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Carbon Nanotube-Reinforced Aluminum A357 Nanocomposite by Using Stir-Casting

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Abstract- Aluminum matrix nanocomposites have attracted considerable attention in recent years due to their superior mechanical properties, lightweight nature, and potential for advanced engineering applications. Among various aluminum alloys, A357 is widely used in the automotive, aerospace, and marine industries because of its excellent castability, good corrosion resistance, and favorable strength-to-weight ratio. However, the mechanical performance of unreinforced A357 alloy can be further enhanced through the incorporation of nanoscale reinforcements such as multi-walled carbon nanotubes (MWCNTs). In the present investigation, A357 aluminum alloy reinforced with different weight fractions of MWCNTs was successfully fabricated using the stir casting technique. Stir casting was selected owing to its simplicity, low production cost, and suitability for large-scale manufacturing. The fabricated nanocomposites were evaluated to determine the influence of MWCNT reinforcement on their mechanical properties, including ultimate tensile strength, yield strength, hardness, and ductility. In addition, microstructural characterization was carried out using optical microscopy and scanning electron microscopy (SEM) to examine the dispersion of MWCNTs, grain refinement, and the quality of interfacial bonding between the matrix and reinforcement. The experimental results revealed that the incorporation of MWCNTs significantly enhanced the mechanical performance of the A357 alloy up to an optimum reinforcement level. Maximum improvement was observed at approximately 1.0 wt.% MWCNT, owing to the uniform distribution of nanotubes, effective load transfer, and grain refinement. Further addition of MWCNTs resulted in a slight reduction in mechanical properties because of nanotube agglomeration and increased porosity. The developed A357–MWCNT nanocomposites exhibit improved strength and hardness while maintaining acceptable ductility, making them promising candidates for lightweight structural components in automotive, aerospace, and other high-performance engineering applications.

Keywords— A357, MWCNTs), Aluminum Matrix Nanocomposites, Stir Casting, Tensile Strength, Hardness.

I. INTRODUCTION

The increasing demand for lightweight, high-strength, and durable materials in modern engineering sectors such as aerospace, automotive, marine, and defence has accelerated the development of advanced composite materials. Weight reduction in structural components contributes significantly to improved fuel efficiency, enhanced payload capacity, lower emissions, and better overall performance. Consequently, metal matrix composites (MMCs) have emerged as promising engineering materials because they combine the superior mechanical properties of reinforcements with the excellent processability of metallic matrices [1–3].

Among various matrix materials, aluminium alloys have gained widespread acceptance due to their low density, high specific strength, excellent corrosion resistance, good thermal conductivity, and ease of fabrication. In particular, A357 aluminium alloy, an Al–Si–Mg casting alloy, is extensively used for manufacturing lightweight components such as engine blocks, cylinder heads, suspension arms, aircraft fittings, and structural automotive parts. The alloy exhibits excellent castability, good weldability, and satisfactory mechanical properties. However, its relatively moderate hardness, wear resistance, and load-bearing capacity restrict its application under severe service conditions involving high mechanical stresses and abrasive wear [2,4,5].

To overcome these limitations, researchers have increasingly focused on reinforcing aluminium alloys with nanoscale materials. Among the available nano-reinforcements, Multi-Walled Carbon Nanotubes (MWCNTs) have attracted considerable attention because of their extraordinary mechanical and physical properties. MWCNTs possess an exceptionally high tensile strength (up to 60 GPa), a Young's modulus approaching 1 TPa, low density, excellent thermal conductivity, and outstanding chemical stability. These unique characteristics make them highly effective reinforcements for aluminium matrix nanocomposites [6–10]. When uniformly dispersed within the aluminium matrix, MWCNTs improve hardness, ultimate tensile strength, yield strength, stiffness, wear resistance, and fatigue performance through efficient load transfer, grain refinement, and dislocation strengthening mechanisms [11–14].

