

Effect of Graphite on the Microstructure and Density of Aluminium Composite AA6061 Using Hot Press Forging

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Abstract

The growing demand for aluminium has resulted in an increase in scrap waste, necessitating the development of efficient recycling methods. This research investigates the application of hot press forging in the production of aluminium AA6061 composites reinforced with graphite particles, aiming to improve physical properties while considering environmental and economic factors. Recycled aluminium AA6061 chips were processed with different graphite contents: Al+0% Graphite, Al+2.5% Graphite, Al+5% Graphite, Al+7.5% Graphite, Al+10% Graphite, and Al+12.5% Graphite. The specimens underwent compaction at 1000 psi and were subjected to hot press forging at 530°C with a pressure of 35 tonnes. The composites were analysed for density, porosity, and microstructure utilizing a Dino-Lite microscope. The results indicated that an increase in graphite content led to a reduction in density and a refinement of grain size, with Al+10% Graphite exhibiting the smallest grain size of 1.28 mm and the lowest porosity at 98.98%. At Al+12.5% Graphite, minor increases in porosity and grain size suggested matrix saturation. The findings indicate that different levels of graphite content have a substantial impact on the density, porosity, and microstructure of aluminium AA6061 composites. This study demonstrates the efficacy of hot press forging as a dependable technique for the production of aluminium-graphite composites, resulting in enhanced physical and structural characteristics.

1. Introduction

The relevance of aluminium alloys has been brought to light as a result of the growing need in the industrial sector for materials that are environmentally friendly, lightweight, and high-strength. Many industries, including the automobile industry, aerospace industry, and construction industry, make substantial use of the aluminium alloy AA6061, which is renowned for its exceptional mechanical capabilities, resistance to corrosion, and lightweight features [1-5]. On the other hand, these enormous waste management difficulties have arisen as a result of the increasing worldwide output of aluminium. The output of aluminium in Malaysia grew from 0.19 million metric tons in 2012 to 0.66 million metric tons in 2021, according to the International Bureau of Metal Statistics [10]. Recycling aluminium is becoming increasingly important as a means of reducing waste, conserving energy, and mitigating the negative effects of environmental issues.

Aluminium recycling has a number of significant advantages, including a reduction in the amount of energy used, a decrease in the emissions of greenhouse gases, and the preservation of natural resources such as bauxite [2]. Aluminium is a very sustainable material since it can be recycled several times without losing its quality [1]. According to Yusuf et al. [6], traditional recycling processes frequently engage in the consumption of a significant

amount of energy and need a longer period of time for processing. Because of this, there has been a surge in interest in solid-state recycling processes, such as direct conversion by hot press forging, which are more suitable for the environment and less energy.

Reinforcements such as graphite have been investigated as potential additions to the aluminium matrix in order to improve the characteristics of recycled aluminium. Because of its low density, superior thermal conductivity, and self-lubricating qualities, graphite has the potential to improve the performance of aluminium composites to a significant degree [8,9].

The rising demand for aluminium has led to a growth in the amount of scrap aluminium trash, which presents a number of serious difficulties, including increased prices, energy consumption, and risk of environmental contamination. According to N. K. Yusuf et al. [6], traditional recycling technologies, which include significant energy consumption and lengthy processing periods, are less sustainable and inhibit the development of the objective of decreasing trash and the impact that it has on the environment. Furthermore, there is still a lack of study with a special focus on composites made of AA6061-Graphite. The objective of this research is to produce a metal matrix composite of AA6061 with graphite through hot press forging. At the same time, the effects of graphite on the microstructure and density of AA6061 composites with different weight percentages of graphite will be evaluated, with the ultimate goal of contributing to the development of high-performance materials that are tailored for future applications.

2. Material and Methods

This research offers a comprehensive account of the experimental procedures, which are detailed in the Materials and Methods section. The major focus is on recycling and processing aluminium chips obtained from the AA6061 alloy, both unreinforced and with variable weight percentages of graphite as reinforcement, using the hot press forging method. The process begins with the milling of aluminium chips, which is then cleaned and dried to assure consistency and quality. The mixing procedure is then carried out to create both reinforced and unreinforced samples. Then, the samples are subjected to hot press forging for 120 minutes at a continuous pressure of 35 tons and 550°C. Physical parameters like as microstructure and density are assessed using dog-bone-shaped samples created particularly for these testing. The study's goal is to investigate how graphite reinforcement affects the structural and physical characteristics of recycled aluminium composites. A complete flowchart is given to graphically portray the process phases, and laboratory tests are carried out to confirm the findings, as seen in Figure 1..

