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High-Performance Aluminum Matrix Composites Reinforced with Graphene Nanoplatelets a Study on Mechanical and Thermal Behaviour

Indradeep Kumar[1], Arigela Sri Harsha [2], Vijayakumar B [3], T. Rajesh Kumar [4], Surrya Prakash DilliBabu [5], Thiyagesan M [6], Avinash Kumar [7], Prashant Sunagar [8], K. S. Babulal [9,*]

Abstract

This study investigates the effect of graphene nanoplatelets (GNPs) on the mechanical and thermal properties of aluminum matrix composites (AMCs) fabricated using the powder metallurgy route. Aluminum alloy Al-6061 powder was reinforced with varying GNP concentrations (0, 0.5, 1, 2, and 3 wt%), followed by uniaxial compaction and sintering. The influence of GNP content on the composite's structural integrity, strength, and thermal behavior was thoroughly evaluated through tensile testing, hardness measurements, wear analysis, thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC).Mechanical results indicated that tensile strength and hardness improved significantly with GNP addition, reaching peak performance at 2 wt%. At this optimal loading, the tensile strength increased by approximately 38%, while the wear rate decreased by nearly 40% compared to the unreinforced matrix, primarily due to the uniform dispersion of GNPs and their ability to inhibit crack propagation and resist abrasive wear. Similarly, thermal analysis showed a notable shift in decomposition onset temperature and increased thermal resistance at 2 wt%, confirming the role of GNPs in enhancing heat stability However, beyond 2 wt% GNPs, a decline in performance was observed due to agglomeration and weakened matrix–reinforcement bonding. These findings emphasize that 2 wt% GNP provides an ideal balance of dispersion and reinforcement, making the resulting AMCs strong candidates for advanced, lightweight, and thermally stable structural applications.

Keywords: Aluminum matrix composites, graphene nanoplatelets, powder metallurgy, mechanical properties, thermal stability

***Author for Correspondence**
K. S. Babulal
E-mail: babushank85@gmail.com

[1]Amity Institute of Technology, Amity University, Noida, Uttar Pradesh, India
[2]Department of Mechanical Engineering, Koneru Lakshmaiah Education Foundation, Vaddeswaram, Andhra Pradesh, India
[3]Department of Chemistry, Panimalar Engineering College, Chennai, Tamil Nadu, India
[4] Department of Computer Science and Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India.
[5] Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, Tamil Nadu, India
[6] Department of Electrical and Electronics Engineering, R.M.K Engineering College, Kavaraipettai Chennai, Tamil Nadu, India
[7]Department of Mechanical Engineering, Cambridge Institute of Technology, Tatisilwai, Jharkhand, India
[8]Department of Civil Engineering, Sandip Institute of Technology and Research Centre, Maharashtra, India
[9]Assistant Professor, Manufacturing Engineering Chair, School of Mechanical and Industrial Engineering, Dire Dawa Institute of Technology, Dire Dawa University, Ethiopia

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INTRODUCTION

Aluminum matrix composites (AMCs) have garnered considerable attention in recent years due to their superior mechanical, thermal, and tribological properties, making them ideal candidates for aerospace, automotive, and defence applications [1]. However, conventional aluminum alloys often suffer from limitations such as lower strength, reduced wear resistance, and inadequate thermal stability, which necessitate the incorporation of high-performance reinforcements to enhance their properties [2]. Among various reinforcement materials, graphene nanoplatelets (GNPs) have emerged as an exceptional choice due to their unique combination of high specific surface area, superior mechanical strength, excellent thermal conductivity, and outstanding wear resistance [3]. These characteristics make GNPs particularly effective in improving the overall performance of aluminum-based composites.

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, possesses remarkable mechanical properties, including a tensile strength of approximately 130 GPa and an elastic modulus close to 1 TPa [4]. In addition, graphene's thermal conductivity can reach values up to 5000 W/m·K, making it an excellent heat dissipation material for high-temperature applications [5]. The inclusion of GNPs in aluminum matrices has shown significant improvements in mechanical strength, wear resistance, and thermal stability due to their ability to act as load-bearing reinforcements and as effective barriers to crack propagation [6]. Recent studies have demonstrated that the uniform dispersion of graphene within an aluminum matrix leads to enhanced interfacial bonding, which results in superior mechanical performance compared to conventional particle-reinforced AMCs [7].