Among the various fabrication techniques available for aluminium matrix nanocomposites, stir casting is one of the most practical and economical methods for large-scale production. The process involves melting the aluminium alloy and mechanically stirring the molten metal while introducing the reinforcement particles to achieve a homogeneous distribution. Stir casting offers several advantages, including simple equipment, low manufacturing cost, high productivity, compatibility with conventional foundry practices, and the ability to produce near-net-shape components [15,16]. Nevertheless, the successful fabrication of MWCNT-reinforced aluminium composites remains challenging because of poor wettability between carbon nanotubes and molten aluminium, nanotube agglomeration caused by strong van der Waals forces, non-uniform particle distribution, and porosity formation during casting. Appropriate processing parameters, such as stirring speed, stirring time, preheating of MWCNTs, and controlled addition of reinforcement, are therefore essential to achieve a uniform microstructure and improved mechanical performance [8,13,17].

Several researchers have reported significant improvements in the mechanical behaviour of aluminium alloys reinforced with MWCNTs. Moderate additions of MWCNTs generally increase tensile strength, yield strength, hardness, and wear resistance because of effective load transfer, Orowan strengthening, thermal mismatch strengthening, and grain refinement. However, excessive reinforcement content often results in nanotube clustering and increased porosity, which adversely affect ductility and reduce the overall mechanical properties. Consequently, identifying the optimum reinforcement percentage is an important aspect in the development of high-performance aluminium matrix nanocomposites [18–23].

In the present investigation, A357 aluminium alloy reinforced with different weight percentages (0 wt.%, 0.5 wt.%, 1.0 wt.%, and 1.5 wt.%) of Multi-Walled Carbon Nanotubes (MWCNTs) was fabricated using the stir casting technique. The fabricated nanocomposites were evaluated for their mechanical properties, including ultimate tensile strength, yield strength, hardness, and ductility. Furthermore, optical microscopy and scanning electron microscopy (SEM) were employed to examine the microstructure, dispersion of MWCNTs, grain refinement, and fracture characteristics. The study aims to determine the optimum MWCNT reinforcement level that provides the best combination of mechanical properties while maintaining structural integrity. The findings contribute to the development of lightweight, high-strength aluminium matrix nanocomposites suitable for advanced engineering applications in automotive, aerospace, and defence industries [24–38].

II. METHODOLOGY

The experimental procedure commenced with the selection of A357 aluminium alloy as the matrix material and Multi-Walled Carbon Nanotubes (MWCNTs) as the reinforcement owing to their excellent mechanical and thermal properties. The A357 alloy was melted in an electric resistance furnace at 750–800°C to obtain a homogeneous molten matrix with adequate fluidity. The MWCNTs were preheated before being gradually introduced into the molten alloy, and mechanical stirring was performed to ensure their uniform dispersion throughout the matrix and to minimize agglomeration. The prepared composite melt was then degassed to remove dissolved gases and subsequently poured into a preheated mould, where it was allowed to cool and solidify under controlled conditions. After solidification, the cast specimens were removed from the mould, cleaned, and machined according to standard specimen dimensions for testing. Finally, the fabricated A357–MWCNT nanocomposites were characterized through tensile testing, Brinell hardness testing, optical microscopy, and scanning electron microscopy (SEM) to evaluate their mechanical properties and microstructural characteristics, thereby determining the influence of different MWCNT weight percentages on the overall performance of the composite.

1. Material Selection

A357 Aluminium Alloy (Matrix Material)

A357 aluminium alloy was selected as the matrix material due to its excellent combination of low density, high strength-to-weight ratio, good castability, and superior corrosion resistance. It is an Al–Si–Mg casting alloy containing approximately 6.5–7.5% silicon and 0.4–0.7% magnesium, which provide excellent fluidity during casting and enhance its mechanical properties after solidification. The alloy is widely used in automotive, aerospace, and marine applications for manufacturing lightweight structural components such as engine blocks, suspension parts, aircraft fittings, and wheel hubs. A357 also exhibits good machinability, weldability, and fatigue resistance, making it an ideal base material for developing advanced metal matrix nanocomposites. Furthermore, its compatibility with the stir casting process enables economical and large-scale production of reinforced composites.