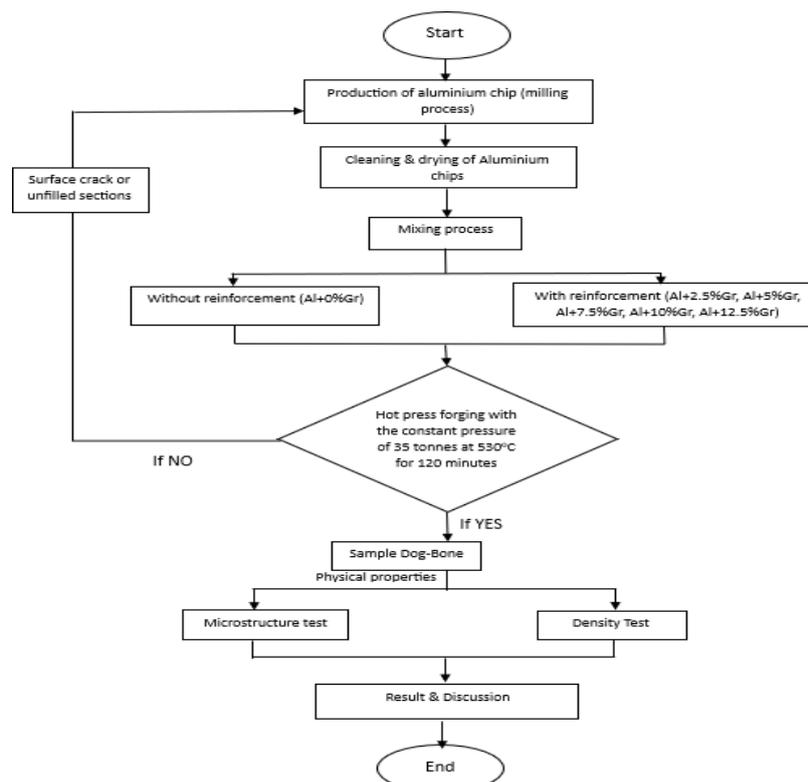


Fig. 1 Flowchart for process AA6061 composite.

2.1 Material Preparation and Processing

The AA6061 aluminium alloy block was milled on a high-speed Sodick-MC 430L milling machine to produce chips, utilizing a feed rate of 1100 mm/min, a depth of cut of 1.0 mm, and 11,000 cycles with a 10 mm diameter carbide tool. The chips underwent cleaning in an ultrasonic bath utilizing acetone and were subsequently dried in an oven. Specimen preparation involved mixing varying quantities of AA6061 and graphite to create composites with each weighing 12.3 grams. The samples underwent compaction process at 1000 psi and hot pressing at 530°C, utilizing 35 tonnes of pressure and a pre-compaction cycle of 120 minutes to produce the composites for testing. The hot press forging process entailed heating the mold to 530°C, the optimal temperature for Aluminium 6061, to ensure uniform heat distribution prior to placing the composite in the mold. A pressure of 35 tonnes was applied during four pre-compaction cycles, each lasting 120 minutes, to facilitate material consolidation and formation. Following the cycles, the temperature was reduced to cool the material, thereby solidifying its shape and ensuring that the composites possessed the necessary strength and properties for subsequent testing.

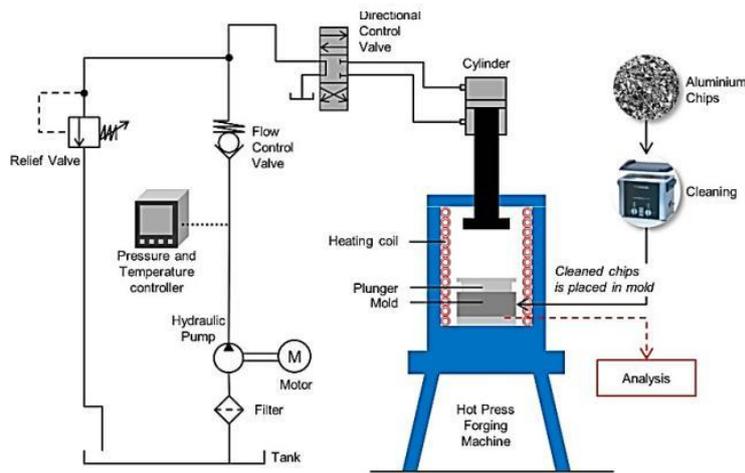


Fig. 2 Experimental set-up of the HPF process (N.K.Yusuf, 2017)

2.2 Microstructure Test

The material testing technique involved preparing specimens for microstructural investigation, including cutting, mounting, grinding, polishing, and etching before inspection with a Dino-Lite microscope. The cutting process was originally executed using a Struers Labotom-3 cutting machine to get the necessary specimen dimensions. Subsequent to sectioning the specimens, they were secured with the Struers Ecompress 52 mounting press to encapsulate the samples in resin, hence ensuring stability during the subsequent operations. The specimen surfaces were ground sequentially using abrasive sheets of grits 240, 320, 400, 600, and 1200 to remove particles and scratches, employing water to reduce friction. Subsequent to grinding, the polishing process begins with a rotating method to get a perfect, mirror-like surface. Meticulous polishing was essential to avoid warping the specimen or leaving scratch marks. The subsequent technique involved etching the specimen using electrolytic etching with a tetrafluoroboric acid solution to enhance the visibility of the microstructure. The specimens were investigated with a Dino-Lite microscope at 50x magnification as shown in Table 1 to see and measure grain size. The Line-Intercept Method is a widely used technique for determining the average grain size of materials, especially in metallographic analysis. This method involves overlaying a known-length line on a polished and etched sample under an optical microscope. By counting the number of intercepts, or intersections, the line makes with the grain boundaries, and measuring the length of these intercepts, the grain size can be calculated. The test involved three measurements : total length of line (LT), total number of intercepts (P).mean intercept length(l), grain size (G), magnification (M).

$$\bar{l} = \frac{L_T}{PM} \tag{1}$$

$$G = - 6.6457 \log \bar{l} - 3.298 \tag{2}$$

Table 1 The Specification of Dino-Lite Microscope

Features	Specifications
Model	Dino-Lite Microscope
Magnification	20x, 50x, 100x, 200x
Resolution	Up to 1.3 Megapixels
Lighting	Built-in LED with adjustable intensity
Connection	USB 2.0/3.0
Software	DinoCapture 3.0 software for image capture, video and measurement.

