

Development of TiB₂-GNP reinforced Al6061 nano-hybrid composites with enhanced wear and mechanical properties

Journal of Composite Materials
2025, Vol. 0(0) 1–27
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DOI: 10.1177/00219983251397768
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Abstract

In this study, nano-hybrid composite materials were produced via powder metallurgy (PM) by adding TiB₂ and graphene nanoplatelets (GNPs) to Al6061 alloy, known for its high ductility, corrosion resistance, and weldability. Sub-150 µm Al6061 powder was used as the matrix, while reinforcement elements included sub-5 µm TiB₂ and 5 nm thick, 18 µm diameter GNPs. Six different materials were fabricated: pure Al6061, Al6061 + 10% TiB₂, and Al6061 + 10% TiB₂ with 0.25%, 0.5%, 1%, and 2% GNP additions. The powder mixtures were first dispersed in ethanol and ultrasonically agitated at 53 kHz for 60 min, followed by magnetic stirring at 580 rpm. Ethanol was removed via vacuum drying, and the dried powders were mixed in a 3D mixer for 30 min with a 1:5 powder-to-ball ratio. Cold pressing was performed at 50 MPa, followed by sintering at 550°C for 30 min and hot pressing at 200 MPa. After cooling to room temperature, T6 heat treatment was applied. Microstructure, density, hardness, tensile strength, and wear properties were examined. Increasing the reinforcement ratio reduced density. While hardness decreased with higher GNP content, tensile strength improved. Wear tests showed that TiB₂ and GNP additions significantly reduced volume loss. The lowest wear was observed in the 10% TiB₂ + 1% GNP sample. Due to the self-lubricating effect of GNPs, the coefficient of friction also decreased, with the lowest value recorded for the 1% GNP-reinforced composite.

Keywords

Al6061, graphene nanoplatelets, TiB₂, hybrid composite, wear resistance

Introduction

In recent years, industries such as automotive, aerospace, and defense have increasingly demanded lightweight yet high-performance materials to enhance fuel efficiency and reduce environmental impact.¹ Aluminum alloys have emerged as preferred materials in these sectors owing to their low density, favorable mechanical properties, and corrosion resistance.² Among these, Al6061—a silicon- and magnesium-containing alloy—has been extensively utilized, particularly in aerospace and automotive applications, due to its excellent strength-to-weight ratio and corrosion resistance.^{3,4}

The mechanical properties of 6000-series aluminum alloys like Al6061 can be substantially improved through T6 heat treatment, which comprises solution treatment followed by artificial aging, leading to significant increases in strength.⁵ Nevertheless, certain applications demand further enhancements in strength, hardness, and wear resistance, where conventional alloys may not suffice.⁶ To meet these requirements, aluminum matrix composites

(AMCs) have been developed, combining the lightweight and processability of aluminum with the superior mechanical properties of ceramic and carbon-based reinforcements.^{7,8}

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Data Availability Statement included at the end of the article

The mechanical and tribological performance of AMCs is critically influenced by the type, size, morphology of the reinforcement, and the interfacial characteristics between the matrix and the reinforcement.^{9,10} Micron-sized ceramic particles such as B_4C , SiC, and TiC enhance strength and hardness but can compromise ductility at higher loadings and increase density.¹¹ In contrast, nano-sized reinforcements provide a high surface area that strengthens interfacial bonding, enabling simultaneous improvements in strength and ductility.¹²

Carbon-based nanomaterials, particularly graphene nanoplatelets (GNPs), have attracted significant attention due to their exceptionally high elastic modulus (~ 1 TPa), superior mechanical strength, and intrinsic self-lubricating properties.^{13,14} Incorporating GNPs into aluminum composites has been shown to markedly enhance tribological performance and wear resistance.¹⁵ However, achieving a uniform dispersion of GNPs within the metal matrix remains challenging, as agglomeration can detrimentally affect composite performance.¹⁶

Titanium diboride (TiB_2) is another reinforcement noted for its exceptional hardness and wear resistance. Its high melting point ($\sim 3225^\circ C$), hardness (2600–3200 HV), and elastic modulus contribute to superior performance under elevated temperature and abrasive conditions.^{17,18} Despite limited application in casting due to poor wettability with aluminum, powder metallurgy and other solid-state processing techniques have effectively addressed this limitation.¹⁹

Recent studies demonstrate that hybrid reinforcement strategies combining GNPs and TiB_2 yield synergistic effects, significantly enhancing the mechanical and tribological properties of aluminum composites. For instance, Bhowmik et al. (2023) reported considerable improvements in wear resistance for Al7075 composites reinforced with SiC and TiB_2 , while Pole et al. (2024) demonstrated that Al- TiB_2 hybrid composites developed for brake disc applications exhibited wear rates three times lower than those of cast iron.^{20,21} Similarly, Keshavarz et al. (2022) observed up to an 80% reduction in wear rate in Al5083 composites containing 0.5% GNP, alongside a homogeneous microstructural distribution.²² However, comprehensive studies systematically exploring the combined effects of GNP and TiB_2 as hybrid nano-reinforcements remain scarce. In this regard, Rangrej et al.²³ reported significant enhancements in microhardness and tensile strength in A713/ TiB_2 /graphene hybrid composites produced by stir casting. Additionally, Cheng et al.²⁴ highlighted that increasing the weld chamber height during porthole die extrusion of aluminum composites reinforced with 0.5% GNP refined the microstructure and promoted homogeneous dispersion, thereby improving mechanical strength and weld quality. These findings underscore the potential advantages of hybrid TiB_2 -GNP reinforcements in developing high-performance aluminum matrix composites.

In the present study, nano-hybrid metal matrix composites were fabricated using powder metallurgy, with a highly ductile Al6061 aluminum matrix reinforced with

10 wt.% TiB_2 and varying amounts of GNPs (0.25, 0.5, 1, and 2 wt.%). The composites were systematically characterized in terms of their microstructural, mechanical, and tribological properties, and the effects of T6 heat treatment were thoroughly examined. This study uniquely addresses the current gap in literature by systematically investigating the co-reinforcement of TiB_2 and GNP in an Al6061 matrix, offering new insights into optimizing hybrid reinforcement strategies for the design of next-generation aluminum matrix composites with superior mechanical and tribological performance.

Experimental methodology

Materials

In this study, Al6061 alloy, Al6061 reinforced with 10 wt.% TiB_2 , and hybrid composites of Al6061/10 wt.% TiB_2 with different graphene nanoplatelet (GNP) contents (0.25, 0.5, 1, and 2 wt.%) were fabricated. The synthesis was carried out using powder metallurgy combined with hot pressing. Figure 1 presents the experimental flowchart of the study. The raw materials used in this study were Al6061 powder (particle size $< 150 \mu m$, 99.6% purity), TiB_2 powder (3–15 μm , 98.5% purity), and graphene nanoplatelets (average thickness ~ 5 nm, lateral size $\sim 18 \mu m$). All powders were supplied by Nanografi Company. Table 1 summarizes the detailed properties of the matrix and reinforcement materials.

Powder mixing process

The composite materials were fabricated using the facilities of the Metallurgical and Materials Engineering Department Laboratory at Gazi University. Preliminary trials were conducted to optimize material consumption and refine the processing parameters. Based on the experience gained from these preliminary studies, the final composites were produced. The powder mixing ratios are listed in Table 2.

Metal powders were weighed with a Precisa brand balance with an accuracy of 0.001 g. The powders were then dispersed in 250 mL of ethanol inside a beaker and ultrasonically mixed using a Kudos ultrasonic bath at 55 kHz for 60 min. After ultrasonic treatment, the suspension was mechanically stirred at 580 rpm using a Topo HSD180 magnetic stirrer. To remove ethanol from the powder mixture, the suspension was dried in a Protherm vacuum oven at $80^\circ C$. The dried powders were further mixed for 30 min in a Turbula 3D mixer using yttrium-coated zirconia balls at a ball-to-powder weight ratio of 5:1.

To ensure compositional accuracy, all powder mixtures were prepared strictly according to weight percentage (wt.%) calculations based on the total batch weight. Each constituent powder—Al6061, TiB_2 , and GNP—was individually weighed in grams using a Precisa analytical balance with an accuracy of ± 0.001 g. No volumetric

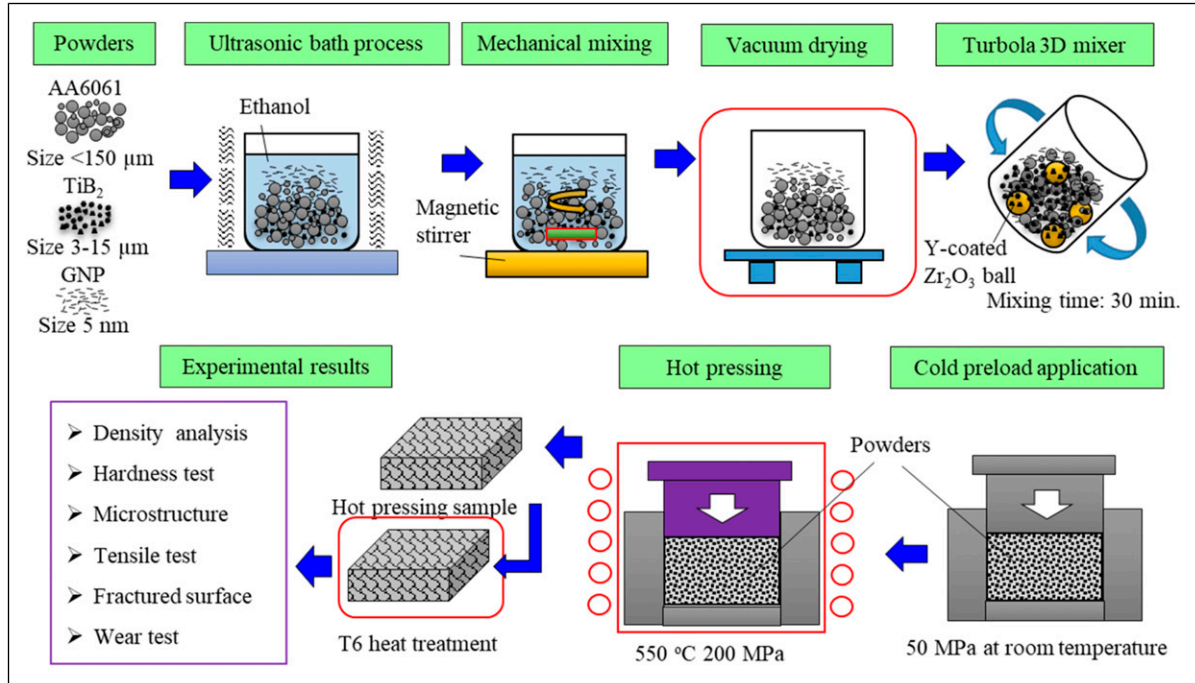


Figure 1. Schematic flowchart of the powder metallurgy process for producing Al6061/TiB₂/GNP hybrid composites.

conversion (vol.%) was employed during composition design. The target wt.% ratios of the constituents are presented in Table 2. The density values of Al6061 (2.70 g/cm³), TiB₂ (4.60 g/cm³), and GNP (2.25 g/cm³) were considered only for theoretical density estimations discussed in the results section. This approach ensures precise control of composition and enhances the reproducibility of the composite fabrication process.

Hot compaction process

The powder mixtures were hot pressed using a specially designed Proterm PLF 120/12 hot pressing unit under an argon protective atmosphere. The pressing process began with an initial cold pressing at room temperature under a pressure of 50 MPa. Subsequently, the die temperature was increased to 550°C at a heating rate of 10°C/min. After

holding at 550°C for 30 min, the powders were hot pressed under a pressure of 200 MPa. Following the hot pressing process, the die was cooled down to room temperature, and specimens with dimensions of 60 × 60 × 10 mm³ were removed. A graphical representation of the hot pressing process is provided in Figure 2(a).

T6 heat treatment

The T6 heat treatment is one of the most commonly applied processes to Al6061 alloys to enhance their mechanical strength. In this study, the fabricated samples were subjected to the T6 heat treatment under the following conditions. The specimens were heated from room temperature to 540°C at a rate of 10°C/min and held at this temperature for 1 h for solution treatment. Subsequently, they were rapidly quenched in water to lock the microstructure. Following

Table 1. Properties of the matrix and reinforcement materials.

Property	Al6061	TiB ₂	Graphene nanoplatelets (GNP)
Particle size (μm)	<150	3 – 15	~0.005 (thickness)
Lateral dimension (μm)	–	–	~18
Purity (%)	99.6	98.5	99.9
Melting point (°C)	582 – 652	2920	–
Density (g/cm ³)	2.7	4.6	2.25
Young's modulus (GPa)	69	41 – 44.8	~1000
Thermal conductivity (W/m·K)	180	26.3	5300
Thermal expansion (10 ⁻⁶ /K)	23.6	5.2	–

Table 2. Powder mixing ratios for composite samples.

S.No	Sample ID	Composition (wt.%)
N1	Al6061	100% Al6061
N2	Al6061 + TiB ₂	90% Al6061 + 10% TiB ₂
N3	Al6061 + TiB ₂ + GNP (0.25%)	89.75% Al6061 + 10% TiB ₂ + 0.25% GNP
N4	Al6061 + TiB ₂ + GNP (0.5%)	89.5% Al6061 + 10% TiB ₂ + 0.5% GNP
N5	Al6061 + TiB ₂ + GNP (1%)	89% Al6061 + 10% TiB ₂ + 1% GNP
N6	Al6061 + TiB ₂ + GNP (2%)	88% Al6061 + 10% TiB ₂ + 2% GNP

quenching, the samples were reheated to 177°C at the same heating rate of 10°C/min and artificially aged for 8 h. Each sample consisted of three main pieces subjected to this aging process separately (Figure 2(b)).

Characterization techniques

The specimens obtained were prepared for microstructural analysis, hardness testing, tensile testing, and wear testing. Initially, the samples were sectioned using a wire electrical discharge machining (EDM) system. The specimens cut by EDM are shown. For tensile testing, surface roughness had to be minimized to meet testing standards. Therefore, 18 specimens were subjected to milling using a vertical machining center to achieve the required surface finish. After milling, the specimens were deemed ready for mechanical testing.

