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Mechanical Properties and Porosity Evaluation of the Casted Composite (Al1050/B_4C/FA) after Multi-Cycles of SPD

Tiba Q Irhayyim*[1], Jabbar Gattmah [1]

[1] Department of Material Engineering, College of Engineering, University of Diyala, Baqubah, Diyala, Iraq

Abstract

Aluminum composite products have become a significant component in advanced engineering applications, due to their lightweight nature and excellent mechanical properties. In this article, pure aluminum grade 1050 with a content 93%, boron carbide of 2%, and fly ash of 5% were mixed using the stir casting process to fabricate Al1050/B_4C/FA composite rods. Severe plastic deformation (SPD) using equal channel angular pressing (ECAP) was adopted to enhance the mechanical properties and to assess the porosity state. The two-channel angles 120° and 135° with multi-cycles of ECAP (1,2,3,4,5, and 6) under room temperature were used to determine the mechanical properties and porosity state of the Al1050/B_4C/FA composite. The results revealed that the number of ECAP cycles (passes) can improve both the yield tensile stress, ultimate tensile stress, and hardness due to strain hardening and microstructural changes. The sixth cycle of ECAP and a channel die angle of 120° have the greatest impact on enhancing the mechanical properties compared to the others. Additionally, the porosity magnitudes recorded discrepancies with multiple ECAP cycles and channel die angles. The increase in ECAP passes showed a slight rise in porosity; moreover, the die angle of 120° gave a greater effect than 135°.

Keywords: Severe Plastic Deformation, Al1050/B_4C/FA Composite, Equal Channel Angular Pressing, Mechanical Properties, Porosity.

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1. Introduction

Through the manufacture of composite materials, products with superior and unique properties in terms of strength, lightweight, and resistance to various environmental influences can be obtained. The aerospace industry is considered one of the most important applications that are replacing heavy materials with composites composed of an aluminum matrix reinforced with various types of ceramic materials, industrial waste [1-3]. Stir casting is the most common method used to produce hybrid aluminum matrix composites (HAMCs) due to its simplicity and cost-effectiveness. To overcome the disadvantages of stir casting, such as poor dispersion, clumps, and voids that affect mechanical properties, researchers conduct subsequent improvement processes. For example, using severe plastic deformation such as ECAP to improve the quality of the final product [4].

The field of severe plastic deformation (SPD) has a long history spanning centuries, and over time, its popularity has grown, and its application has expanded across various fields. Initially, (SPD) processes have been a fundamental and important part of human life since the Bronze Age, when basic tools for food preparation and primitive weapons such as swords were manufactured. Severe plastic deformation (SPD) was applied in 1946 on metals, polymers, organics, inorganics, and other materials. SPD differs from traditional forming methods in that it maintains the dimensions of the workpiece despite exposing it to severe cumulative stress [5]. Equal channel angular pressing (ECAP) is one of the most important methods of SPD, improving the material's properties and enhancing its mechanical and micro-structural efficiency [6].

K. Ravikumar et al. 2021 [7] prepared pure magnesium-based $Al_2O_3$and SiC reinforced hybrid composite through a stir casting process followed by ECAP to enhance mechanical and microstructure features. They show that the tensile strength improved due to the impact of the ECAP operation. Further, the hardness magnitude was also augmented by the addition of silicon carbide particles and the number of cycles for the ECAP. Brahmananda Reddy Sathi et al. 2023 [8] used aluminum

* Corresponding author: teebaqahtan99@gmail.com

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matrix composites reinforced with three types of red mud employing stir casting and then subjected to ECAP for evaluation of wear and structural behavior. Submicron-size grain formation improves the hardness, which significantly reduces loss of wear after ECAP, and with an increase in RM content, a reduction in wear rate accrues, while before ECAP, the reduction in wear rate was at the lowest RM (Red Mud) content.

