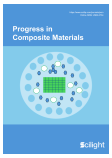
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Systematic Analysis and Design Approach for Tribological Behavior in Composite Materials

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How To Cite: Yoldaş, D.M.; Yalçınkaya, S.; Yoldaş, M.F. Systematic Analysis and Design Approach for Tribological Behavior in Composite Materials. *Progress in Composite Materials* **2026**, *2*(1), 3. https://doi.org/10.53941/pcm.2026.100003

Received: 11 August 2026
Revised: 28 September 2026
Accepted: 15 October 2026
Published: 30 October 2026

Abstract: The tribological behavior of composite materials represents a crucial research domain in modern engineering due to the decisive impact of friction, wear, and surface interactions on operational performance. This study evaluates the material and operating-condition-dependent parameters that dictate the tribological response of composite materials, alongside their predominant wear mechanisms. A comprehensive synthesis of the literature demonstrates that matrix and reinforcement types, filler fraction, fiber orientation, surface topography, interfacial bonding strength, applied load, sliding velocity, and operating temperature significantly govern both the coefficient of friction and wear characteristics. While fiber reinforcement substantially enhances wear resistance when paired with strong interfacial adhesion, weak interfacial bonding accelerates failure mechanisms such as delamination and matrix/particle debonding. Depending on the operational conditions, composites exhibit competing wear mechanisms, including abrasive, adhesive, fatigue, and tribochemical wear. Furthermore, surface engineering strategies such as protective coatings, surface texturing, thermal treatments, and advanced lubrication effectively optimize tribological performance. Notably, hybrid composites incorporating solid lubricant additives demonstrate exceptional potential in minimizing friction and retarding wear rates. Integrating standard empirical testing (e.g., pin-on-disk and block-on-ring) with numerical simulations, finite element analysis (FEA), and artificial intelligence (AI)-assisted modeling offers a robust framework for enhancing design reliability. Overall, achieving optimal tribological performance in composite materials necessitates a holistic design approach that synergizes intrinsic material selection, tailored surface engineering, and operational constraints.

Keywords: composite materials; tribological behavior; wear mechanisms; fiber-reinforced composites; surface engineering; hybrid composites

1. Introduction

Rapid advancements in modern engineering and manufacturing technologies have significantly elevated the performance standards expected from structural materials. Industrial applications no longer rely solely on high mechanical strength; instead, multi-faceted criteria such as low density, extended service life, high-temperature resistance, corrosion resistance, energy efficiency, and reduced maintenance costs have come to the fore. Under these stringent requirements, conventional metallic alloys often prove insufficient, giving way to advanced engineering materials. In this context, composite materials hold a strategic position in modern engineering due to

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their tailored mechanical and physical properties [1]. Composites are multi-phase material systems created by combining two or more macroscopically distinct constituents. Typically, a composite structure consists of a load-bearing reinforcement phase embedded within a continuous matrix phase. While the reinforcement can take the form of fibers, particles, or platelets, the matrix generally comprises polymeric, metallic, or ceramic systems [2].

Through this synergistic architecture, composite materials achieve unique property combinations unattainable by single-component traditional materials. The evolution of composite technology has gained significant momentum, particularly driven by the rigorous demands of the aerospace and defense sectors. The critical need for lightweight yet high-strength structures in aircraft fuselages led to the widespread adoption of carbon fiber-reinforced polymer (CFRP) composites. Similarly, the automotive industry increasingly utilizes lightweight composites to enhance fuel economy, while wind energy applications rely on composite turbine blades possessing superior fatigue resistance. Furthermore, the integration of composite systems continues to expand rapidly across biomedical implants, sports equipment, marine structures, and space applications [3]. In pursuit of sustainable engineering solutions, natural fiber-reinforced composites (NFRCs) and bio-polymeric composites incorporating green fillers (e.g., kenaf, jute, oil palm, coir) have emerged as viable, eco-friendly alternatives to traditional synthetic systems [4,5]. One of the most significant engineering advantages of composite materials is the tailorability of their properties. Mechanical, thermal, and tribological characteristics can be customized by optimizing fiber orientation, reinforcement volume fraction, matrix type, stacking sequence, and additive manufacturing processes, thereby enabling target-driven material design tailored to specific operational environments.

Tribology is an interdisciplinary field of science and engineering focused on the study of friction, wear, and lubrication phenomena between interacting surfaces in relative motion. While frictional forces induce energy losses, wear processes lead to dimensional degradation and system failure [6]. Given that a substantial portion of industrial machinery operates under sliding or rolling contacts, controlling tribological phenomena is of vital economic and technical importance. Studies indicate that a major share of global energy losses and industrial maintenance costs stems directly from tribological issues [7]. The tribological behavior of composite materials involves far more complex mechanisms than that of homogeneous metallic materials, primarily due to their inherent microstructural heterogeneity. Stress fields generated during sliding do not remain confined to the contact surface; rather, they distribute heterogeneously across the matrix phase, reinforcement elements, and interfacial regions [8].

