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Research article

Microstructural investigation and mechanical properties of Al_2O_3-MWCNTs reinforced aluminium composite

Mohammad Na'aim Abd Rahim[1], Mohd Shukor Salleh[1,*], Saifudin Hafiz Yahaya[1], Sivarao Subramonian[1], Azrin Hani Abdul Rashid[2], Syarifah Nur Aqida Syed Ahmad[3] and Salah Salman Al-Zubaidi[4]

[1] Faculty of Industrial and Manufacturing Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Department of Mechanical Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Hub Pendidikan Tinggi Pagoh, Km 1, Jalan Panchor, 84600 Pagoh, Muar, Johor Darul Takzim
[3] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang Darul Makmur
[4] Department of Automated Manufacturing Engineering, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, 10071, Iraq

* **Correspondence:** Email: shukor@utem.edu.my; Tel: +6012-277-3548.

Abstract: Hybrid reinforcement of metal matrix composites (MMCs), particularly those based on aluminum, is widely recognized for resulting in excellent mechanical properties, such as high strength-to-weight ratio, enhanced wear resistance, and superior thermal conductivity. In this study, multi-wall carbon nanotubes (MWCNTs) and alumina (Al_2O_3) were used as the reinforcement for aluminum A356 via electromagnetic stirring (EMS). The composite was fabricated by varying the Al_2O_3 and MWCNT contents. Molten MMCs were then poured into the mold, and samples were collected after solidification. The effect of hybrid reinforcement by EMS on the distribution of microstructure and mechanical properties was investigated. Optical microscopy (OM) revealed that the presence of Al_2O_3-MWCNTs as reinforcement refined the grains, evolving from dendritic to rosette. The grains became closely packed, and reduced porosity was observed. The intermetallic phases in the composite were identified using secondary electron imaging–field emission scanning electron microscope (SEI–FESEM) and X-ray diffraction (XRD). Mechanical properties of the matrix were measured using a universal testing machine and a Vickers hardness test. The results indicate that the reinforcement percentage and stirring time significantly impact mechanical properties. The best properties were obtained with 0.5 wt% MWCNT, 6 wt% Al_2O_3, and 10 min of stirring. Under these conditions, the highest values for yield strength (94 MPa), tensile strength (221 MPa), elongation at break (11.37%), and hardness (89 HV) were achieved. These findings show that an optimum amount of reinforcement content and stirring time greatly influence the mechanical properties of the composite. The results show that the EMS effectively overcomes common challenges associated with hybrid metal matrix composites, namely proper particle distribution, reduced porosity, and enhanced mechanical properties. EMS provides a practical solution for producing high-performance aluminum composites suitable for structural and thermal applications with lower costs.

Keywords: hybrid reinforcement; aluminum metal matrix composite; electromagnetic stirring

1. Introduction

Metal matrix composites (MMCs) are extensively utilized in high-performance applications across various industries, including aerospace, electronics, and automotive sectors, due to their superior properties, such as enhanced hardness, increased tensile strength, and improved wear resistance [1]. These characteristics, along with the potential for improved strength-to-weight ratios compared to unreinforced alloys, make MMCs highly advantageous. Among the various metals used in MMCs, aluminum is especially preferred due to its lightweight nature, high thermal conductivity, and excellent corrosion resistance [2]. MMCs have been widely used in the automotive industry because of their outstanding mechanical and tribological properties. Additional possibilities for increased demand for aluminum come from the electric vehicle revolution, which is entering the market sooner and faster than anyone could expect. Aluminum metal matrix composites (AMMCs) hold immense significance in aerospace applications due to their unique combination of low weight, high strength, and superior mechanical and thermal properties [3]. In the aerospace industry, reducing weight while maintaining structural integrity is a top priority to improve fuel efficiency, payload capacity, and overall performance [4]. By utilizing hybrid reinforcements such as carbon and ceramic particles, these composites achieve a high strength-to-weight ratio, excellent wear and corrosion resistance, and good thermal stability. This makes them ideal for critical aerospace components such as propellers, rotors, undercarriage structures, fuselage sections, engine blades, tail surfaces, and engine mounts [5]. Moreover, hybrid metal matrix composites (HMMCs) also play an important role in improving the mechanical properties of automotive and aerospace products. HMMCs are created by integrating two or more reinforcements with different morphologies that can develop synergistic effects between them, leading to an excellent combination of strength and ductility.

Multi-wall carbon nanotubes (MWCNTs) are particularly effective reinforcements due to their exceptional mechanical strength, low density, high thermal and electrical conductivity, and ability to enhance composite performance through efficient load transfer mechanisms [6]. Similarly, Al_2O_3 serves as an effective reinforcement in MMCs, significantly improving hardness, compressive strength, thermal stability, corrosion resistance, and wear resistance, making it valuable for a wide range of engineering applications [7]. Furthermore, a study conducted by Murthy et al. demonstrated the effect of the particle size of Al_2O_3 on hardness [8]. In this work, Al_2O_3 with different sizes (20, 53, and 88 μm) was used, and the smallest one showed the highest hardness. Finer Al_2O_3 particles provide a larger surface area for bonding with the matrix, improving load transfer and mechanical performance. Additionally, smaller particles contribute to a more uniform dispersion, reducing the risk of weak points and enhancing the composite's overall strength and durability. Finer particles increase the interface area between the matrix and reinforcement, leading to better load transfer and strengthening mechanisms such as Orowan looping and grain refinement [9]. Sharma et al. (2019) suggested that Al_2O_3 at 40 μm is sufficient to provide an optimal balance between strength and processability in AMCs [10]. On the other hand, Malaki et al. (2021) found that the inclusion of magnesium powder serves as an effective strategy to enhance the wettability of CNTs by reducing the contact angle between the liquid and solid phases [11]. This effect is particularly crucial in MMCs, where good wettability ensures uniform dispersion of CNTs, improved interfacial bonding between the matrix, and enhanced mechanical properties.

In a separate study, Shan et al. [12] obtained unforeseen results about the effects of Al-Al_2O_3-CNTs using the powder metallurgy approach. The mechanical properties of 0.5% CNTs and 10 wt% Al_2O_3 offered ideal results in terms of yield strength (357 MPa), ultimate tensile strength (404 MPa), and elongation to fracture (9.1%). Chen et al. [13] investigated the mechanical properties of ex situ and in situ CNTs formed by γ-Al_2O_3-reinforced aluminum powder. The results showed an increase in the following mechanical properties: yield strength (515 ± 17 MPa), tensile strength (542 ± 4 MPa), elastic modulus (95.6 ± 1.7 GPa), and excellent elongation (10.4 ± 0.8). These approaches have successfully demonstrated the positive impact of hybrid reinforcement with CNTs and Al_2O_3 on aluminum matrix composites. However, the fabrication of these composites requires multiple methods or processes, resulting in additional time and cost investments.

Effectively addressing the challenges of uniformly distributing MWCNTs within the metal matrix is vital for optimizing composite performance. Achieving homogeneous dispersion and strong interfacial bonding is crucial to promoting grain refinement, enhancing load transfer, enabling Orowan strengthening, and mitigating thermal expansion mismatches between the matrix and reinforcements [14]. However, attaining an even distribution of reinforcing particles is challenging due to the high viscosity of molten metal and poor wettability between the matrix and reinforcement materials. Mechanical stirring is typically used to produce these composites, but this method has limitations such as air entrapment, oxidation, stirrer blade erosion, composite contamination, and vortex formation, which can trap air bubbles [15]. To address these issues, an alternative approach known as electromagnetic stirring (EMS) has been developed. EMS offers several advantages over conventional MMC fabrication methods because of its ability to achieve a more uniform distribution of reinforcement particles within the matrix, reduce porosity, and enhance mechanical properties [16]. The use of magnetic fields to generate rotational flow within the molten metal can promote a homogeneous mixture. These results could improve interfacial bonding between the matrix and the reinforcement particles, which is critical for enhancing the overall strength and wear resistance of the composite. Additionally, EMS minimizes the formation of gas inclusions and porosity, which are common defects in other methods, thereby increasing the composite's density and mechanical properties [17].

