SERBIATRIB '25

19th International Conference on Tribology

14 – 16 May 2025, Kragujevac, Serbia

PROCEEDINGS

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Serbian Tribology Society

University of Kragujevac
Faculty of Engineering

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TRIBOLOGICAL BEHAVIOR OF ABACA FIBER-REINFORCED EPOXY COMPOSITES: PRELIMINARY INVESTIGATIONS

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Abstract: *This study presents preliminary investigations into the tribological behaviour of epoxy composites reinforced with abaca fibers. Composite samples containing 10%, 20%, and 30% fiber content were fabricated using the vacuum infusion method and subjected to dry sliding tests under controlled conditions (2 mm contact radius, 300 mN normal load, 10 mm/s sliding speed, 500 cycles) on a CSM Nanotribometer in ball-on-plate configuration. The results demonstrated that composites with lower fiber content exhibited reduced friction coefficients and penetration depths, primarily due to fewer structural imperfections. As the fiber content increased, both the number and size of imperfections also increased, significantly affecting the tribological performance. Microscopic analysis of the wear tracks revealed the formation of air bubbles and variations in wear debris behaviour depending on fiber content. These findings suggest that the distribution of fibers and the presence of structural imperfections play a critical role at the microscale under low-load conditions. Further studies involving higher loads, increased numbers of cycles, and a broader range of fiber contents are necessary to fully evaluate the tribological potential of abaca-reinforced composites.*

Keywords: *abaca fiber, epoxy composite, tribological behaviour, wear resistance, vacuum infusion*

1. INTRODUCTION

A substantial share of material-related costs in industrial processes (including energy, raw materials, and tooling) is directly associated with the tribological properties of elements within tribomechanical systems. Enhancing productivity in modern industrial sectors — typically quantified as the annual value of added product per employee — necessitates a comprehensive understanding of the tribological behaviour of all constituent components in tribological assemblies. The tribological properties of solid materials, as well as lubricants used in these systems, are evaluated based on the intensity of the friction force — that is, the coefficient of friction in the system's contact zone — and the degree of wear, expressed through the amount or rate of wear of key system components.

Holmberg and Erdemir [1] conducted a comprehensive analysis demonstrating that approximately 23% of the world's total energy consumption — corresponding to about 119 exajoules (EJ) — is related to friction and wear processes. Of this, around 103 EJ (approximately 20%) is expended on overcoming friction, while the remaining 16 EJ (about 3%) is attributed to the replacement and repair of components damaged by wear.

Building on these findings, the application of modern tribological solutions and materials could significantly reduce energy losses. According to estimates, up to 60% of the total energy consumed in industry is used to overcome friction in numerous tribological systems. In the transportation sector, this percentage is even higher. Therefore, the rationalization of energy consumption in these sectors depends on the effective reduction of friction forces, which occur in tens of thousands of contact assemblies within a single production system. Although the process of material wear cannot be completely eliminated, it can be slowed through the application of tribological knowledge and appropriate technologies.

Efficient reduction of friction forces and energy consumption can be achieved through:

- the selection of appropriate materials and techniques for processing contact surfaces;
- the use of advanced methods for enhancing tribological properties, such as nano-coatings and chemical or physico-chemical treatments;
- the utilization of lubricants with high tribological performance and properly defined lubrication regimes.

The trend toward developing products with extended lifespans, reduced mass, and lower production costs has led to the intensive development of new, advanced materials. Composite materials, particularly those reinforced with natural-origin fibers, are attracting increasing attention due to their exceptional physical, mechanical, and tribological properties compared to the corresponding base materials.

It is well known that synthetic materials, although widely applied, possess numerous shortcomings compared to materials originating from natural sources. Among these drawbacks, higher production costs and negative environmental impacts are particularly notable, as highlighted by Nägeli et al. [2], Dente et al. [3], and Shahinur and Hasan [4]. These factors have contributed to the growing interest of the scientific community in developing composite materials based on natural raw materials, which could offer similar or even superior properties compared to their synthetic counterparts. In this context, natural fibers are increasingly used as fillers in composites and are classified into plant, animal, and mineral fibers [5-7].