2.3 Density and Porosity Test

This test aims to examine the influence of graphite on the density and porosity of aluminium AA6061, as porosity can adversely affect mechanical properties. The density test is conducted initially to determine porosity. The Metler Toledo XS204DR Excellence XS Analytical Balance is utilized for weighing samples. The apparatus consists of a beaker containing distilled water, a thermometer, and a bracket holder, as illustrated in the equipment diagram. A beaker is positioned within a vacuum apparatus, and the lid is securely sealed. The weighing machine is calibrated to measure density, solid state, and water, and subsequently zeroed to ensure stability. The specimen is positioned on the pan, and its weight in air (A) is measured. The specimen is subsequently positioned on the bracket within the water, ensuring that there is no contact between the sample and the beaker wall. The specimen undergoes vacuum treatment for a minimum of 5 minutes, facilitating water absorption attributable to its porosity. The specimen's weight in the auxiliary liquid (B) is documented. The specimen is subsequently removed, dried with filter paper, and reweighed to ascertain the mass suspended in water. The density and porosity of the specimen are determined, and this process is replicated for various specimens. The density is defined as the ratio of mass to volume. The equation below is the principle of density which quotient of the mass and the volume of v.

$$\text{Density, } \rho = \frac{m}{v} \left(\text{g/cm}^3 \right) \quad [3]$$

The density of the solid is determined as stated as follows:

$$\text{Density, } \rho = \frac{A}{A - B} (P_0 - P_L) + P_L \quad [4]$$

$$\text{Volume, } V = \alpha \frac{A - B}{P_0 - P_L} \quad [5]$$

The calculation of porosity and water absorption were stated as follows:

$$\text{Porosity} = \frac{B - A}{(B - C)} \times 100\% \quad [6]$$

$$\rho = \frac{A}{A - B} (P_0 - P_L) + P_L \quad [7]$$

Where

A= weight of sample in air

B = weight of sample in the auxiliary liquid

C = weight of sample suspended in air (in wet condition)

P₀ = Density of the auxiliary liquid

P_L = Air density (0.0012 g/cm³)

α =Balance correction factor (0.99985)

uses.

3. Results and Discussion

3.1 Density Properties

The interrelationship between the density and porosity of aluminium-graphite composites plays a crucial role in determining their performance. The addition of graphite to the aluminium matrix results in a decrease in density,

attributed to the lower density of graphite. However, slight deviations may occur at specific levels due to variations in material compaction and particle distribution. At the same time, the addition of graphite typically leads to an increase in porosity, as the particles have the potential to form voids within the composite matrix, especially in cases of uneven dispersion. As graphite content increases, porosity levels off, suggesting that the matrix has attained its maximum capacity for integrating graphite. The equilibrium between reducing density and stabilizing porosity is essential for enhancing the physical properties of the composite, guaranteeing it attains the ideal blend of lightweight features and structural strength..

3.1.1 Density Result

Based on the Fig 2, the density value recorded for the aluminium-graphite composites exhibit a distinct trend with increasing graphite content. The pure aluminium sample (Al+0%Graphite) exhibits the highest density at 2.7 g/cm³, aligning with the theoretical density of AA6061 aluminium. Upon the addition of 2.5% Graphite, there is a slight decrease in density 2.684 g/cm³, highlighting the effect of graphite's reduced density on the composite. The reduction persists with 5% Graphite, resulting in a further decrease in density to 2.664 g/cm³. The findings indicate a steady decline in overall density with the introduction of graphite. With a graphite content of 7.5%, the density is reduced to 2.642 g/cm³ which consistent with the anticipated trend. At 10% graphite, the density shows a slight increase to 2.624 g/cm³, showing a deviation from the previously observed linear decrease. This slight variation may result from differences in material compaction or particle distribution throughout the forging process. Ultimately, at 12.5% graphite, the density decreased once more to 2.620 g/cm³ which consistent with the anticipated trend of decreasing density as graphite content increases. The composite behaviour suggest that density is mainly affected by the graphite content, given that graphite possesses a lower density compared to aluminium. The minor variation observed at 10% graphite indicates possible inconsistencies in the production process

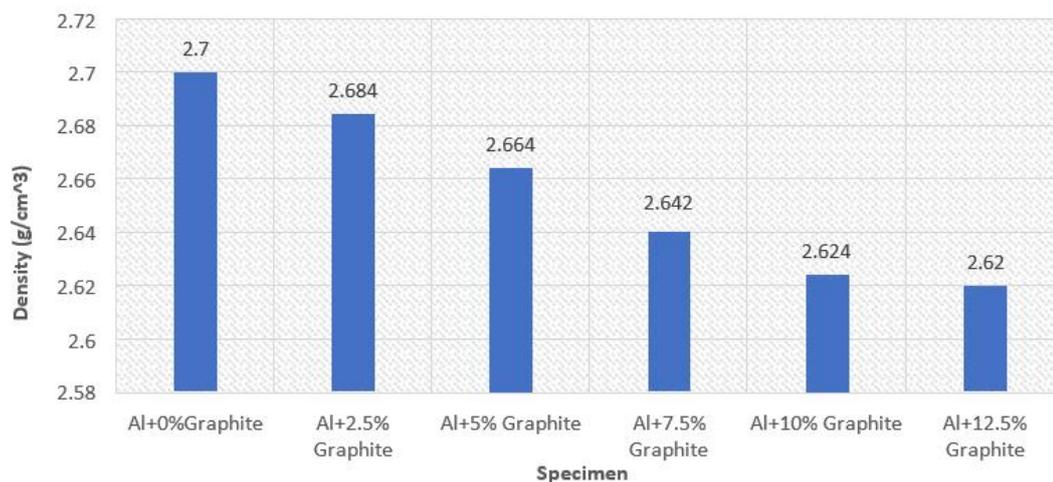


Fig. 2 Graph of density result

3.1.2 Porosity Result

The graph in Fig 3 illustrates how porosity changes as the graphite content in Aluminium AA6061- graphite composites increases. The composite containing no graphite shows the lowest porosity at 91.67%, suggesting a dense material with few voids. This illustrates the dense structure of the aluminium matrix devoid of any reinforcement.