The density of the Al6061/TiB₂/GNP composite specimens was accurately determined using a Sartorius density measurement kit in conjunction with a Precisa analytical balance (sensitivity: 0.0001 mg). The measurements were performed based on Archimedes' principle, a widely accepted method for evaluating the density

of solid materials with high precision. This principle is based on the displacement of fluid by a submerged object, wherein the apparent weight loss of the sample in the fluid corresponds to the volume of the displaced liquid. During the process, each specimen's mass was recorded in air and then in distilled water, enabling the calculation of its experimental density by the following expression:

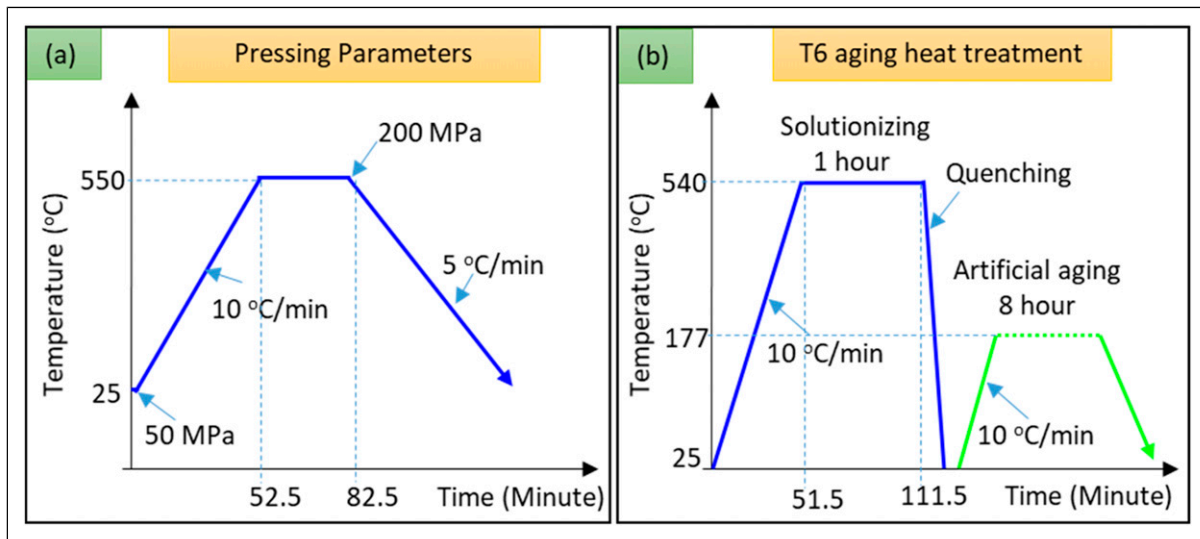
$$\rho = \frac{m_{\text{air}}}{m_{\text{air}} - m_{\text{water}}} \quad (1)$$

where ρ is the experimental density (g/cm^3), m_{air} is the mass measured in air, and m_{water} is the mass measured while submerged in water. Additionally, the theoretical densities of the composites were calculated using the rule of mixtures as follows:

$$\rho_{\text{theoretical}} = \rho_{\text{matrix}} \cdot w_{\text{matrix}} + \rho_{\text{reinforcement}} \cdot w_{\text{reinforcement}} \quad (2)$$

Here, ρ represents the density and w the weight fraction of each constituent. The experimental results were then compared with these theoretical values to evaluate the consolidation quality and relative density of the composites.

For microstructural analysis, specimens previously sectioned using wire electrical discharge machining

**Figure 2.** (a) Schematic illustration of the hot pressing setup; (b) T6 heat treatment cycle diagram.

(WEDM) were mounted in thermosetting bakelite using an ATM GmbH Opal 460.2 mounting press. The mounted samples were subjected to a standard metallographic preparation procedure involving sequential grinding and polishing steps to ensure a mirror-like surface suitable for microscopic examination. Grinding was performed on a water-cooled rotating disc at 300 rpm using silicon carbide (SiC) abrasive papers with grit sizes of 120 and 320 mesh, each for 2 min in a unidirectional manner. Following grinding, polishing was conducted using diamond suspensions of 6 μm and 3 μm particle sizes. A CT Dia Twin Mono paste was used for the 6 μm suspension, while a DiaDuo-2 paste was employed for the 3 μm stage. To achieve a final surface finish, all samples were treated with colloidal silica suspension for 2 min, which also served to remove any residual deformation and produce high contrast for imaging. After polishing, the samples were chemically etched using Keller's reagent, composed of 1 mL HF and 200 mL H₂O, for 15–20 s. This etching process was essential for revealing the microstructural features of the Al6061 matrix and the distribution of reinforcement particles.

Optical microscopy was performed using a Leica DM4000 M metallurgical microscope to observe the general microstructure and identify features such as grain boundaries and phase distributions. Furthermore, detailed interfacial analysis between the Al6061 matrix and the reinforcing particles (TiB₂ and GNPs) was conducted using a JEOL JSM 6060LV scanning electron microscope (SEM). Elemental analysis and phase confirmation were carried out through energy-dispersive X-ray spectroscopy (EDS) integrated with the SEM system.

Hardness is defined as the resistance of a material to localized plastic deformation, typically by indentation. In this study, the Brinell hardness test method was employed in accordance with ASTM E10 standards to determine the hardness of composite specimens produced via powder metallurgy and subjected to T6 heat treatment. The measurements were carried out using an EMCO TEST DuraVision 200 hardness testing machine, utilizing a 2.5 mm diameter steel ball indenter under a test load of 31.25 kgf (approximately 306.5 N). This method was chosen for its suitability in evaluating aluminum-based materials and provides reliable and consistent data regarding the mechanical performance of the composites. To ensure accuracy, hardness values were obtained by performing multiple measurements at predefined locations on the specimen surfaces, as illustrated in Figure 3(a). The results were recorded and analyzed through the device's integrated software, with a representative output shown in Figure 3(b).

Tensile tests were carried out to determine the mechanical performance of the fabricated composite specimens. The samples were prepared with appropriate dimensions suitable for tensile testing, as illustrated in Figure 3(c). Testing was

performed using an Instron 3369 universal testing machine with a maximum load capacity of 50 kN, at a constant crosshead speed of 1 mm/min. Throughout the test, stress and elongation data were continuously recorded by the system's software, allowing the generation of corresponding stress–strain curves. The obtained results were used to evaluate the tensile strength and ductility of the composites. All tests were conducted at room temperature, and the values reported represent the average of at least three specimens for each condition.

Wear experiments were conducted in accordance with the ASTM G132-96 standard using a pin-on-disk wear testing apparatus (Figure 3(d)). The tests were performed under controlled laboratory conditions to ensure repeatability and accuracy of the results. The pin specimens were subjected to varying loads and sliding distances against abrasive paper mounted on a rotating disk to evaluate their wear resistance under dry sliding conditions.

Prior to testing, the surfaces of the specimens were ground using 120-grit SiC abrasive paper to eliminate any surface roughness. A cylindrical test pin with a diameter of 10 mm was then mounted against an abrasive disk covered with 180-grit sandpaper to simulate dry sliding wear conditions. Wear tests were conducted at sliding distances of 100, 200, and 300 m, under constant sliding speeds of 1.2 m/s, and applied normal loads of 5, 10, and 15 N, respectively. Before each test, the specimens were cleaned with acetone to remove surface contaminants, dried, and weighed using a high-precision digital balance with a resolution of 0.001 mg.

The coefficient of friction between the pin and the abrasive surface was determined through the load cell integrated into the wear test setup. The data collected during the tests, including the applied normal force and resulting frictional force, were used to calculate the coefficient of friction using equation (3).

$$\mu = \left(\frac{F}{P} \right) \quad (3)$$

In this context, F represents the frictional force measured by the load cell during the wear test, while P denotes the normal load applied to the specimen. The coefficient of friction (μ) was calculated using equation (3):

$$\text{Volume loss (mm}^3\text{)} = \left(\frac{\text{Weight loss (g)}}{\text{Density (g/mm}^3\text{)}} \right) \times 1000 \quad (4)$$

The wear tests were conducted five times for each specimen to ensure statistical reliability and repeatability of the results. The specific wear rate (W) was calculated according to equation (5):

$$K_o = \frac{W}{\rho L d} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1} \quad (5)$$

In equation (5), W represents the weight loss in kilograms, ρ denotes the density of the pin material in kg/m³,

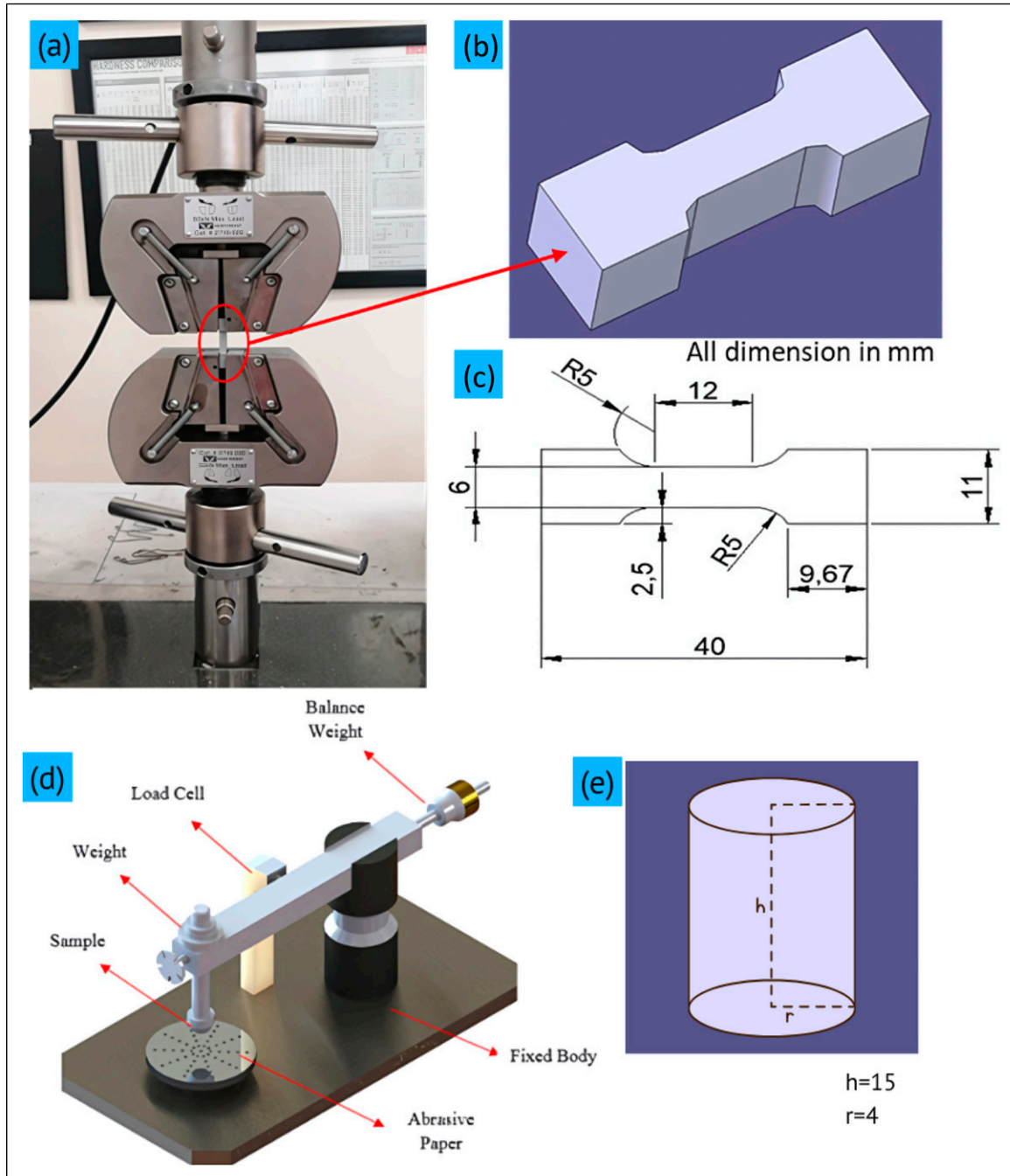


Figure 3. (a) Instron 3369 tensile testing machine (50 kN), (b) 3D model of the tensile specimen, and (c) technical drawing with dimensions, (d) Wear test setup; (e) Technical drawing and 3D view of the wear test specimen.

L is the applied normal load in Newtons, and d corresponds to the total sliding distance in meters. The wear test was repeated five times for each specimen to ensure consistency and reliability of the results. To calculate the specific wear rate, the average of the two most similar weight loss values was used, minimizing the effect of outliers and ensuring a representative evaluation of the wear behavior.

Experimental results and discussion

Powder characterizatton

In this study, the morphological and dimensional characteristics of the Al6061 alloy matrix and the reinforcement elements, titanium diboride (TiB_2) and graphene nanoplatelets (GNPs), were characterized using Scanning Electron Microscopy (SEM) and particle size analysis. SEM

images revealed that the Al6061 alloy powders exhibit predominantly spherical shapes with irregular morphology, TiB_2 particles display irregular and angular structures, while GNPs possess a typical layered, ribbon-like, and non-uniform morphology. The SEM micrographs of the powders are presented in Figure 4. According to the particle size analyses, the Al6061 alloy powders have particle sizes below $150\ \mu\text{m}$, TiB_2 particles range between $3\text{--}15\ \mu\text{m}$, and GNPs have a thickness of approximately $5\ \text{nm}$. These characterization results confirm that the powders possess suitable morphology and size distribution prior to the fabrication process, which is critical for ensuring microstructural homogeneity in the resulting composites.

X-ray diffraction (XRD) analysis

The X-ray diffraction (XRD) patterns of Al6061-based composites, both unreinforced and reinforced with TiB_2 (titanium diboride) and GNP (graphene nanoplatelets), were analyzed to identify phase constituents and investigate

structural changes induced by the reinforcements. The samples labeled N1 through N6 represent a progressive increase in hybrid reinforcement content, with N1 denoting the unreinforced matrix alloy and N6 representing the composite with the highest GNP content (2 wt.%) (Figure 5).

