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Article

Effect of Fiber Orientation on the Tribological Performance of Abaca-Reinforced Epoxy Composite under Dry Contact Conditions

Marko Milosevic [1,*], Dragan Dzunic [2], Petr Valasek [3], Slobodan Mitrovic [2] and Alessandro Ruggiero [1]

[1] Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano, Italy; ruggiero@unisa.it
[2] Faculty of Engineering, University of Kragujevac, Sestre Janjic 6, 34000 Kragujevac, Serbia; dzuna@kg.ac.rs (D.D.); boban@kg.ac.rs (S.M.)
[3] Department of Material Science and Manufacturing Technology, Faculty of Engineering, Czech University of Life Sciences Prague, 16500 Prague, Czech Republic; valasekp@tf.czu.cz
* Correspondence: mmilosevic@unisa.it

Abstract: This paper presents tribological research of an abaca fiber-reinforced epoxy composite material, analyzing fiber orientation and its effect on the tribological performances of the composite. The extremely low viscosity epoxy resin reinforced with NaOH-treated long abaca fibers is investigated under the different operating conditions. The unidirectional abaca fibers reinforced the epoxy resin and formed composite specimens with fibers in three directions, parallel (P-O), anti-parallel (AP-O) and normal (N-O), while keeping the sliding direction. The specimens were fabricated using fiber volume fractions of 10 vol%, 20 vol% and 30 vol% using the vacuum infusion technique. The block-on-disc (BOD) apparatus has been used to exhibit the tribological tests. Normal loads of 35 N and 45 N have been used for testing purposes. The experimental results indicated that the presence of abaca fiber significantly improved the wear characteristics of the matrix. An increased coefficient of friction was observed in samples with anti-parallel-oriented fibers at an applied load of 35 N. The conducted research shows that the use of abaca fibers as fillers could improve the tribological characteristics of the epoxy resin-based composite material.

Keywords: epoxy resin; abaca fiber; fiber orientation; natural composites; friction; wear

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1. Introduction

Composite materials (in the further text: composites) are the basis of many different construction types. Their favorable properties, such as low cost, low specific weight, high tensile strength, elasticity and wear resistance, accelerate the development and deeper research of their tribo-mechanical properties [1]. The use of composites improves the performance of production processes and finished products obtained utilizing such materials. The performance of composites largely depends on the type of fibers, their orientation respecting the sliding direction, chemical treatment, the number of fibers and matrix, the size of the fibers, the shape and the preparation method [2].

Industry and academia pay great attention to the research in the field of composites produced using natural elements. Special emphasis is placed on composites reinforced with natural fibers. Today, natural fibers and their composites are increasingly present in the industrial production of various materials, ranging from the textile industry, through to construction, all the way to the automotive and aerospace industry. Their wide application is justified by the replacement capabilities of composite materials reinforced with synthetic fibers.

Various papers show that abaca possesses various mechanical and tribological properties which make it a potential composite which could be used as a filler of polymers. Of all fibers used for the production of mechanical composites, abaca fiber is among the strongest available, commercially [3]; however, it is not sufficiently exploited as a filler of polymers [4]. Due to its appropriate tribo-mechanical properties, abaca fibers are attracting the attention of many researchers [5–12]. One of the most important factors which affects the reinforcing process is the interfacial adhesion between the fiber and the polymer matrix. This is due to the insufficient adhesion to the matrix in most composites reinforced with plant fibers because of the hydrophilic nature of plant fibers [13]. Therefore, it is necessary to perform chemical treatments in order to improve the level of hydrophobicity of fibers and thus improve their mechanical and tribological properties.

In an attempt to improve the tribological behavior of the friction composite, abaca fibers have played a significant role in the research of Liu et al. [8]. They improved the wear characteristics of the friction composite by adding alkali-treated abaca fibers in the weight fraction of 0–4 wt%. It was concluded that using a constant-speed friction test, the composite reinforced with 3 wt% abaca provides the most favorable wear rate characteristics at a temperature of 200–350 °C, while the friction specimen without reinforcement showed significantly lower wear resistance. Punyamurthya et al. [9] investigated the effect of surface modification of abaca fiber by benzene diazonium chloride treatment on the mechanical properties of polypropylene matrix composites, and they found increased tensile strength in fiber loading up to 40%. In general, research shows increased wear resistance of treated abaca fibers compared to untreated fibers used in the fabrication of composites for tribological investigations.

Abaca fiber's high durability, mechanical strength, flexibility, long fiber length and buoyancy make it excellent for various industrial applications. In the research of Venkatesan and Bhaskar [14], abaca fiber was used as a filler in a hybrid composite to study the mechanical properties due to tensile, flexural and hardness tests. The composite showed higher tensile strength when the fibers were oriented at 90° than the composite with 0°- and 45°-oriented fibers.

As a polymeric material, the epoxy resin belongs to the thermoset. Unlike thermoplastics, thermoset materials cannot be reheated, softened or molded into new materials [15]. In other words, they are not recyclable. However, its excellent properties, such as low cost, high strength, low toxicity and high adhesion to substrates, make it the dominant matrix in developing new composite materials. Epoxy resins have been the subject of numerous studies to improve their properties through the addition of materials, optimal fiber orientation and fiber surface modification. However, due to their inherent fragility, the use of these resins is limited [16].

In an overview by Milosevic et al. [17], it has been found that many researchers have considered the influence of operating parameters and fiber modification on the tribological behavior of epoxy-based composites [18–22]. Valášek et al. [23] reinforced epoxy resin with white/brown coir to improve its abrasive wear resistance through a vacuum infusion process. They focused on the chemical modification of fibers and found that the alkali treatment increased the tensile strength of white and brown fibers by 31% and 47%, respectively. Moreover, for the alkali-treated fibers, the tensile strength of the composite system was increased by 3.7% for a brown coir-based epoxy composite. In comparison, the 0.4% increase in tensile strength for the white coir fiber-based composite is considered negligible.

Yousif and Chin [24] developed the composite based on kenaf fiber-reinforced epoxy resin for the tribological investigation. They examined the effect of fiber orientation on friction and wear under lubricated conditions. The high friction coefficient is found when the fibers are oriented as normal and anti-parallel, while normal-oriented fibers showed the best wear resistance improvement of the epoxy by about 35–57%. This result is justified by the fact that when the fibers are in normal orientation respecting the sliding direction, the pulling out or detachment of fibers is not possible because the ends of the fibers are exposed to the rotating disk while the remaining sections are embedded in the matrix.