The tribomechanical properties of plant fibers and their composites play a crucial role in the reliability and operational lifespan of technical systems. The fundamental influences on the tribological performance of composites stem from the properties of the matrix, the filler, and the interphase bonds between these two elements [8-10]. Additionally, external factors such as loading regimes and the working environment significantly contribute to the development of tribomechanical characteristics [11, 12].

For several decades, composite materials have attracted researchers' attention primarily due to the potential for saving materials and energy, which are basic principles of tribology. By lowering the coefficient of friction, direct energy savings can be achieved, while improving wear resistance prolongs the working lifespan of tribomechanical components, resulting in additional material savings. One of the challenges in composite production is achieving a uniform distribution of reinforcement within the base material. In order to reduce the total mass of contact elements, composites with lightweight matrices have been developed, where the type, size, and share of fibers significantly influence the final material properties.

Liu et al. [13] analysed composites with a 0–4% weight fraction of abaca fibers in a phenolic resin matrix. The results showed that the composites exhibited significantly higher wear resistance compared to the matrix alone, with improvements becoming more pronounced as the fiber content increased.

Regarding hybrid composites, numerous studies indicate that combining different fiber types leads to improvements across a wide spectrum of material properties. For example, the combination of jute and hemp fibers in an epoxy matrix achieves higher wear resistance compared to composites containing only one of these fibers [14].

In the context of plant fibers as reinforcements in composites, fiber orientation represents an important factor influencing tribomechanical material properties. Chin and Yousif [15] demonstrated that a normal orientation of kenaf fibers relative to the sliding direction improved the wear resistance of an epoxy matrix by as much as 85%. In the same study, it was determined that sliding speed and loading had negligible influence on the specific wear rate, whereas fiber orientation significantly shaped friction behaviour and wear resistance. Normally oriented fibers, compared to parallel and antiparallel orientations, exhibited considerably better and more consistent performance.

In order to investigate the tribomechanical properties of abaca fiber-reinforced composites, experimental procedures were designed and carried out, as described in the following section.

2. MATERIALS AND METHOD

Samples of composite material based on epoxy resin and abaca fiber were fabricated using the vacuum infusion method. This technique is highly valued in engineering practice due to its ability to ensure uniform resin distribution within the fibrous reinforcement, resulting in a compact and homogeneous structure with enhanced mechanical characteristics of the final material.

The base materials used in this research were epoxy resin and natural abaca fibers, selected primarily for their high tensile strength and good moisture resistance. The abaca fibers were sourced from the Philippines, the world's largest producer of this plant material. To enhance the chemical compatibility between the fibers and the epoxy matrix, the fibers were treated with a 6% NaOH solution at 24 °C for 10 hours. This procedure effectively removed surface impurities, such as hemicellulose and other unwanted layers, significantly improving adhesion between the fibers and the resin. After treatment, the fiber diameters ranged between 150 and 260 µm.

The matrix material was an epoxy resin characterized by a very low viscosity (500–900 mPa·s at 25 °C), a density of 1.2 g/cm³, an equivalent molecular weight of 180 g/mol, and an epoxy index of 0.51 mol/1000 g. The hardener used was a cycloaliphatic polyamine with a density of 930–960 g/cm³, a viscosity of 7–11 mPa·s at 25 °C, and a hydrogen equivalent weight of 48 g. The resin-to-hardener ratio was maintained at 10:1. This formulation enabled a simple preparation process without the need for complex equipment, while achieving properties comparable to conventional polymers such as polypropylene (PP), polyethylene (PE), and polylactic acid (PLA). Due to its availability and favorable price, the epoxy resin represented an ideal solution for experimental testing in the development of environmentally friendly composite materials.

2.1 Sample fabrication and preparation

For composite fabrication, silicone molds previously treated with release agents were used to prevent bonding between the resin and mold walls. The abaca fibers were carefully prepared — cut to precise lengths and positioned within the molds to ensure a well-defined fiber orientation in accordance with the targeted mechanical properties.

The components of the epoxy resin and the corresponding hardener were mixed in a 10:1 ratio and thoroughly homogenized. Special attention was paid to eliminating air bubbles during mixing, thereby minimizing internal defects and voids within the final composite structure.

The resin mixture was applied to the prepared fiber molds using vacuum infusion at a pressure of 100 mbar, with a pump capacity of 55 L/min. This method enabled complete resin penetration through the fibrous network, with continuous process monitoring to identify and correct potential issues such as insufficient impregnation.

