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Effect of Graphite on the Microstructure and Density of Aluminium Composite AA7075 Using Hot Press Forging

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Abstract

There has been growing interest in developing aluminium composites with improved properties for industrial applications. Aluminium alloy AA7075 is a lightweight material with excellent strength, while graphite enhances lubrication and reduces density. This study aimed to investigate the physical properties of recycled Aluminium AA7075 reinforced with 2.5% Graphite powder through a hot press forging method and compare its performance with AA6061 reinforced with 2.5% Graphite, known for its high strength. Density measurements were performed using the Archimedes principle, and the microstructure was analyzed using Optical Microscopy and Scanning Electron Microscopy (SEM). The findings reveal that the addition of graphite improves microstructural uniformity and reduces density. Comparatively, AA6061-2.5% Graphite exhibited superior strength, highlighting its potential for applications requiring both high performance and lightweight materials. This study underscores the viability of sustainable recycling methods in producing advanced composite materials with enhanced properties for industrial applications.

1. Introduction

The development of advanced materials with enhanced properties has gained increasing attention, particularly in the field of aluminium-based metal matrix composites (MMCs). Aluminium alloy 7075 (AA7075), a high-strength, precipitation-hardened alloy, is widely recognized for its exceptional strength-to-weight ratio and corrosion resistance, which makes it a popular choice in industries like aerospace and automotive. The develop superior mechanical and physical properties appropriate for automotive/aerospace applications.[1] To enhance these properties even further, researchers have begun incorporating reinforcement materials like graphite, which can improve the microstructure and physical characteristics of AA7075, making it even more suitable for demanding applications.

Graphite is known for its unique self-lubricating properties and low density, which can enhance the overall performance of metal matrix composites (MMCs). When added to aluminium alloys, graphite can enhance properties like density and wear resistance, making these materials even more suitable for high-performance applications. Additionally, graphite contributes to the creation of a protective tribological film on the surface of the alloy, which helps reduce wear which helps reduce wear and enhance the material's durability in various industrial applications.

Hot press forging, a solid-state recycling technique, has become an effective method for producing these composites. This process not only enables the recycling of aluminium alloy chips but also improves material strength by compacting them under high pressure and temperature. It is sustainable manufacturing because it reduce waste and conserve valuable natural resources, making it an environmentally-friendly option for fabricating high-quality materials.

However, The physical properties of AA7075-graphite composites, such as microstructure and density, are influenced by the addition of graphite. SEM analysis helps reveal how graphite distributes within the alloy, affecting grain structure and phase formation. Varying graphite content also impacts the density, which in turn influences the material's strength and performance in lightweight, high-demand applications.

The problem statement of this research is to examine how reinforcing recycled AA7075 aluminium alloy with graphite powder can enhance its mechanical properties. While AA7075 is known for its strength and light weight, its high cost makes recycling a more affordable option. However, the impact of graphite content on the material's density, microstructure, and performance is not well understood, especially in terms of hardness, tensile strength, and wear resistance. This study aims to fill this gap by analyzing the effects of graphite reinforcement, providing insights that could lead to the development of sustainable, high-performance materials for industries like aerospace and automotive.

The objective that need to find in this research is to investigate the physical properties of recycled Aluminium AA7075 reinforced Graphite powder through a hot press forging method. The second objective is to analyze the microstructure and density of composites on weight percentages of graphite.

2. Material and Methods

This section outlines the preparation process for aluminium alloy AA7075 mixed with 2.5% graphite using the hot press forging method. It offers a comprehensive explanation of the experimental approach detailed in the Materials and Methods section, focusing on the recycling of metal matrix composites (MMC). The study examines physical properties such as density, porosity, and microstructural characteristics. The microstructure was examined using an optical microscope to gather qualitative information about the grains, including their size, shape, and orientation. Scanning electron microscopy (SEM) was utilized to analyze phase distribution and particle dispersion within the composites. The goal is to investigate the effects of different graphite contents on the physical properties of recycled Al-Gr composites and their potential for industrial use. This study incorporated a flowchart and conducted on-site field tests, as shown in Fig. 1.