While there are many papers presenting the results on the surface modification of the abaca fiber, with various accomplishments in this field, there is a lack of research focusing on the fiber orientation and its effect on the tribological performance [4,6,7,25,26].

Therefore, the main objective of this work is to improve the tribological performance of the epoxy resin by reinforcing it with long abaca fibers. This work studied abaca-reinforced epoxy composites using different volume fractions of abaca and their orientations, respecting the sliding direction and comparing their behavior with neat epoxy to improve the tribological performance of epoxy composites.

2. Materials and Methods

2.1. Material Preparation

Abaca fibers purchased from the Philippines with diameters of 150–260 μm were used as fillers. Before mixing with the matrix, abaca fibers were soaked in a 6% NaOH water solution at the temperature of 24 °C for 10 h. The matrix has extremely low viscosity (500 to 900 mPa·s at 25 °C) epoxy resin LH 288, produced by Havel Composite Company from Czech Republic, with a density of 1.2 g/cm^3, equivalent weight of 180 g/mol and epoxy index of 0.51 mol/1000 g. Cycloaliphatic polyamine-based hardener H 282 with a density of 930–960 g/cm^3, viscosity 7–11 mPa·s at 25 °C and hydrogen equivalent 48 g was utilized. A vacuum infusion was employed in the composite composing process. The material preparation process is described in detail in [23].

As can be seen in Table 1, four different types of materials were prepared. Neat epoxy (NE) samples were prepared utilizing the epoxy resin with identical properties to those used for the epoxy/abaca composite (EAC). With a volume fraction of 10%, 20% and 30%, the abaca fibers are arranged within the epoxy resin in three different orientations. Respecting the sliding direction, the fibers are oriented parallel (P-O), anti-parallel (AP-O) and normal (N-O).

Table 1. The volume fractions of composite phases.

Sample Code	Epoxy (vol%)	Abaca Fiber (vol%)
EAC10%	90	10
EAC20%	80	20
EAC30%	70	30
NE	100	0

2.2. Sample Preparation

The rectangular prism specimen making process consisted of three phases. The first phase consists of cutting the previously prepared composite into samples of size 15 × 10 × 6.35 mm using a CNC saw machine. Furthermore, all cut specimens were polished with wet sandpaper grit with the size of 600, 1200, 2000 and 3000, respectively. In the third phase of sample preparation, the roughness of polished surfaces was measured with Insize ISR-C002—Roughness Tester with 160 μm measurement range and a resolution of 0.001 μm. This measurement was conducted to ensure the quality of the contact surface up to N5. Schematic view of the fiber orientation of the obtained samples is presented in Figure 1.

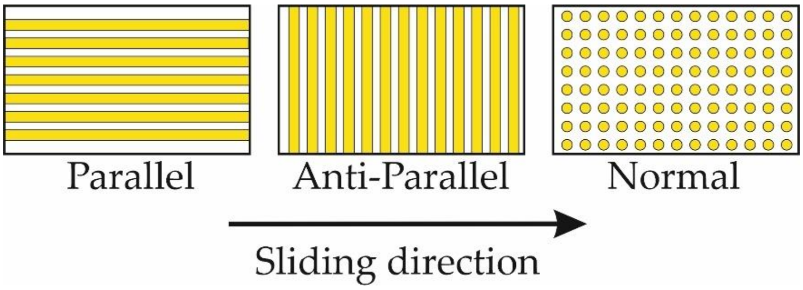
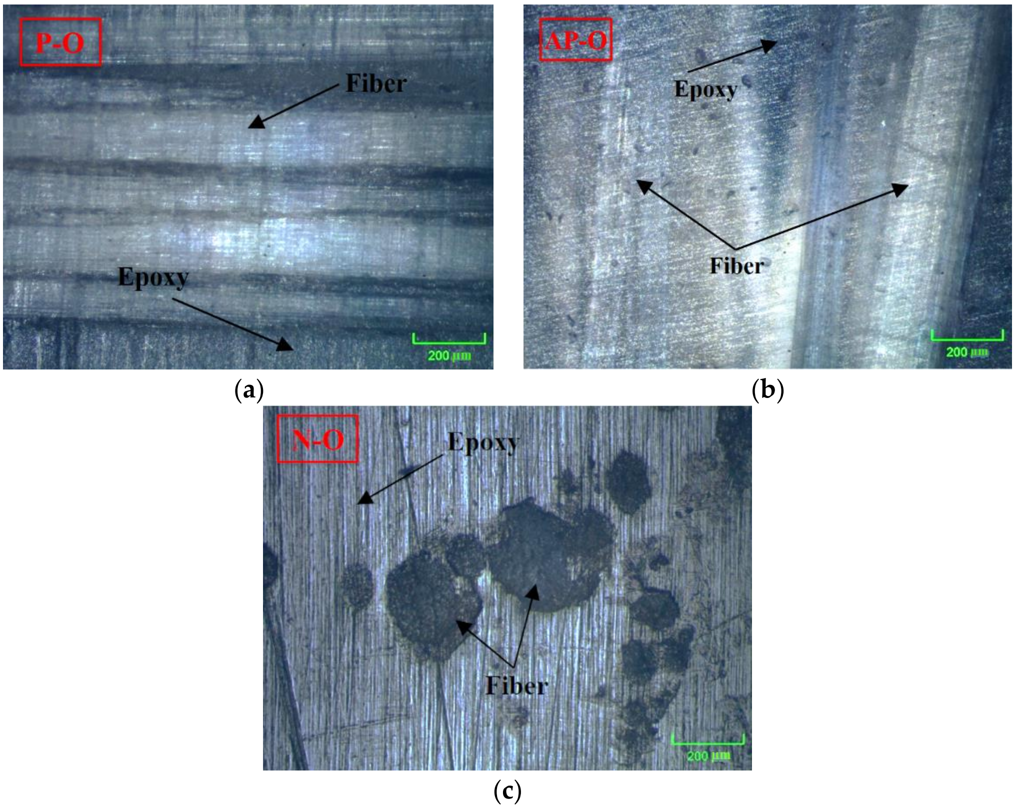


Figure 1. Schematic view of fiber orientation within EACs samples, respecting the sliding direction.

As can be seen from Figure 1, the fibers are oriented in three directions as described. Figure 2a–c show a representative appearance of the contact surface before testing for different fiber orientations, parallel, anti-parallel and normal. Utilizing the optical microscope, presented images show that fiber detection can be difficult, due to insufficient reflection of the surface layer and transparency of the epoxy matrix, as well as the direction of fine grinding identical to the parallel direction of fibers.



