INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOLUME 23, ISSUE 1, 2026, 13356 - 13366
DOI: https://doi.org/10.15282/ijame.23.1.2026.15.1013

RESEARCH ARTICLE

Multi-factorial analysis and optimization of delamination damage parameters in the drilling of woven ramie/epoxy resin composite

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Abstract – The growing demand for lightweight and eco-friendly materials has accelerated the use of natural fiber composites in structural applications. However, drilling-induced delamination remains a significant challenge in machining. This study investigates the influence of drilling parameters on the delamination behavior of woven ramie/epoxy resin composites using a TPR 1100 drilling machine. TPR is the model designation of the pillar-drilling machine used in the experiments. The composite was fabricated from S-type 12/3 woven ramie fiber reinforced with epoxy resin and a polyaminoamide hardener (60:40 ratio). Delamination was quantified using 2400 DPI macrophotography and analyzed with Image-Pro Plus v4.5 software. Four process parameters, namely number of layers (3, 4, and 5), drill bit diameter (6, 8, and 10 mm), spindle speed (88, 455, and 1500 rpm), and feed rate (0.05, 0.09, and 0.15 mm/rev) were optimized using the Taguchi method, with analysis of variance used to assess parameter significance. The results showed that drill bit diameter was the dominant factor influencing delamination (entry: 70.1%; exit: 44.8%), followed by the number of layers and spindle speed, while feed rate had the least effect. The optimal parameter combination (3 layers, 6 mm drill, 88 rpm spindle speed, and 0.09 mm/rev feed) reduced delamination by 7.87% at the entry side and 10.42% at the exit side. These findings provide practical guidelines for minimizing structural degradation during machining, thereby extending the mechanical reliability of ramie/epoxy composites. The outcomes are directly applicable to the automotive, construction, and sustainable product manufacturing sectors, advancing eco-friendly machining standards and providing significant benefits for future industrial applications.

Article History

Received	:	27 July 2025
Revised	:	13 December 2025
Accepted	:	30 January 2026
Published	:	12 March 2026

Keywords
ANOVA
Delamination
Drilling process
Natural fiber composite
Taguchi method
Woven ramie

1. Introduction

In the current industrial age, which emphasizes energy efficiency and sustainability, natural fiber composites offer a compelling alternative to traditional synthetic materials. Ramie fiber is a commonly used natural fiber for composites. Ramie fiber boasts several advantages over other fibers, such as high tensile strength, moisture retention, resistance to bacteria, and heat tolerance, ranking just behind silk among natural fibers. Additionally, it is lighter and more environmentally sustainable than synthetic fibers [1]. These properties highlight ramie's potential for advanced engineering applications; however, systematic investigations of its machining performance remain limited. There has been a growing body of research focused on the use of ramie fiber as a key material in composite production. Composites are created by combining two or more distinct materials. The primary goal of this engineering combination is to effectively address contemporary challenges and meet the design requirements of structural components [2-3]. Composite components need to be assembled, and gluing them can often involve incorporating other parts into the plan. Unlike metals, composite materials cannot be welded together, which is problematic. Consequently, the standard method for joining composite components to other components typically involves mechanical fasteners and rivets. Typically, holes are drilled into the composite materials for mechanical fastening [4-5]. Although drilling is commonly associated with metals because of its effectiveness, it has also been adapted for use with composites. As composites are anisotropic materials, drilling can present specific challenges that may affect their overall strength [6]. Although several studies on composite drilling have focused on synthetic fibers such as GFRP and CFRP [7-9], natural fiber composites exhibit more complex drilling responses due to their hydrophilic behavior, irregular fiber morphology, and weaker fiber–matrix interfacial bonding [10]. These characteristics often lead to greater variability in the thrust force and delamination. Previous studies on hemp, flax, and bamboo composites have reported inconsistent trends regarding the influence of spindle speed and feed rate on delamination, indicating that drilling mechanisms in natural fiber composites are material-dependent [11]. This inconsistency highlights the need for fiber-specific investigations rather than generalizing the findings from synthetic composites. Chandrabakty et al. [6] stated that drilling parameters influence the thrust force and delamination damage in woven hemp composites and identified the process conditions that minimize damage.

