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Mechanical and Dry Sliding Wear Behaviour of Al-6061/Al_2O_3/Mica Hybrid Composites Fabricated via Stir Casting

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Abstract- The present study focuses on the synthesis and performance evaluation of Al-6061-based hybrid metal matrix composites reinforced with alumina (Al_2O_3) and mica particulates. Four composite formulations were fabricated through the stir-casting process by varying Al_2O_3 content (2, 4, 6 and 8 wt.%) while maintaining a fixed 4 wt.% mica reinforcement. Mechanical behaviour was examined through Vickers microhardness and tensile tests, whereas dry sliding wear performance was assessed on a Pin-on-Disc tribometer under varying load, sliding speed and sliding distance conditions. Results revealed a substantial enhancement in hardness and tensile strength for all composites compared with the unreinforced matrix. The highest mechanical performance was achieved in Composite-4 (8 wt.% Al_2O_3 + 4 wt.% mica), primarily due to improved interfacial bonding and effective load transfer. Wear and coefficient of friction increased with applied load across all composites; however, reinforcement addition markedly reduced material loss relative to the base alloy. Composite-4 exhibited the lowest wear rate, followed closely by Composite-3, indicating superior tribolayer stability and resistance to abrasive and adhesive wear. Overall, the findings demonstrate that the incorporation of Al_2O_3 and mica synergistically enhances both mechanical integrity and surface durability of Al-6061, making these hybrid composites suitable for high-strength and wear-resistant engineering applications.

Keywords: Al-6061; Hybrid metal matrix composites; Al_2O_3; Mica; Mechanical properties; Tribological behavior

I. INTRODUCTION

Aluminium alloys are extensively used in engineering applications because of their low density, high strength-to-weight ratio, corrosion resistance, and desirable formability[1]. Among them, Al-6061 is one of the most commercially significant grades, widely adopted in aerospace structures, automotive components, marine parts, and lightweight mechanical systems[2]. However, the inherent limitations of monolithic Al-6061 particularly its moderate wear resistance and restricted mechanical strength under demanding service environments have stimulated the development of aluminium matrix composites (AMCs) to fulfil the performance requirements of advanced industries[3].The incorporation of reinforcements such as ceramic particles, carbon-based nanomaterials, and hybrid strengthening agents into the Al-6061 matrix has proven to be an effective approach for improving its load-bearing capability, hardness, thermal stability, and tribological behavior[4]. Among the available fabrication techniques, stir casting continues to be the most widely employed method due to its low processing cost, adaptability to mass production, and ability to disperse solid reinforcements reasonably well within molten aluminium. A wide range of reinforcement materials has been explored over the past decade[5]. Silicon carbide (SiC), alumina (Al_2O_3), graphene nanoplatelets, tungsten carbide, fly ash, and high-entropy alloy particles have been incorporated into Al-6061 to enhance its properties[6]. Most of these studies consistently report significant improvements in tensile strength, hardness, and wear resistance, highlighting the suitability of AMCs for high-stress and high-temperature environments[6].

Research has also shifted from single-reinforcement composites to hybrid composites, where two or more distinct reinforcements are simultaneously incorporated to exploit synergistic strengthening effects. Hybrid reinforcement allows controlling grain boundaries more efficiently, improves interfacial bonding, and enhances both strength and lubricating characteristics under sliding conditions. Several authors have examined the effect of reinforcement type and percentage on the performance of Al-based composites. Mahalingegowda et al.[7] studied Al-

