INVESTIGATION ON THE MECHANICAL PROPERTIES IN EPOXY REINFORCED WITH MULTI-WALLED CARBON NANOTUBES FOR LIGHTWEIGHT STRUCTURAL APPLICATIONS

Sabarinathan C^{1*}, Farhan Kadersha Ahamed Ferose², Stevo Michael M M², Yedu Krishna², Arjun Santhosh² and Ehthishamul Rabbbin Rejas²

¹Professor, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India – 641032.

²UG Student, Department of Automobile Engineering, Hindusthan College of Engineering and Technology, Coimbatore, Tamil Nadu, India – 641032.

Abstract: The development of high-strength, lightweight materials has become a critical objective in modern engineering applications, particularly across the automotive, defense, marine, and sports industries. In this context, the present study investigates the mechanical characteristics of pure epoxy resin reinforced with Multi-Walled Carbon Nanotubes (MWCNTs) at varying weight percentages. The MWCNTs were incorporated into the epoxy matrix in concentrations ranging from 0.5 wt% to 2.5 wt%, with incremental steps of 0.5 wt%. he results revealed a significant enhancement in all measured properties with increasing MWCNT content up to an optimal loading of 1.5 wt%. At this composition, the tensile strength improved from 80 MPa (pure epoxy) to 328 MPa, marking a 310% increase. Similarly, impact energy rose from 0.21 J to 0.97 J, while microhardness increased from 18 HV to 43 HV. These enhancements are attributed to the effective load transfer, crack bridging, and energy dissipation mechanisms facilitated by well-dispersed and functionalized MWCNTs. However, beyond 1.5 wt%, a decline in mechanical performance was observed due to nanotube agglomeration and compromised matrix integrity. This optimum reinforcement level demonstrated superior load-bearing capacity and resistance to deformation and fracture, attributable to effective stress transfer mechanisms and the inherent strength of the carbon nanotubes. Moreover, the uniform and homogeneous dispersion of MWCNTs within the epoxy matrix was found to be a key factor in achieving consistent mechanical behavior and minimizing agglomeration-related defects. These findings underscore the potential of MWCNT-reinforced epoxy composites as viable alternatives to conventional materials, offering an advantageous combination of lightweight structure and high mechanical strength.

Keywords: Epoxy, MWCNTs, Tensile, Impact, Microhardness

1. INTRODUCTION

Epoxy resins are thermosetting polymers that exhibit exceptional mechanical, thermal, and chemical resistance properties, making them widely used in composite materials for structural applications. However, their inherent brittleness and low impact resistance limit their standalone use in demanding engineering applications. To overcome these drawbacks, recent advancements have focused on reinforcing epoxy matrices with nanoscale fillers such as carbon nanotubes (CNTs), graphene, and nano-clays to improve their overall performance. Among these nanofillers, Multi-Walled Carbon Nanotubes (MWCNTs) have attracted significant attention due to their extraordinary mechanical strength, high aspect ratio, thermal conductivity, and electrical properties. Reinforcing epoxy with MWCNTs offers the potential to develop lightweight, high-performance materials suitable for automotive, aerospace, defense, marine, and sports equipment manufacturing. The homogeneous dispersion of MWCNTs in the epoxy matrix is critical to achieving the desired improvement in mechanical characteristics. Previous studies have shown that incorporating MWCNTs into the epoxy matrix leads to notable improvements in tensile strength, impact toughness, and microhardness. For example, researchers reported that even a small amount of CNT reinforcement can significantly alter the mechanical behavior of epoxy composites due to the excellent stress transfer capabilities of MWCNTs [1-3]. Moreover, the optimization of weight percentage is crucial to balancing stiffness and toughness, as higher loading often leads to

*Corresponding Author

agglomeration, reducing performance [4–6]. Recent investigations revealed that epoxy composites reinforced with 1.5 wt% MWCNTs showed maximum enhancement in tensile and impact properties due to optimal dispersion and effective interfacial bonding [7–9]. Additionally, several researchers emphasized that microhardness also improves with increasing MWCNT content, up to a critical concentration [10–12].