Aqeel Abbas et al. 2020 [9] developed metal matrix composites (MMCs) to improve the strength of AZ91 alloy reinforced with tungsten disulfide (WS_2) using the stir casting method, then ECAP was performed. The results revealed that the grain size was refined into smaller grains, and mechanical properties, including microhardness and tensile yield strength, were increased by 20.45% and 103.5%, respectively, after 4 passes of forming. A. I. Alateyah et al. 2021 [10] studied the effects of ECAP on microstructure, corrosion rate, and hardness of AZ31 Mg alloy at 250°C. The results illustrated highly deformed elongated grains that cause an increase in corrosion resistance with an enhancement in hardness.

S. K. Iyappan et al. 2022 [11] investigated the mechanical properties of ECAPed pure aluminium and Al-SiC composites fabricated by the stir casting process. The hardness, ductility, tensile strength, and machinability were analyzed before and after single and two passes of the ECAP. The hardness of the pure aluminum with two passes was 4% higher than that of the cast sample. Vickers hardness, tensile strength, and machinability of the ECAPed composites were augmented by increasing the SiC particles and ECAP passes. K. M. Agarwa et al. 2022 [12] studied and examined the mechanical behavior of pure Al compressed during ECAP die with three passes. The results showed that the tensile strength from 275.8 to 368.4 MPa was decreased after three cycles of ECAP.

M. Kasaeian-Naeini et al. 2023 [13] used the stir casting process to produce a magnesium composite reinforced with Hydroxyapatite (HA) particles. Then, the obtained composite was subjected to ECAP forming, and its mechanical behavior was evaluated before and after forming. The results showed an 88% enhancement in tensile strength after adding the reinforcement and increasing the number of passes to four. A.M. Hassan et al. (2024) [14] investigated the use of rods made from a hybrid aluminum composite (Al 1050/Al_2O_3/Gr) subjected to SPD through ECAP with varying passes and channel die angles of 120° and 135° to enhance the microstructure and mechanical properties. They revealed that the cycle number of ECAP has a significant impact on hardness and tensile strength.

Although many previous studies have been conducted to fabricate metal matrix composites, such as hybrid aluminum and magnesium, an urgent need to manufacture new composite materials and followed by a cold forming process to improve mechanical properties and porosity evaluation. In this work, a new aluminum matrix composite (Al1050/B_4C/FA) is fabricated employing the stir casting process. Severe plastic deformation (SPD) based on equal channel angular pressing (ECAP) is applied to enhance mechanical properties and to assess the porosity state of the composite.

2. Methodology

In this study, 1050 pure aluminum alloy was selected as the matrix for hybrid aluminum composite production. This is due to its low cost and superior properties, including high conductivity, excellent formability, high strength-to-weight ratio, and corrosion resistance. These properties are important in various advanced industrial applications, such as aerospace, automotive, marine, construction, and the electrical sector [15]. The elements of the pure aluminum grade 1050 in terms of chemical composition are introduced in Table

Table 1: Chemical composition of Al grade 1050

Element	Si	Fe	Cu	Mn	Mg	Cr	Ag	Zn	Zr	Al
Wt.%	0.064	0.155	0.004	0.004	0.004	0.004	0.002	0.008	0.002	Bal.

Two types of material were chosen as reinforcement: first, boron carbide B_4C, which is considered the third hardest known compound on Earth's crust, with excellent mechanical properties of high hardness, high impact strength, and high corrosion resistance compared to diamond and boron nitride. Furthermore, it has a low density (2.52 g/cm^2) and a high melting point that is about 2427ºC [16]. Another material is fly ash (FA), which is an eco-friendly material. FA is the industrial waste produced by coal combustion in thermal power plants with lower density, a low thermal expansion coefficient, low cost, and good mechanical properties [17]. Tables 2 and 3 report the chemical composition of the boron carbide and fly ash, respectively, obtained by EDS tests

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Table 2: Chemical composition of boron carbide (B_4C) obtained by EDS

