Vol. 03, Iss. 1 (2025) 129-136, DOI: 10.61552/JME.2025.01.010

Journal of Materials and Engineering

www.jme.aspur.rs

Research article

Exploring Hybrid Composite Tribological Behaviour: An Insight into Material Characteristics and Performance

Abhinav[a]*, K.V. Manjunath[b], Soni[c]

[a]*Department of Mechanical Engineering, Dayanand Sagar Academy of Technology and Management, Bengaluru 560082, India,*
[b]*Vijaya Vittala Institute of Technology, Bengaluru 560077, India,*
[c]*Alliance University, Bengaluru 562106, India.*

Keywords:

Fibers
SEM
Tribology
Wear rate
Coefficient of friction (CoF)

* Corresponding author:

Abhinav
E-mail: abhinavtechno5@gmail.com

Received: 15 May 2024
Revised: 18 June 2024
Accepted: 7 July 2024

A B S T R A C T

Understanding the physio-technical characteristics of hybrid composites in terms of wear is essential for qualifying them for industrial tribological applications. A standard test according to ASTM G99 was performed on various types of laminated hybrid composites. Various synthetic fibers including e-glass, basalt, carbon, and aramid are blended with natural fibers such as jute (referred to as L1, L2, L3, and L4 respectively), and similarly, above synthetic fibers are also layered with hemp. The hybrid laminated composites were manufactured utilizing the hand lay-up method combined with vacuum bagging technique. Comparative studies were conducted under constant sliding distance and a 10 N load, with variable speeds set at 200, 300, and 400 rpm. The findings indicated that composites fabricated using hand layup and vacuum bagging techniques, particularly those of L3 and L4, exhibit reduced wear and specific wear rates. Reduced wear rate may be attributed to factors such as consistent fiber orientation, enhanced bonding observed in SEM analysis, optimal resin-to-fiber ratios, and decreased porosity. Also, the examination of wear mechanism and causative factors has been thoroughly explored, providing valuable insights for future investigations.

1. INTRODUCTION

Two surfaces, if rubbed on each other can result in the removal of the material in contact. This phenomenon is known as wear. It is a well-known fact that wear in metals happens through plastic deformation of surfaces producing wear debris [1]. The size of the particle usually varies from millimeters to nanometers [2]. The wear is a function of loading, (static or dynamic), impact, the type of motion, either sliding or rolling, lubrication and temperature. Hybrid composite materials with improved wear and friction properties are frequently used in applications like clutches, brakes, pistons, gears and biomedical implants [3]. Wear rate and coefficient of friction are the governing factors that decide the performance of natural fiber reinforced green composites components working under tribological conditions [4-9]. El-Tayeb [10] investigated the tribological properties of composites made using chopped and unidirectional sugarcane fiber. The research inferred that for adhesive wear applications, sugarcane reinforced polymer composites are preferred material. The adhesive wear features of kenaf fiber reinforced epoxy composite for bearing with antiparallel, normal, and parallel orientations of fibers was studied by Chin et al [11]. The group observed that after introducing kenaf fiber into epoxy, the tribological characteristics of the matrix material were enhanced. The composites with random orientation of kenaf fiber showed better wear resistance behaviour as compared to parallel and anti-parallel orientations. Bajpai and group [12] carried out a comparative study of the adhesive wear behavior of sisal, grewia optiva and nettle fiber reinforced with polypropylene (PP). Among these matrix, sisal/PP composite showed the highest specific wear rate, as in this case the wear debris of sisal fiber acted as abrasive particles which enhanced the wear rate. On the other hand, the wear rate of natural fiber reinforced polymer composite was lower than that of neat PP matrix, because of superior fiber-matrix bonding. Xin et al. [13] studied the wear behavior of resin brake composite reinforced with sisal fiber at different temperatures of counter disc (150, 250 and 350^{o}C). They developed the composites with different wt. % of fibers, i.e., 10, 15, 20, 25 and 30 wt. % and observed that for constant disc temperature, the wear rate of composites first increased up to 20 wt. % of fiber concentration and then reduced, whereas at constant weight % of fibers, wear rate of composites improved with the rise in disc temperature. This could be attributed to the breakage of sisal fiber at higher temperatures. Kumar and Rajesh [14] developed a banana fiber reinforced rubber composite. They concluded that banana fiber is a cost-effective way to increase the wear resistance properties of matrix material. Mishra and group [15] investigated the impact of fiber orientation on the wear characteristic of bagasse fiber reinforced epoxy composites under varying loads and observed that composites with normally oriented fibers had the lowest wear rate as compared to parallel and anti-parallel oriented fibers. While the wear rate of composites increased with increasing load, regardless of fiber orientation.