Despite the superior tensile properties of ramie fibers, most machining-related studies have focused on unidirectional ramie composites [8], which exhibit failure mechanisms distinct from those of woven architectures. In woven laminates, the interlacing of warp and weft yarns modifies the stress distribution and influences mechanisms such as fiber bridging and crack propagation [11-12]. Consequently, the results from unidirectional ramie systems cannot be directly generalized to woven ramie/epoxy laminates, leaving a significant knowledge gap regarding their drilling performance. Machining natural fiber composite materials is challenging due to their susceptibility to delamination. This delamination is a critical failure mechanism in fiber-reinforced polymer matrix composite laminates, distinguishing their behavior from that of metallic structures [10]. Scientifically, delamination during the machining of composite materials occurs when cutting

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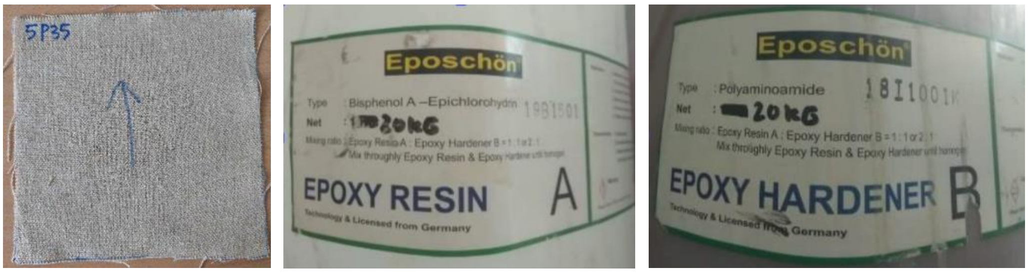
forces are not evenly distributed. High spindle speeds and feed rates increase the shear forces and stresses, thereby escalating fiber pull and the likelihood of debonding [6]. Delamination can lead to variations in the strength around the borehole. Impact damage is present at both the entry and exit points of the drill bit; however, research suggests that outer-side delamination occurs more frequently [2, 10].

Selecting appropriate machining parameters is crucial for minimizing delamination damage in composites. In composite drilling, key parameters, such as spindle speed, feed rate, drill bit diameter, and the number of composite layers, significantly influence damage reduction [2, 11]. The Taguchi method is a statistical tool used to identify the best combination of drilling parameters. Chadha et al. [7] utilized the Taguchi method to find the optimal cutting speed, feed rate, and number of GFRP composite layers. Recent studies on hybrid or natural-fiber reinforced composites have continued to examine drilling parameters and their impact on delamination using Taguchi and analysis of variance (ANOVA) [13]. An alternative method for conducting statistical analysis apart from the Taguchi technique is ANOVA (Analysis of Variance). Shahabaz et al. [9] employed ANOVA to assess the impact of key parameters on delamination factors. Waseem et al. [14] used statistical methods to identify significant drilling parameters for delamination and used these results to suggest optimal conditions (low feed rate and appropriate drill diameter) to minimize delamination during CFRP drilling. Previous studies have primarily applied the Taguchi method for parameter optimization in composite drilling [15], while ANOVA has been used to assess the statistical significance of machining parameters [9, 14]. However, very few studies have combined both approaches in a unified framework, particularly for natural fiber composites. Existing Taguchi studies rarely assess statistical significance, and ANOVA-based analyses typically do not incorporate optimization. This methodological disconnect has been identified as a limitation in composite machining research [16], and no such integrated approach has been applied to woven ramie composites. To date, no research has been conducted on drilling woven ramie/epoxy using Taguchi and ANOVA, so the author is interested in investigating this topic. Although Taguchi and ANOVA have been widely applied in studies on GFRP and CFRP, very few studies have been conducted on woven ramie/epoxy composites. Most previous studies on natural fiber composites have focused on hemp, bamboo, or unidirectional ramie fibers, while the drilling-induced delamination behavior of woven ramie composites remains underexplored. Therefore, this study contributes novelty by (i) systematically evaluating delamination in woven ramie/epoxy composites during drilling, (ii) identifying the most influential drilling parameters for this eco-friendly composite, and (iii) providing optimized machining recommendations that can support wider industrial applications of sustainable composite materials.

