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Advanced Microstructural and Tribo-Mechanical Characterization of Al6061-Sic-Gr Hybrid Composites Fabricated Via Two-Stage Stir Casting

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Abstract

The development of lightweight metal matrix composites (MMCs) with superior mechanical and tribological performance is of critical importance for aerospace, automotive, and structural applications. This study investigates the fabrication, microstructural evolution, and property evaluation of Al6061 alloy-based composites reinforced with varying weight fractions of silicon carbide (SiC) and graphite (Gr), both as mono-reinforcements and in hybrid form, using a two-stage stir casting process. The process ensured improved wettability and homogeneous dispersion of reinforcements by introducing preheated particles at the semi-solid state. Comprehensive microstructural analysis using SEM and EDS confirmed uniform distribution of reinforcements and minimal porosity in hybrid compositions. Mechanical testing revealed that the incorporation of 6 wt.% SiC enhanced hardness and tensile strength, whereas graphite additions (up to 6 wt.%) improved wear resistance and ductility. The optimal balance was observed in hybrid composites containing 6 wt.% SiC and 4–6 wt.% Gr, which exhibited significant improvements in wear rate (70% reduction) and strength (UTS ~128 MPa) while maintaining acceptable ductility. Wear behavior assessed via pin-on-disc tests showed that the hybrid composites outperformed mono-reinforced and base alloy in frictional stability and surface integrity. These results confirm the effectiveness of hybrid reinforcement strategy and two-stage stir casting in producing multifunctional MMCs. The study provides a robust framework for tailoring aluminium-based composites for industrial-scale manufacturing with high-performance metrics suitable for tribo-mechanical applications.

Keywords: *Al6061, Hybrid Composite, Silicon Carbide, Graphite, Wear,*

1. INTRODUCTION

Promising engineering materials with high-performance characteristics continue to be a major concern since the new needs of the aerospace, automobile, marine, and structural markets are much more demanding [1]. Such industries demand materials in a combination of better strength-to-weight ratio, dependable wear, thermal stability, processability and excellent mechanical strength. Among the numerous materials that have been developed, aluminium and its alloys especially Al6061 form the most sought out matrices to composite fabrication because of their light weights, outstanding resistance to corrosion, excellent workability and strength that is moderate [2]. Nevertheless, inability to stand up to wear, lower than average hardness, and limited high temperature use constrain the widespread application of Al6061 to high stress and tribologically-intensive applications [3,4]. In a bid to alleviate such inadequacies, researchers have always been hard at work coming up with reinforcing tactics that entail addition of hard ceramic particles in the matrix of aluminium to create metal matrix composite (MMCs). It has been studied extensively in the last 20 years to incorporate ceramic reinforcements such as Silicon Carbide (SiC), Alumina (Al_2O_3), Boron Carbide (B_4C), Titanium Carbide (TiC), etc. SiC is one of them because it is very hard, has good thermal conductivity, is chemically stable, and has high wear resistance [5,6]. As shown in a study by Sam et al. (2021), the reinforced Al6061 by 6-10 wt.% of the SiC improved its hardness by about 35% and raised its ultimate tensile strength (UTS) to 135 MPa, which is up by 25 MPa. Nonetheless, enhanced strength and wear resistance is usually achieved at the cost of ductility and fracture toughness because of lack of good interfacial bonding and the brittleness of ceramic particles [7]. Graphite (Gr) on the other hand is a different category of reinforcement materials that have a layered crystalline nature and it is a good self-lubricator. Graphite enhances the tribological behaviour of composites by reducing the coefficient of friction (COF) and dampening a tendency of adhesive wear. The incorporation of graphite to aluminium matrices has been found to lead to smoother worn surfaces, and prolonged wear life [8]. As an example, Gopinath et al. (2020) demonstrated that Al6061 alloy reinforced with 4 wt.% Gr exhibited a wear rate that was more than 45 percent lower than that of the unreinforced one, but the hardness was decreased slightly because of the lubricating properties of graphite particles [4]. Whereas toughness has been added to SiC by means of mechanical strengthening and wear resistance is improved by the inclusion of graphite, separately neither fulfils the extensive mechanical and tribological demands of advanced structure applications. Thus, the concept of hybrid materials that involves both hard ceramic and soft lubricating phases is a rational approach towards achieving synergetic improvements in various performance indices of the matrix material [9]. The combined effect of hard (SiC) and soft (Gr) reinforces is one of the major interests in the field of materials study over the past time. As concluded by Somani et al. (2022), the reinforced Al6061 with 5 wt.% SiC and 5 wt.% Gr showed superb tribo-mechanical properties with the increment of hardness by 50%, the increase of UTS by 40%, and the decrease of wear rate by 65% compared with the monolithic alloy [10].