With an increase in graphite content, there is a notable rise in porosity. With a graphite content of 2.5%, there is a significant rise in porosity to 99.14%, indicating the formation of voids attributed to the presence of less dense and weakly bonded graphite particles. Increasing the graphite content to 5% results in a slight increase in porosity, which reaches 99.42%. The porosity at 7.5% graphite is measured at 99.11%. When the graphite content

increases to 10%, the porosity experiences a slight decrease to 98.98%. At 12.5% graphite, the porosity stabilizes at 99.03%. This trend indicates a decreasing influence of increased graphite content on porosity.

The stabilization of porosity at elevated graphite levels suggests that the aluminium matrix has reached its capacity for incorporating further graphite particles. This could result from the even distribution of graphite or the filling of voids formed during the hot-press forging process. Grasping this behavior is crucial for managing porosity and enhancing the physical properties of AA6061-graphite composites for a range of applications.

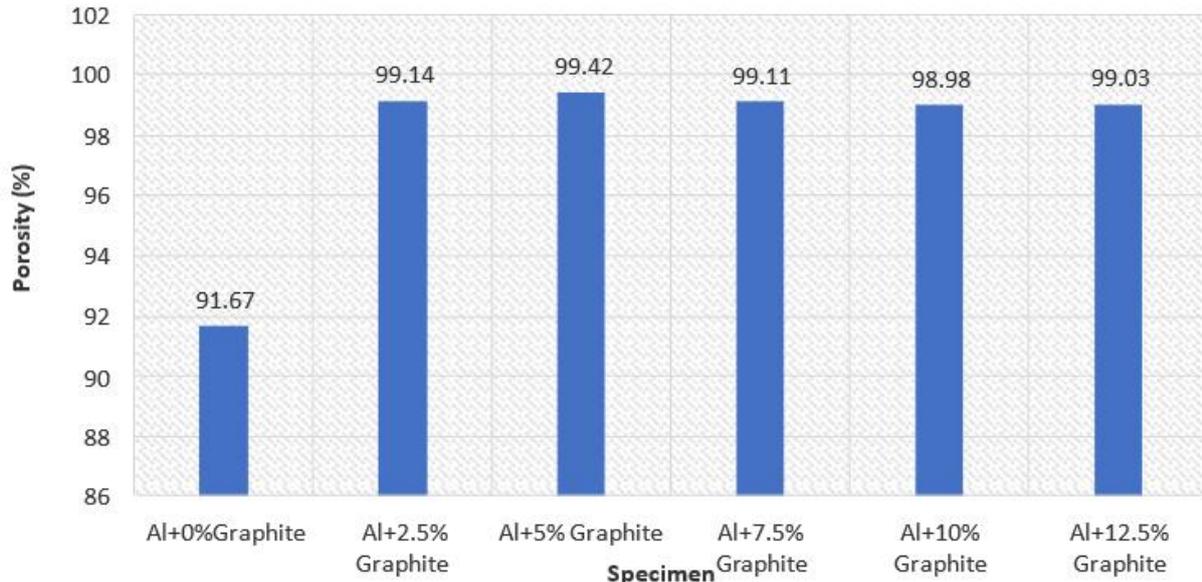


Fig. 3 Graph of porosity result

3.1.3 Correlation Density and Porosity Result

The graph in Fig 4 depicts the correlation between porosity and graphite weight percentages in Aluminium AA6061-graphite composites, as well as the associated variations in density. With 0% graphite, the porosity reaches its minimum at 91.67% while the density peaks at 2.7 g/cm³. This outcome arises due to the fact that, without graphite, the aluminium matrix stays compact and dense, characterized by robust atomic bonds and the absence of voids created by secondary phases.

With a graphite content of 2.5%, there is a significant increase in porosity, reaching 99.14%, accompanied by a decrease in density to 2.684 g/cm³. The introduction of graphite particles into the aluminium matrix leads to a disruption of the compact structure. Graphite exhibits a lower density and weaker interparticle bonding in comparison to aluminium, resulting in the creation of void spaces and a decrease in the overall density of the composite.

With a graphite content of 5%, the porosity achieves a maximum of 99.43%, concurrently resulting in a further decrease in density to 2.664 g/cm³. The elevated porosity at this percentage indicates the ideal distribution of graphite particles throughout the matrix. The increase in these particles leads to a greater number of void spaces, while the overall density diminishes as a result of the combined effect of graphite's lower mass in comparison to aluminium.

With an increase in graphite content to 7.5%, there is a slight reduction in porosity to 99.11%, accompanied by a decrease in density to 2.642 g/cm³. At 10% and 12.5% graphite, the porosity values reach a steady state at 98.98% and 99.03%, respectively, with a slight reduction in density to 2.624 g/cm³ and 2.62 g/cm³. The stabilization occurs as the aluminium matrix attains its saturation threshold for integrating graphite particles. Excess graphite clusters do not disperse uniformly, which restricts additional increases in porosity and results in a slower rate of density reduction.