Several authors have successfully utilized the advantages of EMS in enhancing the properties of metal matrix composites. Chandrasheker (2021) investigated Al7050 alloy reinforced with B_4C particles at varying levels (3%, 6%, 9%) using electromagnetic stir casting [18]. EMS effectively supported initial particle dispersion, with reinforcements up to 6 wt% resulting in improved hardness of 84.27 HV. Soni (2022) employed EMS to fabricate Al6063-SiC/Al_2O_3 hybrid composites, achieving a 28% increase in tensile strength (134.63 MPa) and a 15.4% increase in double shear strength (94.91 MPa) due to uniform dispersion and enhanced interfacial bonding [19]. Similarly, Kantheti et al. (2024) used EMS to disperse 6 wt% graphite and 4 wt% B_4C in an AA7075 matrix, achieving uniform reinforcement distribution and reduced clustering [20]. This led to notable improvements, including approximately 18% higher hardness, a 110% increase in impact resistance, an 85.31% increase in yield strength (YS), and an 88.24% increase in ultimate tensile strength (UTS).

Previous research on hybrid reinforcement involving MWCNTs and Al_2O_3 is limited, with only a few studies exploring their combined effects on composite properties. However, very few studies to date have investigated the use of EMS for processing MWCNTs-Al_2O_3 hybrid-reinforced composites. This presents a significant research gap, as EMS has the potential to enhance the uniform dispersion of reinforcements, improve particle-matrix bonding, and minimize defects, thereby addressing key challenges associated with hybrid reinforcement. This study focuses on finding the optimal parameters for incorporating MWCNTs and Al_2O_3 using EMS to achieve a more uniform microstructure distribution and maximize the composite's mechanical properties.

2. Materials and methods

2.1. Design of experiments

Orthogonal arrays were used in this study to carefully examine each design component while minimizing experiments through Minitab Statistical Software (Minitab 19). Tables 1 and 2 summarize the condition parameters and design of the orthogonal array L8, with three factors at two levels. In this work, MMCs were produced using varying MWCNT and Al_2O_3 contents (wt%) and EMS stirring durations. Meanwhile, magnesium powder was fixed at 0.3 wt% for all experimental runs. The experiment was conducted using the Taguchi Method; the parameters of this experimental work are presented in Table 1. The selected parameter levels for MWCNTs, Al_2O_3, and EMS duration in the L8 orthogonal array were based on recent literature. The choice of 0.5 and 1.0 wt% MWCNT was based on findings by Samal et al. (2022), who reported that these levels significantly enhanced tensile strength and hardness in AA5052 composites [21]. Higher contents (1.5 wt%) caused CNT agglomeration and reduced mechanical performance, making 1.0 wt% optimal. Therefore, the choice to limit CNT content to 0.5 and 1.0 wt% ensures optimal reinforcement while avoiding the negative effects associated with excessive CNT loading.

In previous studies, Chandas et al. (2020) employed 3 wt% Al_2O_3 combined with 7 wt% SiCp in AA6061 using the stir casting method [22]. Similarly, Radha et al. (2022) investigated composites reinforced with 5 wt% Al_2O_3 and 8 wt% TiC using the same technique [23]. Building on these findings, the current research explores the mechanical properties of composites reinforced with 4 and 6 wt% Al_2O_3 to evaluate performance within this intermediate range and to identify the optimal alumina content for enhanced material characteristics. The selection of 5 and 10 min for EMS stirring duration was made to evaluate the effect of stirring time on the dispersion quality of reinforcements within the aluminum matrix. A 5-min duration is generally sufficient to achieve initial homogenization, particularly at lower reinforcement levels, while 10 min allows for more thorough mixing, helping to reduce particle agglomeration and improve interfacial bonding. These durations strike a balance between adequate dispersion and avoiding potential drawbacks of prolonged stirring, such as oxidation or increased porosity.

Table 1. Condition parameters.

Parameter	Level 1	Level 2
MWCNT content (wt%)	0.5	1.0
Al_2O_3 content (wt%)	4	6
EMS stirring time (min)	5	10

Table 2. L8 orthogonal array.

No of run	MWCNT content (wt%)	Al_2O_3 content (wt%)	EMS stirring time (min)
1	0.5	4	5
2	0.5	4	10
3	0.5	6	5
4	0.5	6	10
5	1.0	4	5
6	1.0	4	10
7	1.0	6	5
8	1.0	6	10

2.2. Hybrid composite preparation

The alloy utilized in this procedure was a commercially available A356 aluminum alloy from Malaysian Aluminium & Alloys Sdn Bhd in the form of an ingot with a size of 600 × 220 × 70 mm. Its chemical composition, expressed as weight percentages, was determined through spectrometry. The composition comprised 7.38% Si, 0.26% Mg, 0.0463% Cu, 0.25% Fe, 0.190% Mn, 0.0068% Zn, and 0.0411% Ti. For this research, Al_2O_3 was obtained from MERCK with an average size of 63 µm, and MWCNTs were obtained from Sigma-Aldrich, USA, and featured >95% purity, outside diameter of 20–40 nm, inside diameter of 5–10 nm, and length of 10–30 µm. Magnesium powder with ≥99% purity was obtained from Sigma-Aldrich (ϕ 1 mm) (must be stored in airtight, non-reactive containers in a cool, dry, and well-ventilated area; moisture and heat sources must be strictly avoided, as magnesium reacts with water to produce hydrogen gas, which can lead to explosions).

Figure 1 shows the EMS machine and the fabrication process of the matrix composite. The planetary ball milling process was conducted using Planetary Ball Mill PM 100, maximum speed 650 rpm on the Al_2O_3 for 12 h at 200 rpm, using an alumina jar and alumina balls with a ball-to-powder ratio of 5:1 to reduce particle size. To prevent overheating, the milling cycle included 5-min intervals after every 15 min of operation. The particle size of Al_2O_3 was successfully reduced from 63 µm to 30.2 µm, as confirmed by a particle size analyzer (Malvern Mastersizer Hydro 2000MU & Scirocco 2000 Particle Analyser). The EMS used was a 10 kg aluminum electromagnetic stirring (GW-10) with a power of 15 kW. The melting point of aluminum ingots is 660 °C; however, the ingots were heated to 700 °C to ensure complete liquefaction and facilitate reinforcement incorporation. At the same time, magnesium powder, Al_2O_3, and MWCNTs were thoroughly mixed, wrapped in aluminum foil, and preheated to approximately 200 °C. Simultaneously, the D2 Tool Steel Mould (60 × 60 × 146 mm, ϕ 25) was also preheated to 80 °C to minimize thermal shock during casting; this was controlled using a thermocouple. The EMS current was set to 70 A with a frequency of 50 Hz based on the work by

Khanouki (2023), which achieved the best microstructural and mechanical properties of A356 [24]. The ingot was then heated to 720 °C, and a degassing tablet was added to the melt to remove entrapped hydrogen gas and reduce porosity. Then, the preheated reinforcement mixture was introduced into the melt using a steel plunger. The composite was subsequently stirred using EMS to ensure uniform distribution of the reinforcements, enhancing dispersion and minimizing agglomeration. Prior to pouring, flux was added to remove impurities in the molten composite. Subsequently, the molten material was poured at 670 °C into a billet mold to produce composite feedstock.

