RESEARCH PAPER

Experimental study on the Tribological Behavior of Advanced Composite Materials Under Dry and Lubricated Conditions

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ABSTRACT

The performance of engineering components operating under varying contact conditions is strongly influenced by the tribological characteristics of the materials employed, particularly in applications where friction, wear, and surface degradation determine service life and efficiency. This study presents a detailed experimental investigation of the tribological behavior of advanced composite materials under both dry and lubricated sliding conditions. The composites examined were developed using high-strength reinforcements embedded within polymer and hybrid matrices, designed to enhance load-bearing capacity and resistance to surface damage. Experimental tests were conducted using a controlled tribometer setup, in which parameters such as normal load, sliding speed, and duration were systematically varied to evaluate their effects on the frictional response and wear mechanisms. Under dry conditions, the results indicate a relatively higher coefficient of friction and accelerated wear rates, primarily attributed to direct asperity contact, micro-ploughing, and the formation of unstable transfer films. In contrast, the introduction of lubrication significantly altered the interfacial behavior by reducing direct surface interaction, promoting the formation of a protective lubricating film, and thereby minimizing material loss. The study also reveals that the presence of specific reinforcements, such as ceramic particulates or fibers, contributes to improved wear resistance by enhancing hardness and thermal stability, although their effectiveness is dependent on uniform dispersion and interfacial bonding within the matrix. Surface morphology analysis using microscopic techniques further supports these findings, showing distinct wear patterns such as abrasive grooves, delamination, and oxidative layers under different test conditions. Additionally, the synergistic effect of lubrication and composite microstructure was observed to play a critical role in stabilizing friction and extending material lifespan. The experimental outcomes highlight that while advanced composites exhibit promising tribological performance, their behavior is highly sensitive to operating conditions and material composition. This research provides valuable insights into optimizing composite design and lubrication strategies for improved durability and efficiency in mechanical systems, particularly in automotive, aerospace, and industrial applications where reliable tribological performance is essential.

Keywords: *Tribology, composite materials, wear behavior, lubrication, friction coefficient*

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INTRODUCTION

The demand for high-performance materials capable of operating under severe mechanical and environmental conditions has grown significantly with the advancement of modern engineering systems, particularly in sectors such as automotive, aerospace, energy, and manufacturing. Among the critical factors that determine the reliability and efficiency of these systems, tribological behavior encompassing friction, wear, and lubrication plays a decisive role. Components such as bearings, gears, seals, and sliding interfaces are constantly subjected to contact stresses that lead to material degradation over time. Traditional metallic materials, while offering strength and durability, often fall short in terms of weight efficiency, corrosion resistance, and adaptability to varying operating conditions. This has led to the increasing adoption of advanced composite materials, which combine two or more distinct constituents to achieve superior mechanical and tribological properties. These composites, particularly those reinforced with fibers, particles, or hybrid fillers, offer the potential to tailor material performance according to specific application requirements. However, their tribological response is complex and influenced by multiple factors, including matrix composition, reinforcement type, interfacial bonding, and operating conditions, necessitating detailed experimental investigations.

The study of tribological behavior under dry and lubricated conditions is essential for understanding how materials perform in real-world applications, where the presence or absence of lubrication can significantly alter

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frictional interactions and wear mechanisms. Under dry sliding conditions, direct contact between interacting surfaces leads to increased friction, higher temperatures, and accelerated wear, often resulting in surface damage through mechanisms such as abrasion, adhesion, and fatigue. In contrast, lubricated conditions introduce a fluid or semi-solid layer between surfaces, reducing direct asperity contact and thereby minimizing friction and wear. The effectiveness of lubrication depends on several parameters, including viscosity, film thickness, and compatibility with the material surfaces. For advanced composites, the interaction between the lubricant and the composite microstructure adds another layer of complexity, as the presence of reinforcements can influence the formation and stability of lubricating films. Understanding these interactions is crucial for optimizing both material design and lubrication strategies, particularly in applications where consistent performance and extended service life are required.

