

OPTIMIZATION OF DRILLING PARAMETERS TO REDUCE DELAMINATION IN ABACA-SISAL FIBER EPOXY COMPOSITES

Venkatasudhahar Murugesan^{1,*}, Dharmalingam Ganesan¹, and Purusothaman Mani²

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Abstract

Delamination became a prominent issue during the Computer Numerical Controlled Vertical Milling Machine (CNCVMM) drilling of natural hybrid composite materials. This study aims to investigate the influences of machining parameters such as drilling speed, feed and diameter on Abaca-Sisal fiber reinforced Epoxy Hybrid Composites (ASEHC) during drilling, with a focus on minimizing the delamination factor. Delamination occurrences were carefully examined using a profile projector at both the top and bottom of the drilled holes. Identifying of the optimal machining parameters is key for justifying delamination of ASEHC composites. Taguchi orthogonal array used in the present work. This method allows testing multiple parameters in a structured way without needing to run every possible combination. The key parameters examined in this work included Spindle Speeds 3000, 2000, and 1000 revolutions per minute (rpm), Feed Rates 30, 20, and 10 millimeters per minute (mm/min) and Drilling Diameters 12, 10, and 8 millimeters (mm). The Scanning Electron Microscopic (SEM) analysis were performed the surface morphology of the drilled holes. The optimized drilling process parameters were significantly reduced on the delamination of the ASEHC; Delamination was reduced by 94% under optimal parameters leading to a better performance and durability of the composites.

Keywords: Abaca fiber-Sisal fiber; Delamination factor; Drilling; Optimization

Introduction

The natural fiber reinforced composites (NFRCS) have wide engineering applications, particularly in automotive, aircraft, spaceship, and shipbuilding. Natural fibers hold numerous advantages over synthetic ones: eco-friendly, minimal health hazards, lesser density, low cost, biodegradability, and availability (Raja *et al.*, 2024). Their notable advantages, including high specific strength, corrosion resistance, lightweight construction, low thermal conductivity, and high fatigue strength, make them preferable over alternative materials (Hassan *et al.*, 2020).

¹ Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai 600062, Tamil Nadu, India. Email: venkatasudhahar@gmail.com^{*}; dharmad1sona@gmail.com

² Department of Mechanical Engineering, Sathyabama Institute of Science and Technology, Chennai 600119, Tamil Nadu, India. Email: purusothamani@gmail.com

^{*} Corresponding author

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The mechanical tests were carried out on natural fibers subject to various treatment conditions (Yang *et al.*, 2024). The alkaline treatment conditions of NaOH concentration, soaking time, and drying time were optimized using a Box-Behnken design (Chen *et al.*, 2017). It was found that the treatment variables were significantly involved in the mechanical properties of the natural fiber reinforced epoxy composite (Bibin *et al.*, 2023). However, deformation occurs at the entry and exit points during the drilling processes on these composites (Ferreira *et al.*, 2019). A study was conducted to investigate the material characteristics and addressed these issues. To deal with these concerns, an experimental investigation was undertaken on various NFCs, with varying cutting parameters such as speed, feed, drill sizes, and specimen thickness (Thomas *et al.*, 2019; Venkatasudhahar *et al.*, 2021). The analysis considered abaca fiber composites, applying force and torque during drilling, impacting both entry and exit deformations based on fiber volume fractions (Liu *et al.*, 2018; Yuvaraju *et al.*, 2021). Various drill bits were examined and compared to analyze delamination in drilled composites, focusing on twist drills. The study evaluated the impact of cutting parameters and different drill geometries on defects, emphasizing HSS four-flute drills for NFC composites (Kassaw and Ayele, 2024). Delamination in composite laminates was assessed through Taguchi and ANOVA approaches, establishing connections between speed, feed, and optimal cutting parameters (Murugesan *et al.*, 2022). The 3D surface roughness plots illustrate the effects of the hardness in the foam and the feed rate, spindle speed, and tool path on the yields of surface roughness (Navaneethakrishnan *et al.*, 2020). FT-IR analysis revealed the presence of cellulose and lignin, cross-linked phenol polymers in fiber and particles, which strengthens the bonding between fibers and particles with epoxy resin (Chengoue *et al.*, 2023). The results of ANOVA analysis revealed that feed rate plays a very important role in minimizing burr height, followed by point angle (Anggoro *et al.*, 2021). A thorough investigation into delamination involved different drills, feed rates, and speeds (Roy Choudhury *et al.*, 2018). The microstructure analysis results found that the presence of voids and contaminants in the specimens had a negative impact on the mechanical properties of the composites, as resulted by specimens containing contaminants and voids having low mechanical properties (Wardhono *et al.*, 2020). The contaminants and voids did degrade the mechanical properties of the material (Haniel *et al.*, 2023). The spindle speeds, feed rates, and drilling diameters are selected based on quality of drilled