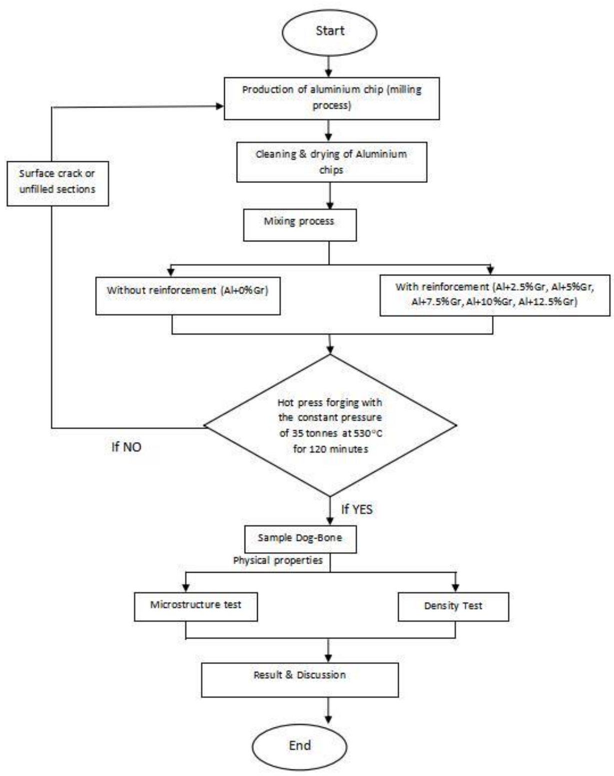

Fig. 1 *Flowchart for process AA7075 composite.*

2.1 Material Preparation and Processing

Appropriate cleaning and preparation are essential to ensure the quality of recycled aluminium chips from machining semi-finished goods. After thorough cleaning with a 99.5% pure acetone solution, the chips were dried in a thermal oven at 60 °C [1, 2]. This cleaning procedure follows ASTM G131–96 standard procedures. Aluminium AA6061 then was combined with graphite powder using a ball milling machine to enhance the recycling process. AA6061 aluminium alloy was mixed with 99.99% pure graphite powder at a percentage by weight (0%, 2.5%) to achieve the desired properties. Applying a constant pressure of 35 tonnes and a four-time pre-compaction cycle with an operating temperature of 530°C and a holding time of 120 minutes, the following recycling process made use of a laboratory hot press forging (HPF) machine as shown in Fig. 2 [1,2]. Following HPF, the specimen will rapidly cool by quenched in water at a rate of 100°C per second until it reaches room temperature followed by artificial ageing at 175°C for 120 minutes [1, 2].

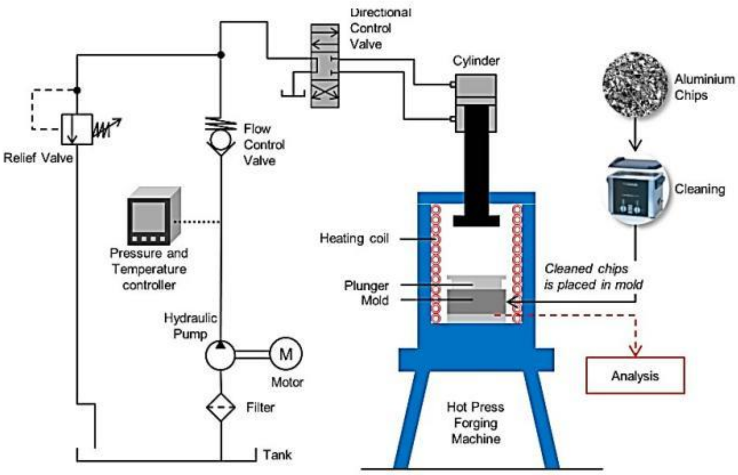

Fig. 2 *Experimental set-up of the HPF process [2].*

2.2 Physical Characterization

The physical properties of the AA7075-graphite composite were evaluated using standardized methods to ensure reliable and reproducible results. The density of the composite was measured using the Archimedean method, where small samples were weighed in ambient air and distilled water. This process utilized a precision density balance (HR-250A, A&D, Seoul, Korea), enabling the determination of material density and porosity by comparing the measured density to the theoretical value.