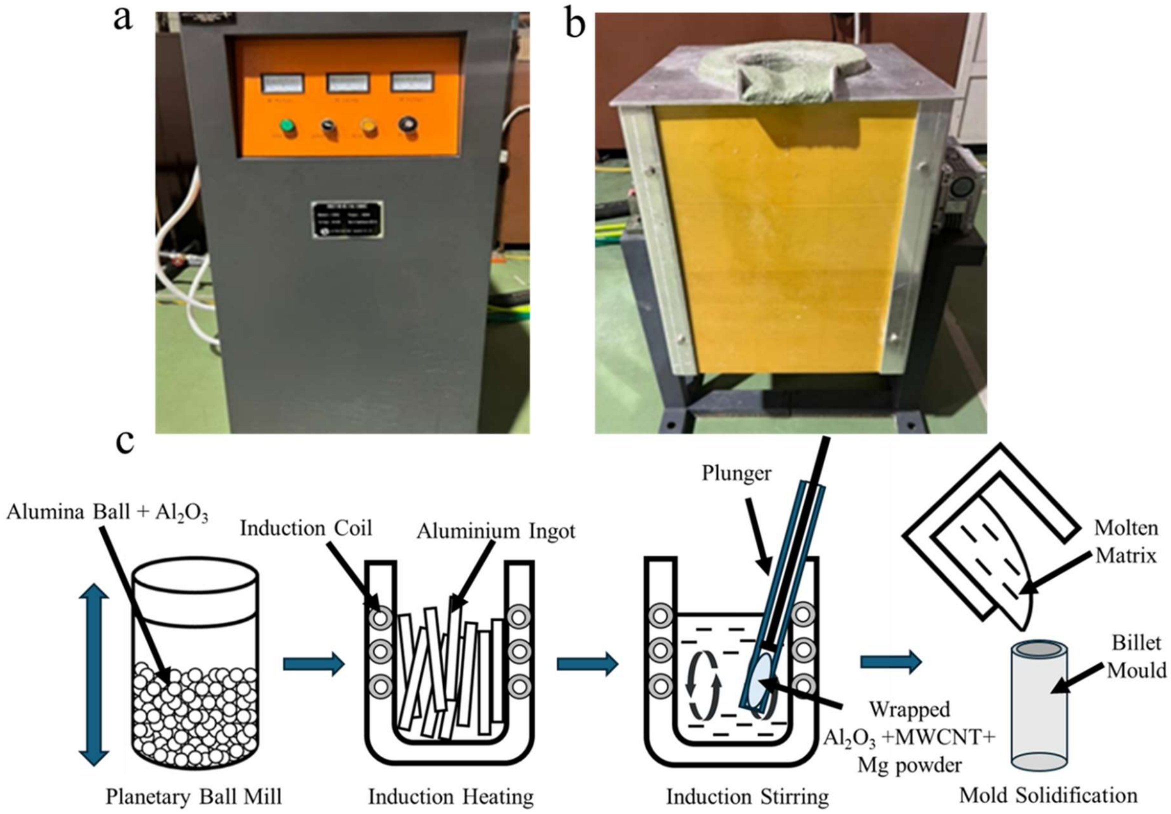

Figure 1. Electromagnetic stirring process. (a) EMS control panel. (b) EMS machine. (c) Illustration of feedstock production.

2.3. Microstructural evaluation and mechanical testing

After casting, the billet underwent material characterization. The Al-MMCs were characterized using several testing and analysis techniques, including optical microscopy, X-ray diffraction (XRD) by PANalytical X'Pert PRO, and mechanical testing. The XRD specifications are shown in Table 3. The microstructural distribution of Al_2O_3-MWCNTs in the composites was examined using a Leica DVM6 optical microscopy and Schottky field emission scanning electron microscope (FE-SEM) (SU5000). Microstructure analysis was performed after grinding the samples with different grit sizes (400, 600, 800, and 1200), polishing with diamond solutions of varying particle sizes (3 and 1 μm), and etching with Keller's reagent solution. Tensile tests were conducted using a 100 kN Shimadzu universal testing machine at a speed of 5 mm/s. The samples were fabricated into dog-bone shapes according to the ASTM E8M standard for each group, as shown in Figure 2. Three measurements of tensile testing were taken for each sample. Then, the results' average was calculated to ensure reliable data analysis. Vickers hardness tests were conducted using Falcon 400G2, according to ASTM E384-05A, to investigate the microhardness of the composites. A diamond indenter was pressed onto the material with a 1 kg force for a dwell time of 15 s. Subsequently, its diagonal lengths were measured using an optical microscope, and the Vickers hardness number was calculated. Average measurements from five different spots were taken for each composite to obtain reliable results.

Table 3. XRD specifications.

X-ray source	Cu-Kα radiation (Kα = 1.54187 Å)
Goniometer radius	240 mm
Geometry	Bragg-Brentano (θ-θ system, vertical goniometer)
Scan range of 2θ	3–150°
Minimum-maximum step size	0.001–1.27°
Incident PreFIX module	Fixed divergence slit holder focusing X-ray mirror for Cu-Kα
Diffracted PreFIX module	X'Celerator linear detector

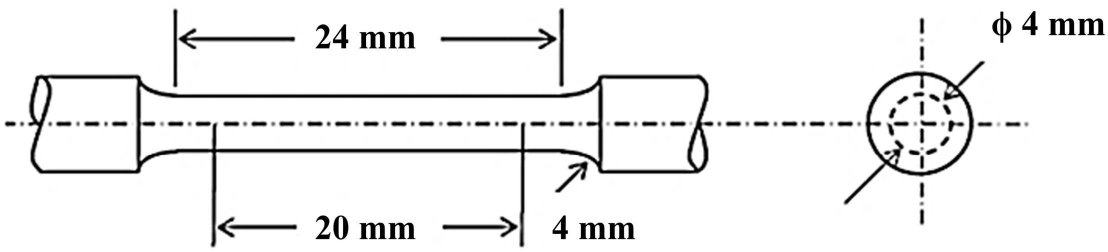

Figure 2. Tensile testing ASTM E8M.

3. Results and discussion

3.1. Microstructural evaluation

The development of metal matrix composites (MMCs) relies significantly on the efficient distribution of reinforcements within the matrix, which is frequently influenced by processing methods and reinforcement material quantities. The initial α-Al exhibited a rosette-like and nearly spheroidal morphology, with a plate-like silicon structure formed from a typical dendritic microstructure, as shown in Figure 3. The microstructure becomes densely packed with a small grain size. Here, Al_2O_3 and MWCNTs serve as reinforcements in an aluminum matrix. Figures 4–7 demonstrate the effects of various parameters on matrix composites through optical microscopy. The optical microscopy results reveal an uneven distribution of the microstructure in all samples. Multiple factors may contribute to this issue, including inhomogeneous mixing of the reinforcement, resulting in clustering or irregular dispersion of particles. Subsequently, solidification front instability in the presence of reinforcements can facilitate heterogeneous nucleation, leading to irregular grain development and distribution. Optical microscopy images indicate that increasing the stirring duration to 10 min (samples 2, 4, 6, and 8) typically enhances reinforcement dispersion. This produces a more refined microstructure with reduced macrosegregation, improved uniformity, and smaller grain size. Moreover, a higher concentration of Al_2O_3 (6 wt%) appears to yield a finer grain structure. This grain size reduction can be attributed to the enhanced nucleation effect from the increased presence of Al_2O_3 particles, which act as potent heterogeneous nucleation sites during solidification.

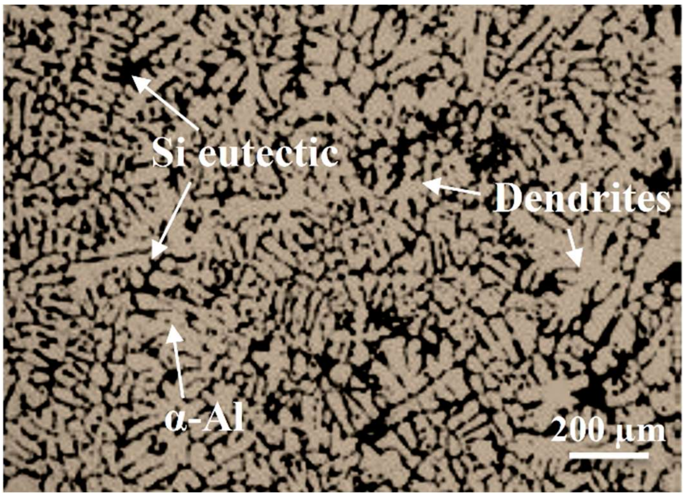

Figure 3. As-cast sample 500×.

