Combined Actions of Graphene and Carbon Nanotube on Energy Absorption and Stress–Strain Behaviour of Aluminium Alloy Composites

S Vinoth Kumar1, S Baskaran2, S Karthikeyan3,a), S Surrya Prakash DilliBabu4, S Kalaiarasan5, S Dineshkumar6, C Manivel7, A Thanikasalam8, Manzoore Elahi M. Soudagar9

1Department of Mechanical Engineering, Vel Tech Multi Tech Dr.RangarajanDr.Sakunthala Engineering College, Avadi, Chennai, 600062, Tamil Nadu, India.

2 Department of Mechatronics Engineering, Rathinam Technical Campus, Coimbatore Tamilnadu 641021, India.

3Department of Mechanical Engineering, Erode Sengunthar Engineering College, Thuduppathi, 638057, Tamil Nadu, India.

4Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, Chennai,600062, Tamil Nadu, India

5 Department of Chemistry, Sona College of Technology, Salem, 636005, Tamil Nadu, India.

6 Department of Mechanical Engineering, Adithya Institute of Technology, Coimbatore , 641107, Tamil Nadu, India

7 Department of Mechanical Engineering, NPR College of Engineering and Technology, Natham, Dindigul, 624401, Tamil Nadu, India.

8 Department of Marine Engineering Academy of Maritime Education and Training (AMET) Deemed to be University 135, East Coast Road, Kanathur, Chennai – 603112, India.

9Department of Mechanical Engineering and University Centre for Research & Development, Chandigarh University, Mohali-140413, Punjab, India

**Corresponding author:** a)[karthiksamynathan@gmail.com](mailto:karthiksamynathan@gmail.com)

**Abstract.** This study investigates the synergistic impact of hybrid nanofillers on the mechanical and energy absorption properties of AA2024 aluminium alloy composites and five composite samples were created via ultrasonic assisted stir casting with a fixed graphene loading of 0.5 wt% and gradually increasing CNT content (0 to 1.5 wt%). Due to improved load transfer mechanisms and homogeneous nanoparticle dispersion, the combination of graphene and carbon nanotubes greatly increased Vickers hardness, stress strain response and energy absorption capacity. The hybrid system outperformed the unreinforced matrix in terms of impact resilience and strain hardening. These findings highlight the material's potential for lightweight structural uses, especially in bicycle frames, where improved ductility, a high strength to weight ratio and crash energy dissipation are crucial design requirements.

# Introduction

Aluminium alloy AA2024 is a high performance material widely utilized in the aerospace and automotive industries due to its remarkable strength to weight ratio excellent fatigue resistance and corrosion resistance. In dynamic load-bearing applications like bicycle frames, there is an ongoing necessity to augment its energy absorption capacity, fracture toughness, and impact resistance. The mixing of carbon based nano reinforcements specifically graphene nanoplatelets and carbon nanotubes has shown some potential in enhancing the mechanical properties of metallic matrices [1-5]. Graphene provides exceptional stiffness and a specific surface area, enhancing load transmission and grain refinement while CNTs deliver remarkable tensile strength, ductility and crack bridging properties and this study examines the synergistic strengthening processes resulting from the incorporation of both nanofillers into the AA2024 matrix, produced via ultrasonic assisted stir casting a method recognised for enhancing uniform nanoparticle dispersion and matrix filler adhesion and aim is to improve both the static and dynamic characteristics that supports the creation of lightweight, robust and crash resistant structural elements like bicycle frames [6-9].