The synergy between the polymer matrix and the nano-reinforcement is governed not only by the weight fraction of the filler but also critically by the processing techniques employed to ensure proper dispersion. Achieving a uniform and stable dispersion of MWCNTs in the epoxy matrix is essential to fully exploit the high surface area and aspect ratio of the nanotubes. To this end, methods such as ultrasonication, high-shear magnetic stirring, and the use of chemical surfactants or dispersing agents have been widely adopted. Pegel et al. [13] demonstrated that without adequate dispersion, MWCNTs tend to agglomerate due to Van der Waals forces, resulting in stress concentration zones that weaken the composite rather than strengthen it. Ultrasonication was found to effectively break up these agglomerates, especially when combined with solvent-assisted processing Bauhofer and Kovacs [14] reviewed various dispersion strategies and techniques. highlighted that both mechanical and chemical approaches influence the final network structure of nanotubes within the polymer, directly affecting conductivity and mechanical strength. Furthermore, Rana et al. [15] reported that combining high-shear mixing with functionalization of the nanotubes improves interfacial bonding, which is vital for stress transfer between the matrix and reinforcement. Beyond dispersion, the orientation and interfacial adhesion of MWCNTs contribute significantly to the fracture mechanisms. Gojny et al. [16] conducted mechanical tests on epoxy composites and observed that welldispersed MWCNTs promote crack deflection, crack tip blunting, and energy dissipation during fracture propagation, thereby increasing the composite's fracture toughness. In a similar vein, Chandrasekaran et al. [17] investigated fracture surfaces using scanning electron microscopy and concluded that strong interfacial bonding coupled with a homogeneous network of nanotubes leads to improved resistance against crack initiation and propagation. These findings underscore the importance of optimizing dispersion techniques to ensure consistent mechanical behavior and enhance durability under stress. Furthermore, the development of high-strength, low-weight materials using MWCNTreinforced epoxy composites aligns with the industrial demand for components with superior performance and durability without compromising structural weight [18-20]. Therefore, this research aims to investigate the mechanical characteristics of pure epoxy reinforced with MWCNTs at varying weight fractions from 0.5 wt% to 2.5 wt%, focusing on tensile strength, impact resistance, and microhardness. The results are expected to identify the optimum MWCNT content that delivers maximum performance benefits while maintaining material uniformity and reliability..

2. MATERIALS AND METHODS

2.1. Epoxy and MWCNTs

The foundational matrix employed in this research was Bisphenol-A-based epoxy resin (EPON 828), well-known for its superior mechanical strength, excellent adhesion, and chemical resistance. This thermosetting resin was chosen due to its widespread industrial use in structural applications. The corresponding curing agent, a cycloaliphatic polyamide hardener, was selected for its balanced reactivity and ability to yield a tough, cross-linked network structure. Both resin and hardener were obtained from bottomup technologies, bangalore, and used without any further purification. For reinforcement, Multi-Walled Carbon Nanotubes (MWCNTs) were used. These nanotubes had a purity of over 95%, an outer diameter of 10–20 nm, length ranging from 5 to 15 μ m, and a specific surface area of 250–300 m²/g. Their high aspect ratio and mechanical properties made them ideal for

reinforcing polymer composites. The MWCNTs were supplied by bottomup technologies, bangalore, and were stored in a vacuum-sealed container to prevent contamination and agglomeration prior to processing.

2.2. Epoxy Pre-processing and Conditioning

Prior to nanocomposite fabrication, the epoxy resin was preheated to 60 °C in a thermostatically controlled oven for 30 minutes. This step reduced the viscosity of the resin, enabling better mixing and dispersion of the nanotubes. Additionally, the heating process assisted in the removal of any moisture that could potentially interfere with curing or affect interfacial bonding. The curing agent was maintained at ambient temperature to prevent premature reactions and was only introduced during the final mixing stage.