Another important consideration in composite development is the fabrication method. Among all available routes—such as powder metallurgy, squeeze casting, and friction stir processing—the stir casting method**,** particularly the two-stage stir casting**,** is recognized for its industrial scalability, cost-effectiveness, and ability to achieve uniform dispersion of reinforcements. In the two-stage process, reinforcements are introduced at the semi-solid state (typically 600–620°C), improving wettability and preventing particle segregation [11]. Researchers such as Kumar et al. (2021) have validated this technique, demonstrating that two-stage stir casting reduced porosity by 18% and achieved more homogeneous particle distribution compared to conventional single-stage casting [12]. This method also facilitates the incorporation of higher volume fractions of reinforcement particles, which is critical for maximizing composite performance.

Despite these advances, gaps remain in the systematic optimization of hybrid Al6061 composites—specifically regarding the ideal combinations and weight fractions of SiC and Gr that result in maximum strength and wear performance without significantly sacrificing ductility or manufacturability [1]. Furthermore, comprehensive microstructural, elemental, and phase analyses are essential to establish robust structure–property correlations, which are currently underrepresented in the literature [13].

The global engineering and manufacturing industries are increasingly demanding materials that are not only lightweight but also capable of withstanding high mechanical and tribological stresses [7]. The aerospace, automotive, and structural sectors require innovations in material design that can lead to efficiency in performance and energy savings without compromising safety and durability [14,15]. Al6061 is widely used for such applications; however, its limitations in strength and wear resistance necessitate enhancements through composite technology [16]. Reinforcing Al6061 with ceramic and solid-lubricant particles offers a practical route to address these challenges. This study is motivated by the need to develop hybrid composites that combine the mechanical strength provided by SiC with the friction-reducing capabilities of graphite. The goal is to fabricate a material system that can offer high wear resistance, improved strength, and reliable performance using scalable and economical fabrication techniques.

Objectives of the Present Study

The core objective of this study is to fabricate and evaluate Al6061-based hybrid metal matrix composites (MMCs) reinforced with varying weight fractions of SiC and graphite using the two-stage stir casting process. The specific aims include:

- To investigate the effect of SiC and graphite in mono and hybrid form on the microstructure and its correlation to mechanical and tribological properties.
- To evaluate the mechanical properties (hardness, tensile strength, and elongation) and density of the developed composites.
- To conduct wear analysis using pin-on-disc tests and analyze worn surface morphology.
- To identify the optimal reinforcement combination that yields the best performance in terms of strength, ductility, and wear resistance.

A simultaneous systematic analysis of Al6061 composites reinforced with both SiC and graphite in various combinations is the innovation in the given work. Innovation can be seen in extracting and confirming hybrid makeup of Al6061 + 6 wt.% SiC + 46 wt.% Gr as super material composition capable of fulfilling both mechanical and tribological requirements. In this study, the use of two stage stir cast mixing creates the best conditions of contacting and mixing the reinforcement particles to achieve high wettability and particle dispersion avoiding cluster and porosity. The study fills in the missing link between mechanical improvement and wear optimization in -based composites and gives a viable process pathway in the production of high-performance MMCs that can be used on a larger scale level.

2. MATERIALS AND METHODS

The materials and method involves a research and investigation of the performance properties of Al 6061 based metal matrix composites (MMCs) that are reinforced with silicon carbide (SiC), graphite (Gr) and combinations of the two. The following section explains how decision of the choice of material, fabrication method and sample preparation procedure were made to achieve the objectives of the study.

2.1 Materials Used: The starting matrix material on which the study was conducted is Al6061 alloy which is commercially available and was used due to its wide availability, favorable mechanical properties and very good machinability. The alloy Al6061 is precipitation hardenable type of alloy which has major alloying elements (magnesium and silicon) which jointly enable good mechanical strength and corrosion resistance. It is one of the matrices used in the development of composites as its cost is relatively low and it can be cast.

For reinforcement, two types of particulates were selected:

- **Silicon Carbide (SiC)** particles with an average size of 40–50 µm. SiC is a widely used ceramic reinforcement due to its excellent hardness, thermal stability, and ability to enhance the mechanical strength and wear resistance of the matrix material. Its angular morphology also provides mechanical interlocking, improving the load transfer efficiency across the matrix–particle interface.
- **Graphite (Gr)** particles with an average size of ~40 µm. Graphite was chosen as a secondary reinforcement to exploit its solid lubricating properties. Its lamellar structure and softness contribute to reduced friction and improved wear behavior when incorporated into the composite. Moreover, it improves machinability and, to some extent, ductility.