Researchers investigated the incorporation of graphene nanoplatelets into 7075 T6 aluminium hybrid fibre laminated composites and discovered gains in mechanical strength and delamination resistance [10-11]. It was explored AA2024 hybrid composites containing carbon nanotubes and silicon nanoparticles which exhibit better tribological and microstructural properties. They utilized powder metallurgy for creating multi walled carbon nanotubes with Al Cu Mg T351 alloy and had significant improvements in fracture toughness and tensile strength [12-14]. It was found that high velocity impacts on graphene reinforced aluminium epoxy composite plates increased damage resistance and energy absorption whereas it was found that Al Graphene CNT hybrids improved hardness and wear performance, confirming the effect of both reinforcements [15-20]

They reported Ni-coated CNTs in 2024 aluminium, which improved interfacial adhesion and mechanical and corrosion performance and replicated their findings on elemental homogeneity and improved load bearing capacity in AA2024 hybrid composites [21-23]. It was enhanced the wear and frictional properties of Al6082 T6 GNP TiB₂ composites using multi criteria decision making, demonstrating favourable tribological performance [24-25]. They provided a comprehensive analysis of recent advancements and prospective problems in graphene-reinforced metal matrix nanocomposites, addressing issues related to uniform dispersion and interfacial integrity [26-28]. The wear resistance and tensile properties of Al6061 reinforced with GNPs by stir casting, revealing a low wear rate and homogenous microstructure. Lin et al.[11] found that co-reinforcing TiC and graphene in Al2024 improved tribological synergy through greater grain refinement and interfacial friction management [29-31]. They conducted a thorough evaluation of several nanoparticles including CNT and graphene concluding that processing techniques and dispersion strategies are important for optimizing mechanical and wear properties [32-33].

# Materials and Methods

## Materials

Aluminium alloy AA2024 was selected as the base matrix owing to its high strength, corrosion resistance, and widespread use in structural applications. As reinforcements, graphene nanoplatelets and multi-walled carbon nanotubes (MWCNTs)—with an average length of approximately 10 µm were employed due to their exceptional mechanical properties and synergistic strengthening potential. The matrix alloy was melted at 750 °C in a graphite crucible under a controlled argon atmosphere to inhibit oxidation. Once fully molten the pretreated reinforcements were gradually added. Concurrent mechanical stirring at 500 rpm for 10 minutes and ultrasonic agitation via a submerged horn were executed to enhance dispersion, minimise clustering and attain a uniform distribution of nanofillers inside the molten matrix [34-36]. The molten material was then placed into a heated steel mould and made to harden under ambient conditions.

## Composite Formulations

**TABLE 1.** Mechanical Composite Formulations Table

|  |  |
| --- | --- |
| **Sample ID** | **Composition** |
| Sample 1 | AA2024 (Unreinforced) |
| Sample 2 | AA2024 + 0.5 wt% Graphene |
| Sample 3 | AA2024 + 0.5 wt% Graphene + 0.5 wt% CNT |
| Sample 4 | AA2024 + 0.5 wt% Graphene + 1 wt% CNT |
| Sample 5 | AA2024 + 0.5 wt% Graphene + 1.5 wt% CNT |

Standard Vickers hardness tests were performed with a 100 g load. Tensile testing was conducted per ASTM E8, and stress-strain data were used to calculate energy absorption (area under the curve).