6061 reinforced with various proportions of Al_2O_3 and Al_2O_3–graphite, reporting noticeable enhancement in mechanical and wear properties. Mohd Shadab Khan et al.[8] analysed abrasive wear behaviour statistically and showed that reinforcement content, applied load, and sliding velocity have major influence on wear response. Madevanagaral et al.[9] observed that hybrid composites containing Al_2O_3 and graphite maintain improved wear behaviour but display a slight reduction in tensile strength with higher graphite content due to the soft lubricating nature of graphite. The significance of hybrid reinforcement is further supported by studies employing SiC/graphite, SiC/mica, SiC/fly ash, and similar combinations. Maniyar et al.[10] reported that SiC/mica hybrid composites display superior microstructural integrity and improved tribological behaviour compared to single-reinforcement LM25 alloys. Zakaulla et al.[11] demonstrated that copper-coated SiC and graphite allow better wettability with molten aluminium and improve wear resistance, further confirming the importance of strong interfacial bonding. Gowri Shankar et al.[12] highlighted the increasing application of hybrid AMCs in aerospace, marine, and transportation sectors due to their stiffness, impact resistance, and corrosion stability. Tribological investigations also point towards the importance of sliding speed, load, and reinforcement content. Studies by Bhaskar, Venkalprasat and others reported that high applied load promotes material removal, whereas the addition of ceramic reinforcement and graphite lubrication decreases wear loss [13]. The Taguchi-based design-of-experiments approach used by multiple researchers also indicated that applied load is generally the dominant factor governing wear rate, followed by sliding speed and reinforcement content. Composites reinforced with fly ash, alumina, tungsten carbide and graphite have additionally shown potential as economical and high-performance engineering materials, particularly when developed through liquid metallurgy routes[14]. The work carried out by Basavaraj et al.[15] concluded that Al/SiC/graphite and Al/SiC/fly ash hybrid systems offer high performance at reduced material cost, which is crucial for large-volume industrial adoption. Veereshkumar et al.[16] demonstrated that the density and hardness of Al-6061/WC/graphite composites increase with increasing WC content, further reaffirming that ceramic reinforcement plays a central role in enhancing the matrix strength. Wear studies on different alloy systems also confirm the durability benefits of hybrid AMCs. Given the growing demand for lightweight and wear-resistant engineering materials. The development of Al-6061-based hybrid metal matrix composites continues to be a highly relevant research direction. Optimizing the selection, proportion, and distribution of reinforcements enables tailoring of the mechanical and tribological properties to specific engineering applications.

The aim of this study is to synthesize Al-6061/Al_2O_3/Mica hybrid metal matrix composites using the stir casting process with varying Al_2O_3 content and fixed mica reinforcement, and to evaluate their mechanical and dry sliding wear behavior under different loading, sliding speed and sliding distance conditions.

II. MATERIALS AND EXPERIMENTATION

In the present study, Al-6061 alloy was selected as the matrix material. The alloy was procured (Fenfee metallurgical lab, Bangalore)), in the form of small ingots, which were sectioned into pieces suitable for placement in the crucible during melting. The elemental composition of Al-6061, obtained from spectral analysis, is presented in Table 1.

Table 1: Chemical analysis of the Al-6061 alloy

Element	Al%	Si%	Mg%	Pb%	Zn%	Cu%	Fe%	Ti%	Al
Al-6061	97.28	1.600	0.045	0.076	0.104	0.176	0.413	0.018	Bal

Reinforcement materials used were alumina (Al_2O_3) and mica, chosen for their high strength-to-weight ratio, corrosion resistance, and solid lubricating behaviour, respectively. The particle size distribution of the reinforcements is reported in Table 2.

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Table 2: Particles size of Al_2O_3 and Mica.

Reinforcement	Practical size range (µm)
Al_2O_3.	30-50
Mica	30-40

2.1. Fabrication of Al-6061 / Al_2O_3 / Mica Hybrid Composites

The hybrid composites were fabricated using the stir casting method. Figure 1 illustrates the electrical melting furnace and stir-casting setup used in this study. Approximately 3 kg of Al-6061 ingots were melted in an induction furnace, and the melt temperature was raised to 800 °C. Flux was added to remove slag and degasifying tablets were introduced to eliminate trapped gases. Al_2O_3 was added in varying weight percentages (2%, 4%, 6%, and 8%), while mica content was kept constant at 4 wt.%. Prior to addition, the reinforcements were preheated on the furnace surface to remove moisture and ensure better wettability with the melt. A coated mild-steel stirrer attached to a radial drill press (80–800 rpm) was inserted into the melt to a depth of approximately 1¼ of the stirrer length, and stirring was initiated at 500 rpm to form a vortex. The reinforcement blend was gradually introduced into the vortex at a rate of 10–20 g/min, maintaining continuous isothermal stirring. After complete addition of the particles, stirring was continued to ensure uniform distribution, after which the stirrer was withdrawn and the molten composite slurry was poured into preheated metallic moulds. The castings were allowed to solidify under atmospheric conditions and later machined to ASTM-specified dimensions for testing. Table 2 shows the designation and composition of fabricated hybrid composites

