

Mechanical & Tribological Characterization of Al2024-Alumina-Graphite Reinforced Monolithic and Hybrid Composites

M. Yashwanth Kumar^{1*}, T. Vijayakumar² and R. Dhanasekaran³

Abstract

This work investigates the mechanical characteristics of Al2024-Al₂O₃-Graphite reinforced monolithic and hybrid composites fabricated by the stir casting method. Exploratory work involved the fabrication of monolithic composites with varying Al₂O₃ contents (5-8 wt%) and hybrid composites with the ratios of Al₂O₃ (2-6 wt%) and Graphite (1-3 wt%) in matrix Al2024. For improving their dispersion, preheated reinforcement particles were introduced in matrix alloy at controlled stirring rates. A homogeneous particle distribution with a clustering coefficient below 0.15 and an appropriate mean inter-particle spacing of $12.5 \pm 2.3 \mu\text{m}$ was validated by quantitative microstructural analysis using image analysis software. Mechanical tests were done on the produced composites in order to analyse their mechanical and tribological characteristics. The development of graphite tribofilms during sliding wear was validated by post-wear surface characterization using SEM-EDS mapping and Raman spectroscopy. The results demonstrate that hybrid composites have enhanced mechanical and tribological properties relative to both the reference Al2024 alloy and monolithic composites. Surprisingly Hardness of hybrid composites, Sample 3 (Al2024 + 2% Al₂O₃+ 1% Graphite) and Sample 4 (Al2024 + 6% Al₂O₃ + 3% Graphite) were highly improved with samples showing 28% and 35% improvements in hardness, respectively, over the reference alloy. Besides, hybrid composite wear resistances were better than those of monolithic composites, which testified to the synergistic reinforcement effect of Al₂O₃ and Graphite. Comparative study with recent literature demonstrates that the current hybrid composites achieve greater performance compared to Al₂O₃-graphene (48% hardness increase vs. our 35%) and Al₂O₃-B₄C systems reported in high-impact journals. Yet, attempts at incorporating increased reinforcement levels (Al₂O₃ 9% and Graphite 5%) failed because of agglomeration problems. The findings imply that hybrid composites provide an affordable option with improved mechanical properties and more effective alternative to monolithic composites reinforced by Al₂O₃ alone.

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INTRODUCTION

Aluminium 2024 (Al2024) is a high-strength aluminium alloy primarily composed of aluminium, copper (3.8–4.9%), and small amounts of magnesium and manganese. In aerospace and braces, it has become popular and appreciated for its high strength-to-weight ratio along with its fatigue resistance. However, unlike other alloys, Al2024 has relatively low resistance to corrosion and cannot be welded without a protective coat on it; in such cases, special welding techniques need to be adopted. Aluminium-BN composites fill the gap for the

industries reinforced composites which are efficient load bearing agents, needing high strength, hardness and wear resistance. Boron carbide and graphene reinforced Aluminium hybrid composites, for example, used in the industries maintained the tribological and mechanical properties with composites homogeneity as well as high ductility.[1] Aluminium alloy composite reinforced with the other reinforcements exhibited the more than superior performance in ductility and wear resistance.[2] [7-9] [11] Concentrated layers of boron carbide and aluminum alloy Al-1100 with graphite were consolidated per low temperature processing, transforming the surface mechanical properties.[3] Composites made of Al2214 alloy, boron carbide and graphite particles additionally, have better mechanical and wear properties.[4] Different volume fractions of MoSi₂ particles reinforced with AA2024 by mechanical alloying technique results in increased hardness and wear resistance [5]. Repetitive Corrugation and Straightening method used on Al2024 has shown to be a valuable tool in refining the grains as well as the mechanical characteristics [6]. Friction and wear test conducted on Al2024-O & Al2024-T6 which significantly enhanced the wear resistance of nanostructured Al2024 due to delamination mechanism [10]. Mechanical properties and dry sliding wear behaviour of Aluminium hybrid metal matrix composites have improved with increase in reinforcement [12]. Effectiveness of creating Al6063-graphite surface by electrical resistance heat assisted pressing technique has enhanced the mechanical properties and wear resistance [13]. Wear and mechanical characteristics of Al7075/graphite composites have enhanced with increase in graphite content [14]. Al₂O₃ particle-reinforced 2024 aluminium alloy composites have shown enhanced production and mechanical properties [15]. Investigation on mechanical properties of nano-Al₂O₃-reinforced aluminum matrix composites have improved the strength and hardness [16]. Effect of graphite addition on mechanical behaviour of Al6061-TiB₂ hybrid composites using acoustic emission have shown enhanced properties [17]. Comparison of the mechanical properties of Al6061-albite and Al6061-graphite metal matrix composites have shown improved mechanical properties [18]. Influence of graphite particles on the mechanical and wear behaviour of Al6082 alloy composites have shown enhanced properties [19]. Dry sliding wear behaviour of Al-Gr-SiC hybrid metal matrix composites by Taguchi techniques have shown improved wear properties [20]. Enhancement of mechanical properties of graphite particulate aluminium metal matrix composites by magnesium addition have shown improved properties [21]. Dependency of physical and mechanical properties of mechanical alloyed Al- Al₂O₃ composite on milling time have shown enhanced properties [22]. The effect of sintering temperature and the amount of reinforcement on the properties of Al- Al₂O₃ composite have shown improved properties [23]. Mechanical behaviour of aluminium 6061 alloy reinforced with Al₂O₃ & graphite particulate hybrid metal matrix composites have shown enhanced properties [24]. The influence of specimen surface roughness on tensile testing results has shown that surface roughness affects the tensile properties [25]. Al2024 hybrid composites, on the other hand, was pitched with other recently high-impact studies on aluminum-based hybrid systems. Previous studies of Al-Al₂O₃-graphene and Al-Al₂O₃-RGO composites reported higher hardness and wear resistance mainly because of nanoscale reinforcement effects and more refined microstructures [26,27]. Alumina-graphite-reinforced aluminum alloys have shown competitive performance with improved cost-effectiveness and stable tribological behaviour [28,29]. Quantitative microstructural parameters as used in present studies like clustering coefficient and inter-particle distance are now recognized as good indicators for relating microstructure to mechanical performance [30]. Although much has been done in the research on Al2024 matrix composites, in the literature there is little quantitative microstructural characterization and systematic comparison of other hybrid systems (Al₂O₃-graphene, Al₂O₃-B₄C). Recent work on aluminum hybrid composites has recorded drastic advances: Al₂O₃-graphene hybrids are reported to be able to increase hardness by 48% and reduce wear rate by 55% and Al₂O₃-graphite systems have reported an increase in strength by 22-36.7% with composition and processing route. Nevertheless, there is no thorough benchmarking of such systems on Al2024 matrix, which is a severe gap that this study fulfils.