Based on these results, the composite with 5% graphite provides the best balance between porosity and density. The high porosity of 99.43% at this composition is ideal for applications that require lightweight and porous materials without significantly compromising structural integrity.

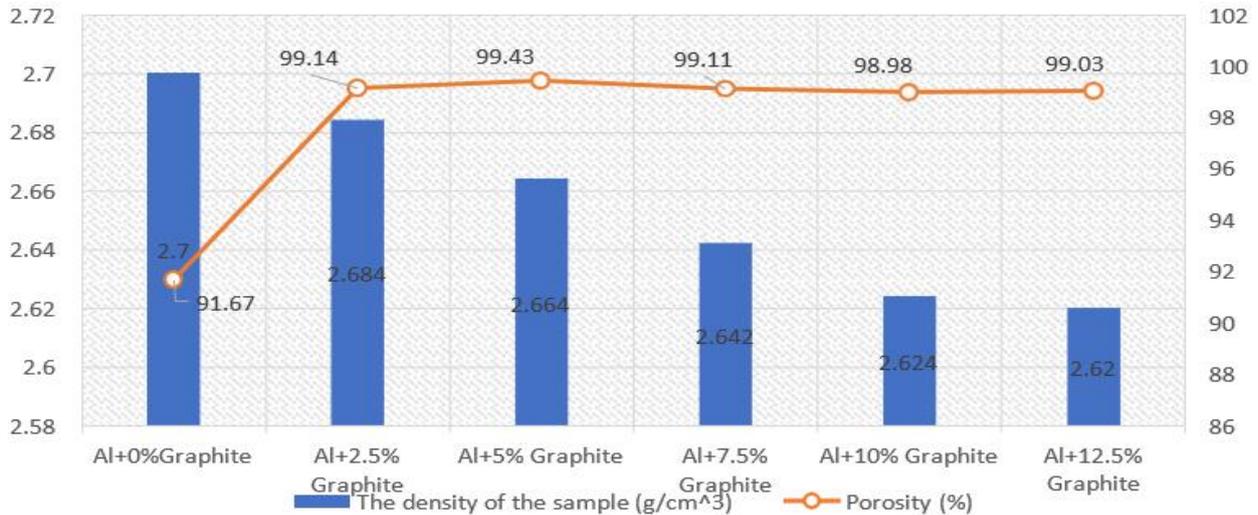


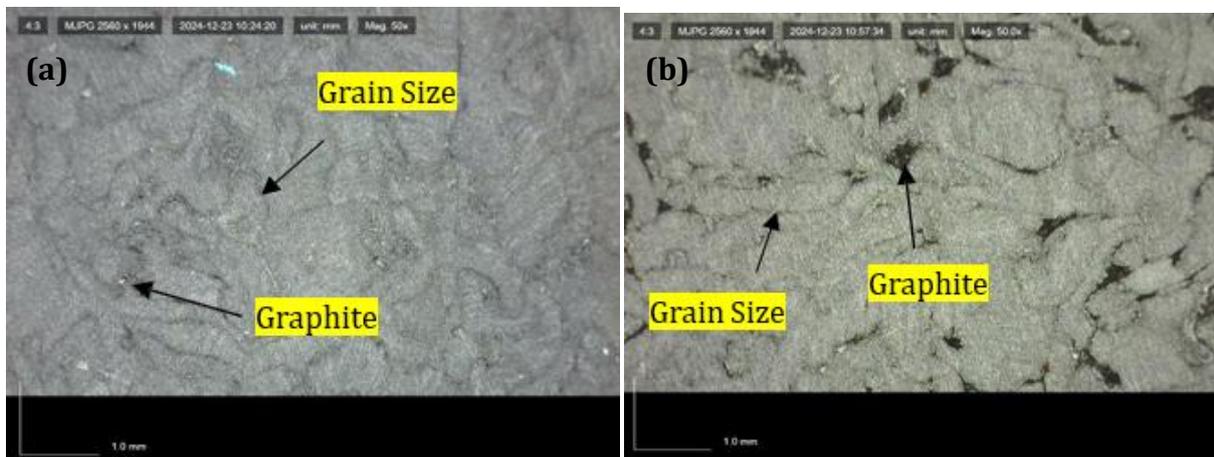
Fig. 4 Correlation between density and porosity

3.2 Microstructure Analysis

Based on Fig 5, the analysis of the microstructure in AA6061-graphite composites with different graphite contents (2.5%, 5%, 7.5%, 10%, and 12.5%) reveals notable variations in grain size and the distribution of graphite. In the Al+2.5% graphite sample (Figure a), the grain structure appears to be relatively larger, with the graphite particles being sparsely distributed throughout the matrix. With an increase in graphite content to 5% (Figure b) and 7.5% (Figure c), there is a noticeable reduction in grain size, accompanied by a more uniform distribution of graphite. This highlights the function of graphite in enhancing the grain structure by serving as obstacles to grain growth throughout the hot press forging process.

With 10% graphite (Figure d), the grain structure exhibits further refinement, characterized by smaller grains and improved dispersion of graphite particles. In the Al+12.5% graphite sample (Figure e), while the grain size continues to be small, indications of porosity start to emerge. This indicates that an overabundance of graphite can interfere with the aluminum matrix's cohesion, resulting in voids that impact the composite's density and mechanical integrity.

These observations emphasize the necessity of optimizing graphite content to attain a refined grain structure and reduce porosity. To enhance the assessment of these effects, the grain size for each sample will be determined and analyzed in relation to the observed porosity. This analysis aims to enhance our comprehension of the interplay between grain refinement, porosity, and graphite content, thereby aiding in the optimization of the composite's material properties.