B_4C	B	C	Si	O
Wt.%	62.64	35.44	0.96	0.97
Error	1.05	1.07	0.04	0.11

Table 3 Chemical composition of fly ash (FA) obtained by EDS

FA	C	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Fe
Wt.%	13.91	43.4	0.28	0.80	13.5	18.2	0.30	0.4	0.5	5.03	0.85	2.84
Error	2.42	1.34	0.10	0.10	0.45	0.59	0.09	0.08	0.09	0.22	0.13	0.23

The matrix material of Al 1050 was placed into a crucible of graphite in the furnace, and heated at a range of 650-750 °C until it melted. Boron carbide of 2% and fly ash of 5% particles were incorporated into molten metal by aluminum foils with a mixing time of two minutes at a stirrer speed of 650-810 rpm. The argon gas was used to prevent oxidation during the mixing process. The mixture was poured into the cast iron mold and allowed to cool to ambient temperature, see Fig. 1 (a).

The ECAP die was made of tool steel and includes two circular channels with angles of 120º and 135º at a constant diameter of 12 mm. The dimensions of the final rods composite (Al 1050/B_4C/FA) obtained by stir casting are 12 mm in diameter and 90 mm in length. The die channels and rods were lubricated using grease oil to minimize friction between the rods and the channel walls of ECAP. The final rods were subjected to multiple cycles of SPD by ECAP passes (1, 2, 3, 4, 5, and 6) using route A. Al1050/B_4C/FA samples were pressed using a tensile testing machine, which has a maximum capacity of 1000 kN, as shown in Figure 1(b).

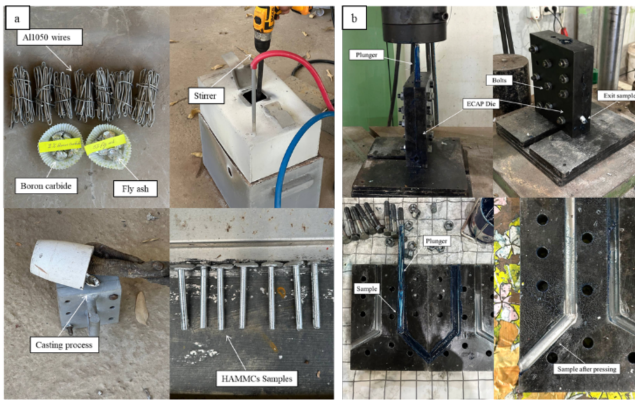

Fig. 1 (a) Stir casting setup and (b) ECAP setup

Energy dispersive spectroscopy (EDS) was applied to investigate the elemental composition of the hybrid aluminum matrix composite (Al 1050/B_4C/FA), by (INSPECTS50) device. The tensile test was adopted to determine the yield and ultimate tensile stress of as-cast Al 1050/B_4C/FA and ECAPed rods that were produced through two angles (120º and 135º) for passes number 2, 4, and 6 by using a tester device (LARYEE UE3450 Universal Testing Machine) with a capacity of 50 kN. The tensile test samples were prepared based on the ASTM E80 standard. Micro Vickers hardness was conducted for as-received Al1050, as-cast Al1050/B_4C/FA, and ECAPed rods at both angles (120º and 135º) according to TH715 – 2008 digital micro Vickers hardness tester, 100 g load applied with 15-second dwell duration.

The porosity of as-cast pure aluminum, hybrid aluminum composite, and ECAPed was also measured based on Archimedes' principle employing a balance model (RADWAG Wagi Elektroniczne Ps 360/C/1). This test was applied to the ASTM C373-88 standard equations (1) and (2) [18]. The test procedure included weighing dry samples, which represent the initial weight, measuring after immersing samples in water, suspending, and weighing them while immersed in water. Then, the sample was suspended and left for 24 hours at room temperature. The sample weight was measured after being saturated with water. From the three weights, porosity, and water absorption are calculated according to the following equations:

$$A.P\,\% = \left[\frac{W_3 - W_1}{W_3 - W_2}\right] \times 100\% \quad (1)$$

$$W.A\,\% = \left[\frac{W_3 - W_1}{W_1}\right] \times 100\% \quad (2)$$

When (A.P) is the porosity of the specimen, (W.A) represents the water absorption of the specimen, (W_1) is the known weight of the dry specimen, (W_2) is the weight of the soaked immersed specimen, and (W_3) symbolizes to weight of the saturated specimen. Figure 2 represents the flow chart of the methodology procedure