holes in composite materials, depending on various factors, including composite type, material composition, and presence of premature failures (Thakre and Soni, 2016; Ganesan *et al.*, 2023). Some factors can be controlled, while others act as variables (Patel *et al.*, 2018; Balaji *et al.*, 2022). While drilling studies on natural fibers exist, limited work has addressed hybrid composites using Taguchi optimization to reduce delamination.

A novel experimental work involves a hybrid composite created through compression molding. This composite combines abaca and sisal fibers with varying stacking sequences. The study's objective is to examine the effects of cutting parameters (feed, speed, and drill bit diameter) on delamination in the ASEHC. The experimental analysis utilized Taguchi and ANOVA methods.

Materials and Methods

Details of machining and its materials

In this experimental investigation, the ASEHC were fabricated through compression molding using woven abaca/sisal fiber-reinforced epoxy resin. The test specimens were prepared as per ASTM standards: ASTM D256 for the impact test, ASTM D790 for the flexural test, and ASTM D638 for the tensile test. The tests were conducted using a Universal Testing Machine and a Charpy Impact Tester (Saminathan *et al.*, 2022). Various tests were conducted and found the ultimate tensile, flexural, and impact strength of 300 MPa, 250 MPa, and 20 Joules, respectively. The drilling tests and drill hole quality were observed using a CNC VMM equipped with a Fanuc controller and VMM, as illustrated in Figures 1 and 2. The key parameters examined in this work included spindle speeds of 3000, 2000, and 1000 revolutions per minute (rpm). The feed rates and drilling diameters used were 30, 20, and 10 mm/min, and 12, 10, and 8 mm, respectively. In this study, the drilling operations were performed using



Figure 1. CNCVMM with Fanuc controller

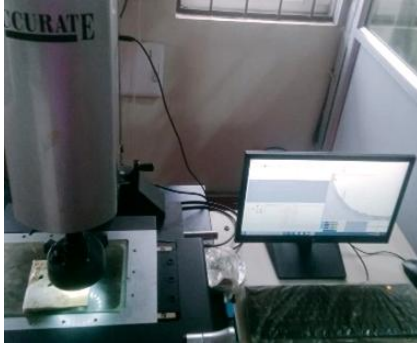


Figure 2. CNCVMM with Fanuc controller

a High-Speed Steel (HSS) drill bit with a point angle of 118° , which is widely used for general-purpose machining due to its effective cutting and centering capabilities. The drill had a helix angle of 30° and a standard two-flute spiral geometry with a straight shank. To improve wear resistance and reduce friction during cutting, the tool was coated with Titanium Nitride (TiN), known for its excellent thermal stability and surface hardness.

Figure 3 displays the fibers employed in the composite materials. The VMM was used to measure and evaluate the damaged parts of the materials to understand the extent and nature of the damage (Saminathan *et al.*, 2022). The VMM provided clear images of the damaged areas. The results showed variations in the damage levels across different sections, which were documented for further review.



Figure 3. ASEHC composite material

Calculation of Delamination Factor

During the drilling process of the ASEHC composite materials, the primary problem toward delamination was identified at both the top and bottom of the drilled hole (Rezghi Maleki *et al.*, 2018). The delamination was measured & calculated with the following equation determining its value (Dilfi *et al.*, 2018).

$$F_d = \frac{D_{drill}}{D_{max}} \quad (1)$$

Where, D_{drill} is the drill size, and D_{max} is the maximum diameter.

