Experimental Investigation on Multi-Walled Carbon Nanotubes reinforced Aluminum Metal Matrix Composites

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Abstract

Driven by the need for lightweight, high-strength materials in the automotive industry to improve fuel efficiency and reduce emissions, composite materials have gained significant importance. The present study focuses on the fabrication and characterization of Multi-Walled Carbon Nanotubes (MWCNTs) reinforced A357 aluminium alloy metal matrix composites for lightweight automotive applications. Composites were produced using a hybrid processing route combining mechanical alloying through ball milling and vacuum-assisted stir casting to ensure uniform dispersion and improved bonding. The reinforcement content was varied from 0 to 2 wt.% in increments of 0.5 wt.%. Mechanical testing revealed a significant improvement in tensile properties with the addition of MWCNTs. The composite containing 1.5 wt.% MWCNTs exhibited the highest tensile strength of 172.4 MPa, indicating optimal reinforcement content. Beyond this level, agglomeration effects slightly reduced performance. However, optical micrograph of the high tensile strength sample depicts better grain refinement of 72 µm compared to 174 µm of pure sample. On overall, the results demonstrate that controlled addition of MWCNTs effectively enhances strength and makes the composite suitable for structural automotive components.

Keywords: Metal Matrix Composites, Multi-Walled Carbon Nanotubes, Stir Casting, Aluminum alloys

1. Introduction

The growing demand for lightweight, high-strength materials in automotive components such as engine parts, brake systems, suspension elements, and transmission housings has intensified the need for advanced nanomaterial-reinforced composites. Nanomaterials offer exceptional mechanical properties and high specific strength, making them ideal for improving performance, durability, and fuel efficiency in modern vehicles [1]. The realization of materials with tailored properties has become essential for next-generation technological applications in mechanical, aeronautical, and automotive sectors. Metal matrix composites (MMCs), particularly Aluminum Metal Matrix Composites (AMMCs), have gained significant attention due to their superior strength-to-weight ratio and enhanced resistance to environmental degradation. Kotteda et al. [2] fabricated fly ash and SiC reinforced AA6061 and AA7075 composites via stir casting and evaluated their mechanical and wear properties along with SEM analysis. The results showed significant improvement in properties due to effective dispersion strengthening.

Among various carbon-based nanomaterials, graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), especially multi-walled carbon nanotubes (MWCNTs), have emerged as highly effective reinforcements because of their extraordinary tensile strength, high aspect ratio, and excellent thermal and electrical properties. Despite the availability of several fabrication techniques, stir casting remains widely preferred due to its simplicity and cost-effectiveness. Several researchers have reported notable improvements in hardness, tensile strength, and wear resistance of CNT-reinforced aluminium composites with optimized reinforcement content [3]. Zhang et al. [4] utilized a combined approach of deformation and controlled pre-dispersion to minimize carbon agglomeration in GNP-reinforced AMMCs, resulting in a remarkable strength improvement of 293.3%. Mina et al. [5] produced graphene-reinforced Al6061 composites via ball milling (30-90 min) followed by hot compaction, and characterized them using SEM and Raman spectroscopy. The study revealed reduced ductility with increased milling time, indicated by fewer ductile dimples on fracture surfaces, while flexural strength improved by 47%. Han et al. [6] fabricated GNP-reinforced aluminium composites using copper as a carrier to enhance dispersion, combined with low-temperature ball milling and subsequent hot extrusion. The composite with 2.5 wt.% GNPs exhibited the best performance, achieving a tensile strength of 402 MPa, representing a 130% increase over pure aluminium.

Kotteda et al. [7] fabricated AMMCs reinforced with GNPs by employing a combination of ball milling followed by vacuum assisted stir casting. Milling time and speed maintained at 2 hours and 300 rpm, the resulting samples were subjected to impinge load transfer and grain refinement mechanisms revealed through optical micrographs and FESEM analysis. Rashad et al. [8] reported that optimal mechanical performance of A356/MWCNTs composites is achieved at 1-1.5 wt.% reinforcement, beyond which a deterioration in properties occurs. SEM and FESEM analyses indicate uniform nanotube dispersion and strong interfacial bonding at these compositions, enabling efficient load transfer. Enhanced wettability and proper melt infiltration are associated with the formation of interfacial Al_4C_3 phases. Energy dispersive spectra confirm the presence of carbon and carbide formation, particularly prominent at 1.5 wt.%. At higher loading (2 wt.%), microstructural observations reveal clustering of MWCNTs and non-uniform distribution. Such agglomeration leads to poor wettability, increased porosity, and reduced mechanical performance. Therefore, superior strength at 1.5 wt.% is attributed to homogeneous dispersion, improved interfacial characteristics, and grain refinement.

