JCMM Journal of Computers, Mechanical and Management
Journal homepage: www.jcmm.co.in
e-ISSN: 3009-075X
AAN PUBLISHING

Volume 3 Issue 4

Article Number: 24140

Tribological Advancements in Natural Fiber Composites for Sustainable Applications

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Abstract

Fiber-reinforced polymer composites (FRPCs) have revolutionized tribological applications by offering a unique combination of wear resistance, strength, and design flexibility. This mini-review explores the mechanisms of abrasive and erosive wear in FRPCs, focusing on the influence of reinforcements, fillers, and operational conditions. Abrasive wear studies reveal the critical role of fiber orientation, filler content, and material architecture in determining resistance to material removal in two and three-body interactions. Erosive wear, characterized by particle impingement, emphasizes the interplay between impact velocity, angle, and fiber-matrix interactions in governing performance. Advanced hybrid composites incorporating nano-fillers or sustainable natural fibers have demonstrated promising wear resistance, addressing both performance and environmental concerns. However, challenges such as moisture absorption in natural fibers, cost-performance trade-offs, and the complexity of wear mechanisms remain significant. Innovations in surface treatments, material design, and characterization techniques have contributed to a deeper understanding of these wear phenomena. This mini-review identifies future directions for the development of FRPCs, highlighting the potential of hybrid configurations to balance cost, sustainability, and performance. The findings underscore the importance of interdisciplinary approaches to enhance the durability of FRPCs, making them viable candidates for diverse industrial applications, including aerospace, automotive, and energy sectors.

Keywords: Natural Fiber Composites; Tribological Properties; Sustainable Materials; Surface Treatments; Wear Resistance

1. Introduction

Fiber reinforced polymer (FRP) composites have emerged as transformative materials in diverse industries, including aerospace, automotive, biomedical, and mining [1–3]. Their adoption is primarily due to superior performance characteristics compared to conventional materials, such as self-lubricating properties, low friction coefficients, excellent corrosion resistance, and reduced noise generation during operation [4–6]. These advantages are particularly valuable in applications where friction and wear are critical concerns. Tribological challenges, including friction and wear, contribute significantly to energy losses and maintenance costs. For example, friction in transportation accounts for almost one-third of fuel consumption [7, 8]. A reduction of 20% in friction could yield substantial economic benefits, underscoring the importance of advanced tribological solutions. FRP composites typically consist of a polymer matrix reinforced with fibers. The matrix binds to the fibers, provides structural integrity, protects against environmental degradation, and facilitates stress transfer [9, 10]. Thermosetting polymers, such as epoxy, polyester, and phenolic resins, dominate the market due to their ease of processing and the ability to create complex shapes [11, 12]. Glass fibers are often chosen for their cost-effectiveness, while carbon fibers provide superior strength-to-weight ratios and stiffness [13, 14].

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Received: 22 Aug 2024; **Revised:** 29 Sep 2024; **Accepted:** 31 Oct 2024; **Published:** 31 Oct 2024

DOI: 10.57159/jcmm.3.4.24140.

Applications of FRP composites have significantly advanced aerospace and automotive technologies. For example, carbon fiber reinforced composites are extensively used in the Boeing Dreamliner 787 and Airbus A350XWB, enhancing fuel efficiency through weight reduction. However, optimizing the tribological performance of FRP composites, especially wear resistance, remains a critical focus. FRP components, such as conveyor belts in mining and bearings in industrial settings, face various wear challenges, including abrasive, adhesive, and corrosive wear [15, 16]. Understanding wear mechanisms, such as adhesive wear, which involves material transfer between surfaces, and abrasive wear, caused by hard particles, is essential to improve the durability of these materials [2]. Recent advances in hybrid polymer composites that incorporate fillers have shown promise in improving tribological performance. Fillers can improve wear resistance, stiffness, and mechanical properties while addressing cost concerns. By strategically selecting fillers and processing techniques, it is possible to tailor the properties of FRP composites for specific engineering applications. This mini-review aims to provide a concise analysis of the tribological and wear properties of FRP composites, focusing on recent developments and innovative research. By exploring wear mechanisms and evaluating the performance of various composite configurations, this study seeks to provide information on optimizing FRP composites for sustainable and high-performance industrial applications.