Exploring new perspectives in terms of tribological properties of hybrid composites is fascinating as well as inspiring. The fiber and matrix characteristics and their manufacturing processes, physical features, interfacial properties etc. impact the tribological performance of laminated composites a lot. The same is true in the case of hybridization of synthetic to natural fiber. Motivated by these facts, a thorough investigation has been done to understand the physio-technical characteristics of hybrid composites.

2. EXPERIMENTAL DETAILS

2.1 Arrangement of laminates

In the present investigation, eight types of laminated composites were developed. The number of layers in a laminated composite can be any appropriate number depending on the required total thickness of the laminate. Usually, the thickness of the laminated composite is limited by the manufacturing technology and requirements. It also depends on the level of residual stress. The arrangement of stacks in each type of laminate is shown in Fig. 1.” L” represents Laminate in the given figure.

The steps followed in the hand layup and Vacuum Bag techniques are shown in Fig.2 and 3 respectively. For the hand layup technique, anti-adhesive coating was done on the mold cavity and the gel coating was applied on the major portions. After that, layers of liquid matrix and reinforcement were laid layer by layer and finally the part is allowed to cure. Vacuum bag process removes the voids and air bubbles present in the moulds and largely produces high-quality composite materials.

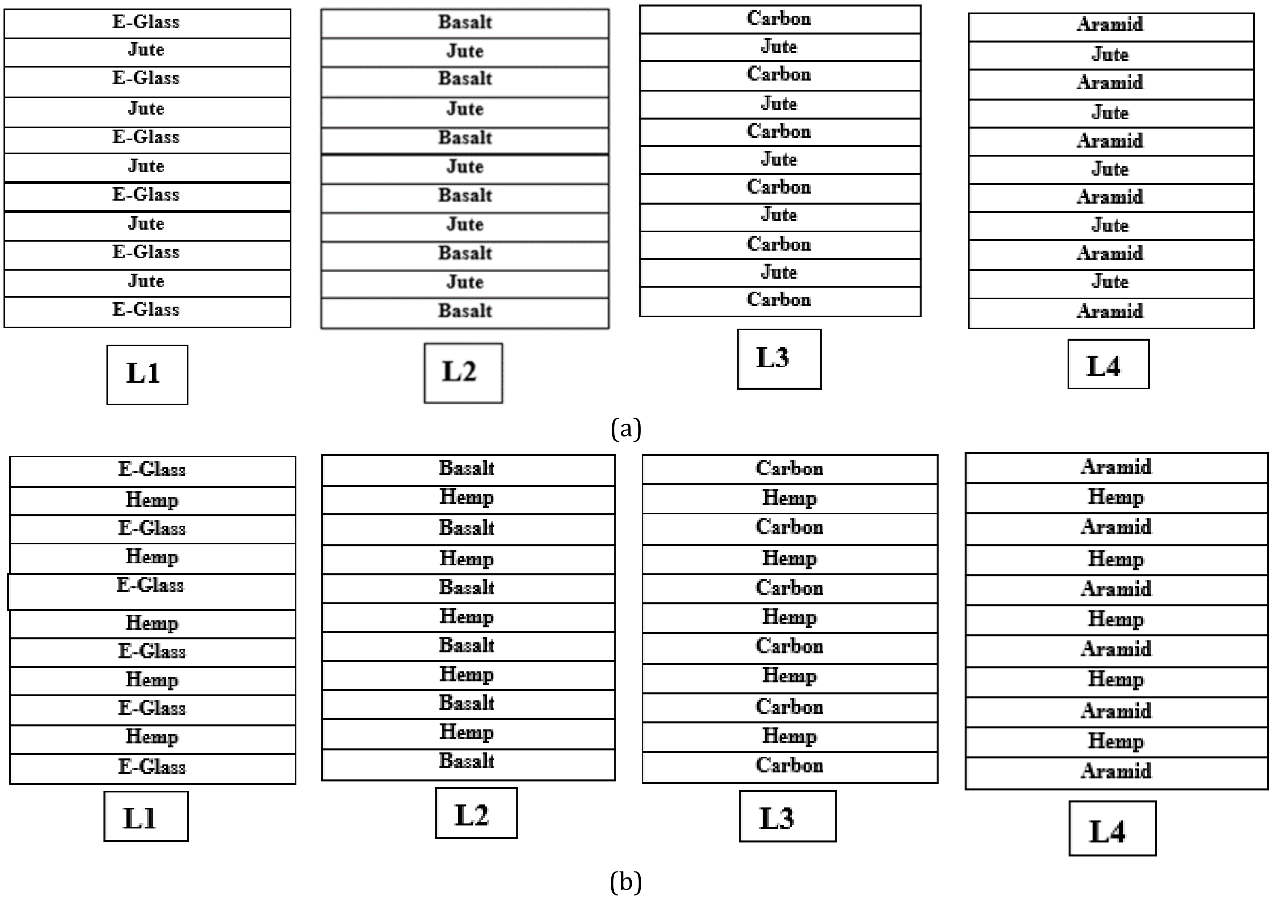

Fig .1. Arrangement of fiber mats (a) with jute as natural fiber (b) With hemp as natural fiber to develop laminated hybrid composites.

Fig. 2. Steps involved in the hand layup technique.