Xudong et al. [9] mitigated graphene agglomeration by surface modification using cerium nitrate and subsequently fabricated graphene-reinforced AMMCs through high-energy ball milling followed by hot vacuum pressing. The developed composites exhibited improved performance, with tensile strength reaching 321 MPa compared to 284 MPa for conventionally processed samples, along with a 12.3% increase in tensile strain. Ghasali et al. [10] fabricated 1 wt.% GNPs/CNTs reinforced aluminium composites using microwave sintering and spark plasma sintering (SPS). Prior to consolidation, powders were processed through milling and ultrasonic mixing to ensure uniform dispersion. XRD analysis revealed only minimal formation of aluminium carbide, while FESEM confirmed homogeneous distribution of reinforcements. Microwave sintering enhanced microhardness, whereas SPS yielded superior bending strength. Ramesh et al. [11] employed equal channel angular pressing (ECAP) with a 120º channel angle following mechanical alloying to produce graphene-reinforced AMMCs, achieving refined grains and uniform dispersion with negligible agglomeration due to applied back pressure. Niteesh et al. [12] developed graphene-reinforced AMMCs via powder metallurgy followed by hot extrusion, reporting slight grain refinement and a 46% increase in ultimate tensile strength.

Gurusamy et al. [13] reported that the addition of MWCNTs into the A356 matrix, particularly at optimized hybrid reinforcement levels (10-15 wt.% SiC_p/MWCNT in a 2:1 ratio), leads to significant microstructural refinement and enhanced mechanical properties due to effective dispersion. SEM and FESEM observations indicate that MWCNTs are uniformly distributed both within the grains and along grain boundaries, serving as nucleation sites and inhibiting grain growth, thereby promoting grain size reduction and enhanced strength. EDS/EDAX analysis confirms dominant aluminium peaks along with carbon signatures, verifying the presence of CNTs, in addition to Mg, Si, and Cu phases; the absence of significant Al_4C_3 formation suggests stable interfacial characteristics. The observed strengthening is primarily governed by Orowan looping, grain refinement, and efficient load transfer mechanisms. Improved wettability achieved through stirring and squeeze casting further aids in minimizing CNT agglomeration. Fractographic analysis reveals fine dimples and reduced porosity, indicating strong interfacial bonding and improved ductility. However, excessive reinforcement may lead to clustering due to Van der Waals forces, reducing overall effectiveness.

A review of existing literature indicates limited exploration on achieving homogeneous dispersion of MWCNT reinforcement within Aluminum/Silicon alloy matrix aimed at enhancing composite strength through hybrid processing routes that integrate liquid metallurgy and powder metallurgy techniques. Furthermore, most investigations emphasize improvements in composite strength with increasing nanoreinforcement content up to an optimum CNT concentration, beyond which a decline in mechanical performance becomes evident. In addition, critical factors such as agglomeration behavior, orientation of particles, and interfacial characteristics between MWCNTs and the metal matrix warrant deeper examination to gain comprehensive insight into the mechanical performance of cast composites. The present study therefore examines the influence of uniformly dispersed MWCNT reinforcement within an Aluminum-based matrix on tensile strength, impact resistance, and hardness of A357 alloy cast composites fabricated via a combined ball milling and stir casting approach. Complementary optical microscopy analysis supports evaluation of grain size variation and its correlation with the resulting mechanical properties of the developed composites.

2. Materials

2.1. Matrix material

A357 aluminum alloy, an Al-Si-Mg system, is distinguished by its low density and superior mechanical performance, making it highly attractive for aerospace and automotive applications. It predominantly contains silicon (6.5-7.5 Wt.%) and magnesium (0.4-0.7 Wt.%), which synergistically enhance castability and enable precipitation hardening. The presence of silicon significantly improves fluidity and minimizes casting defects, facilitating the production of intricate geometries. Magnesium contributes to the formation of strengthening precipitates during heat treatment, thereby elevating strength and hardness. A357 exhibits an excellent strength-to-weight ratio coupled with notable fatigue resistance, essential for load-bearing structures. Its inherent corrosion resistance further ensures durability in aggressive service environments. The alloy also demonstrates good machinability and acceptable weldability, supporting its industrial adaptability. Owing to these attributes, A357 is widely selected as a matrix material in advanced metal matrix composites, particularly for nano-reinforced systems. Because of these attributes, A357 aluminum alloy is considered as a matrix material in the current study. Table 1 shows the chemical composition of the A357 alloy used in the present study.

