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Drilling Response Optimization of Hybrid Bamboo-Sisal-E-Glass Fiber Composites Reinforced with Al_2O_3 Nanofillers

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ABSTRACT

This work explores the optimization of drilling parameters in hybrid epoxy composites fortified with bamboo, sisal, and glass fibers that use Al_2O_3 nanofillers towards reducing surface roughness. Taguchi method using L_{16} orthogonal array was adopted to optimize the drilling process, and the composites were constructed by hand lay-up approach. Surface roughness was the output. The main input factors for optimization were point angle, feed rate, and cutting speed. The most effective drilling parameters were determined to be C_4 (point angle), B_1 (feed rate), and A_4 (cutting speed) for reducing surface roughness based on the signal-to-noise (S/N) ratio. The ANOVA results reveal that 39.46% cutting speed and 30.20% feed rate have a considerable effect on the surface roughness, while point angle contributes 25.84% of the total effect. The model under investigation is appropriate, according to the ANOVA results, which have an estimated S value of 0.4447 and R^2 value of 95.50%. Also, the confirmative results show that the surface roughness values guessed for the best cutting conditions are pretty close to what was found in the experiments and what was expected, with a difference of 2.40%. The results offer insights into effective drilling techniques for hybrid composite materials. The ideal settings can help producers achieve excellent surface quality while machining.

Keywords: Hybrid Composite; Nanofiller; Drilling; Optimization; Surface roughness.

1. INTRODUCTION

Hybrid composite materials have emerged as a result of the growing need for materials with both high strength and low weight, addressing a broad range of industrial applications. Improved mechanical qualities can be achieved while preserving environmental sustainability by combining the advantages of several natural reinforcement fibers,like bamboo and sisalwith artificial fibers like E-glass (Senthilkumar *et al*. 2024c). Since the strength-to-weight ratio of hybrid composites is high, with good biodegradabilityand low weight, they present a possible substitute for conventional materials in a number of contexts, such as automobile industry, aerospace, and building sectors (Mohanty *et al*. 2001; Elfaleh *et al*. 2023). Nanofillers such as aluminum oxide (Al_2O_3) further enhance the electrical, thermal, and mechanical features of polymer composites, while the addition of natural fibers like bamboo and sisal enhances the overall performance(Gao *et al*. 2022; Mosaliganti *et al*. 2023). This combination not only contributes to sustainability but also offers improved durability and resilience in challenging environments. As research continues in order to investigate the uses of these materials, their adoption in industry is likely to increase, paving the way for more eco-friendly and efficient solutions. Epoxy resin commonly serves as a matrix material in composite manufacturing due to its superior mechanical qualities, chemical resistance, and adhesion (Senthilkumar *et al.* 2024d; Mary *et al.* 2024). Adding Al_2O_3 nanofillers to these composites enhances their mechanical strength and wear resistance while also making the end product more heat resistant. This improvement allows for a wider variety of uses, especially in industry where durability and performance under demanding conditions are critical (Vinay and Venkatesh, 2021; Shahabaz *et al.* 2023). The abrasive character of fibers and the variability of the material structure, however, make machining of hybrid composites extremely difficult. Drilling, a crucial machining procedure in the creation of composites frequently results in subpar surface quality, including high surface roughness and fiber pull-out, which negatively impact the longevity and performance of components (Ahuja *et al.* 2023). To address these challenges, researchers are exploring advanced machining techniques and optimized tool geometries that can better accommodate the unique properties of hybrid composites (Priya *et al.*2024; Palanikumar *et al.*2024; Senthil *et al.* 2024). Additionally, the development of

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specialized cutting fluids may further improve the machining outcomes by reducing friction and preventing thermal damage during the drilling process(Yan *et al.*2016; Kumar *et al.*2022b; Chen *et al.* 2023).