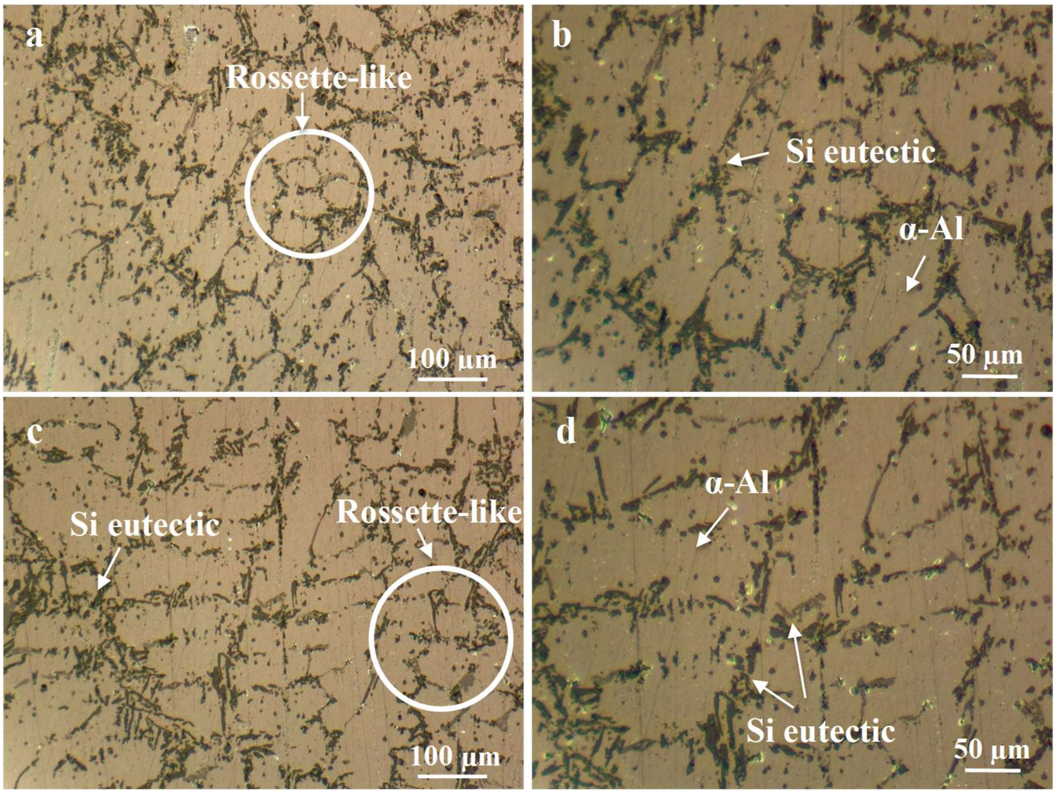

Figure 4. Sample 1 with (a) 1500× magnification and (b) 2500× magnification. Sample 2 with (c) 1500× magnification and (d) 2500× magnification.

According to Li et al., Al_2O_3 plays a crucial role in the uniform distribution of CNTs within the matrix through its vehicle-carrying effect in facilitating CNT dispersion [25]. Due to their fine particle size and surface interactions, Al_2O_3 nanoparticles act as dispersing agents, preventing CNT agglomeration, which is a common issue in CNT-reinforced composites. The strong van der Waals forces between CNTs often cause clustering, but when Al_2O_3 particles are introduced, the CNTs adhere to their surfaces, enabling more uniform distribution. These particles serve as *carriers*, transporting CNTs throughout the matrix and enhancing their mobility, ensuring a well-dispersed network. Reducing Al_2O_3 size is crucial for maximizing its uniform distribution within the matrix. Smaller Al_2O_3 particles possess a higher surface-area-to-volume ratio, significantly enhancing their matrix material bonding. Conversely, a higher concentration of MWCNTs (1 wt%) tends to promote clustering, particularly with shorter stirring durations. This occurs primarily due to strong van der Waals forces between MWCNTs, which promote their entanglement and aggregation, leading to poor matrix dispersion. Although sufficient stirring combined with increased Al_2O_3 can reduce this issue by enhancing mechanical shearing forces and improving particle wetting, MWCNTs still tend to agglomerate within the aluminum matrix composite. This persistent agglomeration can adversely affect the composite's mechanical properties, such as tensile strength and hardness, by forming stress concentration sites that act as potential crack initiation points. Based on Figure 5c,d, a smaller grain size can be achieved using a combination of Al_2O_3 up to 6 wt%, 0.5 wt% of MWCNTs, and 10 min of EMS stirring duration, as represented by sample 4. This enhances the uniform distribution of reinforcements throughout the aluminum matrix.

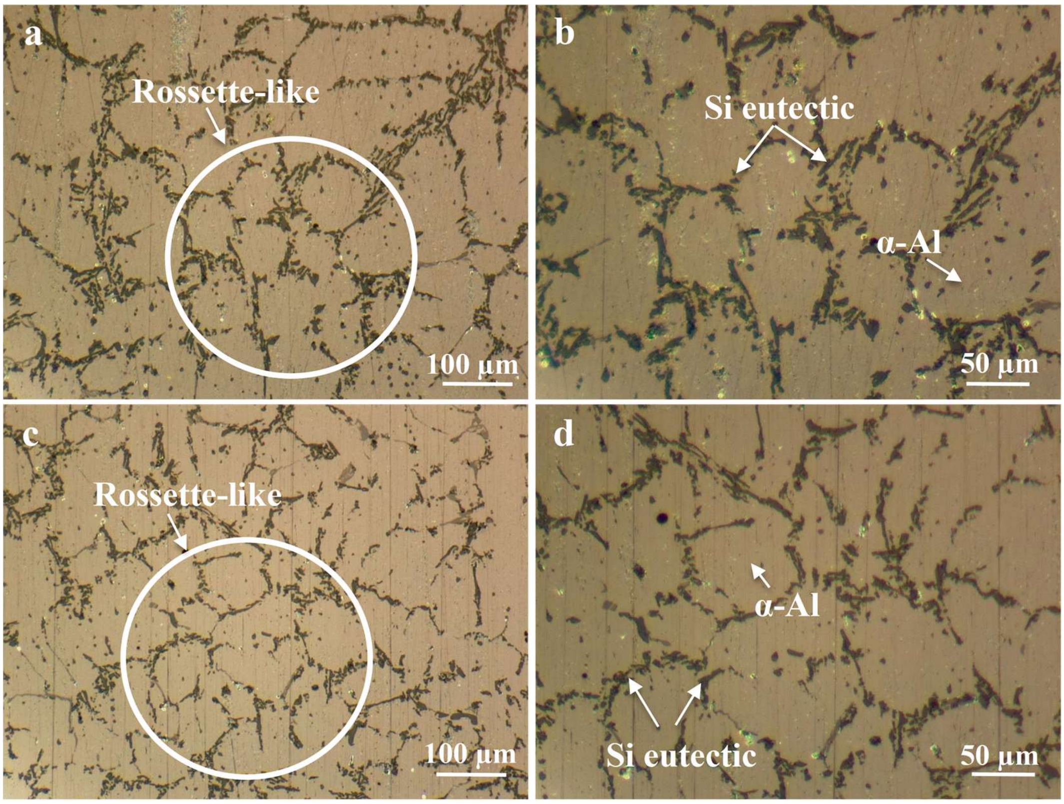

Figure 5. Sample 3 with (a) 1500× magnification and (b) 2500× magnification. Sample 4 with (c) 1500× magnification and (d) 2500× magnification.

