

MICROSTRUCTURAL INVESTIGATION AND MECHANICAL PROPERTIES OF Al₂O₃-CNT REINFORCED ALUMINIUM COMPOSITE

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ABSTRACT: This study investigated how alumina and carbon nanotubes (CNT) can be used together to strengthen the aluminium alloy A356. The composite was mixed using electromagnetic fields to make it better. The main goals were to identify the most optimal parameters for the composition of alumina-CNT and examine the impacts on mechanical strength and microstructural features. A systematic analysis regarding hardness and microstructural characteristics was performed by performing a series of casting tests with different ratios of alumina and carbon nanotubes (CNTs). The Taguchi method had been used to optimise the results. The findings determined the composition that exhibited the most optimal mechanical performance, offering vital insights for the advancement of aluminium composites with superior features for industrial applications. This study improved the overall understanding of hybrid reinforcements in metal matrix composites and the capability of electromagnetic stirring to optimize aluminium composite structures.

KEYWORDS: *Semisolid Processing; Electromagnetic stirring; Hybrid reinforcement.*

1.0 INTRODUCTION

Aluminium has undergone extensive research and application due to its adaptable characteristics, such as a superior strength-to-weight ratio, exceptional resistance to corrosion, and capacity to be recycled. Research showcases the diverse applications of aluminium and its alloys in areas including automotive and aerospace. Aluminium alloys are preferred in aircraft manufacture due to their durability, reliability, and cost-effectiveness, which improve aircraft performance [1]. Aluminium plays a vital role in the automotive and mass transportation industries because of its low density and high strength, which allow for the creation of lightweight structures [2]. Advanced manufacturing techniques like powder metallurgy and evaporative casting enhance the material characteristics of aluminium alloys, enabling them to be used as substitutes for heavier metals. Aluminium's wide range of uses and continuous research on improving its characteristics highlight its importance in contemporary engineering and industry. However, aluminium alone had unsatisfactory mechanical properties. As a result, many researchers have attempted to improve their properties by applying reinforcement to the aluminium.

The study on hybrid reinforcements in aluminum alloys highlights significant progress in the mechanical characteristics and potential uses of these composite materials. The investigations concentrate on several reinforcing agents, including titanium carbide (TiC), silicon carbide (SiC), magnesium oxide (MgO), and carbon nanotubes (CNTs). Every study offers a distinct method for enhancing the composite qualities, such as hardness, wear resistance, and compressive strength. The use of bimodal-sized hybrid TiC-CNT greatly improves hardness and wear resistance, while simultaneously decreasing thermal expansion [3]. Similarly,

Venkatesan (2022) presents a study on optimisation strategies for enhancing the tribo-mechanical properties. The study focuses on employing a combination of carbon nanotubes (CNTs) and nanosilicon carbide (SiC) to achieve minimal wear and maximum hardness [4]. On the other hand, Yunus and Alfattani (2023) looked into the tribological behaviour of AA6061 that had been strengthened with B4C and Gr. They focused on how the lubricating effect of Gr made the material more resistant to wear and better at its mechanical properties [5].

Electromagnetic stirring (EMS) is one way to improve the reinforcing metal. A lot of study has been done on how to use EMS to improve the microstructure and mechanical properties of aluminium alloys. It was found by Shiga et al. (2023) that using EMS to solidify Al-Si-Fe alloys breaks up the dendritic α -Al and changes the shape of the intermetallic β -Al₉Fe₂Si₂, especially at higher frequencies [6]. This was achieved by encouraging a uniform temperature distribution and reducing the movement of solute particles due to temperature differences. Qiu, 2021. It was shown by Li et al. in 2022 that changing the EMS frequency has a big effect on the wear and corrosion resistance of alloys that hold Al and Sn [7]. This effect is achieved by refining the microstructure and enhancing the distribution of Sn. In a separate study, Li et al. (2022) discovered that higher EMS current leads to the formation of smaller, more spherical grains and a more compact corrosion product coating, which makes the material more resistant to corrosion [8]. Bustos et al. (2022) discovered that the use of magnetic stirring during the solidification process of A356 aluminium alloy has several effects. It modifies the cooling curve, increases the range of solidification, and transforms the structure from dendritic to rosette-type. As a result, the grains become finer [9]. The results emphasize the critical role of EMS parameters in customizing the microstructure and characteristics of aluminum alloys.