Following infusion, the composites were initially cured at room temperature and subsequently subjected to additional thermal curing (post-curing) in a controlled oven. This phase was crucial for completing the polymerization process and achieving optimal physical, mechanical, and thermal properties.

After curing, the hardened composite panels were carefully removed from the molds and cut using water jet cutting (WJC) technology. This method ensured high dimensional precision without inducing mechanical or thermal deformation. Samples of various geometries were fabricated to meet the specific requirements of subsequent mechanical and tribological tests.

The sample preparation process consisted of three well-defined stages. In the first stage, composite panels were cut into samples of precisely defined dimensions (15 × 10 × 6.35 mm) using a CNC saw. In the second stage, each sample underwent a polishing process using a series of wet sandpapers with progressively finer grits — 600, 1200, 2000, and 3000 — to improve the surface finish. In the final stage, surface roughness measurements were conducted using the Insize ISR-C002 Roughness Tester, a device characterized by a resolution of 0.001 µm and a measuring capacity of up to 160 µm. The obtained results confirmed that the surface quality corresponded to the N5 standard, ensuring suitability for reliable and precise mechanical testing.

2.2 Tribological Testing

Tribological tests were performed using a CSM Nanotribometer in the ball-on-plate configuration with the application of the rotational module. The contact parameters were kept constant throughout all experiments. All tests were conducted under identical conditions: radius (2 mm), normal force (300 mN), sliding speed (10 mm/s), and the number of cycles (n = 500). In addition, all tests were carried out under dry conditions, without lubrication.

The counter body was a steel ball made of 100Cr6 steel, with a diameter of 1.5 mm. After each experiment, the ball was examined under a microscope and subsequently rotated to present a fresh surface for the next test. No significant or measurable damage was observed on the ball surface after testing, which is attributed to the considerable hardness difference between the ball and the composite samples. This ensured that any material transfer or damage occurred predominantly on the composite surface, allowing for a reliable evaluation of the influence of fiber content on the tribological behaviour of the composites.

3. RESULTS AND DISCUSSION

The dependence of the coefficient of friction and the penetration depth of the ball on the abaca fiber content in the composite is shown in Figure 1: (a) 10%, (b) 20%, and (c) 30%.

Preliminary tests revealed significant oscillations in the values of the coefficient of friction and penetration depth. In the case of the composite with 10% abaca fiber content, a comparative analysis of the friction diagrams and wear tracks indicated that there was no interaction between the ball and the fibers, and the influence of structural imperfections was almost negligible. For the sample with 20% abaca fiber content, noticeable oscillations in the measured values were observed at certain points, attributed to fiber interactions and structural imperfections. In contrast, in the sample with 30% fiber content, it can be concluded that direct interaction with the fibers was minimal, but the presence of structural imperfections significantly affected the wear resistance.

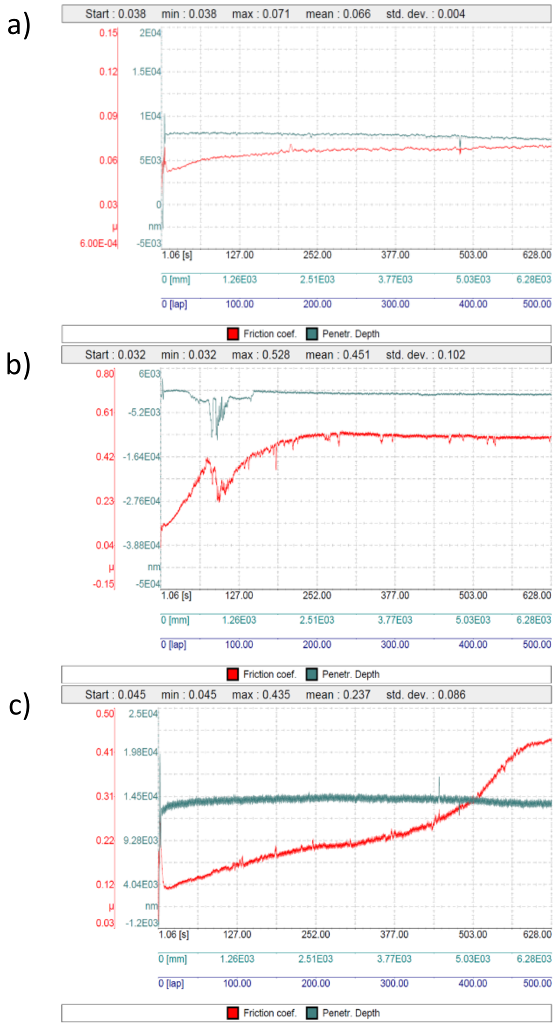


Figure 1. Dependence of the coefficient of friction and penetration depth of the ball on the abaca fiber content in the composite: a) 10%, b) 20%, and c) 30%