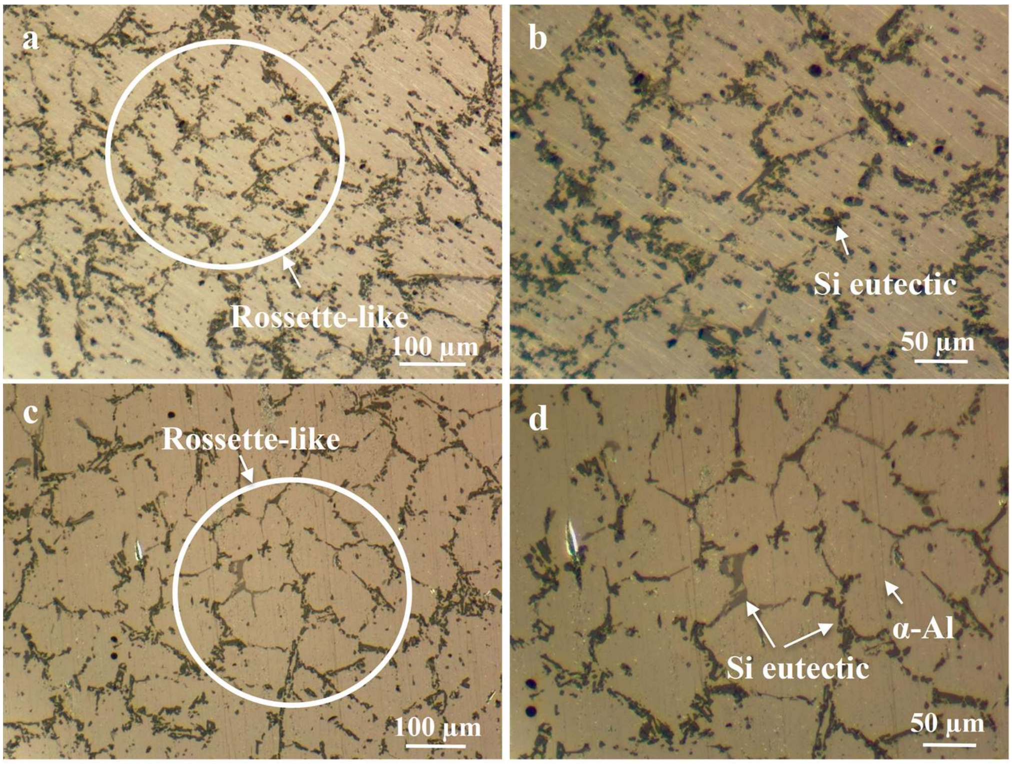

Figure 6. Sample 5 with (a) 1500× magnification and (b) 2500× magnification. Sample 6 with (c) 1500× magnification and (d) 2500× magnification.

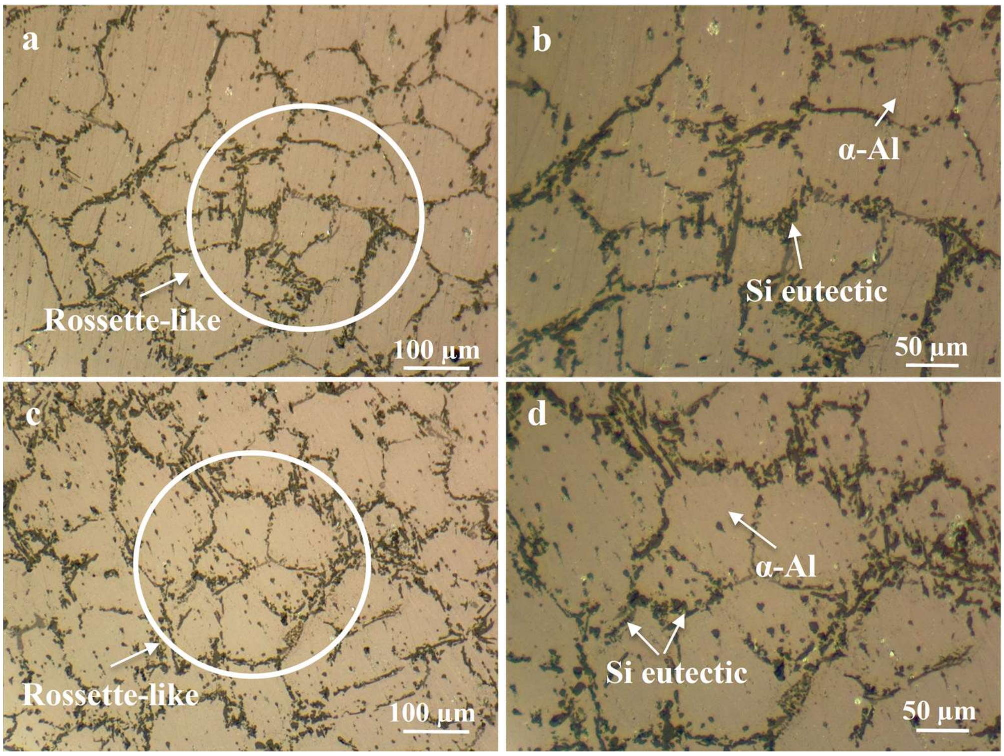

Figure 7. Sample 5 with (a) 1500× magnification and (b) 2500× magnification. Sample 6 with (c) 1500× magnification and (d) 2500× magnification.

3.2. SEI-FESEM

The intermetallic phases are shown in Figure 8 for samples 1–8. Various morphologies are observed in four different spots, including needle-like, rod-shaped, and plate-like structures. These morphologies characterize specific intermetallic compounds formed during solidification. For instance, needle-like features are often associated with brittle phases such as aluminum carbide (Al_4C_3), which typically form at the interface between aluminum and carbon nanotubes during electromagnetic stir casting. These phases develop directionally, resulting in elongated, needle-like structures. Other intermetallics, such as Al-Fe-Si compounds, commonly occur in aluminum alloys and contain trace amounts of iron and silicon, often introduced as impurities or alloying elements. These compounds exhibit similar morphologies and can be identified through XRD analysis. The formation of these intermetallic phases is closely linked to the interaction between the aluminum matrix and reinforcements, including MWCNTs and Al_2O_3, under high-temperature conditions during casting.

The needle-like shape observed in FESEM images is most likely Al_4C_3, characterized by an elongated, fragile morphology. Meanwhile, Al-Fe-Si intermetallics contribute to the hardness and brittleness of industrial aluminum alloys. A Chinese script-like morphology observed in some regions is likely attributable to Mg_2Si, which enhances both toughness and ductility. Similarly, the blocky or chunky morphology is likely associated with Al_2Cu phases, which strengthen the composite by acting as hard, brittle phases that hinder dislocation movement within the aluminum matrix. The formation of spherical microstructures enhances dense packing between barriers, effectively eliminating porosity [26]. However, excessive Al_2Cu content can increase brittleness, thus necessitating careful optimization of its volume fraction to achieve a balance between strength and ductility. The presence of the reinforcements was subsequently confirmed by EDS analysis, as illustrated in Figure 9.