The objective of this study is to investigate the mechanical properties of Al₂O₃-CNT reinforced aluminium composite. Materials characterization and hardness testing were also conducted to identify the structure of the reinforcement material and the strength of the samples.

2.0 METHODOLOGY

2.1 Taguchi Method

Orthogonal arrays are utilised in this Taguchi Method investigation to meticulously analyse each design parameter while reducing the number of experiments. Tables 1 and 2 provide a concise overview of the parameters and design of Taguchi Methods. In this study, Metal Matrix Composites (MMCs) were manufactured using varying weight percentages (wt%) of Al₂O₃ and MWCNTs and different stirring durations. The experiment was conducted utilising the Design of Experiment (DOE) methodology. The stir casting parameters are displayed in Table 1.

Table 1: Condition Parameter

Parameter	Level 1	Level 2
MWCNT Content (wt%)	0.5	1
Al ₂ O ₃ Content (wt%)	4	6
Stirring Time (min)	5	10

Table 2: Parameter of the casting

Run	MWCNT wt%	Al ₂ O ₃ wt%	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	4	5
6	1	4	10
7	1	6	5
8	1	6	10

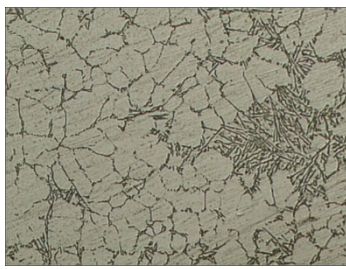
2.2 Experiment Procedure

The alloy utilised in this procedure was a commercially available A356 aluminium alloy in the form of an ingot. Its chemical composition, expressed as weight percentages, was determined through the application of spectrometry. The composition consists of 7.38% silicon (Si), 0.26% magnesium (Mg), 0.0463% copper (Cu), 0.25% iron (Fe), 0.190% manganese (Mn), 0.0068% zinc (Zn), and 0.0411% titanium (Ti). In order to remove moisture, the magnesium powder, alumina and multiwall carbon nanotubes were mixed well and enclosed in aluminium foil and subjected to preheating. Then, they were introduced into the molten using a steel plunger and mixed well by electromagnetic stirring. Ultimately, the molten substance was poured into a billet mould in order to produce composite feedstock.

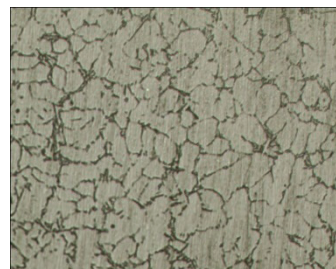
After the casting process, the billet undergoes a process of materials characterisation. The distribution of MWCNT-Al₂O₃ in the composites was analysed using a Nikon optical microscope. The analysis was performed following the grinding of the samples using different grit sizes (400, 600, 800, and 1200), polishing with diamond solutions of varying particle sizes (3µm and 1µm), and etching with Keller's reagent solution.

3.0 RESULTS

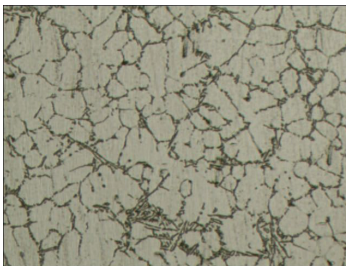
3.1 Optical Microscopy



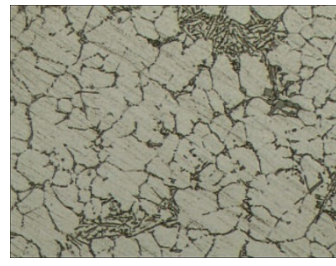
Sample 1 (0.5 wt% MWCNT, 4 wt% Al₂O₃, 5 minutes stir duration)



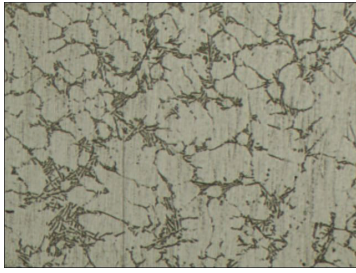
Sample 2 (0.5 wt% MWCNT, 4 wt% Al₂O₃, 10 minutes stir duration)



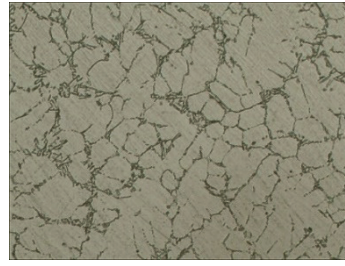
Sample 3 (0.5 wt% MWCNT, 6 wt% Al₂O₃, 5 minutes stir duration)