In the XRD pattern of sample S1, sharp and well-defined diffraction peaks were observed at approximately $2\theta = 38.5^\circ, 44.7^\circ, 65.1^\circ, 78.2^\circ,$ and 82.5° , corresponding to the (111), (200), (220), (311), and (222) crystallographic planes of face-centered cubic (FCC) aluminum (JCPDS card no. 04-0787). The high intensity and clarity of these peaks indicate a highly crystalline structure and phase purity in the Al6061 matrix.²⁵ Upon the incorporation of 10 wt.% TiB_2 in sample S2, new peaks appeared at around $2\theta = 28.2^\circ, 36.7^\circ, 42.5^\circ, 57.2^\circ, 64.5^\circ,$ and 78.0° , corresponding to the (100), (101), (102), (110), (103), and (201) planes of TiB_2 with a hexagonal crystal structure (JCPDS card no. 35-0741).²⁶ The presence of these peaks confirms the successful integration of the ceramic reinforcement into the matrix. The

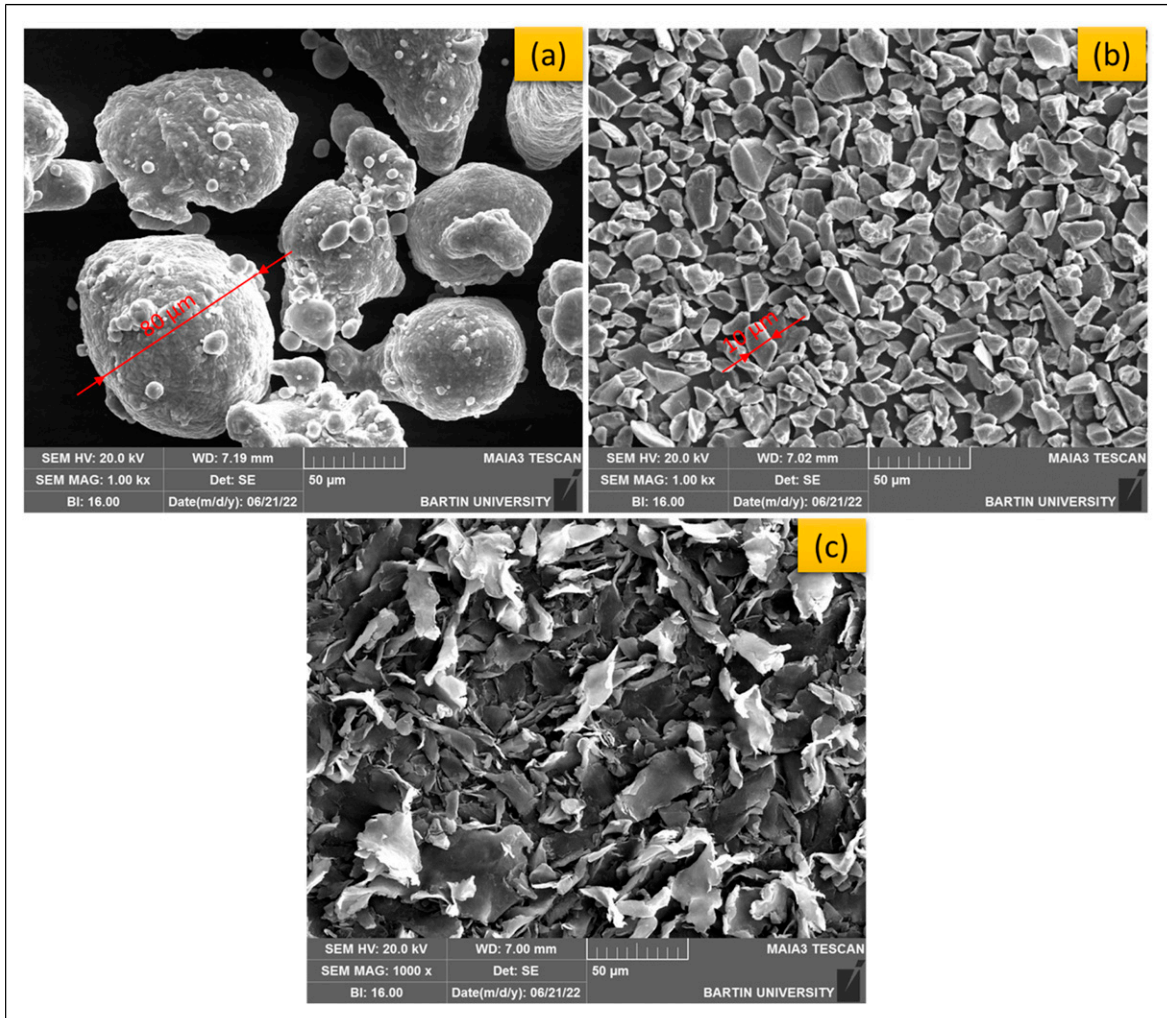


Figure 4. SEM micrographs of (a) Al6061 alloy powder, (b) TiB_2 particles, and (c) GNPs.

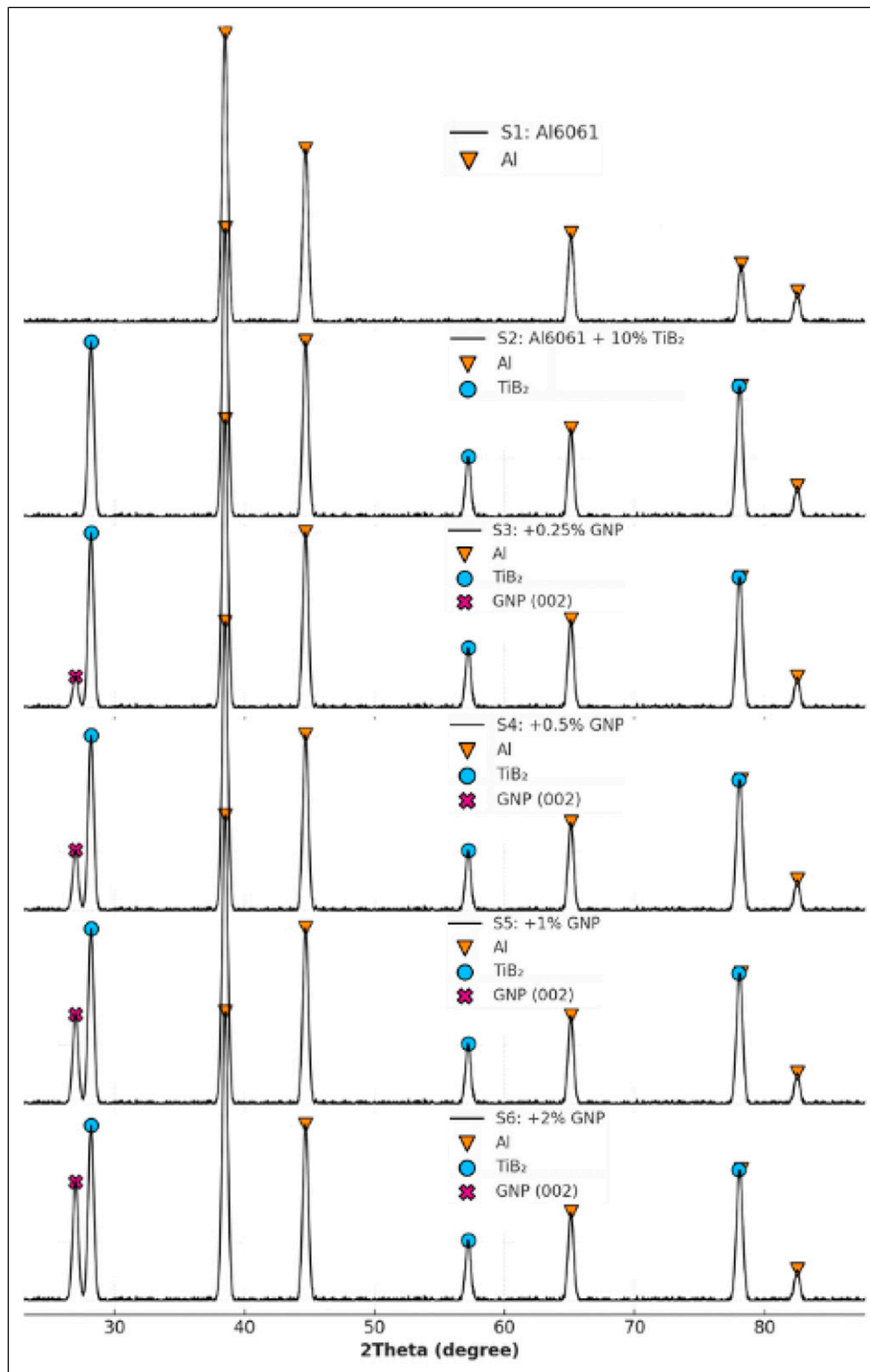


Figure 5. XRD patterns of Al6061-based composites with varying reinforcement compositions.

persistence of TiB_2 peaks in samples N3 through N6 suggests that TiB_2 remains thermally and structurally stable throughout the composite processing stages. In samples N3 through N6, a progressive increase in the diffraction peak near $2\theta = 27.0^\circ$ was observed. This peak is associated with the (002) plane of graphene nanoplatelets (GNP).²⁷ The increasing intensity of this peak, particularly in N6, indicates higher GNP content and improved dispersion within the matrix. This observation is consistent with the findings of Bai et al.,²⁸ who emphasized the efficacy of GNP as a reinforcement phase in metal matrix composites. No diffraction peaks corresponding to intermetallic compounds such as Al_4C_3 or AlB_2 were detected in the XRD patterns. This absence suggests that no significant chemical reactions occurred between the reinforcement materials and the matrix during processing. Consequently, both TiB_2 and GNP are considered to contribute to the composite system primarily through mechanical rather than chemical interactions.²⁹

Microstructural analysis

Figure 6 shows the microstructure images of Al6061 matrix composites obtained under an optical microscope. Sample N1 (pure Al6061) was used as a reference and exhibited distinct grain boundaries with a homogeneous grain distribution. This structure is consistent with typical forged Al6061 without precipitation hardening. In sample N2, reinforced with 10 wt.% TiB_2 , dark-colored and irregularly shaped TiB_2 particles were clearly observed within the matrix. These particles were distributed both along the grain boundaries and within the grains, occasionally showing slight agglomeration. This phenomenon can be attributed to limited interfacial bonding between the Al6061 matrix and TiB_2 particles during solid-state sintering, which may locally restrict the uniform dispersion of the reinforcement. Nevertheless, the presence of TiB_2 effectively inhibited grain growth, leading to a denser and finer-grained microstructure.³⁰ Samples N3, N4, N5, and N6 were reinforced with increasing amounts of GNP (graphene nanoplatelets) in addition to TiB_2 . GNPs had a significant grain refinement effect on the microstructure; a more homogeneous particle distribution, reduced TiB_2 agglomerations, and further grain size reduction were observed. These improvements are directly related to the high surface area, superior mechanical properties, and dislocation movement hindering effect of GNPs.³¹ Furthermore, since GNPs have low surface activity in liquid metal, effective bonding with the matrix is achieved through appropriate mixing and dispersion processes, enhancing structural integrity.³² Particularly in sample N6 (2% GNP), the hybrid reinforcement effect of GNP and TiB_2 particles resulted in a much more refined, dense, and homogeneous microstructure. This structure is an indication of the

synergistic reinforcement mechanism frequently reported in the literature. GNPs increase dislocation density, creating stress fields within the matrix, while TiB_2 supports these fields, enhancing load transfer.³³ Therefore, hybrid reinforced composites exhibit superior mechanical performance compared to single reinforcements.

In Al6061 matrix composites, Mg_2Si precipitates constitute a crucial microstructural feature that significantly influences the overall composite microstructure. These precipitates, formed through the interaction of Mg and Si elements, are finely and uniformly distributed, contributing to grain refinement and enhanced microstructural stability following solution treatment and aging processes.³⁴ Furthermore, the inherent thermal stability of Mg_2Si precipitates plays an important role in improving the high-temperature performance of the composites, which is a key consideration for automotive and aerospace applications.³⁵ Numerous studies have also highlighted the synergistic effect of Mg_2Si precipitates in conjunction with hard reinforcement particles such as TiB_2 and graphene nanoplatelets (GNP), which collectively influence the microstructural evolution and integrity of the composite.³⁶

SEM analysis revealed that black regions correspond to porosity, whereas dark and light gray tones represent distinct reinforcement phases. An increase in the reinforcement content correlates with a noticeable rise in porosity levels (Figure 7). This porosity is typically attributed to powder metallurgy and hot pressing processes, where incomplete filling of inter-particle voids or sub-optimal sintering parameters may result in pore formation.³⁷ Despite porosity generally being detrimental to composite quality, the observed pores were predominantly small, sparse, and discontinuous, suggesting a limited impact on the structural integrity of the material. The Al6061 matrix exhibited dark gray contrast, TiB_2 appeared bright white, and GNP displayed lighter gray tones in the SEM micrographs. Morphologically, Al6061 particles were generally spherical, TiB_2 particles exhibited angular, sharp-edged features, while GNPs were characterized by platelet-like structures predominantly composed of single-layer sheets. These morphological distinctions critically affect the interface characteristics and dispersion uniformity within the composite.³⁸

The homogeneous dispersion and effective interfacial bonding of reinforcement phases facilitate enhanced load transfer mechanisms. Particularly, the hybrid reinforcement of GNP and TiB_2 establishes a robust matrix-reinforcement interface, yielding a synergistic microstructural effect.^{39,40} Additionally, the coexistence of Mg_2Si precipitates and Ti-based intermetallics within the hybrid matrix contributes to improved microstructural stability and mitigates the adverse effects associated with porosity, leading to superior wear resistance and structural integrity.⁴¹ Consequently,