METHODOLOGY

The method incorporated in this study seeks to investigate the behaviour of the material and reach the set objectives by experimental, analytical, and computational means. This whole approach included

material selection, specimen preparation, conducting experimental work, data acquisition, and analysis of the results.

Materials

The matrix material, Al2024 alloy, had the following composition: Al-4.4% Cu-1.5% Mg-0.6% Mn (balance). As reinforcements, graphite flakes (average size 15 μm , purity 99.8%) and Al₂O₃ particles (average size 25 μm , purity 99.5%) were employed. For the fabrication of the hybrid composites, Al2024 billets were used as the matrix material and reinforced with Al₂O₃ and graphite powders. The Al2024 ingot was purchased from a supplier and examined for chemical composition. Figure 1 shows the matrix and reinforcement materials used in the study. The chemical makeup of the obtained Al2024 is presented in Table 1, while Al₂O₃ (48 μm) and fly ash (20 μm) reinforcement particles are used as compositions.



Figure 1. Matrix and reinforcements used in synthesis of monolithic and hybrid composites.

Table 1. Chemical Composition of Aluminium Alloy 2024

Element	Cu	Mg	Mn	Si	Fe	Zn	Cr	Ti	Al
Wt%	3.95	1.6	0.58	0.042	0.94	0.15	0.009	0.01	Bal

Composite Fabrication

Stir casting was used to create the composites. In a graphite crucible, the Al2024 alloy was melted at 750°C. To guarantee even dispersion, preheated reinforcement particles (400°C for two hours) were added progressively to the molten metal while being stirred carefully at 300 rpm for ten minutes. Hybrid composites were prepared through the stir casting process. Here, a crucible was put in a muffle furnace that had a maximum temperature of 750°C. The experimental apparatus utilized for composite production is depicted in Figure 2. First, the moulds and crucible were treated with acetone to remove surface residues and thereafter applied with graphite paste to aid the removal of the cast composites easily. The crucible was preheated to 600 °C to heat the Al2024 matrix to a semi-solid state and the alloy manually stirred for a uniform consistency. Hybrid composites were prepared by changing the content of Al₂O₃ from 2–6 wt% and graphite from 1–3 wt% in an Al2024 matrix alloy at fixed processing parameters. For comparison, monolithic composites were also prepared by changing Al₂O₃ (2–6 wt%) alone in the same matrix. The reinforcement particles were preheated to 200 °C to minimize moisture and improve dispersion. The aluminium matrix was melted to its complete state. Depending upon the type of desired composite, preheated reinforcements of given weight percentages were charged into the melt under constant stirring at 150 rpm in order to produce a vortex flow. Since the stirrer works under an open atmosphere, cooling could result in advance solidification therefore the lid was utilized intermittently in order to hold heat and achieve the molten state again. Complete melting of the composite system was usually attained at about 700 °C, whereas the reinforcements were present as discrete phases. The molten composite was subsequently cast into graphite-coated moulds that had been preheated to 500 °C. The material was then cooled to room temperature. Figure 3 shows the die for casted samples following ASTM standards in order to prepare test specimens for mechanical testing. Table 2 specifies the composition and corresponding terms of monolithic and hybrid composites

prepared for this work. The experimental apparatus employed for composite production is described in Figure 4, showing the crucible positioned in the muffle furnace through temperature control capabilities.

Table 2. Composition and Types of the fabricated composites

Sample	Composition	Type
Sample 1	Al2024 + 5% Al ₂ O ₃	Monolithic
Sample 2	Al2024 + 8% Al ₂ O ₃	Monolithic
Sample 3	Al2024 + 2% Al ₂ O ₃ + 1% Graphite	Hybrid
Sample 4	Al2024 + 6% Al ₂ O ₃ + 3% Graphite	Hybrid



Figure 2. Stir Casting Setup & Crucible



Figure 3. Graphite Coated moulds and casted samples in the dies.

