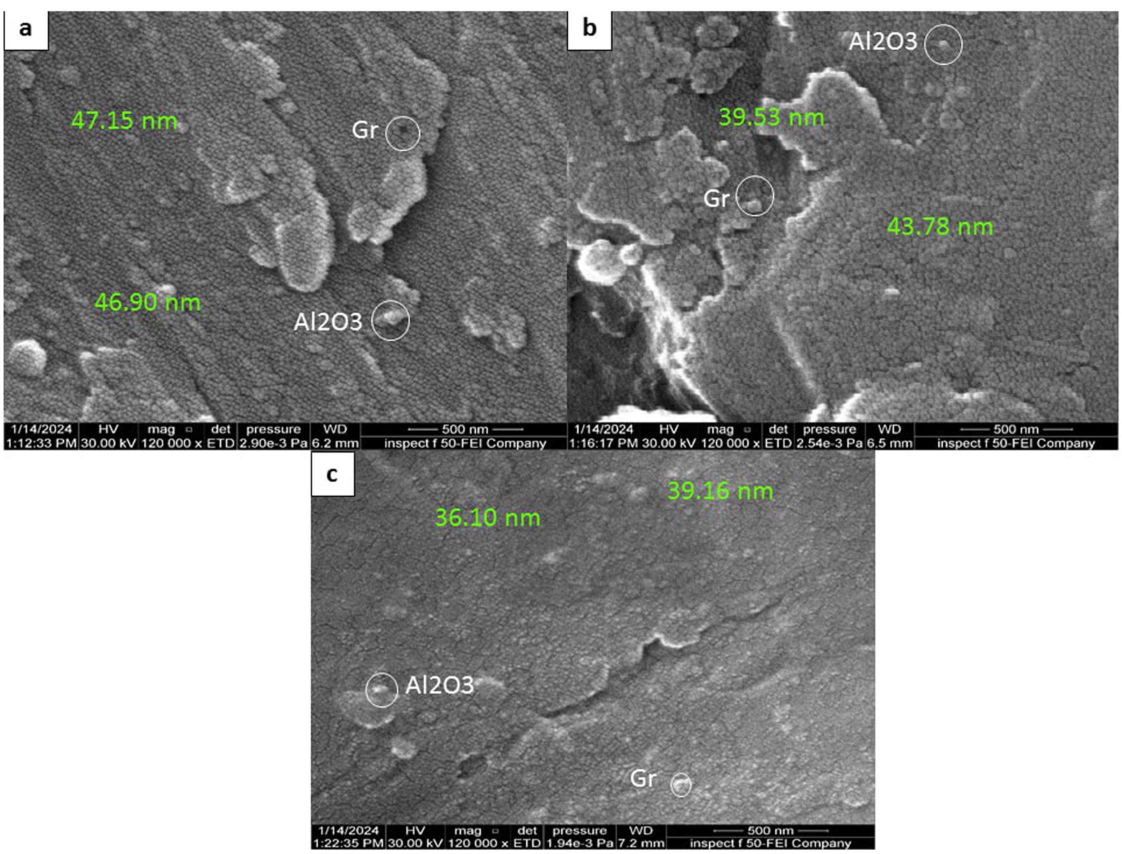

Figure 4: The FE-SEM images of Al1050/Al_2O_3/Gr composite formed by ECAP at a channel angle of 120°: (a) 1P, (b) 3P, and (c) 5P.

Al1050 as well as the distribution of Al_2O_3 and Gr during the composite. It is clear that the number of ECAP passes significantly impacts the grain size of the Al1050. Figure 4a shows the change in the size of the Al1050 particle after it has been subjected to 1P ECAP. From the measurement of the different positions as presented in Figure 4a, the range of grain sizes of the matrix composites was recorded as 46–120 nm. In Figure 4b, the effect of the 3P ECAP on the change in grain size is clearly noticed and determined in a range between 39 and 90 nm. More grain size refinement is displayed in Figure 4c with a range of 36–75 nm which indicates the impact of the 5P ECAP on the microstructure in terms of grain size. The changes in the movement of the particles during the ECAP which causes SPD led to the arrangement of the grains and reduced their size. From Figures 3 and 5, the structure of the particles was largely refined.

