Research Article

Journal of Environmental Nanotechnology

Influences of Hybrid Fiber on Functional and Drilling Characteristics of Polymer Hybrid Nanocomposite

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Received: 27.07.2024 Accepted: 25.09.2024 Published: 30.09.2024
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ABSTRACT

The severe environmental pollution related to the manufacturing, recycling and disposal of metal-based and synthetic fiber-based composites has a major impact on human and animal life. A wide range of studies are conducted on alternative materials in order to reduce greenhouse gas emissions. Various industries are focusing on using natural fibers from banana, jute, coir, hemp, pineapple, areca, kenaf, *Sterculia foetida* and *Delonix regia* that are the key sources of different components for developing nanocomposites. Drilling is a vital factor in the assembly process of composites. The amorphous structure of the natural fibers causes the formation of cracks at the entry and exit sides of the drilled hole. So, in the present work a nanocomposite was synthesized and optimized the machining parameters, which affect the surface finish of the hole at the entry, exit and inner surface of the drilled hole. The effect of the hybridization of glass fiber with the pineapple leaf fiber and areca fiber was studied in terms of tensile properties, delamination around the hole and surface roughness. The microstructure of the holes was studied by Scanning Electron Microscopy.

Keywords: Natural fibers; Glass fiber; Hybridization; Nanocomposite; Drilling; Optimization.

1. INTRODUCTION

Nowadays, the production rate of synthetic fibers is gradually reduced due to the lack of availability of crude oils and mineral oils. The fibers derived from them create environmental pollution and also the disposal, recycling and functional processes produce high amounts of greenhouse gases that directly affect humans and animals (Malik *et al.* 2022; Narayanan *et al.* 2024). Thus, the majority of industries such as aerospace, automotive, marine, civil, and manufacturing of goods and chemicals show interest towards advanced lightweight nanocomposite materials. The lignocellulosic material production rate is increased year by year by using natural agricultural resources instead of artificially produced fibers (Najeeb *et al.* 2021; J *et al.* 2023). Pineapple is one of the widely cultivated fruits in India. The leaf of the pineapple tree has excellent surface properties such as higher surface area and high stiffness, thus promoting its use as the reinforcement material in nanocomposite preparation (Hashim *et al.* 2022). The areca fibers used as the reinforcement with epoxy matrix obtained higher strength properties and low moisture absorption characteristics, due to the non-wettability behavior of areca fiber. The drilling study in bidirectional oriented hybrid fiber reinforced polymer nanocomposites is predominant due to several factors affecting the hole quality such as fiber composition, stacking sequence, volume fraction of composites, speed of drill bit and hole diameter (Vankanti *et al.* 2014). The study made by various researchers stated that the feed rate at 0.3 mm/rev and cutting speed ranging 1000-2000 rpm showed better surface quality. In drilling of woven fiber reinforced polymer composites, interlaminar shear strength plays an important role (Helmi Abdul Kudus *et al.* 2021). It increases the structural integrity of the composites thus increasing the resistance against the tool force, vibration and penetration (Lazar *et al.* 2011). The heat developed in the cutting tool is greatly reduced for the composites with cellulosic fibers (Rezghi Maleki *et al.* 2019). The natural fibers offer good strength and biodegradable nature as advantages. The composite natural fiber developed exhibits better mechanical behaviour, which when featured with nanoparticle finds superior enhancement in tensile and flexural strength (De Poures *et al.* 2024). Polyethylene is light weight and displays good mechanical behaviour. Moreover, hybrid polymer composite shows excellent mechanical and wear behaviour, which could be further be used for light weight applications.

Therefore, the current study focuses on evaluating the effect of fiber hybridization, fiber arrangements and fiber orientation on the tensile characterization and machining optimization of polymer nanocomposites. The fabrication of nanocomposites through compression molding technique and drilling on these fabricated laminates using computer controlled numerical machine was performed. Finally, the analysis of drilling operation on hybrid composites using Taguchi method was done in order to eliminate poor surface finish.