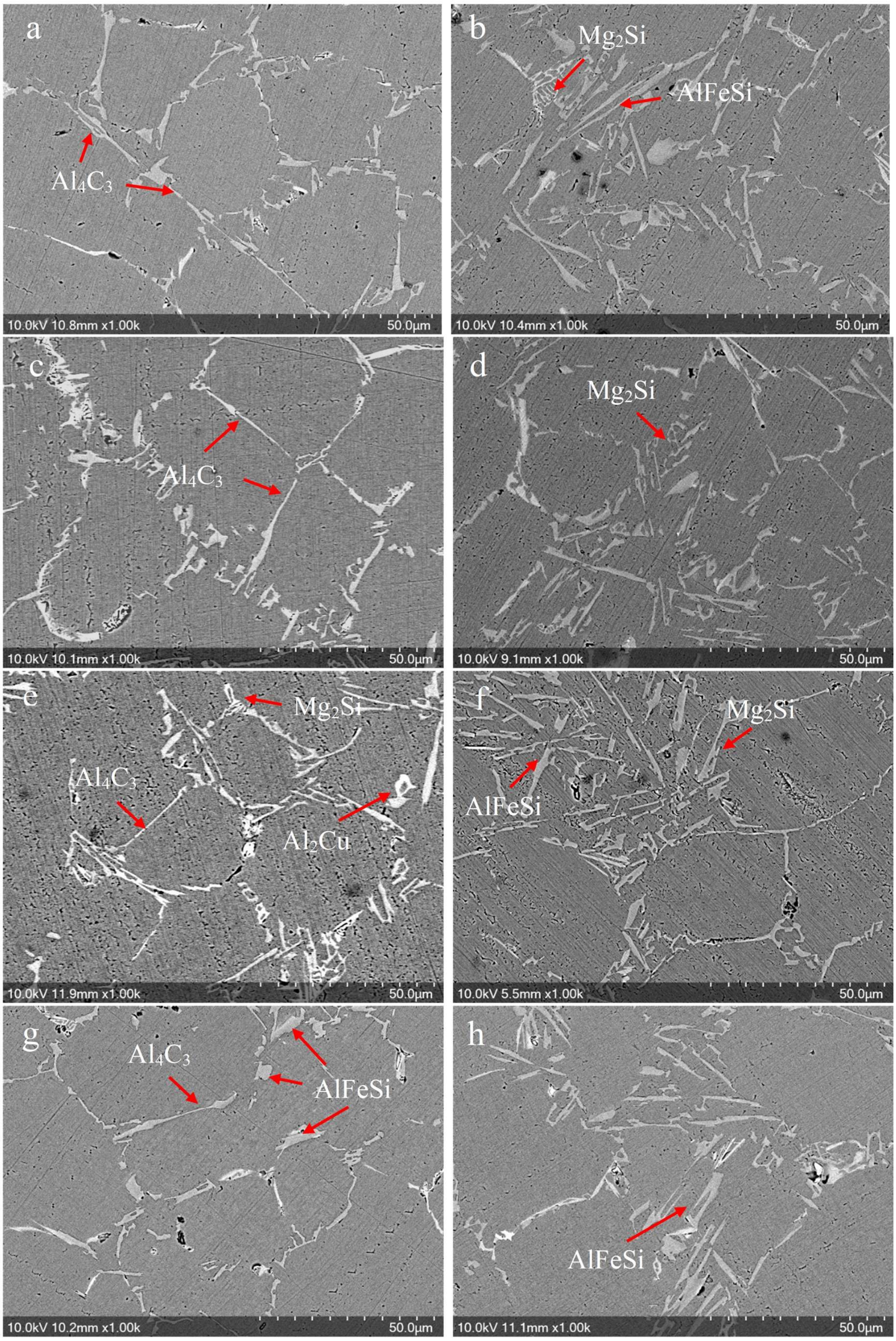

Figure 8. SEI-FESEM for (a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4, (e) sample 5, (f) sample 6, (g) sample 7, and (h) sample 8.

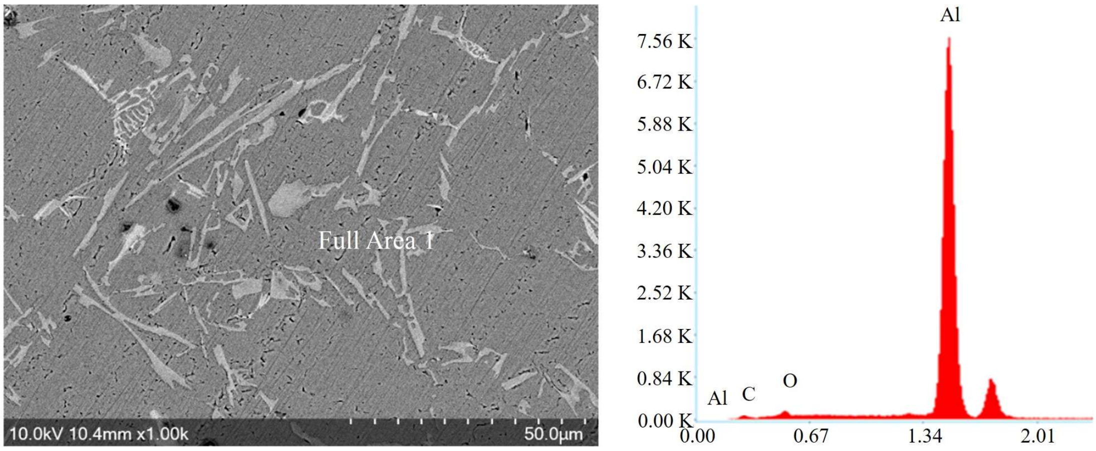

Figure 9. EDS FESEM results.

3.3. X-ray diffraction analysis (XRD)

Figure 10 shows the XRD results of sample 4. The XRD analysis of the aluminum matrix composite indicates the existence of several phases, including primary aluminum (Al) and various intermetallic compounds. The pronounced, distinct peaks associated with the (111), (200), (220), (311), and (222) planes signify the predominance of the face-centered cubic (FCC) structure of aluminum, confirming its status as the principal matrix phase. Alongside the aluminum peaks, several intermetallic phases were recognized, such as Al_2Cu, Mg_2Si, Al_8FeSi, and Al_4C_3. The Al_2Cu (θ-phase) was detected between 78 and 82°, indicating its development during the solidification process, which enhances mechanical properties like hardness and strength via precipitation strengthening. The detection of Mg_2Si at approximately 45 and 65° indicates an interaction between magnesium and silicon, which improves wear resistance and mechanical durability.

Additionally, peaks associated with Al_8FeSi, generally observed between 38 and 45°, indicate the development of iron-rich intermetallic compounds frequently present in aluminum alloys. Although Al_8FeSi enhances wear resistance, excessive quantities may induce brittleness, adversely affecting the composite's ductility. The identification of Al_4C_3 at approximately 40 and 50° indicates an interaction between aluminum and carbon, potentially originating from carbon-based reinforcements such as MWCNTs. While Al_4C_3 enhances interfacial bonding, it is brittle and susceptible to moisture, potentially compromising the composite's integrity over time. Furthermore, the presence of Al_2O_3, identified at approximately 78 and 82°, suggests either intentional reinforcement or oxide formation during processing, contributing to improved hardness, wear resistance, and thermal stability. Peaks associated with carbon, detected at approximately 38 and 45°, are presumably attributable to carbonaceous reinforcements, influencing the composite's electrical and thermal conductivity.

The XRD pattern confirms the predominant aluminum phase alongside intermetallic compounds, including Al_2Cu, Mg_2Si, Al_8FeSi, and Al_4C_3, in addition to reinforcing or oxide phases such as Al_2O_3 and carbon. The intermetallic phases significantly enhance the mechanical and thermal properties of the composite through mechanisms like precipitation hardening and dispersion strengthening. However, the excessive presence of brittle phases such as Al_4C_3 and Al_8FeSi may negatively affect ductility. The integration of these phases enhances the composite's mechanical performance, resulting in increased hardness, wear resistance, and thermal stability.