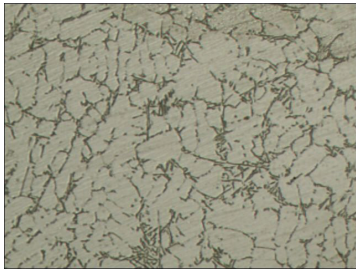
Sample 4 (0.5 wt% MWCNT, 6 wt% Al₂O₃, 10 minutes stir duration)



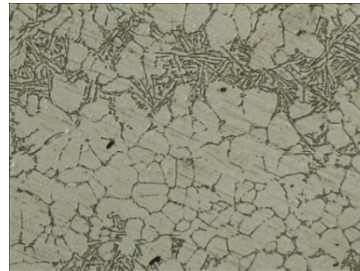
Sample 5 (1 wt% MWCNT, 4 wt% Al₂O₃, 5 minutes stir duration)



Sample 6 (1 wt% MWCNT, 4 wt% Al₂O₃, 10 minutes stir duration)



Sample 7 (1 wt% MWCNT, 6 wt% Al₂O₃, 5 minutes stir duration)



Sample 1 (1 wt% MWCNT, 6 wt% Al₂O₃, 10 minutes stir duration)

The optical microscopy images of the aluminium alloy samples reinforced with alumina-CNT show clear microstructural characteristics that are affected by different stirring durations, Al₂O₃ and MWCNT concentration. The microstructure of Sample 1, which consists of 0.5 wt% MWCNT and 4 wt% Al₂O₃, exhibits relatively homogeneous grain structures with noticeable particle agglomerations, suggesting inadequate stirring during the 5-minute stirring period. Sample 2, which has the same composition as the previous sample, shows enhanced dispersion of reinforcement, finer and more uniform grain structures, and reduced particle agglomerations as a result of the prolonged 10-minute stirring period.

Sample 3, which consists of 0.5 weight percent multi-walled carbon nanotubes (MWCNT) and 6 weight percent aluminium oxide (Al₂O₃), was stirred for 5 minutes. This sample exhibits a higher concentration of Al₂O₃ particles, some of which are clustered together. The grain boundaries exhibit clear delineation, nevertheless, the dispersion of particles remains non-uniform. On the other hand, Sample 4, which has the same composition and is stirred for 10 minutes, exhibits a significantly improved and consistent microstructure. The particles are well-dispersed, there is less clumping, and the grain structure is homogeneous. This clearly demonstrates the beneficial impact of prolonging the stirring process.

Sample 5, containing 1 wt% MWCNT and 4 wt% Al₂O₃, exhibited considerable clustering and agglomeration when the stirring time was set to 5 minutes. This phenomenon was more pronounced with increased MWCNT concentration. While the grain boundaries are evident, the unequal distribution of reinforcement indicates insufficient stirring. Sample 6, which has the same composition but is stirred for 10 minutes, exhibits enhanced dispersion of MWCNTs and Al₂O₃ particles. This leads to a more precise and uniform microstructure with less agglomerations.

Sample 7, which consists of 1 weight percent multi-walled carbon nanotubes (MWCNT) and 6 weight percent aluminium oxide (Al₂O₃), was stirred for 5 minutes. This sample shows comparable clustering of reinforcements as Sample 5, but with a greater amount of Al₂O₃. The grain boundaries are distinct, but the limited duration of churning leads to an uneven dispersion of particles. Sample 8, which has the same composition and was stirred for 10 minutes, exhibits the most sophisticated and consistent microstructure compared to all other samples. By increasing the duration of stirring, the MWCNTs and Al₂O₃ particles are evenly distributed, resulting in little clumping and a uniform grain structure.

To summarise, the optical microscope images suggest that increasing the stirring duration to 10 minutes generally improves the dispersion of reinforcements. This leads to the refining the microstructure and decreases macrosegregation, enhancing the uniformity and reducing grain size. An increased concentration of Al₂O₃ (6 wt%) leads to a higher particle density, which has the potential to enhance mechanical characteristics when the particles are properly dispersed. A higher concentration of MWCNTs (1 wt%) leads to increased clustering, especially with shorter stirring durations. However, adequate stirring can alleviate this phenomenon. The desired microstructural characteristics can be attained by using the combination of increased Al₂O₃ concentration, moderate MWCNT concentration, and extended stirring durations. This will improve the uniform dispersion of reinforcements throughout the aluminium matrix dispersion of reinforcements throughout the aluminium matrix.