Multi-Walled Carbon Nanotubes (MWCNTs) (Reinforcement Material)

Multi-Walled Carbon Nanotubes (MWCNTs) having a purity greater than 99% were selected as the reinforcing material because of their exceptional mechanical, thermal, and physical properties. MWCNTs possess an extremely high tensile strength (up to 60 GPa), a Young's modulus of nearly 1 TPa, low density, excellent thermal conductivity, and outstanding chemical stability. Their high aspect ratio and nanoscale dimensions facilitate efficient load transfer from the aluminium matrix to the reinforcement, thereby improving the strength, hardness, stiffness, and wear resistance of the composite. Additionally, MWCNTs contribute to grain refinement and inhibit dislocation movement, resulting in enhanced mechanical performance. Due to these outstanding characteristics, MWCNTs are considered one of the most effective nano-reinforcements for aluminium matrix composites. However, achieving uniform dispersion of nanotubes is critical, as agglomeration can adversely affect the overall properties of the composite. Therefore, proper mixing and controlled stir-casting parameters were employed to ensure homogeneous distribution of MWCNTs within the A357 aluminium matrix.

2. Stir Casting Process

The A357–MWCNT nanocomposite was fabricated using the stir casting technique because it is a simple, economical, and widely adopted method for producing aluminium matrix composites on a large scale. Initially, the required quantity of A357 aluminium alloy was melted in a graphite crucible using an electric resistance furnace at a temperature of 750–800°C to ensure complete melting and adequate fluidity of the molten metal. Simultaneously, the Multi-Walled Carbon Nanotubes (MWCNTs) were preheated to 250–300°C for approximately 30–45 minutes to remove absorbed moisture, minimize thermal shock during addition, and improve their wettability with the molten aluminium. The preheated MWCNTs were then added gradually into the molten alloy in the desired weight percentages while continuously stirring the melt using a mechanical stirrer at a speed of 300–400 rpm for 10–15 minutes. The stirring action created a stable vortex, which facilitated the uniform dispersion of the nanotubes throughout the aluminium matrix and minimized particle agglomeration. After achieving homogeneous mixing, the molten composite was subjected to a degassing process using a suitable degassing agent to eliminate dissolved hydrogen and other entrapped gases, thereby reducing porosity and improving the quality of the casting. Finally, the degassed molten composite was poured carefully into a preheated mould and allowed to solidify under ambient conditions. The cast specimens were then removed from the mould, cleaned, and machined into standard test specimens for subsequent mechanical testing and microstructural characterization. The optimized stir casting process ensured improved reinforcement distribution, enhanced interfacial bonding, reduced casting defects, and superior mechanical performance of the fabricated A357–MWCNT nanocomposites.

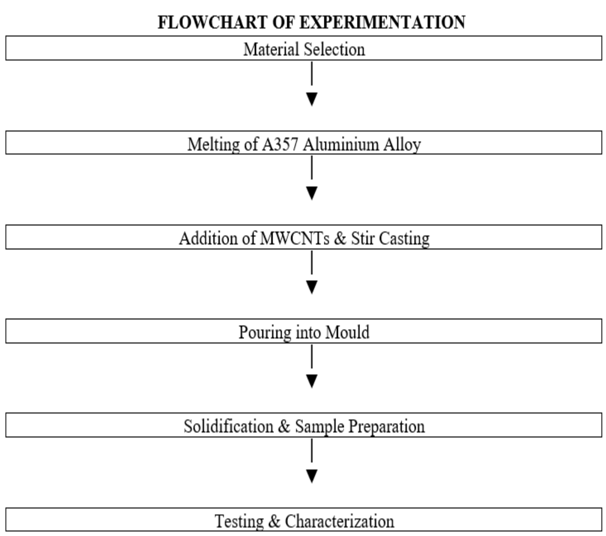

Fig .1 Stir Casting Mechanism

III. SAMPLE PREPARATION AND MECHANICAL TESTING

After solidification, the A357–MWCNT composite castings were removed from the mould and machined into standard test specimens according to the relevant ASTM standards.

The prepared specimens were subjected to mechanical characterization to evaluate the effect of different MWCNT reinforcement percentages on the properties of the composite. Tensile testing was carried out using a Universal Testing Machine (UTM) in accordance with ASTM E8/E8M to determine the ultimate tensile strength, yield strength, and percentage elongation of the fabricated composites. The tensile test provides valuable information regarding the load-bearing capacity, deformation behaviour, and ductility of the material under uniaxial loading. In addition, Brinell hardness testing was performed following ASTM E10 to measure the surface hardness and resistance to plastic deformation of the composite specimens. Three specimens were tested for each reinforcement percentage, and the average values were considered for analysis to improve the reliability and repeatability of the experimental results. The obtained mechanical properties were compared to identify the optimum MWCNT reinforcement level that provided the best combination of strength, hardness, and ductility.