The interfacial bond strength between the fiber and matrix, the load-transfer mechanism, and the flash surface temperature dictate the predominant wear modes. Operational parameters such as applied normal load, sliding velocity, and fiber weight fraction (w_f) critically govern friction coefficients, specific wear rates, and contact temperatures [9]. Moreover, incorporating multi-scale nano-reinforcements (e.g., CNTs, graphene, SiO_2, TiO_2) alongside advanced interface engineering such as chemical grafting and plasma-induced hybrid filler networks can dramatically enhance mechanical durability and wear resistance by preventing nanoparticle agglomeration [10–12]. Furthermore, hybrid reinforcement systems combining distinct fiber/filler types, as well as self-lubricating high-performance polymers (e.g., PEEK composites) integrating solid lubricants (PTFE, MoS_2, graphite), have introduced new design dimensions by providing low friction coefficients and high wear resistance without external lubrication. Recent findings highlight that the formation and stability of third-body transfer patches during sliding play a pivotal role in governing the long-term tribological performance of PEEK-steel interfaces [13]. Environmental factors, advanced surface treatments, and additive manufacturing parameters also play decisive roles; for instance, 3D-printed PEEK composites exhibit pronounced tribological anisotropy, where wear resistance is strongly governed by printed fiber orientation and multi-scale particle architectures [5,14]. Typical wear mechanisms observed in composites include abrasive, adhesive, fatigue, and erosive wear. Fiber orientation relative to the sliding direction exerts a direct influence on friction and wear, where parallel or perpendicular configurations yield distinct damage modes depending on the matrix softness and contact stress distribution [14,15].

Although numerous review articles in the literature focus on isolated aspects of composite tribology such as specific matrix classes, individual nanofillers, or discrete operational regimes there remains a notable gap in synthesizing these parameters into a unified, design-oriented methodology. Conventional testing often generates multi-scale, system-dependent data that are difficult to translate into actionable engineering insights, thereby hindering the transition toward a data-driven triboinformatics paradigm [16]. Existing reviews often present friction and wear phenomena as decoupled outputs, lacking a rigorous evaluation of how constituent selection, hybrid reinforcement strategies, plasma-induced surface treatments, dynamic third-body patch evolution, and self-lubricating mechanisms directly dictate the underlying wear mechanisms under coupled operating conditions [9–13]. To address this gap, this review provides a systematic design framework that bridges the continuum from application requirements and constituent selection (matrix, reinforcement, surface treatments, and interface engineering) to real-time contact dynamics, dominant wear mechanisms, and targeted tribological performance. Furthermore, this study offers an in-depth assessment of the trade-offs between friction reduction and wear

resistance, clarifies the conditional boundary limits of fiber orientations and nanofiller contents, and establishes a comprehensive decision-making methodology for the tribological design of advanced composite systems.

2. Materials and Methods

2.1. General Structure of Composite Materials

Composite materials consist of a continuous matrix phase, structural reinforcements, and an interphase region that mediates load transfer [17]. Rather than viewing these components as isolated structural elements, tribological optimization requires evaluating how constituent properties interact under dynamic contact stresses.

Systematic Methodology and Search Strategy

To construct this systematic analysis, a comprehensive literature search was executed across major databases (Web of Science, Scopus, Google Scholar, ScienceDirect) covering publications from 1985 to 2026. The search strategy utilized combinations of primary keywords: ("composite materials" OR "polymer matrix composites") AND ("tribological behavior" OR "friction coefficient" OR "wear rate") AND ("fiber orientation" OR "nanofillers" OR "FEA modeling" OR "machine learning").

- **Inclusion Criteria:** (i) Peer-reviewed journal articles and foundational textbooks; (ii) Studies providing explicit quantitative tribological data (COF, wear rates); (iii) Literature focusing on micromechanical damage mechanisms and contact modeling.
- **Exclusion Criteria:** (i) Non-peer-reviewed conference abstracts; (ii) Studies lacking clear experimental testing parameters. A total of 42 high-impact studies met all criteria and were incorporated into this review.

2.1.1. Matrix Materials: Operational Boundaries

Matrix materials govern system integrity, heat dissipation, and the initial contact mechanics before tribofilm formation.

- **Polymer Matrices (PMCs):** Dominate low-to-moderate temperature applications due to low density and self-lubricating potential (e.g., PTFE, PEEK). However, thermal softening and localized frictional heating at high sliding speeds lead to matrix degradation and rapid wear rate escalation.
- **Metal Matrices (MMCs):** Preferred for high-temperature and high-load applications (e.g., Al, Mg, Ti alloys). They offer high thermal conductivity to dissipate flash temperatures, but susceptibility to plastic deformation under severe shear limits their unreinforced usage.
- **Ceramic Matrices (CMCs):** Applied under extreme temperatures and aggressive environments (e.g., SiC, Al_2O_3). While offering superior hardness and abrasive resistance, inherent brittleness renders them vulnerable to micro-spalling under dynamic or impact contact.