Figure 5 presents the images of the microstructure including the grain structure of the aluminum matrix as well as alumina and graphite distribution at various ECAP cycles with a channel angle of 135°. It can be seen that the grain size decreases at a varying rate when the number of passes increases due to the SPD which leads to the change in the material movement. Figure 5a shows a reduction in the grain structure at a range of 54–200 nm when the hybrid aluminum composite undergoes 1P ECAP.

The increase in the refinement of the grain size can be observed in the 3P ECAP reaching the range of 42–137 nm as illustrated in Figure 5b while more refinement was obtained at 5P ECAP in the range of 38–117 nm as displayed in Figure 5c. The refinement of the grain occurs in the load direction because of the effect of strain hardening of the hybrid composite. The voids in the rod composite were reduced to the minimum due to the impact of the compressive force [5]. Overall, the comparison of the microstructure shown in Figure 3 which represents as-cast and as-homogenized composite with Figure 5 which indicates the SPD after different ECAP cycles, and the grain structure was completely refined.

From Figures 4 and 5, the effect of the channel angle of 120° gave more refinement of the grain size compared to the 135° for all cycles of the ECAP due to the increase in the forming ratio of the material that was subjected to the SPD. The particles of the Al1050/Al_2O_3/Gr after the 5P ECAP are almost distributed in the whole rod.

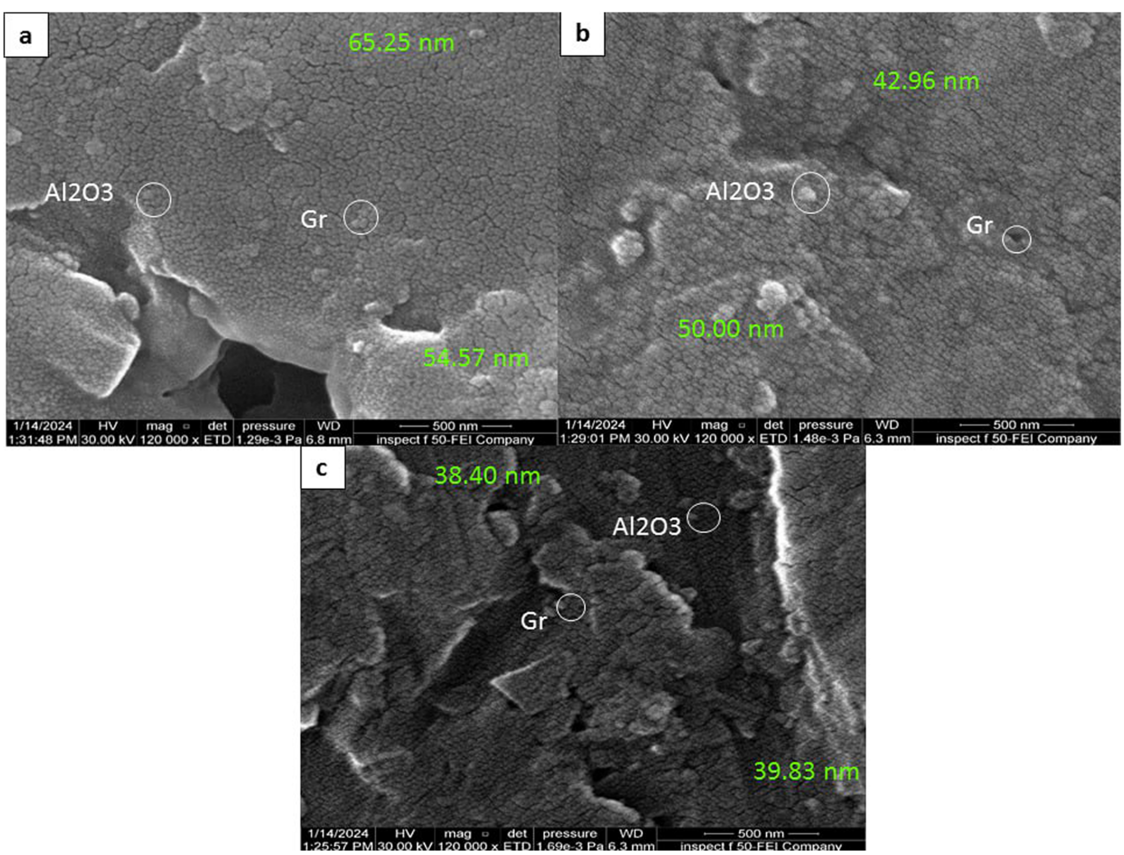

Figure 5: The FE-SEM images of Al1050/Al_2O_3/Gr composite formed by ECAP at a channel angle of 135°: (a) 1P, (b) 3P, and (c) 5P.