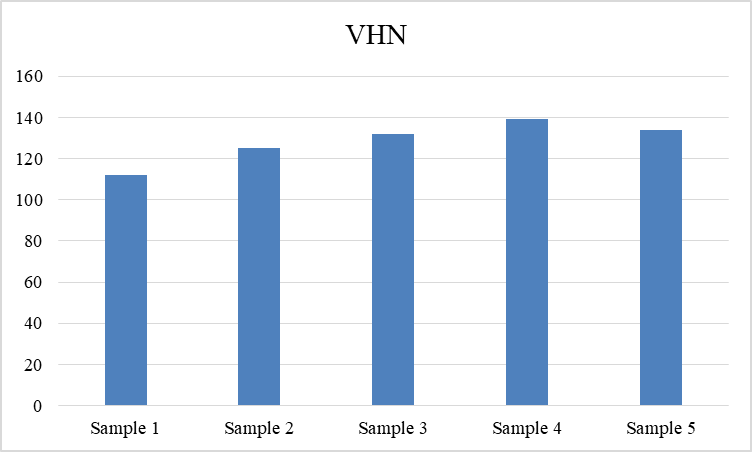
# Results and Discussion

## Vickers Hardness Number (VHN)

The Vickers hardness of AA2024 composites enhanced when graphene and CNTs were added. The base alloy (Sample 1) exhibited a hardness of 112 VHN which rose to 125 VHN upon the addition of 0.5 wt% graphene (Sample 2). Hybrid reinforcement in Sample 3 and Sample 4 (containing 0.5 and 1 wt% CNT, respectively) further increased hardness to 132 and 139 VHN. Sample 4 exhibited the greatest hardness owing to optimum dispersion and reinforcement synergy. Sample 5 (1.5 wt% CNT) experienced a minor decrease to 134 VHN due to CNT clumping diminishing the strengthening effect [37-39].

**TABLE 2.** Vickers Hardness Number (VHN)

|  |  |
| --- | --- |
| **Sample** | **VHN** |
| Sample 1 | 112 |
| Sample 2 | 125 |
| Sample 3 | 132 |
| Sample 4 | 139 |
| Sample 5 | 134 |



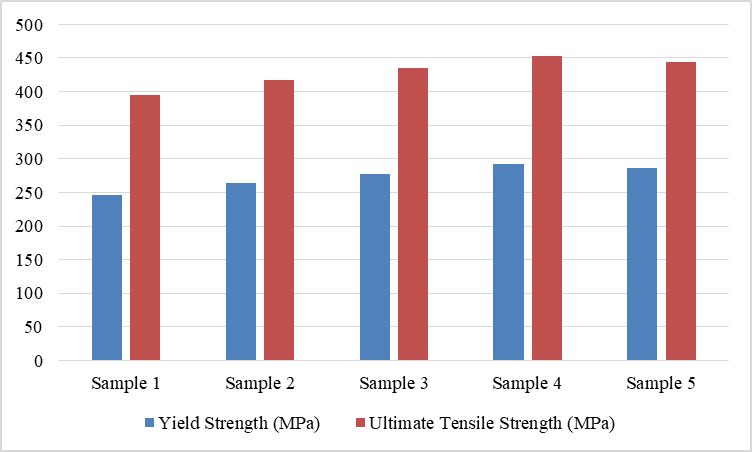
**Figure 1.**Vickers Hardness Number (VHN)

## Tensile Properties and Stress–Strain Behaviour

**TABLE 3.** Energy Absorption

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Yield Strength (MPa)** | **Ultimate Tensile Strength (MPa)** | **Elongation (%)** |
| Sample 1 | 246 | 395 | 12.3 |
| Sample 2 | 264 | 418 | 11.7 |
| Sample 3 | 278 | 435 | 10.4 |
| Sample 4 | 293 | 453 | 9.6 |
| Sample 5 | 286 | 444 | 9.1 |

Due to the improvement in tensile properties Sample 4 shows the maximum yield of 293 MPa and ultimate tensile strength of 453 MPa as a result of the adding graphene with carbon nanotubes in AA2024. Due to their improved interfacial bonding and effective load transfer these hybrid fillers are thought to be the cause of these advantages. Elongation decreased from 12.3% (Sample 1) to 9.1% (Sample 5) indicating a slight decrease in ductility among reinforced samples [40-42]. This resulted from likely CNT clumping at greater concentrations and the hardening effect of nanoparticles. The ductility decreased the most in Sample 1 and the least in Sample 5.