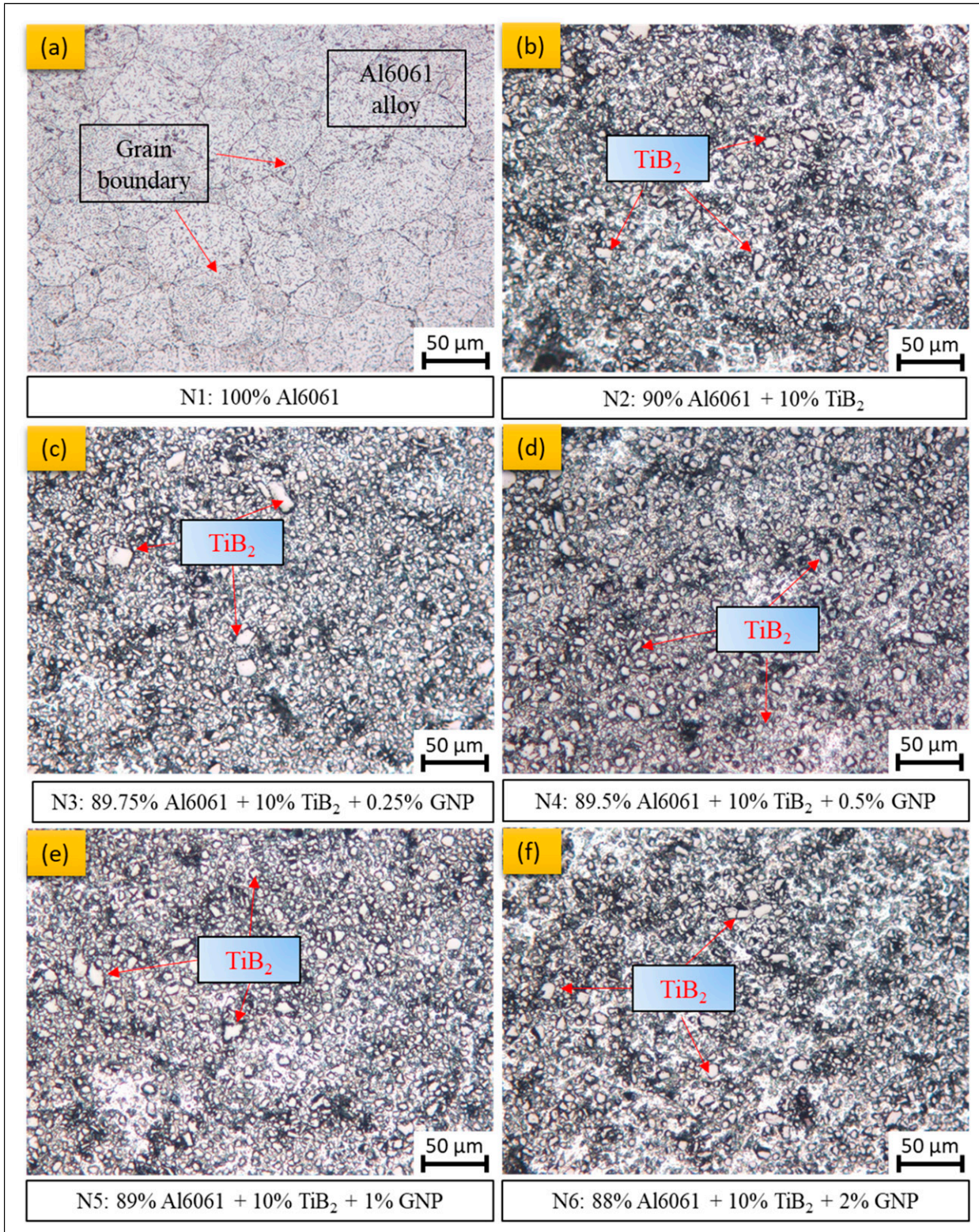


Figure 6. Optical micrographs of composites: (a) N1 (100% Al6061), (b) N2, (c) N3, (d) N4, (e) N5, (f) N6.

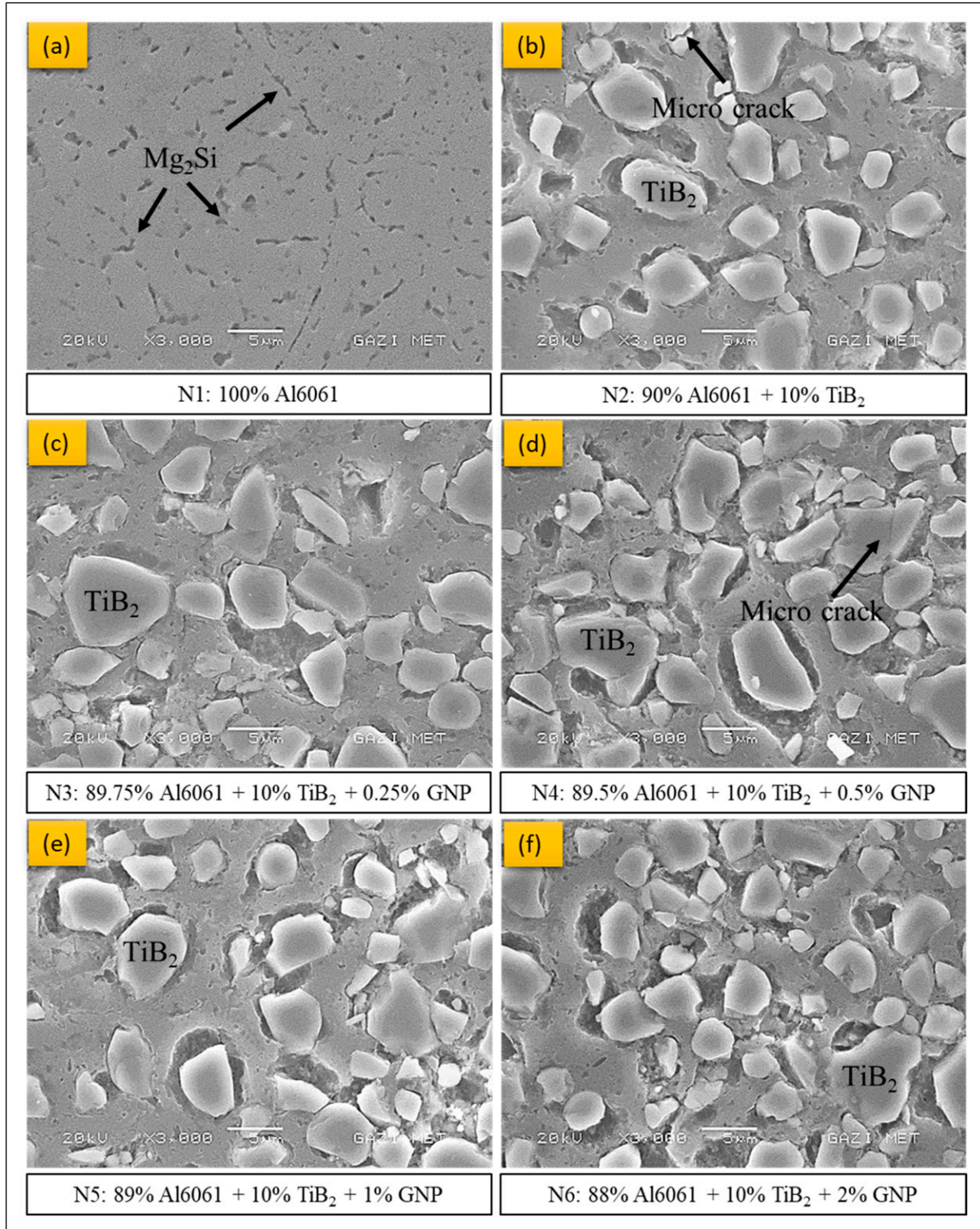


Figure 7. SEM micrographs of composites: (a) N1 (Al6061), (b) N2, (c) N3, (d) N4, (e) N5, (f) N6.

composites fabricated via powder metallurgy and hot pressing demonstrate controlled microstructural features through optimized reinforcement ratios and processing parameters.

The energy-dispersive X-ray spectroscopy (EDS) analysis presented in Figure 8 reveals distinct peaks corresponding to aluminum (Al), titanium (Ti), and carbon (C). The presence of these elemental peaks confirms the

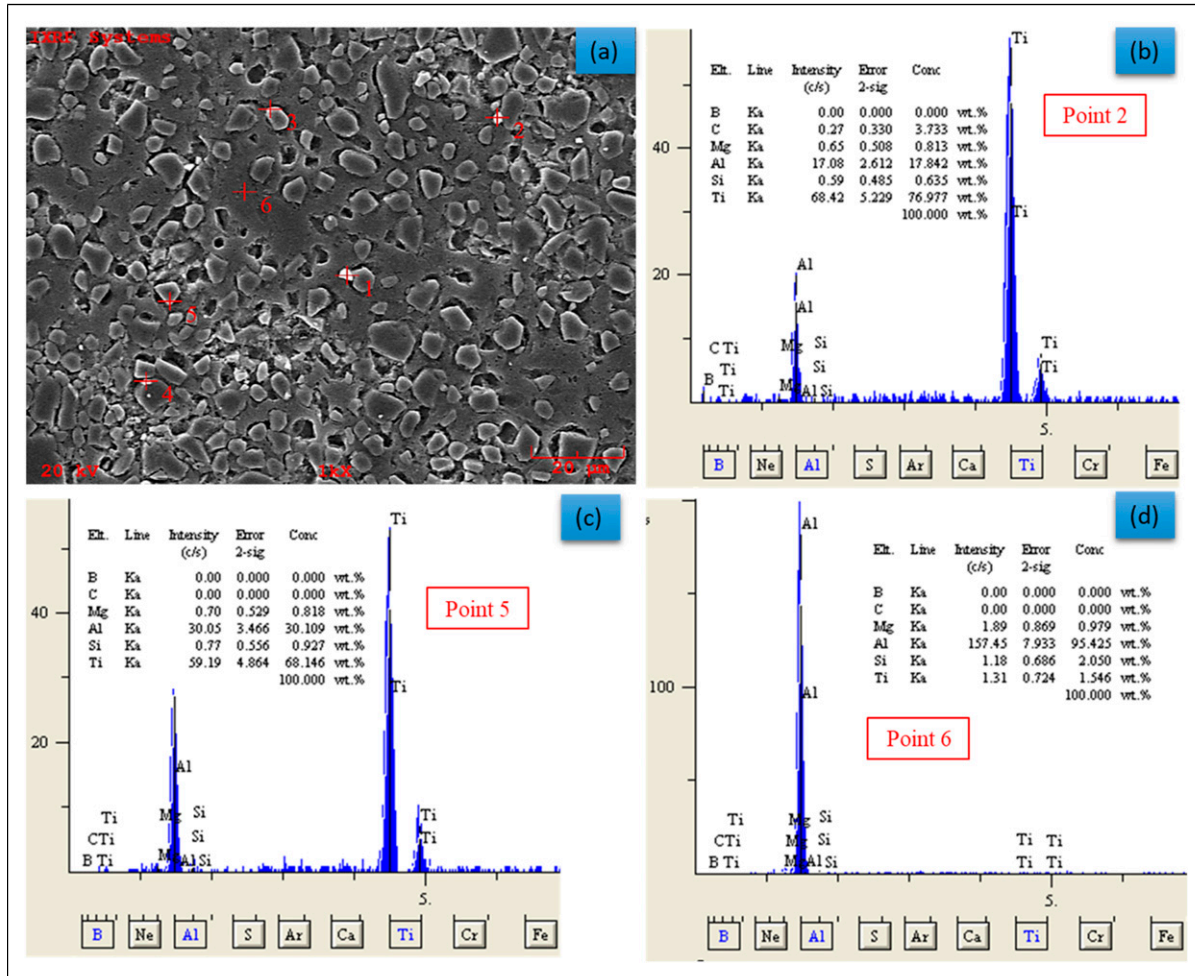


Figure 8. EDS spectrum of specimen N5 confirming elemental distribution.

successful incorporation and homogeneous distribution of the Al6061 matrix, TiB_2 particles, and graphene nanoplatelets (GNP) within the composite material. The EDS results further substantiate the effective interfacial interaction between the reinforcement phases and the matrix. Notably, the detection of titanium indicates that TiB_2 particles are well-dispersed within the matrix with minimal agglomeration. Similarly, the carbon peak verifies the presence of GNP, suggesting robust interfacial bonding that contributes positively to the overall composite integrity and stability.^{42,43} These findings are consistent with the microstructural observations obtained via SEM, collectively confirming the desired chemical composition and uniform reinforcement distribution, which underpin the composite's enhanced performance potential.

Mechanical properties

Table 3 presents the theoretical and experimental density values of the fabricated composites, while Figure 9(a) illustrates their corresponding relative density percentages.