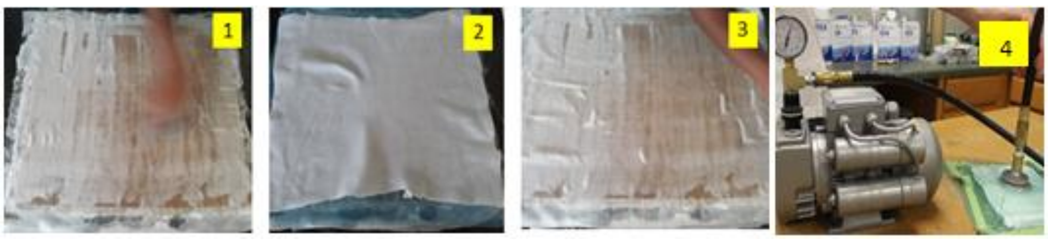

Fig. 3. Steps involved in the vacuum bag technique.

2.2 Wear test

The wear test samples were developed as per ASTM G99 [16] standards from different types of laminate and subjected to a sliding or adhesive wear test using a pin-on disc tribometer. The rest was conducted at room temperature. The load applied and distance travelled by the specimens was kept constant. Three trials of tests were carried out in each sample. The results of two similar trials were analyzed. The tribometer specifications and wear test parameters are represented in Table 1 & 2 respectively. The pictures of test specimens and wear testing machines are shown in Fig.4 & 5 respectively.

Table 1. Pin on Disc test rig specification.

Description	Details
Speed (rpm)	200 to 2000
Normal Load(N)	5 to 200
Friction force (N)	0.1 to 200
Wear (mm)	± 2
Wear track diameter (mm)	10 to 100
Sliding speed (m/sec)	0.5 to 10
pin size (mm)	Ø3,4,5,6,8,10 & 12
Wear disc	EN 31 Steel
Software	Winducom 2010
Software Interface	Comport RS 232 serial port

Table 2. Wear test parameters.

Test parameters for varying load test
Load 1kg(Constant), 200, 300, 400 rpm, constant sliding distance
Test duration = 15 minutes , Weight measured after completion of test
Wear track diameter = 120, 80 and 60mm
Test condition =No lubricant condition & at Ambient temperature
Environment = open to atmosphere , Humidity = 51.5%RH, Temperature = Ambient room temperature

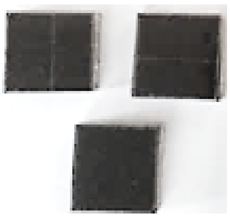

Fig. 4. Actual samples of wear test.

Fig. 5. Pin on Disc Machine with Specimen.

2.3 Structural investigation

The microstructure of the developed composites was studied through Scanning Electron Microscope (ZEISS EVO). The images were captured at 15 kV of acceleration potential.