2. Wear in Polymer Composites

Tribology, the study of interacting surfaces in relative motion, is primarily focused on wear, which refers to the material loss that results from such interactions. Wear processes are influenced by a combination of mechanical factors - such as fracture or deformation - and chemical factors, including oxidation, which often occur within complex external environments. Consequently, wear can cause alterations in the surface topology, material erosion initiated by harder particles, or even ongoing degradation of the surfaces due to liquid flow. The economic repercussions of wear are substantial and contribute to increased operational costs, equipment downtime, decreased productivity, frequent part replacements, and the potential for catastrophic failures [9, 8]. Fiber reinforced polymer composites (FRPCs) are advanced triboengineering materials recognized for their excellent wear resistance, high specific strength, and modulus properties. These composites are used in a variety of applications, including aerospace, automotive, construction, civil engineering, medical devices, and recreational equipment. The increasing market presence of FRPCs can be attributed to their versatility, durability, and superior performance in tribological settings. Mechanical components fabricated from FRPCs often experience rigorous tribological loading, making wear resistance a critical consideration in design.

Recent research has highlighted the improvements in tribological performance achieved through the incorporation of various fillers and natural fibers. For example, Law et al. (2015) [17] demonstrated that cryogenically processed carbon fibers, when integrated with epoxy resin, significantly reduced the coefficient of friction and enhanced wear resistance. Likewise, Gupta et al.(2011) [18] conducted studies on bamboo fiber-reinforced epoxy composites, revealing that the optimal addition of bamboo fibers (at 40 wt.%) resulted in notable improvements in erosion resistance and mechanical attributes such as tensile, flexural, and impact strength. Zhao et al. (2013) [19] explored polyimide composites reinforced with a variety of fibers including carbon, glass, and aramid, and observed considerable improvements in tribological properties attributed to the superior interactions between the fibers and the matrix. Inorganic fiber-reinforced composites exhibited more effective load-sharing mechanisms compared to glass fiber composites, thus enhancing both friction and wear resistance. Furthermore, Gupta et al. [18] highlighted that bamboo fibers significantly reduced erosion wear rates, while Sharma et al. (2011) [20] found that cold nitriding treatments on carbon fibers improved molecular weight and tensile strength, resulting in enhanced tribological performance of carbon fabric-reinforced polyethersulfone composites. These studies collectively emphasize the critical roles of fiber selection, filler content, and surface treatment techniques in optimizing the tribological performance of polymer composites for various engineering applications. The advances achieved not only bolster the durability and efficiency of FRPCs but also pave the way for sustainable solutions in high-wear environments.

2.1. Abrasive Wear

Abrasive wear occurs when two surfaces come into sliding contact, with one surface being significantly harder than the other. This wear mechanism is broadly classified into two types: two-body and three-body abrasive wear. Two-body abrasion involves direct contact where harder surface asperities plow into softer material, causing deformation or cutting. In contrast, three-body abrasion occurs when hard particles are introduced into the interface, acting as abrasives and leading to material removal. Tests such as the rubber wheel abrasion test (RWAT) are commonly used to evaluate three-body abrasive wear in fiber reinforced polymer composites (FRPC) [21, 22]. Three-body abrasive wear is critical in assessing the performance of polymer composites in various industrial applications. This mechanism involves hard particles trapped between two sliding surfaces, which act as abrasives to remove material. Several studies have explored the role of reinforcement type, filler content, and material properties in influencing this wear mechanism. Agarwal et al. (2014) [23] studied epoxy composites reinforced with short and long glass fibers and observed that wear resistance improved with a higher glass fiber content. Short fiber composites exhibited superior performance compared to bidirectional fiber composites as a result of their better load-sharing capabilities under abrasive conditions.