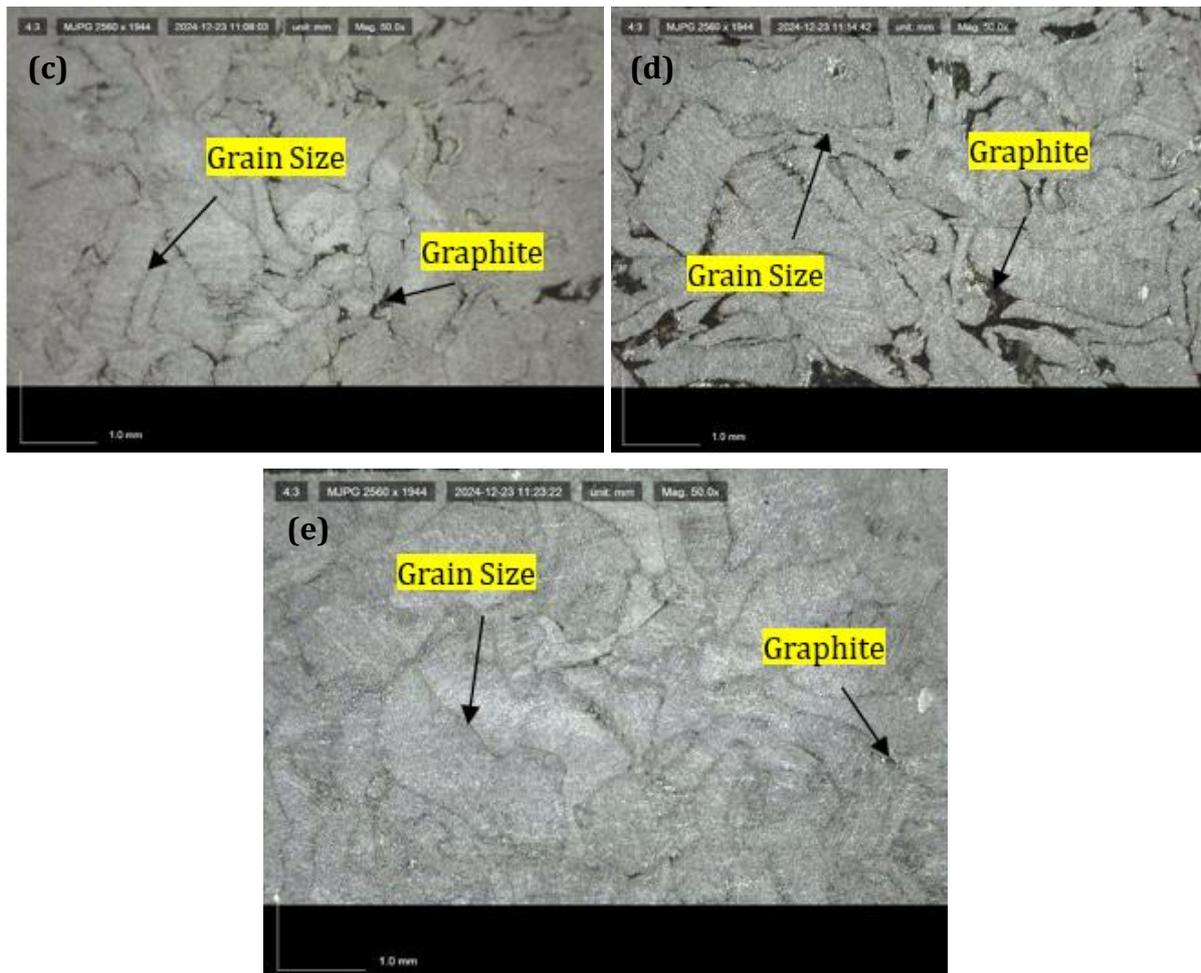


Fig 5 Microstructure of the sample (a) Al+2.5%Graphite, (b) Al+5%Graphite, (c) Al+7.5%Graphite, (d) Al+10%Graphite, (e) Al+12.5%Graphite

3.2.1 Grain Size

The bar chart in Fig 6 presents the grain size of AA6061-graphite composites across different graphite content levels (2.5%, 5%, 7.5%, 10%, and 12.5%). The grain size starts at 1.60 mm for the Al+2.5% graphite sample and rises to 1.76 mm for the Al+5% graphite sample. The observed increase may be linked to the inadequate distribution of graphite particles at lower percentages, which facilitates the growth of larger grains during the processing phase.

With an increase in graphite content to 7.5% and 10%, the grain size diminishes to 1.50 mm and 1.28 mm, respectively. The observed reduction can be attributed to the presence of graphite particles, which serve as impediments to grain growth, thereby enhancing the refinement of the microstructure. At a concentration of 12.5% graphite, there is a slight increase in grain size to 1.46 mm. This could suggest the beginning of porosity or the clustering of surplus graphite particles, potentially disrupting the uniformity of the grain structure and diminishing the matrix's ability to manage grain boundaries effectively.

To deepen the understanding of the composites' behavior, an analysis will be conducted on the correlation between grain size and porosity. This analysis aims to elucidate the impact of grain size variations at different graphite concentrations on porosity, and consequently, on the mechanical and physical characteristics of the composites.