3. RESULTS AND DISCUSSION

3.1 Wear and coefficient of friction

The study conducted wear tests on hand layup and vacuum bagging jute and hemp hybrid composites, varying speeds at 200, 300, and 400 rpm under a constant load of 10N. Fig 6a, 6b, 7a and 7b depict wear and coefficient of friction versus time graphs at 300 rpm for jute and hemp hybrid composites respectively, for hand layup method. For the jute hybrid composites, wear exhibits four stages, with an initial sudden increase attributed to surface spikes disappearing, followed by gradual linear wear as the matrix layer erodes, a sudden rise possibly due to fiber debonding, and finally a relatively constant wear as fiber-matrix composition resists wear. Similar trends are observed across other cases. Notably, L1 composite exhibits higher wear than L2, L3, and L4, likely due to weaker interfacial layer bonding. Conversely, L3 and L4, known for their superior mechanical characteristics, show lower wear. The reason could be attributed to better resin to fiber ratio, consistency in fiber orientation, reduced porosity and enhanced bonding etc.

Figure 8a, 8b, 9a and 9b shows the wear and coefficient of friction Vs time graphs for jute and hemp hybrid composites respectively, for vacuum bagging process. Hemp hybrid composites generally exhibit lower wear due to their better mechanical properties, especially evident in vacuum bagging composites. Coefficient of friction (CoF) graphs indicate initial spikes due to surface irregularities followed by stabilization once spikes wear out, with slight fluctuations likely due to worn-out matrix material exposing fibers. CoF decreases from L1 to L4, with vacuum bagging composites showing lower CoF, indicating better wear performance. Overall, vacuum bagging techniques yield composites with superior wear resistance, attributed to their better and smoother surface, which reduces localized wear points and friction, reduced porosity and air pockets.

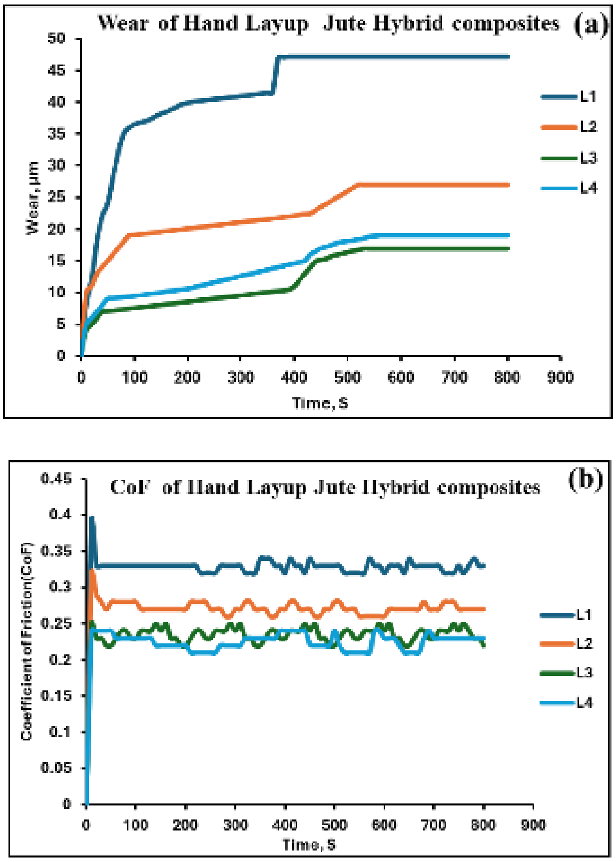

Fig. 6. (a) wear (b) Coefficient of Friction of Hand Layup Jute Hybrid composites at 300 rpm.