Additionally, an analysis of the friction diagram for the 30% abaca fiber sample showed an increase in the coefficient of friction without achieving stabilization, suggesting the necessity of extending the test duration or increasing the number of cycles.

Since these are preliminary investigations aimed at determining the future research direction, it is necessary to repeat the experiments on a larger number of samples with varying fiber contents to obtain a more realistic picture of the composite behavior. It is evident that, at this microscale, with the given contact geometry and under low load conditions, the distribution of fibers and the presence of structural imperfections have a significant influence on both friction and wear performance.

Moreover, although rotational motion was applied during testing, it is not possible to predict the exact location of fibers in the surface layer or the nature of their interaction with the counter body (i.e., the angle at which contact occurs), both of which can considerably affect the measured values.

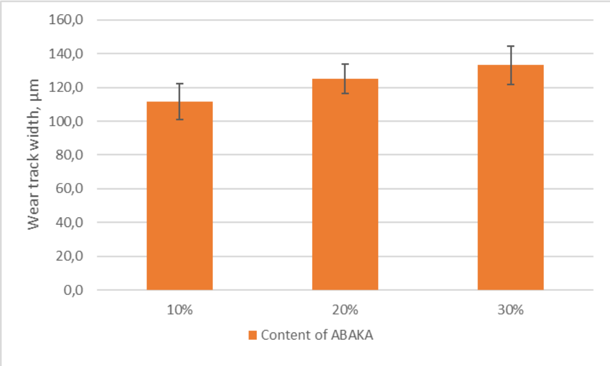
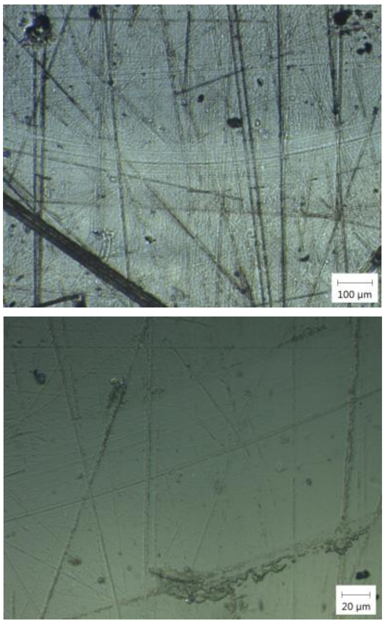


Figure 2. Histogram representation of the wear track widths for the tested samples with different abaca fiber contents

From Figure 2, it is clearly observed that the measured wear track widths for the samples with 10% abaca fiber content are the smallest. This can be attributed to the lower presence of structural imperfections in the surface layer. An analysis of the wear tracks further revealed the existence of structural imperfections in the form of air bubbles within the surface layer, with their number increasing as the abaca fiber content increased.

Figure 3 shows the wear track of the composite with 10% abaca fiber content, where a minimal number of structural imperfections can be observed both around and within the wear track itself. Additionally, a minimal amount of wear debris was observed at the outer edge of the track.

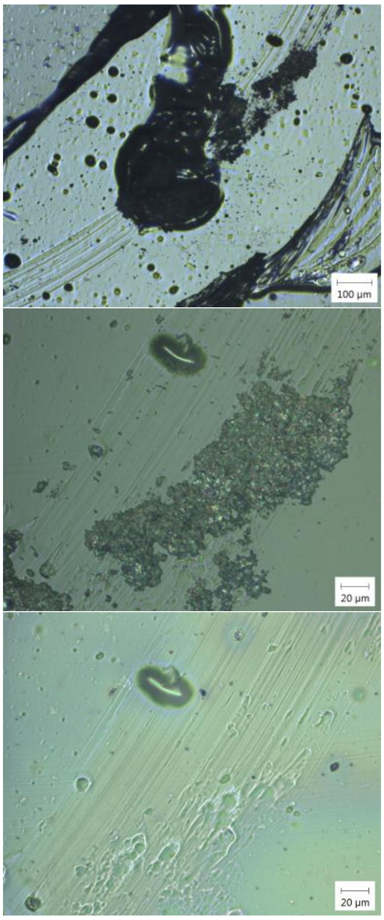
To further investigate the influence of abaca fiber content on the wear behaviour of the composites, the wear track of the sample with 20% fiber content was analysed using optical microscopy.