2. Materials and Methods

2.1 Composite Manufacturing Process

The composite laminates in this study were fabricated using S-type 12/3 woven ramie fiber sourced from local plantations in Sulawesi, Indonesia, where ramie (*Boehmeria nivea*) has been widely cultivated as a textile fiber owing to its high tensile strength and durability [1]. The matrix system consisted of an epoxy resin (Bisphenol-A based, PT Justus Kimiaraya, Indonesia) and a polyaminoamide hardener supplied by the same manufacturer. The epoxy–polyaminoamide system was selected because of its excellent adhesion to natural fibers, good mechanical performance, and relatively low shrinkage during curing, making it a common choice for natural fiber-reinforced composites [2, 3]. A resin-to-hardener weight ratio of 60:40 was applied, per the supplier's recommendations, to achieve optimal cross-linking density and mechanical stability. The laminates were fabricated using the hand lay-up method, in which woven ramie layers were impregnated with the epoxy–hardener mixture and consolidated under mild pressure. Three different stacking sequences were prepared, consisting of three, four, and five layers of woven ramie, to investigate the effect of laminate thickness on drilling-induced delamination. The selection of these layer numbers was based on previous studies indicating that delamination behavior and thrust force are strongly influenced by laminate thickness and stacking sequence in natural fiber composites [4, 5]. Thinner laminates (three layers) tend to be more flexible and prone to push-out delamination, whereas thicker laminates (five layers) offer greater resistance but may accumulate greater interlaminar stresses during drilling [6]. This range (three to five layers) represents a practical variation for structural applications, enabling systematic evaluation of drilling performance. After lay-up, the composites were cured at room temperature (25 ± 2 °C) for 8 hours under constant pressure to minimize air voids and ensure proper resin impregnation. The cured laminates were then cut into standard workpieces for the drilling experiments. The primary materials used in this study are illustrated in Figure 1: woven ramie fiber reinforcement and an epoxy-based matrix system. These materials were selected to ensure effective resin impregnation, strong fiber–matrix adhesion, and stable mechanical performance of the laminated composites.



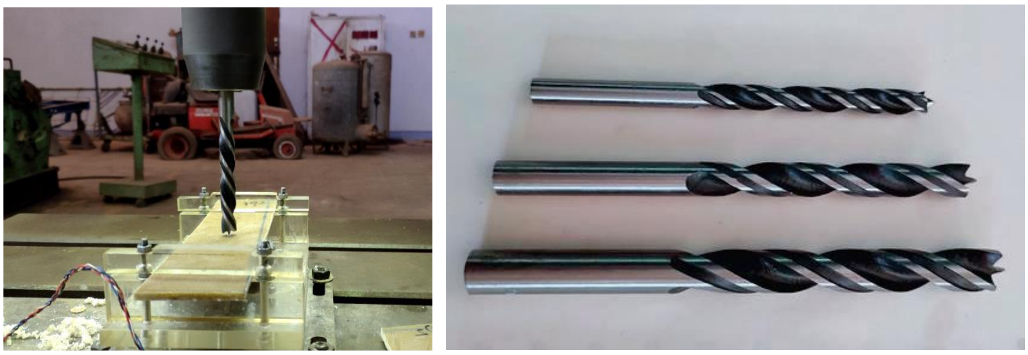
(a) (b) (c)

Figure 1. (a) Ramie woven fiber; (b) Epoxy resin; (c) Epoxy hardener

2.2 Drilling Process

The drilling experiments were performed using a TPR 1100 pillar drilling machine with a maximum spindle speed of 1500 rpm. The tests were conducted in accordance with the general guidelines for machining composite laminates, with reference to ASTM D5766/D5766M–11 (Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates) and ASTM D7336/D7336M–16 (Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Open Holes), which recommend controlled drilling procedures for producing open holes in composite specimens intended for mechanical evaluation [1, 2]. Four process parameters were selected for evaluation: laminate thickness (3, 4, and 5 woven ramie layers), drill bit diameter (3, 4, and 5 mm), spindle speed (88, 455, and 1500 rpm), and feed rate (0.05, 0.09, and 0.15 mm/rev). Brad and spur drill bits were employed due to their proven ability to reduce delamination and improve hole quality in fiber-reinforced composites compared to conventional twist drills [3].