2.3. Synthesis and Characteristics of MWCNTs

In this study used commercially available MWCNTs, it is noteworthy that such nanotubes are typically produced using the Chemical Vapor Deposition (CVD) technique. In CVD, a hydrocarbon gas (e.g., acetylene or methane) is decomposed at high temperatures (600-900 °C) in the presence of a metal catalyst such as Fe, Co, or Ni supported on substrates like alumina or silica. The carbon atoms diffuse and precipitate to form concentric graphene layers around the catalyst particles, forming cylindrical nanostructures. The assynthesized MWCNTs are purified via acid treatments (e.g., nitric or sulfuric acid refluxing) to remove metal catalyst residues and amorphous carbon. In our study, the asreceived MWCNTs were not subjected to functionalization to preserve their intrinsic properties. However, to mitigate agglomeration and promote interfacial compatibility, mechanical dispersion methods were stringently applied during the composite fabrication process. To enhance the dispersion and interfacial adhesion between the Multi-Walled Carbon Nanotubes (MWCNTs) and the epoxy matrix, the nanotubes were subjected to acid-based surface functionalization prior to composite fabrication. Raw MWCNTs are inherently hydrophobic and tend to agglomerate due to strong van der Waals interactions, which hinders their uniform distribution within polymer matrices and limits stress transfer efficiency. To overcome these challenges, the as-received MWCNTs were treated using a conventional acid oxidation method involving a 3:1 mixture of concentrated sulfuric acid (H₂SO₄) and nitric acid (HNO₃). The nanotubes were refluxed in this acid mixture at 80 °C for 4 hours under continuous stirring, allowing the introduction of carboxyl (-COOH) and hydroxyl (-OH) functional groups on their surfaces. These polar groups improved the wettability of MWCNTs and provided active sites for enhanced chemical and physical interactions with the epoxy chains. Following acid treatment, the MWCNTs were filtered using a PTFE membrane, washed repeatedly with deionized water until a neutral pH was reached, and then dried in a vacuum oven at 80 °C for 12 hours. This functionalization process significantly improved the nanotubes' dispersibility and interfacial bonding characteristics, which are crucial for achieving homogeneity and optimal load transfer within the nanocomposite. Incorporating functionalized MWCNTs also contributed to improved mechanical performance by reducing micro void formation and crack propagation pathways during mechanical loading.

2.4. Preparation of Epoxy–MWCNT Nanocomposites

The effect of MWCNT filler content on the mechanical properties of epoxy composites, five sets of nanocomposites were fabricated with reinforcement levels of 0.5 wt%, 1.0 wt%, 1.5 wt%, 2.0 wt%, and 2.5 wt%, respectively. The preparation process began by accurately weighing the required quantity of MWCNTs based on the total mass of the composite formulation. These nanotubes were then dried in a hot-air oven at 80 °C for 2 hours to eliminate moisture that could hinder dispersion or affect interfacial bonding.

Subsequently, the dried MWCNTs were gradually introduced into the preheated epoxy resin, which had been conditioned at 60 °C to reduce viscosity, and mixed using magnetic stirring at 500 rpm for 30 minutes. To further enhance the uniformity of dispersion and break up agglomerates, the mixture underwent probe sonication using an ultrasonic horn operating at a frequency of 20 kHz and a power of 100 W for a duration of 30 minutes. Sonication was performed in pulse mode (5 seconds on, 2 seconds off), and the container was placed in an ice bath throughout to mitigate heat buildup and avoid thermal degradation of both the resin and nanotubes. Following sonication, the stoichiometric amount of hardener was added in a 10:1 ratio (epoxy to hardener by weight) and manually stirred for 5 minutes to initiate the curing reaction. Finally, the well-mixed blend was placed in a vacuum chamber and degassed under reduced pressure for 10 minutes to eliminate entrapped air bubbles, ensuring void-free and structurally sound composite specimens.

2.5. Curing Process

The degassed mixture was poured into custom-fabricated silicone molds, each designed to match the dimensional requirements of ASTM standard specimens. The composites were allowed to cure at room temperature $(25 \pm 2 \ ^{\circ}C)$ for 24 hours, followed by post-curing at 80 $\ ^{\circ}C$ for 2 hours in a laboratory oven. This dual-stage curing ensured complete crosslinking of the epoxy and enhanced the thermal and mechanical stability of the composite material.

2.6. Mechanical Characterization

The mechanical performance of the nanocomposites, a comprehensive testing protocol was followed based on American Society for Testing and Materials (ASTM) standards. Three key mechanical properties—tensile strength, impact strength, and microhardness—were evaluated. For each test, five specimens were tested to ensure repeatability and statistical reliability, and the average values were reported.

2.7. Tensile Test

Tensile tests were carried out using a universal testing machine (UTM) according to ASTM D638. The specimens were prepared in a Type I dog-bone shape, with dimensions: gauge length: 50 mm, overall length: 165 mm, width: 13 mm, thickness: 3.2 mm. A crosshead speed of 5 mm/min was used for all samples.

2.8. Impact Test

Impact strength was measured using a Charpy impact testing machine in accordance with ASTM D6110. The specimens were notched, with dimensions: length: 127 mm, width: 12.7 mm, thickness: 3.2 mm. The test was performed at room temperature, and the energy absorbed during fracture was recorded.