(**a**) (**b**)

(**c**)

Figure 2. Optical microscopy of contact surface prior to tribological test: (**a**) parallel, (**b**) anti-parallel and (**c**) normal.

2.3. Experimental Procedures

Frictional and wear test of the EACs and NE was conducted using block-on-disc (BOD) configuration, presented in Figure 3, following ASTM G77 standard. The sample was fixed in a rectangular holder and loaded with normal force (35 N and 45 N), with sliding distance of 800 m and sliding velocity of 0.8 m/s. Respecting the sliding direction, the samples were placed in the holder in the direction of P-O, AP-O and N-O. Friction and wear tests were conducted for each orientation, applied load, and volume fraction of abaca fiber. The tests were repeated three times. For comparison purposes, the neat epoxy samples were tested as well. In total, 30 samples were tested. EACs and NE were tested against the 90MnCrV8 steel rotating disc counterface of nitrated surface layer and hardness of 60–62 HRC. Before and after the run of each test, the specimen and counterface were cleaned with 70% ethyl alcohol solution to remove any impurity that increases the abrasive wear of materials in contact.

The width of the block wear track was measured after 30, 60, 90, 150, 300, 600 and 800 m of sliding. Wear curves are given through the dependence of the measured values of the width of the wear track on the sliding distance. The reason for such a choice of wear parameters is that wear curves clearly show the initial period or the period of running-in.

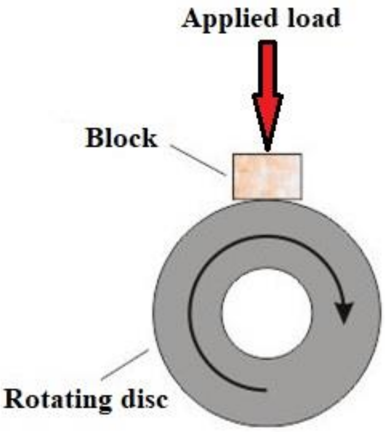


Figure 3. Block-on-disc configuration.

3. Results and Discussion

3.1. Determination of Roughness Characteristics of Contact Surfaces

The device on which the contact surfaces were characterized, in terms of determining the roughness parameters, is Insize ISR-C002—Roughness Tester. Each measurement was repeated at least three times and on several samples of the same material. Thus, Table 2 shows the mean values of roughness parameters for all types of samples.

Table 2. Roughness parameters of tested materials in µm.

	NE	EAC10%			EAC20%			EAC30%		
	±SD	P-O ± SD	AP-O ± SD	N-O ± SD	P-O ± SD	AP-O ± SD	N-O ± SD	P-O ± SD	AP-O ± SD	N-O ± SD
Ra	0.16 ± 0.003	0.32 ± 0.002	0.18 ± 0.001	0.15 ± 0.008	0.12 ± 0.007	0.27 ± 0.005	0.24 ± 0.01	0.21 ± 0.002	0.42 ± 0.004	0.25 ± 0.008
Rt	0.96 ± 0.001	2.34 ± 0.002	1.23 ± 0.001	0.98 ± 0.003	1.33 ± 0.002	2.31 ± 0.001	1.87 ± 0.004	1.41 ± 0.005	2.34 ± 0.001	1.49 ± 0.004
Rp	0.45 ± 0.003	1.01 ± 0.001	0.52 ± 0.006	0.46 ± 0.002	0.46 ± 0.004	0.78 ± 0.004	0.73 ± 0.001	0.72 ± 0.007	0.76 ± 0.002	0.74 ± 0.003
Rv	0.51 ± 0.002	1.33 ± 0.002	0.7 ± 0.005	0.51 ± 0.002	0.87 ± 0.003	1.53 ± 0.001	1.14 ± 0.006	0.69 ± 0.005	1.58 ± 0.009	0.75 ± 0.007

Ra—Arithmetic average height; Rt—Maximum height of the profile (Rmax); Rp—Maximum height of peak; Rv—Maximum depth of valleys.

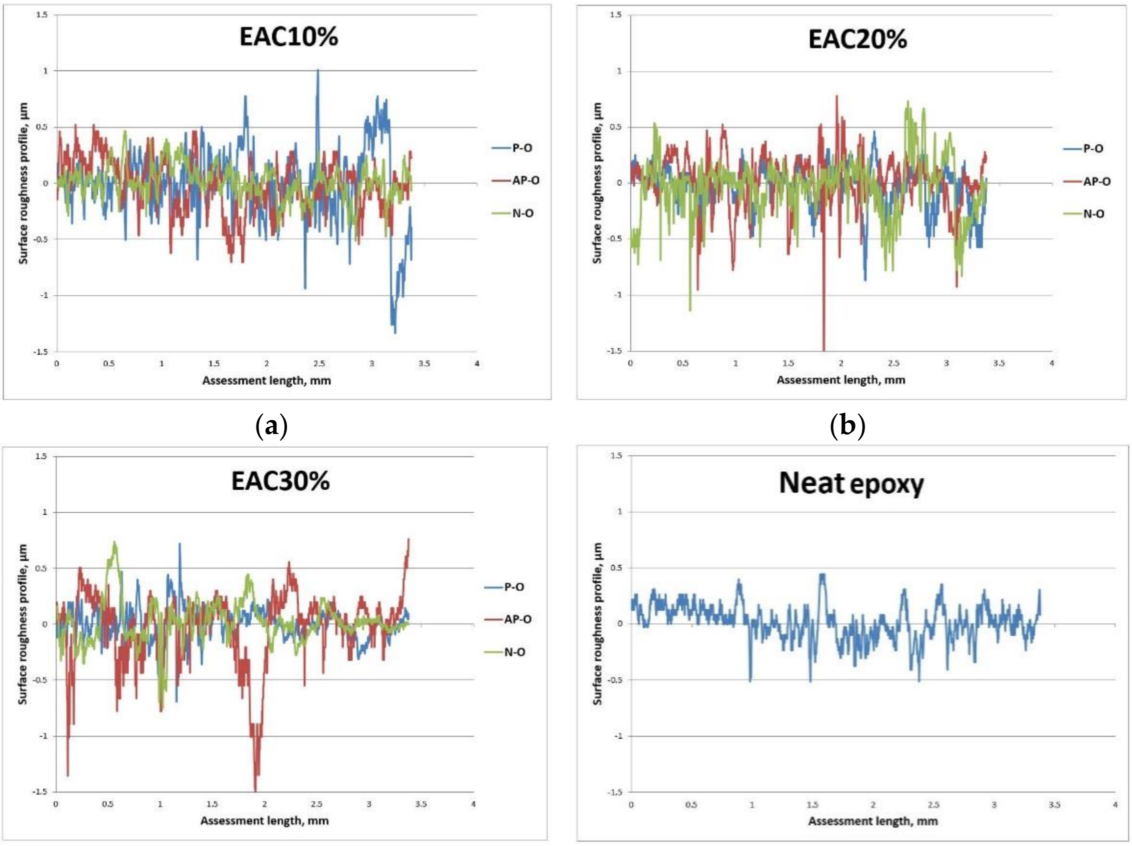
In addition to the numerous values of the roughness parameters, the roughness profiles are provided, one for each type of material. Figure 4 shows the roughness profiles of epoxy/abaca composite materials for the volume fraction of 10%, 20% and 30% of abaca fiber, as well as neat epoxy.