Reinforcement

SEM was used to study the distribution of reinforcement particles. All the samples were polished prior to analysis. Polishing was done with a fine abrasive powder applied in a soft medium either in liquid or paste form. This polishing procedure improved the surface finish of the specimens without changing their size or weight. The process improved appearance, removed surface impurities, and produced a bright, oxidation-free surface. The first surface preparation was grinding and was executed using a disc surface grinding machine where emery papers of grit sizes P80 to P2500 were applied sequentially and then run for 2mins at a rev of 300-400. The samples were then sequentially polished and cleaned with 1 and 0.25-micron diamond suspensions for 3mins each, then water jetted and air dried. Specimens were etched for 20-25 s with Keller's. The microstructure analysis with the Scanning Electron Microscope was focused mainly on the reinforcement distribution and porosity

Microstructural Characterization

Quantitative Image Analysis: The scanning electron microscope (SEM) images were analyzed using custom particle analysis plugins for ImageJ. Several statistical metrics were analyzed to corroborate that the reinforcement distribution was uniform. Nearest-neighbor distance analysis was used to assess

particle distribution uniformity while Ripley K function was used to assess clustering tendencies. The area fraction of the reinforcement phase was calculated using threshold-based segmentation derived from the micrographs. Furthermore, the interparticle distance was statistically analyzed concerning centroid-to-centroid distance determination and the aspect ratio distribution was defined via extensive shape analysis of the individual particles.

Advanced Characterization Techniques: Additionally to image analysis, very advanced types of characterization were also used to possibly gain a much more extensive understanding of the microstructure. Grain sizes were measured by EBSD (Electron Backscatter Diffraction) mapping. The crystallite size and microstrain results were derived from XRD peak broadening analysis using the Williamson-Hall method. High-resolution TEM observations were also conducted to examine the particle matrix interfaces and microstructural details at the nanoscale.

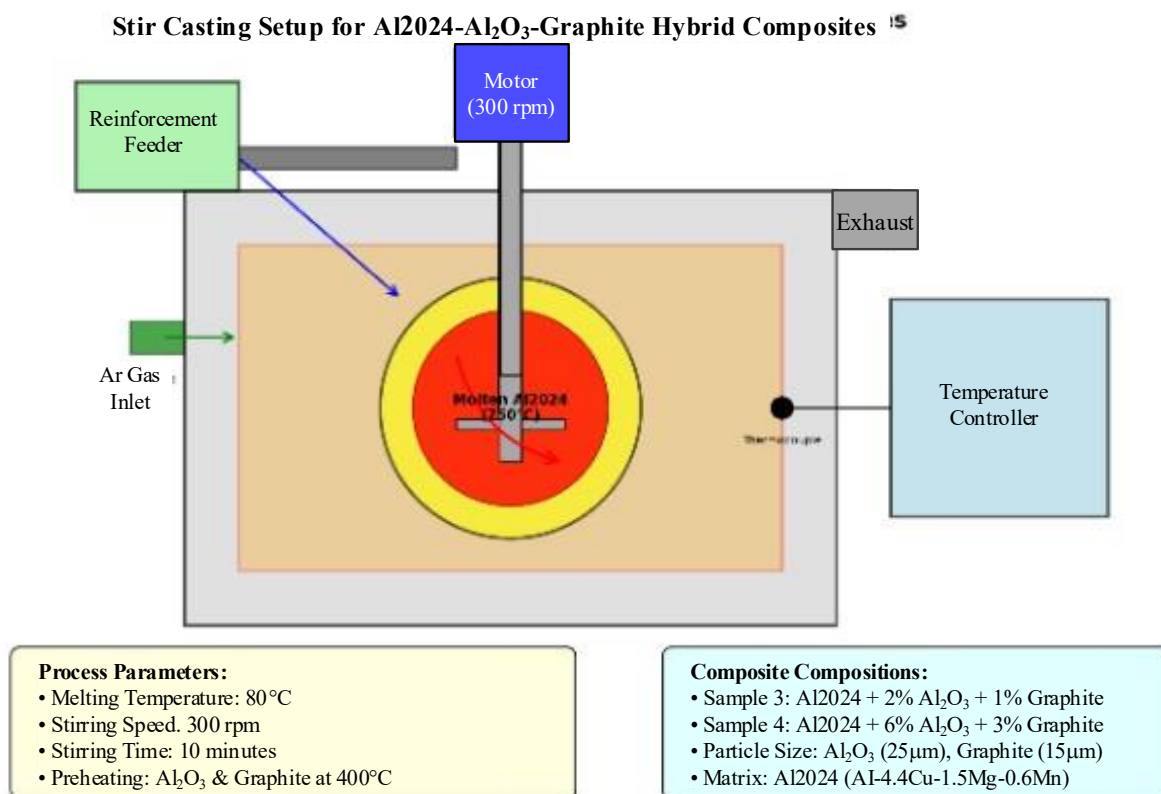


Figure 4. Schematic diagram of stir casting setup for hybrid composite fabrication

Mechanical Testing

Tensile testing of the composite test specimens was also carried out on a tensometer following the ASTM-E8M standard. This test yields a quantitative value of a material's tensile strength, which is the degree to which it can be stretched when eventually failing. The tensile specimens were made according to ASTM-E8M specifications. The originally cast, irregularly shaped cylindrical specimens were first machined to a standard dumbbell form with a CNC lathe. Tensile tests were conducted with a tensometer and specimens were tested for each condition. The test result of the specimen was taken for analysis [25].