Surface roughness plays a key role in determining the excellence of drilled holes and directly affects the performance of the composite material in real-world applications. High surface roughness can lead to issues such as stress concentration, material degradation, and poor aesthetic quality (Phadke, 2021). Therefore, minimizing surface roughness during the drilling process must be met to guarantee the functional performance and endurance of composite components (Fedai, 2023). To address these challenges, optimizing drilling factors is vitalinabating surface roughness and refining the excellence of drilled holes. Key drilling factors *viz.*, tool geometry, feed and speed significantly influence the quality of the drilled surface (Rampal *et al.* 2022). Several optimization techniques have been employed in machining with Taguchi method that is widely used for its simplicity and effectiveness in identifying optimal parameter combinations (Taguchi *et al.* 1986; Senthilkumar and Tamizharasan, 2014*)*. Taguchi method helps in reducing the experimental burden by using orthogonal arrays to systematically vary the parameters, thus allowing for efficient optimization (Senthilkumar *et al.* 2024e). In particular, the L_{16} orthogonal array has been frequently used for multi-parameter optimization problems, where it provides a balanced approach to learn about the variables that affect the final result(Slamani and Chatelain, 2023; Yalçın *et al.* 2023; Yalçın *et al.* 2024). This work aims to improve the parameters of drilling in epoxy composites supplemented with hybrid bamboo-sisal-glass fibers and Al_2O_3 nanofillers in order to decrease surface roughness.Taguchi method (L_{16} array)is used for optimizing the feed and speed, and point angle, which are crucial drilling factors,with surface roughness as the output response. The results of the study will provide valuable insights into the optimal parameter combinations for drilling hybrid composite materials, thereby enhancing the surface quality of these advanced composites.

Table 1. Composition of fibers and nano fillers

Bamboo	Sisal	E-Glass	Nano Al_2O_3	Epoxy
10%	10%	10%	2%	68%

2. MATERIALS AND METHODS

2.1 Materials

In the experiments, Al_2O_3 nanofillers were used as supplementary reinforcing agents in the epoxy matrix alongside sisal, bamboo, and e-glass fibers. Sisco Research Laboratories Pvt. Ltd., situated in Poonamallee, Chennai, India, supplied the Al_2O_3 nanofillers, which were 60 nm in size. Additionally, all the fibers were purchased from the same laboratory.Araldite (LY556), an epoxy resin founded on bisphenol-A, and Aradur (HY951), a hardener was procured from Hayael Aerospace India Pvt. Ltd., Chennai, India. Table 1 displays the fiber and nanofiller compositions used to create the hybrid nanocomposites, while Table 2 displays the mechanical features of all the fibers and matrix.

Table 2. Properties of fibers, and resin

Fibers	Density(g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)
Bamboo	0.6 – 1.1	11 – 17	140 – 230	~ 2
Sisal	1.20 – 1.40	9.40 - 22.0	511 - 635	~ 2.0 – 2.5
E-Glass	2.55	80	2000	~ 2.5
Epoxy	1.1-1.45	1.5-3.5	35-100	-

2.2 Fabrication of Composite Materials

Initially trimming of bamboo, sisal, and E-glass fiber cloths into the appropriate-size fiber heaps were done. A male and a female die make up the hand layup machine. The epoxy:hardener(10:1 ratio) blend was thoroughly mixed with nanofillers in a bowl using a glass rod (Jebaraj and Rajendran, 2024), avoiding bubble formation. The fibers were positioned in the female die between 0 and 90°. The next step in the fabrication process was to cover the mold surface with a releasing film(Ramu *et al*. 2024). The sheets were then coated with the polymer and rolled using a cylindrical mild steel rod. The final plies were coated with the polymer to ensure a smooth surface. Following that, a releasing sheet was placed on top and gently rolled. Then, the dies were positioned,fastened and cured for 72 hours to ensure proper solidification. The samples (300×300×5 mm) were prepared in accordance with ASTM standards(Hemnath *et al.* 2021; Senthilkumar *et al.*2024a). Fig.1 shows the procedure forfabricating hybrid nanocomposites using hand lay-up methods.