Experimental Design by Using the Taguchi Approach

Conventional experimental design approaches are often very complex and challenging to implement. Furthermore, these methods demand extensive experiments, especially when dealing with an increased number of parameters (Kuo *et al.*, 2017). Taguchi developed the experimental design methodology, a potent tool for crafting high-quality systems, to streamline the experimental process and minimize the required tests (Malik *et al.*, 2022). Traditional experimental design methods tend to be intricate and become more challenging as the number of parameters grows (Mishra *et al.*, 2018; Khan *et al.*, 2020). The Taguchi method was employed to achieve high-quality designs, thereby reducing the number of required tests (Omrani *et al.*, 2017; Shetty *et al.*, 2017). The Taguchi method was applied to analyze the experimental results, and the Signal-to-Noise (S/N) ratios were calculated using the “smaller-the-better” criterion, as the primary objective was to minimize delamination during drilling. During this experimentation, three machining variables were utilized as control factors, each associated with three levels for every parameter, denoted as 1, 2, and 3, as outlined in Table 1.

Table 1. Drilling input values

Parameters & level	Level 1	Level 2	Level 3
Cuttingspeed in rpm	1000	2000	3000
Feed in mm/min	10	20	30
diameter in mm	8	10	12

The analysis of mean response and variation for each run is to be chosen appropriately by signal-to-noise ratio S/N.

Using the quadratic loss function, S/N ratios are derived, of which three (Eqs. 2, 3, and 4) are widely applicable.

$$\text{- for nominal: } \frac{S}{N} = 10 \log \frac{y^{-2}}{s^2} \quad (2)$$

$$\text{- for lower: } \frac{S}{N} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 = 1 \frac{1}{y^2} \right) \quad (3)$$

$$\text{- for higher: } \frac{S}{N} = -10 \log \frac{1}{n} \left(\sum \frac{1}{y^2} \right) \quad (4)$$

In the provided formula, y denotes the observed average data, s^2 represents the variance in y , and n signifies the number of experiments. Using

the Taguchi method, multiple experiments were systematically monitored and performed to examine the relationship between the process parameters and the output responses, as detailed in Table 2 (Prabakaran *et al.*, 2023a).

The lowest S/N ratio indicates superior performance, as evident in Table 2, regardless of the outward appearance of the results. Consequently, minimal process variations were associated with a favorable S/N ratio (Lau *et al.*, 2018). Using variance analysis, the contributions of individual factors, the effects of observed values, and their interactions were thoroughly examined. The software Design of Expert was employed for graphical and regression analyses of the delamination factor and its associated parameters (Prabakaran *et al.*, 2023b).

Results and Discussions

The experimental results were validated through the design of the experiment and compared with theoretical and experimental values. A machining test was conducted to assess the damage to the workpiece and surface roughness of drilled holes

under the influence of cutting parameters. Utilizing a Vision Measuring Machine, deformations around the holes were quantified. The Dmax around damaged holes were measured, and the delamination factor was computed using Eq. 1. Table 2 presents the deformation factor values at entry and exit points, considering speed and feed rates. The S/N ratio in Taguchi's method serves as a metric for quality measurement and deviation from a specified value. Mean S/N ratio values, referred here as L27 of experiments, were computed by the summarizing of cutting parameters and cut depth. Table 3 displays the results of L27 S/N values for each experiment, calculated using Eq. 3. Delamination during both entry and exit were observed at a feed rate of level 1 (10 m/min), a cutting speed of 3000 rpm, and an 8 mm drill diameter. ANOVA was utilized to more precisely determine delamination factors associated with cutting parameters. Table 3 details the outcomes of deformation or delamination during drilling in ASEHC. The factor of deformation or delamination during feeding exhibits a substantial impact, accounting for 93.70% at the entry point and 51.65% at the exit point. Additionally, cutting speed influences the delamination factor, contributing

