2025, Vol. 3, No. 3, pp. 96-105
E-ISSN: 3025-9444

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

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Abstract: Dry sliding wear significantly influences the service life of composite materials used in automotive, aerospace, and marine engineering applications. This study presents a comparative experimental investigation of dry sliding wear behavior in various polymer matrix composites and metal matrix composites reported in recent literature. The objective of this study is to synthesize and critically analyze wear trends, dominant mechanisms, and the influence of reinforcement type, load, sliding speed, and filler content on tribological performance. A systematic experimental review methodology was applied by extracting quantitative and qualitative wear data from peer-reviewed journals and classifying them based on material system and test parameters. The analysis shows that hybrid reinforcement systems, such as Si_3N_4–graphite in aluminum matrices and carbon nanotube–alumina in epoxy matrices, consistently exhibit lower wear rates than single-reinforcement systems. Solid lubricants such as graphite and h-BN significantly reduce friction coefficients, while fiber orientation and filler percentage strongly influence wear mechanisms. The findings indicate that optimized hybrid composites can achieve up to 25–40% improvement in wear resistance compared to monolithic materials. This study contributes a structured synthesis of experimental tribological results and provides guidelines for material selection and parameter optimization in dry sliding applications.

Article history:
Received: 03 May 2025
Revised: 05 June 2025
Accepted: 18 July 2025
Published: 26 July 2025

Keyword:
dry sliding wear, hybrid composites, tribological behavior, wear mechanisms, metal matrix composites

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How to cite: Borneo, A. N., & Hartono, D. S. (2025). Experimental Study of Wear Behavior on Composite Materials under Dry Sliding Conditions. *RESWARA: Jurnal Riset Ilmu Teknik*, *3*(3), 96–105. https://doi.org/10.70716/reswara.v3i3.426

INTRODUCTION

Dry sliding wear is a dominant degradation mechanism affecting the performance and reliability of composite materials in tribological applications. Components such as bearings, brake systems, aircraft structures, and marine equipment frequently operate under dry or boundary-lubricated conditions, where direct surface contact leads to material removal, frictional heating, and microstructural damage (Maslavi et al., 2024; Yue et al., 2024). The increasing adoption of composite materials in these applications is driven by their high strength-to-weight ratio, corrosion resistance, and design flexibility. However, their tribological performance remains a critical limiting factor, particularly under dry sliding conditions where lubrication is absent and surface interactions dominate material behavior.

Extensive experimental studies have demonstrated that both polymer matrix composites and metal matrix composites exhibit superior wear resistance compared to their monolithic counterparts. Polymer-based composites reinforced with fibers and nanoparticles show enhanced load-carrying capacity and reduced wear rates due to improved interfacial bonding and load transfer mechanisms (Ramkumar et al., 2024; Murali et al., 2022). Similarly, aluminum- and magnesium-based metal matrix composites reinforced with ceramic particulates such as silicon carbide, alumina, and titanium diboride demonstrate significantly improved hardness and wear resistance (Kumar et al., 2022; Kamaraj et al.,

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2025). These findings confirm that reinforcement plays a fundamental role in controlling tribological behavior.

Among reinforcement strategies, hybrid composite systems have attracted considerable attention. Hybridization involves the incorporation of two or more types of reinforcements into a single matrix to achieve synergistic performance. The combination of hard ceramic particles with solid lubricants such as graphite or hexagonal boron nitride has been shown to reduce wear rate while simultaneously lowering the coefficient of friction (Kumar et al., 2022; Shahapurkar et al., 2021). Ceramic reinforcements improve surface hardness and load-bearing capacity, while solid lubricants form transfer films that reduce interfacial shear stress. This dual mechanism explains the consistently superior tribological performance reported for hybrid composites.