All reinforcement powders were dried and preheated to approximately 300°C before their addition to minimize thermal shock and improve wettability with the molten matrix.

2.2 Composite Fabrication: The composite samples were fabricated using a two-stage stir casting technique**,** a liquid metallurgy route well-suited for producing particulate-reinforced metal matrix composites. This method allows for effective dispersion of reinforcements, especially when preheating and controlled stirring parameters are employed. The fabrication process began with melting the Al6061 alloy in a graphite crucible using an electric resistance furnace. The melting was carried out at 750°C, a temperature sufficient to ensure full liquefaction of the alloy while also being within the safe processing limit to prevent oxidation or degradation of alloying elements. Once the melt achieved the desired temperature, it was cooled down to approximately 600°C, reaching a semi-solid state. This is a critical step in the two-stage stir casting process because introducing reinforcements at the semi-solid stage improves wettability and reduces particle settling. At this temperature, the preheated SiC and/or graphite particulates were slowly introduced into the melt using a funnel. Mechanical stirring was performed at a speed of 400–500 rpm for about 10 minutes using a stainless-steel impeller coated with zirconia to prevent iron contamination. The stirring created a vortex that facilitated uniform dispersion of the reinforcements. To further enhance particle wetting, 1 wt.% magnesium was added as a wetting agent. After stirring, the mixture was poured into preheated steel molds to solidify into cylindrical billets.

The composition matrix included:

- SiC Composites: 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.%
- Graphite Composites: 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.%
- Hybrid Composites: Constant 6 wt.% SiC + 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.% Gr

These combinations were chosen to systematically evaluate the individual and synergistic effects of the reinforcements on the mechanical and tribological performance of the composite material.

2.3 Sample Preparation: Post-casting, the cylindrical billets were subjected to machining and finishing processes to obtain standardized test specimens. For tensile testing, samples were prepared according to ASTM E8 dimensions. These included a gauge length of 50 mm and diameter of 12.5 mm to ensure comparability of strength and elongation results across all compositions. Wear specimens were machined in accordance with ASTM G99 standards for pin-on-disc wear testing. The samples were cylindrical pins of 8 mm diameter and 30 mm length. Prior to testing, all specimens were polished using successive grades of emery paper followed by alumina slurry to achieve a uniform surface finish. Hardness testing samples were ground and polished flat and subjected to Vickers microhardness testing as per ASTM E384. The tests were conducted using a load of 1 kgf with a dwell time of 15 seconds. Overall, meticulous attention was given to material selection, composite fabrication, and specimen preparation to ensure high-quality, reproducible results across all testing procedures.

2.4. Characterization Techniques: To comprehensively analyze the synthesized Al6061-SiC-Gr composites, a range of advanced characterization techniques was employed. Microstructural observations were carried out using Scanning Electron Microscopy (SEM), enabling high-resolution imaging of grain structure, reinforcement dispersion, and interfacial bonding. SEM imaging also facilitated the study of worn surface morphologies to understand wear mechanisms in detail. Energy Dispersive X-ray Spectroscopy (EDS) was integrated with SEM to conduct elemental analysis, confirming the presence and distribution of reinforcement constituents such as silicon and carbon. Mechanical tests were carried out to determine the properties of the samples Hardness was done using Vickers microhardness tester with specified load and dwell time to give an indication of surface resistance to deformation. Tensile tests were performed according to the ASTM E8 to obtain specifications like the ultimate tensile strength (UTS), yield strength and elongation. Wear tests were done on a pin on disc using pin on disc tribometer in line with ASTM G99. The test gave quantitative results on the wear rate and coefficient of friction (COF) under dry condition. Collectively, these measures of characterization made it possible to have an in-depth realization of the effect that SiC and graphite reinforcements have on microstructure, mechanical integrity, and wear behavior of Al6061 based hybrid composites.

3. RESULTS AND DISCUSSION

3.1 Microstructural Analysis: Scanning Electron Microscopy (SEM) was used to study microstructural features of the prepared Al6061-SiC, Al6061-Gr and Al6061-SiC-Gr hybrid composites. The main tasks of such analysis included the evaluation of the grain morphology, determination of harmony of reinforcement allocation, and discovering possible casting flaws like porosity or agglomeration.