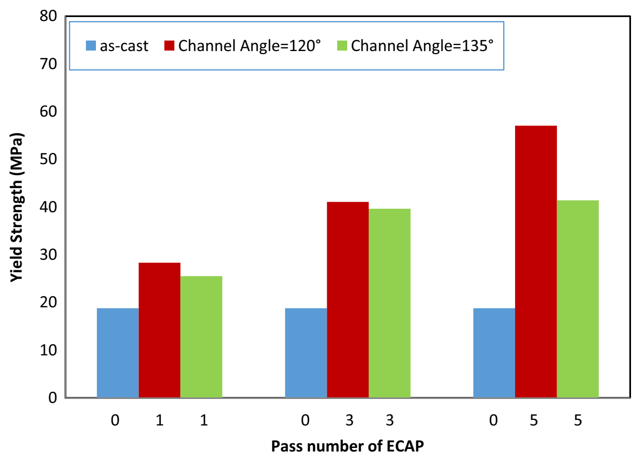

Figure 6: Yield strength (YS) before and after ECAP cycles.

3.2 Results of mechanical properties for the hybrid composite processed by ECAP

Figure 6 illustrates the YS magnitudes obtained by typical tensile tests for the as-cast case and different ECAP cycles.

YS determined 18.8 MPa before the ECAP process while it was enhanced to be 57.05 MPa and 41.41 MPa at channel angles 120° and 135°, respectively, with the 5P ECAP. On the other hand, 1P and 3P ECAP gave lower values of YS compared to the 5P ECAP at two die angles. The impact of the die angle of 120° recorded the increase in YS compared to the 135° for all ECAP cycles in addition the best enhancement for YS was determined with the 5P ECAP at channel angle 120°. On the other side, the YS is near together for two die angles at 3P ECAP, and it seems almost constant at a channel angle of 135° for both 3P and 5P ECAP.

Figure 7 depicts the UT before and after ECAP passes at the die angles of 120° and 135°.

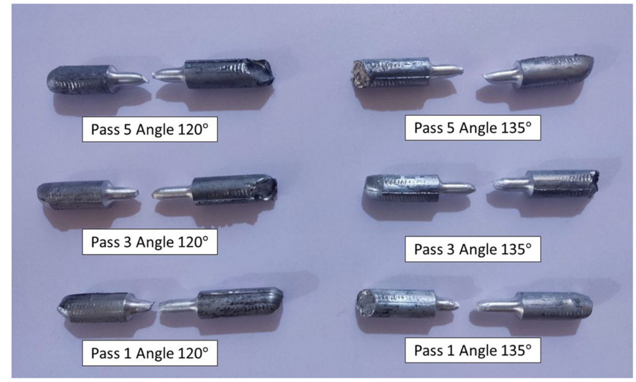

Figure 8: Fractography of the tensile sample after various cycles of ECAP at channel angles 120° and 135°.

The initial value of UT was measured which was 34.06 MPa, and then, it gradually augmented when the number of passes increased until it reached the 5P ECAP and improved to be valued at 139.98 and 120.04 MPa at channel angles 120° and 135°, respectively. The improvement in UT of the Al10150/Al_2O_3/Gr composite can be attributed to three factors: grain refining, turbulence enhancement, and sediment formation and fragmentation during the ECAP process [24]. By augmenting the number of ECAP cycles, the dislocation density was enhanced, resulting in grain refinement and the formation of high-angle grain boundaries. The presence of newly produced dislocations and grain boundaries, in addition to pre-existing grain boundaries, poses additional challenges to viscous dislocations [25]. Effective stabilization of grain boundaries and dislocation motion is achieved by the presence of evenly distributed Al_2O_3 and Gr additions.