The base material Al6061 exhibits a nominal density of 2.70 g/cm^3 , whereas the densities of the reinforcement materials TiB_2 and GNP are 4.52 g/cm^3 and 2.30 g/cm^3 , respectively. As the GNP content increases, a gradual decrease in both theoretical and experimental densities is observed, which can be attributed to the inherently low density of graphene nanoplatelets. Conversely, the incorporation of TiB_2 leads to an increase in overall density due to its significantly higher density compared to the matrix alloy. The highest relative density (99.04%) was recorded in the unreinforced Al6061 sample, while the lowest value (98.09%) was observed in the hybrid composite reinforced with 10% TiB_2 and 2% GNP. This reduction in relative density is primarily associated with the diminished compressibility of powder blends containing rigid and high-surface-area reinforcements. GNPs, owing to their lamellar morphology and tendency to restack or agglomerate, can act as barriers during compaction, limiting the formation of dense particle contacts and resulting in residual porosity. Similarly, the presence of TiB_2 particles, which may exhibit limited wettability and interfacial compatibility with the

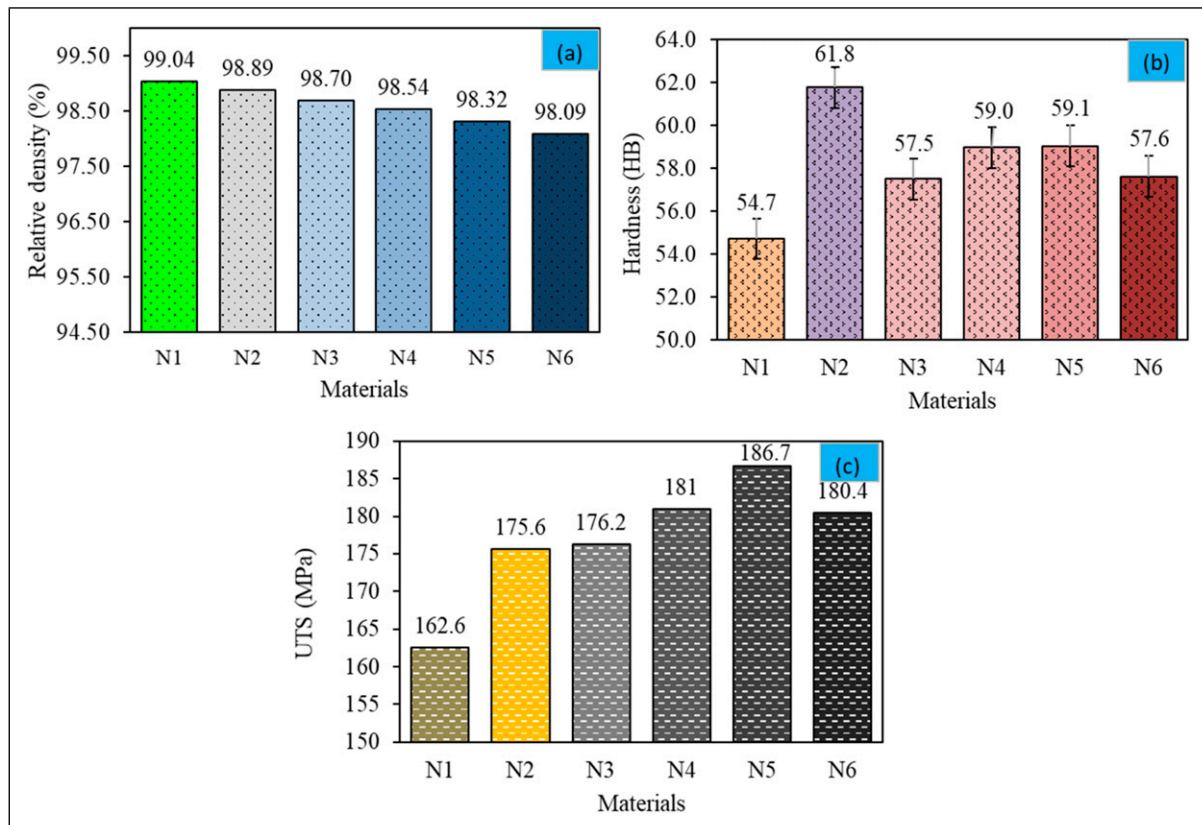
Table 3. Comparison of theoretical and experimental densities of the produced samples.

S. No.	Material composition (wt%)	Theoretical density (g/cm ³)	Experimental density (g/cm ³)	Porosity (%)
N1	100% Al6061	2.700	2.674	0.963
N2	90% Al6061 + 10% TiB ₂	2.882	2.850	1.110
N3	89.75% Al6061 + 10% TiB ₂ + 0.25% GNP	3.151	3.110	1.301
N4	89.5% Al6061 + 10% TiB ₂ + 0.5% GNP	3.150	3.104	1.460
N5	89% Al6061 + 10% TiB ₂ + 1% GNP	3.148	3.095	1.684
N6	88% Al6061 + 10% TiB ₂ + 2% GNP	3.144	3.084	1.908

aluminum matrix, can lead to localized microvoid formation at the particle-matrix interfaces. These findings are in good agreement with prior studies, which observed that increasing the volume fraction of ceramic or nanostructured reinforcements typically results in decreased relative density due to reduced packing efficiency and increased interfacial defects.⁴⁴ Reinforcement type, particle size, and processing parameters must be optimized to improve densification and minimize porosity in Al matrix composites.

The hardness values of the fabricated composite materials are presented Figure 9(b). Examination of the graph reveals that the highest hardness value was obtained in specimen 2, consisting of 90% Al6061 and 10% TiB₂. This result aligns with the reinforcing effect of TiB₂ particles due

to their inherently high hardness and ceramic nature, which effectively strengthen the matrix.⁴⁵ As the GNP content increased, a general decrease in hardness was observed. Literature reports indicate that when carbon-based nanoparticles such as GNP are not uniformly dispersed within the matrix, increased porosity and agglomeration occur at higher concentrations, adversely affecting mechanical properties.^{46,47} The findings of this study corroborate these observations. Under normal circumstances, since both TiB₂ and GNP possess higher hardness compared to Al6061, an increase in reinforcement content would be expected to enhance hardness.³³ However, with a constant TiB₂ fraction, the increase in GNP content led to a reduction in hardness, suggesting that the rise in porosity and particle clustering

**Figure 9.** (a) Relative density values of the fabricated composite specimens, (b) average hardness values of all composite groups, (c) tensile strength comparison of composite specimens.

negatively influenced the mechanical performance. Similarly, Saboori et al. (2019) reported an increase in porosity and a corresponding decrease in hardness with higher GNP contents.⁴⁷ Interestingly, hardness decreased up to 0.5% GNP addition but exhibited a slight increase at 1% GNP, which may indicate a more homogeneous distribution of GNP at this level, thereby contributing positively to the mechanical response. Beyond 1% GNP, the subsequent decline likely reflects more pronounced porosity and agglomeration effects. Overall, the present study demonstrates that while the addition of reinforcement phases improves composite hardness, excessive GNP content can induce microstructural defects that limit mechanical performance. The highest average hardness value was recorded as 61.775 HB in specimen 2 (%10 TiB₂), while the lowest was 54.725 HB in the pure Al6061 specimen.

As shown in Figure 9(c), the highest tensile strength was observed in specimen 5, containing 10% TiB₂ and 1% GNP, with an average value of 186.7 MPa, whereas specimen 2, reinforced solely with 10% TiB₂, exhibited the lowest tensile strength at 175.6 MPa. The unreinforced pure

Al6061 sample demonstrated an average tensile strength of 162.8 MPa (Figure 9(c)). The observed enhancement in tensile strength with increasing reinforcement content highlights the positive effect of TiB₂ addition on the composite's mechanical properties.⁴⁸ The incremental improvement in tensile strength with the addition of GNP at specific fractions (0.25%, 0.5%, and 1%) can be attributed to graphene's high surface area and excellent mechanical properties, which facilitate efficient load transfer within the matrix.⁴⁹ However, a decline in tensile strength at 2% GNP content is likely due to particle agglomeration and increased porosity, which introduce microstructural heterogeneities and stress concentration sites that detrimentally affect the composite's performance.⁵⁰ Supporting these findings, Yang et al.⁵¹ reported that while reinforcement particles inhibit dislocation movement, thereby enhancing strength, they concurrently reduce ductility and increase brittleness. Similarly, Sindhu et al. (2021) observed improvements in hardness and strength in TiB₂-reinforced Al matrix composites, but noted that excessive reinforcement adversely impacted powder compaction efficiency and relative

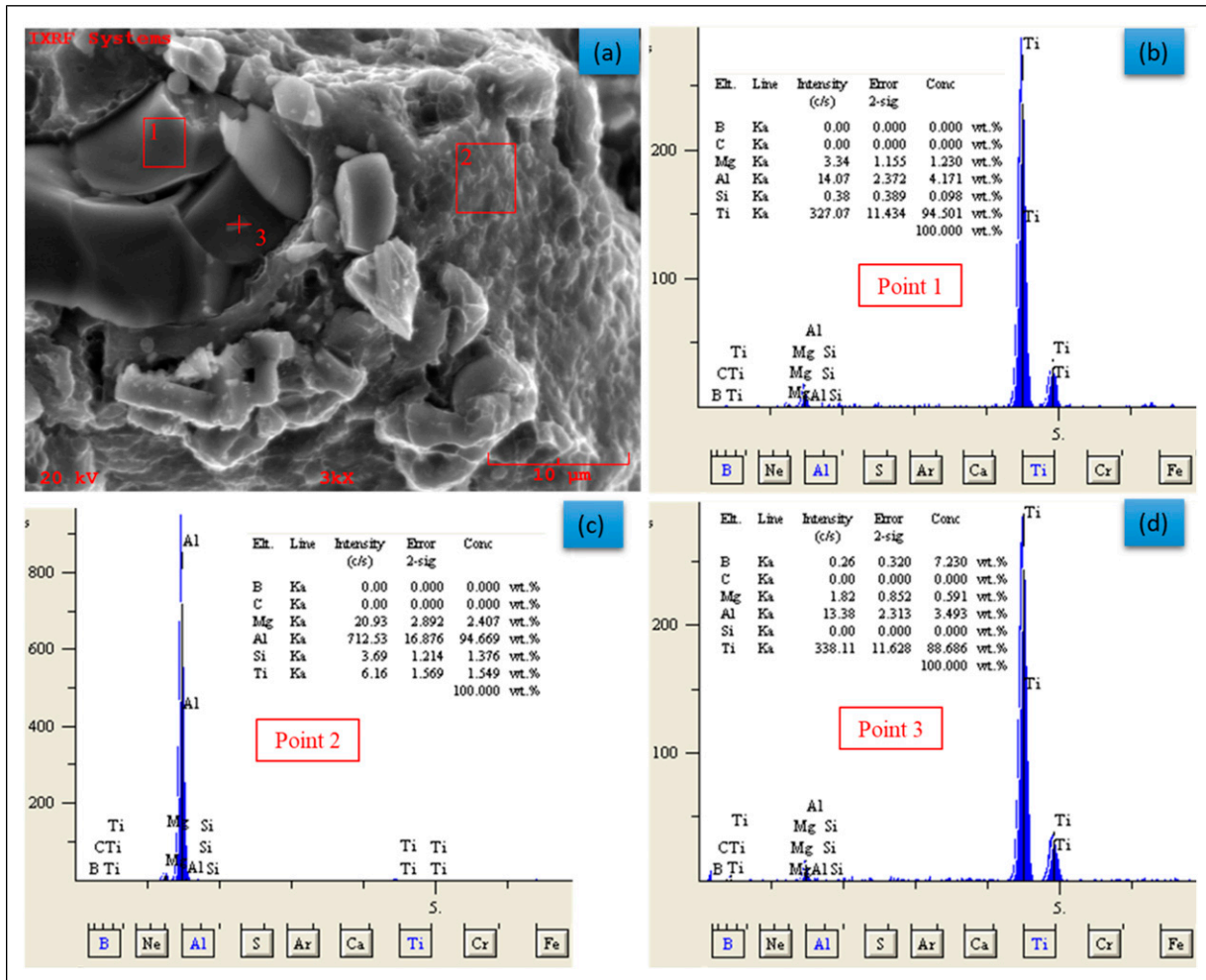


Figure 10. (a) SEM fracture image of specimen N3, (b) and (c) EDS spectra of two selected points on the fracture surface.

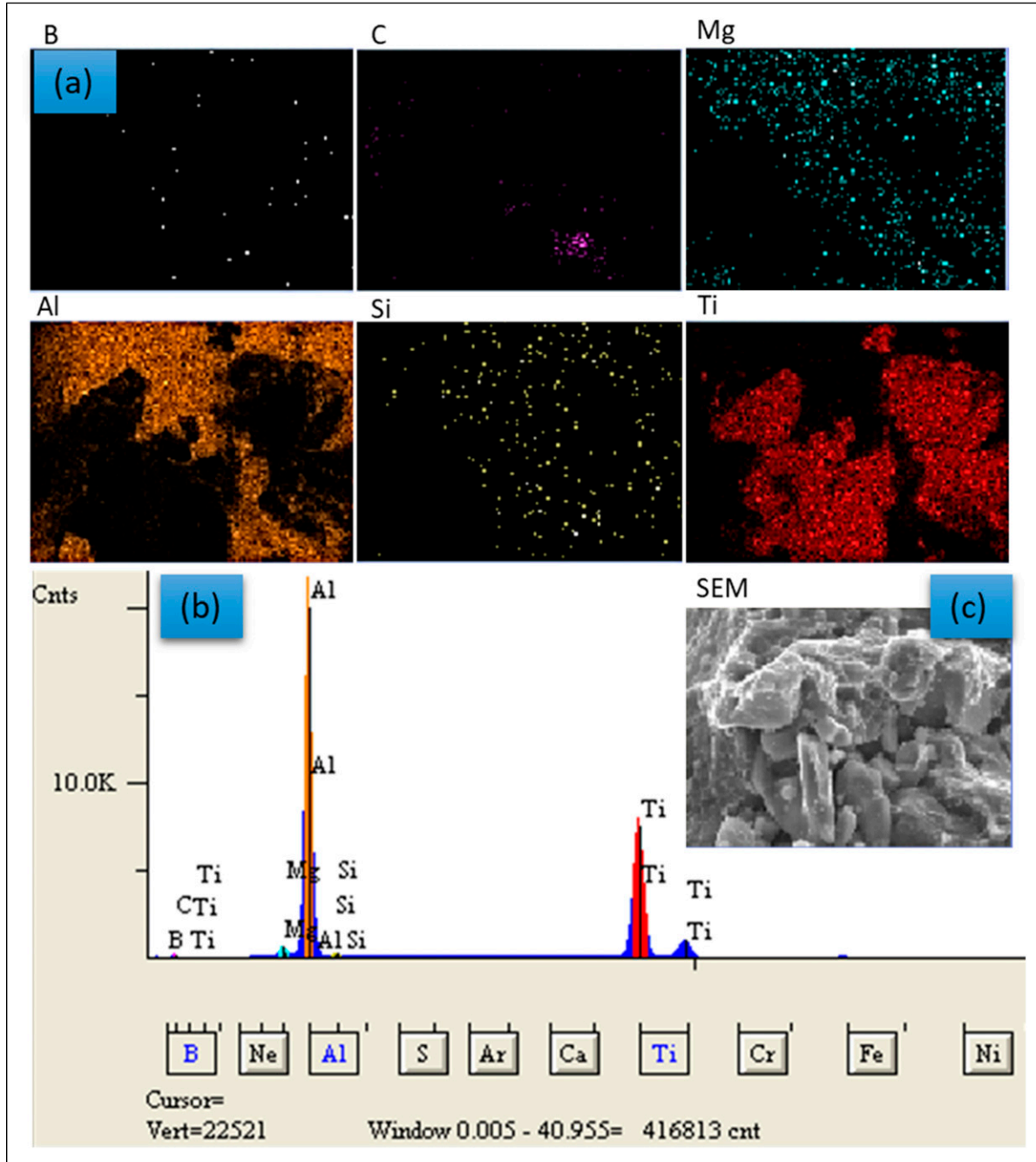


Figure 11. (a) EDS and (b) elemental mapping of the fracture surface in specimen N5.

density.⁵² Therefore, optimizing the reinforcement fraction is critical to balancing mechanical performance and processability. Overall, the present study demonstrates a synergistic effect of TiB_2 and GNP reinforcements in improving tensile strength, while also emphasizing that excessive GNP content may lead to agglomeration and microstructural defects that compromise mechanical integrity.