The roughness measurement preceded tribological tests in order to confirm that all tested samples were brought to the same quality of the contact surface by the pre-processing. Deviations in the measured values of roughness parameters result from the direct exposure of fibers in the surface layer. Additionally, higher roughness may be due to the removal of fibers by grinding. The orientation of the fibers has no significant effect on 2D roughness since the roughness value is a stochastic quantity and depends on the measurement site.

Figure 4 shows that there are no significant differences in the roughness profiles, which means that approximately equal conditions of contact geometry have been created. It leads to the conclusion that the topography of surfaces will not have a great influence on the results of tribological tests.

3.2. Tribological Experiments

Tribological tests included the characterization of tribological phenomena, friction and wear, in relation to contact conditions, sliding distance and variations in the structure of the material being tested. Based on the literature, we decided to perform tribological tests in conditions without lubrication, because the primary goal of these tests was to determine the influence of the type and proportion of reinforcements on the tribological characteristics of composites. It should be emphasized that the block is a static element of the tribomechanical system and that the disk rotates around its axis, while the sliding speed is calculated based on the number of revolutions and the radius of the disk. The block and disk are made according to the recommendations and dimensions defined by the ASTM G77 standard.



(**a**) (**b**)

(**c**) (**d**)

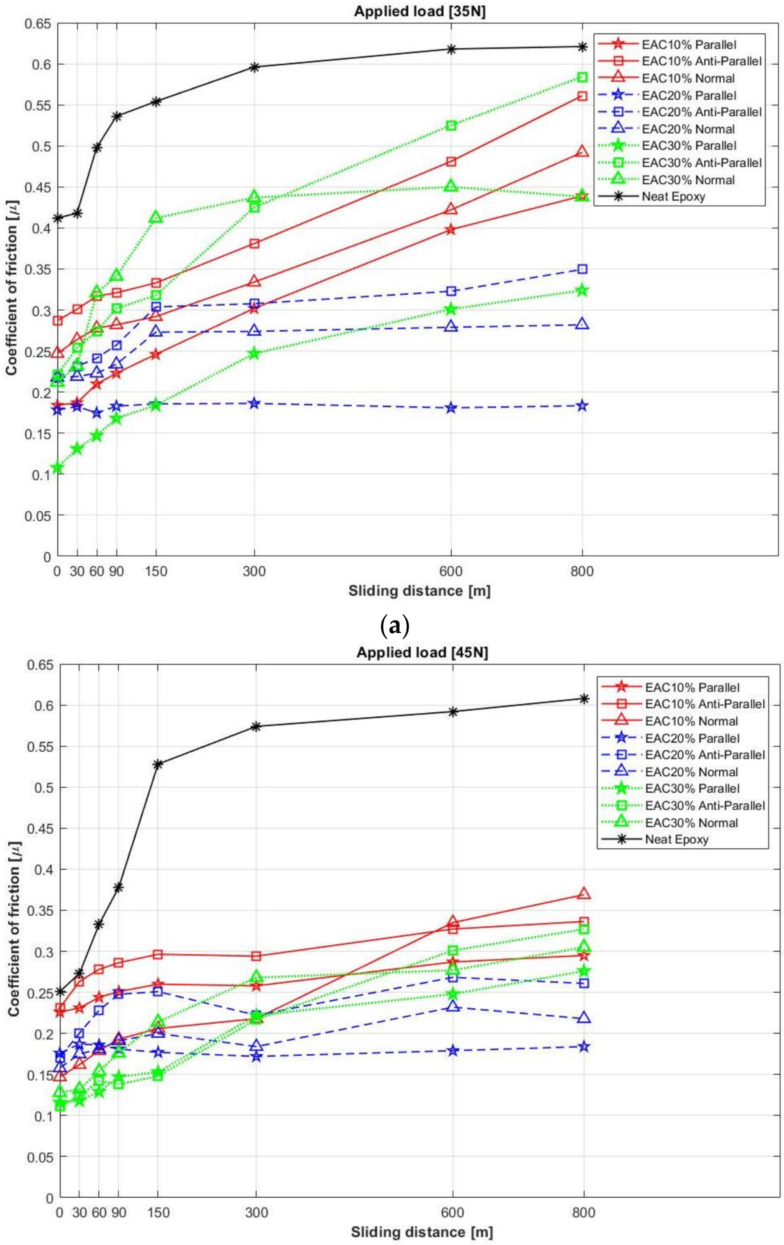
Figure 4. Contact surface roughness of samples per volume fraction of abaca fiber: (**a**) parallel, (**b**) anti-parallel, (**c**) normal and (**d**) neat epoxy.

3.2.1. Friction

In addition to the tribological characteristics of natural composites, frictional characteristics were monitored, such as friction force and coefficient of friction. According to the experimental plan, the coefficient of friction was obtained for tribological tests with variation in two applied loads in conditions without lubrication, as well as the orientation of abaca fibers.

Figure 5a,b present the dependence of the coefficient of friction on the sliding distance and the orientation of abaca fibers, for 35 N and 45 N applied loads of all tested materials. For the purpose of comparison, the values of the friction coefficient of the neat epoxy resin are also given.

Figure 5a,b show that the coefficient of friction increases with the increasing sliding distance. This may be due to the transfer of the epoxy layer to the steel disc, which may lead to the contact of two identical epoxy materials. The increasing trend is expressed more after a period of running-in of 150 m of sliding distance, which, according to Tang et al. [27], is the consequence of a rapid change in wear mechanism from dominant abrasive to a combination of abrasive and adhesive wear. Additionally, it is noticed that the coefficient of friction increases when the applied load is 35 N and that the growth trend is significantly higher for all types of fiber orientation when the epoxy matrix is reinforced by 10% abaca fibers. However, when applying a normal load of 45 N, a slight deviation in the trend of the increasing friction coefficient was observed during the sliding period.