Figure 8 illustrates the fractography of the tensile sample after the ECAP process with different passes at

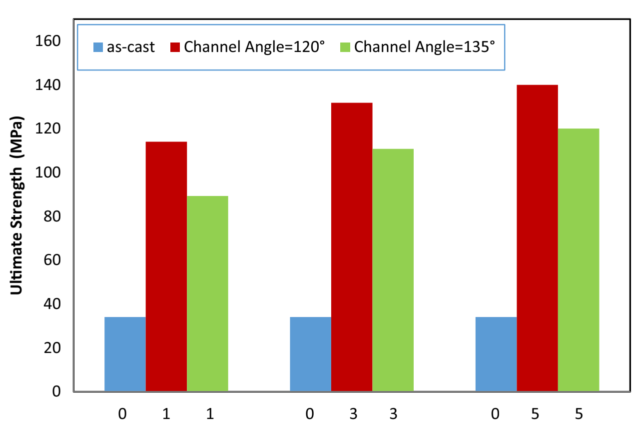

Figure 7: UT before and after ECAP cycles.

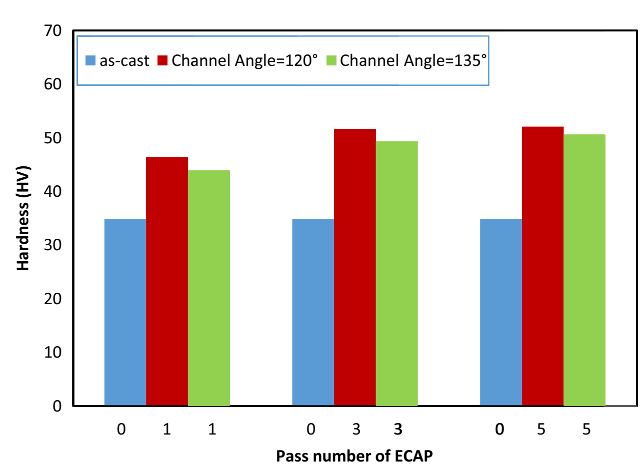

Figure 9: Vickers hardness (HV) before and after ECAP cycles.

channel angle 120° and 135°. It can be seen that the increase in ECAP passes leads to improve ultimate and fracture stress. At cycle 5 for both die angles 120° and 135°, the position of the fracture neck was in the middle of the samples that refers to the mechanical properties enhancement.

Figure 9 points the Vickers hardness measurements for the Al10150/Al_2O_3/Gr composite in the case as received rod and after different ECAP cycles at channel angles 120° and 135°.

The improvement of microhardness can occur after the ECAP process and raises with increasing the number of passes. Compared to the initial rod of Al10150/Al_2O_3/Gr, the microhardness was significantly enhanced for all ECAP passes at two die angles due to the impact of the ultrafine grain which reduces the voids and porosity for the aluminum matrix. On the other hand, there is dispersion strengthening that occurs because of the increase in grain refinement and improvement in morphology. The initial rod had microhardness of 34.96 HV while after ECAP cycles it was measured to be 46.39, 51.62, and 52.08 HV for 1P, 3P, and 5P in order at the channel angle equal 120°. Regarding angle 135°, it showed a similar increase in hardness. The 1P, 3P, and 5P resulted in values of 43.9, 49.34, and 50.63 HV in order. Therefore, it was determined that the maximum stiffness was achieved at an angle of 120° after five iterations of the ECAP pass. The channel angle also impacted the hardness as a result of a close correlation with increased grain refinement with a lower die angle [26]. Based on the results in terms of mechanical properties, ultrafine grains have a sufficient combined impact to ensure the appropriate service and technological characteristics for aluminum alloy [27].

4 Conclusion

This article presented the effect of the ECAP cycles on the microstructure and mechanical properties of the Al1050/Al_2O_3/Gr composite. The grain refinement, YS, ultimate strength, and hardness were extensively studied using two die angles (120° and 135°) at three ECAP-nominated passes including 1P, 3P, and 5P. The following conclusions were summarized:

1. From the obtained FE-SEM results, the grains of the hybrid aluminum composite were elongated in the direction of the load after undergoing SPD (after ECAP cycles).
2. The increase in the number of passes for the ECAP can improve the grain particle, YS, UT, and hardness.
3. The grain size refinement of the aluminum matrix leads to an increase in the UT at channel angles 120° and 135°.
4. The impact of the ultrafine grain can reduce the voids and porosity of the aluminum matrix; thus, the hardness is enhanced.
5. The improvement of the grain refinement, YS, UT, and hardness with a channel angle of 120° is highest as compared to the channel angle of 135°.

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Conflict of interest: The authors state no conflict of interest.

Data availability statement: All used data in this article were provided and analyzed by the researchers.

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