3.2 Hardness Test

No of Run	Test 1	Test 2	Test 3	Test 4	Test 5	Average
As-Cast	64.55 HV	62.86 HV	63.74 HV	65.33 HV	66.56 HV	64.61 HV
Sample 1	70.04 HV	73.40 HV	69.16 HV	70.00 HV	70.92 HV	70.71 HV
Sample 2	69.2 HV	71.63 HV	69.6 H V	72.06 HV	71.11 HV	70.72 HV
Sample 3	70.85 HV	70.92 HV	72.25 HV	70.85 HV	68.93 HV	70.76 HV
Sample 4	77.73 HV	78.86 HV	80.66 HV	74.52 HV	77.53 HV	77.86 HV
Sample 5	71.36 HV	73.41 HV	81.26 HV	77.30 HV	83.53 HV	77.37 HV
Sample 6	76.73 HV	73.53 HV	76.02 HV	79.05 HV	71.36 HV	75.34 HV
Sample 7	72.49 HV	69.18 HV	66.91 HV	65.92 HV	70.25 HV	68.95 HV
Sample 8	65.27 HV	68.52 HV	70.39 HV	69.68 HV	67.77 HV	68.33 HV

The Vickers hardness test results for the aluminium metal composite demonstrates the way the hardness of the material is affected by stirring duration, the weight percentage of Al₂O₃, and MWCNT. When the Al₂O₃ concentration is at 4 wt%, extending the stirring time from 5 to 10 minutes has a negligible impact on the hardness of samples containing 0.5 wt% MWCNT. Nevertheless, as the concentration of Al₂O₃ reaches 6 wt%, the average hardness experiences a substantial increase from 70.76 HV to 77.86 HV when the stirring duration is extended. In contrast, when the samples contain 1 wt% MWCNT, a longer stirring period leads to a reduction in hardness for Al₂O₃ at 6 wt% and a minor drop for Al₂O₃ at 4 wt%.

When the Al₂O₃ concentration is increased from 4 wt% to 6 wt% at 0.5 wt% MWCNT and a stirring time of 10 minutes, the hardness increases dramatically from 70.72 HV to 77.86 HV. Nevertheless, when the MWCNT concentration is 1 wt% and the stirring period is 5 minutes, raising the Al₂O₃ content from 4 wt% to 6 wt% results in a reduction in hardness from 77.37 HV to 68.95 HV.

When the stirring time is 5 minutes and the Al₂O₃ content is 4 wt%, increasing the MWCNT content from 0.5 wt% to 1 wt% results in an increase in hardness from 70.71 HV to 77.37 HV. During a stirring process lasting 10 minutes and with a concentration of 4 wt% Al₂O₃, the addition of MWCNT content increases from 0.5 wt% to 1 wt%, resulting in a modest drop in hardness from 70.72 HV to 75.34 HV.

Essentially, the Vickers hardness of the aluminium metal composite is affected by the duration of stirring, the amount of Al₂O₃, and the amount of MWCNT. Longer stirring times often result in higher hardness, particularly when the Al₂O₃ concentration is high and the MWCNT content is low. Increasing the Al₂O₃ content for longer stirring times has a substantial impact on hardness, particularly when the MWCNT content is low. However, the effect of increased MWCNT content on hardness depends on the Al₂O₃ content and stirring time, since it can either increase or reduce hardness. These findings indicate intricate relationships among these characteristics.

4.0 CONCLUSION

The point of the study was to find out how MWCNT- Al_2O_3 had impacted the aluminium matrix composite's mechanical properties and microstructure by electromagnetic casting. The material's mechanical characteristics have been measured by hardness testing. Based on the microstructural analysis, it can be said that the concentration of MWCNT- Al_2O_3 had a substantial impact on the hardness of the composite. However, 1 wt% of MWCNT had shown the sign of agglomeration which had reduced the hardness of composite. Meanwhile, alumina shown otherwise. The increase of alumina content did not give affect to the downgrade on the hardness. It can conclude that, the stirring time play crucial role in breaking the agglomeration of MWCNT- Al_2O_3 during the stirring.

The present of electromagnetic stirring as the medium of CNTs- Al_2O_3 hybrid reinforcement aluminium composite had proof that the refines of microstructure and decreases macrosegregation, enhancing the uniformity and reducing grain size can be achieved.

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