Microstructural analysis was performed to assess grain size, phase distribution, and particle dispersion. Samples were prepared through a sequence of grinding by using silica carbide papers with grades 240, 500, 1000,2000,and 3000 grain/in^2 and polishing steps, followed by etching with nitric acid (HNO_3) to reveal structural features. The microstructure was examined using an optical microscope (Olympus BX60M), which provided high-resolution imaging at magnifications up to 200x. Digital imaging software connected to the microscope facilitated the detailed analysis and documentation of the composite's internal structure.

These physical characterisation methods offered critical insights into the density, porosity, and microstructural attributes of the AA7075-graphite composite, which directly influence its performance and suitability for industrial applications.

2.3 Porosity and Density Test

The porosity of the AA7075-graphite electrolyte composite was measured using the Archimedes principle. The test involved three weight measurements: weight of sample in air (A), weight of sample in the auxiliary liquid (B), and weight of samplw suspended in air(in wet condition)(C), density of the auxiliary liquid (P_0.), density air (P_L). The porosity (P) and density (ρ) were calculated using the following equations:

$$Porosity = \frac{B - A}{(B - C)} \times 100\% \quad [1]$$

$$\rho = \frac{A}{A-B}(P_0 - P_L) + P_L \quad [2]$$

The relative density was determined by comparing the measured density to the theoretical density of the composite. This technique offered valuable information about the porosity and overall density of the AA7075-graphite composite, which are essential physical properties that affect its structural stability, microstructure, and performance in various applications.

2.4 Microstructure Test

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 (L_T), total number of intercepts (P, mean intercept length(l), grain size (G), magnification (M)

$$\bar{l} = \frac{L_T}{PM} \quad [3]$$

$$G = -6.6457 \log \bar{l} - 3.298 \quad [4]$$

The microstructure of the AA7075-graphite composite was examined to gain insights into its grain structure, phase distribution, and overall material behavior. By analyzing the microstructural characteristics, such as the dispersion of graphite particles and the interaction between the phases, a better understanding of the composite's physical properties and performance in industrial applications can be achieved. These microstructural features are crucial for predicting the material's strength, durability, and suitability for specific uses.

3. Results and Discussion

3.1 Porosity and Density analysis

Fig 3 shows the density with different composition. It is found that the density values of the addition of 2.5% graphite (Gr) significantly reduces the density of aluminum alloys 6061 and 7075. For aluminum 6061, the density decreases from approximately 2.70 g/cm^3 (0% Gr) to a lower value when 2.5% Gr is added. Similarly, for aluminum 7075, the density drops from around 2.80 g/cm^3 to a reduced value with the same graphite content. This reduction is expected, as graphite has a significantly lower density than aluminum, and its uniform dispersion within the matrix lowers the composite's overall density.

Comparing the two alloys, aluminum 7075 consistently exhibits a higher density than aluminum 6061 at both graphite levels due to its higher-strength alloy composition. However, the percentage reduction in density is similar across both alloys, demonstrating the consistent influence of graphite in reducing weight. The decrease in density is particularly beneficial for weight-sensitive applications such as aerospace and automotive industries, where material weight significantly impacts fuel efficiency and performance.

Despite the benefits of reduced density, its impact on mechanical properties must be carefully considered. Excessive density reduction may lead to increased porosity or reduced structural integrity, especially under high load conditions. Aluminum 6061 with graphite offers a lighter alternative, making it suitable for applications prioritizing weight reduction. In contrast, aluminum 7075 provides a higher-density and higher-strength option, ideal for strength-critical applications. The observed trend underscores the importance of balancing weight reduction with maintaining mechanical performance when optimizing composites for specific applications.