Fig. 1: Steps for fabrication of composites

Fig. 2: Drilling machine used to perform drilling operations

Fig. 3: Surface roughness measuring instrument

2.3 Characterization and Drilling Operations

The specimens weredrilled with a high-speed steel (HSS) drill bit of Ø10 mm as the cutting tool on aBFW AGNI BMV 45++TC24 vertical machining center (Fig.2). No coolant was used throughout to minimize experimental error. After the drilling was completed, the surface roughness was measured using a Surfcorder SJ 201, as shown in Fig. 4. The environment was maintained at room temperature (20 °C) and 50% humidity. Surface polish criteria were typically expressed in Ra rather than an RMS value. The mean roughness (Ra) of the tiny peaks and valleys was then determined.

2.4 Optimization Technique

This study adopts Taguchi approach in a fractional factorial design to minimize experimental runs(Taguchi *et al*. 2005b; Taguchi *et al*. 2005a). We carried out the experiments at four levels for three parameters *viz*., feed, speed, and point angle using the orthogonal array L_{16}(Table 3). The Taguchi technique optimizes the parameters of any process to obtain ideal parameters that remain unaffected by noise and environmental factors(Shahabaz*et al.*2020; Sahin and Şahin 2021; Senthil Kumar *et al.*2023; Raja *et al*. 2024). The loss function calculates the discrepancy between the experimentalvalues and the projected values obtained by the Taguchi approach. A S/N ratio is also obtained by transforming this loss function, which is determined by the categories of the responses. Equations (1), (2), and (3) were used to determine the S/N ratio (Jain *et al*. 2019; Seif *et al*. 2023) to illustrate that smaller, nominal, and larger values are better, respectively (Muthukumar *et al.*2015; Senthilkumar *et al*. 2024b).

$$\text{Minimize}\,\frac{S}{N} = -10\log\left(\sum Y^2/n\right) \tag{1}$$

The number of trials is denoted by n, while the mean of the outcomes is represented by y.

Table 3. Levels and factors used for optimization

Symbol	Factors	Units	Level 1	Level 2	Level 3	Level 4
A	Cutting speed	rpm	250	500	750	1000
B	Feed rate	mm/rev	0.1	0.2	0.3	0.4
C	Point Angle	degree	103	108	113	118

3. RESULTS AND DISCUSSION

3.1 Analysis of Signal-to-Noise Ratios

Using Minitab, a statistical program, the outputs of the study were examined. The S/N ratio is calculated by the Minitab software after the data from the experiment is analyzed (Tsao 2007). The objective of this study is to smooth down drilling surfaces as much as possible. The impact of variables on surface roughness was calculated when the process parameters vary from one level to another. The average values of S/N ratio were calculated to ascertain the impact of different factors and their magnitude. (Senthil Babu *et al*. 2023; Fedai 2023). Both the S/N ratio strategy and the ANOVA technique make it simple to examine the data, which speeds up the process of drawing conclusions. Table 4 displays the mechanical features, while Table 5 provides the outcomes of investigation for the measured surface roughness value for specific drilling parameters. The SEM image of the fabricated specimenpresented in Fig.4 shows near uniform dispersal of nanofillers in the hybrid fiber reinforced polymer composite.

Since less surface roughness indicates greater efficacy, we chose the smaller-the bettercondition to have the least roughness profile to obtain the optimal drilling settings. The lowest S/N ratio of the levels (Seif *et al.* 2024; Kumar *et al.* 2024) indicates an ideal drilling parameter level. Table 5 displays the computed S/N ratio and surface roughness findings for each factor level. To prioritize the cutting factors, the average S/N ratio for all parameters were calculated(Fig. 5 and Table 6). Table 6 presentsthe three most important factors impacting surface roughness. The optimal surface roughness values for the lowest S/N ratio are $A_4B_1C_3$. Cutting speed, feed rate, and point angle for achieving the lowest surface roughness for this experiment are 1000 rpm, 0.4 mm/rev, and 1180, respectively.