The parameter ranges were determined based on prior literature and preliminary trials. The spindle speeds (88–1500 rpm) and feed rates (0.05–0.15 mm/rev) fall within the ranges commonly reported in natural fiber composite drilling studies [4, 5]. Although these values may appear lower than the typical industrial machining speeds for metals, they are appropriate for natural fiber composites, which are more prone to thermal degradation, fiber pull-out, and interlaminar failure under higher cutting loads. Similarly, the selected drill diameters (3–5 mm) reflect the common fastener hole sizes in lightweight structural components. The laminate thickness variation (three, four, and five layers) was chosen to represent practical ranges for natural fiber composite applications while enabling the analysis of thickness-dependent delamination behavior. To evaluate delamination, the drilled specimens were scanned at 2400 DPI using an EPSON L360 flatbed scanner, and delamination factors were calculated using Image-Pro Plus v4.5 [8]. The drilling setup and cutting tools employed in this study are illustrated in Figure 2. Figure 2(a) shows the experimental drilling configuration used for producing holes in the composite laminates, while Figure 2(b) presents the brad and spur drill bits applied during the experiments. These tools were selected to minimize delamination and improve hole quality in natural fiber–reinforced composite materials.



(a) (b)

Figure 2. (a) Drilling process; (b) Brad and spurs drill bits, 6, 8, and 10 mm

2.3 Taguchi Method

The experimental design used an L9 orthogonal array to reduce the number of combinations while adequately representing all the parameters. We used the signal-to-noise (S/N) ratio to evaluate the performance of each combination based on the observed delamination damage. The control factors and their variation levels are outlined in Table 1.

Table 1. Control factors and research levels

Control Factor	Variations		
	Level 1	Level 2	Level 3
Number of Layers	3	4	5
Drill Bit Diameter	6	8	10
Feed Rate	0.05	0.09	0.15
Spindle Speed	88	455	1500

Table 2. Control factors with L9 orthogonal array format

No. Experiment	Control Factor			
	Number of Layers	Drill Bit Diameter (mm)	Feed Rate (mm/rev)	Spindle Speed (rpm)
1	3	6	0.05	88
2	3	8	0.09	455
3	3	10	0.15	1500
4	4	6	0.09	1500
5	4	8	0.15	88
6	4	10	0.05	455
7	5	6	0.15	455
8	5	8	0.5	1500
9	5	10	0.9	88

Table 3. Entry side delamination result

No. Experiment	Entry Side Delamination Result							Standard Deviation	Calculation		
	1	2	3	4	5	6	7		Mean	S/N Smaller-The Better	S/N
1	1.042	1.030	1.037	1.037	1.037	1.033	1.041	0.004	1.037	0.313	0.313
2	1.112	1.101	1.112	1.122	1.149	1.112	1.121	0.015	1.118	0.970	0.970
3	1.144	1.156	1.140	1.122	1.162	1.144	1.156	0.013	1.146	1.184	1.184
4	1.087	1.051	1.065	1.080	1.108	1.051	1.080	0.021	1.075	0.621	0.621
5	1.127	1.122	1.132	1.112	1.154	1.132	1.112	0.014	1.127	1.039	1.039
6	1.152	1.144	1.143	1.144	1.130	1.152	1.141	0.007	1.144	1.166	1.166
7	1.087	1.087	1.080	1.087	1.073	1.087	1.080	0.006	1.083	0.692	0.692
8	1.191	1.180	1.186	1.186	1.154	1.191	1.180	0.013	1.181	1.445	1.445
9	1.166	1.107	1.164	1.146	1.175	1.107	1.164	0.029	1.147	1.184	1.184

Table 4. Exit side delamination result

No. Experiment	Exit Side Delamination Result							Standard Deviation	Calculation		
	1	2	3	4	5	6	7		Mean	S/N Smaller-The Better	S/N
1	1.051	1.044	1.065	1.058	1.058	1.051	1.064	0.008	1.056	0.472	0.472
2	1.127	1.085	1.127	1.127	1.106	1.116	1.085	0.019	1.110	0.907	0.907
3	1.180	1.218	1.219	1.226	1.197	1.180	1.218	0.020	1.205	1.620	1.620
4	1.122	1.129	1.129	1.087	1.115	1.129	1.087	0.019	1.114	0.934	0.934
5	1.143	1.143	1.170	1.127	1.170	1.127	1.170	0.020	1.150	1.211	1.211
6	1.160	1.177	1.152	1.190	1.164	1.160	1.175	0.013	1.168	1.350	1.350
7	1.122	1.108	1.143	1.108	1.129	1.108	1.143	0.016	1.123	1.005	1.005
8	1.268	1.245	1.243	1.272	1.261	1.246	1.248	0.012	1.255	1.970	1.970
9	1.204	1.189	1.172	1.180	1.169	1.189	1.172	0.013	1.182	1.452	1.452

