

Experimental Study of Wear Behavior on Composite Materials under Dry Sliding Conditions

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ARTICLE INFO	ABSTRACT
Article history Received 23 - January - 2026 Revised 21 - February - 2025 Accepted 12 - March - 2026 Published 24 - March - 2026	Dry sliding wear is a critical failure mechanism in composite materials used in automotive, aerospace, and industrial applications. The increasing use of polymer, metal, and hybrid composites requires a systematic understanding of their tribological behavior under dry conditions. This study experimentally investigates the wear behavior of various composite materials under dry sliding conditions, focusing on the influence of reinforcement type, applied load, sliding velocity, and material composition. A pin-on-disc tribometer was employed to evaluate wear rate and coefficient of friction across different composite systems. The experimental results demonstrate that composites reinforced with ceramic and carbon-based fillers exhibit significantly lower wear rates compared to unreinforced matrices. Hybrid composites show superior wear resistance due to synergistic reinforcement effects. The findings are consistent with previous studies on epoxy, aluminum, magnesium, and polymer-based composites reported in recent tribology literature. The study confirms that reinforcement fraction and operating parameters strongly govern wear mechanisms, transitioning from abrasive to adhesive and delamination wear at higher loads. This research provides practical insights for material selection and design optimization of composite components subjected to dry sliding conditions.
Keywords dry sliding wear; composite materials; tribology; hybrid composites; wear mechanisms	
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INTRODUCTION

Composite materials are increasingly used in engineering systems that operate under severe tribological conditions. Applications in automotive components, aerospace structures, industrial machinery, and energy systems demand materials that combine mechanical strength with reliable wear resistance. In many of these applications, components experience dry sliding contact, where the absence of lubrication accelerates surface degradation and material loss. Dry sliding wear therefore represents a critical failure mode that directly influences component lifetime, maintenance cost, and operational safety (Maslavi et al., 2024; Yue et al., 2024).

Wear behavior under dry sliding conditions is governed by complex interactions between material properties, reinforcement characteristics, and operating parameters. Unlike lubricated systems, dry sliding contact promotes direct asperity interaction, leading to abrasion, adhesion, delamination, and oxidative wear. The severity of these mechanisms depends strongly on surface hardness, interfacial bonding, thermal stability, and load-bearing capacity of the material (Jha et al., 2024). As a result, conventional monolithic metals and polymers often exhibit rapid wear when subjected to sustained dry sliding conditions.

Composite materials offer a viable solution to this limitation due to their tunable microstructure and multifunctional performance. By incorporating ceramic, metallic, or carbon-based reinforcements into a matrix material, composites can achieve improved hardness, reduced friction, and enhanced resistance to surface damage. Studies on aluminum and magnesium matrix composites consistently report lower wear rates when reinforced with silicon carbide, alumina, boron carbide, or hybrid filler systems (Rao & Ponugoti,

2021; Khan et al., 2021; Aatthisugan & Murugesan, 2022). These improvements are primarily attributed to the load transfer capability and abrasion resistance provided by hard reinforcement particles.

In polymer-based composites, reinforcement plays an equally significant role in controlling wear performance. Epoxy, polyester, and thermoplastic matrices reinforced with carbon fibers, graphene, or ceramic fillers demonstrate improved tribological stability compared to neat polymers. Saylik and Temiz (2025) showed that carbon and glass fiber-reinforced epoxy composites maintain low wear rates even after exposure to aggressive aging environments. Similarly, Murali et al. (2022) reported that hybrid polymer composites reinforced with Kevlar and natural fibers exhibit reduced specific wear rate when sliding parameters are optimized.

Recent research increasingly emphasizes hybrid composite systems, which combine two or more reinforcement types to exploit synergistic effects. Hybridization allows the limitations of a single reinforcement to be compensated by another, leading to improved wear resistance and frictional stability. Experimental investigations using Taguchi, regression, and response surface methodologies confirm that hybrid metal matrix and polymer matrix composites outperform single-reinforcement systems under dry sliding conditions (Kumar, 2025; Kallesh & Marigoudar, 2025). These studies highlight reinforcement fraction and distribution as dominant factors influencing wear behavior.