Table 1. Properties of the reinforcement and matrix materials (Hashim *et al.* 2022; Narayanan *et al.* 2024)

Raw Material Used	Density, g/cm³	Diameter µm	Tensile Strength, MPa	Young's Modulus, GPa	Percentage Elongation	Water Absorption, %
PALF	0.95 - 1.53	65 - 95	290 - 330	5.38 - 9.68	3.1 - 6.9	0.7 - 1.21
Glass Fiber	2.4 - 2.9	10 - 28	2000 - 3500	70 - 86	2.5 - 3	-
Areca	0.7 - 0.95	30 - 48	140 - 325	2.3 - 3.2	3.0 - 11	0.8 - 7.3
Epoxy	1.25 - 1.42	-	34 - 115	2.5 - 7.8	0.8 - 6	0.12 - 0.47

2. MATERIALS AND METHODS

2.1 Nanocomposite Fabrication

The areca, pineapple leaf fiber (PALF) and glass fibers were cut according to the mold size of 300 mm × 300 mm. The epoxy polymer and the corresponding hardener were mixed as per the standard ratio of 10:1. Table 1 shows the properties of the materials used in this study

The compression mold process was used for fabricating three different hybrid composites. Initially, the mold was heated to 140-180 °C and the pre-impregnated layups were prepared inside the mold cavity. Then, the mold was closed with minimum pressure and was kept for about 15 minutes. Later, the cooled and cured nanocomposite laminate was removed from the mold. The nanocomposite layup sequence and designation of each nanocomposite is given in Table 2. The nanocomposite with glass/areca/epoxy (GA-B) after fabrication is shown in Fig.1.

Table 2. Designation and fiber arrangements in each composite

Nanocomposite	Fiber arrangements
GP-A	G+P+P+G
GA-B	G+A+A+G
GPA-C	G+P+A+G

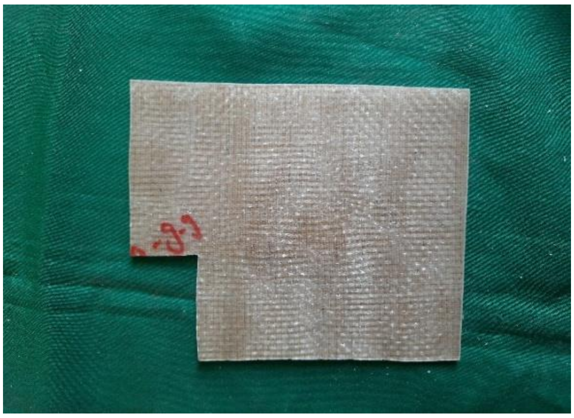

Fig. 1: Fabricated nanocomposite GA-B

2.2 Drilling of Nanocomposite and Optimization by Taguchi Method

The fabricated hybrid nanocomposite laminates were drilled using computer controlled numerical machine under four different process parameters with three levels as shown in Table 3. The composite laminates were placed over the wooden plate at the fixture in order to increase resistance against the drilling force during the exit of drill bit at bottom of the laminate. The present work uses ANOVA from the Taguchi experimental design for determining the most influencing parameters with optimal levels. The Minitab software was used for analyzing the variance and the Signal to Noise ratio (S/N ratio). The L9 orthogonal array for selected parameters and levels are shown in Table 4.

Table 3. Parameters and levels used in drilling

Level	Drilling speed rpm P_1	Feed rate mm/rev P_2	Diameter of the hole mm P_3	Composite type (Fiber composition) P_4
1	1000	0.05	5	GP-A (G+P+P+G)
2	1500	0.1	7.5	GA-B (G+A+A+G)
3	2000	0.15	10	GPA-C (G+P+A+G)

Table 4. L9 array with factors and levels

Experiment	L_9 Orthogonal array				L_9 array with factors and levels			
	P_1	P_2	P_3	P_4	P_1	P_2	P_3	P_4
1	1	1	1	1	1000	0.05	5	GP-A
2	1	2	2	2	1000	0.1	7.5	GA-B
3	1	3	3	3	1000	0.15	10	GPA-C
4	2	1	2	3	1500	0.05	7.5	GPA-C
5	2	2	3	1	1500	0.1	10	GP-A
6	2	3	1	2	1500	0.15	5	GA-B
7	3	1	3	2	2000	0.05	10	GA-B
8	3	2	1	3	2000	0.1	5	GPA-C
9	3	3	2	1	2000	0.15	7.5	GP-A

2.3 Mechanical and Drilling Characterization

The tensile strength and Young's modulus of the hybrid nanocomposites were determined using the universal testing machine at a cross head speed of 2 mm/min. The prepared specimens as per the ASTM D638 standard are shown in Fig. 2. The effect of layup sequence, fiber orientation and hybridization was analyzed in terms of bonding, uniform distribution, fiber and matrix gap, fiber breakage during tensile test, matrix crack propagation through a high resolution Scanning Electron Microscope (SEM). The quality of the drilled holes was examined for surface roughness, surface deviations around the entry and exit side of the hole. The surface waviness was analyzed using the Surfcoder surface roughness tester. Delamination of the hole was determined using the machine vision software by importing the high resolution picture of the hole. The ratio between the actual diameter of the hole and the maximum deviation of the hole measured was used to determine the delamination. In each experiment, three holes were drilled and totally, 27 holes were analyzed in order to determine the average values.