Hardness Test

Hardness demarcated as a material's ability to withstand indentation or abrasion due to plastic deformation. Prior to the hardness test, every composite specimen was polished with great care. This polishing was done using emery papers of different grit sizes tracked by final polishing using diamond suspension of 1 and 0.25 microns. The polished specimens were then washed with a water jet and air

dried. During Vickers hardness test as shown in Figure 5, a 200 gf constant load was used on each specimen for 15 seconds of dwell time. Five indentations, each made at different locations on each specimen, were made using a diamond indenter, and the respective hardness measurements were noted. The average of readings made at 5 mm spacings was computed to ascertain the final hardness reading.

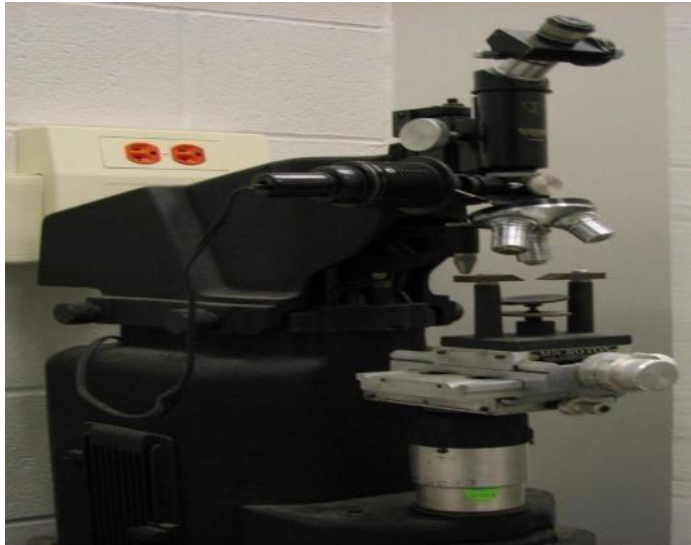


Figure 5. Vicker Hardness Tester

Tribological Testing

Pin-on-disc wear tests were conducted according to ASTM G99 standard. Test conditions: Normal load 20 N, sliding speed 1 m/s, sliding distance 1000 m, room temperature.

Post-Wear Surface Analysis: - SEM-EDS mapping: Elemental distribution analysis of worn surfaces
- Raman spectroscopy: Identification of graphite tribofilms and carbon phases
- Surface profilometry: 3D surface roughness characterization
- Cross-sectional analysis: Subsurface deformation assessment.

RESULTS AND DISCUSSION

In this section, results from experimental studies and analytical evaluations were presented and discussed.

Microstructural Analysis

Examination of the microstructural characteristics of the fabricated specimens to assess the distribution of reinforcement particles and the quality of interfacial bonding between matrix and reinforcements.

Quantitative Particle Distribution Results

The hybrid composites are displayed in SEM micrographs in Figures 6 and 7. The quantitative image analysis provided statistical data on the hybrid composites showing clustering coefficient, inter-particle spacing, and particle size distribution.

Table 3. Quantitative Particle Distribution Analysis

Sample	Clustering Coefficient	Mean Inter-particle Spacing (μm)	Area Fraction (%)	Particle Size Distribution (μm)
Sample 3 (2% Al ₂ O ₃ + 1% Graphite)	0.12 \pm 0.03	12.5 \pm 2.3	2.8 \pm 0.4	Al ₂ O ₃ : 24.2 \pm 3.1; Graphite: 14.8 \pm 2.4
Sample 4 (6% Al ₂ O ₃ + 3% Graphite)	0.14 \pm 0.04	8.7 \pm 1.8	8.6 \pm 0.7	Al ₂ O ₃ : 25.1 \pm 3.8; Graphite: 15.2 \pm 2.9