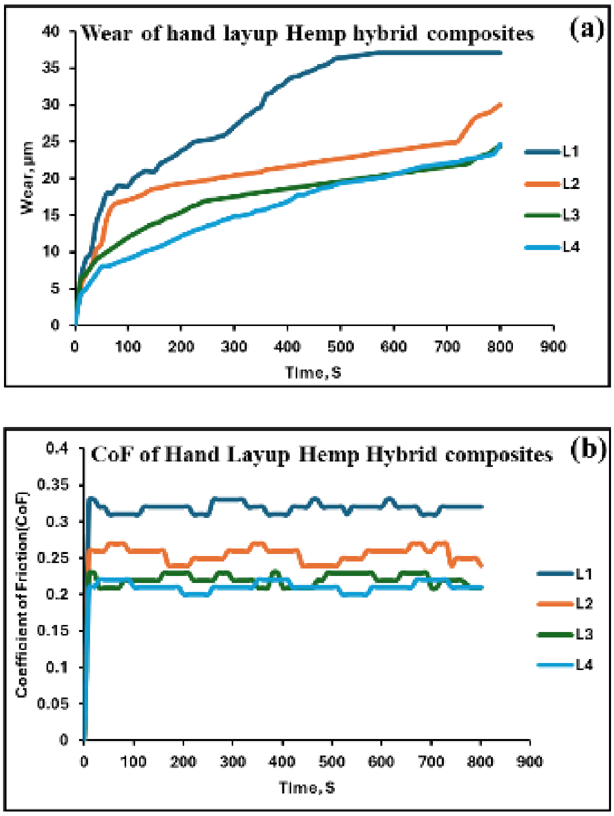

Fig. 7. (a) wear (b) Coefficient of Friction of Hand Layup Hemp Hybrid composites at 300 rpm.

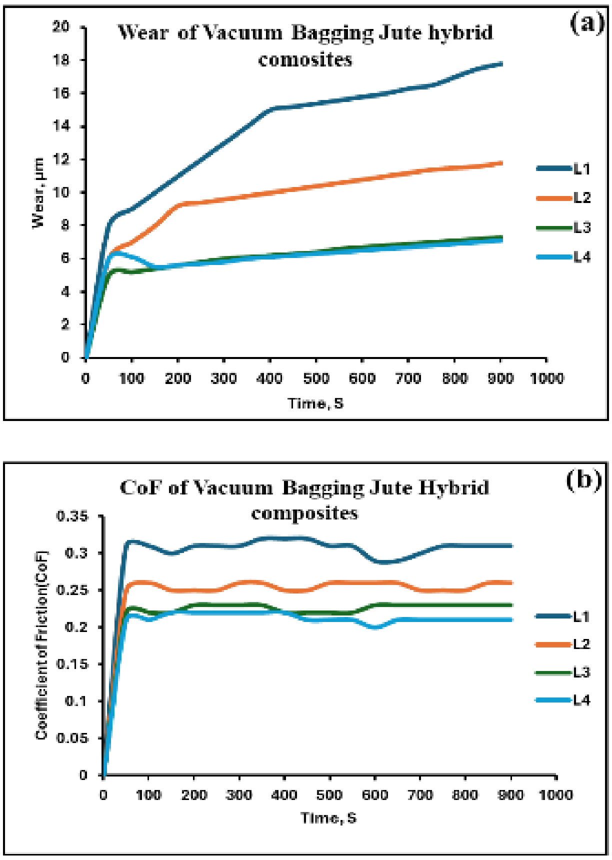

Fig. 8. (a) wear (b) Coefficient of Friction of Vacuum Bagging Jute Hybrid composites at 300 rpm.

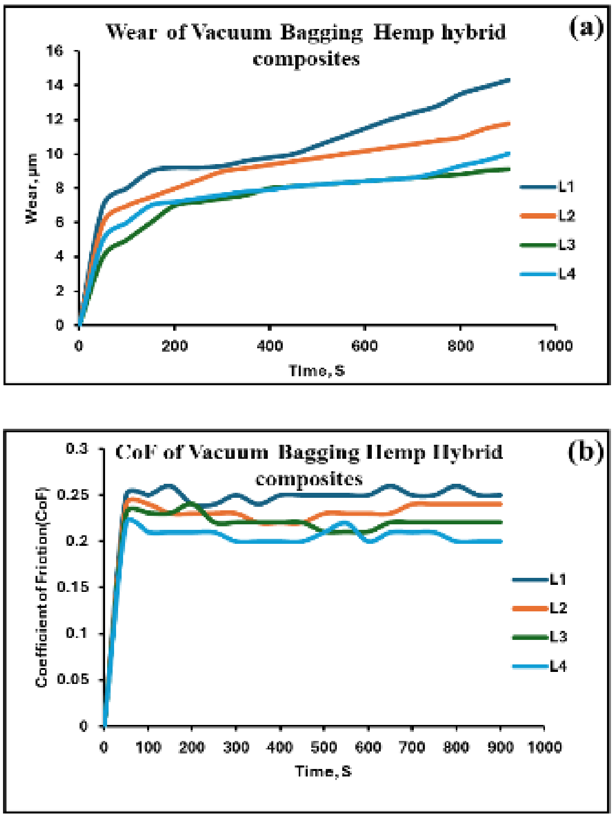

Fig. 9. (a) wear (b) Coefficient of Friction of Vacuum Bagging Hemp Hybrid composites at 300 rpm.