Table 4. Composites mechanical properties

Sample	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)
S1	92	105	16

Table5. Surface roughness of composites for chosen drilling parameters

Trail	Cutting Speed (rpm)	Feed Rate (mm/rev)	Point Angle (degree)	Surface roughness (µm)	S/N ratio
1	250	0.1	103	1.15	-1.214
2	250	0.2	108	1.09	-0.749
3	250	0.3	113	1.18	-1.438
4	250	0.4	118	1.39	-2.860
5	500	0.1	108	1.27	-2.076
6	500	0.2	103	1.02	-0.172
7	500	0.3	118	1.26	-2.007
8	500	0.4	113	1.37	-2.734
9	750	0.1	113	1.59	-4.028
10	750	0.2	118	1.38	-2.798
11	750	0.3	103	1.26	-2.007
12	750	0.4	108	1.42	-3.046
13	1000	0.1	118	1.96	-5.845
14	1000	0.2	113	1.32	-2.411
15	1000	0.3	108	1.34	-2.542
16	1000	0.4	103	1.43	-3.107

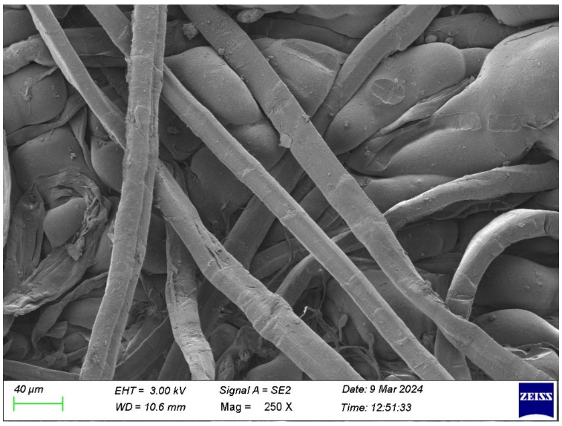

Fig. 4: SEM image of the nano polymer composite

Table 6. S/N ratio response table

Level	Cuttingspeed	Feed rate	Point angle
1	-1.565	-3.291	-1.625
2	-1.747	-1.532	-2.103
3	-2.970	-1.999	-2.653
4	-3.476	-2.937	-3.378
Delta	1.911	1.758	1.753
Rank	1	2	3

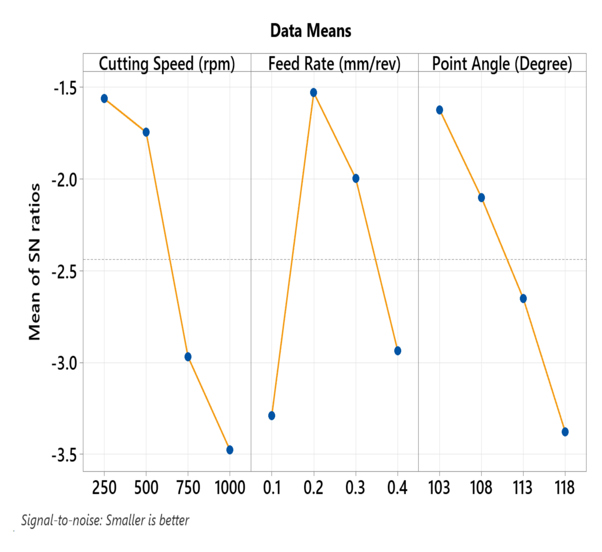

Fig. 5: Linear plot for S/N ratios

3.2. Analysis of Variance (ANOVA)

While the Taguchi approach is unable to assess and determine the influence of each factor on the entire procedure, ANOVA provides a reliable way to calculate the percentage influence of individual parameters(Özdemir *et al*. 2023; Řehoř*et al*. 2023; Kaushik *et al*. 2023). With the goal of learning how cutting parameters affect surface roughness, the Minitab 17 software'sANOVA module was used. Results showing a 95% confidence interval are shown in Table 7. The percentage input of each parameter to surface roughness is shown in Fig.6. Among the three factors, speed is the major contributor (39.46%) to surface roughness. After thoroughly reviewing all the data, we obtained an estimated S value of 0.4447, along with R^2 and R^2(adjusted) values of 95.50% and 88.74%, correspondingly. This means that the model under analysis is appropriate.