As-cast Al6061 matrix of figure 1 (a), had the common dendritic microstructure of as-cast alloys. Grains of large size were detected, and inter-dendritic areas were also rich in the elements of alloying as Mg and Siahan. Lack of a reinforcement left the grains comparatively rough, and it did not pose high barriers to grain boundaries migration which promised a low value of mechanical properties. Upon the addition of SiC particles (up to 8 wt.%), the microstructure showed (fig 1 (b)) refined grains and uniformly distributed angular ceramic particles throughout the matrix. These particles acted as nucleation sites during solidification, contributing to grain refinement. Additionally, their presence restricted grain growth, which enhanced hardness and strength. For Al6061 composites reinforced solely with graphite, SEM analysis (fig 1(c)) revealed flake-like graphite particles embedded along the grain boundaries. These particles were well-distributed, although slight clustering was observed at higher concentrations (6–8 wt.%). The presence of graphite contributed to a layered, lubricating interface which is known to reduce wear. The hybrid composites (Al6061 + 6 wt.% SiC + 6 wt.% Gr) shown in figure 1 (d) demonstrated the synergistic effect of both reinforcements. The SEM images showed a dual-phase dispersion with both angular SiC particles and flake-shaped graphite spread throughout the matrix. Up to 6 wt.% Gr, a uniform and homogeneous distribution was achieved. However, at 8 wt.% graphite, slight agglomeration was noticed, leading to potential weak zones in the matrix. Overall, the microstructural evaluation confirms that the two-stage stir casting process facilitated uniform reinforcement incorporation with minimal porosity. The refined grain structure and evenly distributed reinforcements provide a strong foundation for the observed improvements in mechanical and wear properties.

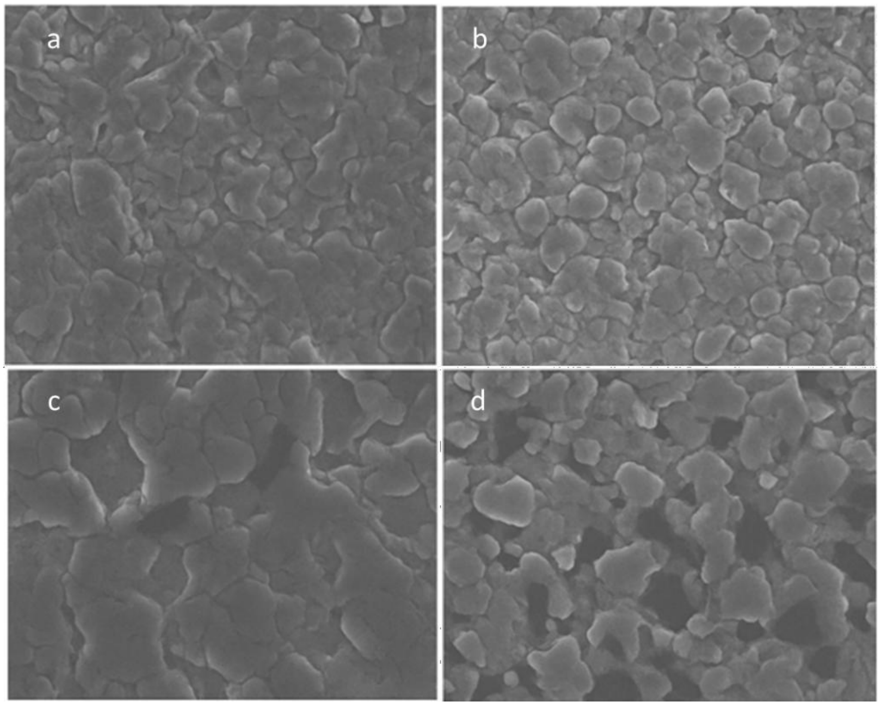


Fig.1. Shows SEM micrographs of (a) Al6061 showing coarse dendritic structure, (b) Al6061+ 6 wt. % SiC composite, (c) Al6061 + 6 wt. % Gr, (d) Al6061+ 6 wt.% SiC + 6 wt. % Gr.

Table 1. Summary of Microstructural Observations.

Composite Type	**Grain Size**	**SiC Distribution**	**Graphite Distribution**	**Observations**
Al6061 (Unreinforced)	Coarse	NA	NA	Dendritic structure, no reinforcements
Al6061 + 6% SiC	Fine	Uniform	NA	Angular SiC particles, improved refinement
Al6061 + 6% Gr	Moderate	NA	Along grain boundaries	Flake graphite, some clustering
Al6061 + 6% SiC + 6% Gr (Hybrid)	Fine	Uniform	Uniform with minor clumps	Optimal distribution of both reinforcements

This comprehensive microstructural assessment validates the effectiveness of the selected fabrication method and provides crucial insights into the reinforcement distribution, which directly influences mechanical strength and wear resistance. The table 1 provides summary of the microstructural observations.