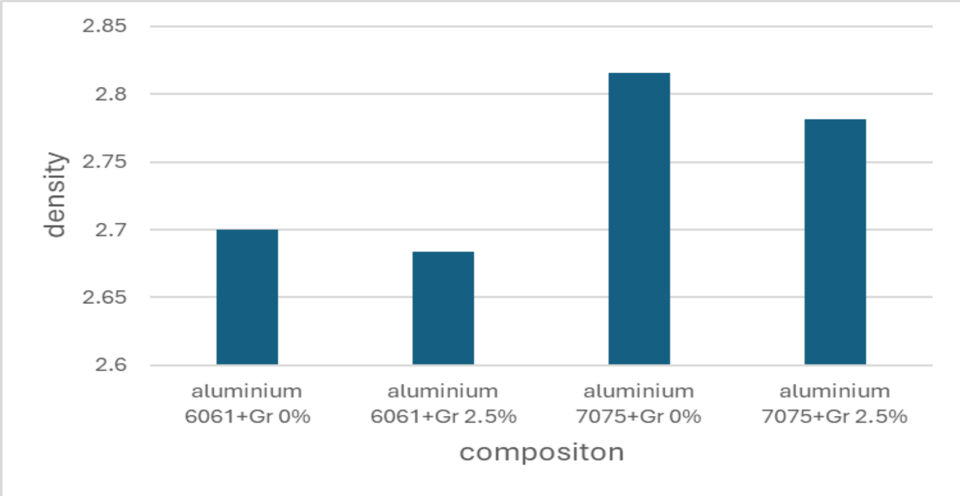

Fig. 3 Graph of Density with different composition

Based from Fig 4, it is evident from the porosity percentage values that the addition of 2.5% graphite (Gr) significantly influences the porosity characteristics of aluminum alloys 6061 and 7075. Comparing aluminum 6061 with 0% Gr and 2.5% Gr, the porosity percentage increases from 91.67% to 99.0%, indicating a clear enhancement in the porous structure. Similarly, for aluminum 7075, the porosity rises from 97.7% to 98.5%. This consistent increase across both alloys can be attributed to the presence of graphite, which introduces voids and microdefects during fabrication, thereby increasing the overall porosity.

Moreover, aluminum 6061 exhibits a higher porosity percentage than aluminum 7075 at both graphite levels. This difference suggests that the microstructural characteristics of aluminum 6061 allow for a more uniform dispersion of graphite, which promotes greater void formation compared to aluminum 7075. The increase in porosity is beneficial in applications where reduced weight or enhanced gas or liquid permeability is critical, as it decreases the overall density of the composite material. However, the rise in porosity could also weaken the material's mechanical strength and stiffness, particularly in load-bearing applications.

The comparison between the two alloys highlights the balance between increased porosity and mechanical performance. While aluminum 6061 with graphite addition offers higher porosity and lighter weight, aluminum 7075 provides slightly lower porosity but greater structural integrity. The observed changes emphasize the importance of optimizing graphite content and alloy selection to meet specific application requirements, particularly in industries such as aerospace and automotive, where both weight reduction and mechanical durability are essential.

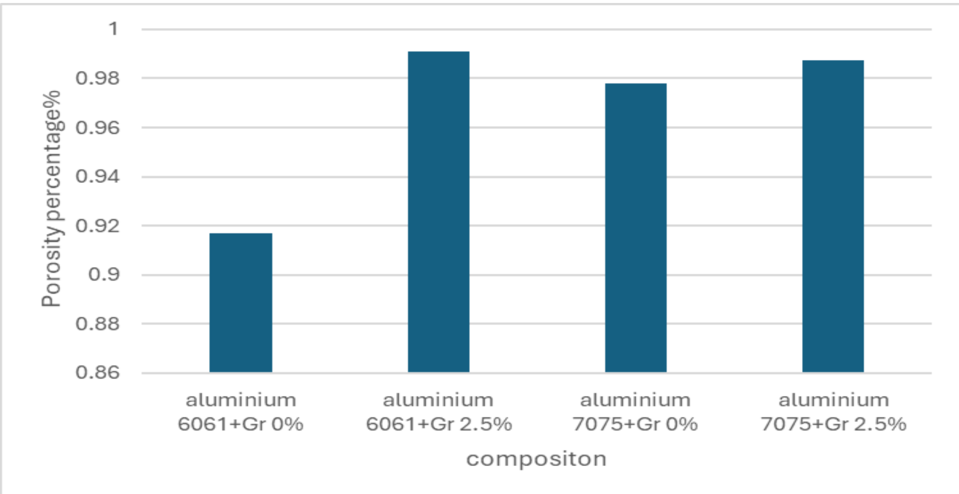

Fig. 4 Graph of Porosity with different composition

3.1.1 Porosity and Density analysis

The relationship between porosity and density in materials is illustrated in Fig 5. It is found thatr it is inversely proportional, as demonstrated in the aluminum alloys 6061 and 7075 with the addition of 2.5% graphite (Gr). As porosity increases, the density of the material decreases, reflecting the influence of voids or spaces within the composite structure. This phenomenon occurs because the addition of graphite, which has a lower density than aluminum, introduces microvoids into the alloy matrix, reducing the material's overall compactness and increasing its porosity.