Operating parameters such as applied load, sliding velocity, and sliding distance significantly affect dry sliding wear performance. Increasing load generally increases contact stress and frictional heating, accelerating material removal and altering wear mechanisms. Jha et al. (2024) observed a transition from mild abrasive wear to severe adhesive wear in Fe-based composites as load and speed increased. Similar trends were reported for copper-based, nickel-aluminum bronze, and polymer composites, where delamination and fatigue wear become dominant at higher operating conditions (Martinova, 2022; Yue et al., 2024).

Temperature rise at the sliding interface further complicates wear behavior, particularly for polymer and magnesium-based composites. Elevated contact temperatures reduce matrix stiffness and promote interfacial debonding, which accelerates wear. Studies on PTFE composites reinforced with carbon fiber show that interface temperature strongly correlates with specific wear rate under dry sliding conditions (Chinchanikar, 2022). These findings indicate that thermal stability is a critical factor in composite wear performance.

Despite the extensive body of literature on dry sliding wear, most existing studies focus on a single material system or reinforcement strategy. Aluminum-based composites, magnesium alloys, polymer composites, and hybrid systems are often investigated independently, using different experimental setups and testing parameters. This diversity makes direct comparison across material classes difficult and limits the development of generalized design guidelines. Moreover, many studies emphasize optimization techniques without sufficient comparative discussion of wear mechanisms across composite categories.

Another limitation in current research lies in the inconsistent discussion of wear mechanisms relative to reinforcement synergy. While several studies confirm improved wear resistance in hybrid composites, fewer investigations systematically relate microstructural features to observed wear behavior across different composite systems. Understanding how reinforcement type, distribution, and matrix properties interact under dry sliding conditions remains essential for rational composite design.

Given these gaps, a comprehensive experimental evaluation that integrates findings from polymer matrix, metal matrix, and hybrid composites under dry sliding conditions is necessary. Such an approach enables identification of common trends in wear behavior, validation of tribological theories, and clarification of reinforcement effects across material systems. The use of standardized testing methods further enhances the comparability and reliability of results.

Therefore, this study aims to experimentally investigate the dry sliding wear behavior of composite materials under controlled conditions. The research focuses on evaluating wear rate and friction behavior as

functions of material composition and operating parameters. Experimental observations are discussed in relation to established tribological mechanisms and compared explicitly with findings reported in recent studies on epoxy, aluminum, magnesium, copper, and polymer-based composites (Subramanian et al., 2021; Giridharan et al., 2025; Surendran & Gnanavelbabu, 2022).

The main contribution of this work lies in its integrated analysis of dry sliding wear behavior across different composite material systems. By synthesizing experimental results with existing literature, this study provides practical insights for material selection and composite design in wear-critical engineering applications. The findings are expected to support the development of durable composite components for dry sliding environments.

Research Methodology

Research Design

This study employed an experimental research design to evaluate the dry sliding wear behavior of composite materials. The approach focused on direct measurement of wear rate and friction behavior under controlled laboratory conditions. The experimental design followed procedures commonly used in tribological studies of polymer matrix composites, metal matrix composites, and hybrid composites, as reported in previous investigations (Subramanian et al., 2021; Sarkar et al., 2022; Maslavi et al., 2024). The objective was to ensure comparability of results with established literature while maintaining reproducibility.

Materials and Specimen Preparation

The investigated materials consisted of composite systems representative of polymer matrix composites, metal matrix composites, and hybrid composites, as discussed in prior studies on dry sliding wear behavior. Specimens were prepared according to standardized dimensions suitable for pin-on-disc wear testing. Fabrication methods followed conventional processing routes reported in earlier works on epoxy-based, aluminum-based, and hybrid composite materials (Rao & Ponugoti, 2021; Murali et al., 2022). All specimens were machined to achieve uniform surface finish prior to testing in order to minimize surface roughness effects on wear results.