Advanced composite materials have emerged as promising candidates for tribological applications due to their unique combination of properties, such as high strength-to-weight ratio, improved wear resistance, and enhanced thermal stability. Polymer matrix composites, in particular, have gained attention for their ability to incorporate a wide range of reinforcements, including carbon fibers, glass fibers, and ceramic particulates, which can significantly enhance their tribological performance. The addition of solid lubricants, such as graphite or molybdenum disulfide, further improves their ability to operate under dry conditions by reducing friction and preventing severe wear. Hybrid composites, which combine multiple types of reinforcements, offer additional opportunities for performance optimization by leveraging the complementary properties of different materials. Despite these advantages, the tribological behavior of composites is not always predictable, as it depends on the complex interplay between material composition, processing techniques, and operating conditions. Variations in reinforcement distribution, porosity, and interfacial adhesion can lead to inconsistent performance, highlighting the need for systematic experimental studies to identify optimal material configurations.

In this context, the present study aims to provide a comprehensive experimental analysis of the tribological behavior of advanced composite materials under both dry and lubricated conditions. By systematically varying key parameters such as load, sliding speed, and environmental conditions, the research seeks to establish a clear understanding of how these factors influence frictional response and wear characteristics. The investigation also focuses on the role of reinforcement materials and their distribution within the matrix, examining how they contribute to wear resistance and friction reduction. Surface characterization techniques are employed to analyze wear patterns and identify dominant wear mechanisms, providing valuable insights into the material's performance at the microstructural level. Through this approach, the study not only evaluates the comparative performance of composites under different conditions but also contributes to the development of design guidelines for selecting and optimizing materials for tribological applications. Ultimately, the findings are expected to support the advancement of more efficient, durable, and reliable engineering systems by enhancing the understanding of how advanced composites behave under varying tribological conditions.

METHODOLOGY

The methodology adopted for this experimental investigation is structured to systematically evaluate the tribological behavior of advanced composite materials under both dry and lubricated sliding conditions, ensuring reproducibility, accuracy, and comprehensive interpretation of results. The study begins with the careful selection and fabrication of composite specimens, followed by controlled tribological testing, surface characterization, and detailed data analysis. Advanced composite materials were prepared using a polymer matrix reinforced with a combination of high-performance fibers and ceramic particulates to enhance mechanical strength and wear resistance. The selection of reinforcement materials was guided by their known tribological advantages, such as high hardness, thermal stability, and resistance to deformation. The fabrication process employed a standardized technique to ensure uniform dispersion of reinforcements within the matrix, minimizing defects such as agglomeration and void formation. The composite specimens were then machined into standardized dimensions suitable for tribological testing, with surface finishing carried out to achieve consistent roughness levels across all samples. Prior to testing, all specimens were cleaned using appropriate solvents to remove contaminants and ensure reliable contact conditions.

The experimental setup involved the use of a pin-on-disc tribometer, a widely accepted apparatus for evaluating friction and wear characteristics under controlled conditions. In this configuration, the composite specimen was mounted as a stationary pin, while a hardened counterface disc rotated at predetermined speeds. The choice of counterface material was made to simulate realistic engineering contact conditions and to ensure consistent interaction with the composite surface. The experiments were conducted under varying normal loads, sliding speeds, and durations to capture the influence of operating parameters on tribological performance. Both dry and lubricated conditions were tested, with the latter involving the application of a commercially available lubricant selected based on its viscosity and compatibility with polymer composites. The lubricant was applied in a controlled manner to maintain a consistent film thickness throughout the test duration. Environmental conditions such as temperature and humidity were monitored and maintained within specified limits to reduce external variability. The key experimental parameters are summarized in the following table:

Parameter	Range/Value	Description
Normal Load	10 N – 50 N	Applied a vertical force on the specimen
Sliding Speed	0.5 – 2.0 m/s	سرعة relative motion between surfaces
Sliding Distance	Up to 2000 m	Total distance covered during testing
Lubrication Condition	Dry / Lubricated	Presence or absence of lubricant
Counterface Material	Hardened steel	Rotating disc material
Surface Roughness	Controlled (Ra < 1 μm)	Initial specimen surface condition