The mechanical strengthening trends observed in this study are in close agreement with previous investigations on Al6061 composites reinforced with TiB_2 and graphene-

based reinforcements. Şenel and Demir⁵³ reported that incorporating only 0.15 wt.% graphene into Al6061 increased hardness from 95 HV to 151 HV and compressive strength from 253 MPa to 395 MPa, while reducing the friction coefficient to 0.23. Likewise, Sendhil Kumar et al.⁵⁴ found that 10 wt.% graphene improved tensile strength by about 60% and enhanced impact resistance. Gobiraman et al.⁵⁵ observed a 22.9% decrease in specific wear rate with GNP reinforcement, emphasizing the solid-lubricating effect of graphene layers. In addition, Kumar et al.⁵⁶ demonstrated

that Al6061–6 wt.% TiB₂–4 wt.% graphite composites exhibited ~21%–29% higher hardness and tensile strength due to effective particle–matrix load transfer. These trends are consistent with the present findings, where the 10 wt.% TiB₂ + 1 wt.% GNP composite showed the highest combination of hardness (61.8 HB) and tensile strength (186.7 MPa). The synergistic action of TiB₂ (grain refinement and Orowan strengthening) and GNP (crack-bridging and tribofilm formation) resulted in a balanced mechanical–tribological response, demonstrating that the developed hybrid composite is both competitive and usable compared with other Al6061-based systems.^{56–58}

Fractured surface after tensile test

Figure 10 presents the SEM images of the fracture surface of specimen 3, along with EDS analyses conducted on regions labeled 1, 2, and 3. The EDS results confirm the presence of TiB₂ and Al in the analyzed areas. In Region 1, a high concentration of titanium was detected, indicating the presence of TiB₂ particles. Region 2 predominantly exhibited aluminum, magnesium, and silicon, which are the primary alloying elements of the Al6061 matrix. In Region 3, the presence of Ti and B elements further confirmed the localization of TiB₂ reinforcement. Moreover, at the interface between Regions 1 and 3, a TiB₂ particle was observed to initiate a microcrack. This suggests that under applied tensile loading, the stress was transferred from the matrix to the reinforcement through the interfacial bond, resulting in localized stress concentration and subsequent fracture initiation. This behavior underscores the critical role of the matrix–reinforcement interface in determining the fracture characteristics of metal matrix composites.

Figure 11 presents the SEM images, EDS, and MAP analyses of the fracture surfaces of selected samples. Consistent with the polished surface observations, the presence of TiB₂ and GNP particles embedded within the Al6061 matrix was clearly confirmed. The fracture morphology exhibits a predominantly brittle fracture mode, characterized by relatively flat and faceted surfaces, indicative of cleavage with limited plastic deformation. Closer inspection reveals that the reinforcement particles remained well bonded within the matrix and were not dislodged during fracture, suggesting strong interfacial adhesion and effective load transfer under mechanical stress. This behavior reflects the mechanical compatibility and integrity of the composite system. Additionally, localized regions of porosity were observed, likely arising due to the restriction of plastic flow around the stiff reinforcement particles. These particles act as stress concentrators, initiating void formation in areas of matrix weakness. Although the pores are sparse and small, they underscore the importance of homogeneous particle dispersion and optimized interfacial engineering in enhancing structural performance.

The corresponding SEM images of the samples are presented in Figure 12. In metal matrix composites (MMCs), fracture behavior is generally governed by three primary

mechanisms related to the matrix material, reinforcement particles, and the matrix–particle interface. When localized stresses exceed the fracture strength of the reinforcement particles, particle fracture occurs (Mechanism 1). If the stresses surpass the interface bonding strength but remain below the particle fracture strength, debonding at the matrix–particle interface takes place (Mechanism 2). Lastly, if both the interface and reinforcement particles are significantly stronger than the matrix, fracture occurs via void or pore formation within the matrix (Mechanism 3).⁵⁹ In this study, SEM and macrostructural examinations of the fracture surfaces revealed predominantly ductile fracture with significant plastic deformation in the unreinforced Al6061 matrix. However, with increasing reinforcement content—particularly due to the addition of hard ceramic TiB₂ particles—more distinct brittle fracture features such as cleavage facets were observed, indicating an increase in matrix hardness accompanied by a reduction in ductility.⁶⁰ The embedding of TiB₂ particles within the fracture surfaces confirmed a strong interfacial bonding between the matrix and the reinforcement, which plays a critical role in the enhancement of mechanical properties.⁶¹ It was observed that with increasing reinforcement content, particle fracture and interfacial debonding become more prominent fracture mechanisms, consistent with findings in similar Al-based composites.⁶² Furthermore, the influence of varying graphene nanoplatelet (GNP) contents on fracture behavior was noted. Low GNP concentrations appeared to promote crack bridging, thereby improving toughness, whereas higher GNP contents resulted in increased agglomeration and porosity, which intensified stress concentration and led to premature fracture.⁶³ Fractographic SEM analyses demonstrated distinct fracture behaviors in Al6061 matrix composites reinforced with varying amounts of TiB₂ and graphene nanoplatelets (GNP). The unreinforced Al6061 sample (N1) predominantly exhibited ductile fracture characteristics, as evidenced by widespread deep dimples on the fracture surface. Introduction of 10% TiB₂ in specimen N2 led to increased occurrences of interfacial debonding and microcrack formation, consistent with the expected brittleness induced by hard ceramic reinforcements restricting dislocation motion.⁶⁴ In specimen N3 (0.25% GNP), ductile features like dimples remained visible, though localized microcracks began to emerge at the matrix–particle interface. Increasing GNP to 0.5% (N4) intensified interfacial debonding and microcrack density due to agglomeration and void formation.⁶⁵ In N5 (1% GNP), improved dispersion enhanced dimple formation and mechanical integrity, consistent with literature on optimal GNP content and stress distribution.⁶⁶ However, at 2% GNP (N6), excessive agglomeration and porosity led to brittle fracture, with dominant microcracks and interfacial separation.

Tribological behavior of the composites

Effect of the weight percentage of reinforcement, sliding distance and load on the volume loss. The influence of TiB₂ and GNP

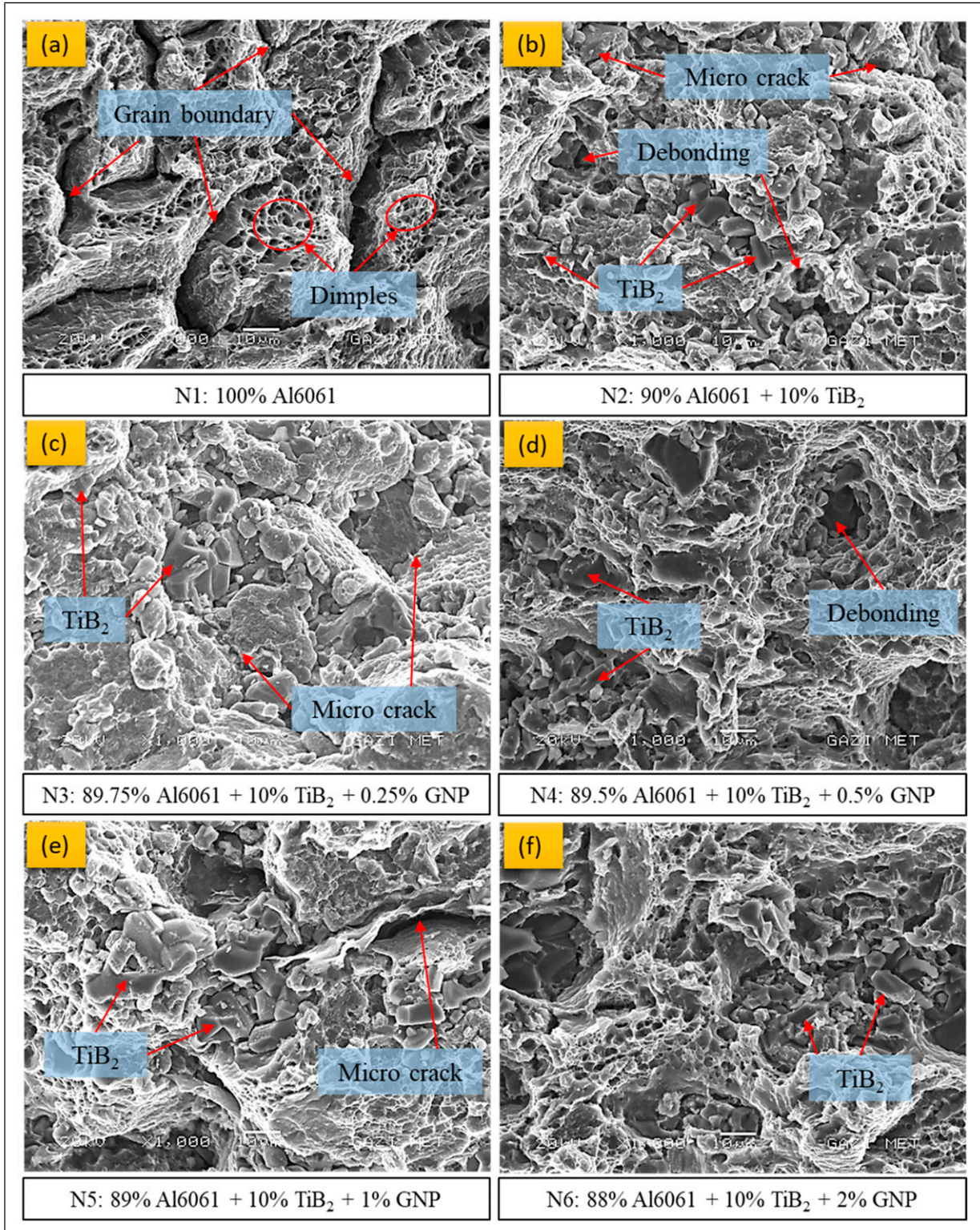


Figure 12. High-resolution SEM images showing fracture morphology of all specimens.

weight percentages on the abrasive wear resistance of the hybrid composites is presented in Figure 13 under various applied loads and sliding distances. As observed, wear resistance improves with the optimized addition of TiB_2 and

GNP. Specifically, volume loss increases with higher normal loads and longer sliding distances across all samples. The unreinforced Al6061 exhibited the highest volume loss, which can be attributed to its relatively low hardness. This

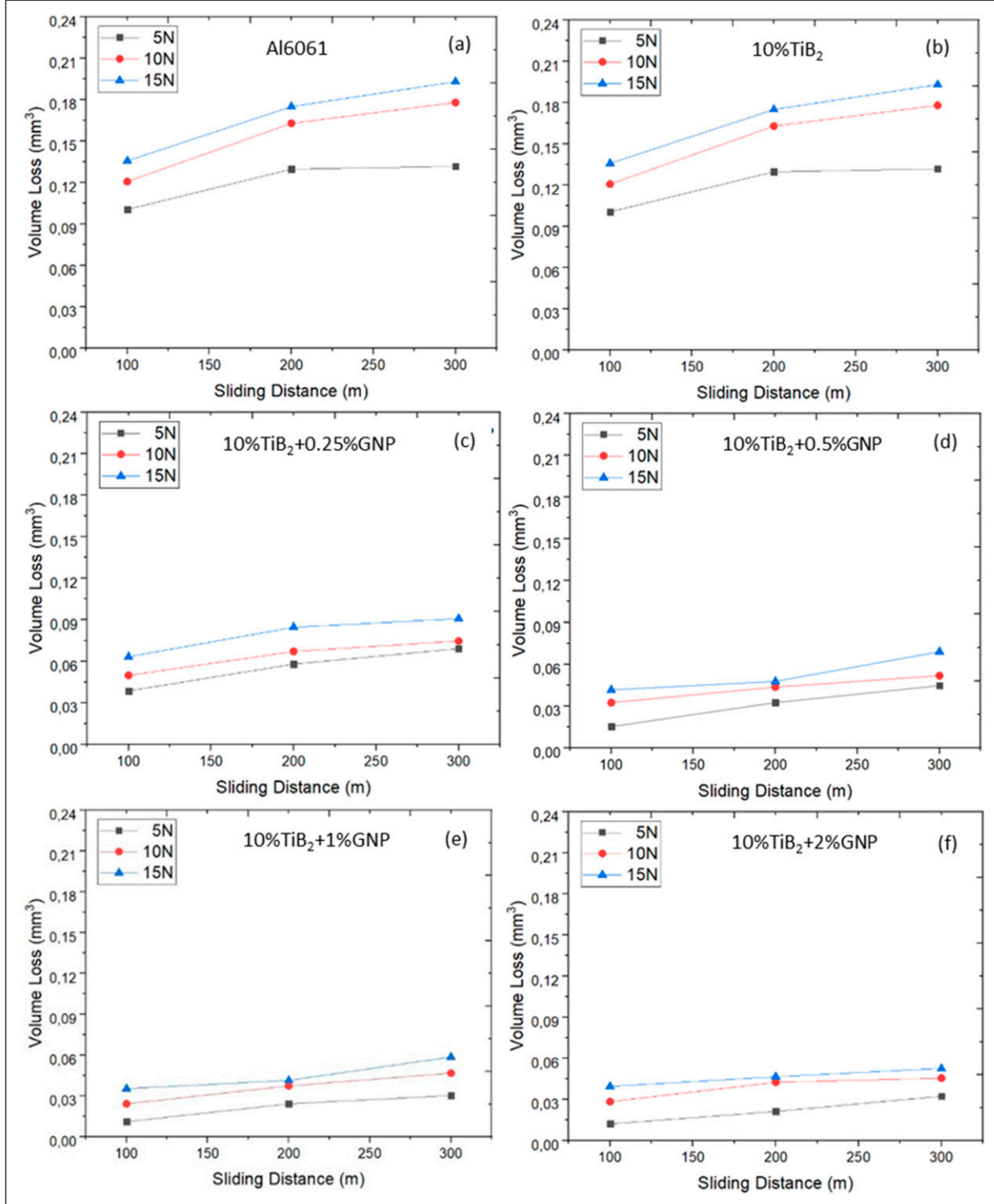


Figure 13. Volume loss vs. sliding distance under different loads for: (a) Al6061, (b) 10% TiB_2 , (c) 10% TiB_2 +0.25%GNP, (d) 10% TiB_2 +0.5%GNP, (e) 10% TiB_2 +1%GNP, (f) 10% TiB_2 +2%GNP.