Table 1: Material composition of A357 alloy

Element	Si	Mg	Cu	Fe	Zn	Al
Weight %	7.2	0.52	0.12	0.14	0.10	Balance

2.2. Launching material

A major challenge in fabricating nanocomposites through the stir casting process is inadequate wettability, primarily arising from the disparity in surface energies between the reinforcement and the matrix. To address this, Kang et al. [14] enhanced the wettability of CNTs by electroplating them with aluminum, selected for its comparatively high surface tension. This treatment was subsequently followed by high-temperature annealing, promoting the formation of strong covalent interfacial bonds and thereby improving compatibility. Furthermore, since the melting point of pure aluminum powder is lower than that of the A357 alloy matrix employed in the present study, the added aluminum particles readily melt and integrate into the matrix. Consequently, microscale pure aluminum powder is utilized as a carrier in the present investigation. At present study, aluminum launching powder, with an average particle size of approximately 70 µm is used.

2.3. Reinforcement material

MWCNTs have gained significant attention as an effective reinforcement material in advanced composites owing to their outstanding structural and functional characteristics. They are composed of multiple concentric graphene layers arranged in a cylindrical morphology, with diameters typically in the nanometer range and lengths extending to several micrometres, resulting in a very high aspect ratio. MWCNTs exhibit exceptional mechanical strength, superior stiffness, and excellent electrical and thermal conductivity, which make them highly suitable for improving the overall performance of metal matrix composites. In comparison to other carbon-based nanomaterials, MWCNTs offer advantages such as ease of synthesis, enhanced structural stability, and relatively lower cost, enabling their wider applicability. Moreover, their ability to act as effective load-bearing constituents and barriers to dislocation movement contributes to significant enhancement in mechanical properties. Considering these attributes, high-purity MWCNTs with controlled dimensions are employed as reinforcement in the present study. At present study the reinforced MWCNTs are dimensioned with 10 nm in diameter and 12 µm in length.

3. Experimental Procedure

Carbonaceous reinforcements generally exhibit inadequate wettability with molten aluminum; however, recent studies indicate that ball milling can significantly enhance interfacial compatibility by disrupting the outer surface layer, thereby promoting better bonding with the matrix. In the present work, mechanical alloying (MA) was initially carried out between nano-scale reinforcements (MWCNTs) and a carrier medium (pure aluminum) in a proportion of 1:5 to achieve uniform pre-dispersion using a planetary ball mill. This process facilitates the progressive adherence of reinforcement particles onto the surfaces of micro-sized aluminum particles in a layered manner. Subsequently, the pre-dispersed powders were incorporated into the molten matrix through a controlled-atmosphere stir casting process to fabricate the composites. The milling operation was conducted for 2.5 hours at a rotational speed of 350 rpm, followed by preheating at 220°C to eliminate residual impurities and adsorbed contaminants from the milled mixture.

The preheated powder blend was then introduced into the molten A357 alloy maintained at 715°C, ensuring complete melting and effective incorporation of the reinforcements. This elevated temperature was deliberately selected to enhance wettability and facilitate proper fusion between the matrix and the reinforcement phases. The entire process was performed under an inert argon atmosphere to minimize oxidation, with independent gas flow maintained in both the crucible and die chambers. To further investigate the particle rejection phenomenon, specific experimental modifications were implemented. The argon flow rate was increased to elevate the internal pressure within the crucible, thereby restricting atmospheric contamination during the removal of floating particulates. The composite synthesis involved 720 gm of A357 alloy, with MWCNT content varied from 0 to 2 wt.% in increments of 0.5 wt.% (0, 5, 10, 15, and 20 gm for samples A/B/C/D/E), while the amount of pure aluminum powder was consistently maintained at five times the weight fraction of the reinforcement. The fabricated composite samples were produced with dimensions of 230 mm×45 mm×25 mm. Figure 3 illustrates the experimental arrangement employed for the synthesis of the composites. Following fabrication, the composite specimens were subjected to tensile testing using a universal testing machine in accordance with ASTM standards. Hardness evaluation was performed using the Brinell hardness testing method. Furthermore, optical microscopy was employed to examine the microstructural features and to analyze the grain characteristics of the composites.