a)

b)

Figure 3. Optical microscopy of the wear track of the sample with 10% abaca fiber content, at 5× magnification a) and 20× magnification b)



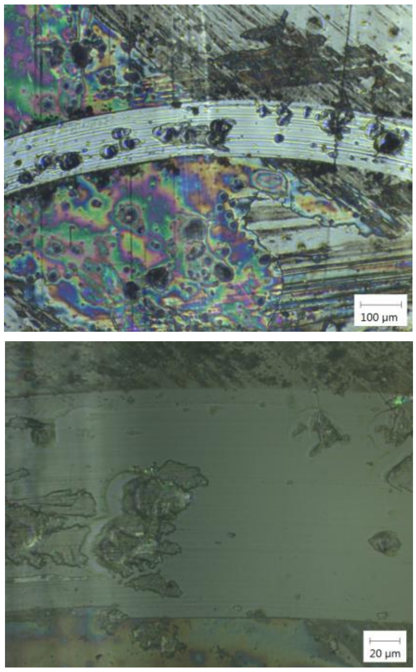
a)

b)

c)

Figure 4. Optical microscopy of the wear track of the sample with 20% abaca fiber content: (a) 5× magnification showing a structural imperfection inside the track, (b) 20× magnification showing wear debris at the track edge, and (c) surface after gentle mechanical cleaning showing residual surface deformation

In the sample with 20% abaca fiber content, an increased concentration of structural imperfections was observed both around and within the wear track, not only in quantity but also in size. Figure 4a was deliberately selected to highlight the presence and size of a structural imperfection located within the wear track. Figure 4b shows the presence of wear debris inside the track and along its edge. In most cases, wear debris tends to accumulate at the edge of the track; however, in this instance, the image was captured immediately after the structural imperfection shown in Figure 4a, but at a higher magnification of 20×. This wear debris was not firmly attached to the sample surface, as demonstrated in Figure 4c, where it can be seen that the debris was removed by gentle mechanical cleaning with cotton, without the use of alcohol or other chemical agents. Additionally, Figure 4c reveals that the passage of the ball over the debris plastically deformed the surface, leaving indentations at the points where the ball traveled over the loosened particles.



a)

b)

Figure 5. Optical microscopy of the wear track of the sample with 30% abaca fiber content: (a) 5× magnification and (b) 20× magnification

To further evaluate the influence of increased abaca fiber content on wear behaviour, the wear track of the sample with 30% fiber content was analysed by optical microscopy.

The analysis of the wear track and the surrounding surface of the sample with 30% abaca fiber content revealed a further increase in the concentration of structural imperfections both around and within the wear track compared to the previously analysed composites with 10% and 20% abaca fiber content.

An examination of the entire wear track showed no evidence of direct interaction with fibers, but structural imperfections of larger dimensions were present within the track itself. These findings correlate with the measured values of the coefficient of friction and penetration depth shown in Figure 1c.

4. CONCLUSION

Based on the preliminary investigations, it can be concluded that significantly broader testing is necessary, involving variations in contact parameters such as normal load, sliding speed, and the number of cycles, as the value of 500 cycles proved insufficient in some cases.

An increase in normal load and the number of cycles is expected to lead to a greater number of interactions between the ball and the fibers, resulting in a more pronounced influence on the coefficient of friction, penetration depth, and overall wear behaviour of the composites.
It is anticipated that under such conditions, the presence of fibers may compensate for structural imperfections and even enhance the wear resistance of the composites.

Additionally, particular attention should be paid to the behaviour of the counter body (the ball surface) to evaluate the overall performance of such a tribomechanical system.

These findings highlight the importance of continued investigation into fiber-reinforced composites under varied loading and operating conditions to better understand their full tribological potential and optimize their performance in practical applications.

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