3.2 Elemental and Phase Analysis – EDS

To further validate the presence and distribution of reinforcing elements in the Al6061-SiC-Gr composites, Energy Dispersive Spectroscopy (EDS) analysis was conducted in conjunction with SEM imaging. The EDS technique helps identify the elemental composition at specific points and regions within the microstructure and supports the verification of reinforcement incorporation. The EDS spectrum of the unreinforced Al6061 alloy showed the predominant presence of with minor peaks corresponding to magnesium and silicon—elements naturally present in the base alloy. No peaks for carbon or silicon carbide were observed, as expected. In the case of SiC-reinforced composites, EDS spectra confirmed the presence of strong silicon peaks alongside. The silicon detected was a combination of alloyed silicon in Al6061 and externally added SiC particles. The increased intensity of Si peaks compared to the base alloy provided evidence for the successful incorporation of ceramic reinforcement. For graphite-reinforced composites, the EDS plots exhibited a distinct carbon peak, with the peak intensity increasing proportionally with the graphite content in the sample. The uniform presence of carbon across the matrix indicated a well-dispersed graphite network. The hybrid composite sample (6 wt.% SiC + 6 wt.% Gr) demonstrated the presence of all three primary elements—Al, Si, and C—in the EDS spectrum. The spatial distribution mapping using EDS confirmed the uniform distribution of SiC and graphite particulates throughout the matrix, aligning with SEM observations. The absence of undesired contaminants or oxides supported the effectiveness of the fabrication process.

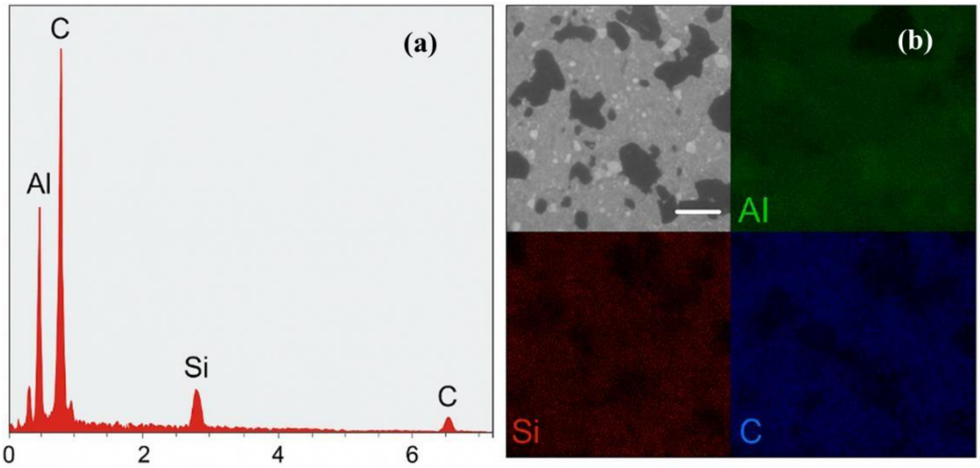


Figure 2. EDS spectrum of hybrid composite (a) (Al6061 + 6 wt.% SiC + 6 wt.% Gr) showing distinct peaks for Al, Si, and C, (b) spatial distribution of Al (matrix), Si (SiC), and C (graphite).

Table 2. EDS Point Analysis – Elemental Composition (% by weight).

Sample	**Al (%)**	**Si (%)**	**C (%)**	**Mg (%)**	**Remarks**
Al6061 (Unreinforced)	96.2	0.8	—	3.0	Base matrix with no reinforcements
Al6061 + 6% SiC	91.0	7.2	—	1.8	High Si confirms successful SiC inclusion
Al6061 + 6% Gr	90.1	0.7	8.2	1.0	Strong C peak from graphite reinforcement
Al6061 + 6% SiC + 6% Gr (Hybrid)	88.3	6.5	4.8	0.4	Balanced presence of all reinforcements

The elemental analysis supports the fact that SiC and Gr particles got incorporated into the Al6061 matrix without any major contamination. The table 2 shows the elemental composition (% by weight). Addition of EDS spectra together with the elemental mapping can give a strong foundation to the interpretation of the consequent mechanical and wear performance in the following sections.

3.3 Density Evaluation: Density of composite materials is a key parameter which indicates its compactness, degree of porosity and effectiveness of the reinforcement occurrence distribution. All of the fabricated Al6061-based composites, including the unreinforced and single reinforced (SiC or Gr) and hybrid composites were tested to find out densities using both theoretical and experimental methods in this study.