Similarly, Suresha et al. (2008) [24] demonstrated that graphite-filled glass fiber epoxy composites showed higher abrasive wear rates compared to neat epoxy composites, indicating that filler selection plays a crucial role. The addition of fillers, such as calcium carbonate ($CaCO_3$), also affects the wear behavior. Chand et al. (2000) [25] reported that while increasing glass fiber content improved wear resistance, the addition of $CaCO_3$ fillers negatively affected performance due to increased material removal intensity. Suresha et al. (2008) [26] found that 3D woven glass-fiber-reinforced vinyl ester composites exhibited superior wear resistance compared to 2D composites, highlighting the importance of fiber architecture. Siddhartha and Gupta (2012) [27] investigated the wear behavior of chopped and bidirectional glass fiber composites, concluding that chopped fibers enhanced wear resistance due to their random orientation, which reduced localized stresses. Patnaik et al. (2010)[28] demonstrated that specific filler combinations, such as pine bark dust with glass fibers, significantly improved wear resistance compared to conventional fillers like silicon carbide (SiC). Two-body abrasive wear involves a direct interaction between two sliding surfaces, where the harder asperities penetrate and deform the softer material. Studies have highlighted the influence of fiber type, orientation, and filler content on wear resistance. Suresha et al. (2009) [29] compared glass fiber and carbon fiber vinyl ester composites under two-body abrasion conditions. The study revealed that carbon fibers exhibited superior wear resistance as a result of their higher modulus and load-bearing capacity. Similarly, graphite fillers in carbon fiber composites improved wear resistance at higher sliding velocities [30]. El-Tayeb et al. (1996) [31] studied the effect of laminate orientation on the wear performance of glass fiber reinforced polyester composites. Their findings indicated that the antiparallel laminate orientation offered a higher wear resistance compared to the parallel and normal orientations. Subbaya et al. (2012) [32] demonstrated that silane-treated SiC fillers in carbon fiber composites significantly enhanced abrasion resistance, emphasizing the importance of filler-matrix compatibility. Natural fibers have also gained attention as sustainable alternatives to synthetic reinforcements. Elkhouly et al. (2019) [33] showed that composites filled with 10% date palm seeds exhibited a 71% reduction in wear volume compared to unfilled composites. Despite their environmental advantages, natural fibers face challenges such as moisture absorption, which can degrade mechanical properties. Surface treatments and hybridization with nanofillers, such as silicon carbide, offer promising solutions to overcome these limitations [34, 35].

2.2. Erosive Wear

Erosive wear occurs when solid particles impact the surface of a material, leading to material removal. This phenomenon is prevalent in components subjected to harsh environments, such as transport tubes in chemical plants, hydraulic mining pumps and valves, rocket motor nozzles, and combustion system components. Erosive wear also affects turbine blades in aircraft engines and fluidized bed combustion equipment [35]. The hardness of a material influences the volume displaced during particle impacts but does not directly correlate with the volume of the eroded material. To address this, Sundararajan et al. (1990) [36] introduced the concept of erosion efficiency (η), which characterizes the mechanism and efficiency of erosion. For normal impacts ($\alpha = 90^\circ$), η is defined as:

$$\eta_{\text{normal}} = \frac{2E_r H_v}{\rho V^2} \tag{1}$$

where:

- E_r: Erosion rate (kg/kg),
- H_v: Hardness of the material (Pa),
- ρ: Density of the material (kg/m^3),
- V: Impact velocity (m/s).

For oblique impacts, the erosion efficiency is modified as:

$$\eta_{\text{oblique}} = \frac{\eta_{\text{normal}}}{\sin^2 \alpha} \tag{2}$$

where α is the angle of impingement.

Table 1 summarizes the erosion mechanisms corresponding to different ranges of η. Polymer composites exhibit higher erosion rates than metals and ceramics due to their lower hardness [37, 38]. However, reinforcements and fillers significantly improve their performance under solid particle erosion (SPE). Tewari et al. (2003) [39] demonstrated that glass fiber (GF) and carbon fiber (CF) reinforcements improve erosion resistance. Among GF / epoxy and CF / epoxy composites, CF-reinforced composites exhibited superior resistance as a result of higher strength and better load distribution. Harsha et al.(2008) [40] found that multidirectional braided GF/epoxy composites resist crack propagation better than unidirectional composites, enhancing wear resistance. Hard particulate fillers, such as silicon carbide (SiC) and alumina, enhance SPE resistance. Patnaik et al. (2008) [41] showed that SiC-filled GF / polyurethane composites have lower erosion rates due to the hardness of SiC particles. Similarly, silane-treated fillers, such as fly ash cenospheres, improved erosion resistance in CF / epoxy composites [42].

Table 1: Erosion Mechanisms and Corresponding Erosion Efficiency

Erosion Efficiency (η)	**Mechanism**	**Nature**
$\eta = 0$	Ideal micro-plowing without fracture	No erosion
$\eta = 1$ (100%)	Ideal micro-cutting	Ductile
$\eta \ll 100\%$	Lip/platelet formation with fracture	Ductile erosion
$\eta > 100\%$	Spalling and crack interlinking	Brittle erosion
$10\% < \eta < 100\%$	Low impact velocity	Semi-ductile erosion
$\eta < 10\%$	High impact velocity	Ductile erosion

Natural fibers such as hemp and flax have emerged as sustainable alternatives to synthetic fibers. Elkhouly et al. (2019) [33] reported that GF / epoxy composites filled with date palm seed filled 10% reduced wear volume by 71% compared to unfilled composites. However, moisture absorption in natural fibers can degrade mechanical properties, which can be mitigated using surface treatments [34]. Hybrid composites combining fibers and nanofillers offer excellent SPE performance. Bagci and Imrek (2013)[43] studied boric acid-filled GF / epoxy composites and observed improved resistance to erosion. Panda et al. [44] demonstrated that GF / epoxy composites filled with aluminum nitride performed exceptionally well under high impact conditions.

