Fabrication and Mechanical Characterization of MWCNT-Reinforced LM25 Aluminium Matrix Nanocomposites

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Abstract

Advanced lightweight materials such as aluminium-based metal matrix nanocomposites reinforced with nano-carbon phases are increasingly explored for aerospace structures, with variations in reinforcement content significantly influencing performance. In this work, LM25 aluminium alloy reinforced with Multi-Walled Carbon Nanotubes (MWCNTs) was developed by varying the reinforcement fraction from 0 to 2 wt.% in steps of 0.5 wt.% to study its effect on mechanical behaviour. A hybrid fabrication route integrating mechanical alloying through ball milling and vacuum-assisted stir casting was employed to ensure effective incorporation of MWCNTs into the matrix. Micro-sized aluminium particles (approximate average particle size of 72 µm) were utilized as carrier media to promote uniform dispersion of nanotubes during processing. The mechanical characterization involved tensile testing, hardness evaluation, and impact testing. Results revealed a progressive enhancement in tensile strength with increasing reinforcement, reaching a maximum of 175 MPa at 1.5 wt.% MWCNTs, attributed to improved load transfer and dislocation strengthening mechanisms. Brinell hardness and Charpy impact strength also showed notable improvement, with peak values of 72 BHN and 150 kJ/m^2 respectively at 1.5 wt.% reinforcement, followed by a decline due to agglomeration effects. Overall, the same composite sample demonstrated the most balanced and superior mechanical performance among all samples.

Keywords: Nanocomposites, Metal matrix composites, Aluminium, Powder metallurgy, Liquid metallurgy

1. Introduction

Development across all domains of engineering has always been constrained by the availability and performance of materials. This limitation is especially critical in the automotive and aerospace industries, where components must simultaneously satisfy requirements of high strength, reduced weight, durability, and thermal stability. Conventional aluminium casting alloys such as LM25 (Al-Si$_7$-Mg), A356, and A357 have been extensively used in automotive applications including engine blocks, cylinder heads, gearbox housings, brake components, and suspension systems, as well as in aerospace structures such as fuselage frames, brackets, and housings. Among these, LM25 alloy is particularly suitable for manufacturing complex, pressure-tight castings due to its excellent fluidity, corrosion resistance, and heat-treatable characteristics. However, the growing demand for lightweight vehicles, improved fuel efficiency, and reduced emissions has exposed the limitations of monolithic alloys, particularly in terms of wear resistance, stiffness, and high-temperature performance. To overcome these drawbacks, Metal Matrix Composites (MMCs) have emerged as advanced alternatives, offering superior mechanical and tribological properties [1]. In particular, carbon-reinforced aluminium composites are gaining prominence as next-generation materials capable of replacing traditional alloys in critical automotive and aerospace components due to their exceptional strength-to-weight ratio and enhanced thermal and wear performance [2].

In modern automotive engineering, MMCs are increasingly being explored for components such as piston rings, brake discs, cylinder liners, connecting rods, and drive shafts, where improved wear resistance and thermal conductivity are essential. Likewise, in aerospace applications, components including actuator housings, fuel access panels, exit guide vanes, and structural fittings require materials capable of withstanding cyclic stresses and extreme environmental conditions. Aluminium-based MMCs derived from LM25, A356, and A357 alloys provide an effective balance between lightweight characteristics and enhanced mechanical performance. For example, aircraft fuselage structures composed of frames and stringers are subjected to significant internal pressure and dynamic loading. The use of reinforced composites such as SiC/Al or graphene/Al systems can reduce structural weight while maintaining strength and stiffness, thereby improving fuel efficiency and payload capacity. Such improvements are equally beneficial in automotive systems, where weight reduction directly translates into better mileage and reduced emissions [3,4].