2.1.2. Critical Assessment of Reinforcement Types

Reinforcement selection represents a continuous trade-off between load-bearing enhancement and wear mitigation. Table 1 critically compares major reinforcement categories based on their operational sweet spots, failure conditions, and primary performance limitations.

As highlighted in Table 1, carbon fibers excel in dry sliding due to graphite-like tribofilm formation, yet their brittle fracture under transverse loading can degrade counterface quality. Glass fibers provide cost efficiency but tend to generate hard, angular wear debris that accelerates third-body abrasive wear. Ceramic particles suppress abrasive indentation but can dislodge if interfacial bonding is insufficient, acting as aggressive free abrasives. Nano-fillers (e.g., CNTs, graphene) provide exceptional solid-lubrication and thermal conductivity at low concentrations, but their tendency to agglomerate at higher loadings creates localized stress concentrations that compromise both structural and tribological performance.

Table 1. Comparative summary of reinforcement types in composite tribology.

Reinforcement Type	Favorable Operating Conditions	Ineffective/Unfavorable Regimes	Primary Limitations & Failure Modes
Carbon Fiber (CF)	High contact loads, dry sliding, high speeds	Highly oxidative high-temperature environments	Fiber fracture under transverse orientation, potential counterface scratching
Glass Fiber (GF)	Moderate loads, corrosive/marine wet environments	Dry unlubricated sliding, high speed/temperature	Brittle fracture, angular debris causing severe 3rd-body abrasive wear
Aramid Fiber (AF)	Impact-dominated contact, abrasive/slurry environments	High-temperature contact, highly humid/aqueous conditions	Moisture absorption, fibrillation, thermal degradation at elevated temps

Table 1. *Cont.*

Reinforcement Type	Favorable Operating Conditions	Ineffective/Unfavorable Regimes	Primary Limitations & Failure Modes
Ceramic Particles	Extreme contact pressures, severe two-body abrasive wear	Dynamic or impact loading conditions	Agglomeration, interfacial debonding, debris-induced third-body wear
Nano-fillers (CNT/Graphene)	Low-to-moderate loads, high heat dissipation requirements	High filler loadings (>3–5 wt.%)	Severe agglomeration, weak dispersion, poor stress transfer at high contents

2.1.3. Interface Engineering and Subsurface Stress Transfer

The interfacial region governs load transfer efficiency from the flexible matrix to high-modulus reinforcements under shear force. Weak interfacial bonding triggers premature debonding, fiber pull-out, and localized micro-cracking, converting potential reinforcements into loose third-body abrasive debris (Figure 1).

To prevent early interfacial failure, targeted surface modifications are deployed:

- **Chemical Treatments & Silanization:** Enhance surface energy and covalent bonding, improving shear strength at the matrix-fiber junction.
- **Nano-Coatings & Interlayer Grafting:** Create a gradual stiffness gradient across the interface, suppressing peak stress concentrations and retarding subsurface crack propagation.
- **Plasma Modifications:** Increase mechanical interlocking by modifying fiber surface topography without altering bulk mechanical properties.

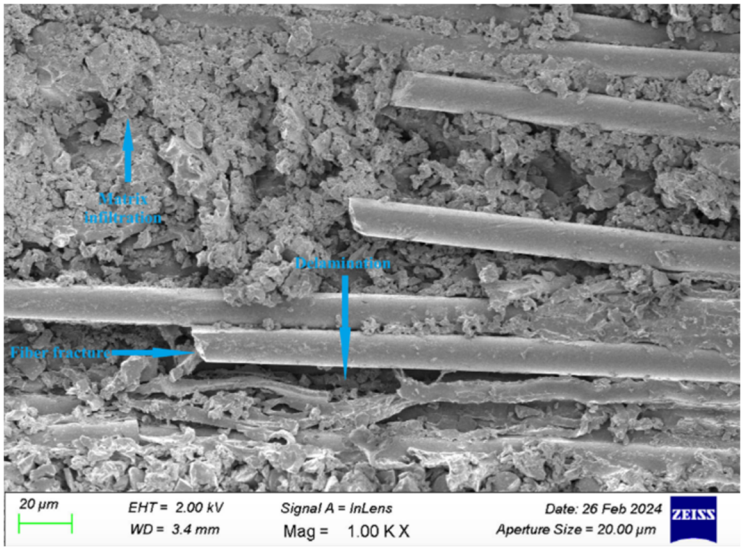


Figure 1. Delamination and fiber breakage mechanisms Adapted from [18], under the terms of the Creative Commons Attribution License.