3.2. Effect of sliding speed on specific wear rate

The study highlights the wear resistance of laminated composites, particularly focusing on the specific wear rate measured in terms of volume loss per load applied and sliding distance. The wear rate of jute and hemp hybrid composites by hand layup and vacuum bagging at different sliding rates is tabulated in Table 3. The graphical representation of wear rate at different speed for different laminates of jute and hemp composites is shown in Fig. 10. The findings reveal that the specific wear rate generally increases with sliding speed across different composite types. However, both hand layup and vacuum bagging techniques show a decrease in wear rate for jute, hemp, and their hybrid composites, with vacuum bagging demonstrating superior performance. Notably, the L3 composite, especially when produced through vacuum bagging, exhibits the lowest specific wear rate. This reduction in wear rate is attributed to factors such as consistent fiber orientation, improved resin-to-fiber ratio, smoother surface finish, and enhanced bonding between layers. Additionally, the study identifies a mechanism involving the transfer of epoxy polymer layers during wear tests, which reduces the roughness of the metal disc and subsequently decreases contact between the composite pin and disc, thereby contributing to the wear resistance of L3 and L4 composites. These insights underscore the importance of manufacturing techniques and material composition in enhancing the wear resistance of laminated composites.

Table 3. Wear Rate of Laminated composites at different sliding speeds.

Natural fiber	Laminate type	Hand layup			Vacuum Bagging		
		Wear rate, x10^{-3}mm^3/Nm			Wear rate, x10^{-3}mm^3/Nm		
		200rpm	300rpm	400rpm	200rpm	300rpm	400rpm
Jute	L1	0.18	0.22	0.298	0.16	0.199	0.24
	L2	0.14	0.18	0.24	0.11	0.12	0.18
	L3	0.12	0.099	0.15	0.05	0.06	0.09
	L4	0.1	0.12	0.13	0.06	0.07	0.1
Hemp	L1	0.17	0.21	0.28	0.14	0.16	0.22
	L2	0.18	0.17	0.23	0.1	0.11	0.14
	L3	0.09	0.091	0.13	0.059	0.06	0.07
	L4	0.1	0.11	0.13	0.05	0.07	0.08

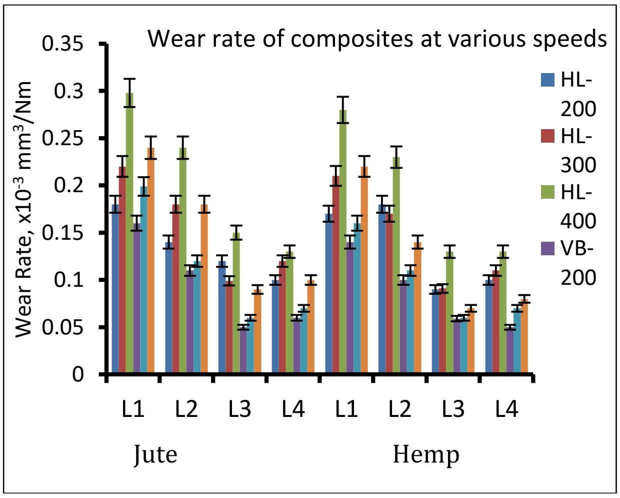

Fig. 10. Wear rate of laminated composites at 200, 300 and 400rpm.