observation aligns with previous findings, where softer materials typically exhibit greater material removal under abrasive conditions.⁶⁷ The incorporation of TiB_2 and GNP notably reduced the volume loss, with the lowest wear observed in the composite containing 10 wt.% TiB_2 and 1 wt.% GNP. The enhanced wear resistance is partially due to the self-lubricating nature of GNPs, which helps reduce the contact area between the interacting surfaces during sliding. As GNP content increases, the formation of a lubricating film becomes more pronounced, effectively lowering friction and reducing material removal.⁶⁸ However, it is important to note that excessive GNP content can lead to reduced effectiveness of the self-lubricating mechanism. Overloading may promote agglomeration, which inhibits uniform film formation and can deteriorate tribological performance. Liyun et al.⁶⁹ also emphasized the role of GNPs in enhancing wear resistance through their wrapping effect on wear debris and bridging behavior at subsurface cracks, which contribute to maintaining structural integrity during sliding. Additionally, previous studies have reported the formation of a stable mechanically mixed layer (MML) on the worn surfaces of GNP-reinforced composites during wear tests.⁷⁰ This layer acts as a barrier that reduces direct metal-to-metal contact, thereby lowering friction forces and enhancing overall wear resistance.

Effect of the weight percentage of reinforcement, sliding distance and load on the friction coefficient. The friction coefficient

(COF) is one of the key indices used to evaluate the wear resistance of hybrid metal matrix composite properties. To examine the influence of GNP weight percentage on the coefficient of friction (COF) in hybrid composites, wear tests were conducted under a constant normal load of 15 N. Figure 14 presents the COF values of both Al6061 and the hybrid composite samples as functions of sliding distance under different reinforcement conditions. As shown in Figure 14, the weight percentages of TiB_2 and GNP directly influence the COF of the samples. The addition of GNP significantly reduces the friction force due to its self-lubricating properties. Therefore, the lowest COF, 0.3, was obtained for the 10 TiB_2 -1GNP sample. On the other hand, the Al 6061 samples exhibited the highest COF (0.6). Due to insufficient self-lubricating effects, higher COF values were obtained at lower GNP contents (Figure 14). GNPs provide interlayers and tribofilms at the contact interface. Interlayer sliding of GNPs occurs due to weak van der Waals interactions; therefore, the COF can be reduced.⁷¹ Crack initiation is also eliminated because the tribofilms have a wrapping effect.⁷² Previous studies have also shown that a stable mechanically mixed layer (MML) can form on the worn surface by adding GNP, which decreases the friction between contact pairs.⁷³

Effect of the weight percentage of reinforcement, sliding distance and load on the wear rate. To investigate the relationship between the reinforcement wt.% of GNP, sliding distance,

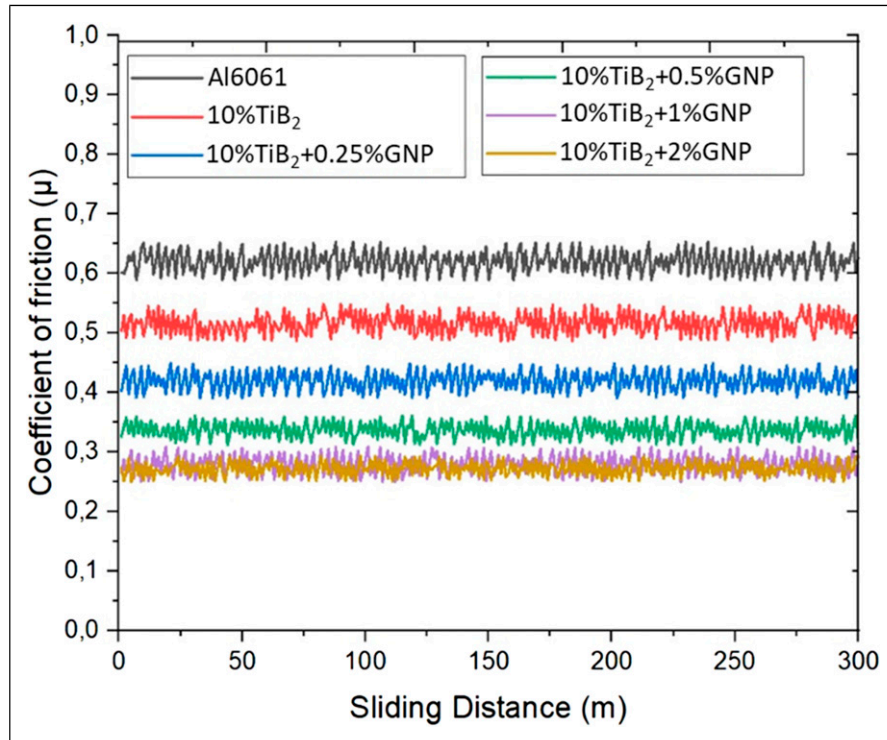


Figure 14. Friction coefficient vs. sliding distance under 15 N load for all composites.

and applied load, the wear rate was calculated. The variation of wear rate with normal load for Al6061, Al6061–0.5 wt.% GNP, Al6061–1 wt.% GNP, Al6061–1.5 wt.% GNP, and Al6061–2 wt.% GNP is presented in Figure 15.

It can be clearly observed that the wear rate increases with increasing normal load and sliding distance. This result

can be attributed to the hardness of the counter surface, as the temperature at the interface of the counter surface increases with increasing load and sliding distance.⁷⁴ The Al6061–1 wt.% GNP samples exhibited the lowest wear rate, recorded as $4 \times 10^{-8} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 5 N under a 100 m sliding distance. In contrast, the Al6061 base alloy showed the highest wear rate, measured as $2.5 \times 10^{-8} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at

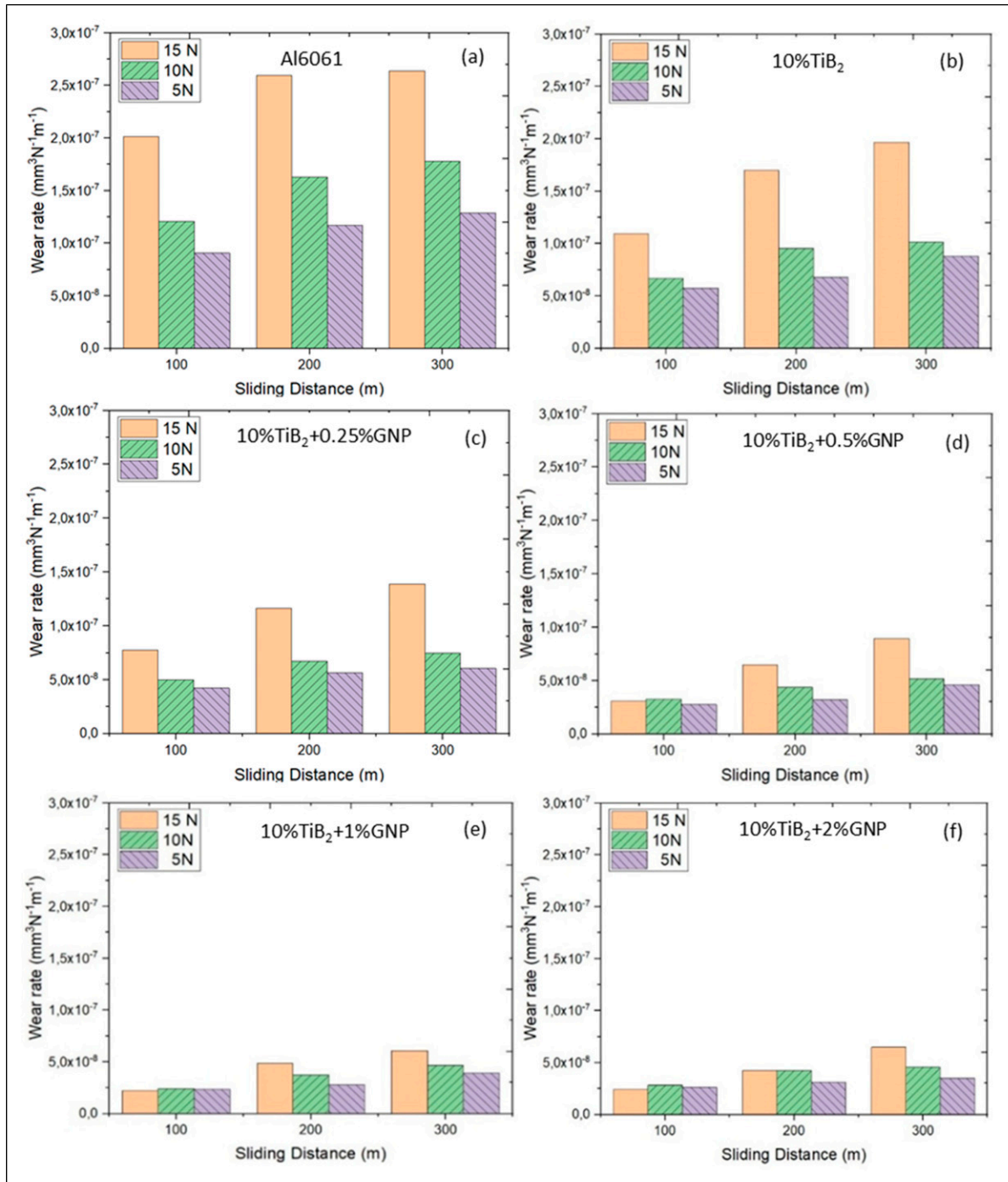


Figure 15. Volume loss vs. sliding distance under all loads for: (a) Al6061, (b) 10%TiB₂, (c) 10%TiB₂+0.25%GNP, (d) 10%TiB₂+0.5%GNP, (e) 10%TiB₂+1%GNP, (f) 10%TiB₂+2%GNP.

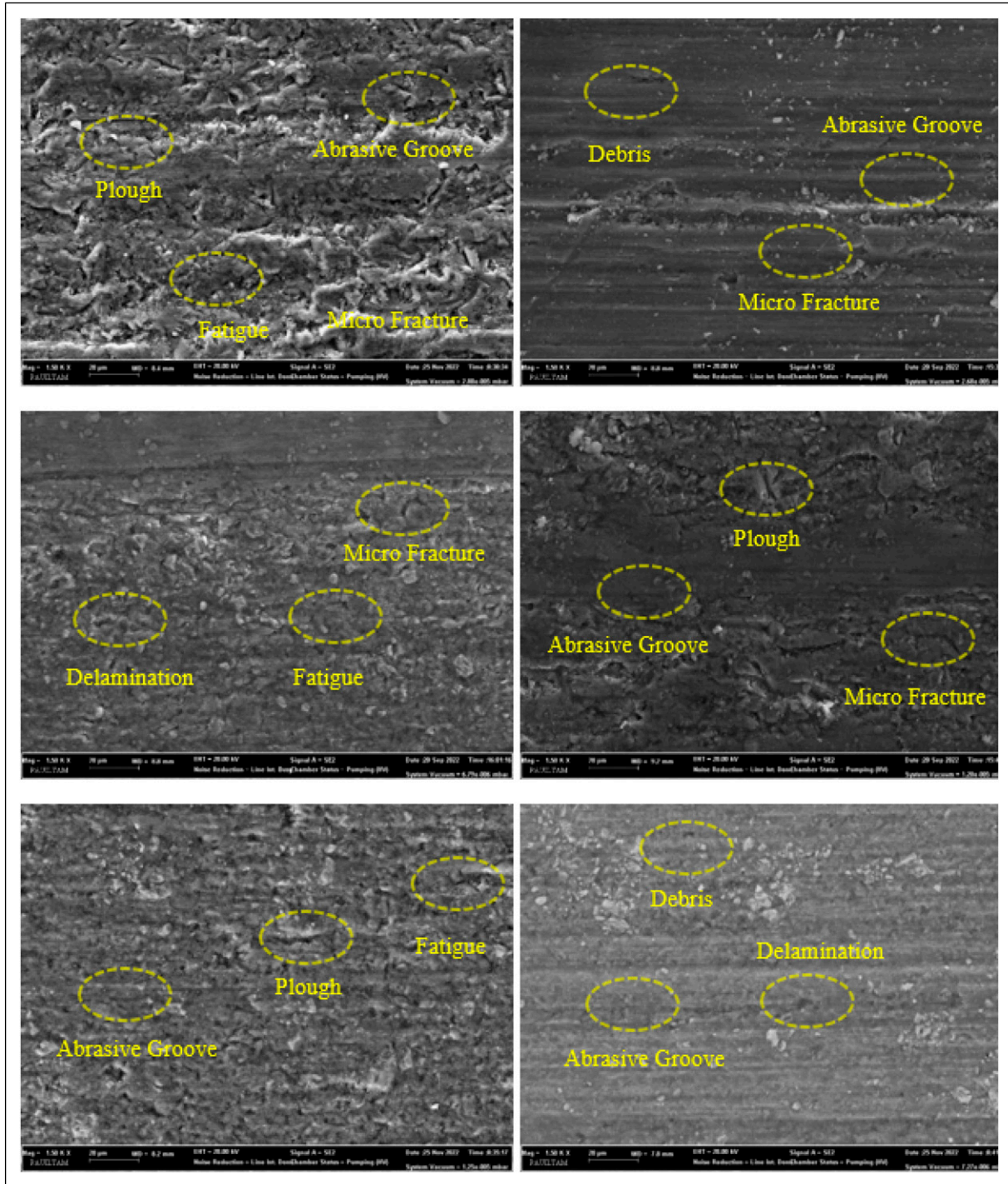


Figure 16. SEM images of worn surfaces after wear testing: (a) Al6061, (b) 10TiB₂, (c) 10TiB₂+0.25GNP, (d) 10TiB₂+0.5GNP, (e) 10TiB₂+2GNP, (f) 10TiB₂+1GNP.