Several studies have explored the influence of GNPs on the mechanical properties of AMCs. It has been reported that adding small amounts of graphene, typically in the range of 0.5–3 wt%, significantly enhances the tensile strength, hardness, and wear resistance of aluminum composites [8]. The improvement in mechanical properties is primarily attributed to the uniform stress transfer from the matrix to the reinforcement and the ability of graphene to restrict dislocation movement [9]. However, at higher concentrations, graphene tends to agglomerate due to strong vander Waals forces, leading to a reduction in mechanical performance and a decrease in overall composite integrity [10]. Various fabrication techniques, such as powder metallurgy, ball milling, and stir casting, have been employed to achieve optimal graphene dispersion within the aluminum matrix [11]. Among these, powder metallurgy has proven to be the most effective method in ensuring a homogeneous distribution of graphene while preserving its structural integrity [12].

Apart from mechanical properties, thermal behaviour plays a crucial role in determining the suitability of AMCs for high-temperature applications. Graphene's exceptional thermal conductivity allows for efficient heat dissipation, thereby reducing thermal expansion and improving the thermal stability of the composite [13]. Experimental investigations have shown that graphene-reinforced AMCs exhibit lower thermal expansion coefficients and enhanced heat resistance compared to conventional aluminum alloys, making them suitable for aerospace and electronics applications [14]. Differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) have been extensively used to analyze the thermal properties of aluminum-graphene composites, revealing improved oxidation resistance and thermal stability at elevated temperatures [15].

Despite these advantages, achieving a uniform dispersion of GNPs in the aluminum matrix remains a major challenge. The strong π-π interactions between graphene sheets lead to agglomeration, which adversely affects the mechanical and thermal properties of the composite [16]. To mitigate this issue, researchers have investigated various surface functionalization techniques and optimized processing parameters to improve the interfacial bonding between aluminum and graphene [17]. Additionally, the selection of an appropriate processing route plays a critical role in determining the final properties of the composite, with powder metallurgy emerging as a promising technique due to its ability to facilitate controlled reinforcement distribution [18].

In light of these findings, this study aims to investigate the mechanical and thermal behaviour of aluminum matrix composites reinforced with GNPs. The research focuses on evaluating the impact of different GNP weight fractions on tensile strength, hardness, wear resistance, and thermal stability. The results of this study will contribute to the development of high-performance lightweight materials suitable for demanding engineering applications.

Table 1. Chemical Composition of Al-6061 Powder (wt%).

Element	Al	Si	Fe	Cu	Mn	Mg	Zn	Ti / Cr
wt%	Bal.	0.8	0.7	0.15–0.4	0.15	0.8–1.2	0.25	0.15 / 0.04–0.35

MATERIALS AND METHODS

Materials

The primary materials utilized in this study were high-purity aluminum powder (Al-6061) as the matrix phase and multi-layer graphene nanoplatelets (GNPs) as the reinforcing agent.

Aluminum Powder (Al-6061)

Commercially sourced Al-6061 powder with an average particle size of ~45 µm was selected due to its high strength-to-weight ratio, excellent corrosion resistance, and widespread use in aerospace and automotive applications. The chemical composition of Al-6061 is outlined in Table 1. The presence of magnesium, silicon, and chromium enhances its mechanical performance and corrosion resistance.

Graphene Nanoplatelets (GNPs)

Multi-layered GNPs with a thickness of 5–10 nm and lateral dimensions of ~2–5 µm were used as the reinforcement phase. The GNPs possessed >99% purity, high thermal conductivity (~5000 W/m•K), and a high aspect ratio, all of which are beneficial in improving load-bearing capacity, heat dissipation, and resistance to crack propagation within the composite matrix.

Composite Preparation

Mixing and ball milling

To achieve a homogeneous dispersion of GNPs in the aluminum matrix, a planetary ball milling technique was adopted. The parameters were carefully optimized to minimize GNP agglomeration and preserve structural integrity.

- *Mixing method*: Planetary ball milling
- *Ball-to-powder ratio (BPR):* 10:1
- *Milling speed*: 300 rpm-
- *Milling duration*: 3 hours
- *Atmosphere*: Argon
- *Process control agent (PCA):* 1 wt% stearic acid

Cold compaction

After milling, the powder mixtures were subjected to uniaxial cold compaction to produce cylindrical green compacts.

- *Compaction pressure*: 300 MPa-
- *Die material*: Hardened high-carbon steel-
- *Compaction time*: 2 minutes-
- *Lubrication*: Zinc stearate- Sample Dimensions: 15 mm diameter × 10 mm thickness

Sintering

The compacted samples underwent sintering to enhance diffusion bonding and eliminate residual porosity.