Figure 3: Stir casting setup used for synthesizing the composite

4. Results and discussion

4.1. Mechanical behaviour

Understanding the mechanical behavior of composite materials is essential to ensure their reliability, safety, and performance in real-world applications. Composites often exhibit complex, anisotropic responses under loading due to the interaction between matrix and reinforcement phases, making their behavior difficult to predict without systematic evaluation. Therefore, studying their mechanical characteristics is crucial for optimizing material design, enhancing structural efficiency, and ensuring suitability for advanced engineering applications such as aerospace, automotive, and structural systems. At present study, tensile strength and hardness of AMMnCs have been tested on Universal testing machine and Brinell’s hardness setup as per ASTM standards.

Relative density is commonly understood as the measure of a material’s heaviness compared to water. However, for differential analysis, such a comparison becomes insignificant. In this study, relative density is defined with respect to the density of aluminum ingots in the as-received condition (2.66 gm/cm^3), which serve as the reference standard. Accordingly, it is expressed as the ratio between the density of the cast composite sample and that of the benchmark aluminum sample. A relative density of 100% indicates that the cast composite has achieved a density equivalent to the as-received aluminum. It is well established that higher relative density corresponds to lower porosity, thereby reducing stress concentration sites and improving mechanical performance. The incorporation of MWCNTs enhances the relative density of the nanocomposite linearly up to 1.5 wt.%, indicating an optimal reinforcement threshold. Beyond this concentration, a decline in relative density is observed. Furthermore, the maximum relative density attained among the nanocomposite samples (Sample D) remains slightly lower than that of the pure cast aluminum sample (Sample A), suggesting a marginal increase in porosity due to reinforcement addition as depicted from Figure 4. This behavior can be attributed to the presence of nanoscale reinforcements during solidification, which increases melt viscosity and limits its ability to fully infiltrate fine-scale features. Consequently, reduced wettability between the reinforcement and matrix leads to slight porosity formation.

The variation of ultimate tensile strength (UTS), as illustrated in Figure 5, indicates a progressive increase with increasing weight fraction of MWCNT reinforcement, reaching a maximum value of 172.4 MPa for sample D. Beyond this level, no further improvement is observed, suggesting a threshold reinforcement content. The incorporation of MWCNTs, however, adversely affects ductility, which is inherently a key characteristic of aluminum alloys. This reduction in ductility can be attributed to the non-uniform dispersion and localized agglomeration of nanotubes within the matrix. Since strength and ductility exhibit an inverse relationship, enhancement in strength is accompanied by a decline in ductility. Overall, the mechanical response indicates that 1.5 wt.% MWCNTs represents an optimal reinforcement level for achieving improved strength in the A356 matrix. Similarly, hardness values show an increasing trend with reinforcement content, attaining a peak value of 74 BHN for sample D. The relatively higher hardness can be associated with the clustering and entanglement tendency of MWCNTs, which contribute to localized resistance against deformation.