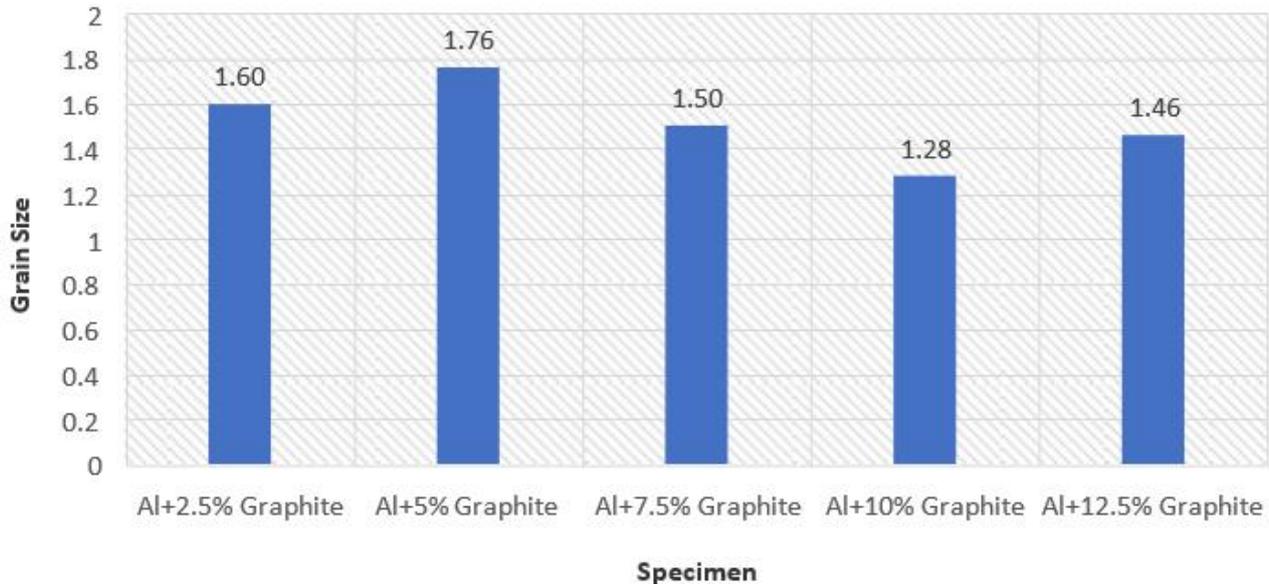


Fig 6 Graph of grain size of the specimen

3.2.2 Correlation between Grain Size and Porosity

The chart in Fig 7 illustrates the correlation between grain size and porosity in AA6061-graphite composites, highlighting the effects of different graphite content levels. The grain size shows a consistent decrease from 2.5% to 10% graphite, with the smallest grain size noted in the Al+10 % graphite sample. At a concentration of 12.5% graphite, there is a slight increase in grain size. Conversely, porosity shows an initial rise, reaching its maximum in the Al+5% graphite sample, before declining to its minimum at 10 % graphite. With a graphite content of 12.5 %, there is a slight increase in porosity.

The initial rise in porosity from 2.5% to 5% graphite is linked to the incorporation of graphite particles, which may generate voids in the matrix if not adequately dispersed. The observation is clear in the Al+ 5% graphite sample, where there is an increase in grain size, likely resulting from inadequate particle refinement and matrix cohesion. With an increase in graphite content to 7.5% and 10%, there is a noticeable reduction in grain size, resulting in a more refined microstructure. This enhancement leads to improved particle packing and a decrease in voids, ultimately reducing porosity.

With a graphite content of 12.5%, the refinement of grain size, when compared to lower graphite levels, accounts for the slight increase in porosity, which can be attributed to the agglomeration of excess graphite particles. This alters the consistency of the matrix and creates micro-voids, counteracting the benefits associated with grain size reduction. Achieving lower porosity hinges on the delicate interplay of graphite content, grain refinement, and matrix uniformity.

The results show that porosity is not following density trends, as density is decreasing even if porosity is decreasing. The grain size data corroborates this inconsistency, providing evidence of the structural variations that lead to this outcome. Hence, the analysis of grain size corroborates the identified trends in porosity and clarifies the inconsistencies observed between porosity and density. The sample consisting of aluminium and 10 % graphite demonstrates the smallest grain size and the lowest porosity. This finding indicates that porosity is affected by the interplay between grain structure and the distribution of graphite.