Table 2. An orthogonal array of Taguchi L27 experimental input /output values

Exp. number	Cutting speed in RPM	Feed in mm/min	Diameter in mm	Delamination		Signal-to-Noise Ratio	
				at entry	at exit	at entry	at exit
1	1000	10	8	0.98	1.01	-1.61	-1.74
2	1000	10	10	0.99	1.01	-2.15	-2.50
3	1000	10	12	0.99	1.01	-2.57	-2.97
4	1000	20	8	0.99	1.01	-1.95	-1.88
5	1000	20	10	0.99	1.01	-2.52	-2.93
6	1000	20	12	0.99	1.01	-2.93	-3.16
7	1000	30	8	0.99	1.01	-2.08	-2.08
8	1000	30	10	1.01	1.01	-2.71	-2.96
9	1000	30	12	1.01	1.01	-3.06	-3.26
10	2000	10	8	1.01	0.94	-2.17	-2.58
11	2000	10	10	1.01	0.95	-2.95	-3.36
12	2000	10	12	1.01	0.95	-3.19	-3.96
13	2000	20	8	1.01	0.96	-2.26	-2.98
14	2000	20	10	1.01	0.97	-2.94	-3.76
15	2000	20	12	1.01	0.97	-3.33	-4.26
16	2000	30	8	1.02	0.98	-2.52	-3.05
17	2000	30	10	1.02	0.98	-3.08	-3.97
18	2000	30	12	1.04	0.99	-3.56	-4.46
19	3000	10	8	1.00	1.00	-2.79	-3.55
20	3000	10	10	0.99	1.01	-3.16	-4.16
21	3000	10	12	0.99	1.01	-3.74	-4.77
22	3000	20	8	0.99	1.01	-2.88	-3.75
23	3000	20	10	0.99	1.02	-3.25	-4.46
24	3000	20	12	1.01	1.02	-3.96	-5.10
25	3000	30	8	1.01	1.02	-2.91	-4.35
26	3000	30	10	1.01	1.03	-3.35	-5.26
27	3000	30	12	1.01	1.03	-3.94	-5.80

4.85% at the entry and 43.43% at the exit. Despite the noise, the significance of $F = 96.05$ underscores its significance, with only a 0.01% likelihood of occurring. Consequently, both speed (A) and feed (B) demonstrate similar effects. The R^2 value of 0.9709 is considered reasonable, with an adjusted R^2 value of 0.9875. The S/N ratio's precision exceeding 4 signifies discrimination in an adequate model.

The influence of drilling parameters on delamination was analyzed by considering the underlying physical mechanisms associated with each factor. An increase in feed rate led to higher thrust force generation, which promotes delamination, particularly at the hole exit, due to push-out effects. The elevated force caused greater interlaminar stresses in the composites, resulting in fiber-matrix separation. In contrast, a higher spindle speed reduced the tool-composite interaction time per revolution, thereby minimizing the peel-up effect at the hole entry. The reduced contact duration

at higher speeds also helps in decreasing the heat buildup and friction, contributing to lower delamination. Regarding drill diameter, larger diameters tend to produce higher thrust forces due to increased contact area, which can intensify delamination damage if not compensated by appropriate tool geometry or cutting conditions. Understanding these parameter effects is essential for optimizing drilling performance and minimizing damage in composite materials.

In the above Figure 4, it is observed that the increase in cutting speed reduces the signal-to-noise ratio and improves the drill hole quality. Whereas drill tool diameter increases with decreases in the signal-to-noise ratio and also decreases the hole quality, similarly increasing the feed rate and also behaving in the same pattern on signal-to-noise ratio and quality of the drilled hole.

The value of $\text{Prop} > F$, Which is less than 0.05, is shown in Table 4, and is significant and advisable. So, both speed (A) and feed (B) are similar in these

Table 3. The signal-to-noise ratio for the delamination factor

Symbol	Cutting conditions	Mean S/N ratio		
		Level 1	Level 2	Level 3
At Entrance				
A	Cutting speed in rpm	-2.398	-2.889	-3.331
B	Feed in mm/min	-2.703	-2.891	-3.023
C	Diameter in mm	-2.352	-2.901	-3.364
At Exit				
A	Cutting speed in rpm	-2.609	-3.598	-4.578
B	Feed in mm/min	-3.288	-3.587	-3.91
C	Diameter in m	-2.884	-3.707	-4.193