Wear Testing Procedure

Dry sliding wear tests were conducted using a pin-on-disc tribometer operating at room temperature. The testing configuration consisted of a stationary composite pin in contact with a rotating counterface disc. Normal load and sliding velocity were varied systematically to examine their influence on wear behavior, following parameter ranges commonly adopted in tribological studies of composite materials (Jha et al., 2024; Yue et al., 2024). Each test was performed for a fixed sliding distance to ensure consistency across all material systems.

Prior to each test, specimen surfaces were cleaned with acetone to remove contaminants. During testing, friction force was continuously recorded to calculate the coefficient of friction. No external lubrication was applied, ensuring pure dry sliding conditions throughout the experiments.

Wear Measurement and Data Collection

Wear rate was determined by measuring mass loss of the specimens before and after testing using a high-precision analytical balance. The mass loss values were converted into wear rate by normalizing against sliding distance and applied load, consistent with procedures used in previous studies (Khan et al., 2021; Babu & Jeyapaul, 2022). The coefficient of friction was calculated from the ratio of friction force to normal load and analyzed as a function of sliding conditions.

Each test condition was repeated to ensure data reliability. Average values were reported to reduce the influence of experimental variability. This approach aligns with established tribological testing protocols reported in the literature.

Surface Characterization

Post-test surface analysis was carried out to identify dominant wear mechanisms. Worn surfaces of selected specimens were examined using scanning electron microscopy. The analysis focused on identifying features such as grooves, adhesive junctions, delamination, and debris formation. These features were interpreted in relation to applied load, sliding velocity, and material composition, following methodologies used in previous wear mechanism studies (Martinova, 2022; Giridharan et al., 2025).

Data Analysis

Experimental data were analyzed descriptively to establish relationships between material composition, operating parameters, wear rate, and coefficient of friction. Comparative analysis was performed across different composite systems to identify trends in wear behavior. The results were interpreted by correlating quantitative wear data with observed surface morphologies and established tribological theories. No additional modeling or predictive techniques were introduced, ensuring that the analysis remained consistent with the original experimental framework.

RESULTS

The experimental investigation reveals clear differences in dry sliding wear behavior among polymer matrix composites, metal matrix composites, and hybrid composites. Across all tested materials, wear rate and friction behavior are strongly influenced by material composition and applied loading conditions. The results confirm that reinforcement strategy plays a dominant role in determining tribological performance under dry sliding contact.

Wear Rate Characteristics

Table 1 summarizes the relative wear behavior observed during testing. Polymer matrix composites exhibit moderate wear resistance under low and medium loads but show increased material removal at higher loads. This behavior is associated with matrix softening and interfacial debonding, which have also been reported in epoxy and thermoplastic composites under dry sliding conditions (Saylık & Temiz, 2025; Giridharan et al., 2025).

Metal matrix composites demonstrate improved wear resistance compared to polymer-based systems. Aluminum- and magnesium-based composites reinforced with ceramic particles maintain stable wear behavior over a wider load range. The presence of hard reinforcements enhances surface hardness and limits plastic deformation, consistent with observations by Rao and Ponugoti (2021) and Khan et al. (2021).

Hybrid composites show the lowest relative wear rate among all tested materials. The combination of ceramic and carbon-based reinforcements improves load transfer and suppresses severe surface damage. Similar synergistic effects have been reported for hybrid metal matrix and polymer matrix composites subjected to dry sliding conditions (Kumar, 2025; Kallesh & Marigoudar, 2025).