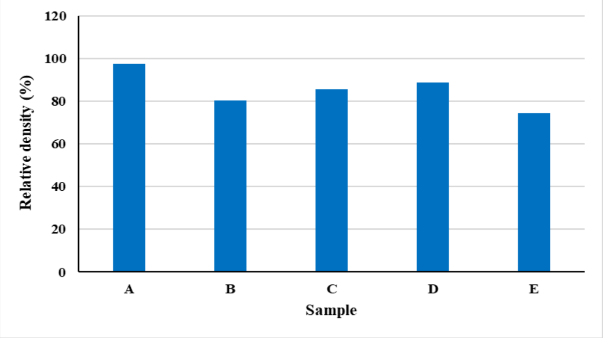

Figure 4: Relative density of various samples

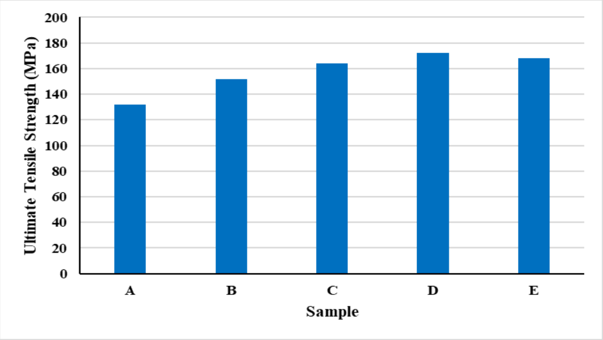

Figure 5: Ultimate tensile strength of various samples

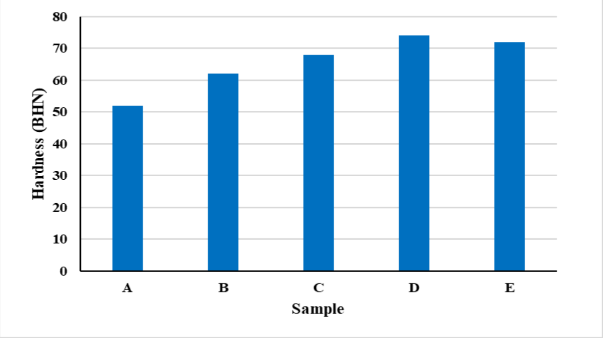

Figure 6: Hardness of various samples

4.2. Optical microscopy

Optical microscopy is a fundamental characterization technique employed to examine the microstructural features of composite materials. It enables the visualization of grain morphology, and size, which are critical in understanding material behavior. Through this analysis, the effectiveness of reinforcement addition and processing conditions can be evaluated. Hence, optical microscopy serves as a vital tool for correlating microstructure with mechanical performance in advanced composites. Grain size plays a decisive role in determining the mechanical properties of AMMnCs. A reduction in grain size leads to an increase in grain boundary area, which acts as a barrier to dislocation movement, thereby enhancing strength and hardness. This phenomenon is explained by the Hall-Petch relationship, where finer grains result in improved yield strength. In the present study, Keller's reagent was employed as the etchant to reveal the microstructure, and the optical micrographs were captured at a magnification of 200x. Figure 7 presents the optical micrographs illustrating the evolution of grain morphology in the as-cast nanocomposite samples.