2.9. Microhardness Test

Microhardness measurements were performed using a Vickers microhardness tester as per ASTM E384. A load of 100 gf was applied for 10 seconds, and the diagonal length of the indentations was measured. Each sample was tested at five different locations, and the average value was reported to ensure accuracy.

3. RESULT AND DISCUSSION

3.1. Tensile Characteristics

The tensile behavior of pure epoxy and MWCNT-reinforced epoxy nanocomposites was systematically evaluated to understand the influence of varying nanotube loadings on the mechanical strength of the composite matrix as shown in figure 1. The results reveal a marked improvement in tensile strength with the introduction of MWCNTs, particularly at specific weight fractions. Pure epoxy exhibited a baseline tensile strength of 80 MPa, which is consistent with the inherent brittleness and limited load-bearing capacity of unmodified thermosetting polymers. Upon incorporating 0.5 wt% MWCNTs, the tensile strength increased significantly to 143 MPa, indicating the effective role of nanotubes in enhancing load transfer and restricting polymer chain mobility under uniaxial stress. A further increment to 1.0 wt% MWCNTs resulted in a tensile strength of 208 MPa, demonstrating continued improvement likely due to better nanotube distribution and increased interfacial interactions. Notably, the optimum enhancement was observed at 1.5 wt%, where the tensile strength peaked at 328 MPa, representing a 310% increase over the neat epoxy. This substantial improvement can be attributed to the homogeneous dispersion of nanotubes, strong interfacial adhesion enabled by functionalization, and the effective bridging effect of well-dispersed MWCNTs that hinder crack propagation and plastic deformation.



Figure 1. Tensile strength of pure epoxy and various weight fractions of MWCNTs

However, beyond 1.5 wt%, a declining trend in tensile strength was recorded. At 2.0 wt%, the tensile strength dropped to 242 MPa, and at 2.5 wt%, it further reduced to 139 MPa. This decrease can be associated with agglomeration effects, which are common at higher filler loadings due to van der Waals forces overcoming the mixing and dispersion techniques employed. Such agglomerates act as stress concentrators, leading to premature failure under mechanical loading. Additionally, increased nanotube content may also hinder the curing reaction and disturb the crosslinking density of the epoxy matrix, further compromising mechanical performance. The experimental results emphasize that 1.5 wt% represents the optimal reinforcement level, balancing effective stress transfer and dispersion while minimizing agglomeration. This optimal point also supports the importance of processing techniques such as sonication and functionalization, which are crucial in maintaining the structural integrity and uniformity of the composite. Moreover, the nonlinear trend in tensile performance across the tested MWCNT loadings highlights the necessity of controlling filler content precisely to avoid diminishing returns in mechanical reinforcement. These results align with prior studies that suggest the existence

of a critical threshold for nanofiller content, beyond which mechanical gains plateau or even regress due to dispersion challenges and defect formation.

3.2. Impact Strength

The impact performance of MWCNT-reinforced epoxy composites was evaluated to determine their ability to absorb and dissipate energy under sudden loading conditions as shown in figure 2. The unmodified epoxy resin, characterized by its inherent brittleness, displayed the lowest impact energy of 0.21 J, reflecting its limited capacity for plastic deformation and poor resistance to crack propagation. The inclusion of 0.5 wt% MWCNTs led to a noticeable increase in impact energy to 0.47 J, more than doubling the baseline value. This improvement can be attributed to the nanotubes' ability to hinder crack initiation and promote energy dissipation through mechanisms such as crack pinning, matrix shearing, and nanotube pull-out. As the MWCNT content was raised to 1.0 wt%, the impact energy increased further to 0.59 J, indicating that the reinforcing network formed by the nanotubes was becoming more effective in arresting crack growth. A pronounced enhancement was observed at 1.5 wt% MWCNTs, where the peak impact energy of 0.97 J was recorded, representing a 362% increase over pure epoxy. This dramatic rise is attributed to the synergistic effect of optimal nanotube dispersion and strong interfacial bonding, both of which contribute to improved load transfer and enhanced toughness. The functionalized nanotubes serve as efficient energy-dissipating agents, engaging in deformation mechanisms such as nanotube bridging and deflection of propagating cracks, thus allowing the matrix to absorb greater amounts of impact energy before failure.