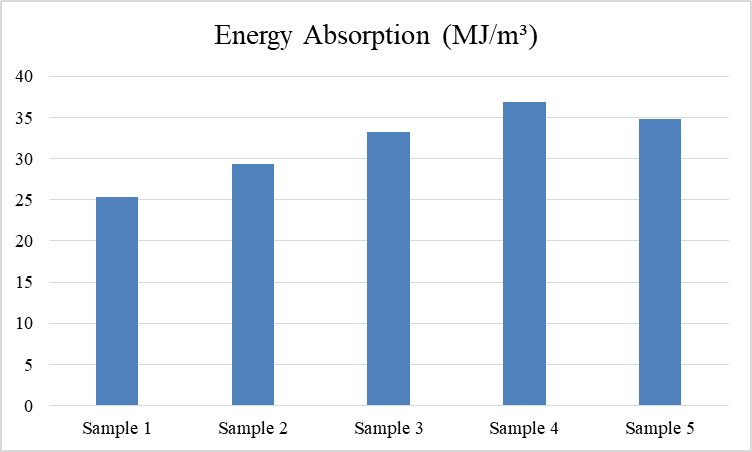


**Figure 2.** Yield Strength (MPa)&Ultimate Tensile Strength (MPa)

## Energy Absorption

**TABLE 4.** Energy Absorption

|  |  |
| --- | --- |
| **Sample** | **Energy Absorption (MJ/m³)** |
| Sample 1 | 25.3 |
| Sample 2 | 29.4 |
| Sample 3 | 33.2 |
| Sample 4 | 36.9 |
| Sample 5 | 34.8 |



**Figure 3.**Energy Absorption

The stress strain behaviour of composites based evaluation on AA2024 was carried out under uniaxial tensile loading with the primary emphasis being placed on energy absorption as a measure of resistance to stress. The area under the stress-strain curves was used to determine energy absorption, which is a reflection of the material's capacity to endure impact and deformation [43-45]. As can be seen in Table 4 and Figure 3, the amount of energy absorbed rose as the reinforcement content increased, reaching its highest point at Sample 4 (36.9 MJ/m3). At a weight percentage of 0.5 wt% and 1 wt% respectively graphene and carbon nanotubes have the best possible synergy. There was a minor decrease in Sample 5 which indicates that an excessive amount of CNTs may have caused agglomeration which reduces deformability [46-47].

Sample 4 demonstrated the highest energy absorption capacity. This reflects an optimal balance of strength and deformability achieved through 0.5 wt% graphene and 1 wt% CNT content.

# Application in Automotive Interior Trims

The created hybrid nanocomposites based on AA2024 show great promise for high performance structural applications, especially in areas where mechanical durability, low weight and high energy absorption are critical including the bicycle frames and car interior trims. With a Vickers hardness of 139, tensile strength of 453 MPa and energy absorption of 36.9 MJ/m³ in Sample 4 which contained 0.5 weight percent graphene and 1 weight percent carbon nanotube, demonstrated the most balanced and excellent performance. These improvements show better resistance to plastic deformation, better matrix reinforcement bonding and efficient load transfer. For components subjected to frequent dynamic and impact stress such as in cycling and automotive settings, these qualities are crucial. The higher surface hardness adds to longer service life and less maintenance in addition to improving wear resistance confirming the appropriateness of these nanocomposites for cutting edge lightweight engineering applications [48-50].

# Conclusion

The mechanical properties of AA2024 aluminium alloy are demonstrated to be enhanced by the addition of graphene nanoplatelets and multiwalled carbon nanotubes for hybrid reinforcement. By using ultrasonic aided dispersion, nanollers were uniformly distributed that results in strong interfacial bonding and efficient stress transfer between the matrix and reinforcements. The best combination of tensile strength, Vickers hardness and energy absorption among the composite formulations was shown by Sample 4, which contains 0.5 weight % graphene and 1 weight % CNT with just a minor loss in ductility making it ideal for dynamic structural applications.

These improvements demonstrate the promise of graphene and CNT hybrid nanocomposites in lightweight, high performance structures where durability and impact resistance are crucial.

Applications where weight reduction, mechanical integrity and energy dissipation are crucial design criteria such bicycle frames electric vehicle interiors and sports equipment, are especially well suited for the material system. The importance of hybrid nanocomposite engineering in next-generation manufacturing is further supported by this strategy which is in line with the increased focus on high eciency and sustainable materials in the aerospace and mobility sectors.

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