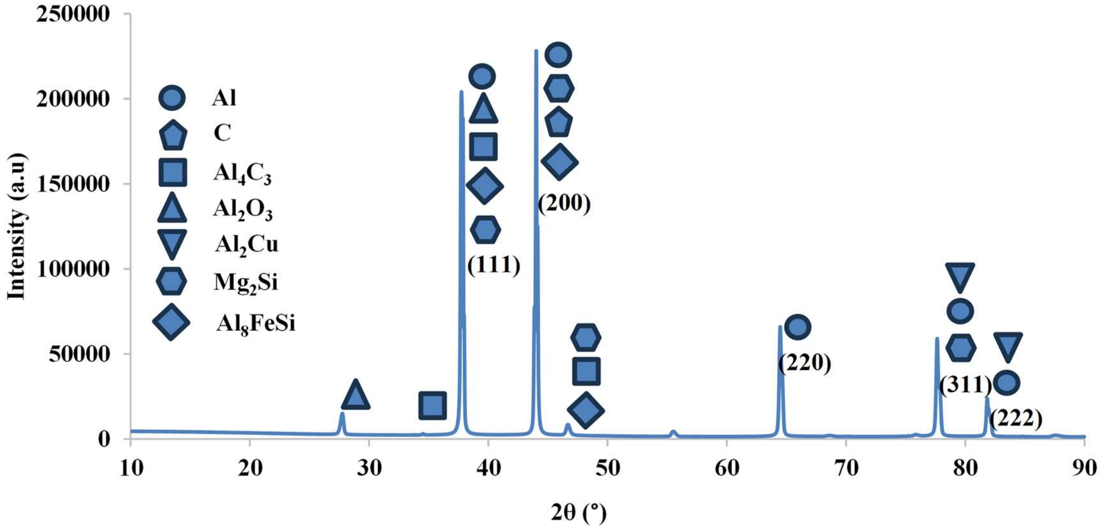

Figure 10. XRD results of the composite.

3.4. Mechanical testing

Based on the design of experiments conducted using the Taguchi method, the mechanical properties of aluminum matrix composites reinforced with Al_2O_3 and MWCNT, presented in Table 4 and Figure 11, provided valuable insights into how variations in composition and stirring time affect key properties such as yield strength, ultimate tensile strength, elongation to fracture, and hardness. Sample 4 stands out as the most successful matrix composite, demonstrating optimal yield strength (94 MPa), ultimate tensile strength (221 MPa), elongation at fracture (11.37%), and hardness (89 HV). This suggests that a mixture of 0.5 wt% MWCNT and 6 wt% Al_2O_3 and a stirring duration of 10 min produces optimal mechanical performance. Conversely, sample 1, with the lowest strength and ultimate tensile strength (UTS) values, illustrates the negative impact of insufficient stirring (5 min) on both strength and reinforcement distribution.

Samples containing 1 wt% MWCNT (samples 5 and 7) show increased clustering and reduced uniformity in reinforcement distribution, resulting in lower strength and ductility compared with those with 0.5 wt% MWCNT. According to percolation theory, an optimal concentration of CNTs exists that ensures proper dispersion within the matrix. Exceeding this concentration can cause excessive agglomeration, which diminishes the composite's strengthening potential. This occurs because CNTs have high surface energy and are strongly attracted to each other through van der Waals forces, which causes them to clump together rather than disperse uniformly throughout the matrix. When CNTs agglomerate, they create weak spots in the composite structure, resulting in poor load transfer, increased stress concentration, and a higher likelihood of crack initiation. As a result, instead of improving mechanical performance, excessive CNT content can actually reduce properties like tensile strength, ductility, and hardness. In this case, the optimal concentration of CNTs is 0.5 wt%, and concentrations higher than that lead to matrix composite degradation. The EMS duration is crucial in preventing reinforcement clumping throughout the process. Furthermore, composites with higher Al_2O_3 content demonstrate enhanced mechanical properties. The results confirm the effectiveness of incorporating Al_2O_3 alongside MWCNTs as reinforcement in the matrix composite. This highlights the importance of balancing reinforcement concentrations to avoid excessive clustering, which could impair mechanical performance.

Table 4. Mechanical testing of the matrix composite.

Experiment	MWCNT content (wt%)	Al_2O_3 content (wt%)	Stirring duration (min)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation to fracture (%)	Hardness (HV)
As-Cast	-	-	-	69	114	4.82	78
1	0.5	4	5	75	170	9.33	81
2	0.5	4	10	84	206	10.32	85
3	0.5	6	5	82	205	9.23	85
4	0.5	6	10	94	221	11.37	89
5	1.0	4	5	76	201	8.96	87
6	1.0	4	10	93	210	9.34	87
7	1.0	6	5	87	211	9.47	80
8	1.0	6	10	89	212	10.31	81

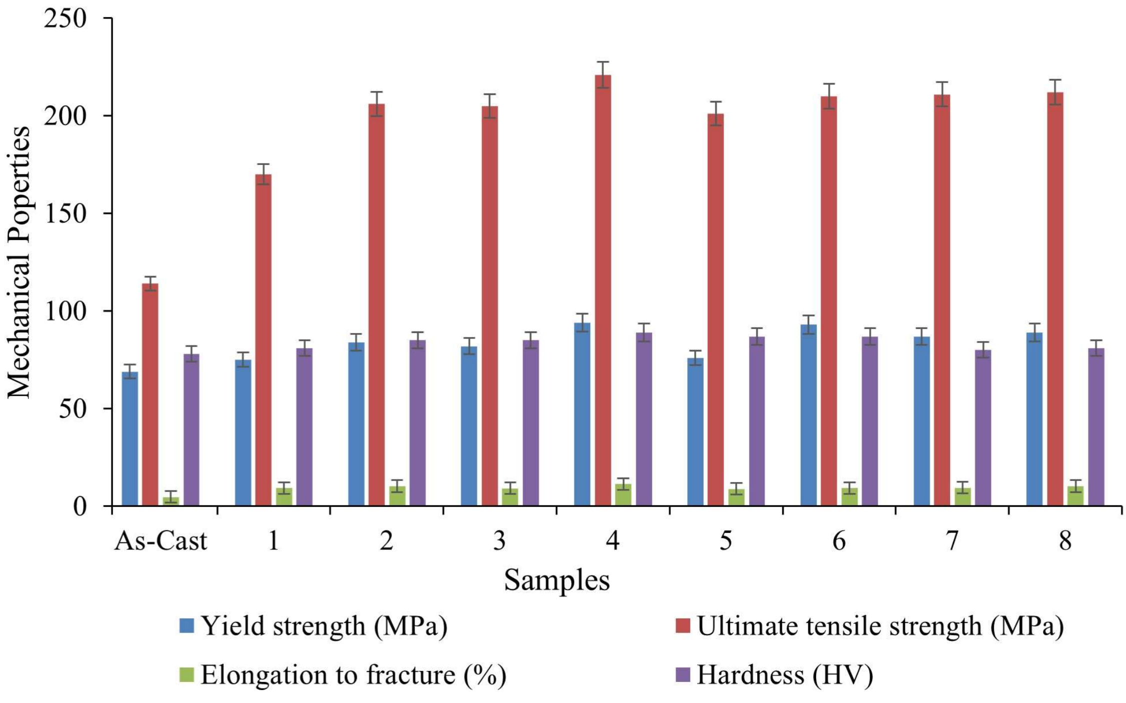

Figure 11. Mechanical properties of the composite.

4. Conclusions

The study aimed to investigate the effects of different parameters of hybrid reinforcement of Al_2O_3-MWCNTs in the A356 alloy matrix on mechanical properties and microstructures. The stirring process, utilizing electromagnetic stirring, successfully integrated Al_2O_3-MWCNTs into the composite, as confirmed by EDX-FESEM and XRD. The microstructure observed by OM was nearly globular or rosette-like. These reinforcements act as nucleating agents, leading to finer and more equiaxed grains that increase the grain boundary area, impeding dislocation motion and thus enhancing the yield strength and hardness through the Hall-Petch effect. Additionally, the thermally stable Al_2O_3 particles pin the grain boundaries, further suppressing grain growth and contributing to the composite's microstructural stability. MWCNTs, known for their exceptional tensile strength and modulus, facilitate efficient load transfer when uniformly dispersed within the matrix. At an optimal concentration of 0.5 wt%, stress is effectively transferred from the ductile aluminum matrix to the stiffer nanotubes, thereby improving both the ultimate tensile strength and ductility. However, at higher concentrations (e.g., 1.0 wt%), MWCNTs tend to agglomerate, leading to stress concentration sites that reduce the composite's mechanical performance. The Orowan strengthening mechanism plays a crucial role, primarily due to the fine size and uniform distribution of Al_2O_3 and MWCNT reinforcements. These non-deformable particles impede dislocation motion by inducing dislocation bowing and looping around them, thereby enhancing resistance to plastic deformation. The quality of interfacial bonding between the reinforcements and the A356 matrix further enhances mechanical performance. Strong interfacial adhesion ensures effective load transfer and minimizes the likelihood of interfacial debonding under applied stress. Al_2O_3 also plays a critical role in promoting the uniform distribution of MWCNTs by acting as a carrier, which reduces agglomeration and supports the formation of a well-connected reinforcement network. Collectively, these mechanisms explain the significant improvements observed in the composite's mechanical properties, with sample 4 (0.5 wt% MWCNT, 6 wt% Al_2O_3, and 10 min of stirring) exhibiting optimal performance: a yield strength of 94 MPa, an ultimate tensile strength of 221 MPa, elongation of 11.37%, and hardness of 89 HV.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Conceptualization, methodology and writing: Mohammad Na'aim Abd Rahim, Mohd Shukor Salleh, Saifudin Hafiz Yahaya; methodology and material processing: Sivarao Subramonian, Azrin Hani Abdul Rashid, Syarifah Nur Aqida Syed Ahmad, Salah Salman Al-Zubaidi. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