Table 1. Test Methods

Test	Equipment / Method	Measured Properties
Tensile Test	Universal Testing Machine (UTM)	Ultimate Tensile Strength (UTS)
Brinell Hardness Test	Brinell Hardness Tester	Brinell Hardness Number (BHN)

IV. EXPERIMENTAL COMPOSITION

The A357 aluminium alloy was selected as the matrix material, while Multi-Walled Carbon Nanotubes (MWCNTs) were used as the reinforcement. Four composite samples with varying MWCNT weight percentages were fabricated using the stir casting process to investigate the effect of reinforcement on the mechanical properties of the composites. The composition of each experimental sample is presented in Table.

Table 2: Experimental Composition of A357–MWCNT Nanocomposites

Sample ID	Matrix Material	MWCNT Reinforcement (wt.%)
S1	A357 Aluminium Alloy	0.0
S2	A357 Aluminium Alloy	0.5
S3	A357 Aluminium Alloy	1.0
S4	A357 Aluminium Alloy	1.5

V. RESULTS AND DISCUSSION

This section presents the experimental results obtained from the mechanical characterization of A357 aluminium alloy reinforced with different weight percentages of Multi-Walled Carbon Nanotubes (MWCNTs). The fabricated composites containing 0 wt.%, 0.5 wt.%, 1.0 wt.%, and 1.5 wt.% MWCNTs were evaluated through tensile and Brinell hardness tests. The influence of MWCNT reinforcement on the mechanical properties of the A357 alloy is discussed in detail.

1. Tensile Strength Analysis

The ultimate tensile strength (UTS) of the fabricated A357–MWCNT nanocomposites was determined using a Universal Testing Machine (UTM) according to ASTM E8/E8M. The results are presented in Table 3.

Table 3 Ultimate Tensile Strength of A357–MWCNT Nanocomposites

Sample	MWCNT (wt.%)	Ultimate Tensile Strength (MPa)
S1	0.0	180
S2	0.5	235
S3	1.0	260
S4	1.5	241

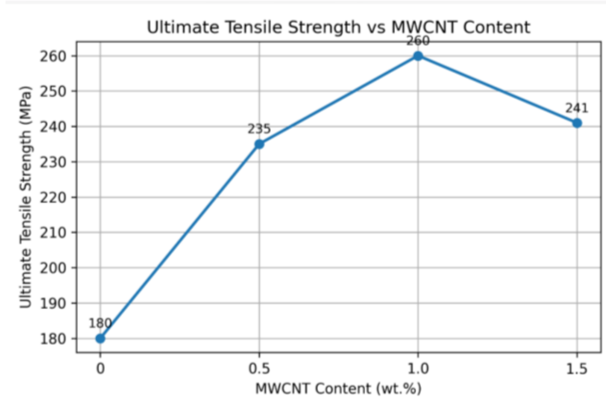

Fig. 2 – Tensile Strength Behavior

The tensile strength of the A357 aluminium alloy increased significantly with the addition of MWCNT reinforcement up to 1.0 wt.%. The unreinforced alloy exhibited an ultimate tensile strength of 180 MPa, whereas the composite reinforced with 0.5 wt.% MWCNTs showed an increase to 235 MPa, representing an improvement of approximately 30.6%. The maximum tensile strength of 260 MPa was obtained for the composite containing 1.0 wt.% MWCNTs, corresponding to an enhancement of 44.4% over the base alloy. This improvement is mainly attributed to the uniform dispersion of MWCNTs within the aluminium matrix, efficient load transfer between the reinforcement and the matrix, grain refinement, and the restriction of dislocation movement during deformation. However, increasing the reinforcement content to 1.5 wt.% resulted in a slight reduction in tensile strength to 241 MPa. This decrease can be attributed to the agglomeration of carbon nanotubes, inadequate wettability, and the formation of porosity, which reduce the effectiveness of reinforcement and create localized stress concentration sites. Nevertheless, the tensile strength at 1.5 wt.% remained considerably higher than that of the unreinforced alloy

2. Brinell Hardness Analysis

The Brinell hardness test was conducted according to ASTM E10 to evaluate the resistance of the fabricated composites to plastic deformation. The average hardness values obtained for different reinforcement percentages are presented in Table 4.