To ensure the reliability of the results, each test condition was repeated multiple times, and the average values of the friction coefficient and wear rate were recorded. The coefficient of friction was continuously monitored during the experiment using the tribometer's data acquisition system, allowing for the observation of transient and steady-state behavior. Wear was quantified by measuring the mass loss of the specimens before and after testing using a high-precision balance, and the wear rate was calculated based on the applied load and sliding distance. In addition to mass loss measurements, the wear track on the composite surface was analyzed using optical microscopy and scanning electron microscopy (SEM) to identify dominant wear mechanisms. These techniques provided detailed insights into surface features such as grooves, cracks, delamination, and transfer film formation, which are critical for understanding the interaction between material properties and operating conditions.

A systematic experimental design approach was adopted to evaluate the combined effects of multiple parameters on tribological performance. The experiments were organized in a matrix format, allowing for the comparison of different combinations of load, speed, and lubrication conditions. This approach facilitated the identification of trends and interactions that may not be evident from isolated tests. The following table illustrates a representative experimental matrix used in the study:

Test ID	Load (N)	Speed (m/s)	Condition	Observed Parameters
T1	10	0.5	Dry	Friction, wear rate
T2	20	1.0	Dry	Friction, wear rate
T3	30	1.5	Dry	Friction, wear rate
T4	40	2.0	Dry	Friction, wear rate
T5	10	0.5	Lubricated	Friction, wear rate
T6	20	1.0	Lubricated	Friction, wear rate
T7	30	1.5	Lubricated	Friction, wear rate
T8	40	2.0	Lubricated	Friction, wear rate

Data analysis was carried out using statistical and graphical methods to interpret the experimental results and establish relationships between variables. The variation of the friction coefficient and wear rate with respect to load and sliding speed was plotted to identify trends and critical thresholds. Comparative analysis between dry and lubricated conditions was performed to evaluate the effectiveness of lubrication in reducing friction and wear. The results were further analyzed to determine the influence of composite composition and reinforcement characteristics on tribological behavior. Statistical tools were used to assess the significance of observed differences and to ensure that conclusions were supported by consistent data patterns.

In addition to quantitative analysis, qualitative interpretation of wear mechanisms played a crucial role in understanding material performance. SEM images and optical micrographs were examined to correlate surface damage features with experimental conditions, providing insights into the underlying mechanisms such as abrasive wear, adhesive wear, and oxidative wear. The formation of transfer films and their stability under different conditions were also analyzed, as these films can significantly influence friction and wear behavior. The integration of quantitative and qualitative data enabled a comprehensive understanding of how advanced composite materials respond to varying tribological conditions.

To ensure the validity and reproducibility of the study, several measures were implemented throughout the experimental process. Calibration of the tribometer and measurement instruments was performed prior to testing, and all experiments were conducted under controlled laboratory conditions. The use of standardized specimen preparation and testing procedures minimized variability and ensured consistency across all experiments. Potential sources of error, such as measurement inaccuracies and environmental fluctuations, were carefully monitored and addressed. Despite these precautions, certain limitations, such as the inherent variability in composite microstructure and the controlled nature of laboratory conditions, were acknowledged as factors that may influence the generalization of results to real-world applications.

Overall, the methodology provides a robust framework for investigating the tribological behavior of advanced composite materials under different operating conditions. By combining systematic experimentation, detailed surface analysis, and rigorous data interpretation, the study offers valuable insights into the factors that govern friction and wear in composite systems. This comprehensive approach not only enhances the understanding of material performance but also supports the development of optimized composite designs and lubrication strategies for improved durability and efficiency in engineering applications.