References

1. Sharma AK, Bhandari R, Aherwar A, et al. (2020) A study of advancement in application opportunities of aluminum metal matrix composites. *Mater Today Proc* 26: 2419–2424. https://doi.org/10.1016/j.matpr.2020.02.516
2. Ashok N, Johnson Santhosh A, Diriba Tura A, et al. (2022) Effect of stirring speed and time on the mechanical properties of Al8011-SiC metal matrix composites. *Mater Today Proc* 64: 194–199. https://doi.org/10.1016/j.matpr.2022.04.364
3. Lakshmanan K, Pandian P, Sivaprakasam R, et al. (2025) Studies on progress of aluminum based composites for automotive applications and its damping characteristics–A review. *Mech Adv Compos Struct* 12: 25–42. https://doi.org/10.22075/MACS.2024.32547.1589
4. Li SS, Yue X, Li QY, et al. (2023) Development and applications of aluminum alloys for aerospace industry. *J Mater Res Technol* 27: 944–983. https://doi.org/10.1016/j.jmrt.2023.09.274
5. Oyewo AT, Oluwole OO, Ajide OO, et al. (2024) A summary of current advancements in hybrid composites based on aluminium matrix in aerospace applications. *Hybrid Adv* 5: 100117. https://doi.org/10.1016/j.hybadv.2023.100117
6. Norzawary NHA, Bachok N (2023) Slip flow via nonlinearly stretching/shrinking sheet in a carbon nanotubes. *JARMNE* 14: 8–19. https://doi.org/10.37934/armne.14.1.819
7. Singh B, Kumar I, Saxena KK, et al. (2023) A future prospects and current scenario of aluminium metal matrix composites characteristics. *Alexandria Eng J* 76: 1–17. https://doi.org/10.1016/j.aej.2023.06.028
8. Murthy BV, Auradi V, Nagaral M, et al. (2023) Al2014-alumina aerospace composites: Particle size impacts on microstructure, mechanical, fractography, and wear characteristics. *ACS Omega* 8: 13444–13455. https://doi.org/10.1021/acsomega.3c01163ACS
9. Singh S, Singh R, Gill SS (2021) Investigations for wear characteristics of aluminium-based metal matrix composite prepared by hybrid reinforcement. *Proc Natl Acad Sci India Sect* A 91: 569–576. https://doi.org/10.1007/s40010-020-00683-z
10. Sharma VK, Kumar V (2019) Development of rare-earth oxides based hybrid AMCs reinforced with SiC/Al_2O_3: Mechanical & metallurgical characterization. *J Mater Res Technol* 8: 1971–1981. https://doi.org/10.1016/j.jmrt.2019.01.013
11. Malaki M, Tehrani AF, Niroumand B, et al. (2021) Wettability in metal matrix composites. *Metals* 11: 1034. https://doi.org/10.3390/met11071034
12. Shan Y, Pu B, Liu E, et al. (2020) In-situ synthesis of CNTs@Al_2O_3 wrapped structure in aluminum matrix composites with balanced strength and toughness. *Mater Sci Eng A* 797: 140058. https://doi.org/10.1016/j.msea.2020.140058
13. Chen B, Kondoh K, Li JS, et al. (2020) Extraordinary reinforcing effect of carbon nanotubes in aluminium matrix composites assisted by in-situ alumina nanoparticles. *Compos B Eng* 183: 107691. https://doi.org/10.1016/j.compositesb.2019.10769
14. Liu Q, Fan G, Tan Z, et al. (2021) Reinforcement with intragranular dispersion of carbon nanotubes in aluminum matrix composites. *Compos B Eng* 217: 108915. https://doi.org/10.1016/j.compositesb.2021.108915
15. Kar A, Sharma A, Kumar S (2024) A critical review on recent advancements in aluminium-based metal matrix composites. *Crystals* 14: 412. https://doi.org/10.3390/cryst14050412

16. Jabbari AH, Sedighi M (2020) Investigation of electromagnetic and mechanical stirring sequence effects on production of magnesium matrix nanocomposite. *Int J Metalcast* 14: 489–504. https://doi.org/10.1007/s40962-019-00374-5
17. Li Y, Wang Z, Zhou X, et al. (2024) A review of electromagnetic stirring on solidification characteristics of molten metal in continuous casting. *Metall Res Technol* 121: 20. https://doi.org/10.1051/metal/2024029
18. Chandrasheker J, Raju NVS (2020) Mechanical characterization of Al7050 metal matrix composite reinforced with b4c by electromagnetic stir casting method. *Mater Today Proc* 37: 1834–1838. https://doi.org/10.1016/j.matpr.2020.07.419
19. Soni S, Verma S (2022) Double shear performance of the hybrid aluminium metal matrix composite Al6063-SiC/Al_2O_3 fabricated through electromagnetic stir casting process. *Mater Today Proc* 62: 5942–5947. https://doi.org/10.1016/j.matpr.2022.04.639
20. Kantheti PR, Meena KL, Chekuri RBR (2024) Experimental investigation on mechanical and tribological behavior features of Gr/B_4C reinforced AA7075 alloy matrix using induction stir casting. *Cogent Eng* 11: 2380806. https://doi.org/10.1080/23311916.2024.2380806
21. Samal P, Tarai H, Vundavilli PR (2022) Combining effect of annealing and reinforcement content on mechanical behavior of multi-walled CNT reinforced AA5052 composites. *Mater Today Proc* 62: 2762–2767. https://doi.org/10.1016/j.matpr.2022.01.340
22. Chandradass J, Thirugnanasambandham T, Jawahar P, et al. (2020) Effect of silicon carbide and silicon carbide/alumina reinforced aluminum alloy (AA6061) metal matrix composite. *Mater Today Proc* 45: 7147–7150. https://doi.org/10.1016/j.matpr.2021.02.143
23. Radha A, Antony Prabu D, Jayakumar KS, et al. (2022) Mechanical behavior and characterization of Al7075 reinforced with Al_2O_3 and TiC hybrid metal matrix composite. *Mater Today Proc* 62: 876–881. https://doi.org/10.1016/j.matpr.2022.04.059
24. Khanouki MTA (2023) Mechanical properties and microstructural evolution of rheocast A356 semi-solid slurry prepared by annular electromagnetic stirring. *China Foundry* 20: 315–328. https://doi.org/10.1007/s41230-023-3041-2
25. Li H, Fan J, Geng X, et al. (2014) Alumina powder assisted carbon nanotubes reinforced Mg matrix composites. *Mater Des* 60: 637–642. https://doi.org/10.1016/j.matdes.2014.04.017
26. Abd Rahim MN, Salleh MS, Yahaya SH, et al. (2024) Effect of graphene addition on microstructure and mechanical properties of cast aluminium alloy composite. *JARMNE* 25: 66–75. https://doi.org/10.37934/armne.25.1.6675

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