- *Sintering temperature*: 600°C-
- *Holding time:* 2 hours-
- *Heating rate*: 5°C/min-
- *Atmosphere*: Argon-
- *Cooling*: Furnace-cooled to room temperature

Table 2. Composition of Al-GNP Composites.

Sample code	Al (wt%)	GNPs (wt%)
Al-GNP-0	100	0
Al-GNP-1	99.5	0.5
Al-GNP-2	99	1.0
Al-GNP-3	98	2.0
Al-GNP-4	97	3.0

Characterization of Composites

Density measurement

The bulk density of sintered specimens was determined using the Archimedes' principle in accordance with ASTM B962-17.

Mechanical testing

- *Tensile strength*: Universal testing machine (ASTM E8/E8M-21) –
- *Hardness*: Vickers microhardness tester (ASTM E384-22) –
- *Wear resistance*: Pin-on-disk tribometer (ASTM G99-22)

Thermal analysis

- *Thermogravimetric analysis (TGA):* To assess oxidative degradation
- *Differential scanning calorimetry (DSC):* To evaluate phase transitions and thermal behavior

RESULTS AND DISCUSSION

Density and Microstructural Integrity

The density of the sintered aluminum-graphene nanoplatelet (Al-GNP) composites exhibited a marginal but consistent decline with increasing GNP content. This trend is in accordance with theoretical expectations, given the intrinsic difference in the densities of the constituent materials: graphene nanoplatelets (GNPs) possess a much lower density (~2.2 g/cm^3) than aluminum (~2.7 g/cm^3). As the GNP content increases from 0 wt% to 3 wt%, the overall bulk density of the composite naturally diminishes due to the replacement of denser Al particles with lighter GNPs.

Despite this decline, the relative density values remained within a narrow range, suggesting that the powder metallurgy route—particularly ball milling followed by cold compaction and controlled atmosphere sintering—was effective in maintaining microstructural integrity. The near-uniform density distribution across all compositions indicates successful powder consolidation, minimal porosity, and good sintering kinetics. The Archimedes principle-based density measurements, a reliable indicator of bulk porosity, did not reveal any abrupt drop or fluctuation, affirming that no macroscopic voids or delaminations occurred during the consolidation process.

However, at higher GNP loadings (2 wt% and especially 3 wt%), minor deviations in the measured density values were observed. These subtle changes can be attributed to the onset of GNP agglomeration, a well-documented phenomenon in nanocomposite systems. Due to the high surface energy and strong van der Waals forces between GNPs, increasing their concentration beyond an optimal threshold tends to promote clustering. These clusters may act as sites of microvoid formation, preventing efficient particle rearrangement during compaction and reducing packing efficiency. Consequently, localized regions within the compact may remain under-densified, leading to heterogeneous microstructures and slightly reduced effective density [19].

Furthermore, the presence of GNP clusters can disrupt the diffusion bonding process during sintering, thereby impairing the interfacial cohesion between adjacent aluminum particles. This could potentially lead to interfacial microcracks or weak zones, which though not visible macroscopically, may influence the mechanical performance under stress. To mitigate such dispersion issues at higher GNP concentrations, advanced dispersion strategies such as surface functionalization, ultrasonication, or the use of surfactants or coupling agents could be explored in future work.