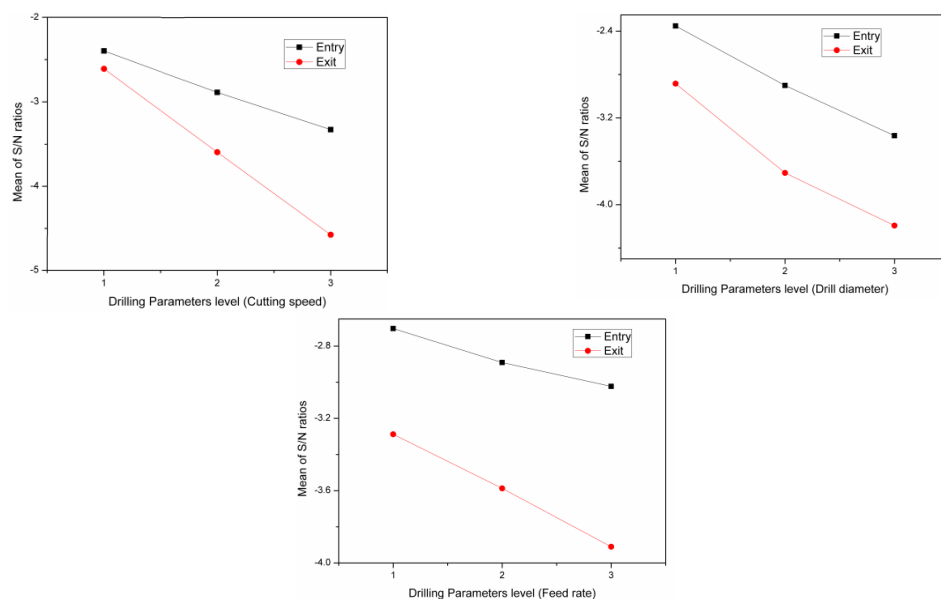


Figure 4. Influence of machining parameters on defects

terms. The value of F (29.85) it indicates a significant model, with only a 0.01% chance that the result is due signal to noise ratio.

The predicted and adjusted R^2 values (0.8789 predicted and 0.9145 adjusted) are reasonable. Consequently, the S/N ratio, with a precision ratio exceeding 4, indicates discrimination in an adequate model. In this case, the adequate signal registers at 19.561, suggesting the design's suitability for route design space. The negligible 0.01% probability of obtaining a high 'f' value is attributed to noise. The predicted and adjusted R^2 values (0.9605 predicted and 0.9145 adjusted) further affirm the model's reliability. The impact of machining parameters and the residuals for the normal probability is as depicted in Figures 4 and 5, respectively. In this delamination, peel-up and push-out also increase with higher feed and diameters, and vice versa. However, as the spindle speed is raised, the delamination decreased. Conversely, the quality of the drilling and the holes in the composites was enhanced by reduced drill diameter, increased feed rate, and spindle speed. A three-dimensional response graph illustrates how delamination varies when drilling into composite materials. The straight-line pattern of the residuals indicates normally distributed errors. Delamination levels were minimized at entry and exit points with a

minimum feed of 10 mm/min, a cutting speed of 3000 rpm, and an 8 mm drill bit diameter.

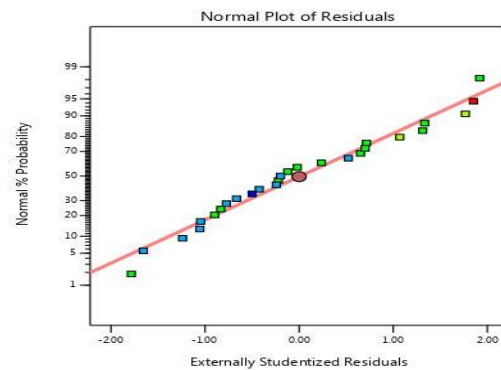


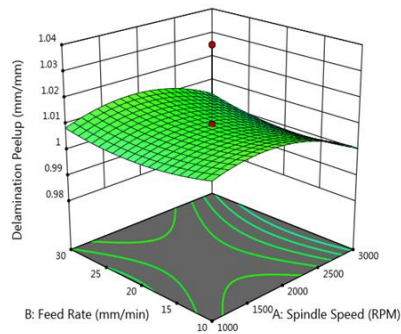
Figure 5. Residuals vs. normal probability plot during drilling