(**a**)

(**b**)

Figure 5. Coefficient of friction of EACs and neat epoxy per sliding distance: (**a**) 35 N applied load and (**b**) 45 N applied load.

In general, with the change in sliding distance, significant changes in the friction coefficient of all tested materials were noticed, which are probably due to the inhomogeneous distribution of fibers in the matrix and also due to a more extended running-in period.

A comprehensive analysis of the experimental results shows that the highest value of the coefficient of friction in contact with the steel disk after 800 m sliding is expressed by neat epoxy (0.621 when 35 N is applied and 0.608 when the applied load is 45 N), see Figure 6. Furthermore, for both normal loads, an increased coefficient of friction is noticed when the fibers are in anti-parallel orientation, respecting the sliding direction.

The minimum value of the coefficient of friction has been noticed during the testing EAC20% samples with parallel-oriented fibers at an applied load of 45 N (0.183). Based on that, it can be said that the addition of abaca fibers in the epoxy matrix can significantly reduce the coefficient of friction. In general, it can be said that by increasing the normal load, there is a significant decrease in the coefficient of friction.

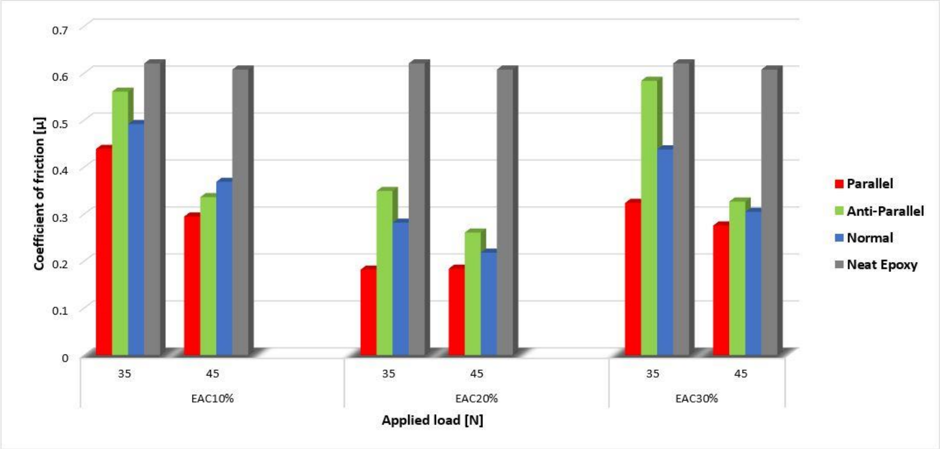


Figure 6. Coefficient of friction of EACs and neat epoxy, per two applied loads, after 800 m of sliding distance.

3.2.2. Wear

The wear of the tested materials is given in the form of wear volume, which is calculated based on the known block width and the measured wear track width and the value of the disk radius. Considering the results, presented in Figure 7, it can be concluded that the tested composite materials have better wear resistance than neat epoxy, regardless of the volume fraction and fiber orientation. Additionally, based on the presented values, it is clear that samples with 20 vol% abaca have the best wear resistance in identical test conditions. The following Figure 7 indicates the changes in wear volume, depending on the change in the normal load of EAC's and neat epoxy materials. Wear of the tested materials is due to the sliding contact with the steel disk, whose hardness is 60–62 HRC. High disk hardness is necessary to monitor the wear of the tested materials. During sliding, the wear of the steel disc occurs, but these values are negligible in relation to the wear of the tested materials.

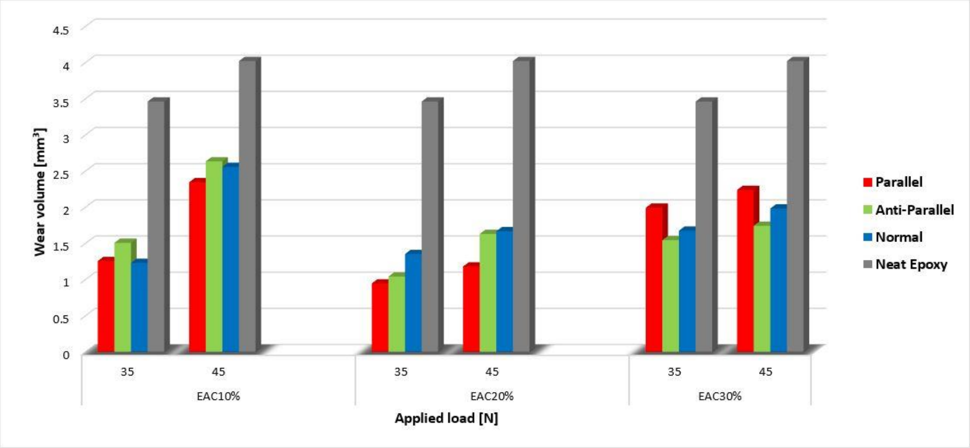
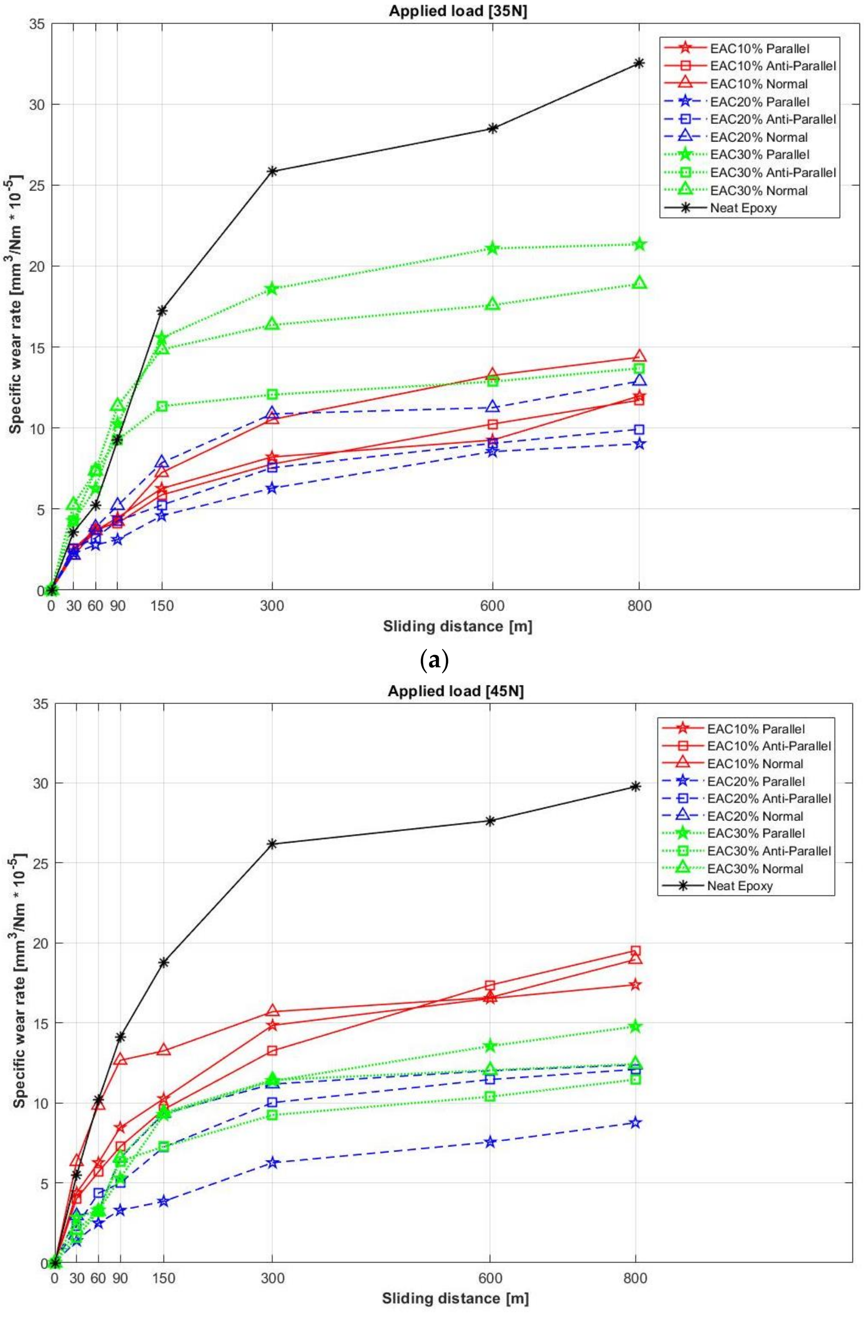