Fig. 2: Tensile specimens prepared according to ASTM D638 standard

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

The pineapple leaf fiber with glass fiber polymer composites (GP-A) showed higher tensile strength than the areca and glass composites and pineapple/areca/glass composites (Fig. 3). The stacking sequence and fiber composition showed variations in the tensile strength of the composites fabricated in this study. Four layers of pineapple in between glass fiber mats (GP-A) exhibited 38.5 - 43.6% higher tensile strength while the areca fiber (GA-B) and areca/PALF at middle (GPA-C) exhibited lower values. This is due to the higher surface area of the PALF fiber that improved the interlocking and reduced the gap between the fiber and matrix at interface. In a recent study, non-woven hemp and glass fiber composites were shown to display a tensile strength in the range 58-81 MPa (Singh *et al.* 2023). The unidirectional PALF fiber reinforced hybrid composite displayed 21.6 - 43.7% lower tensile strength than that observed in the present work. The bidirectional fiber reinforcement was found to increase the load bearing capacity in both perpendicular and parallel directions of the force acting.

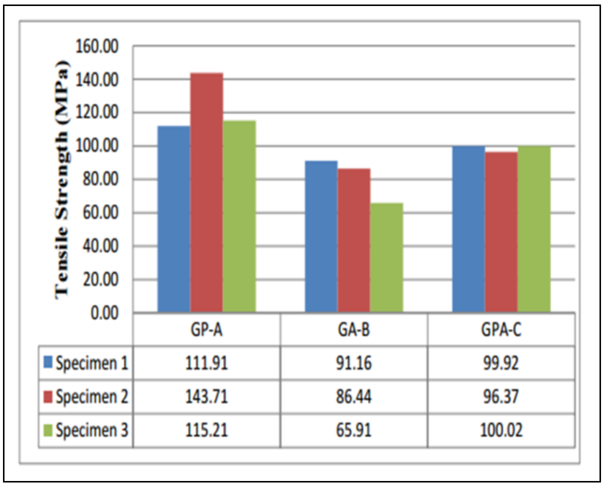

Fig. 3: Tensile strength of the hybrid composites

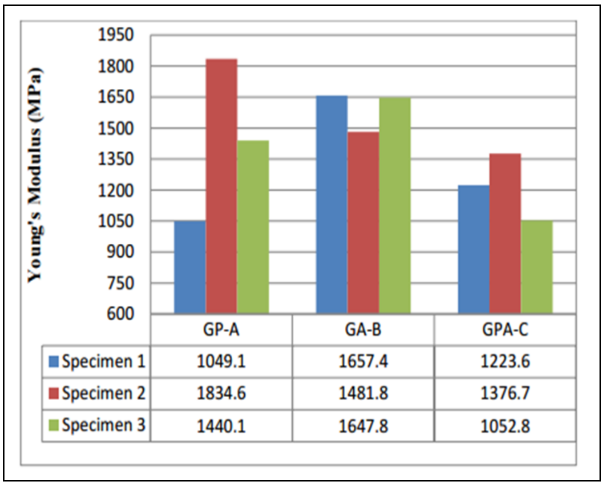

Fig. 4: Young's modulus of the hybrid composites

The modulus of the composites is directly dependent on the maximum elongation observed at the breaking point during tensile load acting on it. From Fig. 4, it is seen that the Young's modulus is higher for the PALF/glass composites than the composite consisting areca/glass and PALF/areca/glass fibers. The reason behind this phenomenon is higher frictional resistance between the hybrid PALF/Glass fibers with matrix against the deformation of the molecules inside the composites (Boopathi *et al.* 2023). The areca/glass/epoxy composites used in this present work showed 10-30 % higher Young's modulus than that of flax fiber with glass and epoxy studied by (Ismail *et al.* 2022). Table 5 shows the tensile properties obtained for the composites fabricated in the present study.