Despite these advantages, conventional composites used in high-temperature applications, such as automotive exhaust systems and aerospace thermal protection components, often exhibit insufficient fracture toughness and crack resistance. To address these issues, nano-reinforcements such as Graphene Nanoplatelets (GNPs) and Carbon Nanotubes (CNTs) have been incorporated into aluminium matrices. These nanomaterials exhibit extraordinary mechanical properties, including high tensile strength, modulus, and thermal conductivity, which significantly enhance the performance of aluminium alloys. Graphene, in particular, offers advantages over CNTs due to its larger surface area, lower tendency for agglomeration, and improved interfacial bonding with the matrix [5,6]. Furthermore, hybrid reinforcement strategies combining graphene and CNTs have been shown to provide synergistic effects, leading to enhanced mechanical and functional properties [7,8].

Among the various fabrication techniques available for producing aluminium MMCs, stir casting remains the most economical and scalable method, especially for automotive mass production. It is widely used for LM25 and A356-based composites due to its simplicity and compatibility with existing casting processes. However, a major challenge associated with this technique is the agglomeration of nano-reinforcements, which leads to non-uniform distribution and degradation of mechanical properties. Achieving homogeneous dispersion of reinforcement particles is therefore critical for improving the overall performance of MMCs. Recent studies highlight that improper dispersion results in weak interfacial bonding and reduced load transfer efficiency, ultimately limiting the benefits of nano-reinforcements [9,10].

To overcome this issue, pre-distribution techniques involving ball milling of nano-reinforcements with metal powders have been developed. This approach enhances wettability and promotes uniform dispersion within the molten matrix. Recent investigations on A356-based composites reinforced with graphene nanoplatelets demonstrate that controlled dispersion significantly improves hardness and wear resistance. For instance, recent studies reported that A356/GNP composites exhibited up to 51% improvement in hardness and a notable reduction in wear rate, highlighting their suitability for automotive tribological applications such as brake components and engine parts. Similarly, ultrasonic-assisted stir casting has been shown to effectively disperse hybrid reinforcements such as graphene and CNTs, reducing agglomeration and improving interfacial bonding in A356 composites. Further studies on A356 and A357 alloys reinforced with CNTs reveal significant improvements in tensile strength, elongation, and hardness due to enhanced load transfer mechanisms. For example, CNT-reinforced A356 composites fabricated through mechanical stirring and thixoforming processes demonstrated substantial increases in yield strength and ultimate tensile strength, indicating their potential for high-performance automotive components [11-13]. Additionally, recent research indicates that CNT incorporation promotes grain refinement and dynamic recrystallization in aluminium matrices, leading to improved mechanical performance and structural stability.

In the context of LM25 alloy, reinforcement with ceramic particles such as SiC, Al_2O_3, and TiB_2 has been widely investigated to enhance mechanical and tribological properties. These composites exhibit improved hardness, wear resistance, and load-bearing capacity, making them suitable for applications such as pump impellers, engine components, and brake systems. Hybrid composites combining ceramic particles with nano-reinforcements such as graphene or CNTs further enhance performance by providing both strengthening and lubrication effects. Such materials are particularly beneficial in automotive braking systems, where both wear resistance and friction control are critical. Graphene-reinforced aluminium composites have also shown remarkable improvements in microstructural characteristics. Recent studies indicate that graphene addition leads to grain refinement, improved load transfer, and enhanced mechanical strength due to mechanisms such as Orowan strengthening and thermal mismatch strengthening. However, challenges such as poor wettability and agglomeration persist, necessitating advanced processing techniques such as surface modification of graphene or the use of carrier materials. Recent research emphasizes the importance of controlling solidification conditions and interface characteristics to achieve uniform dispersion and optimal performance [14].