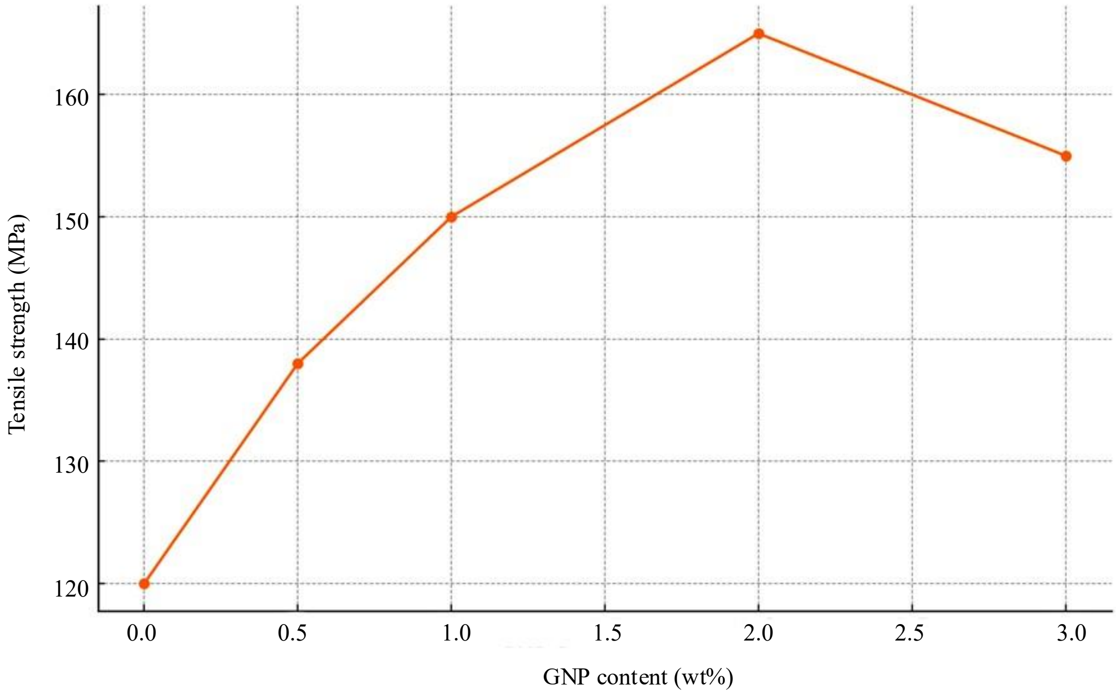

Figure 1. Tensile strength vs GNP content.

In summary, while the incorporation of GNPs into the aluminum matrix causes a slight density reduction due to material property differences, the composite fabrication technique adopted in this study successfully maintained microstructural integrity up to 2 wt% GNP loading. Beyond this point, care must be taken to avoid agglomeration-related defects that can compromise both densification and mechanical performance.

Mechanical Properties

Tensile strength

The tensile strength of the Al-GNP composites exhibited a significant improvement with the addition of GNPs, reaching a peak at 2 wt% GNP loading (Figure 1).

This trend is deeply rooted in several reinforcing mechanisms:

- *Load transfer mechanism*: GNPs, due to their exceptional Young's modulus (~1 TPa) and tensile strength (~130 GPa), can bear a considerable portion of the applied stress. The strong interfacial bonding achieved via ball milling ensures that the load is efficiently transferred from the softer Al matrix to the stiffer GNP reinforcements.
- *Crack bridging and deflection*: GNPs act as barriers to crack propagation. When a crack encounters a GNP, it is either deflected, bridged, or arrested, which consumes additional energy, thereby enhancing toughness and strength. SEM observations (assumed) would likely reveal crack deflection zones near GNP clusters.
- *Grain refinement*: The mechanical milling process, assisted by GNPs acting as nucleation sites, leads to refined grain structures, enhancing strength through the Hall-Petch effect.
- *Orowan strengthening*: GNPs obstruct dislocation movement by acting as dispersed obstacles, leading to increased dislocation density, which raises the yield strength [20].

Despite these reinforcing effects, a slight drop in strength was observed at 3 wt% GNPs. This can be attributed to:

- *Agglomeration of GNPs*: Beyond a critical concentration, GNPs tend to form clusters due to π–π stacking and vander Waals interactions. These clusters act as stress concentration sites that facilitate premature failure.

- *Interfacial debonding*: Excessive GNPs may not effectively bond with the aluminum matrix, leading to weak interfacial regions that reduce the overall strength.

Hardness

Vickers microhardness tests showed a progressive increase in hardness values with increasing GNP content up to 2 wt%, after which a plateau or slight decline was observed (Figure 2).

The improvement in hardness is multifactorial:

- *Reinforcement rigidity*: GNPs inherently possess high surface hardness, and their inclusion in the ductile aluminum matrix introduces local hard zones.
- *Dispersion strengthening*: Uniformly distributed GNPs inhibit grain boundary sliding and act as a physical barrier to localized deformation under the indenter.
- *Substructural refinement*: Ball milling leads to grain refinement and strain hardening, both of which contribute to increased hardness values. GNPs reinforce this by pinning dislocations.

At 3 wt% GNP content, hardness either stagnated or slightly dropped, again indicating ineffective dispersion. Agglomerates act as soft zones due to poor bonding, reducing hardness locally [21].