Figure 7. Wear volume of the EAC's and NE for different percentages of abaca fiber and applied load, after 800 m of sliding distance.

The values of wear volume are given depending on the applied load and the fiber orientation, after 800 m sliding of the rotating disc against EACs and NE specimens. From Figure 7, it can be seen that the wear volume increases with increasing applied load. This trend occurs in all tested materials and all types of fiber orientation, and a significant increase in the wear volume of neat epoxy was observed between 3.462 and 4.022, while increasing the applied load from 35 N to 45 N, respectively.

The specific wear rate is a commonly used way of representing the wear of a material as a function of the sliding distance or the operating time of a tribomechanical system. The specific wear rate was calculated based on the width of the wear track obtained on the contact surface of the tested block. Measurement of the width of the wear track of the tested materials was performed on a microscope according to the established procedure. The wear process was monitored so that after a certain sliding distance (30, 60, 90, 150, 300, 600 and 800 m) the friction process was stopped and the width of the wear track on the block was measured. Figure 8 presents the specific wear rate of the EACs and neat epoxy in the dependence on the sliding distance for applied loads of 35 N and 45 N. Specific wear rates were obtained for all test conditions for all tested materials and are shown in the following figures.



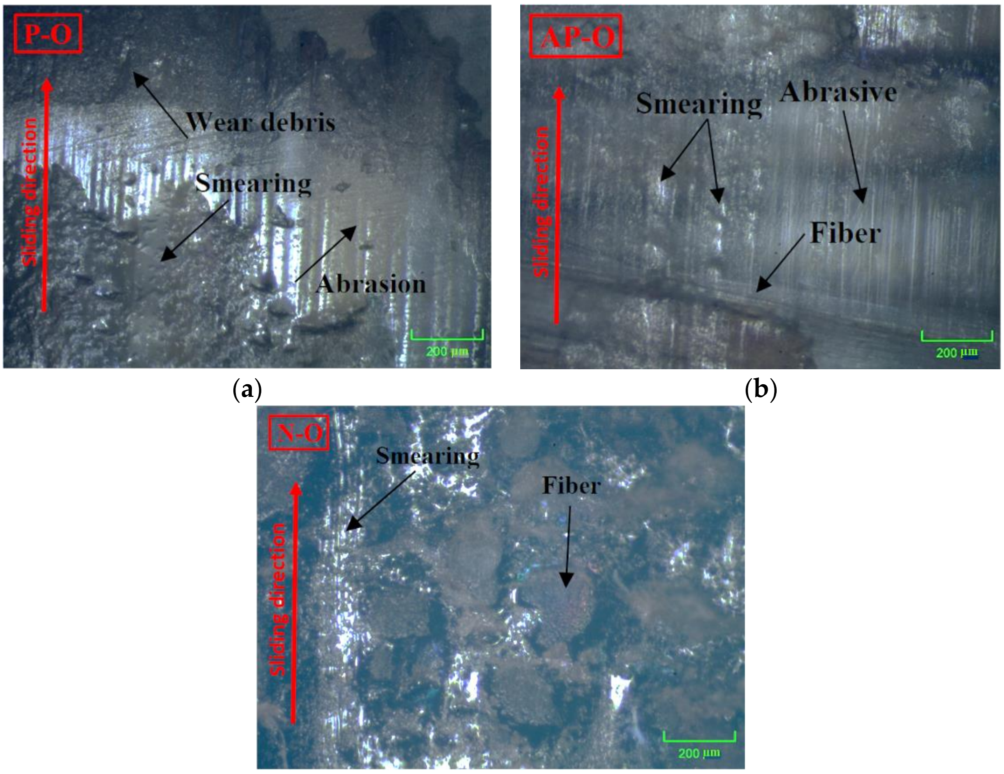
(**a**)

(**b**)

Figure 8. Specific wear rate of EACs and neat epoxy: (**a**) 35N applied load and (**b**) 45N applied load.

From Figure 8, it is noticeable that the tested samples made of neat epoxy have a significant trend of increasing the wear rate for all test conditions, which is also proven in the research of Kurien et al. [26]. It can easily be noticed that the values of the specific wear rate in samples with normal fiber orientation for the tested types of materials with 10 vol% and 20 vol% of abaca fiber are slightly expressed compared to samples with the other two orientations. However, there are no significant deviations in specific wear between samples of reinforced fibers.