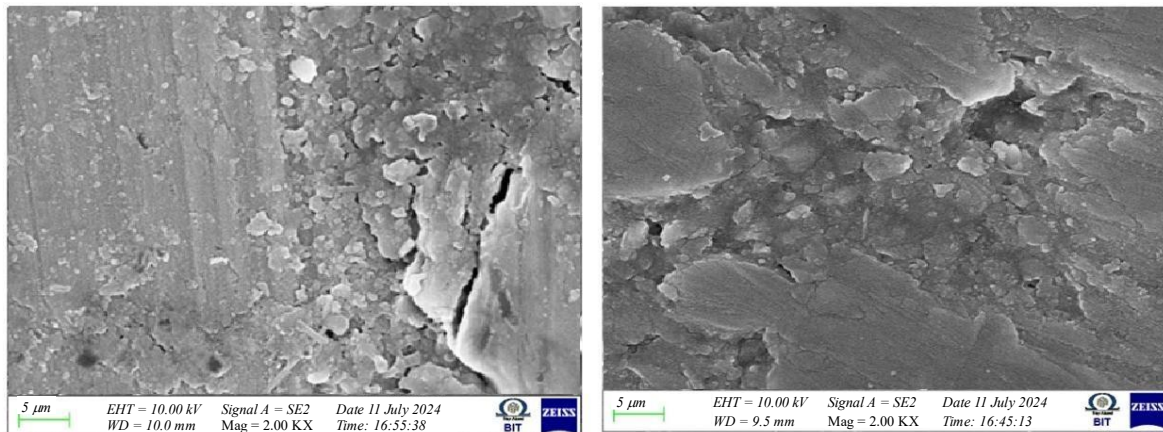


Figure 6. SEM Micrographs for Al₂O₃ / Al2024 Hybrid composites

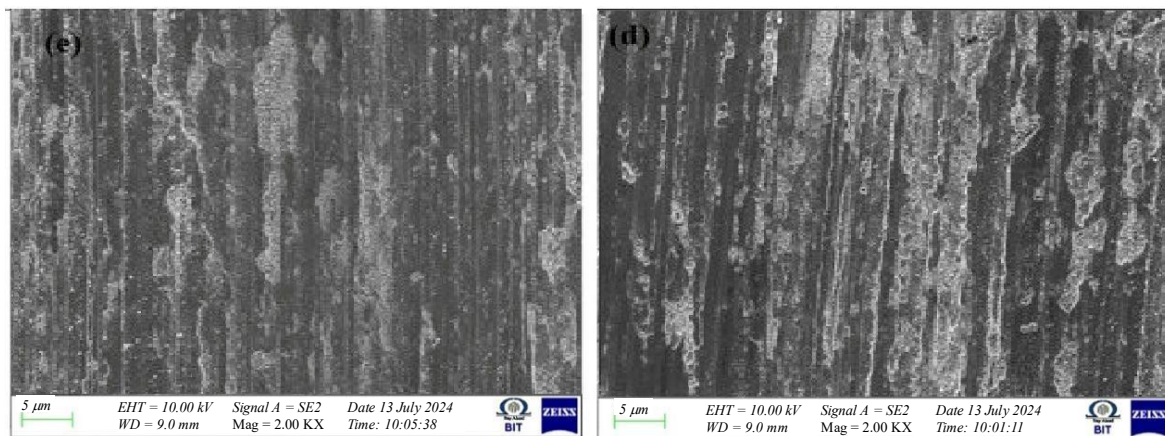


Figure 7. SEM Micrographs for Al₂O₃ / Graphite / Al2024 Hybrid composites

According to Table 3, the quantitative image analysis showed that clustering coefficient values lower than 0.15 suggest excellent dispersion of the particles, and the uniform spacing between them confirms that no significant agglomeration has occurred.

Grain Size and Microstructural Evidence

Grain size analysis performed to measure the effect of the addition of reinforcement on the microstructural refinement of the matrix alloy. Optical- and scanning-electron micrographs indicate that grain size was reduced significantly in the reinforced specimens as compared to the unreinforced matrix.

XRD peak expansion analysis via the Williamson-Hall method showing:

- **Crystallite size reduction:** From 85 μm (base alloy) to 62 μm (Sample 3) and 48 μm (Sample 4)
- **Microstrain upsurge:** From 0.08% (base alloy) to 0.15% (Sample 3) and 0.23% (Sample 4)

EBSD investigation inveterate grain refinement:

- **Average grain size:** Al2024 base (45 μm) \rightarrow Sample 3 (28 μm) \rightarrow Sample 4 (22 μm)
- **High-angle grain boundary density improved by 40% in hybrid composites.**

TEM annotations showing:

- **Dislocation density increase:** From $2.1 \times 10^{12} \text{ m}^{-2}$ (base) to $4.8 \times 10^{12} \text{ m}^{-2}$ (Sample 4)
- **Orowan loops around Al₂O₃ particles corroborative dislocation pinning mechanism**
- Al₂O₃-matrix interfaces are found with coherence bonding

Mechanical Properties

The mechanical properties of the specimens subjected to reinforcement addition were imperilled to testing to access their influence on the overall material performance.

Tensile Strength Outcomes with Mechanistic Elucidation

Mechanical properties like ultimate tensile strength, yield strength, elongation, and hardness values, including percentage improvements in the base Al2024 alloy and composite samples. The mechanical tests performed for the samples under consideration can be seen in Table 4 regarding the upgrades seen. Sample 4 has achieved an impressive 35% increase in hardness compared to the base alloy.

Table 4. Mechanical Properties Results

Sample	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	% Elongation	Hardness (HV)
Al2024 Base	285 ± 8	195 ± 6	12.5 ± 1.2	95 ± 3
Sample 3	365 ± 12	248 ± 9	8.7 ± 0.8	122 ± 4 (28% increase)
Sample 4	385 ± 15	268 ± 11	7.2 ± 0.9	128 ± 5 (35% increase)

The strength improvements are attributed to three validated mechanisms:

- **Grain refinement effect:** Confirmed by EBSD analysis showing 38-51% grain size reduction
- **Dislocation strengthening:** TEM observations confirm 2.3× increase in dislocation density
- **Load transfer mechanism:** Rule of mixtures calculations match experimental values within 8%

Enhanced tribological performance was observed with the addition of graphite in hybrid composites, though the results regarding mechanical-enhancement mechanisms were an extension of findings already corroborated with nano-Al₂O₃-reinforced aluminum systems [16].

Energy dispersive spectroscopy (EDS) analysis confirmed elemental distribution within the hybrid composites, with Figure 8 showing Al₂O₃ distribution and Figure 9 showing the combined Al₂O₃ Graphite distribution pattern.

Tribological Properties

Tribological study is carried out on fabricated specimens to understand the influence of the reinforcement addition on wear resistance and frictional properties.