A survey of prior research reveals that achieving a uniform distribution of multi-walled carbon nanotubes (MWCNTs) within an Aluminum/Silicon/Magnesium (LM25) alloy matrix has not been extensively addressed, particularly through hybrid processing methods that combine liquid metallurgy with powder metallurgy. Most reported studies highlight that mechanical strength improves with increasing CNT content only up to an optimal level, after which further addition leads to a deterioration in properties. Moreover, key aspects such as CNT agglomeration, particle alignment, and the nature of interfacial bonding between the nanotubes and the metallic matrix require more detailed investigation to fully understand their influence on composite performance. In this context, the present work focuses on evaluating the effect of uniformly dispersed MWCNTs in an aluminum-based LM25 matrix on tensile strength, impact toughness, and hardness. The composites are fabricated using a hybrid approach involving ball milling and stir casting, where pure aluminum powder (average particle size of 72 µm) is employed as a carrier or initiating medium to promote better dispersion.

2. Materials

2.1. Matrix material

LM25 aluminum alloy, belonging to the Al-Si-Mg family of casting alloys, is well regarded for its ability to combine low density with reliable mechanical performance, making it a preferred choice in marine, automotive, and structural engineering applications. The alloy typically contains silicon in the range of 7 wt.% and magnesium between 0.35 wt.%, both of which play a crucial role in determining its characteristics. Silicon enhances the molten alloy’s fluidity and reduces the likelihood of casting defects, thereby supporting the manufacture of components with complex geometries. Meanwhile, magnesium contributes to precipitation strengthening through the formation of Mg_2Si phases during heat treatment, resulting in improved strength and hardness. LM25 also offers a favourable strength-to-weight ratio and satisfactory fatigue behavior, which are important for components subjected to repeated loading conditions. Its notable resistance to corrosion, especially in saline or humid environments, further extends its service life. In addition, the alloy exhibits good machinability and weldability, which facilitates ease of processing and fabrication. Owing to this combination of properties, LM25 is widely utilized as a matrix material in metal matrix composites, including advanced reinforced systems. In view of these advantages, LM25 aluminum alloy has been selected as the matrix material for the present study, and its chemical composition is detailed in Table 1.

Table 1: Material composition of LM25 alloy

Element	Si	Mg	Fe	Cu	Zn	Al
Weight %	7	0.35	0.2	0.15	0.10	Balance

2.2. Launching material

A key limitation associated with the stir casting of nanocomposites is the poor wettability between the reinforcement phase and the molten matrix, which mainly stems from differences in their surface energies. To overcome this issue, previous studies [15] have reported the modification of carbon nanotubes (CNTs) through aluminum/copper coating via electroplating, as aluminum possesses relatively higher surface tension. This surface modification, followed by subsequent heat treatment at elevated temperatures, facilitates the development of strong interfacial bonding, thereby improving the overall compatibility between the reinforcement and the matrix. In addition, the melting temperature of pure aluminum powder is lower than that of the LM25 alloy used as the base matrix in this study. As a result, the aluminum particles can easily melt during processing and become uniformly incorporated into the molten matrix. Hence, micro-sized pure aluminum powder is adopted as a carrier material in the present work. In this investigation, aluminum carrier powder with an average particle size of approximately 72 µm is utilized.

2.3. Reinforcement material

MWCNTs have emerged as a promising reinforcement phase in advanced composite systems due to their unique combination of structural and functional properties. Structurally, MWCNTs consist of several concentric graphene cylinders, typically possessing nanometer-scale diameters and micrometre-scale lengths, which impart a very high aspect ratio. This distinctive geometry, along with their intrinsic characteristics, contributes to exceptional mechanical strength, high stiffness, and excellent thermal as well as electrical conductivity. Such properties make MWCNTs highly effective in enhancing the performance of metal matrix composites. Compared with other carbon-based nanoreinforcements, MWCNTs are relatively easier to synthesize, exhibit better structural integrity, and are more cost-effective, thereby supporting their broader utilization. In addition, their capability to facilitate load transfer and impede dislocation motion plays a significant role in improving the mechanical behavior of the composite. In light of these advantages, high-purity MWCNTs with controlled morphology are selected as the reinforcement material in the present investigation. The MWCNTs used in this study possess an average diameter of approximately 8 nm and a length of about 10 µm.