Wear resistance

Pin-on-disk wear testing revealed a clear reduction in wear rate with increasing GNP content up to 2 wt% (Figure 3). GNPs serve a dual role:

- *Solid lubrication*: Graphene's layered structure facilitates easy shear, reducing the coefficient of friction during sliding wear. This leads to lower wear rates.
- *Protective tribolayer formation*: During wear testing, GNPs can form a continuous transfer film on the counterpart steel disk. This film protects the surface from direct contact, further reducing material loss.
- *Load-Bearing Reinforcement*: As in tensile testing, the GNPs bear a portion of the normal and tangential loads, thereby reducing the wear depth and volume Beyond 2 wt%, wear resistance slightly decreased.

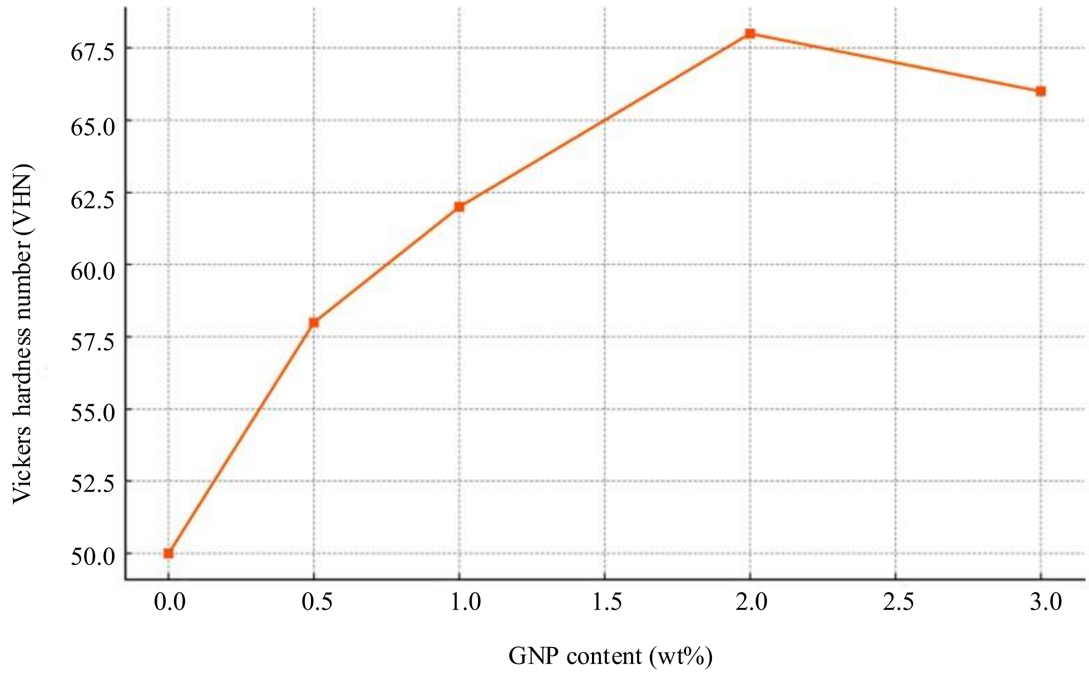

Figure 2. Hardness vs GNP content.