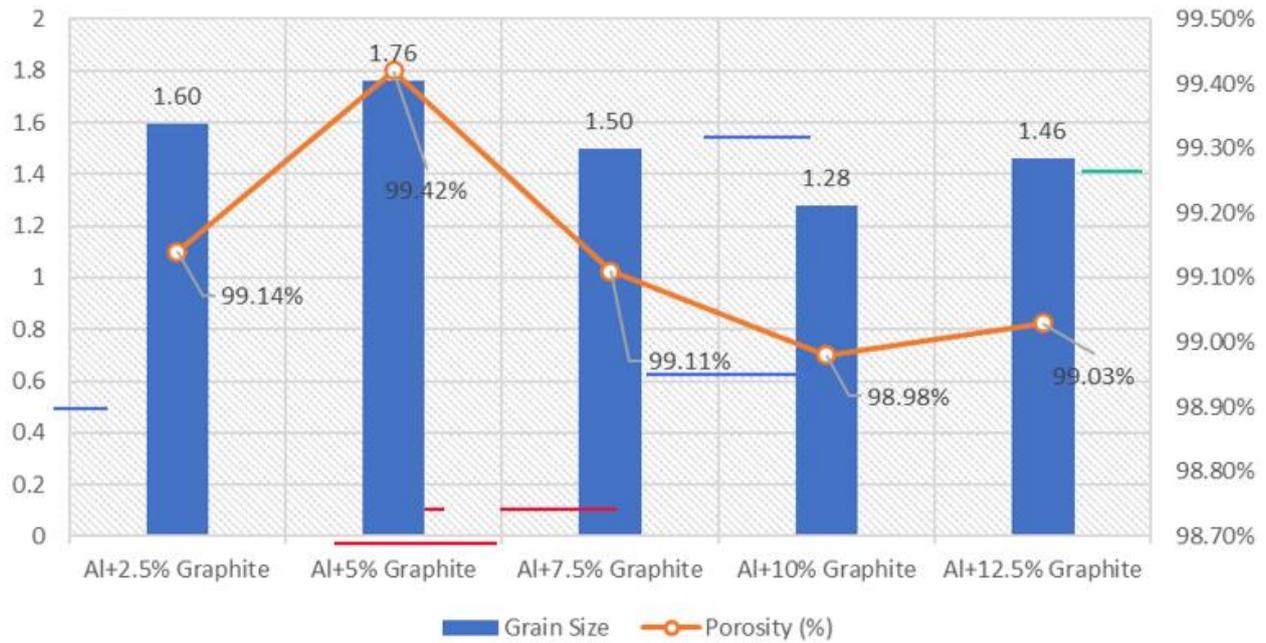


Fig 7 Graph correlation between grain size and porosity

4. Conclusion

In conclusion, the hot press forging method of adding graphite to Al AA6061 effectively creates composites with noticeable differences in microstructure, density, and porosity at all graphite content levels, including Al+0%, Al+2.5%, Al+5%, Al+7.5%, Al+10%, and Al+12.5%. The findings indicate that an increase in graphite content leads to a reduction in density, attributed to the lower density of graphite in comparison to aluminium. The maximum density was observed at Al+0% Graphite, while the minimum was noted at Al+12.5% Graphite. The reduction in grain size is observed as the graphite content increases, achieving the smallest dimensions at Al+10% Graphite. This composition also shows the least porosity, suggesting an optimal level of structural refinement. At Al+12.5% Graphite, there are minor increases in porosity and grain size, indicating potential matrix saturation and graphite agglomeration. The results indicate that the characteristics of Al AA6061 composites are significantly influenced by the amount of graphite present, highlighting the necessity for careful optimization to improve their efficacy in sophisticated applications..

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Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Fatin Shamila Shamsul, Mohammad Sukri Mustapa; **data collection:** Fatin Shamila Shamsul; **analysis and interpretation of results:** Nurathirah Mohammad Aris; **draft manuscript preparation:** Fatin Shamila Shamsul, Mohammad Sukri Mustapa. All authors reviewed the results and approved the final version of the manuscript.*

References

- [1] Bertram, M. (2006). The global and European dimension of aluminium recycling. International Aluminium Institute, European Aluminium Association and Organization of European Aluminium Refiners and Remelters (Vol. 202006). <https://www.world-aluminium.org>
- [2] Cui, J., & Roven, H. J. (2010). Recycling of automotive aluminum. Transactions of Nonferrous Metals Society of China (English Edition), 20(11), 2057–2063. [https://doi.org/10.1016/S1003-6326\(09\)60417-9](https://doi.org/10.1016/S1003-6326(09)60417-9)

- [3] Farhan Latif, I.A. & Mohd Nor, M.K. (2023). High-Velocity Impact Penetration Behavior of Recycled Aluminum Alloy 6061: A Brief Look. *Journal of Advanced Mechanical Engineering Applications*, 4(2), 004. <https://doi.org/10.30880/jamea.2023.04.02.004>
- [4] Nakajima, H. (2007). Fabrication, properties and application of porous metals with directional pores. *Progress in Materials Science*, 52(7), 1091–1173. <https://doi.org/10.1016/j.pmatsci.2006.09.001>
- [5] Youness, R. A., & Taha, M. A. (2021). Review on using powder metallurgy method for production of metal-based nanocomposites. *Egyptian Journal of Chemistry*, 64(12), 7215–7222. <https://doi.org/10.21608/ejchem.2021.68216.3478>
- [6] Yusuf, N. K., Lajis, M. A., & Ahmad, A. (2017). Hot press as a sustainable direct recycling technique of aluminium: Mechanical properties and surface integrity. *Materials*, 10(8), 902. <https://doi.org/10.3390/ma10080902>
- [7] Yusuf, N. K., Lajis, M. A., & Ahmad, A. (2019). Multiresponse optimization and environmental analysis in direct recycling hot press forging of aluminum AA6061. *Materials*, 12(12), 1918. <https://doi.org/10.3390/ma12121918>
- [8] Zubairu, P., Mohammed, A., Egbe, P., Jabo, U., & Babazhitsu, K. (2021). Investigation of microstructure and mechanical properties of developed AA6061-SiC/Graphite hybrid composite. <https://doi.org/10.1007/s12633-021-01236-4>
- [9] Song, L., Gao, H., Bhatt, L., Kong, C., & Yu, H. (2023). Microstructure and mechanical properties of AA1050/AA6061 multilayer composites via accumulative roll bonding and cryorolling and subsequent aging. *Materials Science and Engineering A*, 874, 145069. <https://doi.org/10.1016/j.msea.2023.145069>
- [10] International Bureau of Metal Statistics. (2022). Malaysia: Aluminum production. <https://international-aluminium.org/>
- [11] Redstone Manufacturing. (n.d.). 6061-T6 equivalent materials & metal specifications. Retrieved January 2, 2025, from <https://redstonemanufacturing.com/6061-t6-equivalent-materials-metal-specifications/>