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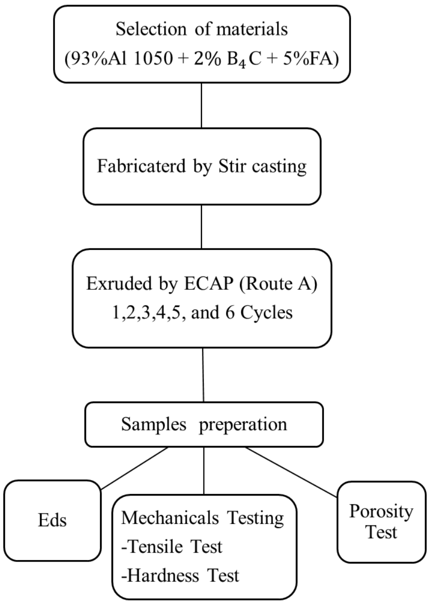

Fig 2. Flow chart of experimental work

3 Results and Discussion

Fig. 3 shows the result of energy dispersive spectrometry (EDS), which indicates the distribution and quantities of the constituent elements of the hybrid (Al 1050/B_4C/FA) composite material manufactured by the stir casting route. It is noted that the highest percentage of constituent elements is aluminum, while the distribution of other elements, such as calcium, iron, and titanium, carbon, and oxygen. These elements are among the main components of fly ash, which consists of a group of oxides of these elements. On the other hand, boron cannot be observed with the other elements due to its low atomic weight, which makes it difficult to detect during examination [19,20].

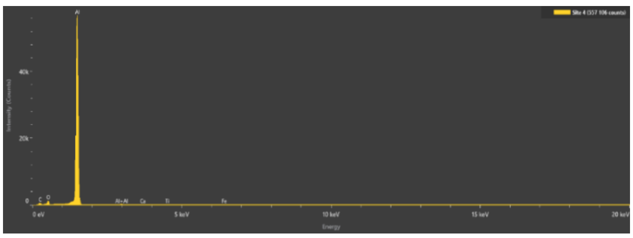

Fig. 3 Element ratio of hybrid Al 1050/B_4C/FA obtained by EDS

Fig. 4 demonstrates the relationship between compression force and displacement of the Al 1050/B_4C/FA recorded during the ECAP process for the various cycles (1 to 6 passes) at 120° die angle under room conditions. The increase in the number of ECAP cycles generates a higher compression force due to the energy consumed as plastic deformation. At the start of the forming by ECAP, the compression force rises rapidly before staying at a steady state (almost constant). The behavior of force vs displacement at the die angle 135° in Figure 5 is similar to Figure 4, with different magnitudes of c. The die angle of 120° gave large values of forces compared to the 135° angle because of the shear stress effect. The increased force required to pass through the corner of the die channel angle is due to the increased strain hardening, which leads to increased friction and the material's resistance to deformation, which requires greater force to pass through the die channel [21].

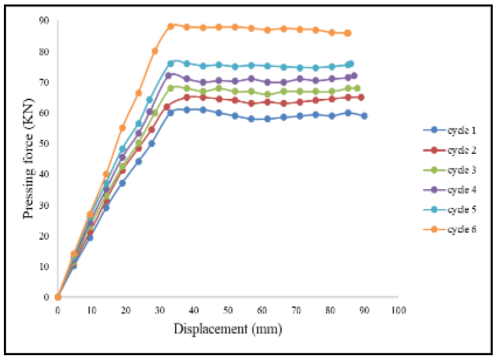

Fig. 4 Compression force vs displacement at the die angle of 120° with various ECAP passes.