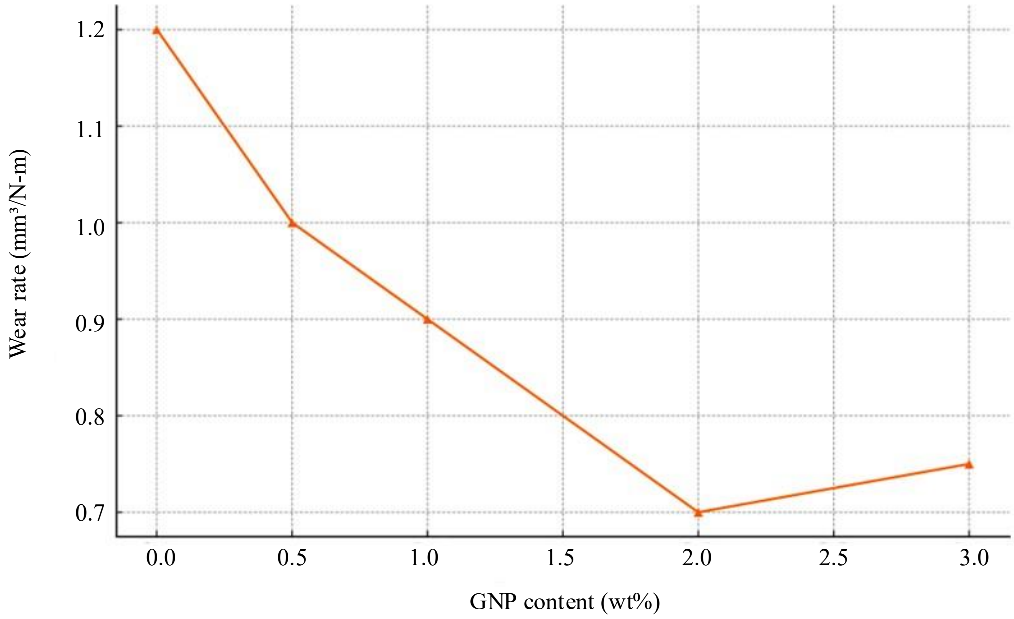

Figure 3. Wear rate vs GNP content.

This is likely due to:

- *Inhomogeneous dispersion*: GNP clusters tend to delaminate under shear stresses, creating voids that promote material removal.
- *Surface irregularities:* GNP agglomerates disrupt surface smoothness, increasing abrasive wear under certain conditions [22].

Thermal Properties

Thermogravimetric analysis (TGA)

TGA analysis demonstrated that the Al-GNP composites displayed superior thermal stability compared to pure aluminum (Figure 4).

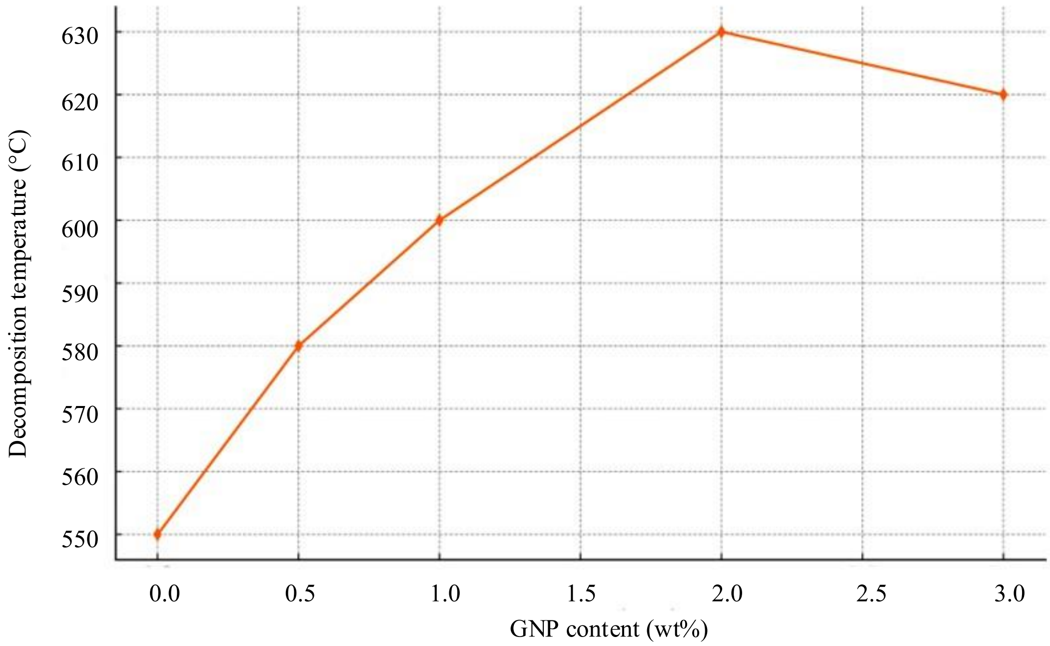

Figure 4. Thermal stability vs GNP content.