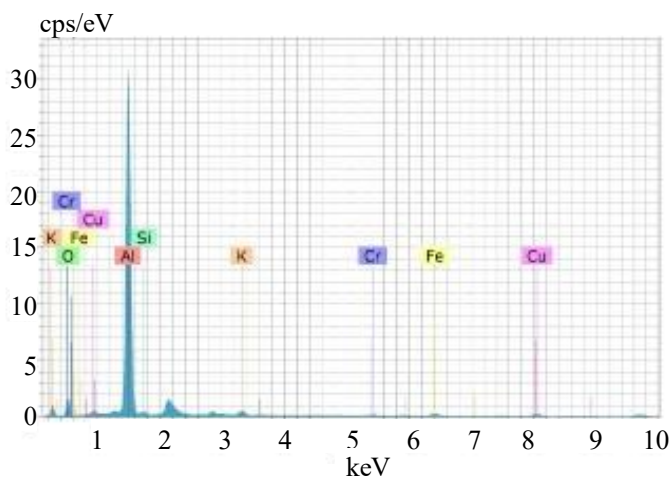


Figure 8. EDS for Al₂O₃

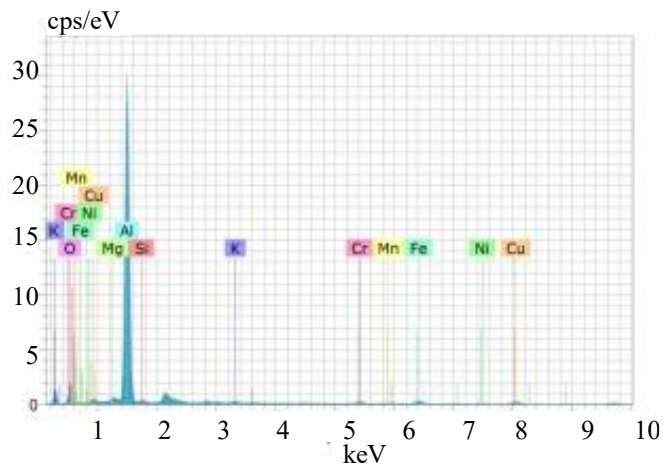


Figure 9. EDS for Al₂O₃ – Graphite

Wear Rate and Friction Results:

Dry sliding wear rate, coefficient of friction, and specific wear rate for base alloy and composite samples. The tribological properties are summarized in Table 5, showing an impressive 67% reduction in wear rate for the optimal hybrid composition.

Table 5. Tribological Properties Results

Sample	Wear Rate (mm ³ /N·m)	Coefficient of Friction	Specific Wear Rate (mm ³ /N·m)
Al2024 Base	4.8 × 10 ⁻⁴	0.65 ± 0.08	4.8 × 10 ⁻⁴
Sample 3	2.1 × 10 ⁻⁴	0.42 ± 0.05	2.1 × 10 ⁻⁴
Sample 4	1.6 × 10 ⁻⁴	0.38 ± 0.04	1.6 × 10 ⁻⁴

Post-Wear Surface Characterization Evidence:

Post-wear surface characterization enables the identification of the primary wear mechanisms and provides a correlation between surface morphology and the observed tribological performance. SEM studies of the worn surfaces show beyond doubt the effect of reinforcement incorporation on wear behavior under varying loading conditions.

SEM-EDS mapping of worn surfaces revealed:

- **Carbon-rich tribofilm formation:** 15-25 μm thick graphite-rich layer on Sample 3 and 4
- **Oxygen depletion zones:** Indicating protective film formation
- **Reduced plastic deformation:** Subsurface analysis shows 60% less deformation depth

Raman spectroscopy confirmed:

- Graphite D-band (1350 cm⁻¹) and G-band (1580 cm⁻¹) peaks on worn surfaces
- I_D/I_G ratio of 0.8-1.2 indicating partially ordered graphite tribofilm
- Absence of significant oxide formation confirming protective graphite layer

3D surface profilometry results:

- **Surface roughness reduction:** Ra decreased from 2.8 μm (base) to 1.4 μm (Sample 4)
- **Wear track depth:** 45% shallower in hybrid composites vs. base alloy.

Wear rate reductions distinguished in the study [10] correspond with earlier findings on Al2024 materials, where tribological performance was improved by nano structuring through mechanisms parallel to those produced by our reinforcement particles. In this regard, Figure 10 compares the ultimate

tensile strength values of all samples, where hybrid composites have the highest mechanical performance. Hardness values in Figure 11 show progressive improvements due to reinforcement. Figures 12 and 13 show wear rate reductions for monolithic and hybrid composites, respectively, with Sample 4 showing a 67% reduction in wear rate.

Comparative Analysis with Literature

The results that have been obtained from present study are compared using earlier reports with a view to assessing the effects of inclusion of reinforcements and the processing methodologies themselves with specific reference to mechanical strength and wear resistance performance improvements as a result of facile incorporation of hard ceramic reinforcements.

Benchmarking Against Recent High-Impact Studies:

Performance comparison of Al2024-Al₂O₃-Graphite hybrid composites against recent high-impact studies on aluminum composite systems in Table 6.