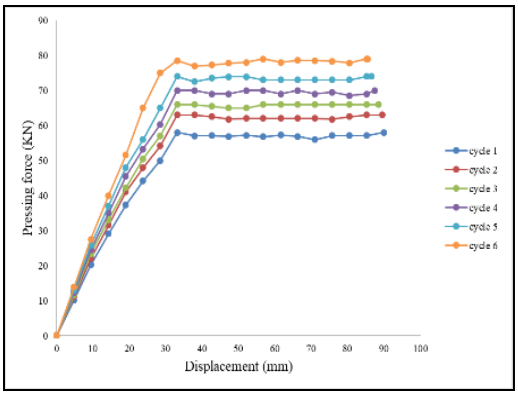

Fig. 5 Compression force vs displacement at the die angle of 135° with various ECAP passes.

Fig. 6 depicts the influence of the ECAP cycle numbers on the tensile yield stress of the hybrid aluminum composite. Comparison of the two-channel die angles shows that the six cycles of ECAP in the highest force value for both die angles, 120° and 135°, due to the impact of severe plastic deformation. The yield stress at a die angle of 120° was higher than the channel die angle of 135° because the channel die angle decreases, and the deformation load increases. The yield stress at the sixth cycle was 270 MPa for the 120º die angle, while for the 135º die angle reached 240 MPa.

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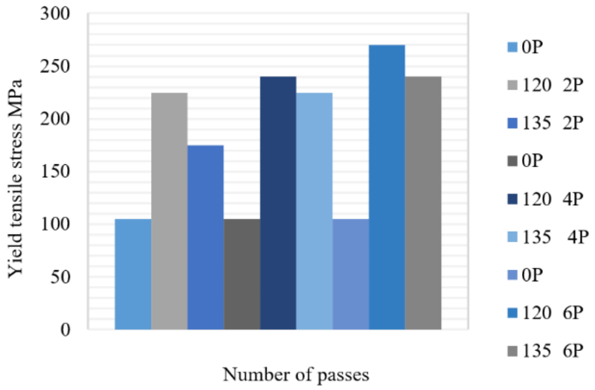

Fig. 6 Yield tensile stress before and after ECAP passes at die angles of 120° and 135°.

Fig. 7 compares the ultimate tensile stress before severe plastic deformation and after different cycle numbers (2, 4, and 6 cycles) for both channel die angles, 120° and 135°. It is evident from Figure7 that the highest value of ultimate tensile stress was recorded at cycle number six at 120°, reaching 288 MPa, while at 135° it was 261 MPa due to influencing the grain refinement, Strain hardening due to increasing number of Passes, and dislocation density. thus leading to higher resistance to deformation and higher tensile strength, these results are in agreement with Ref [22,23].

Figure 8 clarifies the comparison result of the micro Vickers hardness (HV) for the two-channel die angle samples at 120 ° and 135 ° with different cycles, as well as the HV of the base matrix before the ECAP pressing process, and the base matrix before stir casting. The micro Vickers hardness value was recorded at three different positions of the surface, one at the center of the sample and the other at the edge of the surface. The highest value was achieved at a 120 ° die angle for cycle number six, compared to the other cycles, followed by cycle number six at 135° due to Strain hardening by increasing the ECAP cycles led to more grain refinement, more dislocation density, and better homogeneity. Thus, leading to higher resistance to deformation and higher hardness, these results are in agreement with Ref [22, 23].

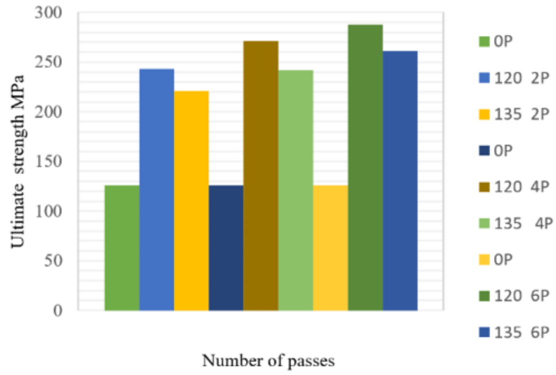

Fig. 7 Ultimate tensile stress before and after ECAP passes at die angles of 120° and 135°