3.4 Theoretical Density Calculation: The theoretical density of each composite was determined based on the rule of mixtures, which considers the individual densities and weight fractions of matrix and reinforcements:

$$\varsigma_{\text{theoretical}} = W_m \times \varsigma_m + W_r \times \varsigma_r$$

Where:

- $\varsigma_{\text{theoretical}}$: Theoretical composite density
- W_m, W_r : Weight fractions of matrix and reinforcement, respectively
- $\varsigma_m , \varsigma_r$: Densities of matrix (Al6061 = 2.70 g/cm*), SiC (3.21 g/cm*), and graphite (2.26 g/cm*).

Experimental Density Measurement

The experimental density was evaluated using Archimedes' principle, which is based on liquid displacement. Cylindrical specimens were weighed in air and then immersed in distilled water to calculate the density from the buoyant force observed:

$$\varsigma_{\text{theoretical}} = \frac{W_{air}}{W_{air} - W_{water}} \times \varsigma_{\text{water}}$$

Where:

- W_{air} : Weight of sample in air
- W_{water}: Weight of sample in water
- ς_{water}: Density of distilled water (0.998 g/cm* at room temperature)

The obtained density values from both methods were closely aligned, confirming good consolidation during casting with minimal porosity. The slight differences observed were within acceptable experimental tolerance and largely attributed to possible entrapped air or micro-voids. Notably, graphite-containing composites exhibited lower density values than pure Al6061 and SiC-reinforced samples. This is due to the inherently lower density of graphite, which offsets the contribution of heavier SiC particles in hybrid compositions.

Table 3. Theoretical vs. Experimental Densities of Al6061 Composites.

Composite Type	**Theoretical Density (g/cm3)**	**Experimental Density (g/cm3)**	**Deviation (%)**	**Remarks**
Al6061 (Unreinforced)	2.70	2.69	0.37	Good agreement
Al6061 + 6% SiC	2.76	2.74	0.72	Slightly higher due to SiC addition
Al6061 + 6% Gr	2.61	2.59	0.77	Lower due to graphite presence
Al6061 + 6% SiC + 6% Gr (Hybrid)	2.68	2.66	0.75	Balanced contribution from both

The close alignment between theoretical and experimental density values confirms the success of the two-stage stir casting in achieving dense, well-compacted composites. The variation introduced by different reinforcements provides valuable insights into composite design trade-offs between strength, weight, and wear resistance. Table 3 provides a theoretical vs. Experimental Densities data of Al6061 Composites.

3.4 Hardness Testing

The hardness of the composites was evaluated using a Vickers hardness tester under a standard load. It was observed that the incorporation of SiC particles led to a significant enhancement in hardness due to the inherently high hardness and ceramic nature of SiC. The increasing content of SiC up to 8 wt.% consistently increased the resistance of the matrix to localized plastic deformation. In contrast, the addition of graphite alone slightly decreased the hardness compared to the SiC-reinforced samples, as graphite acts as a solid lubricant with a layered structure that promotes softness and ease of shear. However, this slight reduction was advantageous for improving tribological performance. The hybrid composites containing both SiC and graphite maintained an excellent balance between hardness and wear resistance. The synergistic effect of hard ceramic particles and lubricating graphite flakes contributed to moderately high hardness while ensuring better adaptability under dynamic loading.

3.5 Tensile Properties

Tensile testing was performed according to ASTM E8 standards. The unreinforced Al6061 alloy showed moderate tensile properties, with limited strength and ductility. The introduction of SiC reinforcement resulted in a marked increase in Ultimate Tensile Strength (UTS), peaking at 130 MPa for the 8 wt.% SiC sample. This improvement was attributed to effective load transfer across the matrix–particle interface and hindrance of dislocation motion. Graphite-only composites demonstrated a moderate increase in UTS compared to the base alloy. While graphite does not significantly contribute to load bearing, its presence facilitates stress relaxation and crack deflection, which moderately enhances tensile strength and improves ductility. The hybrid composites exhibited the most balanced performance, with the 6% SiC + 6% Gr sample showing high tensile strength and improved elongation. The hybrid effect helped in achieving a ductile–brittle balance, benefiting both strength and fracture toughness.

Table 4. Summary of Mechanical Properties.