3-Dimensional response graphs are shown in Figure 6 for delamination, peel-up, and push-out. The observed feed rate was a critical factor compared to the other two drilling parameters, which were spindle speed and tool diameter. An increase in feed rate and drill diameter results in higher peel-up and push-out delamination, whereas a decrease leads to reduced delamination. However, delamination was reduced when the spindle speed was increased. Meanwhile, decreased drill diameter

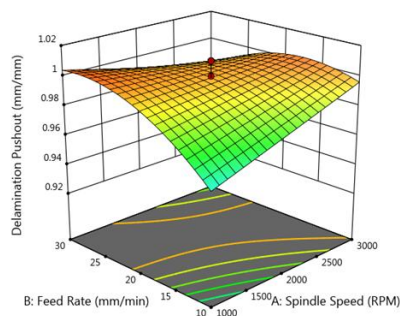
Table 4. ANOVA experimental analysis

Source of variance	SDQ	DF	MS	F-value	Prop > F	Contribution (%)
Entrance						
Model	0.29	9	0.054	96.05	<0.0001	Significant
speed in rpm	0.026	3	3.978E-003	11.87	0.0035	4.85
Feed in mm/min	0.20	3	0.084	180.95	<0.0001	93.70
Diameter in mm	0.25	3	0.095	220.75		1.45
Error	3.555E-003	17	3.792E-004			100.0
Total	0.48	26				
S.D.	0.020	C.V.	1.61	R^2	0.9955	Predicted R^2
Mean	1.44	PRESS	0.020	Adjusted R^2	0.9875	Adequate precision
Exit						
Model	0.35	9	0.057	29.85	0.43	Significant
speed in RPM	0.17	3	0.049	26.87	0.15	43.43
Feed in mm/min	0.19	3	0.059	31.95	0.28	51.65
Diameter in mm	0.21	3	0.085	40.15	0.019	5.92
Error	0.019	17	1.95E-003		0.44	100.0
Total	0.45	26				
S.D.	0.055	C.V.	2.61	R^2	0.9605	Predicted R^2
Mean	1.70	PRESS	0.060	Adjusted R^2	0.9145	Adequate precision

and feed rate, and increased spindle speed improved the quality of drilling and the holes in composites. The delamination variation during drilling in composites is as shown in a 3-dimensional response graph.



(a) Delamination Peelup



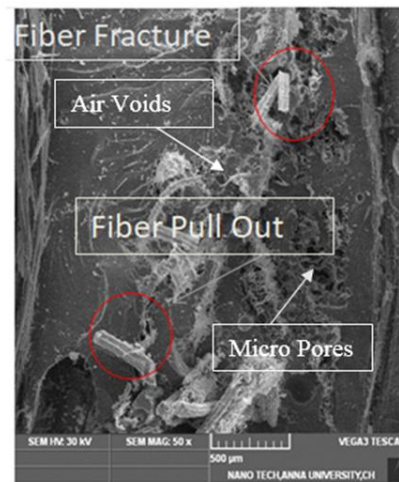
(b) Delamination Pushout

Figure 6. 3D Surface Graphs for Delaminations

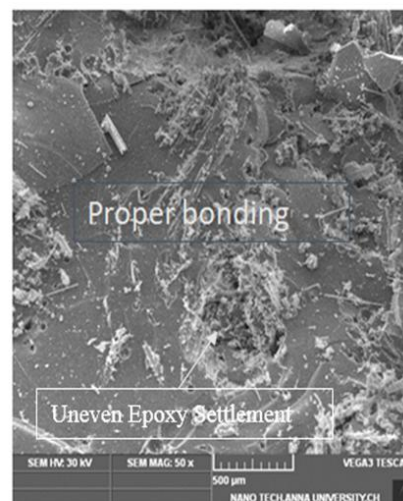
Figure 7 represents the morphology of the drilled hole after cross-sectioning, revealing the presence of defects such as fiber pullout, micro-cracks, micropores, uneven epoxy resin settlement, and air voids in the composites. Some defects were attributed to manufacturing, while others were influenced by the thrust force and torque governing the drilling process. Optimal drilling parameters significantly reduced defects, emphasizing the importance of proper composite manufacturing. The fiber volume fraction also played a crucial role in determining composite quality by avoiding fiber pullout, which is crucial for maintaining proper drilling parameters.