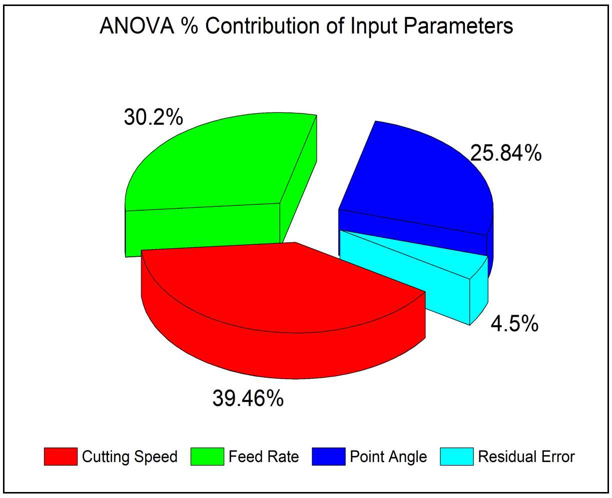

Fig. 6: Contribution of drilling factors to surface roughness

The likelihood of one factor interacting with one or more different variables is greatly increased when planned tests contain larger variable size. When the quantities of one factor affect the outcome of another, an interaction takes place (Phate *et al*. 2019). When the lines of the two factors are identical, an interaction chart often shows no interconnection; when the lines diverge, it shows an interaction (Hameed *et al*. 2022). When the two variables do not interact, the first factor's influence and the second component's level are independent. The degree of interaction between the components is shown by the skewness of lines. When the two variables interact, the first factor's influence is determined by its relative importance, and vice versa (Kumar *et al.* 2022a). The surface roughness achieved is shown in Fig. 7, which also includes an interaction map for the provided input factors. The outcomes of the interaction are not linear. An interaction relationship is simultaneously displayed by nonparallel lines. The greater interaction between the input components indicates that each input component has a considerable impact on the relative closeness values when paired with other inputs. At every level, every variable exhibits an interaction with every other variable (Upputuri and Nimmagadda, 2020).

The histogram, residuals against the fitted values, residuals against the S/N ratio, and the normal probability of the residuals are plotted in Fig.8. The normal probability plot given in Fig. 8(a), clearly illustrates a normal distribution of errors (Tamilvendan *et al*. 2024). Additionally, Figs. 8(b), 8(c), and 8(d) show that the data donot exhibit any discernible trends or anomalies. This outcome suggests that the model under analysis is adequate.

Table 7. ANOVA for S/N ratios

Source	**DF**	**Seq. SS**	**Adj. SS**	**Adj. MS**	**F**	**P**
Cutting speed(rpm)	3	10.398	10.398	3.4662	17.53	0.002
Feed rate (mm/rev)	3	7.957	7.957	2.6522	13.41	0.005
Point angle (degree)	3	6.808	6.808	2.2695	11.48	0.007
Residual Error	6	1.186	1.186	0.1977		
Total	15	26.350				
Model Summery	S	R-Sq.	R-Sq. (adj.)			
	0.4447	95.50%	88.74%			