Table 2: Designation and composition of fabricated hybrid composites

Composite Code	Matrix Material	Al_2O_3 (wt.%)	Mica (wt.%)
Composite-1	Al-6061	2	4
Composite-2	Al-6061	4	4
Composite-3	Al-6061	6	4
Composite-4	Al-6061	8	4

Figure 1. Electrical melting furnace and stir casting set up

2.2. Mechanical Testing

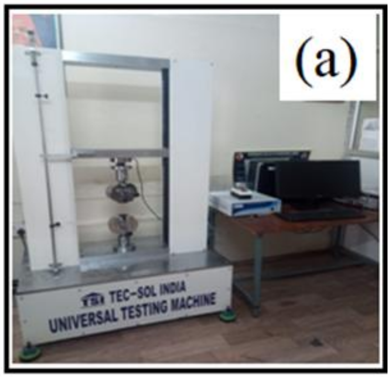
2.2.1. Hardness

Vickers microhardness measurements were performed using a diamond indenter with a 0.30 kg load and 10 s dwell time. Three readings were taken at different locations along the specimen cross-section, and the average value was considered for analysis (Figure. 2).

Figure 2. Vickers Micro hardness (Mitutoyo) tester

2.2.2. Tensile Strength

Tensile specimens were machined from the as-cast composites per ASTM E8 standards. Tests were carried out using a UTM (TEC-SOL, India; 3-Ton capacity) to determine ultimate tensile strength and percentage elongation. Photographs of the UTM and specimen dimensions are shown in Figure 3.



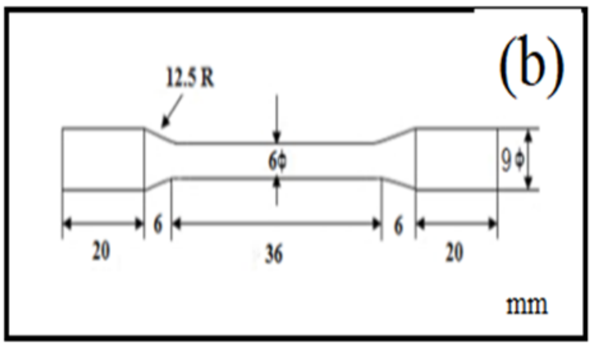
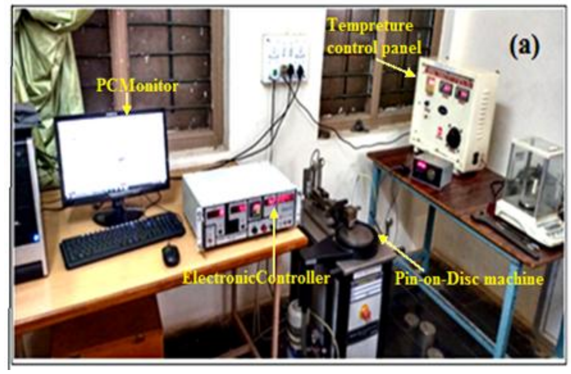


Figure3. (a) Universal Tensile testing machine (b) Tensile test specimen .