Table 5. Tensile properties of the hybrid polymer composites

Fiber Type	Sample ID	Tensile Strength (MPa)	Average Tensile Strength (MPa)	Elongation at Breakage (%)	Average Elongation at Breakage (%)	Young's Modulus 'E' at Breaking (MPa)	Average 'E' at Breaking (MPa)
GP-A	A1	111.91	123.61	10.67	8.83	1049.125	1441.852
	A2	143.71		7.83		1834.578	
	A3	115.21		8		1440.086	
GA-B	B1	91.158	81.169	5.5	4.92	1657.417	1595.663
	B2	86.439		5.83		1481.808	
	B3	65.911		4		1647.764	
GPA-C	C1	99.923	98.771	8.17	8.22	1223.551	1217.698
	C2	96.371		7		1376.734	
	C3	100.02		9.5		1052.809	

3.2 Scanning Electron Microscopic Analysis

The SEM investigation on the hybrid bidirectional nanocomposites shows that the complete peeling of fiber takes place during tensile test. It shows the successful distribution of stress at the interface region of the composites as shown in the Fig. 5. It is noted that during the breaking of areca/glass composites, the fiber breakage from matrix occurs (Fig. 6) without peeling due to less or elastic behavior of areca fiber (Jothibasu *et al.* 2020). The glass with both the natural fibers shows fiber agglomeration and fiber bundle formation (Fig. 7) because of the higher amorphous content in cellulose fibers.

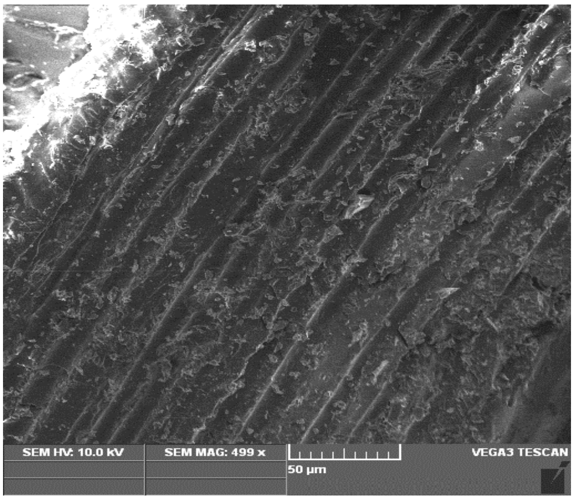

Fig. 5: Microstructure of Glass/PALF/Epoxy composite

3.3 Microstructure of Glass/Areca/ PALF/Epoxy composite

The surface waviness throughout the surface of the drilled hole and cracks at tip of the holes was analyzed using the ANOVA optimization technique. The response table and primary main effect plot for S/N ratio on their effect on the drilling process were produced.

3.3.1 Surface Roughness

The surface roughness (Ra) of the composites was noted directly on the display unit of the Tokyo surfcoder surface roughness instrument. Table 6 shows the surface waviness in terms of Ra and corresponding S/N ratio.