3. Methodology

Carbon-based reinforcements typically exhibit poor wettability with molten aluminum, which limits effective interfacial bonding. However, recent findings suggest that ball milling can improve compatibility by modifying the surface of the reinforcement, thereby enhancing its interaction with the metallic matrix. In the present study, mechanical alloying was first performed between nanoscale MWCNTs and pure aluminum powder, used as a carrier, in a weight ratio of 1:5. This pre-dispersion step was carried out using a planetary ball mill, enabling gradual attachment of the nanotubes onto the surfaces of the micron-sized aluminum particles in a layered configuration. The milling process was conducted for 2 hours at a rotational speed of 350 rpm. Following milling, the powder mixture was preheated to 200ºC to remove moisture, volatile impurities, and surface contaminants. The treated powder blend was then introduced into molten LM25 alloy maintained at approximately 720ºC. Considering the melting range of the base alloy (approximately 620ºC), a superheat of about 100ºC was employed to ensure complete melting, improved fluidity, and effective incorporation of the reinforcement. This elevated processing temperature also assists in enhancing wettability and promoting sound interfacial bonding. The entire fabrication process was carried out under an inert argon atmosphere to minimize oxidation, with controlled gas flow maintained separately in the crucible and die regions. To examine the possibility of particle rejection during processing, additional modifications were implemented by increasing the argon flow rate, thereby raising the internal pressure within the crucible and limiting atmospheric interaction during the removal of surface-floating particles. Composite fabrication was performed using 720 gm of LM25 alloy, with MWCNT content varied from 0 to 2 wt.% in increments of 0.5 wt.% (corresponding to 0, 5, 10, 15, and 20 g for samples A, B, C, D, and E, respectively). The quantity of pure aluminum carrier powder was consistently maintained at five times the reinforcement content. The experimental setup adopted for composite synthesis is depicted in Figure 1. After fabrication, the specimens were subjected to mechanical characterization. Tensile properties were evaluated using a universal testing machine in accordance with ASTM standards, while hardness was measured using the Brinell hardness test. Impact strength was assessed using a Charpy impact testing setup.

Figure 1: Stir casting setup for composite preparation.

4. Results and discussion

A comprehensive understanding of the mechanical behavior of composite materials is essential to ensure their reliability, safety, and performance in real-world engineering applications. In contrast to monolithic materials, composites exhibit highly complex and direction-dependent (anisotropic) mechanical responses due to the combined influence of the matrix and reinforcement phases. The interaction between these constituents leads to non-uniform stress distribution, making the prediction of material behavior more challenging without detailed experimental investigation. Furthermore, factors such as interfacial bonding, reinforcement dispersion, and processing conditions significantly influence the overall performance of composites. Therefore, systematic characterization of mechanical properties is indispensable not only for optimizing material composition but also for enhancing structural efficiency and ensuring consistent performance under service conditions. In the present study, key mechanical properties of aluminum matrix nanocomposites (AMMnCs), including tensile strength, impact strength, and hardness, were experimentally evaluated. Standardized testing procedures were followed using a universal testing machine for tensile behavior, a Charpy impact testing setup for energy absorption characteristics, and a Brinell hardness tester for surface resistance, all in accordance with ASTM standards to ensure reproducibility and reliability of results.