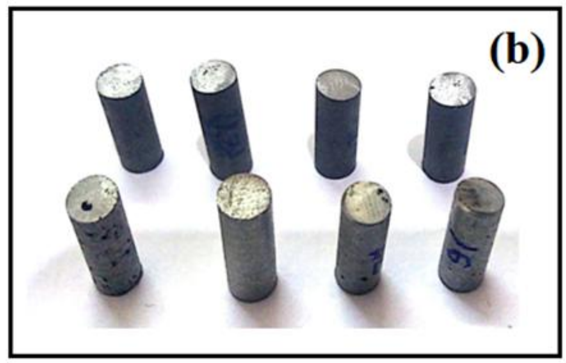


Figure 4. (a) Pin- on- Disc wear testing machine and (b) wear test specimen

2.3. Wear Testing

Dry sliding wear tests were conducted on a Pin-on-Disc tribometer conforming to ASTM G133-05 standards (Fig. 4). A cylindrical pin specimen of 15 mm height and 6 mm diameter was slid against an EN32 steel disc of dimensions 40 × 40 × 5 mm. Prior to testing, each pin specimen was weighed to obtain its initial mass (W_1) and was then mounted on the specimen holder. The wear experiments were performed under different test conditions by varying the normal load (1 kg, 2 kg, 3 kg and 4 kg), sliding velocity (1 m/s, 2 m/s and 3 m/s) and sliding distance (500 m, 1000 m and 1500 m). Before every trial, the contact surface of the pin was polished with 600-grit emery paper to ensure uniform surface finish and proper contact with the rotating disc. Upon completion of the sliding cycle, the pin was removed, cleaned thoroughly to eliminate any adhered debris and re-weighed to obtain the final mass (W_2). The wear loss was calculated based on the difference between W_1 and W_2.

III. RESULTS AND DISCUSSION

3.1. Hardness Test

A Vickers hardness tester (Model FV-700) was used to measure hardness. The specimen surfaces were metallographically prepared using 100–1000 grit emery papers. A load of 0.3 kg and a dwell time of 10 s were applied for each indentation. The hardness results for unreinforced Al-6061 alloy and the composites are shown in Table 3. A clear increase in hardness is observed from the base alloy to the reinforced composites. Pure Al-6061 exhibits the lowest hardness (59.20 HV), while Composite-4 records the highest (85.67 HV), followed by Composite-3, Composite-2, and Composite-1. The improvement is attributed to the presence of reinforcement particles, which restrict plastic deformation and enhance resistance to indentation through load transfer, reduced dislocation mobility, and uniform particle distribution.

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Table 3: Hardness measurement of Matrix and Composites

Sample No.	Load (kg)	Sample Type	Trial -1	Trial -2	Trial -3	Mean Hardness (HV)
1	0.3	Pure Al6061 (Matrix)	60.80	59.50	57.30	59.20
2	0.3	Composite-1	62.40	56.30	68.30	62.33
3	0.3	Composite-2	64.50	62.00	69.30	65.26
4	0.3	Composite-3	63.70	66.00	72.30	67.33
5	0.3	Composite-4	86.20	83.30	88.40	85.67

3.2. Tensile strength

Table 4 shows the tensile properties of matrix and composites .The tensile test results reveal a significant improvement in UTS and YS for all the composites compared to the unreinforced matrix. The UTS increases progressively from 124 N/mm² (matrix) to 210.54 N/mm² for Composite-4, indicating the strengthening influence of reinforcement particles. However, the ductility decreases with increasing reinforcement content, which is a typical trade-off in particle-reinforced MMCs. The reduction in ductility is attributed to restricted plastic deformation and increased brittleness due to ceramic particulates and strong interfacial bonding

Table 4: Mechanical properties of matrix and composites

Composite	UTS (N/mm^2)	YS (N/mm^2)	Ductility (%)
Matrix	124	116	5
Composite-1	165.58	136	3
Composite-2	172.58	143	2.5
Composite-3	182.58	134	1.9
Composite-3	210.54	128	1.3

3.3. Wear test

Figure 5 shows the variation in volumetric wear rate of the four composites with increasing applied load at a constant sliding speed of 2 m/s and sliding distance of 1000 m. All composites exhibit a progressive rise in wear rate with load, indicating that higher contact pressure intensifies abrasive and adhesive wear at the pin–disc interface. At lower loads (1–2 kg), the wear rates are minimal, suggesting that the reinforcement particles efficiently support the applied stress and protect the matrix. Composite-3 records the lowest wear in this range, reflecting superior interfacial bonding and load-sharing. At 3 kg, the wear rate increases noticeably for all materials, with Composite-2 showing the highest wear, likely due to particle fracture or weak bonding leading to pull-out and three-body abrasion. Composite-4, however, maintains relatively low wear at this load. At 4 kg, all composites exhibit a sharp increase in wear rate due to thermal softening of the matrix and breakdown of the mechanically mixed layer. Composite-3 consistently demonstrates the best wear resistance across all loads, while Composite-2 performs poorest. These results highlight that reinforcement distribution significantly affects wear behavior, with Composite-3 displaying superior load-bearing capacity and tribolayer stability.