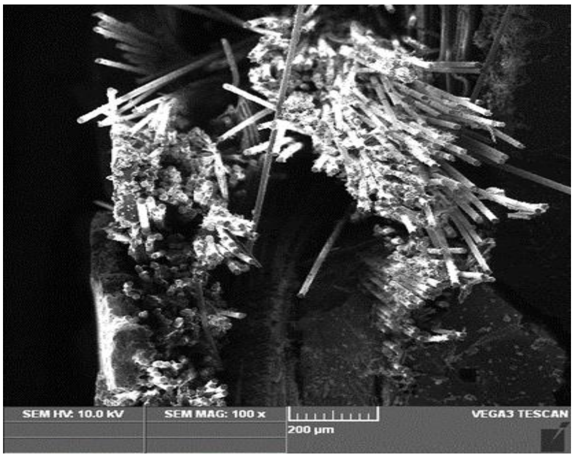

Fig. 6: Microstructure of Glass/Areca/Epoxy composite

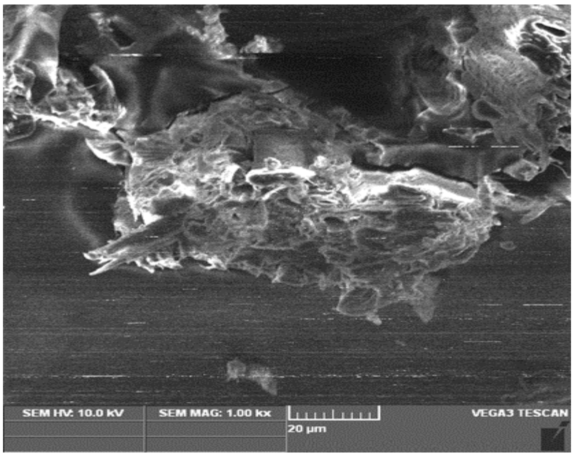

Fig. 7: Microstructure of Glass/Areca/ PALF/Epoxy composite

Table 6. Experimental value and SN ratios for surface roughness

Experiment	P_1 Speed (rpm)	P_2 Feed (mm/rev)	P_3 Drilling Bit Dia (mm)	P_4 Composite	Surface Roughness (Ra) Trial 1	Trial 2	Trial 3	Avg	SNRA1
1	1000	0.05	5	GP-A	1	5.38	2.29	2.89	2.89
2	1000	0.1	7.5	GA-B	7.54	6.38	5.39	6.436667	6.44
3	1000	0.15	10	GPA-C	1.33	1.19	0.72	1.08	1.08
4	1500	0.05	7.5	GPA-C	1.13	0.92	1.58	1.21	1.21
5	1500	0.1	10	GP-A	2.9	1.83	2.15	2.293333	2.93
6	1500	0.15	5	GA-B	5.18	3.51	4.45	4.38	4.38
7	2000	0.05	10	GA-B	6.69	6.92	7.11	6.906667	6.91
8	2000	0.1	5	GPA-C	3.11	2.14	2.07	2.44	2.44
9	2000	0.15	7.5	GP-A	2.93	6.01	2.11	3.683333	3.68

The response table (Table 7) shows the optimized parameters and the levels for the surface roughness. The fiber combination in the composites has a major influence on achieving the good surface finish in drilling (Fig. 8). The nanocomposite with the both PALF and areca seems to have optimal parameters as it offers low resistance against drill bit rotation. Also, it resulted in a smoother surface than the other two types of composites (Mahadevappa *et al.* 2020). Speed is an important parameter in drilling of bidirectional hybrid fiber reinforced polymer composites. At lower speed (1000 rpm considered in this work), the GPA-C nanocomposite displayed lower surface roughness while at a higher speed (2000 rpm) the GP-A showed lower surface roughness. From this, it is noted that the individual properties of fiber play important role in the drilling process. Higher properties of the fiber tend to resist the force to a greater extent (Mohan Kumar *et al.* 2021).

Table 7. Response Table for SN Ratios – Surface Roughness

Level	Speed (rpm)	Feed (mm/rev)	Drilling Bit Dia (mm)	Nanocomposite type
1	8.688	9.221	9.932	9.957
2	4.941	11.088	9.717	15.266
3	11.951	8.272	8.932	3.357
Delta Δ	4.011	2.816	1.000	11.908
Rank	2	3	4	1

The drill bit diameter did not show any variation in the surface roughness of the hybrid composites. (Kiran *et al.* 2020) showed that the drilled hole quality of sisal/ glass/ epoxy and sisal/ glass/ polypropylene composites has a discontinuous chip formation due to the brittle nature of the fiber. Also, the hybridization of fibers reduced the heat produced during drilling at higher spindle speed thus resulting in a better surface finish. Similar results were observed in the present study.

3.3.2 Delamination

The deviations in the circularity at the entry and exit side of the hole is determined using the machine vision LABVIEW software. The measured experimental delamination and the corresponding SN ratios for both the peel-up and push-down delamination are collected in Tables 8 and 9, respectively.