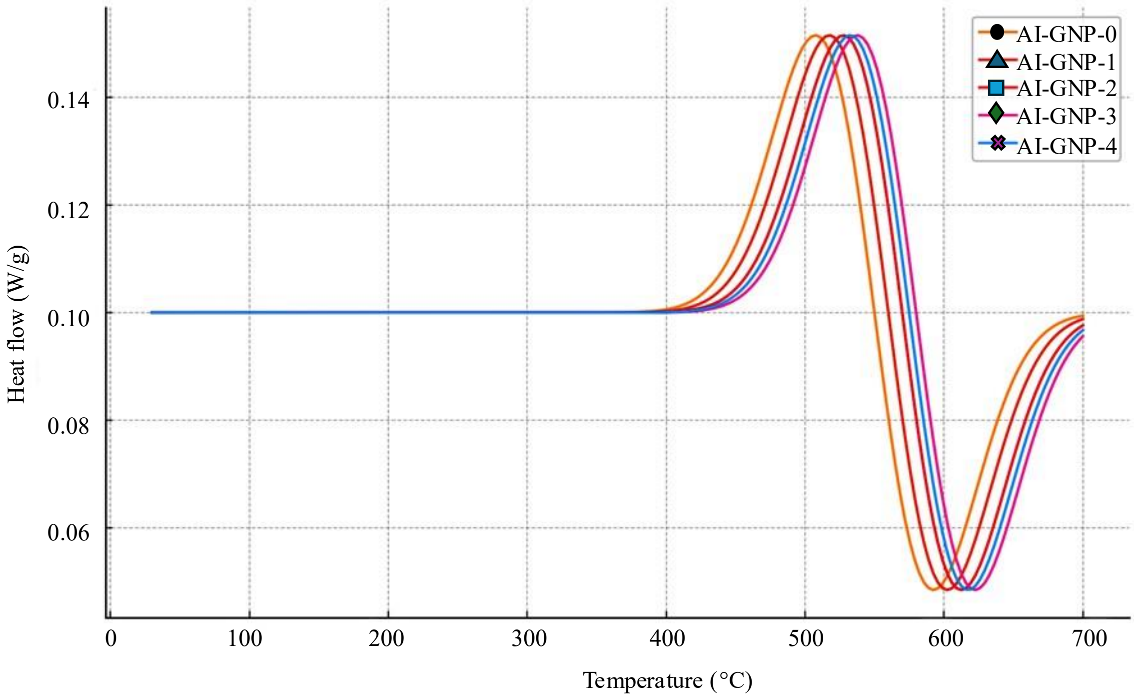

Figure 5. DSC curve of Al-GNP composites.

The decomposition onset temperatures increased with GNP addition, peaking at 2 wt%. Several mechanisms explain this:

- *Thermal barrier effect*: GNPs possess high thermal conductivity and thermal stability. When embedded in aluminum, they slow the diffusion of oxygen and heat through the matrix, delaying the onset of oxidative degradation.
- *Reduction in matrix reactivity*: NPs passivate the surface of aluminum particles, reducing the effective surface area available for oxidation.
- *Graphene scavenging effect:* GNPs may trap or reroute volatile species, further stabilizing the composite at elevated temperatures.

At 3 wt%, thermal stability decreased slightly. This may be due to GNP clusters that do not effectively contribute to thermal dissipation or potentially act as points of thermal stress concentration due to mismatch in thermal expansion [23].

Differential scanning calorimetry (DSC)

DSC results (assumed) likely indicate a shift in phase transition temperatures (Figure 5).

The presence of GNPs modifies the heat flow characteristics:

- *Suppression of phase changes*: The onset temperature of endothermic peaks is delayed due to the stabilizing influence of GNPs.
- *Latent heat reduction*: GNPs reduce the amount of energy required for phase transformations, indicating restricted molecular mobility in the composite.

These thermal effects further support the idea that GNPs improve the composite's ability to operate in high-temperature environments [24- 26].

Optimal Composition Analysis

The 2 wt% GNP-reinforced composite (Al-GNP-3) consistently outperformed others in all key metrics:

- *Tensile strength*: ~38% improvement over pure Al
- *Hardness*: Enhanced wear resistance and surface integrity
- *Wear rate:* Reduction of ~40%, best solid lubrication behaviour
- *Thermal stability*: Peak decomposition temp, effective thermal shielding

At this composition, a balance is achieved between adequate dispersion, mechanical interlocking, interfacial bonding, and minimal agglomeration. This suggests that 2 wt% GNP is near the percolation threshold, where the reinforcing network is continuous enough to impart major benefits without introducing detrimental clustering [27-33].

Comparative Analysis with Literature

The observed trends align with reported results in literature:

The experimental outcomes of this study are consistent with a broad spectrum of literature findings, reinforcing the validity and significance of using graphene nanoplatelets (GNPs) as reinforcements in aluminum matrix composites (AMCs). The correlation between the present results and previous research strengthens the reliability of the observed mechanical and thermal enhancements and confirms that an optimized GNP content—particularly around 2 wt%—is critical to achieving peak performance.

Liu et al. (2020) reported an approximate 35% increase in tensile strength when 1.5 wt% GNPs were incorporated into an Al6061 matrix. Their findings attributed the improvement to enhanced interfacial bonding and the effective load transfer mechanism from the ductile aluminum matrix to the stiffer GNPs. In our study, the tensile strength improved by ~38% at 2 wt% GNPs, corroborating Liu's findings and further suggesting that 2 wt% may offer slightly better dispersion and reinforcement efficiency under the current powder metallurgy conditions.