Figure 6 presents the volumetric wear rate of the four composites under different applied loads at a constant sliding speed of 3 m/s and sliding distance of 1000 m. All materials exhibit a clear rise in wear rate with increasing load, confirming that higher normal forces intensify asperity deformation and promote abrasive and adhesive wear. At 1 kg, wear rates remain minimal for all composites, indicating sufficient reinforcement effectiveness. Composite-3 shows the lowest wear, while Composite-1 displays slightly higher wear.

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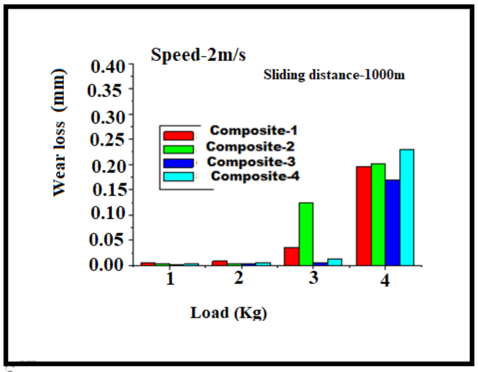

Figure 5. Volume loss with load at sliding seed of 2.0m/s.

At 2 kg, wear increases for all composites, with a sharp rise in Composite-1 and the lowest wear again recorded for Composite-3. This suggests stronger interfacial bonding and load-bearing capability in Composite-3 and greater particle pull-out in Composite-1. At 3 kg, wear rates further increase due to thermal softening and subsurface deformation; Composite-3 and Composite-2 show relatively lower wear, whereas Composite-1 and Composite-4 experience more severe microploughing and delamination. At 4 kg, wear rises sharply for all composites due to tribolayer breakdown and severe sliding conditions. Although differences narrow, Composite-3 continues to display the best wear resistance, while Composite-4 and Composite-1 show the highest wear.

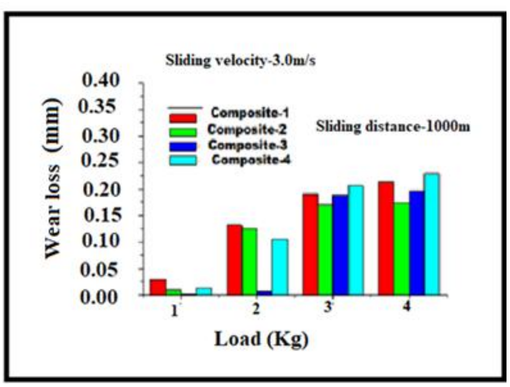

Figure 6. Volume loss with load at sliding speed of 3.0 m/s.

Overall, Composite-3 consistently delivers superior wear performance owing to improved reinforcement distribution, strong interfacial bonding, and stable tribofilm formation; whereas Composite-1 and Composite-4 undergo more aggressive abrasive and adhesive wear at higher loads.