Fiber pullout and fiber cracks were identified in the cross-section of the drilled hole through scanning electron microscopy. Figure 7(a) illustrates more material failures occurring at a 30 mm/min feed rate, a spindle speed of 1000 rpm, and a drill bit diameter of 12 mm. In contrast, fewer failures were observed at a feed rate of 10 mm/min, a spindle speed of 3000 rpm, and a drill bit diameter

of 8 mm, as shown in Figure 7(b). This indicates that employing a minimum drill bit diameter, maximizing spindle speed, and minimizing the feed rate results in higher-quality drilled holes.



(a) 1000 rpm, 30mm/min, 12mm diameter



(b) 3000rpm, 10mm/min, 8mm diameter

Figure 7. SEM image of drilled hole for different drilling input parameters

Comparison of results with existing drilling on natural fiber reinforced composites

The optimized parameters employed in the current work on abaca-sisal/epoxy composites are demonstrated by the comparative analysis of drilling performance in different natural fiber-reinforced composites, as shown in Table 5. The fiber-matrix composites, drill type, spindle speed, and feed rate all had a substantial impact on the delamination factor (F_d) across the trials. Based on the literature, flax/polyester composites drilled with twist drills displayed somewhat higher delamination (1.2-1.45), whereas jute/epoxy composites drilled with brad

Table 5. Comparison of Drilling Parameters and Delamination in Natural Fiber Composites

Fiber-Matrix composites	Drilling Type	Spindle Speed (rpm)	Feed Rate (mm/min)	Delamination Factor (F_d)	References
Jute / Epoxy	Brad Drill	1000 - 2500	30 - 100	1.15 - 1.4	Panneerselvam <i>et al.</i> , 2022
Flax / Polyester	Twist Drill	1200 - 3000	40 - 120	1.2 - 1.45	Ramesh <i>et al.</i> , 2020
Coir / Epoxy	Step Drill	2000 - 3000	60 - 120	1.05 - 1.2	Kumar and Singh, 2021
Hemp / Epoxy	Twist Drill	1500 - 3000	60 - 180	1.1 - 1.35	Thomas <i>et al.</i> , 2019
Abaca-Sisal/ Epoxy (ASEHC)	Twist Drill	1000 - 3000	10 - 30	0.99 - 1.0	Present work

drills displayed F_d values ranging from 1.15 to 1.4. Hemp/epoxy composites drilled with twist drills produced F_d values between 1.1 and 1.35, while coir/epoxy composites drilled with step drills obtained reduced delamination (1.05-1.2). In contrast, the current study on abaca-sisal/epoxy (ASEHC) composites used a twist drill with modest feed rates (10-30 mm/min) and spindle speeds of 1000-3000 rpm to obtain a substantially reduced delamination factor of 1. The comparative analysis suggested that delamination can be significantly decreased with optimized parameters, and the current optimized drilling parameters are more successful than those described in previous research.

Conclusions

This paper investigates the impact of machining conditions on delamination during the drilling of natural fiber composites (NFC) by using the Taguchi method. Through ANOVA and Taguchi's experimental design, the results were analyzed, revealing delamination at both the top and bottom of the drilled holes, also were observed by using a profile projector. Maximum deformation occurred at low cutting speeds, and the influence of high depth of cut was confirmed through ANOVA. Damage in the hybrid composite was more prominent at higher drill diameters and feed rates. A comparison between lower feed rates and higher spindle speeds with minimum drill diameter showed similar damage levels, as supported by ANOVA results. SEM analysis demonstrated that drilling speed, feed rate, and drill diameter are the most influential parameters affecting the drilling performance of abaca-sisal epoxy hybrid composites (ASEHC). The minimum delamination factor was achieved at a feed rate of 10 mm/min, a drill diameter of 8 mm, and a spindle speed of 3000 rpm.

Declarations

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