In aluminum 6061, the higher porosity percentage (up to 99.0% with 2.5% Gr) corresponds to a lower density, making it suitable for lightweight applications. Conversely, aluminum 7075, with a slightly lower porosity percentage (98.5% with 2.5% Gr), retains a relatively higher density, offering better mechanical strength and structural integrity. This relationship highlights a critical trade-off: higher porosity reduces weight but may compromise mechanical properties, such as strength and stiffness, due to the increased presence of voids.

The interplay between porosity and density emphasizes the need to optimize these properties based on the specific requirements of the application. In industries like aerospace and automotive, materials with higher porosity and lower density are advantageous for weight reduction and fuel efficiency. However, for load-bearing applications, lower porosity and higher density may be preferred to maintain structural reliability. This balance between porosity and density must be carefully managed to achieve the desired combination of lightweight design and mechanical performance.

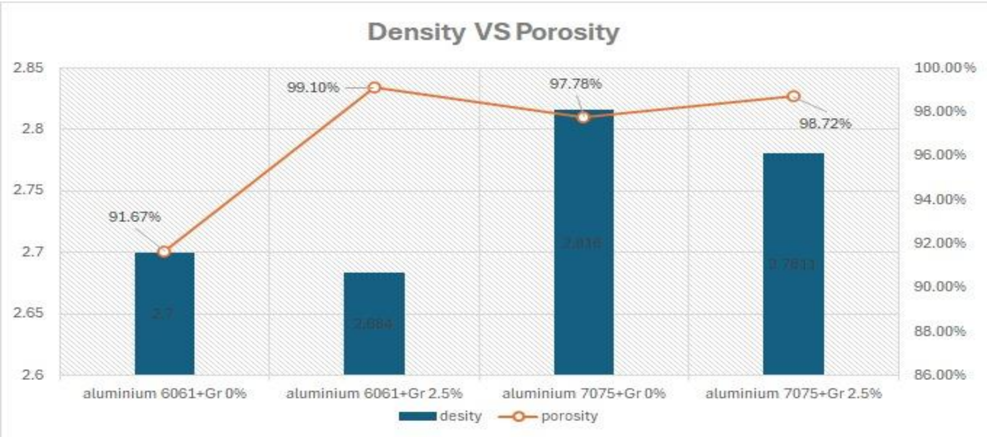

Fig. 5 Relationship between Density and Porosity

3.1.2 Scanning Electron Microscopy analysis

Scanning Electron Microscopy (SEM) is a valuable tool for analyzing porosity in composites, allowing direct observation of voids and spaces within the microstructure. The SEM images highlight the non-uniform dispersion of graphite particles and the presence of voids, which directly influence the material's porosity and mechanical performance