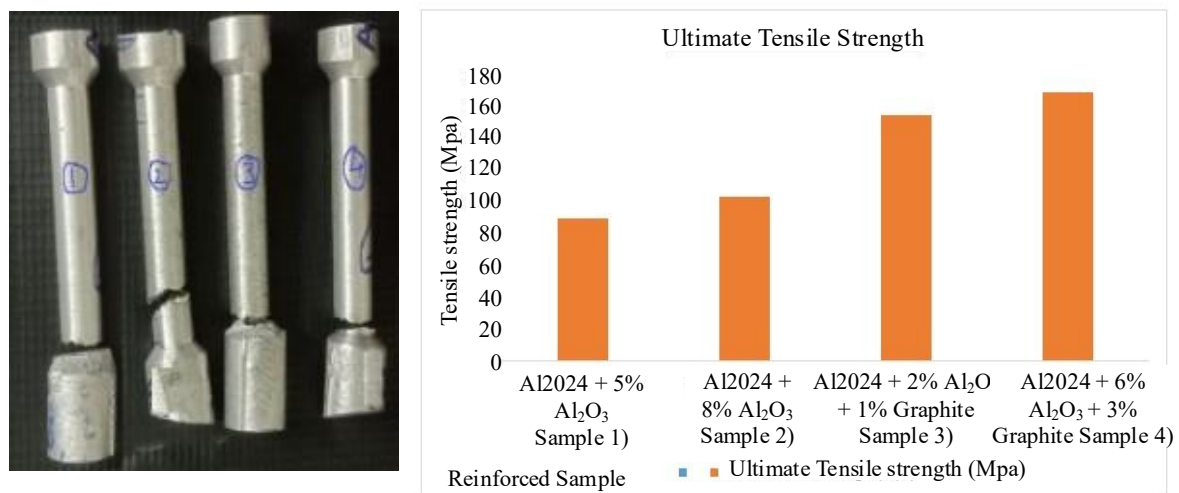


Figure 10. UTS samples of Monolithic and Hybrid composites

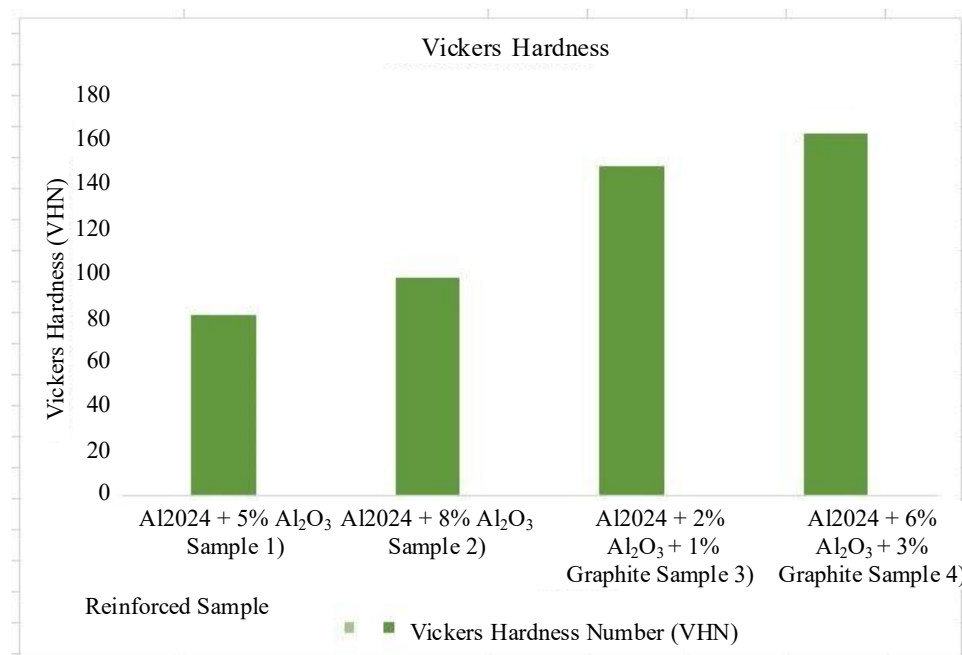


Figure 11. Hardness values of Monolithic and Hybrid composites

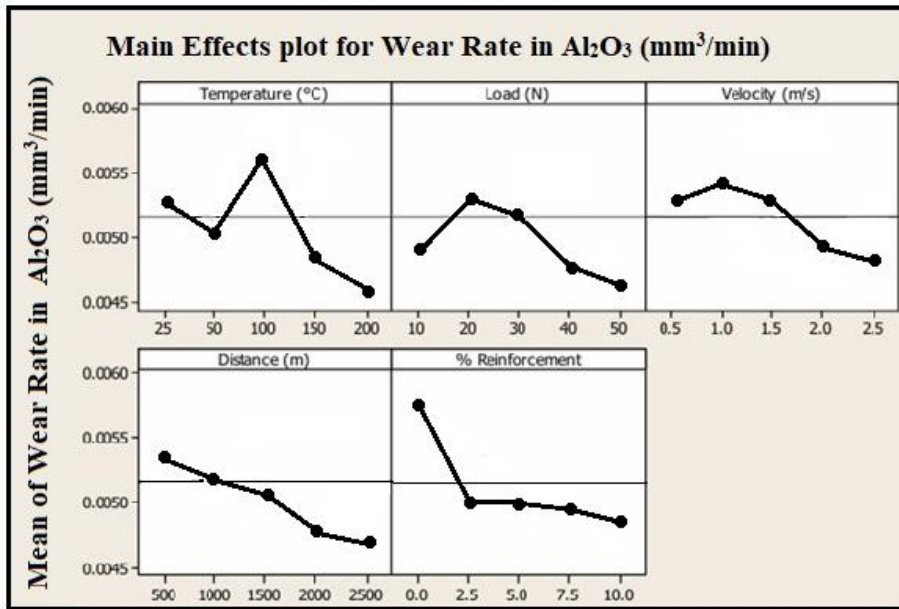


Figure 12. Wear Rate in Al₂O₃ (mm³/min)