2.2. Basıc Prıncıples of Trıbology

Tribology encompasses the multi-scale analysis of friction, wear, and interfacial phenomena between interacting surfaces in relative motion [19]. In engineered contact systems, surface degradation is dominated by adhesive, abrasive, fatigue, and tribo-chemical wear mechanisms. While classical lubrication regimes delineated by the Stribeck continuum (boundary, mixed, and hydrodynamic regimes) traditionally dictate liquid-lubricated metallic contacts, solid-lubricated and multi-phase composite systems rely heavily on interfacial tribofilm stability to suppress direct surface shearing. Beyond conventional machinery, tribological principles are vital across advanced applications including MEMS/NEMS, biotribology, and space mechanisms, where friction-induced thermal dissipation directly dictates service lifetime. Given that parasitic friction losses account for a major fraction of global energy consumption, optimizing composite tribosystems through tailored surface engineering and microstructural design remains critical for high-efficiency, sustainable technologies.

2.2.1. The Concept of Friction

Friction in composite materials originates primarily from interfacial adhesion, micro asperity deformation, and mechanical interlocking. Micro scale contact occurs only at discrete asperity junctions, where intense local shear stresses drive flash temperatures and microstructural softening, directly dictating kinetic friction coefficients [20].

The classical macroscopic sliding behavior of composite materials is traditionally described by Amontons' First Law of Friction:

$$F_f = \mu F_N$$

where F_f is the friction force, μ is the coefficient of friction (COF), and F_N is the applied normal force. While a significant portion of mechanical energy generated during friction converts into thermal energy inducing localized flash temperatures and microstructural transformations, classical macro-scale relationships often fail to capture real contact dynamics in heterogeneous systems [7].

2.2.2. The Concept of Wear

Material loss in tribological contact is governed by complex subsurface damage and dynamic transfer film formation [21]. Although the classic Archard model ($Q = k \cdot F_N \cdot L/H$) provides a fundamental relation between wear volume (Q), normal load (F_N), sliding distance (L), and hardness (H), its direct application to composite systems presents key limitations.

In composite materials, the wear coefficient (k) is not a static material constant. It varies dynamically depending on matrix degradation, fiber pull-out, localized micro-cracking, and the stability of the protective tribofilm formed at the counterface. Consequently, relying strictly on bulk hardness (H) oversimplifies the wear kinetics, as interfacial shear strength and reinforcement-matrix debonding play a far more decisive role in controlling material loss rates.

In composite materials, the k coefficient varies over a wide range depending on the matrix-reinforcement interface properties and lubrication conditions.

2.3. Fundamental Tribological Phenomena and Damage Mechanisms

Tribological performance optimization requires evaluating contact interactions across multi-scale physical domains. Lubrication systems minimize direct solid-solid contact to reduce frictional energy dissipation and mechanical damage [22]. Lubrication efficiency is mapped on the Stribeck continuum using the Sommerfeld number ($\eta \cdot N/P$), delineating boundary, mixed, and hydrodynamic regimes based on oil film thickness.

2.3.1. Regimes of Lubrication

- Boundary Lubrication: The load is predominantly supported by solid surface asperities, with film thickness comparable to surface roughness. Boundary additives (EP, AW) are critical, yielding friction coefficients in the range of $\mu = 0.08 - 0.15$.
- Hydrodynamic Lubrication: A fully pressurized fluid film completely separates the counterfaces, eliminating solid contact and dropping friction to $\mu = 0.001 - 0.01$ under high speeds and low normal loads.
- Elastohydrodynamic Lubrication (EHL): High localized contact pressures (Hertzian contact) induce elastic deformation of the surfaces, governing gear, bearing, and cam-rocker interactions as quantified by the Hamrock-Dowson relationship.
- Solid Lubricants: Deployed when extreme temperatures, high vacuum, or chemical aggressiveness prevent liquid film formation. Incorporating MoS_2, graphite, PTFE, or hBN into composite matrices promotes solid tribofilm formation (Table 2).

Table 2. Comparative Overview of Solid Lubricant Media in Composite Tribosystems.

Solid Lubricant	Friction Coefficient (μ)	Thermal Limit (°C)	Primary Mechanism & Limitations
PTFE	0.04–0.10	~260	High transfer film capability; vulnerable to cold flow under severe load.
MoS_2	0.02–0.15	~400 (air)/>1000 (vac)	Easy basal plane shearing; degrades rapidly in high-humidity ambient air.
Graphite	0.05–0.15	~500	Interlayer shearing; requires absorbed moisture/gas to exhibit low shear.
hBN	0.15–0.30	~900	High thermal conductivity & oxidation stability; higher friction than MoS_2.