Figure 9 shows wear track of the tested samples with (a) parallel-, (b) anti-parallel- and (c) normal-oriented abaca fibers. Wear tracks were analyzed by using optical microscopy. The analysis showed that the fibers in the wear tracks remained unbroken, i.e., that they were immersed in epoxy resin. During the sliding contact of the prepared samples and the steel disk, the contact layers of the tested composite are heated over time. The epoxy resin surrounding the fibers softens and smears [28]. In such conditions, the action of normal load ensures that fiber is immersed into the sample and it prevents cracks, which may occur with the parallel- and anti-parallel-oriented fibers. In the thin exit zone of the wear track, micro abrasion is observed, presented in Figure 9a,b. Figure 9a presents wear debris due to the accumulation of material in the zone where the disk leaves the wear track. The middle zone of the track is mainly covered with smeared epoxy resin. This confirms the irregular relief structure of the rounded shape of the wear track.



(**a**) (**b**)

(**c**)

Figure 9. Wear tracks of tested samples. (**a**) Parallel orientation, (**b**) anti-parallel orientation and (**c**) normal orientation, obtained by optical microscopy.

In the case of normal fiber orientation, it can be assumed that the applied normal load cannot push the fibers down into the softened surrounding epoxy, but that the fibers wear evenly during the sliding contact. This can be seen in Figure 9c, where the edge of the wear track and the cross-section of the wear track fiber to the edge itself are seen. Additionally, optical microscopy of all obtained wear tracks of the samples with normal-oriented fibers has not shown significant deviations in the appearance of the track, regardless of the proportion of abaca.

Analysis of the wear tracks of all tested samples, all fiber orientations and abaca contents by optical microscopy has not proven sufficient to adequately perceive the characteristic appearance of wear mechanisms, as is the case with metallic materials [29].

Based on the analysis of all obtained wear tracks and wear volume values, the presence of abaca significantly increases wear resistance. Improvements were achieved for the EAC10% samples, then even more significant for the EAC20% sample, but this trend did not continue for the EAC30% samples. The reason for this is undoubtedly structural imperfections in the form of gas bubbles, which become much more enunciated with an increase in the proportion of abaca in the matrix. The fibers are neither microscopically straight nor utterly parallel to each other, so they partially overlap and cross, making it impossible for the epoxy resin to penetrate such an "enclosed" space. With an increase in the volume fraction of abaca, the number of interactions between fibers increases and thus the number of structural imperfections within the obtained material increases. In the case of the EAC10% and EAC20% samples, the influence of abaca is more dominant on wear resistance compared to the presence of gas bubbles and, to some extent, cancels the negative influence of structural imperfections, which is not the case with the EAC30% samples. The application of the vacuum injection technique reduced the percentage of structural imperfections to a minimum, but they still exist, which is especially evident in the EAC30% samples.

4. Conclusions

The nature of tribological processes, which is accompanied by the appearance of friction and wear during exploitation, highlights the need to introduce new tribological knowledge and create new products and materials. One of the main goals regarding the development of society is the use of renewable energy sources, the use of recycled materials and the use of lighter materials. In order to solve the presented problems, from the aspect of tribology, new, tribologically advanced materials are being developed. Natural fiber composites have emerged as a significant class of material, giving engineers the ability to specify material characteristics as needed.

By comparing the obtained results of roughness parameters, it was found that the obtained values of surface roughness are relatively close to all tested materials, which also provided identical contact conditions for all experimental tests. This condition is very important because, in the initial period of contact, microgeometry and roughness of contact surfaces have a great influence on tribological phenomena, friction and wear.

Within the tribological tests, the characterization of tribological phenomena, friction and wear, according to the defined contact conditions, was performed on all materials being tested. By analyzing the results obtained using a tribometer, the following conclusions can be drawn:

- All samples had a trend of decreasing coefficient of friction with increasing applied load due to the influence of a third body in the contact zone. It is concluded that when increasing the sliding distance, the samples with anti-parallel-oriented fibers respecting the sliding direction had the highest coefficient of friction compared to other tested reinforced materials;
- Wear volume values had a trend of progressive growth with increasing values of normal load, in all types of tested materials;
- The lowest value of the wear rate was shown for epoxy resin reinforced with 20 vol% abaca, whereas samples with parallel-oriented fibers showed better wear resistance compared to other types of materials. The lowest wear resistance was shown by the samples made of neat epoxy;
- Experimental studies have shown that epoxy reinforced with a 20% volume fraction of abaca fibers has the best wear resistance and coefficient of friction.

In conclusion, this experimental research led to original results that will lay the foundation for all future tribological tests of natural composites, based on the prescribed methodology of laboratory tests presented in this paper. Additionally, this paper has made a significant contribution to the literature in the field of bio-tribology, which relates to the testing of materials based on epoxy resin reinforced with abaca fibers.