Relative density is commonly defined as the ratio of a material's density to that of water; however, such a definition offers limited practical significance when comparing materials within the same class. In this work, relative density is more appropriately defined with respect to the density of as-received LM25 aluminum alloy ingots (2.7 g/cm^3), which serve as the baseline material. Accordingly, relative density is expressed as the ratio of the experimentally measured density of the composite specimen to that of the reference alloy. A value of 100% indicates complete densification equivalent to the base material, whereas lower values suggest the presence of internal defects such as porosity. It is well established that higher relative density corresponds to reduced porosity levels, which in turn minimizes stress concentration sites and improves mechanical integrity. The experimental results reveal that the incorporation of MWCNTs leads to a progressive increase in relative density up to a reinforcement level of 1.5 wt.%, indicating improved packing efficiency and matrix-reinforcement interaction at this concentration. However, beyond this threshold, a slight reduction in relative density is observed. Notably, even at its maximum value (Sample C3), the relative density of the composite remains marginally lower than that of the unreinforced alloy (Sample P), suggesting the introduction of minor porosity during composite fabrication (Figure 2). This behavior can be attributed to the increased viscosity of the molten metal due to the presence of nanoscale reinforcements, which restricts fluidity and impedes complete mold filling. Additionally, inadequate wettability between the aluminum matrix and MWCNTs can result in weak interfacial bonding and localized void formation, further contributing to density reduction.

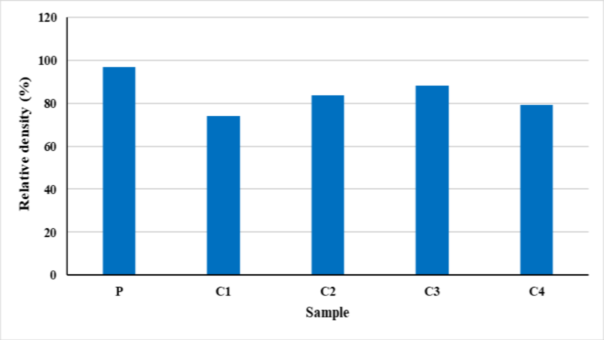

Figure 2: Relative density of various samples

The variation in ultimate tensile strength demonstrates a consistent improvement with increasing MWCNT content, as illustrated in Figure 3. The maximum tensile strength of 175 MPa is achieved for Sample C3, corresponding to 1.5 wt.% reinforcement. This enhancement can be attributed to multiple strengthening mechanisms, including load transfer from the matrix to the high-strength nanotubes, grain refinement, and the obstruction of dislocation motion by the dispersed reinforcements. However, beyond this optimal reinforcement level, no significant increase in tensile strength is observed, indicating a saturation point in the effectiveness of MWCNT addition. It is important to note that while strength is enhanced, ductility tends to decrease with increasing reinforcement content (Figure 4). This reduction in ductility is primarily associated with the formation of agglomerates and non-uniform dispersion of MWCNTs, which act as stress concentrators and initiate early crack propagation. Such behavior reflects the typical trade-off between strength and ductility in composite systems. The findings suggest that a reinforcement level of 1.5 wt.% strikes an effective balance between strength enhancement and acceptable ductility, making it an optimal composition for improving the tensile performance of LM25-based nanocomposites.