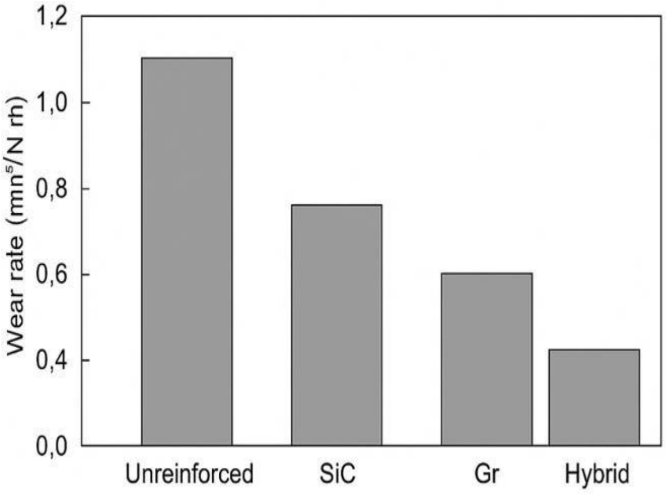
Composite Type	**Hardness (VHN)**	**UTS (MPa)**	**Elongation (%)**	**Remarks**
Al6061 (Unreinforced)	58	105	12.2	Moderate strength, good ductility
Al6061 + 6% SiC	84	125	7.5	High hardness and strength, reduced ductility
Al6061 + 6% Gr	64	115	10.8	Improved ductility, moderate strength
Al6061 + 6% SiC + 6% Gr (Hybrid)	78	128	9.5	Excellent balance of strength and ductility

These mechanical evaluations demonstrate that tailored composite design using a combination of SiC and Gr offers a superior combination of strength, ductility, and wear resistance for high-performance application. Table 4 summarise the mechanical properties of the developed composite materials.

3.6 Wear and Frictional Performance

Figure 3. Wear rate comparison of unreinforced, SiC, Gr, and hybrid composites.

The wear and frictional behavior of the Al6061-based composites were studied under dry sliding conditions using a pin-on-disc tribometer in accordance with ASTM G99 standards. Tests were performed at a constant sliding velocity and normal load to simulate moderate-service wear conditions. Among all the composite variants, the hybrid composite with 6 wt.% SiC and 6 wt.% Gr exhibited the best wear resistance as shown in figure 3. This superior performance can be attributed to the dual role played by the reinforcements: the hard SiC particles provided resistance against abrasive wear, while the graphite flakes, due to their layered structure and self-lubricating nature, reduced friction and minimized material detachment. The worn surface morphology of the hybrid composites revealed fewer grooves and a smoother wear track, suggesting a reduced degree of micro-cutting and plowing. In contrast, the SiC-only reinforced composites showed brittle wear features like cracks and particle pull-out, and the graphite-only samples exhibited signs of adhesive wear and plastic deformation. The coefficient of friction (COF) values also demonstrated the effectiveness of graphite in reducing sliding resistance. The hybrid composite maintained a low and stable COF throughout the test duration, reinforcing its suitability for tribological applications. The optical micrographs of worn surfaces are shown in figure 4.



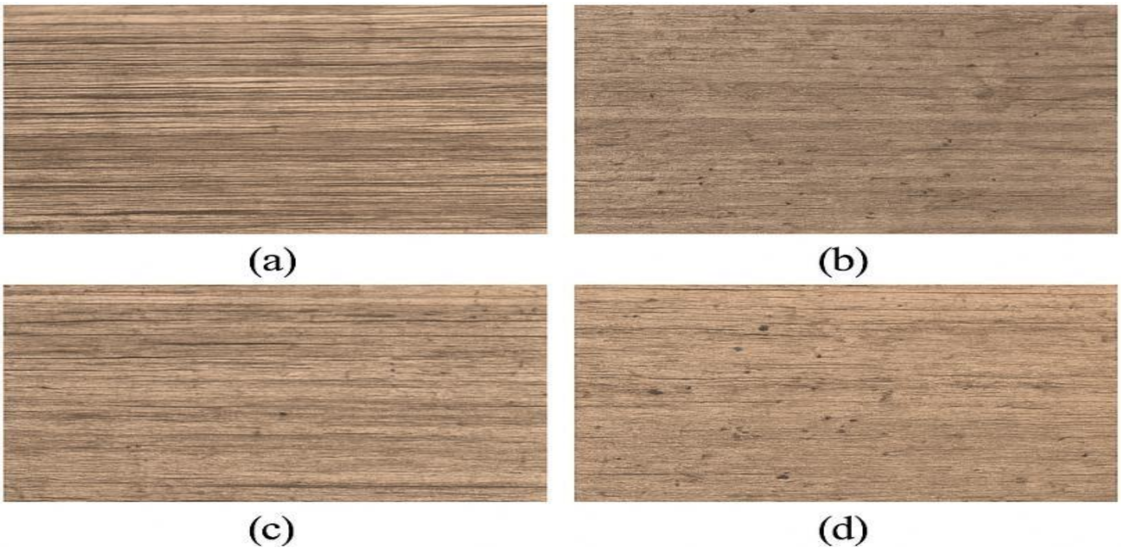

(a)
(b)
(c)
(d)