2.3.2. Friction and Wear Kinetics in Composite Systems

Friction in heterogeneous composites is highly complex due to the simultaneous interplay of matrix-reinforcement interfaces, secondary phases, and process-induced residual stresses [23] (Figure 2).

True contact occurs at discrete micro-asperities ($A_r/A_n \approx 10^{-3}$), where localized shear stresses drive adhesion [24]. In polymer matrices, low elastic modulus, viscous chain mobility, and surface energy compatibility govern transfer film stability. Concurrently, subsurface material undergoes plastic deformation [25]. Hard ceramic particles (SiC, Al_2O_3) resist this deformation by forming a load-bearing skeleton and retarding subsurface crack propagation. Accumulated wear residues act as a third body [24,26], functioning either as a protective self-lubricating tribofilm or as harsh abrasive particles.

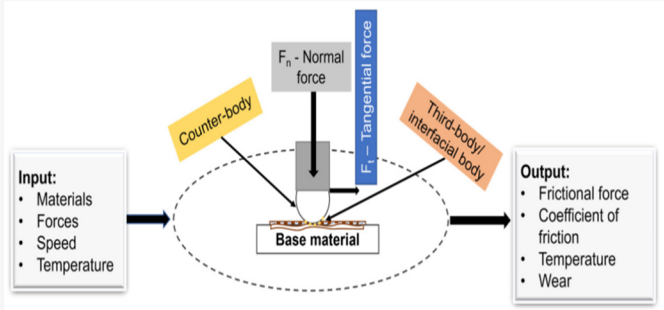


Figure 2. Friction mechanisms in composite systems. Adapted from [27], under the terms of the Creative Commons Attribution License.

Primary failure modes must be explicitly identified and evaluated during the design phase.

- **Adhesive Wear:** Driven by interfacial welding and material transfer [28]. Influenced by normal load, surface energy compatibility, contact temperature, shear rate, and interface chemistry (Figure 3).

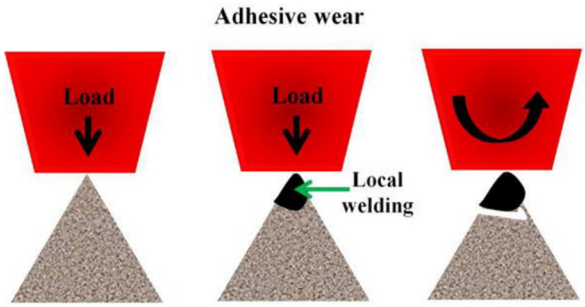


Figure 3. Schematic representation of adhesive wear. Adapted from [29], under the terms of the Creative Commons Attribution License.

- **Abrasive Wear:** Two-body or three-body micro-plowing caused by hard particles or detached reinforcement fragments [20], governed by Rabinowicz relationships (Figure 4).

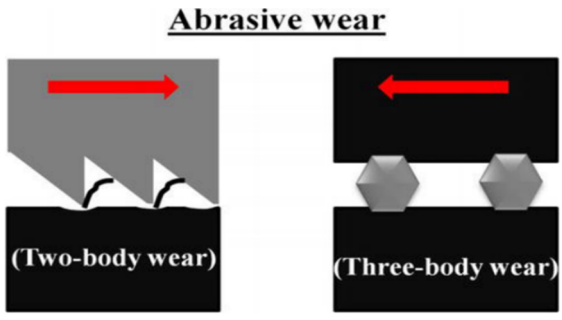


Figure 4. Schematic representation of abrasive wear. Adapted from [29], under the terms of the Creative Commons Attribution License.

- **Fatigue Wear:** Cyclic Hertzian contact stresses induce subsurface micro-cracks that coalesce into spalling damage [30] (Figure 5).

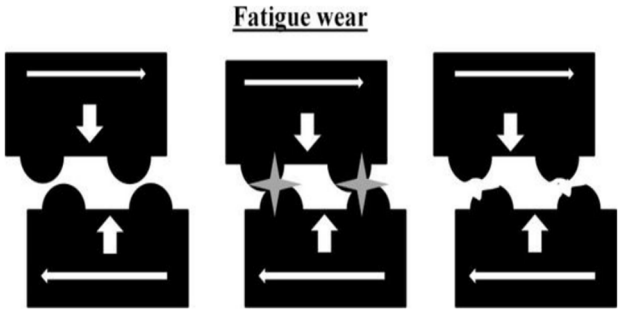


Figure 5. Schematic representation of fatigue wear. Adapted from [29], under the terms of the Creative Commons Attribution License.

- **Corrosive Wear:** Synergistic tribo-chemical degradation under aggressive chemical/aqueous environments [31] (Figure 6).