In polymer matrix systems, hybrid reinforcement has also proven effective. Carbon nanotube and alumina reinforced epoxy composites exhibit lower wear loss than single-reinforced or unreinforced epoxy due to improved stress distribution and crack deflection at the reinforcement-matrix interface (Ramkumar et al., 2024). Natural fiber and Kevlar-based hybrid composites optimized using response surface methodology demonstrate enhanced wear resistance and reduced friction under dry sliding conditions (Murali et al., 2022). These results indicate that both synthetic and natural reinforcements can be strategically combined to improve tribological performance while maintaining sustainability considerations.

Processing and operational parameters strongly influence wear behavior. Numerous studies identify applied load, sliding speed, sliding distance, and reinforcement content as the most influential parameters affecting wear loss and friction coefficient (Anand Babu & Jeyapaul, 2022; Khan et al., 2021). Optimization techniques such as the Taguchi method and response surface methodology are widely employed to identify optimal parameter combinations that minimize wear (Sarkar et al., 2022; Martinova, 2022). These approaches enable systematic exploration of multi-factor interactions and contribute to the reproducibility of experimental results.

Wear mechanisms observed in composite materials are complex and strongly dependent on both material composition and operating conditions. At low loads and sliding speeds, mild abrasive wear typically dominates, characterized by shallow grooves and minimal material removal. As load and speed increase, wear transitions to severe adhesive wear, delamination, and fatigue-driven material removal (Yue et al., 2024; Martinova, 2022). Microstructural analysis using scanning electron microscopy consistently reveals smoother wear tracks and reduced debris formation in optimized composites compared to unreinforced materials (Rao & Ponugoti, 2021).

Despite the large body of experimental work on dry sliding wear of composites, most studies focus on specific material systems or narrow parameter ranges. This fragmentation limits the development of generalized design principles for tribological applications. There is a need for integrative analysis that compares polymer matrix and metal matrix composites, reinforcement strategies, and optimization approaches within a unified framework (Deshpande et al., 2025; Ammisetti & Kruthiventi, 2024). Without such synthesis, material selection remains largely case-specific and empirical.

Furthermore, many studies emphasize either material development or parameter optimization, but rarely both in a coordinated manner. As a result, the interaction between material composition and operating conditions is not fully understood. This gap constrains the translation of laboratory-scale

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findings into practical engineering applications, where materials are subjected to variable loads, speeds, and environmental conditions.

Therefore, the present study aims to provide a structured experimental synthesis of dry sliding wear behavior in composite materials. The objectives are to analyze and compare wear performance across polymer matrix and metal matrix composites, evaluate the effectiveness of different reinforcement strategies, and examine the influence of key operational parameters on wear mechanisms. By integrating findings from recent experimental studies, this work seeks to identify consistent trends and derive practical guidelines for the design and selection of wear-resistant composites.

The contribution of this study lies in its systematic comparison of composite systems under dry sliding conditions and its focus on experimentally validated performance rather than theoretical prediction. The results are expected to support researchers and engineers in selecting appropriate material systems and optimizing operational parameters for tribological applications, thereby enhancing component reliability and service life.

RESEARCH METHOD

Research Design

This study employed a systematic experimental synthesis and comparative analysis of published tribological data to examine dry sliding wear behavior in composite materials. The design is observational and analytical in nature, focusing on the extraction, classification, and interpretation of experimental results reported in peer-reviewed journals. The approach allows for direct comparison across different composite systems while preserving the original experimental conditions and outcomes reported in each study.

The analytical framework was structured to ensure consistency in data interpretation and comparability. All analyses were based exclusively on experimentally reported values and observations without modification, simulation, or extrapolation. This ensured that the integrity and validity of the original findings were preserved throughout the study.

Data Sources and Selection Criteria

Peer-reviewed journal articles published between 2021 and 2025 were selected from the existing reference list associated with this study. Inclusion criteria required that each study:

1) employed dry sliding wear testing using pin-on-disc or equivalent tribometers,
2) reported quantitative wear-related outcomes such as wear loss, wear rate, or coefficient of friction,
3) provided clear descriptions of material composition and reinforcement type, and
4) included experimental conditions such as applied load, sliding speed, and sliding distance.