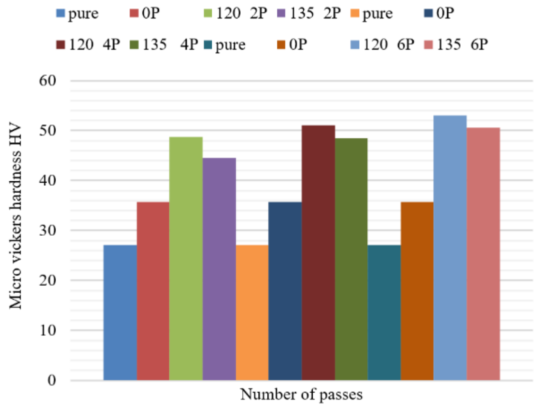

Fig. 8 Micro Vickers hardness HV at die angles of 120° and 135°

Table 4 reports the values of porosity, which include the weight of the dry samples, the weight of the immersed and suspended samples, and the weight of the saturated samples, in addition to the percentage of porosity and absorption for casted composite (Al 1050/B_4C/FA) and extruded rods at 120° and 135° ECAP die angle for three different cycles: 2, 4, and 6. Results reveal a slight increase in porosity compared to the casted samples, with an increase in the number of cycles at both channel die angles. Despite this increase, the value remains close to zero, indicating that the quality of the samples is good.

The increase in the percentage of porosity is attributed to the effect of severe plastic stress with increasing number of cycles, which leads to high dislocation of the internal structure, affecting void formation, and also due to the lack of use of back pressure [24]. Compared to the 120° die angle, the porosity was found to be lower than at the 135° die angle. However, the porosity percentage and absorption at both angles were low. The porosity decreases when the hardness is high. In contrast, the effect of the tightening process in terms of an increase in yield and ultimate tensile stress leads to a rise in porosity due to stress concentration that appears in cracks and fractures compared to non-porous materials

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Table 4: Porosity at multi ECAP cycles with two die angles of 120° and 135°.

Description	W_1 (g)	W_2 (g)	W_3 (g)	W.A %	A.P%
As cast pure aluminum	7.623	5.179	7.629	0.0008	0.0024
As cast hybrid Al 1050/B_4C/FA	9.599	7.195	9.605	0.0007	0.0027
Cycle 2 at 120°die angle	8.974	4.627	8.988	0.0016	0.0032
Cycle 4 at 120°die angle	9.001	4.547	9.031	0.0032	0.0065
Cycle 6 at 120°die angle	8.090	4.655	8.120	0.0037	0.0087
Cycle 2 at 135°die angle	9.655	7.132	9.663	0.9997	0.0028
Cycle 4 at 135°die angle	8.688	6.345	8.698	0.0012	0.0043
Cycle 6 at 135°die angle	7.620	5.179	7.632	0.0016	0.0050

4 Conclusion

In this article, the stir casting process was successfully performed to fabricate Al 1050/B_4C/FA composite rods. Then, these rods were formed by ECAP at multiple cycles with die angles of 120° and 135°. Tensile, Micro Vickers hardness, and porosity tests were conducted to evaluate mechanical properties and porous state. Based on the results of this study, the following conclusions were drawn:

- The yield stress, ultimate stress, and micro Vickers hardness are increased with the rise in the number of ECAP cycles, reaching to sixth pass at both the die angles of 120° and 135°.
- The rods formed through a die angle of 120° showed more enhancement in mechanical properties compared to a channel angle of 135°.
- The increase in the number of ECAP passes resulted in a slight increase, accompanied by some variation in porosity.
- The channel die angle of 120° had a higher effect on the porosity compared to the angle of 135°.

According to this article, it has become clear that there are important relationships between mechanical properties and porosity states for Al 1050/B_4C/FA that need in-depth study in future work. We recommended using back pressure during the extrusion process to enhance mechanical properties and, at the same time, reduce porosity.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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