This study involved four control factors and three variations (levels), leading to a total of 81 tests (runs) calculated factorially as $3^4 = 81$. The experiment was repeated 7 times per sample, resulting in a total of 81 formulas. However, when applying the Taguchi method with the same number of factors and levels, only nine tests (runs) are required. Given the control factors and levels outlined in this study, we utilized the L9 orthogonal array from the Taguchi method, as demonstrated in Table 2. Tables 3 and 4 present the error analysis, expressed as the standard deviations of the entry-side and exit-side delamination results from the nine experiments. We used control factor limits, namely the number of layers, drill bit diameter, feed rate, and spindle speed, which refer to the control factors with an L9 orthogonal array format.

2.4 Analysis of Variance

Similar to the Taguchi method, employing ANOVA requires managing factors and levels of variation. By controlling these factors and levels of variation, we derived an appropriate orthogonal array similar to the Taguchi Method, specifically the L9 orthogonal array presented in Table 2. The following is Figure 3, illustrating the research flowchart for this study.

Figure 3. Research flowchart

3. Results And Discussion

3.1 Analysis Using the Taguchi Method

From Table 2, we can discover the control factors and variations (levels) that most significantly influence the ramie fiber woven composites by inputting the necessary data and executing them in Excel. The results of this data calculation are shown in Table 5, where the characteristics of the delamination factor indicate that "smaller is better". The graphs clearly depict the relationship between the control factor and low S/N for both the entry and exit sides, as shown in Figures 4 and 6. Figures 5 and 7 illustrate the correlation between the control factor and the average responses on these sides. The graphs reveal the factors influencing delamination on the panel's entry side. For low S/N delamination, optimal results were obtained when the delamination factor was minimized for each machining parameter. In contrast, the best outcomes for the mean delamination occur when the delamination factor approaches 1 across all machining parameters. Specifically, for low S/N data on the control factors of 3, 4, and 5 layers, the optimal result for the entry side is achieved at 3 layers with a value of 0.82249; similarly, for the mean case, the best outcome also corresponds to 3 layers with a value of 1.10048.

Table 5. Calculation results based on the L9 orthogonal array of entry and exit sides

Control Factor		Entry Side		Side Out	
		S/N LB	Mean	S/N LB	Mean
Number of Layers	3 Layer	0.82249	1.10048	0.99930	1.12390
	4 Layer	0.94179	1.11519	1.16487	1.14410
	5 Layer	1.10705	1.13705	1.47580	1.18662
Drill Bit Diameter	6 mm	0.54197	1.06476	0.80375	1.09762
	8 mm	1.15124	1.14229	1.36234	1.17171
	10 mm	1.17811	1.14567	1.47387	1.18529
Feed Rate	0.05 mm/rev	0.97453	1.12052	1.26367	1.15962
	0.09 mm/rev	0.92498	1.11333	1.09767	1.13552
	0.15 mm/rev	0.97182	1.11886	1.27863	1.15948
Spindle Speed	88 rpm	0.84534	1.10367	1.04477	1.12933
	455 rpm	0.94277	1.11505	1.08716	1.13390
	1500 rpm	1.08323	1.13400	1.50803	1.19138