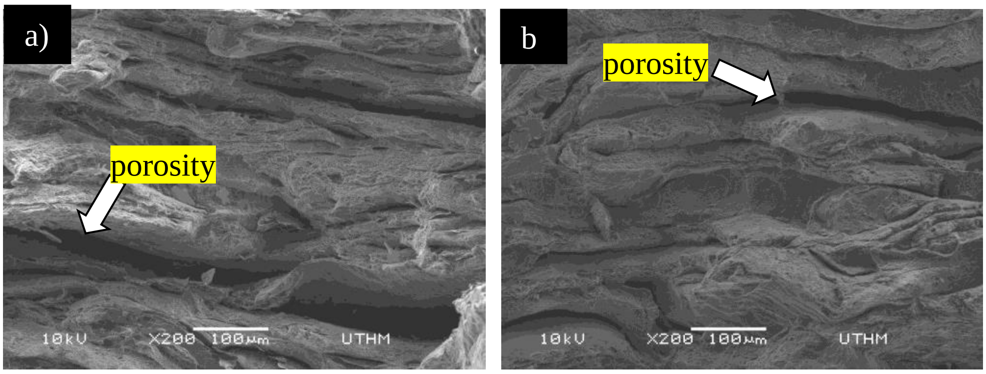

Fig 6 SEM Micrographs of (a) 7075-2.5%Gr, (b) 7075-0%Gr

From the sample 1 Aluminum 7075 with 2.5% graphite (Gr), the microstructure clearly shows the presence of porosity, indicated by voids and gaps within the material. These voids are likely caused by the introduction of graphite into the aluminum matrix, where the graphite particles may not have dispersed uniformly. This results in areas with insufficient bonding between the graphite and aluminum phases, creating pathways for porosity. The observed porosity aligns with the porosity graph, where aluminum 7075+2.5% Gr shows a significant increase in porosity compared to the aluminum 7075+0%. This increase in porosity directly influences the material's density, as evident in the density graph, where aluminum 7075+2.5% Gr demonstrates a reduced density due to the low-density graphite and the void spaces.

From the SEM sample 2 of aluminum 7075 with 0% graphite, the microstructure shows fewer voids compared to its counterpart with 2.5% graphite. While some porosity is still visible, it is significantly reduced, indicating better particle packing and interfacial bonding within the aluminum matrix. The absence of graphite reinforcement eliminates the likelihood of void formation due to particle dispersion challenges, resulting in a more compact structure. This observation correlates with the porosity graph, where aluminum 7075+0% graphite exhibits lower porosity compared to the sample with 2.5% graphite. Consequently, the density of the 7075+0% graphite sample is higher, as shown in the density graph, due to the absence of low-density graphite and minimal void spaces.

3.2 Microstructure analysis

Fig 7 presents the microstructure analysis of Aluminium 7075 with 0% graphite and 2.5% graphite (Gr2.5%) reveals distinct differences in grain size, porosity, and overall structural characteristics, as observed in the provided images. For the 0% graphite sample, the grains appear larger and more uniform, reflecting unobstructed grain growth during the hot forging process. This uniformity is accompanied by minimal porosity, indicating effective densification, which enhances the material's mechanical strength and overall density.

In contrast, the 2.5% graphite sample demonstrates finer and less uniform grains, attributed to the grain boundary pinning effect of graphite particles. While the refinement of grain size may improve certain mechanical properties, such as hardness, the presence of graphite introduces microvoids or defects, which are visible as dark regions in the microstructure. This increased porosity reduces the density of the material and could compromise its mechanical integrity.

The comparison between these two samples highlights the trade-offs introduced by graphite addition. While the inclusion of 2.5% graphite can potentially enhance tribological properties, such as wear resistance and lubrication, it increases porosity and affects density negatively. Therefore, optimizing processing parameters, such as forging temperature and pressure, is essential to mitigate porosity while leveraging the benefits of graphite addition.