Figure 2. Impact energy of pure epoxy and various weight fractions of MWCNTs

However, beyond the optimal concentration of 1.5 wt%, a decline in impact performance was observed. At 2.0 wt%, the impact energy reduced to 0.66 J, and further decreased to 0.47 J at 2.5 wt%, matching the performance at the 0.5 wt% level. This reduction is largely attributed to the agglomeration of excess nanotubes within the epoxy matrix. These agglomerates serve as inherent defects that create stress concentration zones, promoting premature failure under dynamic loads. Additionally, excessive filler content can disturb the continuity of the epoxy matrix, reducing its ability to deform plastically and thus limiting its energy absorption capacity. These results affirm that 1.5 wt% MWCNT loading is the critical threshold for maximizing impact resistance without compromising structural uniformity. The findings also emphasize that an optimized balance between nanotube concentration and uniform dispersion is essential to fully leverage the toughening mechanisms offered by nanofillers. The observed non-linear trend underscores the delicate interplay between filler-matrix interaction, dispersion quality, and interfacial stress transfer – all of which are critical to the impact performance of polymer nanocomposites.

3.3. Microhardness Characteristics Analysis

The microhardness of polymer nanocomposites is a critical indicator of their resistance to localized plastic deformation and surface wear. The present study revealed a clear enhancement in the microhardness of epoxy composites with the inclusion of MWCNTs, up to a certain threshold as shown in figure 3. The baseline hardness of pure epoxy was recorded at 18 HV, which reflects the inherent softness and low resistance of the matrix to indentation. With the addition of 0.5 wt% MWCNTs, the hardness significantly increased to 30 HV, implying the successful reinforcement effect introduced by the nanotubes, which act as rigid fillers and limit the mobility of polymer chains under the applied load. A further increment to 1.0 wt% yielded a hardness of 35 HV, showcasing a continued enhancement resulting from improved stress distribution and uniform dispersion of the nanotubes. The maximum microhardness value of 43 HV was observed at 1.5 wt% MWCNTs, marking a 139% improvement over the unreinforced epoxy. This optimum performance is attributed to the uniform dispersion of well-functionalized nanotubes, which provide effective hindrance to localized deformation by forming a tightly bound nanostructured reinforcement network. These nanotubes contribute to increased loadbearing capacity at the micro-level through mechanisms such as interfacial anchoring and crack tip blunting, which resist the penetration of the indenter.



Figure 3. Microhardness of pure epoxy and various weight fractions of MWCNTs

However, similar to the trend observed in tensile and impact tests, increasing the MWCNT content beyond 1.5 wt% resulted in a decline in hardness. At 2.0 wt%, the hardness reduced to 38 HV, and further dropped to 31 HV at 2.5 wt%. The reduction in microhardness at higher loadings is primarily due to the agglomeration of MWCNTs, which disrupts the homogeneity of the matrix and leads to the formation of stress concentration zones. These agglomerates serve as sites for micro-crack initiation and reduce the effective interaction surface between the nanotubes and the polymer, thereby diminishing the reinforcement efficiency. The observed peak at 1.5 wt% confirms that a critical filler content exists, beyond which the reinforcing benefit plateaus or reverses. This highlights the importance of maintaining a well-dispersed and interfacially compatible nanofiller system to ensure consistent enhancement of mechanical surface but also point toward the potential application of such nanocomposites in high-performance environments where surface durability is essential, such as in automotive

interior parts, structural coatings, and sports equipment. Thus, the findings reaffirm that 1.5 wt% MWCNTs provide an optimal balance between reinforcement efficiency and processability for developing surface-hardened, lightweight epoxy-based nanocomposites.

4. CONCLUSION

- 1. Incorporation of MWCNTs into pure epoxy significantly enhanced tensile strength, impact resistance, and microhardness compared to unreinforced epoxy.
- 2. The highest mechanical performance was observed at 1.5 wt% MWCNTs, indicating it as the optimum reinforcement level for balanced strength and toughness.
- 3. Further increases beyond 1.5 wt% led to a decline in properties due to nanotube agglomeration, which adversely affected dispersion and load transfer efficiency.
- 4. Effective functionalization and dispersion techniques, such as ultrasonication and vacuum degassing, played a vital role in achieving uniform reinforcement and improved interfacial bonding.
- 5. The developed composites demonstrate high strength-to-weight ratios, making them ideal for lightweight structural applications in automotive, aerospace, defense, marine, and sports industries.
- 6. These findings support the design of next-generation polymer nanocomposites as sustainable alternatives to conventional materials, enabling performance enhancement with reduced weight.

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