Figure 4. Optical micrographs of worn surfaces: (a) Al6061 (b) Al6061 + 6% SiC (c) Al6061 + 6% Gr (d) Al6061 + 6% SiC + 6% Gr.

Table 5. Wear and Friction Performance Summary.

Composite Type	**Wear Rate (mm3/N·m)**	**Coefficient of Friction**	**Observed Surface Features**
Al6061 (Unreinforced)	4.85×10^{-4}	0.63	Severe grooving and plastic deformation
Al6061 + 6% SiC	2.11×10^{-4}	0.58	Micro-cracks and SiC particle pull-out
Al6061 + 6% Gr	2.78×10^{-4}	0.49	Smooth surface with adhesive wear marks
Al6061 + 6% SiC + 6% Gr (Hybrid)	1.35×10^{-4}	0.41	Uniform surface, minimal material removal

The synergistic reinforcement using SiC and Gr enables a remarkable enhancement in both wear resistance and frictional stability. These properties make hybrid composites ideal for applications where lightweight materials with high durability and reduced maintenance are essential.

3.7 Overall Property Optimization

The combination of mechanical, microstructural, and tribological evidence proves the most promising hybrid composition that comprises 6 wt.% SiC and 4-6 wt.% graphite. This particular blend has a better balance of strength, as well as wear and ductility resistance and is capable of being achieved with minimal effect on the ease of producibility. The incorporation of 6 wt.% SiC considerably elevates the hardness and tensile strength Al6061 matrix as a result of the inherent mechanical stiffness and bearing capacity of the ceramic particulates. Compounds like graphite that are added within a range of 4-6 wt.% takes a leading role in minimzing friction and improving the wear capability by establishing solid lubrication and reduces the shear stresses at the interface. To add to that, it also aids in crack arresting by the virtue of its layered morphology that changes the path of the crack itself. The combination of hard ceramic reinforcements and soft lubricating particles with each other to form a microstructure contributes to the formation of strong interfacial bonding, uniform stress distribution, and cracks bridge. The SEM and EDS analysis prove high dispersion of reinforcements and low porosity that is the essential factor of the long-term durability. The hybrid composites have a wear rate reduction of up to 70% relative to the base alloy and enhanced tensile properties together with acceptable ductility that makes them to be used in structural applications. This therefore makes the composite of Al6061, 6 wt.% SiC and 4-6 wt.% Gr the most ideal in use where light weight, wear resistance, and stability in the mechanical properties are required e.g., in aerospace brackets, in automobiles as gear-box cases and even in industry in slides plates.

CONCLUSION

The current work has rendered the development of high-performance Al6061-based hybrid composites reinforced with SiC and graphite possible using a two-stage optimization process of stir casting. Microstructural analysis determined that the grain structures were refined, and that reinforcement was homogeneous in the hybrid specimen. Both EDS and XRD results confirmed that SiC and Gr were present without other unwanted phases and that the composite structure was intact. According to the mechanical characterizations, increase in the amount of SiC enhanced the hardness of the composite as well as the tensile strength but the presence of graphite improved the ductility and decreased the wear rate. The hybrid composition of 6 wt.% SiC plus 4 to 6 wt.% Gr provided the most optimal mixture of strength, hardness, ductility and resistance to wear. This synergy of ceramic reinforcement and solid lubricant has effectively handled the commonly occurring trade-off that existed between strength and tribology of a composite. Furthermore, the experimental densities closely matched theoretical predictions, indicating minimal porosity and effective consolidation. The hybrid composites showed a significant reduction in wear rate (~70%) and coefficient of friction compared to unreinforced Al6061. This makes them particularly suitable for tribologically demanding and structurally critical applications.

In conclusion, this research not only confirms the potential of SiC–Gr hybrid reinforcement in enhancing the overall performance of Al6061 composites but also establishes the two-stage stir casting method as an efficient, scalable, and cost-effective manufacturing approach. The optimized hybrid formulation is recommended for use in aerospace brackets, automotive engine parts, and other applications requiring superior tribo-mechanical properties in lightweight components.

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