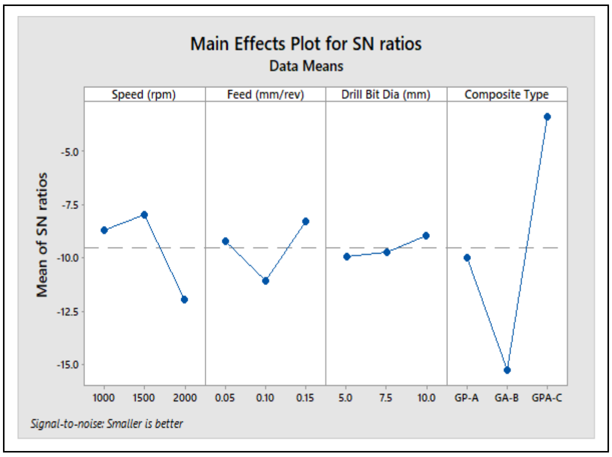

Fig. 8: SN ratios of surface roughness

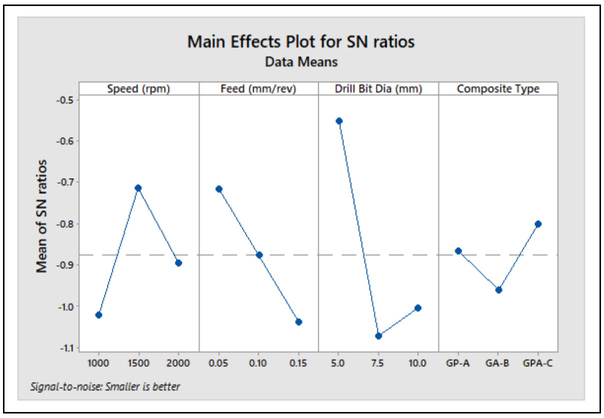

Fig. 9: SN Ratios of peel up delamination

The influence of process parameters considered in this present work for both the peel up and push down delamination is ranked based on the S/N ratio obtained for each experiment as shown in the Tables 10 and 11, respectively. The drilling with 7.5 mm drill bit produced less damage than other drill bits (5 mm and 10 mm) considered. The delamination observed at the entry side was slightly larger compared to that at the exit side. It is due to placing the wooden plate at the bottom of the work material. The resistance offered by the nanocomposite laminate is maintained as it enters the specimen throughout the drilled hole. Secondly, the feed rate contributes to the formation of delamination around the hole. Feed at 0.05 mm/min caused lesser deviations. When increasing the feed to 1 mm/min and 0.15 mm/min the deviations slightly increased. The slow movement of drill bit induces less force on the work surface thus results in the good surface finish at entry and exit of hole. Similar results were obtained when experiments were conducted on drilling of hemp/flax fiber composites (Díaz-Álvarez *et al.* 2018; Saraswati *et al.* 2019). The back support reduced the bending stress developed by the drill bit due to the interlaminar strength of the bidirectional fiber composites (Athijayamani *et al.* 2022). Table 12 provides the significant parameters and their optimal values to control the damage of the hybrid composites.

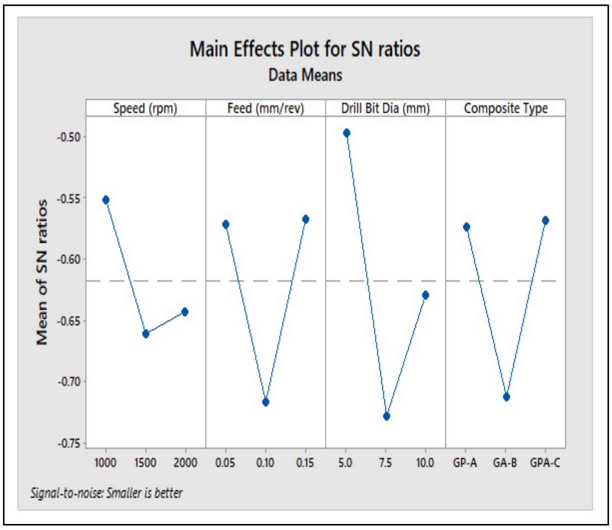

Fig. 10: SN Ratios of push down delamination

Table 8. Experimental value and SN Ratios for Peel up delamination

Experi-ment	P1 Speed (rpm)	P2 Feed (mm/rev)	P3 Milling Cutter Dia (mm)	P4 Comp osite	Delamination Factor (Peel up) DF-entry				
					Trial 1	Trial 2	Trial 3	Avg	SNRA1
1	1000	0.05	5	GP-A	1.03397	1.089172	1.063694	1.062279	-0.52477
2	1000	0.1	7.5	GA-B	1.18259	1.161359	1.140127	1.161359	-1.29933
3	1000	0.15	10	GPA-C	1.178344	1.129512	1.150743	1.152866	-1.23558
4	1500	0.05	7.5	GPA-C	1.082803	1.067941	1.091295	1.080679	-0.67394
5	1500	0.1	10	GP-A	1.097665	1.104034	1.099788	1.100495	-0.83176
6	1500	0.15	5	GA-B	1.072187	1.078556	1.076433	1.075725	-0.63403
7	2000	0.05	10	GA-B	1.112527	1.116773	1.116773	1.115357	-0.94828
8	2000	0.1	5	GPA-C	1.050955	1.048832	1.076433	1.05874	-0.49579
9	2000	0.15	7.5	GP-A	1.165605	1.150743	1.144374	1.153574	-1.24091