3.3. SEM Morphology of worn-out surfaces

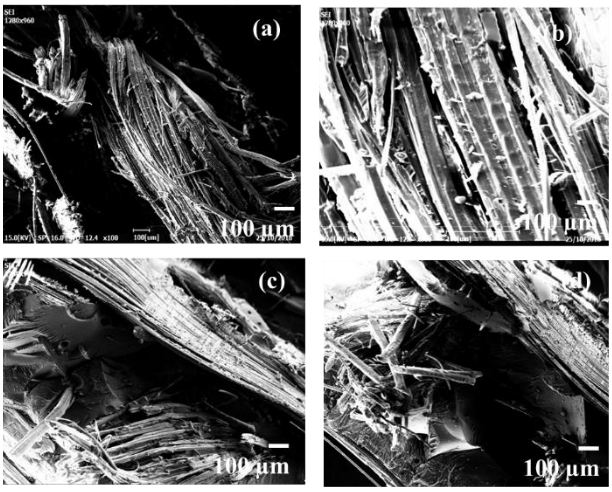

Fig. 11. SEM Micrographs of Fractured surfaces of a. L1 b. L2 c. L3 d. L4 Hand layup composites with Jute as natural fiber.

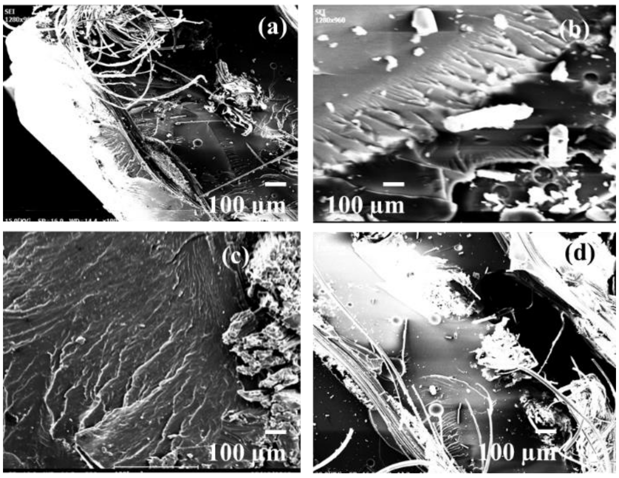

Fig. 12. SEM Micrographs of Fractured surfaces of a. L1 b. L2 c. L3 d. L4 Hand layup Composites with Hemp as Natural Fiber.

The SEM micrographs of worn-out surfaces of laminated composites reveal significant insights into the wear mechanisms and damage characteristics. The SEM images of worn-out surfaces for jute and hemp-based composites is shown in Fig. 11 and 12 respectively. Plastic deformation of the epoxy resin matrix, along with fiber damage and severe debonding, is evident. At higher sliding speeds, particularly 400 rpm, severe matrix deformation exposes fibers to the disc, leading to their damage and subsequent debonding. This results in pronounced delamination and increased wear in laminated composites, especially those produced by hand layup techniques due to higher void content and reduced compactness between the matrix and fiber. The predominant wear type observed is adhesive, attributed to temperature rise and matrix melting during rubbing action between the pin and disc. Poor bonding between fibers, uneven distribution of reinforcement, and void formation contribute to reduced mechanical strength. Microcracks on the matrix surface and at the fiber-matrix interface are observed, subjected to shear loading during sliding, leading to further fiber debonding and fracture. The SEM micrographs depict the deposition of damaged fibers on worn-out surfaces, with some regions showing support from the sublayer matrix. However, increased shear loading results in severe wear of the sublayer matrix, leading to complete fiber exposure and fracture.

4. CONCLUSIONS

1. The study comprehensively assessed wear characteristics of hand layup and vacuum bagging jute and hemp hybrid composites under varying speeds and loads, providing valuable insights into wear patterns and frictional behavior, crucial for material selection and performance optimization in practical applications.

2. SEM analysis elucidated the underlying mechanisms of wear in laminated composites, revealing significant plastic deformation of the epoxy resin matrix, fiber damage, and debonding, particularly pronounced at higher sliding speeds. Poor bonding between fibers, uneven distribution of reinforcement, and void formation were identified as contributing factors to reduced mechanical strength and increased wear susceptibility.
3. Vacuum bagging techniques exhibited superior wear resistance, attributed to factors such as consistent fiber orientation, improved resin-to-fiber ratio, smoother surface finish, and enhanced interlayer bonding, highlighting the significance of advanced manufacturing methods and material composition in mitigating wear-related degradation and extending the lifespan of laminated composites in various engineering applications.