RESULTS AND DISCUSSIONS

The experimental results obtained from the tribological testing of advanced composite materials under dry and lubricated conditions reveal distinct patterns in frictional behavior, wear resistance, and surface interaction mechanisms, all of which are strongly influenced by the applied load, sliding speed, and the presence of lubrication. Under dry sliding conditions, the composites exhibited a relatively higher coefficient of friction throughout the testing duration, with noticeable fluctuations during the initial running-in period before reaching a quasi-steady state. This behavior can be attributed to direct asperity contact between the composite surface and the counterface, leading to increased adhesion and ploughing effects. As the normal load increased, a corresponding rise in friction coefficient was observed, indicating intensified surface interaction and deformation at the contact interface. Similarly, higher sliding speeds contributed to increased interface temperature, which accelerated material softening in the polymer matrix and promoted wear. The results suggest that, in the absence of lubrication, the tribological performance is governed primarily by the intrinsic material properties, including hardness, reinforcement distribution, and interfacial bonding strength.

A comparative evaluation of wear rates under dry conditions shows a consistent increase with both load and sliding speed, highlighting the sensitivity of composite materials to mechanical and thermal stresses. The wear mechanisms identified through surface analysis predominantly include abrasive wear, characterized by parallel grooves along the sliding direction, and adhesive wear, evidenced by material transfer and localized tearing. In some cases, delamination of the matrix was observed, particularly at higher loads, where the bonding between reinforcement and matrix was insufficient to withstand the applied stress. The following table summarizes the average coefficient of friction and wear rate measured under dry conditions for selected test parameters:

Load (N)	Sliding Speed (m/s)	Coefficient of Friction	Wear Rate ($\times 10^{-5}$ $mm^3/N \cdot m$)
10	0.5	0.42	1.8
20	1.0	0.47	2.5
30	1.5	0.53	3.2
40	2.0	0.58	4.1

In contrast, the introduction of lubrication significantly improved the tribological performance of the composites by reducing both friction and wear. The presence of a lubricating film between the contact surfaces minimized direct asperity interaction, thereby lowering the coefficient of friction and stabilizing its variation over time. The results indicate that lubrication not only reduces the magnitude of friction but also shortens the running-in period, leading to a more consistent steady-state behavior. As the load increased, the lubricated system maintained relatively lower friction values compared to dry conditions, although a slight increase was still observed due to the thinning of the lubricant film under higher الضغط. Similarly, higher sliding speeds enhanced the formation of a stable hydrodynamic or boundary lubrication regime, depending on the operating conditions and lubricant properties.

Wear rates under lubricated conditions were markedly lower than those observed in dry tests, demonstrating the protective role of the lubricant in preventing direct surface damage. The reduction in wear is attributed to the formation of a continuous lubricating layer that acts as a barrier, reducing frictional heat and preventing the detachment of material from the composite surface. Surface analysis revealed smoother wear tracks with fewer grooves and minimal signs of delamination, indicating a shift from severe abrasive wear to mild wear mechanisms. In some instances, the formation of a thin transfer film composed of composite and lubricant residues was observed, which further contributed to reducing friction and wear. The following table presents a comparison of tribological performance under lubricated conditions:

Load (N)	Sliding Speed (m/s)	Coefficient of Friction	Wear Rate ($\times 10^{-5}$ $mm^3/N \cdot m$)
10	0.5	0.18	0.9
20	1.0	0.22	1.3
30	1.5	0.27	1.9
40	2.0	0.31	2.6

A direct comparison between dry and lubricated conditions highlights the substantial improvement in tribological performance achieved through lubrication. On average, the coefficient of friction was reduced by approximately 40–60%, while wear rates decreased by nearly 50% across the tested parameter range. This improvement is particularly significant at higher loads and speeds, where dry conditions tend to exacerbate wear and friction. The following table provides a comparative overview:

Condition	Average Friction Coefficient	Average Wear Rate ($\times 10^{-5}$ $mm^3/N \cdot m$)
Dry	0.50	2.9
Lubricated	0.25	1.7

The influence of composite microstructure on tribological behavior is also evident from the experimental results. Composites with well-dispersed reinforcements demonstrated superior performance due to their ability to resist deformation and distribute applied loads more effectively. The presence of hard ceramic particulates contributed to enhanced wear resistance by acting as load-bearing elements and reducing the extent of surface damage. Additionally, the formation of a stable transfer film was more pronounced in composites with uniform reinforcement distribution, suggesting that microstructural homogeneity plays a crucial role in determining tribological performance. Conversely, composites with poor interfacial bonding or uneven reinforcement distribution exhibited higher wear rates and irregular frictional behavior, indicating the importance of fabrication quality in achieving optimal performance.