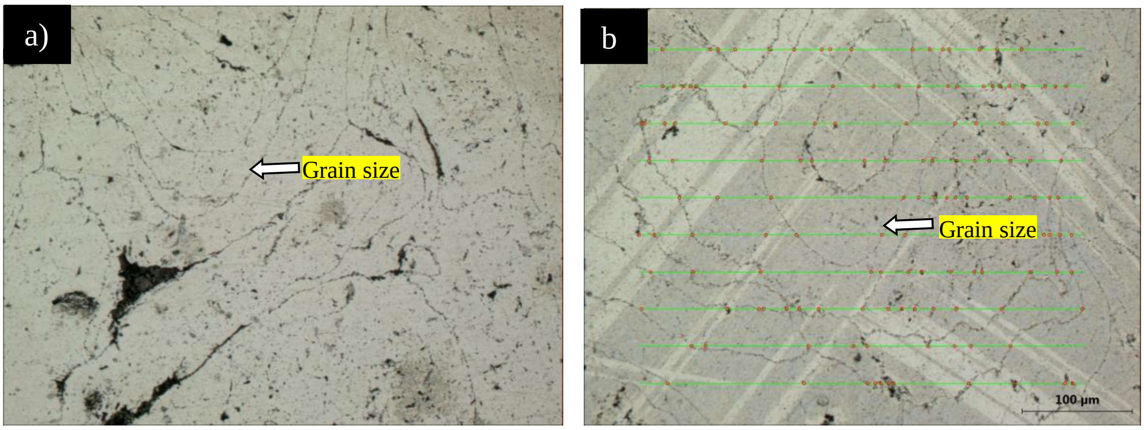

Fig 7 Optical Microscopic of (a) 7075-2.5%Gr, (b) 7075-0%Gr

3.4 Grain Size of Microstructure

Fig 8 shows how the composition of the alloy and the addition of graphite affect grain size, showing how the samples are very different from one another. The Al7075 + 0% Graphite sample has the biggest grains(1.742). This is because the lack of graphite lets the grains grow freely during the hot forging process, making the structure more compact and dense with fewer holes. On the other hand, the Al7075 + 2.5% Graphite sample has the smallest grains (1.562), which is because the graphite particles pin down the edges of the grains. These particles stop the movement of the grain boundaries, which limits grain growth and makes the grain structure more uniform. This effect is stronger in Al7075 because its matrix is harder, which makes graphite's control over grain size stronger. The sample of Al6061 + 2.5% Graphite, which has grains that are 1.595 õm, shows a similar trend but with a less noticeable refinement effect. This is probably because the material's composition and how it interacts with graphite are different. Adding graphite makes the grains smoother and might make the metal stronger through the Hall-Petch effect, but it also makes the material less dense and more porous because the graphite particles get in the way of the matrix staying together and compacting during the forging process.

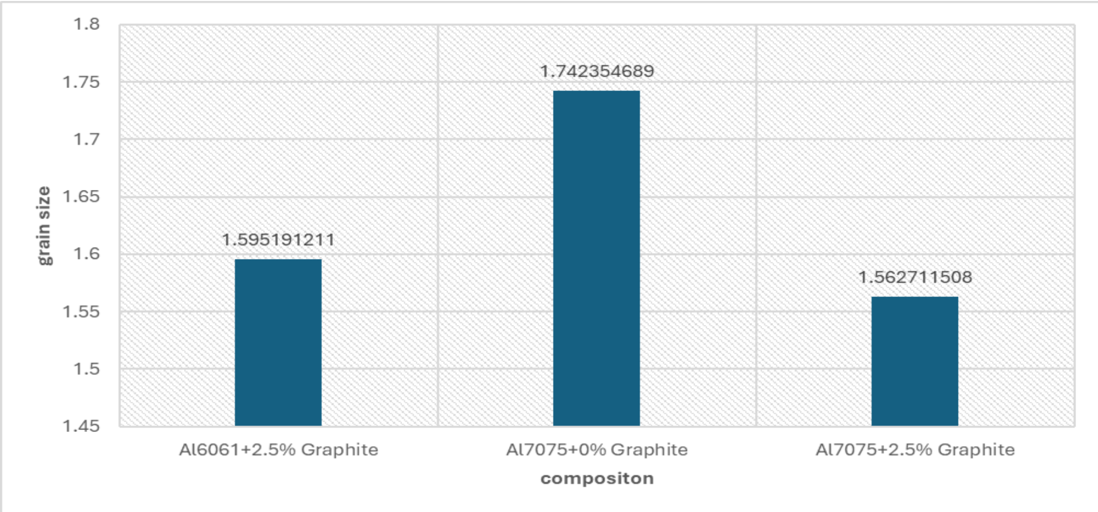

Fig 8 grain size of Al6061+ 2.5% Gr, Al7075+ 2.5% Gr, Al7075+ 0% Gr,

4. Conclusion

In conclusion the microstructural analysis of Aluminium 7075 with 0% and 2.5% graphite (Gr2.5%) reveals key differences in grain size, porosity, and their impact on material properties. The 0% graphite sample exhibits larger and more uniform grains with minimal porosity, resulting in higher density and improved mechanical strength. On the other hand, the 2.5% graphite sample displays finer but less uniform grains, with increased porosity due to the presence of graphite particles. While the addition of graphite offers benefits such as improved wear resistance and tribological properties, it introduces challenges such as reduced density and potential compromises in structural integrity. To optimize the properties of Aluminium 7075 with graphite additions, it is recommended to refine the hot forging process parameters, such as temperature and pressure, to reduce porosity and achieve better grain refinement. Additionally, exploring alternative graphite dispersion techniques, such as pre-mixing or advanced alloying methods, can help enhance uniformity and reduce defects. Further studies should also investigate the balance between mechanical performance and tribological benefits to develop an ideal composite structure for specific applications.

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Author Contribution

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

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