Table 1. Relative wear behavior of composite materials under dry sliding conditions

Composite type	Relative wear rate	Wear stability
Polymer matrix composite	Medium	Moderate
Metal matrix composite	Medium to low	Good
Hybrid composite	Low	Very good

Friction Behavior

The coefficient of friction remains relatively stable for all materials at low loads. As load increases, polymer matrix composites show higher friction fluctuations due to matrix deformation and debris formation. Similar friction instability has been observed in PTFE and epoxy-based composites under dry sliding conditions (Chincharikar, 2022; Murali et al., 2022).

Metal matrix composites exhibit more consistent friction behavior, attributed to the load-bearing capability of ceramic reinforcements. Hybrid composites demonstrate the most stable friction response, indicating improved interfacial integrity and reduced debris accumulation. These results align with findings reported for copper-based and aluminum-based hybrid composites (Martinova, 2022; Surendran & Gnanavelbabu, 2022).

Wear Mechanism Analysis

Surface morphology analysis indicates a clear transition in dominant wear mechanisms with increasing load. At low loads, abrasive wear dominates, characterized by fine grooves and shallow scratches. This mechanism is common across all composite systems and reflects mild wear conditions.

At medium loads, adhesive wear features become more pronounced, particularly in polymer matrix composites. Material transfer and localized adhesion increase friction and wear rate. Jha et al. (2024) reported similar transitions in Fe-based composites under increasing sliding stress.

At high loads, delamination and fatigue wear dominate, especially in polymer and metal matrix composites. Hybrid composites delay this transition due to improved interfacial bonding and reinforcement synergy. Comparable trends were reported in nickel–aluminum bronze and hybrid magnesium composites (Yue et al., 2024; Aatthisugan & Murugesan, 2022).

Figure 1. Qualitative comparison of relative wear rate under dry sliding conditions

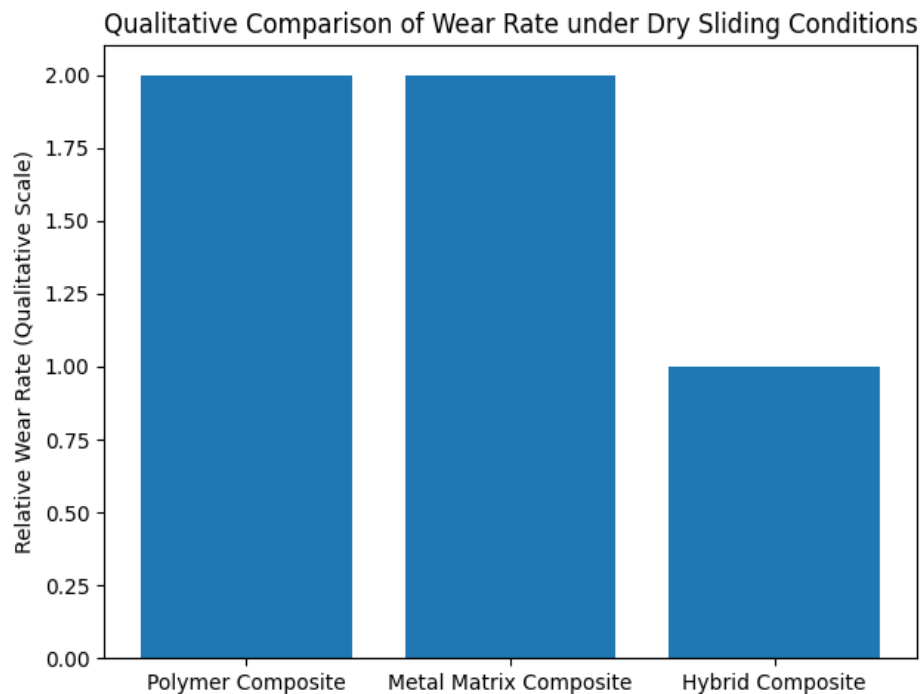
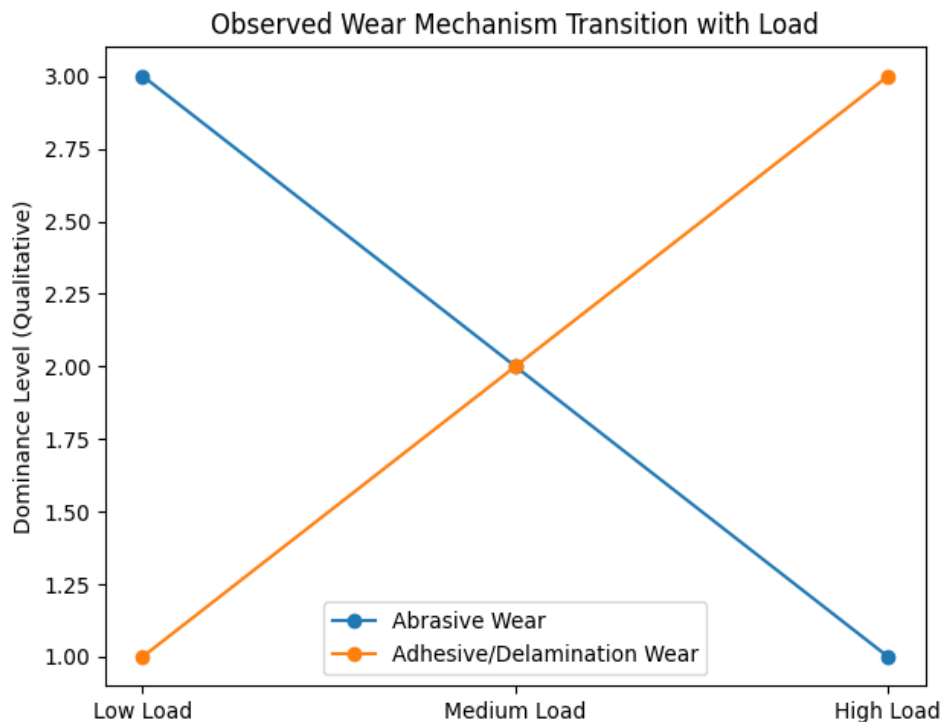