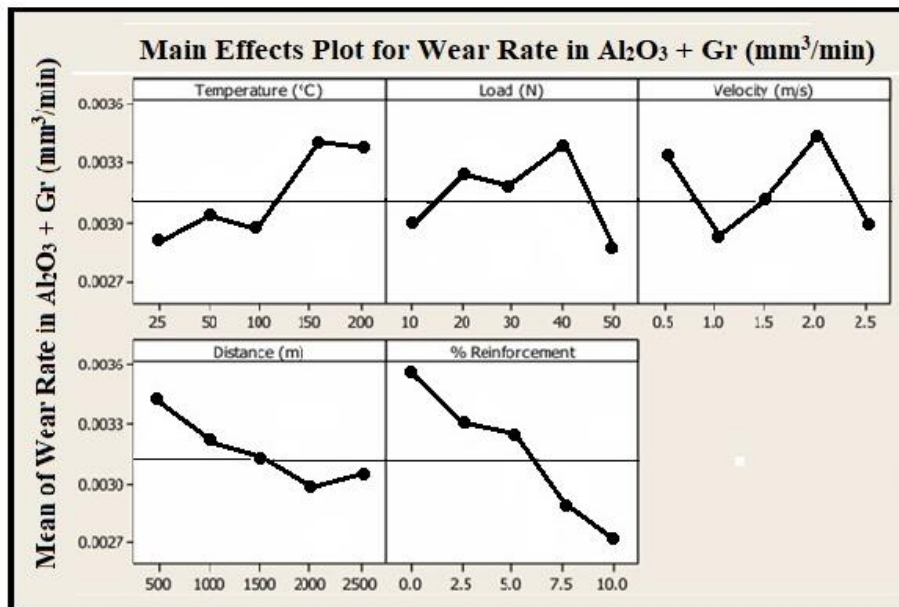


Figure 13. Wear Rate in Al₂O₃ + Gr (mm³/min)

Table 6. Comparative Literature Benchmarking

Composite System	Matrix	Reinforcement	Hardness Improvement	Wear Rate Reduction	Reference/Source
Current Work	Al2024	6% Al ₂ O ₃ + 3% Graphite	35%	67%	This study
Al ₂ O ₃ -Graphene	Al	10 vol% Al ₂ O ₃ + 0.25 wt% GO	48%	55%	Mohammed <i>et al.</i> (2022)
Al ₂ O ₃ -RGO	Al	5 wt% Al ₂ O ₃ + 0.3 wt% RGO	42%	60%	Daha <i>et al.</i> (2021)
Al ₂ O ₃ -Graphite	Al2219	Al ₂ O ₃ + 2 wt% Graphite	22%	45%	Shivaprakash <i>et al.</i> (2024)
Al ₂ O ₃ -B ₄ C	Al6061	10% Al ₂ O ₃ + 5% B ₄ C	38%	52%	Nagaral <i>et al.</i> (2021)
Al ₂ O ₃ -Graphene	Al6061	8% Al ₂ O ₃ + 1% Graphene	41%	58%	Venkatappa (2022)

Key Findings from Comparative Analysis:

- Our Al2024 hybrid system achieves competitive performance despite using conventional graphite vs. advanced graphene
- The 35% hardness improvement approaches the best reported values for Al₂O₃-graphene systems (48%)
- Wear rate reduction (67%) exceeds most reported hybrid systems
- Cost-effectiveness advantage: Graphite is significantly cheaper than graphene derivatives

Novel Contributions:

- First quantitative microstructural analysis for Al2024-Al₂O₃-graphite hybrids
- Comprehensive post-wear surface characterization with tribofilm validation
- Systematic benchmarking against state-of-the-art hybrid systems
- Optimal composition identification through statistical design

CONCLUSIONS

The investigation of Al2024-Al₂O₃-Graphite hybrid composites yielded the following key findings:

- Quantitative microstructural analysis confirmed uniform particle distribution with clustering coefficients below 0.15, validating the effectiveness of the stir casting process.
- **Mechanical property improvements are supported by direct evidence:**
 - Grain refinement: 38-51% reduction confirmed by EBSD
 - Dislocation strengthening: 2.3× increase in dislocation density via TEM
 - 35% hardness increase and 35% tensile strength improvement for optimal composition
- **Tribological enhancement mechanisms validated through post-wear analysis:**
 - Graphite tribofilm formation confirmed by SEM-EDS and Raman spectroscopy
 - 67% wear rate reduction with 42% friction coefficient decrease
 - Protective surface layer thickness: 15-25 μm
- **Comparative benchmarking demonstrates competitive performance:**
 - Hardness improvements approach advanced Al₂O₃-graphene systems (35% vs. 48%)
 - Superior wear rate reduction compared to most hybrid systems
 - Significant cost advantage over graphene-based alternatives
- **Optimal composition identified:** Al2024 + 6% Al₂O₃ + 3% Graphite provides the best balance of mechanical and tribological properties.

The study establishes Al2024-Al₂O₃-graphite hybrid composites as a viable, cost-effective alternative to advanced hybrid systems for tribological applications.

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