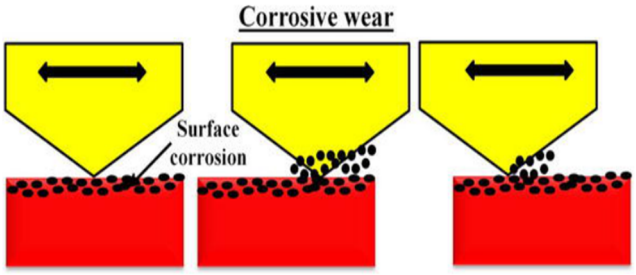


Figure 6. Schematic representation of corrosive wear. Adapted from [29], under the terms of the Creative Commons Attribution License.

- **Erosive Wear:** High-velocity solid particle or droplet impingement causing localized surface loss ($E \propto v^n \cdot f(\alpha)$).

Subsurface shear stresses trigger plastic flow, micro-cracking, delamination, fiber fracture, and matrix debonding [32]. Peak contact stresses ($\sigma_{max} = \frac{3F}{2\pi a^2}$) govern crack initiation beneath the contact plane [33].

2.3.3. Role of Fiber Architecture, Orientation, and Nano-Fillers

Fiber-reinforced composites offer superior specific strength. Carbon fibers (CFRP) provide excellent self-lubrication ($\mu = 0.12 - 0.22$), high stiffness, thermal dissipation, and graphite tribofilm formation [34]. Glass fibers (GFRP) offer high strength at lower cost but lack self-lubrication ($\mu = 0.35 - 0.52$), exhibiting brittle fracture and hard debris that induces severe 3rd-body abrasion.

The spatial orientation of fibers fundamentally dictates the anisotropic wear behavior of the composite material.

The spatial orientation of fibers relative to the sliding direction, contact geometry, matrix toughness, and interfacial shear strength fundamentally dictates the anisotropic wear behavior of composite materials:

- **Normal (Perpendicular) Orientation:** Fiber ends act as vertical load-bearing columns, effectively suppressing subsurface shear deformation, micro-cracking, and delamination to yield maximum wear resistance. However, direct contact between hard fiber tips and the counterface locally concentrates contact stresses, which can elevate initial friction before a stable tribofilm is established [14,15].
- **Parallel Orientation:** Fibers lie parallel to the sliding motion, distributing normal loads uniformly along their lengths and promoting smooth transfer film formation. Nevertheless, continuous interfacial shear stress makes this orientation susceptible to longitudinal matrix cracking, fiber debonding, and fiber stripping under aggressive sliding conditions [14].
- **Transverse Orientation:** Fibers lie perpendicular to the sliding direction within the contact plane, representing the most detrimental state. Transverse shear forces induce severe bending stresses, triggering micro-fracture, interface debonding, and rapid fiber fragmentation. Trapped sharp debris transforms the process into aggressive third-body abrasive wear [15].
- **Random Orientation:** Typically observed in short-fiber composites, offering an isotropic tribological response suitable for multidirectional sliding environments, albeit with moderate overall wear resistance (Figure 7).

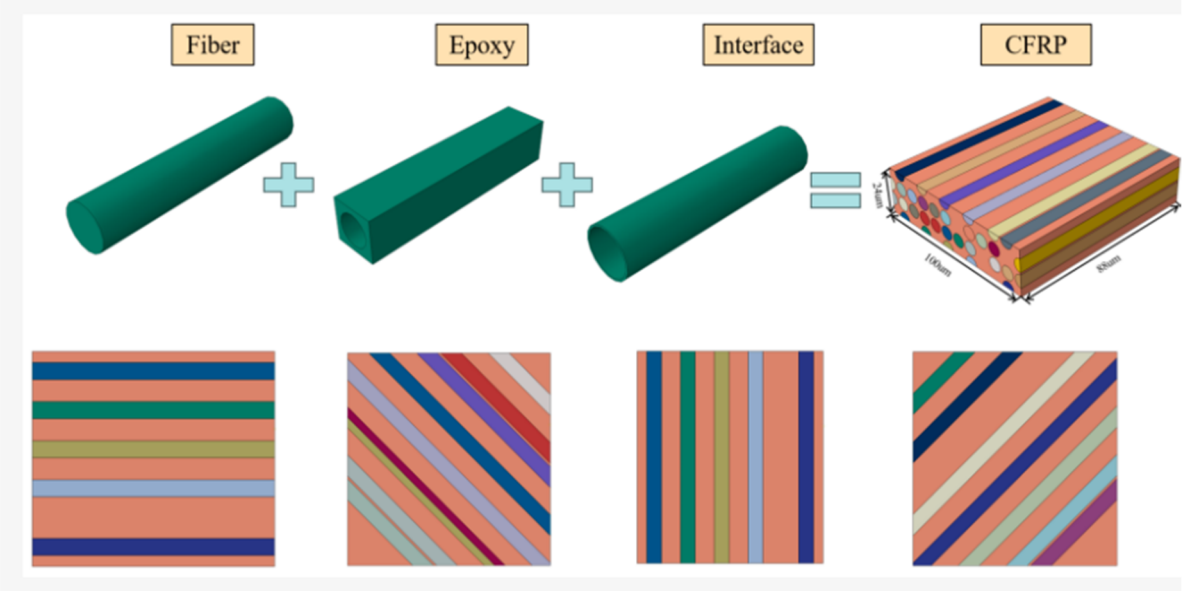


Figure 7. Representation of fiber orientation configurations in the microscale model. Adapted from [35], under the terms of the Creative Commons Attribution License.