Table 4 Brinell Hardness of A357–MWCNT Nanocomposites\

Sample	MWCNT (wt.%)	Brinell Hardness (BHN)
S1	0.0	68.40
S2	0.5	86.30
S3	1.0	98.80
S4	1.5	94.50

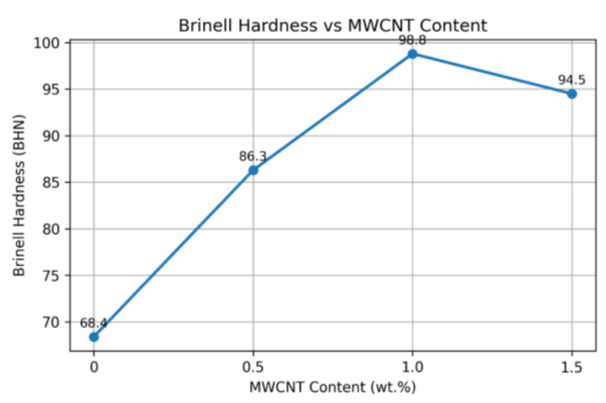

Fig. 3 – Hardness Behavior

The hardness of the A357 aluminium alloy improved progressively with increasing MWCNT content up to 1.0 wt.%. The unreinforced alloy exhibited a hardness of 68.40 BHN, while the addition of 0.5 wt.% MWCNTs increased the hardness to 86.30 BHN, representing an improvement of approximately 26.2%. The highest hardness value of 98.80 BHN was achieved at 1.0 wt.% MWCNTs, corresponding to an increase of approximately 44.4% compared with the unreinforced alloy. The improvement in hardness is attributed to the exceptional stiffness of MWCNTs, effective grain refinement, and the resistance offered by the nanotubes to localized plastic deformation and dislocation movement. When the reinforcement content was increased to 1.5 wt.%, the hardness decreased slightly to 94.50 BHN. This reduction is mainly due to nanotube agglomeration and the increased likelihood of porosity, which adversely affect the uniformity of reinforcement distribution. Despite this slight decline, the hardness remained substantially higher than that of the base A357 alloy, indicating that MWCNT reinforcement effectively enhances the surface hardness of the aluminium matrix.

VI. CONCLUSION

The present work successfully fabricated Multi-Walled Carbon Nanotube (MWCNT)-reinforced A357 aluminium alloy nanocomposites using the stir casting technique with reinforcement contents of 0 wt.%, 0.5 wt.%, 1.0 wt.%, and 1.5 wt.%. Based on the experimental investigation, the following conclusions can be drawn:

- A357 aluminium alloy reinforced with different weight percentages of Multi-Walled Carbon Nanotubes (MWCNTs) was successfully fabricated using the stir casting technique.
- The addition of MWCNTs significantly enhanced the mechanical properties of the A357 alloy compared to the unreinforced material.
- The ultimate tensile strength increased from 180 MPa for the unreinforced alloy to 235 MPa at 0.5 wt.% MWCNT and reached a maximum value of 260 MPa at 1.0 wt.% MWCNT. At 1.5 wt.% MWCNT, the tensile strength decreased slightly to 241 MPa due to reinforcement agglomeration.
- The Brinell hardness improved from 68.40 BHN for the base alloy to 86.30 BHN at 0.5 wt.% MWCNT and reached a maximum of 98.80 BHN at 1.0 wt.% MWCNT. A slight reduction to 94.50 BHN was observed at 1.5 wt.% MWCNT.
- The optimum mechanical performance was obtained at 1.0 wt.% MWCNT, which provided the best combination of tensile strength and hardness.
- The reduction in mechanical properties at 1.5 wt.% MWCNT is attributed to the agglomeration of carbon nanotubes, poor wettability, and increased porosity during the stir casting process.
- The developed A357–MWCNT nanocomposites exhibit improved mechanical performance and have strong potential for automotive, aerospace, and other lightweight structural engineering applications where high strength-to-weight ratio and enhanced hardness are required.

Future Scope

Investigate hybrid nanocomposites by combining MWCNTs with ceramic reinforcements such as SiC, Al_2O_3, TiC, or B_4C.

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