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References

1. Dawoud, M.M.; Saleh, H.M. Introductory Chapter: Background on Composite Materials. In *Characterizations of Some Composite Materials*; Chapter 1; Saleh, H., Ed.; Intech d.o.o: Rijeka, Croatia, 2018.
2. Marathe, U.; Bijwe, J. High performance polymer composites—Influence of processing technique on the fiber length and performance properties. *Wear* **2020**, *203189*, 446–447. [CrossRef]
3. Faruk, O.; Bledzki, A.K.; Fink, H.-P.; Sain, M. Biocomposites reinforced with natural fibers: 2000–2010. *Prog. Polym. Sci.* **2012**, *37*, 1552–1596. [CrossRef]
4. Sinha, A.K.; Narang, H.K.; Bhattacharya, S. Tensile Strength of Abaca Epoxy Laminated Composites. *Mater. Today Proc.* **2018**, *5*, 27861–27864. [CrossRef]
5. Vinod, B.; Anandajothi, M. Mechanical and Tribological Properties of Abaca-Roselle/Cardanol Formaldehyde Hybrid Composites. *Mater. Res. Express* **2020**, *6*, 125363. [CrossRef]
6. Narendiranath, B.T.; Himanth, K.T.; Sahith, K.; Kamal, B. Study on mechanical and tribological behaviour of sisal, abaca and sun-hemp hybrid reinforced epoxy composites. *Int. J. Mech. Eng. Technol.* **2018**, *9*, 865–875.
7. Kurien, R.A.; Selvaraj, D.P.; Sekar, M.; Rajasekar, R.; Koshy, C.P. Experimental Investigation on Tribological Characteristics of NaOH Treated Chopped Abaca Fiber Reinforced Epoxy Composites. *Mater. Sci. Forum* **2019**, *1019*, 25–31. [CrossRef]
8. Liu, Y.; Ma, Y.; Yu, J.; Zhuang, J.; Wu, S.; Tong, J. Development and characterization of alkali treated abaca fiber reinforced friction composites. *Compos. Interfaces* **2019**, *26*, 67–82. [CrossRef]
9. Punyamurthy, R.; Sampathkumar, D.; Ranganagowda, R.P.; Bennehalli, B.; Badyankal, P.; Venkateshappa, S.C. Surface modification of abaca fiber by benzene diazonium chloride treatment and its influence on tensile properties of abaca fiber reinforced polypropylene composites. *Ciência Tecnol. Dos Mater.* **2014**, *26*, 142–149. [CrossRef]
10. Barba, B.J.D.; Madrid, J.F.; Penaloza, D.P., Jr. A Review of Abaca Fiber-Reinforced Polymer Composites: Different Modes of Preparation and Their Applications. *J. Chil. Chem. Soc.* **2020**, *65*, 4919–4924. [CrossRef]
11. Tumolva, T.; Kubouchi, M.; Aoki, S.; Sakai, T. Effect of Fiber Loading on the Mechanical Strength of NFR Hybrid Composites. *ASEAN J. Chem. Eng.* **2010**, *10*, 22–27.
12. Valášek, P.; Müller, M.; Šleger, V.; Kolář, V.; Hromasová, M.; D'Amato, R.; Ruggiero, A. Influence of Alkali Treatment on the Microstructure and Mechanical Properties of Coir and Abaca Fibers. *Materials* **2021**, *14*, 2636. [CrossRef]
13. Cai, M.; Takagi, H.; Nakagaito, N.A.; Li, Y.; Waterhouse, I.N.G. Effect of alkali treatment on interfacial bonding in abaca fiber-reinforced composites. *Compos. Part A Appl. Sci. Manuf.* **2016**, *90*, 589–597. [CrossRef]
14. Venkatesan, K.; Bhaskar, G.B. Evaluation and Comparison of Mechanical Properties of Natural Fiber Abaca-sisal Composite. *Fibers Polym.* **2020**, *21*, 1523–1534. [CrossRef]
15. Bello, S.A.; Agunsoye, J.O.; Hassan, S.B.; Zebase Kana, M.G.; Raheem, I.A. Epoxy Resin Based Composites, Mechanical and Tribological Properties: A Review. *Tribol. Ind.* **2015**, *37*, 500–524.
16. Jagtap, S.B.; Srinivasa Rao, V.; Ratna, D. Preparation of flexible epoxy/claynanocomposites: Effect of preparationmethod, clay modifier and matrix ductility. *J. Reinf. Plast. Compos.* **2013**, *32*, 183–196. [CrossRef]
17. Milosevic, M.; Valášek, P.; Ruggiero, A. Tribology of Natural Fibers Composite Materials: An Overview. *Lubricants* **2020**, *8*, 42. [CrossRef]
18. Alshammari, F.Z.; Saleh, K.H.; Yousif, B.F.; Alajmi, A.; Shalwan, A.; Alotaibi, J.G. The influence of fibre orientation on tribological performance of jute fibre reinforced epoxy composites considering different mat orientations. *Tribol. Ind.* **2018**, *40*, 335–348. [CrossRef]
19. Valášek, P.; Ruggiero, A.; Müller, M. Experimental description of strength and tribological characteristic of EFB oil palm fibres/epoxy composites with technologically undemanding preparation. *Compos. Part B Eng.* **2017**, *122*, 79–88. [CrossRef]
20. Gupta, M.K.; Srivastava, R.K. Tribological and dynamic mechanical analysis of epoxy based hybrid sisal/jute composite. *Indian J. Eng. Mater. Sci.* **2016**, *23*, 37–44.
21. Chaudhary, V.; Bajpai, P.K.; Maheshwari, S. An Investigation on Wear and Dynamic Mechanical behavior of Jute/Hemp/Flax Reinforced Composites and Its Hybrids for Tribological Applications. *Fibers Polym.* **2018**, *19*, 403–415. [CrossRef]

22. Rao, C.H.C.; Madhusudan, S.; Raghavendra, G.; Rao, E.V. Investigation in to Wear behavior of coir Fiber Reinforced Epoxy Composites with the Taguchi Method. *Int. J. Eng. Res. Appl.* **2012**, *2*, 371–374.
23. Valášek, P.; D'Amato, R.; Müller, M.; Ruggiero, A. Mechanical properties and abrasive wear of white/brown coir epoxy composites. *Compos. Part B Eng.* **2018**, *146*, 88–97. [CrossRef]
24. Yousif, B.F.; Chin, C.W. Epoxy Composite Based On Kenaf Fibers for Tribological Applications under Wet Contact Conditions. *Surf. Rev. Lett.* **2012**, *19*, 1250050. [CrossRef]
25. Yogeshwaran, S.; Natrayan, L.; Udhayakumar, G.; Godwin, G.; Yuvaraj, L. Effect of waste tyre particles reinforcement on mechanical properties of jute and abaca fiber- epoxy hybrid composites with pre-treatment. *Mater. Today Proc.* **2021**, *37*, 1377–1380. [CrossRef]
26. Kurien, R.A.; Selvaraj, D.P.; Koshy, C.P. Worn Surface Morphological Characterization of NaOH-Treated Chopped Abaca Fiber Reinforced Epoxy Composites. *J. Bio- Tribo-Corros.* **2021**, *7*, 31. [CrossRef]
27. Tang, F.; Wu, X.; Ge, S.; Ye, J.; Zhu, H.; Hagiwara, M.; Schoenung, J. Dry sliding friction and wear properties of B4C particulate-reinforced Al-5083 matrix composites. *Wear* **2008**, *264*, 555–561. [CrossRef]
28. Helmy, O.M.; El-Hofy, M.H.; El-Hofy, H. Effect of cutting fluid delivery method on ultrasonic assisted edge trimming of multidirectional CFRP composites at different machining conditions. *Procedia CIRP* **2018**, *68*, 450–455. [CrossRef]
29. Babic, M.; Stojanovic, B.; Dzunic, D.; Pantic, M. Micro/nanoscale structural, mechanical and tribological characterization of ZA-27/SiC nanocomposites. *J. Compos. Mater.* **2020**, *54*, 2113–2129. [CrossRef]