Integrating nano-fillers (CNTs, graphene, nano-ceramics) radically enhances performance due to high specific surface areas and stress transfer capability [36]. Nano-fillers lower friction by 20–60% via rolling mechanisms, enhance crack pinning, improve hardness, and elevate axial thermal conductivity (e.g., CNTs ~3500 W/m·K, Graphene ~5000 W/m·K). Quantitative tribological metrics reported in the literature exhibit strong system dependencies. For example, the incorporation of 1–3 wt.% carbon-based nanofillers (such as CNTs or graphene) into epoxy and PEEK matrices generally yields a 20–60% reduction in friction coefficient under moderate dry sliding conditions (10–30 N, 1.0 m/s against smooth steel counterfaces) by promoting protective transfer film formation and rolling friction mechanisms [11,12]. Similarly, carbon fiber-reinforced polymer (CFRP) composites typically exhibit friction coefficients ranging from $\mu = 0.12$ to 0.22 under dry pin-on-disk sliding due to graphite-like tribofilm evolution, whereas glass fiber-reinforced polymers (GFRP) display higher friction levels ($\mu = 0.35 - 0.52$) under identical testing parameters owing to brittle debris formation and hard third-body micro-plowing [9,14]. Nanofiller contents offer optimum tribological performance generally at 1–3 wt. %, while exceeding 5 wt. % leads to severe agglomeration and performance degradation.

However, filler contents must be constrained to 1–5 wt.%; exceeding this threshold causes severe agglomeration, weak stress transfer, and third-body abrasive wear. To summarize the application of advanced computational methodologies in predicting composite friction and wear, recent machine learning studies reported in the literature are presented in Table 3.

Table 3. Summary of Machine Learning (ML) and Artificial Intelligence (AI) Applications in Composite Tribology.

AI/ML Model/Algorithm	Input Parameters	Target Outputs	Key Findings & Performance Metrics	References
Artificial Neural Networks (ANN)	Load, sliding speed, fiber orientation, filler content	Coefficient of Friction (COF), Specific Wear Rate (K_v)	Achieved $R^2 > 0.98$; accurately predicted non-linear wear transitions in polymer matrix composites.	[37]
Random Forest (RF) & XGBoost	Temperature, contact pressure, nanofiller wt. %, counterface roughness (R_a)	Dominant wear mechanism, wear volume	Feature importance analysis identified operating temperature and interface bonding as critical parameters.	[16]
Deep Convolutional Networks (CNN)	SEM micro-topography images, surface roughness profiles	Micro-crack density, debonding identification	Automated wear surface classification with over 95% accuracy; detected early-stage fatigue spalling.	[16]

2.4. Integrated System-Engineering Framework for Composite Tribo-Design

To evaluate the performance of different composite systems, experimental tribological data reported in the literature are summarized in Table 4.

Table 4. Summary of Experimental Tribological Data Across Various Composite Material Systems.

Composite System (Matrix/Reinforcement)	Test Setup Configuration	Operating Conditions (Load/Speed)	Friction Coefficient (COF, μ)	Specific Wear Rate (Kv) [mm³/N·m]	Dominant Wear Mechanism	References
PEEK/Carbon Fiber (10–30 wt.%)	Pin-on-Disk (Dry sliding vs. Steel)	10–50 N, 0.5–2.0 m/s	0.12–0.22	1.2×10^{-6} $- 4.5 \times 10^{-6}$	Transfer film formation, micro-plowing	[13,14]
Epoxy/Glass Fiber (15–40 wt.%)	Block-on-Ring (Ambient air)	20–100 N, 1.0 m/s	0.35–0.52	8.0×10^{-5} $- 3.1 \times 10^{-4}$	Micro-fracture, third-body abrasive wear	[9]
Natural Rubber/Pyrolysis CB + CNT	Reciprocating Tribometer	5–20 N, 0.1 m/s	0.25–0.40	3.2×10^{-5}	Elastic deformation, adhesive tearing	[10]
Epoxy/Carbon Fiber + CNTs (1–3 wt.%)	Pin-on-Disk	30 N, 1.5 m/s	0.15–0.25	5.5×10^{-7}	Nanofiller rolling, crack suppression	[11]