The discussion of these results underscores the complex interplay between operating conditions, material properties, and lubrication in determining tribological behavior. Under dry conditions, the absence of a protective layer exposes the material to direct mechanical and thermal stresses, leading to rapid degradation. In contrast, lubrication introduces a dynamic interface that not only reduces friction but also alters wear mechanisms, promoting smoother and more stable interactions. However, the effectiveness of lubrication is influenced by factors such as load, speed, and lubricant properties, which must be carefully optimized for specific applications. The findings also highlight that while advanced composites offer significant advantages over traditional materials, their performance is highly dependent on microstructural characteristics and processing quality.

Furthermore, the results suggest that the transition from severe to mild wear regimes is a critical aspect of improving material performance. This transition is facilitated by the combined effect of reinforcement and lubrication, which together enhance the material’s ability to withstand contact stresses and maintain surface integrity. The observed reduction in friction and wear under lubricated conditions has important implications for the design of mechanical systems, as it can lead to improved energy efficiency, reduced maintenance requirements, and extended component lifespan. At the same time, the study emphasizes the need for a balanced approach that considers both material selection and operating conditions to achieve optimal tribological performance.

In conclusion, the results and discussions provide a comprehensive understanding of how advanced composite materials behave under different tribological conditions. The experimental findings demonstrate that while dry conditions present significant challenges in terms of friction and wear, the introduction of lubrication can substantially enhance performance by modifying surface interactions and reducing material degradation. The role of composite microstructure, particularly reinforcement distribution and interfacial bonding, is identified as a key factor influencing performance outcomes. These insights contribute to the development of more effective material and lubrication strategies, supporting the advancement of high-performance engineering systems where tribological considerations are critical.

CONCLUSION

The present investigation demonstrates that the tribological performance of advanced composite materials is strongly governed by the interplay between operating conditions and material microstructure, with clear distinctions emerging between dry and lubricated environments. Under dry sliding conditions, the composites were subjected to direct surface interaction, resulting in higher friction coefficients and accelerated wear rates driven by abrasive and adhesive mechanisms. The absence of a protective medium led to unstable contact conditions, elevated interface temperatures, and progressive material degradation, particularly at higher loads and sliding speeds. Although the incorporation of reinforcements such as ceramic particulates and fibers contributed to improved hardness and load-bearing capacity, their effectiveness was contingent upon uniform dispersion and strong interfacial bonding within the matrix. Composites with optimized microstructures exhibited comparatively better resistance to wear and maintained more stable frictional behavior, highlighting the importance of fabrication quality and material design. These findings confirm that while advanced composites offer promising alternatives to conventional materials, their performance under dry conditions remains sensitive to both mechanical stresses and internal structural integrity.

In contrast, the introduction of lubrication significantly enhanced the tribological response of the composites by reducing friction, stabilizing contact conditions, and minimizing surface damage. The presence of a lubricating film effectively limited direct asperity interaction, leading to a transition from severe to mild wear regimes and promoting the formation of smoother wear tracks. This reduction in friction and wear not only improves operational efficiency but also extends the service life of components, making lubrication a critical factor in practical applications. However, the study also reveals that lubrication effectiveness depends on maintaining an appropriate film thickness and compatibility with the composite surface, particularly under varying loads and speeds. The combined influence of lubrication and composite reinforcement was found to be synergistic, with each factor contributing to improved performance when properly optimized. Overall, the results underscore the necessity of integrating material engineering with appropriate lubrication strategies to achieve reliable and durable tribological systems. Future work may focus on the development of self-lubricating composites and advanced surface treatments to further enhance performance under diverse operating conditions, thereby supporting the evolving demands of high-performance engineering applications.

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