3.4. Coefficient of friction (COF)

Figures 7 show the variation in coefficient of friction and volumetric wear rate of the composites under different loads at a constant sliding distance of 1000 m. For all specimens, the coefficient of friction increases with increasing load, mainly due to enlargement of the real contact area and intensified adhesive interaction at the sliding interface. At 1 kg, friction values remain low for all materials, with Composite-2 exhibiting the lowest value, while Composite-1 and Composite-4 show slightly higher friction. At 2 kg, all composites show a moderate rise in friction, with Composite-3 and Composite-4 maintaining comparatively lower values owing to the formation of a stable lubricating tribolayer. Under higher loads (3–4 kg), the coefficient of friction rises sharply due to thermal softening of the matrix and stronger asperity interlocking. Although friction values converge at 4 kg, Composite-3 exhibits slightly lower friction, indicating better interfacial stability. The volumetric wear rate also increases consistently with load. At 1 kg, wear is minimal for all composites, confirming the effectiveness of reinforcement in restricting material removal under mild sliding. Composite-3 shows the lowest wear at this stage. At 2 and 3 kg, wear increases for all materials due to subsurface deformation and partial breakdown of the mechanically mixed layer. Composite-4 consistently records the lowest wear at these intermediate loads, while Composite-1 displays higher wear. At 4 kg, a significant increase in wear occurs due to severe abrasive and adhesive mechanisms.

Inferior performance due to weaker particle–matrix bonding and reduced surface integrity under high loads.

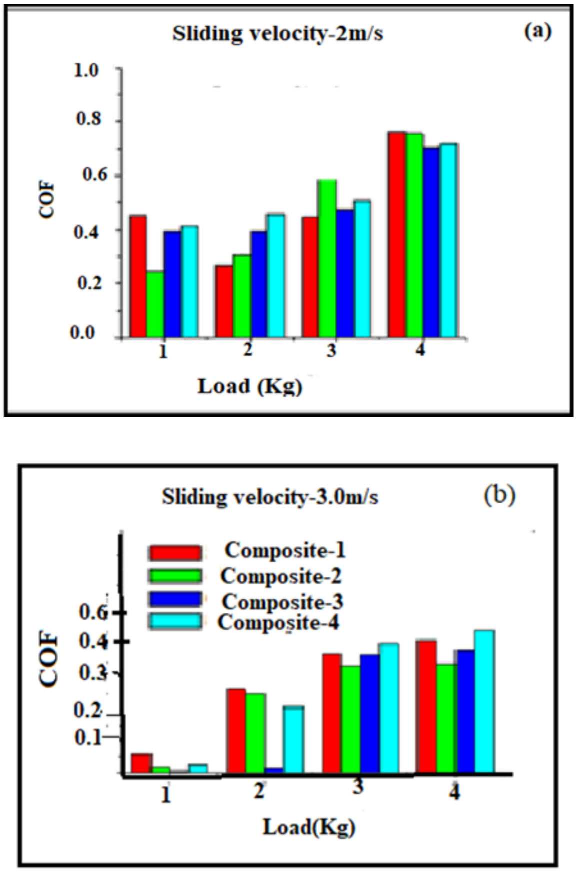

Figure 7.Variation of COF with load at sliding speed of (a) 2.0m/s and (b) 3.0m/s

Composite-4 shows the best wear resistance, followed by Composite-3, whereas Composite-1 remains the least resistant. Overall, tribological performance is strongly influenced by applied load and reinforcement distribution. Composites with higher reinforcement content and better interfacial bonding (Composite-4 and Composite-3) exhibit lower friction and wear because of enhanced hardness, effective load sharing, and stable tribolayer formation. Composite-1 shows

IV. CONCLUSION

- Al-6061-based hybrid composites reinforced with Al_2O_3 and mica were successfully fabricated through stir casting and evaluated for mechanical and tribological performance.
- Reinforcement addition significantly improved overall properties compared to the unreinforced alloy.
- Tensile strength (UTS and YS) increased for all composites, while ductility decreased with higher reinforcement levels.
- Composite-4 achieved the highest tensile strength, followed by Composite-3 and Composite-2, indicating superior load-transfer capability.
- Hardness values increased for all composites, with Composite-4 showing the maximum hardness due to greater reinforcement content and stronger interfacial bonding.
- Coefficient of friction and wear rate increased with applied load for all materials; however, reinforced composites performed better than the base alloy.
- Composite-4 consistently exhibited the lowest wear rate across all load conditions, followed by Composite-3 and Composite-2, owing to high hardness and stable tribolayer formation.
- Composite-1 showed relatively higher wear and friction due to weaker load-bearing ability.
- Composite-4 emerged as the best-performing material overall, suitable for applications requiring high strength and enhanced surface durability.

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