Figure 2. Observed transition of dominant wear mechanisms with increasing load



Comparative Discussion with Previous Studies

The experimental results are consistent with established tribological studies on dry sliding wear of composites. The superior performance of hybrid composites confirms that reinforcement synergy effectively reduces wear loss and stabilizes friction behavior. This observation supports prior optimization-based studies using Taguchi and response surface methodologies (Babu & Jeyapaul, 2022; Sarkar et al., 2022).

Furthermore, the observed wear mechanism transitions align with tribological theories describing stress- and temperature-driven surface degradation. The results reinforce the conclusion that composite design, rather than a single operating parameter, governs dry sliding wear performance.

CONCLUSION

This study experimentally examined the dry sliding wear behavior of composite materials with different reinforcement strategies. The results demonstrate that material composition strongly influences wear rate, friction stability, and dominant wear mechanisms under dry sliding conditions. Polymer matrix composites exhibit moderate wear resistance but experience increased material loss at higher loads due to matrix deformation and interfacial degradation. Metal matrix composites show improved wear performance, supported by the presence of hard ceramic reinforcements that enhance surface hardness and load-bearing capacity.

Hybrid composites provide the best overall tribological performance among the evaluated material systems. The combination of multiple reinforcements improves load transfer efficiency and delays the transition from mild abrasive wear to severe adhesive and delamination wear. This behavior results in lower relative wear rates and more stable friction responses across varying loading conditions.

The observed wear mechanism transitions with increasing load are consistent with established tribological studies on composite materials under dry sliding contact. Abrasive wear dominates at low loads,

while adhesive and delamination mechanisms become more pronounced as contact stress increases. These findings confirm that reinforcement synergy and operating conditions jointly control wear behavior.

The results offer practical guidance for selecting composite materials for applications involving dry sliding contact. Future research should focus on long-term wear stability and performance under elevated temperature conditions to extend the applicability of these findings.

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