Table 9. Experimental value and SN Ratios for push down delamination

Experi-ment	P1 Speed (rpm)	P2 Feed (mm/rev)	P3 Milling Cutter Dia (mm)	P4 Composite	Delamination Factor (Push down) DF-exit				
					Trial 1	Trial 2	Trial 3	Avg	SNRA1
1	1000	0.05	5	GP-A	1.053079	1.03397	1.031847	1.039632	-0.33759
2	1000	0.1	7.5	GA-B	1.104034	1.093418	1.112527	1.103326	-0.85408
3	1000	0.15	10	GPA-C	1.059448	1.050955	1.053079	1.054494	-0.46088
4	1500	0.05	7.5	GPA-C	1.091295	1.078556	1.072187	1.080679	-0.67394
5	1500	0.1	10	GP-A	1.082803	1.093418	1.084926	1.087049	-0.72498
6	1500	0.15	5	GA-B	1.067941	1.097665	1.042463	1.069356	-0.58245
7	2000	0.05	10	GA-B	1.078556	1.082803	1.091295	1.084218	-0.70233
8	2000	0.1	5	GPA-C	1.082803	1.078556	1.042463	1.067941	-0.57094
9	2000	0.15	7.5	GP-A	1.078556	1.099788	1.057325	1.078556	-0.65686

Table 10. Response Table for SN Ratios – Peel up Delamination

Level	Speed (rpm)	Feed (mm/rev)	Drill bit Dia (mm)	Composite
1	1.126	1.086	1.066	1.105
2	1.086	1.107	1.132	1.117
3	1.109	1.127	1.123	13097
Delta Δ	0.040	0.041	0.066	0.020
Rank	3	2	1	4

Table 11. Response Table for SN Ratios – Push down Delamination

Level	Speed (rpm)	Feed (mm/rev)	Drill bit Dia (mm)	Composite
1	0.5509	0.5713	0.4970	0.5731
2	0.6605	0.7167	0.7283	0.7130
3	0.6434	0.5667	0.6294	0.5686
Delta Δ	0.1096	0.1499	0.2313	0.1444
Rank	4	2	1	3

Table 12. Parameters contributing to the hole quality of drilled composites

Experimental Specimen Details	Most contributed Order	Surface Roughness		Peel Up Delamination		Push Down Delamination	
		Most contributed Parameter	Optimal Value of Parameter	Most contributed Parameter	Optimal Value of Parameter	Most contributed Parameter	Optimal Value of Parameter
Pine Apple Leaf Fiber /Epoxy, Areca Fiber / Epoxy and Glass Fiber / Epoxy	1	Composite	GPA-C	Hole Diameter	5 mm	Hole Diameter	5 mm
	2	Speed	1500 rpm	Feed	0.05 mm/rev	Feed	0.05 mm/rev
	3	Feed	0.15 mm/rev	Speed	1500 rpm	Composite	GPA-C

4. CONCLUSION

The study investigates the effect of incorporating glass fibers with natural fibers such as PALF and areca fiber on the tensile properties and drilling characterization of hybrid polymer composites. The consequence of fiber composition for the surface waviness and the delamination around the hole was analyzed. It was found that the nanocomposite with the PALF/glass fibers showed higher tensile strength than the composites with areca fibers. The higher surface area of the fibers and hybridization of glass fiber with the natural fibers confirmed a well-bonded fiber/matrix interface. The selection of drill diameter was crucial in measuring the drilling quality of the composites. Overall, drilling bit speed at 1500 rpm, feed rate at 0.5 mm/min, and nanocomposite with Glass/PALF/Areca displayed the optimal machining parameters in drilling with the aid of back support at the bottom of the nanocomposite laminate. The damage and cracks at the exit side of the drilled hole were reduced as compared to the entry side of the hole. In order to eliminate the rejection during the nanocomposite component assembly, the drill bit diameters and the fiber stacking sequence should be considered carefully.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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