Optimizing composite tribosystems cannot be achieved by tuning isolated variables. Frictional work (W_f) converts directly into localized thermal energy, accelerating matrix softening, oxidation, and lubricant degradation [38]. To unify material properties, contact mechanics, modeling tools, and wear outputs, an Integrated Tribological Design Framework is established. This multi-stage methodology links operational inputs to material synthesis, computational optimization, and performance prediction:

1. **Operational & Boundary Definition**
   - **Primary Variables:** Normal load (F_N), sliding velocity (v), contact pressure-velocity limit (PV), interface temperature (T), and contact geometry [39].
   - **Secondary Variables:** Environmental humidity, corrosive media, counterface surface roughness (R_a), and initial residual stress state [40].
2. **Material & Interphase Synthesis**

Matrix & Reinforcement Selection: Polymer, metal, or ceramic matrices matched to thermal boundaries [41]. Fiber architecture (CF, GF, AF), orientation relative to sliding direction (Parallel, Normal, Transverse), and nano-filler functionalization (typically 1–3 wt. % CNT/Graphene) [42].

Surface Functionalization & Manufacturing Process: Optimization of surface chemistry (e.g., silanization, plasma) is essential for homogeneous nanoparticle distribution [43]. Unfunctionalized CNTs and graphene tend to form severe agglomerates via van der Waals forces. High-shear dispersion techniques (ultrasonic dispersion, solvent mixing, three-roll milling) directly govern matrix-filler interphase bonding and material homogeneity [44].

Hybrid Nano-Composites & Interphase Engineering: Synergistic effects are observed when nano-reinforcements with complementary geometries (e.g., 1D CNT + 0D nano-SiO_2 or 1D CNT + 2D graphene) are used together to construct multi-scale thermal and load-bearing networks while suppressing subsurface delamination [45].

3. **Multi-Physics Computational Optimization**
   - **Finite Element Analysis (FEA):** FEA serves as a critical numerical tool beyond conceptual modeling in composite tribology [46]. Micromechanical 2D/3D FEA models incorporating Cohesive Zone Modeling (CZM) explicitly capture interfacial stress concentrations, fiber-matrix debonding, and crack propagation pathways under dynamic sliding contact. Furthermore, dynamic thermo-mechanical FEA simulations quantify localized frictional flash temperatures and subsurface stress distributions (σ) beneath contact asperities. This enables accurate predictions of contact stress/deformation, thermal softening profiles, interfacial debonding, and volumetric wear rates across complex sliding regimes.
   - **Design of Experiments (DoE) & Machine Learning (ML):** Uses response surface methodologies and ML algorithms to explore non-linear design spaces, predicting friction coefficient (μ) and specific wear rate (K_v) prior to experimental fabrication [47].
4. Dynamic Contact Feedback Loop
   - **Real-time Empirical Feedback:** Dynamic contact interactions at the sliding interface (tribofilm formation, micro-plowing, third-body evolution) serve as dynamic feedback to refine FEA models and material formulation iterations.

3. Discussion and Conclusions

This study reviews material selection, interface design, contact mechanics, and computational modeling in composite tribology. Looking at the literature as a whole, the main findings, common contradictions, and key open questions are summarized below:

- **Key Findings**
  1. Adding low amounts of nanofillers (1–3 wt.%) lowers friction and wear rates by creating a rolling effect and stopping crack growth, as long as the particles are evenly mixed.
  2. Normal (perpendicular) fiber orientation gives better wear resistance than transverse orientation because vertical fiber tips support the load and resist surface damage.
  3. Combining solid lubricants (such as PTFE, MoS_2, or graphite) helps reduce adhesive wear and creates a stable protective film on the contact surface during sliding.
- **Contradictions in the Literature**
  1. Studies disagree on the effects of adding more than 3 wt.% nanofillers. Some report continued improvements, while others observe higher wear due to particle clumping, material brittleness, and surface scratching from loose debris. These differences mainly come from varying mixing methods and surface treatments.
  2. Findings also differ regarding friction in parallel versus perpendicular fiber orientations. This is caused by variations in surface roughness (R_a), applied load (F_N), and bonding strength between fibers and matrix.
- **Future Work**
  1. Transfer Film Behavior: More work is needed to measure how protective surface films form and hold up over long periods under changing moisture and heavy loads.
  2. Integrated Modeling: Models need to move from simple stress simulations toward combined frameworks that link small-scale atomistic behavior with real-time wear life prediction.
  3. Self-Healing Materials: Developing composites that can automatically seal micro-cracks or release lubricants when contact temperatures rise remains an important goal.

Author Contributions

D.M.Y.: Project Administration, Conceptualization, Validation, Formal Analysis; S.Y.: Methodology, Writing—Original Draft Preparation, Writing—Review and Editing, Data Curation; M.F.Y.: Investigation, Resources, Visualization. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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