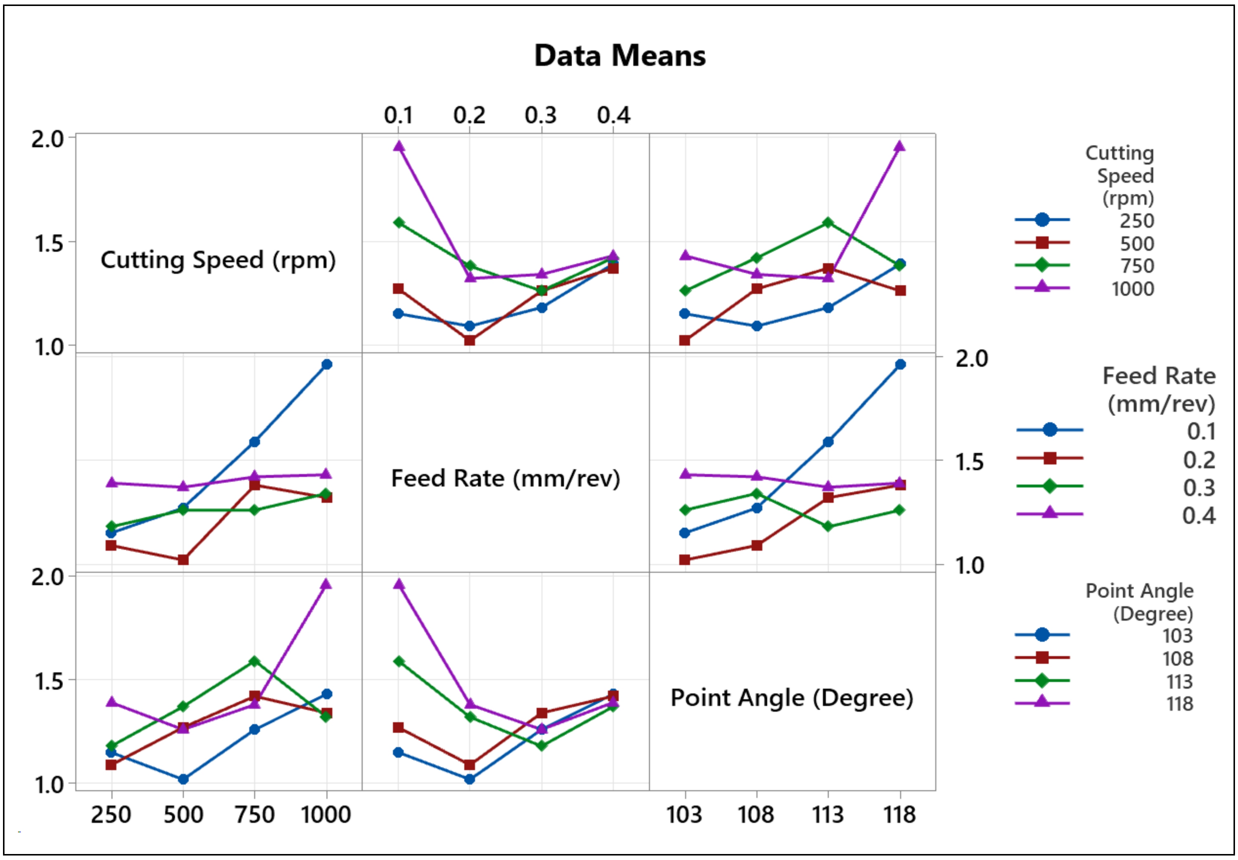

Fig. 7: Interaction plot of variables on surface roughness

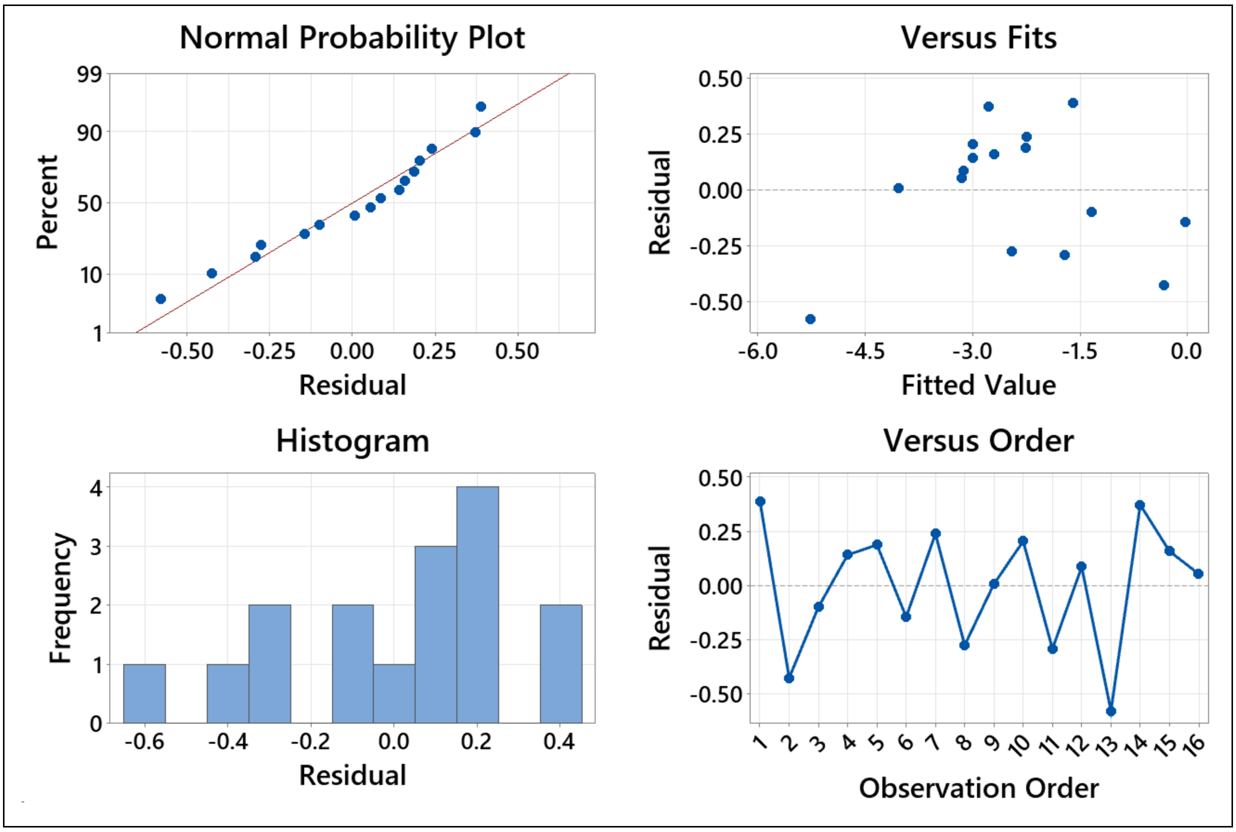

Fig. 8: Residual Plots for S/N ratio

Table 8. Confirmation test result

Optimal settings	Predicted Ra (µm)	Experimental Ra (µm)	Error %
$A_4B_1C_4$	1.057	1.083	2.4

3.3 Confirmation Test

For the purpose of experimentally demonstrating the minimum surface roughness at the optimum process, a confirmatory test was carried out. The optimal cutting conditions are shown in Table 8. Comparing the actual and projected findings from Table 8, we find that the values of surface roughness inferred for ideal cutting circumstances are in excellent agreement with a variance of 2.40%. The confirmation test shows that the resulting roughness values are lower than the minimal values acquired from the Taguchi study outcomes shown in Table 5.

4. CONCLUSIONS

Drilling settings were optimized to minimize surface roughness in hybrid composites reinforced with glass, sisal, and bamboo fibers employing Al_2O_3 nanofillers. The parameters of the drilling were optimized by Taguchi's approach with an L_{16}design. The following conclusions were drawn.

- The optimal parameters for lowering surface roughness were 1000 rpm cutting speed, 0.1 mm/rev feed rate, and 118°-point angle during drilling of synthetic composite. The primary factor influencing surface roughness is cutting speed, followed by feed rate, and point angle.
- ANOVA reveals that the cutting speed has larger influence, making up 39.46% of the total, followed by feed rate (30.20%) and point angle (25.84%).
- The estimated S value is 0.4447, R^2 and adjusted R^2 values are 95.50% and 88.74%.
- The confirmation test indicates a variance of 2.40%, demonstrating that the surface roughness values obtained under ideal cutting conditions corroborate each other and the experimental findings.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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