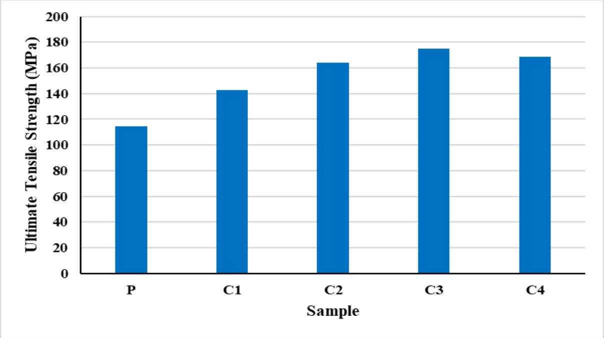

Figure 3: Ultimate tensile strength of various samples

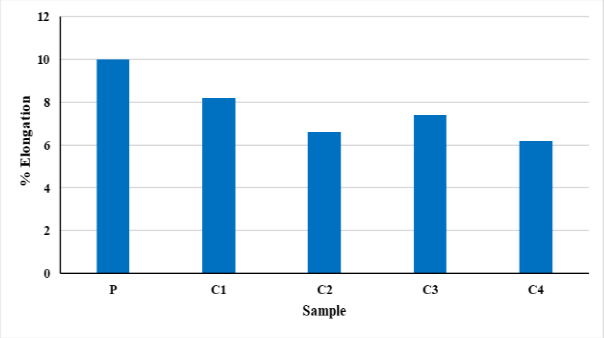

Figure 4: Ductility of various samples

A similar trend is observed in hardness measurements, where the hardness values increase progressively with the addition of MWCNTs, reaching a peak value of 72 BHN for Sample C3 (Figure 5). The improvement in hardness can be attributed to the presence of stiff and hard nanotube reinforcements, which resist localized plastic deformation and enhance surface wear resistance. Additionally, the interaction between dislocations and the dispersed MWCNTs contributes to strain hardening, further increasing hardness. The entanglement and clustering of nanotubes at higher reinforcement levels also play a role in restricting matrix deformation under applied loads. Impact strength measurements reveal that Sample C3 exhibits the highest energy absorption capacity, with a value of 150 kJ/m^2 (Figure 6). The improvement in impact strength up to 1.5 wt.% MWCNTs can be associated with effective load distribution and energy dissipation mechanisms facilitated by well-dispersed reinforcements. However, beyond this concentration, the absence of further improvement suggests that excessive reinforcement leads to agglomeration, which negatively affects the material's ability to absorb impact energy. Overall, the results clearly indicate the presence of an optimal reinforcement threshold at 1.5 wt.% MWCNTs, beyond which the beneficial effects of reinforcement diminish due to microstructural limitations.

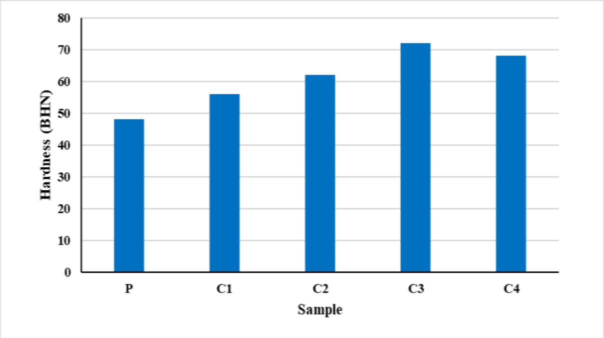

Figure 5: Hardness of various samples

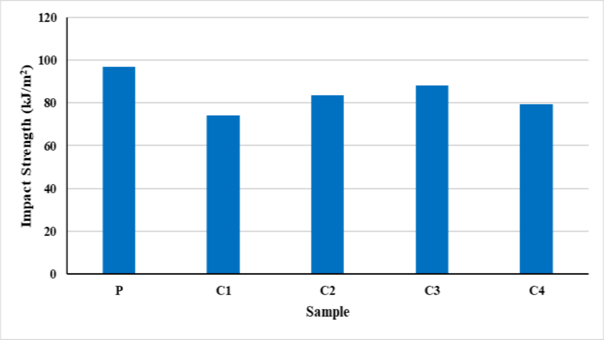

Figure 6: Impact strength of various samples

5. Conclusion

The key findings obtained from the processing and mechanical assessment of LM25/MWCNT nanocomposites are summarized as follows:

- The use of mechanical alloying with aluminum carrier powder effectively improved the distribution and wettability of MWCNTs, resulting in stronger interfacial bonding within the LM25 matrix.
- Relative density increased progressively up to 1.5 wt.% MWCNTs, indicating better matrix-reinforcement interaction, while a slight reduction at higher content suggests the formation of porosity due to agglomeration and decreased melt fluidity.
- Tensile strength, hardness, and impact resistance improved with increasing reinforcement, reaching optimum values at 1.5 wt.% as a result of efficient load transfer and resistance to dislocation movement.
- Beyond this optimum level, property enhancement plateaued or slightly declined, mainly due to nanotube clustering and uneven dispersion that act as stress concentration sites.
- The LM25/MWCNT composite with 1.5 wt.% reinforcement offers a favourable combination of strength and toughness, indicating its suitability for lightweight structural applications.

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