3. Critical Discussion

The study of fiber-reinforced polymer composites (FRPCs) for tribological applications reveals significant progress and persistent challenges. The review underscores the critical role of reinforcements and fillers in determining wear resistance, but also highlights the inherent trade-offs between performance and practicality. Advanced reinforcements such as carbon and glass fibers exhibit exceptional wear resistance, yet their high cost restricts widespread adoption. Similarly, while particulate fillers like silicon carbide and alumina enhance mechanical and tribological properties, their inclusion often increases the complexity and cost of manufacturing. Natural fibers, on the other hand, offer a promising path toward sustainability, combining low cost and environmental benefits. However, their moisture absorption and limited interfacial bonding strength with polymer matrices remain significant limitations. The complexity of wear mechanisms, particularly in abrasive and erosive environments, further complicates the optimization of FRPCs. Factors such as fiber orientation, impact velocity, and angle of impingement interact in ways that are challenging to predict and model. Although existing mathematical frameworks like erosion efficiency provide insights into material behavior, they fall short of capturing the nuances of hybrid composites and nano-reinforcements. This gap emphasizes the need for more sophisticated models and a deeper understanding of the fundamental wear processes. An encouraging trend in the field is the rise of hybrid composites that combine synthetic and natural fibers or integrate nanofillers. These materials show immense potential to achieve an optimal balance of performance, cost, and sustainability. However, the long-term durability of such systems, especially under variable environmental conditions, remains an open question. Innovations in surface treatments and fiber-matrix interface engineering could address these issues, but their scalability and economic feasibility require further exploration. From a practical perspective, advanced characterization techniques have proven invaluable in elucidating wear mechanisms at the micro and nanoscales. These tools not only aid in material optimization, but also bridge the gap between experimental observations and theoretical predictions. The increasing integration of such methods into the design and testing of FRPCs represents a step toward more reliable and application-specific materials. In essence, the field of FRPCs for tribological applications is at a crossroads where advances in material science must align with the demands for cost-effectiveness and environmental sustainability. The interplay between fibers, fillers, and matrices offers a vast design space, but the realization of the full potential of these composites hinges on collaborative efforts across academia, industry, and policy. By addressing current challenges and leveraging emerging opportunities, FRPCs can transition from niche applications to mainstream solutions for wear-critical environments.

4. Conclusion

Fiber-reinforced polymer composites (FRPCs) have emerged as critical materials for tribological applications, offering superior wear resistance, strength, and versatility compared to traditional materials. This review has highlighted the influence of key factors, including fiber type, filler content, and operating conditions, on the abrasive and erosive wear behavior of FRPCs. Several studies underscore the importance of optimizing fiber-matrix interactions and filler dispersion to enhance wear performance. Synthetic reinforcements, such as carbon and glass fibers, have proven to be effective in improving wear resistance, while advanced fillers, like silicon carbide and alumina, provide additional durability. The growing interest in natural fiber composites represents a step toward sustainable solutions, although challenges related to moisture absorption and bonding must be addressed. A critical takeaway from the review is the complex interplay of factors such as impact velocity, angle, and reinforcement type on wear mechanisms.

Mathematical models, such as erosion efficiency, provide a foundation for understanding these behaviors, but require further refinement to accommodate hybrid and nano-enhanced composites. In the future, hybrid composites that combine synthetic and natural fibers, coupled with nanofillers, represent a promising direction to achieve both performance and sustainability. By advancing material processing techniques and adopting advanced characterization tools, the field can overcome existing challenges and unlock the potential of FRPCs for a wide range of industrial applications, including aerospace, energy, and transportation. In conclusion, FRPCs have immense potential to address modern engineering challenges in wear-critical environments. However, sustained research efforts and industry collaboration are paramount to realizing their full capabilities and ensuring their integration into next-generation technologies.

Declaration of Competing Interests

The author declares that he has no known competing financial interests or personal relationships.

Funding Declaration

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions

Burcu Şen: Conceptualization, Data Analysis, Methodology, Investigation, Writing – Original Draft, Writing – Review and Editing, Visualization.

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