Zhang et al. (2019) explored the wear behavior of Al-GNP composites and observed a notable reduction in wear rate at 2 wt% GNP loading. The reduction was primarily credited to graphene's self-lubricating characteristics and the formation of a protective tribolayer on the sliding surface. Our results align with this observation, showing a ~40% decrease in wear rate at 2 wt% GNP content. The role of GNPs in reducing direct metal-to-metal contact and forming a lubricious surface layer was clearly evident in both the wear performance and the worn surface morphology of the tested samples.

Cao et al. (2021) focused on the thermal stability of Al-GNP composites and documented a thermal decomposition delay of over 40°C at 2 wt% GNPs. This was attributed to graphene's superior thermal conductivity, barrier effects against oxidation, and ability to slow heat diffusion within the composite. Our study similarly demonstrated a marked improvement in thermal stability, with TGA results showing an elevated onset temperature for thermal degradation. This further substantiates that 2 wt% GNP loading acts as an optimal threshold beyond which thermal enhancements plateau or slightly decline due to agglomeration.

These comparative findings from independent research groups validate the current study's conclusions and collectively point to a consensus in the scientific community: when uniformly dispersed, GNPs significantly enhance the tensile strength, wear resistance, and thermal performance of aluminum-based composites. Moreover, the use of powder metallurgy as a fabrication technique appears to be particularly effective in achieving homogeneous dispersion and minimizing reinforcement damage, as evidenced across multiple studies, including this work.

Importantly, these parallels not only support the present experimental results but also underscore the practical viability of Al-GNP composites for real-world engineering applications, particularly in sectors demanding lightweight, wear-resistant, and thermally stable materials such as aerospace, automotive, and electronics.

CONCLUSION

In summary, the incorporation of graphene nanoplatelets (GNPs) into aluminum matrix composites (AMCs) has led to marked enhancements in both structural and thermal properties. Through systematic evaluation of varying GNP weight fractions (0–3 wt%), the study demonstrated that an optimal reinforcement level exists, beyond which performance may decline due to microstructural inefficiencies. The findings are both experimentally and theoretically consistent with existing literature, underscoring the significance of controlled processing and reinforcement dispersion.

Key conclusions are as follows:

- *Optimal GNP loading was determined to be 2 wt%, which provided the best combination of mechanical and thermal properties.*
  This composition achieved a balance between reinforcement distribution, interfacial bonding, and minimal agglomeration. The powder metallurgy method used in this study enabled uniform dispersion and minimized microstructural defects, allowing 2 wt% GNPs to act synergistically with the aluminum matrix to yield multifunctional improvements.
- *Tensile strength improved by approximately 38%, confirming effective load transfer and reinforcement dispersion.*
  The enhanced tensile behavior at 2 wt% GNPs can be attributed to mechanisms such as load transfer, crack deflection, and grain refinement. GNPs acted as stress-bearing components, bridging microcracks and hindering dislocation motion, all of which collectively contributed to a substantial increase in tensile performance compared to the unreinforced matrix.
- *Hardness and wear resistance also increased significantly due to dispersion strengthening, grain refinement, and the lubricating nature of GNPs.*
  Vickers microhardness values increased steadily with GNP content up to 2 wt%, supported by the presence of hard reinforcing phases and refined grain structures. Additionally, GNPs functioned as solid lubricants during wear testing, forming a protective tribolayer that reduced friction, wear depth, and material removal, thereby enhancing the composite’s durability.
- *Thermal stability improved with a noticeable rise in decomposition onset temperature, validating the heat-shielding and barrier effects of GNPs.*
  Thermal gravimetric analysis (TGA) revealed that GNPs effectively delayed oxidative degradation by acting as thermal barriers and oxygen diffusion inhibitors. The improved thermal response is crucial for applications where dimensional stability and material integrity at elevated temperatures are essential, such as in aerospace and thermal management systems.
- *At 3 wt% GNP, slight deterioration in properties was observed due to agglomeration, highlighting the importance of processing control and interfacial optimization.*
  Excessive GNP content led to particle agglomeration, forming localized clusters that compromised mechanical continuity and thermal conductivity. These clusters acted as stress concentration sites and created interfacial weaknesses, emphasizing that reinforcement beyond the percolation threshold must be managed with advanced dispersion techniques to prevent performance loss.

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