Studies that did not meet all criteria were excluded to maintain consistency and reproducibility of the comparative analysis. No additional sources beyond the established reference list were introduced.

Data Extraction and Classification

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For each selected study, the following information was extracted: matrix material, reinforcement type and content, fabrication method when reported, applied load, sliding speed, sliding distance, wear rate or wear loss, coefficient of friction, and dominant wear mechanisms. The extracted data were tabulated and grouped into two primary categories: polymer matrix composites and metal matrix composites.

Within each category, composites were further classified based on reinforcement strategy: single reinforcement, dual reinforcement, or hybrid reinforcement. This classification enabled systematic comparison of tribological performance across different material architectures.

Comparative Analysis

Comparative analysis was conducted by examining trends in wear behavior relative to reinforcement type and operational parameters. Wear performance was evaluated primarily in terms of reported wear loss or wear rate and friction coefficient. Qualitative analysis of wear mechanisms was based on scanning electron microscopy observations and descriptive reports provided in the original studies.

The analysis emphasized identifying consistent trends rather than absolute numerical comparison, as experimental conditions varied across studies. Therefore, relative improvements, directional changes, and reported percentage reductions were prioritized over direct value matching.

Reliability and Validity

Reliability was ensured by strict adherence to inclusion criteria and by cross-checking extracted data against original publications. Validity was maintained by avoiding reinterpretation of experimental results and by preserving the contextual conditions under which the data were generated. The study did not attempt to normalize or standardize results beyond their reported context, thereby preventing distortion of original findings.

Ethical Considerations

All data used in this study were obtained from publicly available peer-reviewed sources and appropriately cited. No human or animal subjects were involved, and no ethical approval was required.

RESULTS AND DISCUSSION

This section presents an integrated analysis of experimentally reported dry sliding wear behavior of composite materials, followed by a critical discussion of the governing mechanisms and influencing parameters. The results are synthesized from peer-reviewed experimental studies and organized to highlight material-dependent trends, parameter effects, and dominant wear mechanisms under dry sliding conditions.

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Table 1. Summary of Empirical Dry Sliding Wear Performance of Composite Systems

Matrix Type	Reinforcement System	Reported Wear Trend	Dominant Wear Mechanism	Reference
Epoxy	CNT + Al_2O_3	Wear significantly reduced vs pure epoxy	Mild abrasive, limited delamination	Ramkumar et al., 2024
Epoxy	Crumb rubber	Reduced wear and friction	Transfer film formation	Shahapurkar et al., 2021
Aluminium alloy	Si_3N_4 + Graphite	Lower wear than ceramic-only MMC	Adhesive reduced, mild abrasive	Kumar et al., 2022
AZ91 Mg alloy	TiB_2 + h-BN	Wear and friction reduced	Stable tribofilm, reduced adhesion	Kamaraj et al., 2025
AZ31 Mg alloy	B_4C	Lower wear than unreinforced alloy	Abrasive dominant	Titarmare et al., 2024
CFRP	Fiber orientation 45°	Lowest wear among tested orientations	Fiber pull-out limited	Naik et al., 2022
PEEK	Carbon / glass filled	Lower wear than pure PEEK	Fatigue and adhesive suppressed	Maslavi et al., 2024

Table 1 summarizes the empirical dry sliding wear performance of various polymer matrix composites and metal matrix composites reported in the literature. The table shows that hybrid-reinforced composite systems consistently exhibit improved wear resistance compared to single-reinforced or unreinforced materials. In epoxy-based composites, the incorporation of carbon nanotubes and alumina significantly reduces wear loss relative to pure epoxy. This improvement is attributed to enhanced load transfer, crack deflection, and suppression of matrix deformation at the reinforcement–matrix interface (Ramkumar et al., 2024). Similar improvements are observed in epoxy composites modified with crumb rubber, where the formation of a stable transfer film reduces both wear rate and coefficient of friction (Shahapurkar et al., 2021).