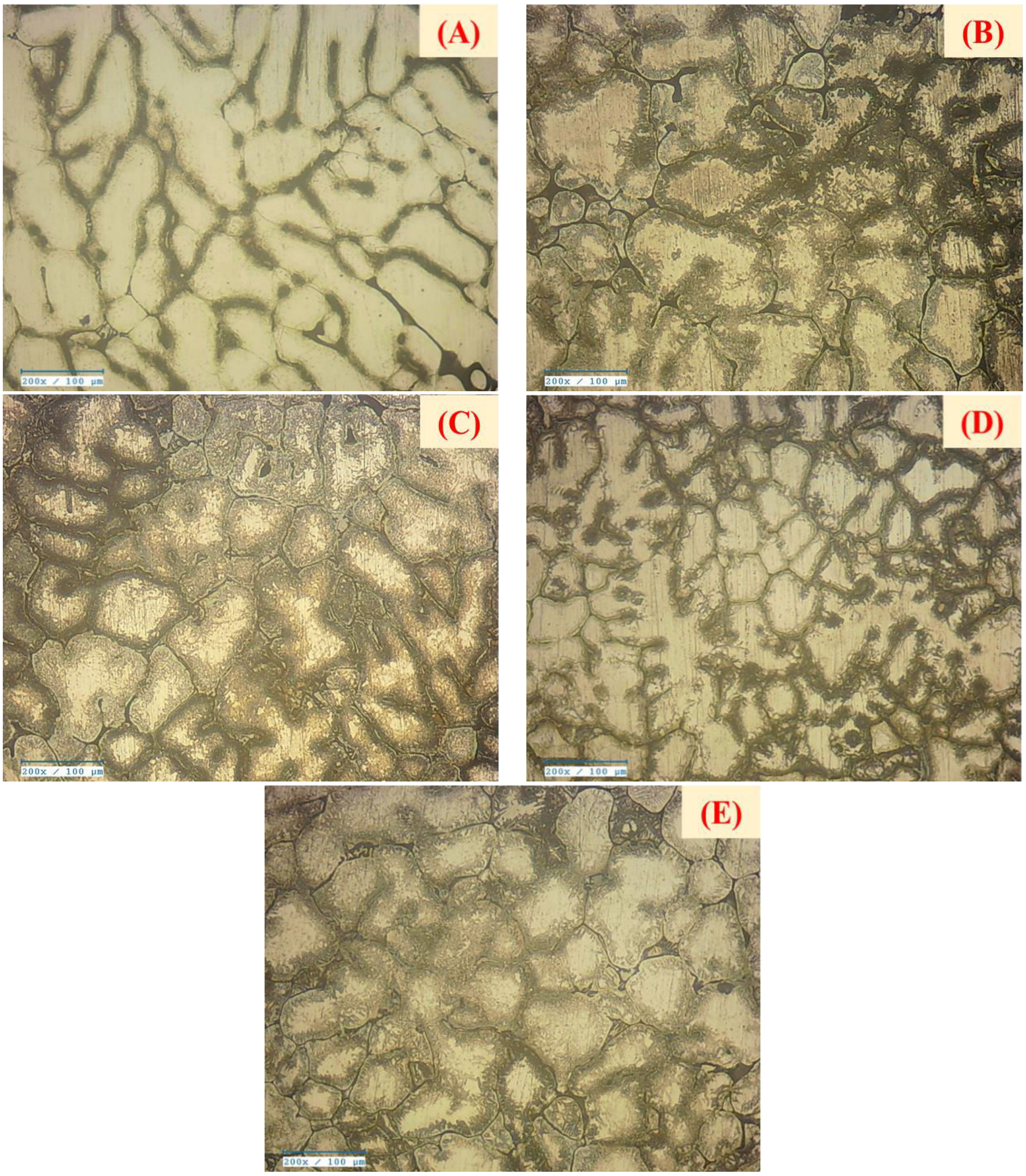

Figure 7: Microstructure of various casted samples

In Figure 7(A), corresponding to the unreinforced matrix alloy, the microstructure is predominantly characterized by elongated columnar grains, accompanied by a limited fraction of equiaxed grains. In contrast, the remaining micrographs exhibit a distinct transformation in grain morphology, where equiaxed grains dominate the microstructure with only a minor presence of columnar features. Notably, Figure 7(D) reveals a fully equiaxed grain structure comprising both fine and comparatively coarser grains, with a complete absence of columnar grains. This progressive transition from columnar to equiaxed grains, along with the refinement in equiaxed grain size, clearly indicates an effective grain refinement mechanism operating within the composite system. It is well established that equiaxed grains contribute more favourably to mechanical performance than columnar grains due to their uniform orientation and isotropic characteristics. Furthermore, finer equiaxed grains enhance mechanical properties more significantly than coarser ones, owing to the increased grain boundary area which impedes dislocation motion. Therefore, both grain size and morphology play a crucial role in governing the mechanical response of the material [7]. Based on the present observations, sample 'D' demonstrates the highest degree of grain refinement. This improvement can be attributed to the Hall-Petch strengthening effect, where reduced grain size leads to enhanced resistance to deformation. Consequently, this sample is anticipated to exhibit superior mechanical properties compared to the others. Additionally, Table 2 provides a quantitative representation of grain size variation across the cast composite samples, offering deeper insight into the relationship between grain refinement and strength enhancement.

Table 2: Variation of grain size in the composite samples

Sample name	Grain size (µm)
A	174
B	128
C	97
D	72
E	86

5. Conclusion

The key findings derived from the combined analysis of mechanical testing and optical microscopy of A357/MWCNTs nanocomposites are summarized as follows.

- A357 aluminum alloy is a suitable matrix for nanocomposites due to its excellent castability and high strength-to-weight ratio.
- The combined use of aluminum carrier powder and mechanical alloying enhanced the dispersion and wettability of MWCNTs within the matrix.
- Mechanical properties, including tensile strength and hardness, improved with the addition of MWCNTs. Optimum mechanical performance was achieved at 1.5 wt.% MWCNTs reinforcement. Further increase in MWCNTs content led to property deterioration due to agglomeration and increased porosity.
- Addition of MWCNTs resulted in significant grain refinement, transforming coarse columnar grains into fine equiaxed structures. Thus, strength enhancement is attributed to grain refinement following the Hall–Petch mechanism.
- Overall, the developed A357/MWCNTs nanocomposite exhibited improved mechanical performance, confirming its potential for advanced structural applications.

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