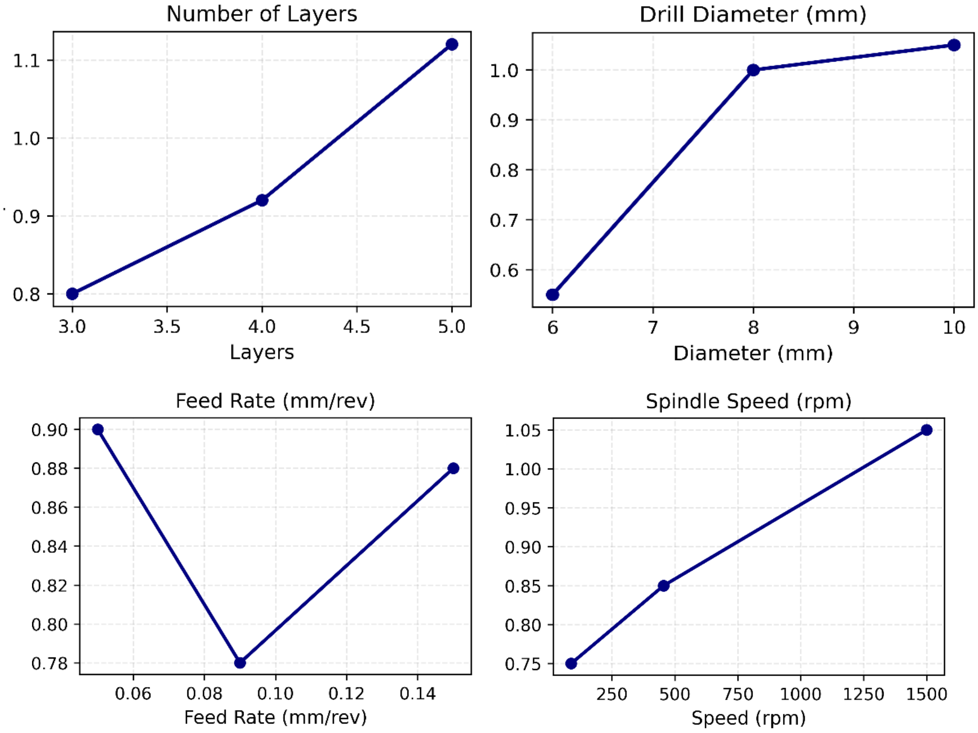


Figure 4. A lower S/N value is better on the entry side of the control factor and variation (level) in ramie woven composites

The factor analysis results and the average value of the entry-side response indicated that the optimal result corresponded to the lowest delamination factor, indicating a preference for a smaller signal-to-noise (S/N) ratio, while the mean value approached 1. The figure above illustrates that the best results are achieved with a configuration of three layers, a diameter of 6 mm, a feed rate of 0.09 mm/rev, and a spindle speed of 88 rpm, yielding S/N ratio values of 0.822, 0.541, 0.924, and 0.845, and mean values of 1.100, 1.064, 1.113, and 1.103. From the optimal conditions obtained on the entry side, we can determine the value of Y_{optimal}. Alternatively, the prediction of the optimal parameters is obtained as follows:

It is known that $T_{(\text{average})}$= 1.117, where this value is the average of the responses.

$$Y_{\text{optimal}} = T_{average} + \left(F_l - T_{average}\right) + \left(F_d - T_{average}\right) + \left(F_f - T_{average}\right) + \left(F_s - T_{average}\right) \tag{1}$$

$$Y_{\text{optimal}} = 1.117 + (1.100 - 1.117) + (1.064 - 1.117) + (1.113 - 1.117) + (1.103 - 1.117) = 1029$$

$$\%_{\text{improve}} = \frac{Y_{\text{optimal}} - T_{average}}{T_{average}} \times 100\% \tag{2}$$

$$\%_{\text{improve}} = \frac{1.029 - 1.117}{1.117} \times 100\% = -7.87\%$$

By applying the optimal parameter settings, specifically a diameter of 6 mm on a composite with three layers of reinforcement, a spindle speed of 88 rpm, and a feed rate of 0.09 mm/rev, the delamination factor can be predicted to be 1.029, reflecting a reduction of 7.87% from the average response.