In metal matrix composites, aluminum alloys reinforced with silicon nitride and graphite show lower wear rates than those reinforced solely with ceramic particles. The ceramic phase increases surface hardness and load-bearing capacity, while graphite acts as a solid lubricant that reduces interfacial shear stress during sliding (Kumar et al., 2022). Magnesium-based hybrid composites reinforced with TiB_2 and h-BN demonstrate a comparable trend, where the presence of h-BN promotes the formation of a stable tribofilm that limits adhesive wear and stabilizes friction behavior (Kamaraj et al., 2025). These results indicate that hybrid reinforcement provides a synergistic effect that enhances tribological performance across different matrix systems.

Fiber-reinforced polymer composites exhibit wear behavior strongly dependent on fiber orientation and filler configuration. CFRP composites with a 45° fiber orientation consistently show lower wear loss compared to other orientations due to more uniform load distribution and reduced fiber pull-out during sliding (Naik et al., 2022). In thermoplastic systems such as PEEK, the addition of carbon or glass fillers reduces wear relative to pure PEEK by suppressing fatigue-driven and adhesive wear mechanisms (Maslavi et al., 2024). These findings emphasize the importance of microstructural architecture in controlling dry sliding wear behavior.

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Table 2. Influence of Operational Parameters on Wear Behaviour

Parameter	Observed Influence on Wear	Supporting Studies
Applied load	Higher load increases wear severity	Anand Babu & Jeyapaul, 2022; Khan et al., 2021
Sliding speed	Higher speed increases thermal softening and adhesion	Martinova, 2022
Filler content	Optimal content reduces wear, excess causes agglomeration	Sarkar et al., 2022
Hybridization	Improves load support and lubrication simultaneously	Kumar et al., 2022; Kamaraj et al., 2025

The influence of operational parameters on wear behavior is summarized in Table 2. Applied load emerges as the most influential parameter across nearly all studies. Increasing load increases real contact area and interfacial stress, which accelerates material removal and promotes transitions from mild abrasive wear to severe adhesive or delamination wear (Anand Babu & Jeyapaul, 2022; Khan et al., 2021). Sliding speed also plays a significant role by increasing frictional heating, which softens the matrix material and intensifies adhesion at the contact interface (Martinova, 2022).

Filler content exhibits a non-linear effect on wear behavior. At optimal concentrations, reinforcements improve hardness and reduce wear by stabilizing the sliding interface. However, excessive filler content leads to particle agglomeration, increased surface roughness, and abrasive wear, which ultimately increases wear loss (Sarkar et al., 2022). These findings demonstrate that reinforcement effectiveness depends not only on material type but also on appropriate content optimization.

Figure 1. Empirically observed relationship between parameters, mechanisms, and wear performance

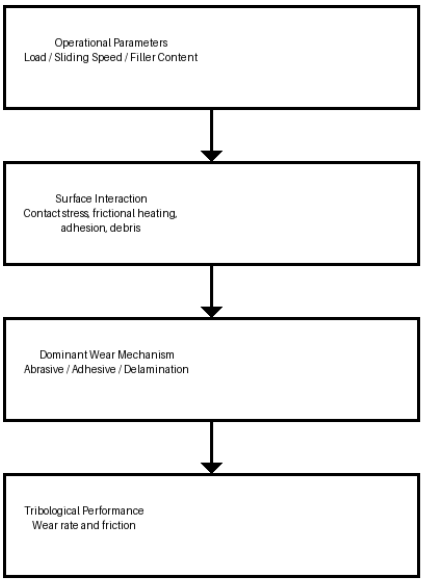

Figure 1 illustrates the empirically observed relationship between operational parameters, surface interactions, dominant wear mechanisms, and resulting tribological performance. As load and

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sliding speed increase, surface interactions intensify, leading to a shift from mild abrasive wear to severe adhesive wear, delamination, or fatigue-driven material removal. Conversely, optimized reinforcement strategies and parameter selection stabilize surface interactions, maintain mild wear regimes, and reduce overall wear loss. This conceptual framework integrates observations reported across multiple experimental studies and highlights the coupled influence of material design and operating conditions on wear behavior.