15 N under a 300 m sliding distance. The higher wear rate can be explained by the increased friction between the contacting surfaces.⁵³

Effect of the weight percentage of reinforcement worn surface. Worn surfaces characterization with SEM of all

samples under various normal loads and sliding distance are performed in order to define wear mechanisms. Micro cutting, Plough, Micro Fracture, Micro Cutting, Abrasive and Fatigue wear mechanism were distinguished for all samples. In the wear behavior investigation of aluminum MMCs, the common wear mechanisms involve fatigue,

abrasive, and delamination wear.⁷⁵ In wear mechanisms, the graphene improves to limiting the wear.^{75,76} Delaminated zone due to adhesion are also observed on the worn surface. Generally shallow and narrow wear grooves are shown on the worn surface. As shown in Figure 16, delamination of Al6061-1. wt.% GNP samples are significantly less than all other samples. Al 6061 samples show deeper abrasive grooves when compared to other samples. The worn surface analysis show that the wear mechanism changes from abrasive wear to delamination, severe plastic deformation and fatigue mechanism and with the increasing wt.% GNP The examination of worn surfaces is clearly showed that wear mechanisms can be controlled with optimization of wt.% GNP.

Characterization of wear map mechanisms. The wear mechanisms observed under all wear conditions are illustrated in Figure 17. As shown in Figure 18, micro cutting is dominant

wear mechanism under lower cutting force and sliding distance. Wear maps are also created in Order to investigate wear mechanism characterization of GNPs reinforced hybrid metal matrix composite (Figure 18). It is well known that wear mechanism changes under various wear conditions.⁷⁷ Fatigue and Micro Fracture wear mechanisms become active mechanisms under over wear conditions. Plough mechanism observed under all wear conditions. It is also defined severe mechanism because of severe plastic deformation while mild mechanisms are observed under lower normal load and sliding distance. Because of hardening and embrittlement performed under over wear conditions.⁷⁸ The trend of volume loss decline varied with changes in wear conditions.

It is well established that wear mechanisms evolve depending on the severity of the wear conditions. Under extreme conditions, fatigue and micro-fracture become the

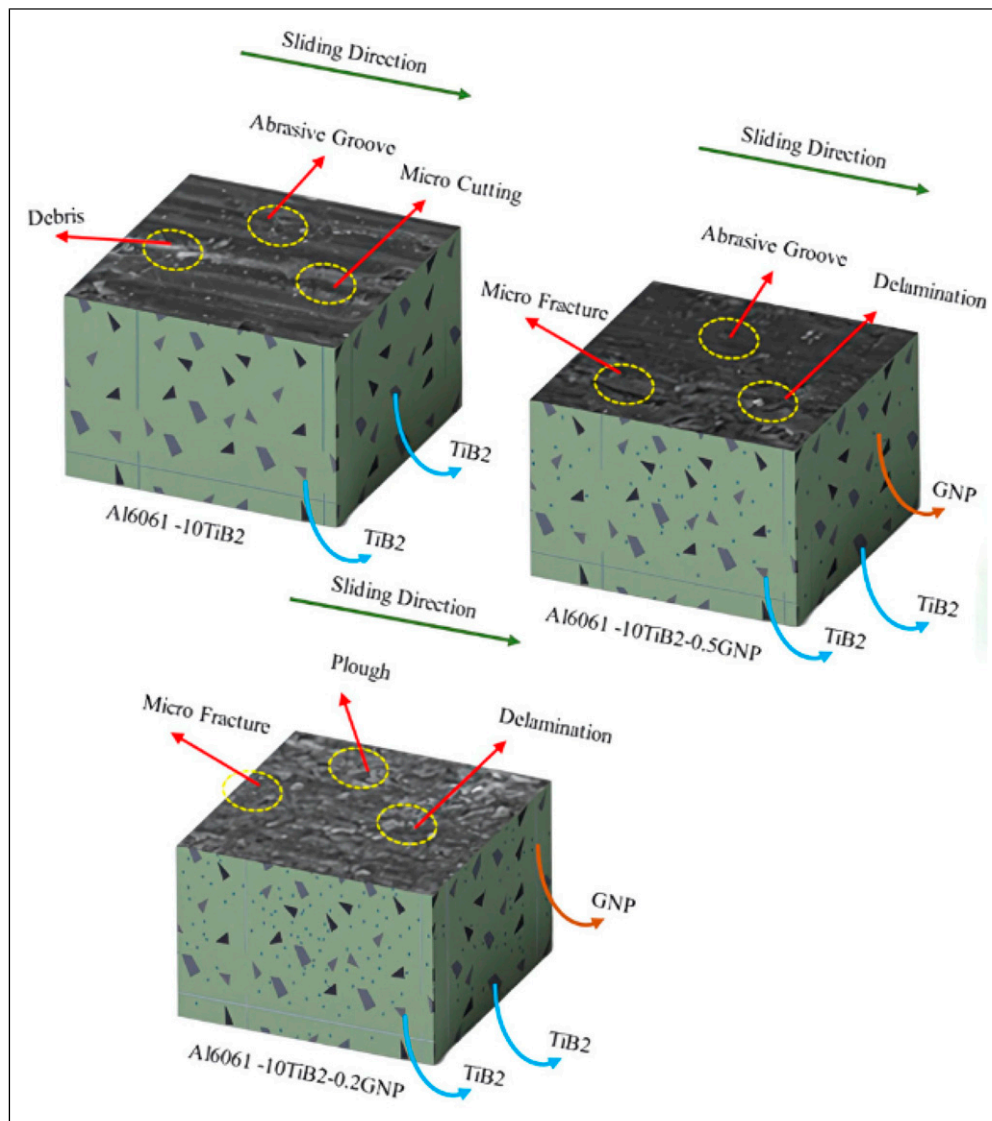


Figure 17. Schematic illustration of dominant wear mechanisms under varying loads.

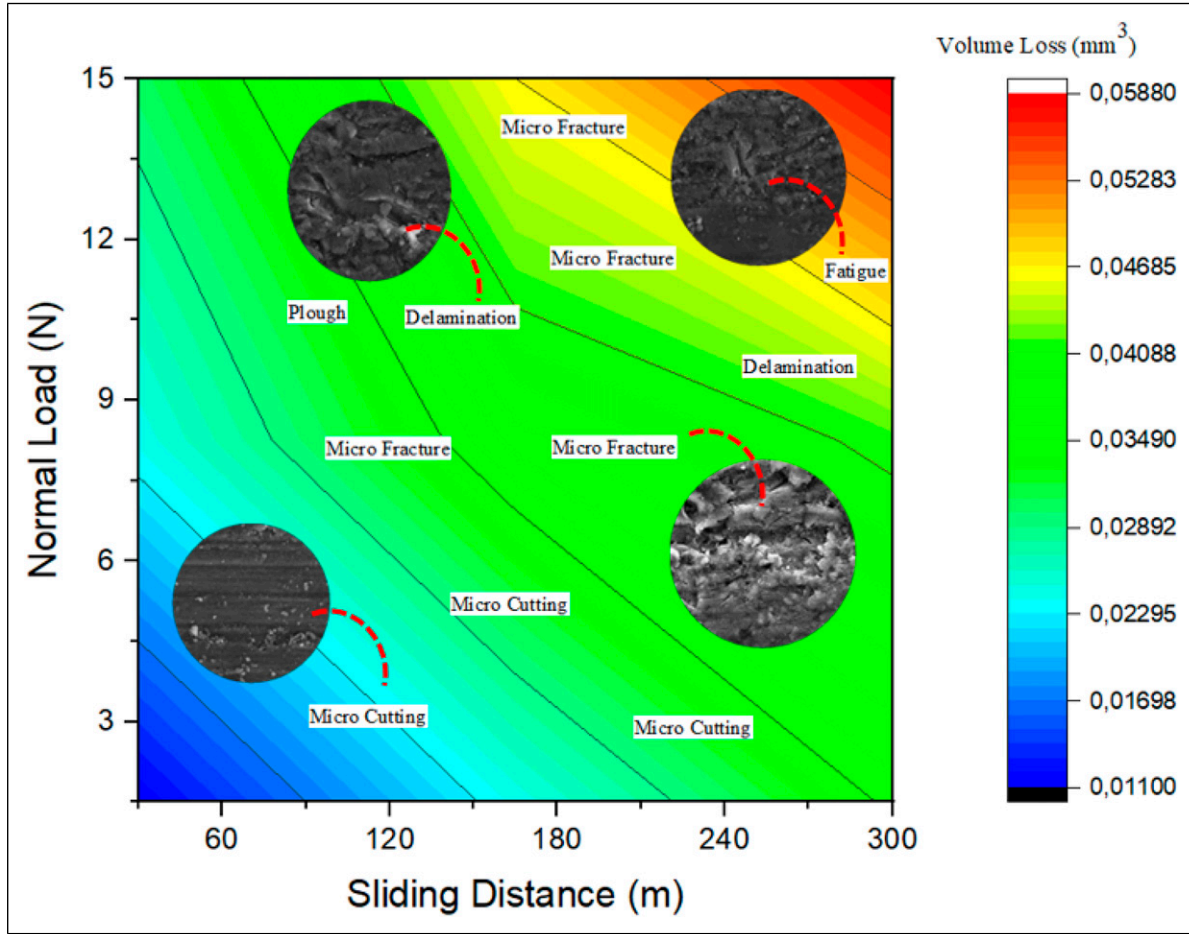


Figure 18. Distribution of wear mechanisms as a function of sliding distance and load.

dominant wear mechanisms. Grooving, however, is observed under all test parameters. At lower applied loads and shorter sliding distances, shallow grooves are typically formed, whereas under severe plastic deformation, more pronounced and deeper grooves are evident. This phenomenon is likely attributed to hardening and embrittlement of the surface layer occurring under excessive wear conditions. The trend of volume loss reduction varies with changes in wear conditions, indicating a transition in the dominant wear mechanism. Consistent with findings in the literature, the addition of graphene particles as a solid lubricant to Al6061 aluminum alloy has been shown to improve its tribological performance by reducing friction and wear rates, particularly under high-stress conditions.⁷⁹

Conclusion

In this study, nano-hybrid Al6061-based composites reinforced with titanium diboride (TiB_2) and graphene nanoplatelets (GNPs) were successfully synthesized through a powder metallurgy route, followed by T6 heat treatment. The synergistic effects of TiB_2 and GNP

additions on microstructural integrity, mechanical performance, and tribological behavior were systematically analyzed. The following key conclusions were drawn.

- The optimal relative density of 98.7% was obtained in the composite containing 10 wt.% TiB_2 + 0.25 wt.% GNP, reflecting superior compaction and minimal porosity at low GNP contents. Conversely, a slight density reduction at higher GNP loadings (98.09% for 2 wt.% GNP) was attributed to the restacking and agglomeration tendency of GNPs, leading to incomplete sintering and reduced compressibility.
- SEM and EDS results confirmed a uniform dispersion of reinforcements at low GNP concentrations, while excessive loading led to microstructural heterogeneity and interfacial porosity. The formation of fine Mg_2Si precipitates, grain refinement via TiB_2 , and the presence of uniformly distributed GNPs promoted interfacial integrity and thermal stability.
- XRD analysis confirmed the presence of primary phases (Al, TiB_2 , GNP) with no deleterious intermetallic formation such as Al_4C_3 or AlB_2 ,

underscoring the thermal compatibility and chemical stability of the composite system during processing.

- The highest hardness (61.775 HB) was observed in the 10 wt.% TiB₂-reinforced composite, demonstrating the intrinsic contribution of ceramic particles. However, increasing GNP beyond 0.25 wt.% reduced hardness due to clustering and interfacial discontinuities. In tensile tests, the optimal strength (186.7 MPa) was achieved at 1 wt.% GNP, benefiting from dislocation blocking and crack-bridging mechanisms. A decline beyond this threshold highlighted the negative effects of nanoparticle agglomeration on load transfer efficiency.
- Fractography revealed a transition from ductile failure in monolithic Al6061 to quasi-brittle behavior in reinforced samples. Dimples in the base alloy were replaced by cleavage planes, interfacial cracks, and voids in composites with higher reinforcement levels. Notably, 0.5–1 wt.% GNP composites exhibited improved fracture toughness, indicative of effective stress redistribution and bridging action.
- The hybrid reinforcement significantly improved wear resistance, particularly in the 10 wt.% TiB₂ + 0.5 wt.% GNP composite, which exhibited the lowest volume loss. This was ascribed to increased surface hardness, the formation of protective tribofilms, and the development of a mechanically mixed layer (MML) that resisted abrasion and plastic deformation.
- GNP addition markedly reduced the coefficient of friction (COF) owing to its solid-lubricant nature. The lowest COF (0.3) was achieved with 1 wt.% GNP, driven by the formation of lubricating films and van der Waals-assisted interlayer shearing. However, excessive GNP content reduced the efficiency of lubrication due to agglomerate-induced surface defects.

In summary, the strategic integration of TiB₂ and GNP in Al6061 matrix composites offers a promising pathway for tailoring lightweight, wear-resistant, and structurally robust materials. The optimal reinforcement window (10 wt.% TiB₂ + 0.5–1 wt.% GNP) delivers balanced mechanical and tribological performance, making it suitable for advanced engineering applications requiring simultaneous strength, durability, and frictional stability.

Acknowledgements

We thank the authors Hidrolift for their support in the preparation of mechanical test specimens. In addition, as the authors, we would like to thank Döksan Isıl Process Company for their support in hardness measurements.

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Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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