REFERENCES

[1] J. E. Merwin and K. L. Johnson, "An Analysis of Plastic Deformation in Rolling Contact," *Proceedings of the Institution of Mechanical Engineers*, vol. 177, no. 1, pp. 676-690, 1963, doi: 10.1243/PIME_PROC_1963_177_052_02.

[2] "Ecofuel and its compatibility with different automotive metals to assess diesel engine durability," *Advances in Eco-Fuels for a Sustainable Environment*, pp. 337-351, 2019, doi: 10.1016/b978-0-08-102728-8.00012-7.

[3] T. G. Yashas Gowda, M. R. Sanjay, et al., "Tribological applications of polymer composites," in *Tribology of Polymer Composites*, Elsevier, 2021, pp. 355-368, ISBN: 9780128197677, doi: 10.1016/B978-0-12-819767-7.00017-7.

[4] V. Yadav, S. Singh, N. Chaudhary, M. P. Garg, S. Sharma, A. Kumar, and C. Li, "Dry sliding wear

characteristics of natural fibre reinforced poly-lactic acid composites for engineering applications: Fabrication, properties and characterizations," *Journal of Materials Research and Technology*, vol. 23, pp. 1189-1203, 2023, doi: 10.1016/j.jmrt.2023.01.006.

[5] M. Milosevic, P. Valášek, and A. Ruggiero, "Tribology of Natural Fibers Composite Materials: An Overview," *Lubricants*, vol. 42, pp. 1-20, 2020, doi: 10.3390/lubricants8040042.

[6] E. Omrani, P. L. Menezes, and P. K. Rohatgi, "State of Art on Tribological Behavior of Polymer Matrix Composites Reinforced with Natural Fibers in the Green Materials World," *Engineering Science and Technology, an International Journal*, vol. 19, pp. 717-736, 2015, doi: 10.1016/j.jestch.2015.10.007.

[7] K. Mohan and T. Rajmohan, "Tribological characteristics of natural fiber composite-Review," in *IOP Conference Series: Materials Science and Engineering*, vol. 954, pp. 012048, 2020, doi: 10.1088/1757-899X/954/1/012048.

[8] C. J. Silva, A. G. Barbosa de Lima, et al., "Water Absorption in Caroa-Fiber Reinforced Polymer Composite at Different Temperatures: A Theoretical Investigation," *Diffusion Foundations*, vol. 10, pp. 16-27, 2017.

[9] P. K. Bajpai, I. Singh, and J. Madaan, "Tribological behavior of natural fibre reinforced PLA composites," *Wear*, vol. 297, pp. 829-840, 2013.

[10] N. S. M. El-Tayeb, "Tribo-characterization of natural fibre reinforced polymer composite material," *Proc IME J J Eng Tribol*, vol. 222, no. 7, pp. 935-946, 2008.

[11] C. W. Chin and B. F. Yousif, "Potential of kenaf fibres as reinforcement for tribological applications," *Wear*, vol. 267, pp. 1550-1557, 2009.

[12] P. K. Bajpai, I. Singh, and J. Madaan, "Frictional and adhesive wear performance of natural fibre reinforced polypropylene composites," *Proc IME J J Eng Tribol*, vol. 227, no. 4, pp. 385-392, 2013.

[13] X. Xin, C. G. Xu, and L. F. Qing, "Friction properties of sisal fibre reinforced resin brake composites," *Wear*, vol. 262, no. 5-6, pp. 736-741, 2007.

[14] R. G. Kumar and D. R. Rajesh, "A study on the abrasion resistance, compressive strength and hardness of banana fibre reinforced natural rubber composites," *Int. J. Adv. Res. En. Technol.*, vol. 7, no. 3, pp. 42-55, 2016.

[15] P. Mishra and S. K. Acharya, "Anisotropy abrasive wear behavior of bagasse fibre reinforced polymer composite," *Int. J. Eng. Sci. Technol.*, vol. 2, no. 11, pp. 110-112, 2010.

[16] D. Amrishraj and T. Senthilvelan, "Dry Sliding wear behavior of ABS Composites reinforced with nano Zirconia and PTFE," *Materials Today: Proceedings*, vol. 5, no. 2, part 2, pp. 7068-7077, 2018, doi: 10.1016/j.matpr.2017.11.371.