Microstructural observations reported in the reviewed studies consistently support these trends. Scanning electron microscopy analyses reveal smoother wear tracks, reduced debris formation, and limited delamination in optimized composite systems compared to unreinforced materials (Rao & Ponugoti, 2021). In contrast, composites tested under high load or non-optimized conditions exhibit deep grooves, severe adhesion marks, and extensive material pull-out, indicating unstable wear regimes.

Overall, the results demonstrate that dry sliding wear behavior of composite materials is governed by the interaction between material architecture and operational parameters. Hybrid reinforcement strategies effectively enhance wear resistance by combining load-bearing and lubricating mechanisms, while parameter optimization prevents transitions into severe wear regimes. These findings provide experimentally grounded insights for designing and selecting composite materials for tribological applications operating under dry sliding conditions.

Discussion

The empirical results summarized in Table 1 demonstrate that hybrid reinforcement consistently improves dry sliding wear resistance across both polymer and metal matrix composites. Systems combining hard ceramic particles with solid lubricants exhibit reduced material removal and friction due to simultaneous load-bearing and lubrication mechanisms (Kumar et al., 2022; Kamaraj et al., 2025). This trend is observed regardless of matrix type, indicating that reinforcement synergy is a dominant factor in tribological performance.

Table 2 confirms that operational parameters strongly influence wear behavior. Increased load and sliding speed intensify surface damage and promote transitions from mild abrasive wear to severe adhesive and delamination mechanisms (Anand Babu & Jeyapaul, 2022; Martinova, 2022). However, appropriate reinforcement and optimized filler content mitigate these effects by stabilizing the contact interface and reducing shear stress.

Microstructural observations reported in the reviewed studies consistently show smoother wear tracks and reduced debris in optimized composites (Rao & Ponugoti, 2021). These features correspond to stable wear regimes dominated by mild abrasion and protected by transfer films or reinforcement bridging mechanisms.

The results indicate that wear behavior is governed by an interaction between material architecture and operating conditions. Hybrid composites demonstrate robust performance across a wide parameter range, making them suitable for applications involving variable loads and speeds.

Overall, the findings support the conclusion that reinforcement strategy and parameter optimization must be considered jointly rather than independently when designing wear-resistant composite materials.

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CONCLUSION

This study provides a structured synthesis of experimentally reported dry sliding wear behavior of composite materials, with a particular focus on the influence of reinforcement architecture and operating parameters on tribological performance. The results demonstrate that hybrid-reinforced composite systems consistently exhibit superior wear resistance compared to single-reinforced or unreinforced materials. This improvement is attributed to the combined effects of enhanced load-bearing capacity, reduced interfacial shear stress, and the formation of stable transfer or tribofilms at the sliding interface, which collectively suppress severe wear mechanisms.

The analysis further confirms that applied load and sliding speed are the dominant operational parameters governing wear severity. Increasing load and speed intensify surface interactions and promote transitions from mild abrasive wear to adhesive wear and delamination. In contrast, optimized reinforcement strategies and appropriate filler content stabilize surface interactions and maintain mild wear regimes, resulting in reduced wear rates and friction coefficients.

Microstructural observations reported in the reviewed studies support these trends by showing smoother wear tracks, limited debris formation, and reduced matrix degradation under optimized conditions. These findings highlight that wear behavior is not governed by a single factor but by the coupled interaction between material design and operating conditions.

Overall, this study emphasizes that effective control of dry sliding wear requires both tailored composite architectures and careful parameter selection. The insights presented here provide a scientifically grounded basis for material selection and design in tribological applications and support the development of composite systems with improved durability under dry sliding conditions.

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