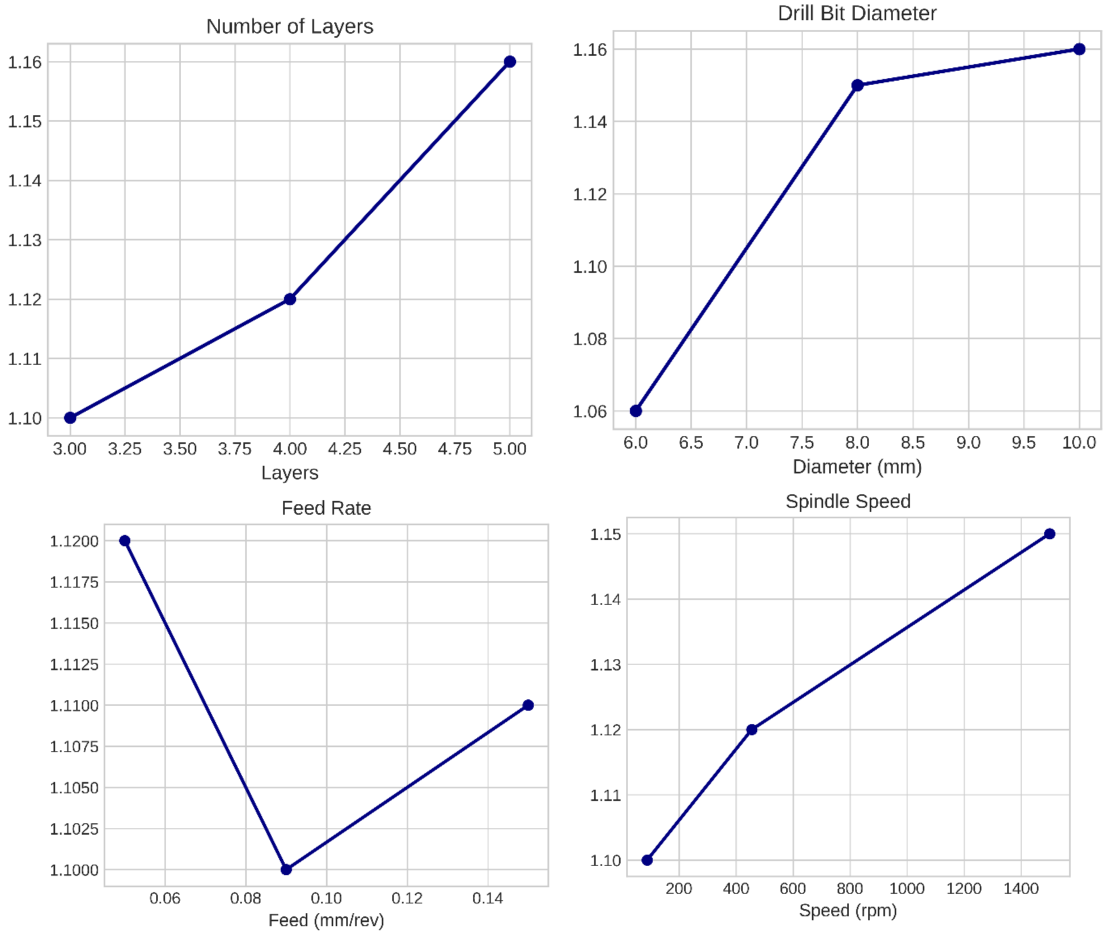


Figure 5. Mean values of the control factor for the entry side and the variation (level) of the ramie woven composite

Similarly, the optimal exit side for a low S/N ratio improved when the mean was approximately 1, with configurations consisting of three layers, a diameter of 6 mm, a feed rate of 0.09 mm/rev, and a spindle speed of 88 rpm. This setup yielded values of 0.999, 0.803, 1.097, and 1.044 for low S/N, along with mean values of 1.123, 1.097, 1.135, and 1.129, respectively. From the optimal conditions obtained on the exit side, we can determine the value of Y_{optimal} or the prediction of the optimal parameters obtained as Eq. (4). It is known that $T_{(\text{average})}$= 1.151, where this value is the average of the responses.

$$Y_{\text{optimal}} = T_{average} + \left(F_l - T_{average}\right) + \left(F_d - T_{average}\right) + \left(F_f - T_{average}\right) + \left(F_s - T_{average}\right) \tag{3}$$

$$Y_{\text{optimal}} = 1.151 + (1.123 - 1.151) + (1.097 - 1.151) + (1.135 - 1.151) + (1.129 - 1.151) = 1.031$$

$$\%_{\text{improve}} = \frac{Y_{\text{optimal}} - T_{average}}{T_{average}} \times 100\% \tag{4}$$

$$\%_{\text{improve}} = \frac{1.031 - 1.151}{1.151} \times 100\% = -10.42\%$$

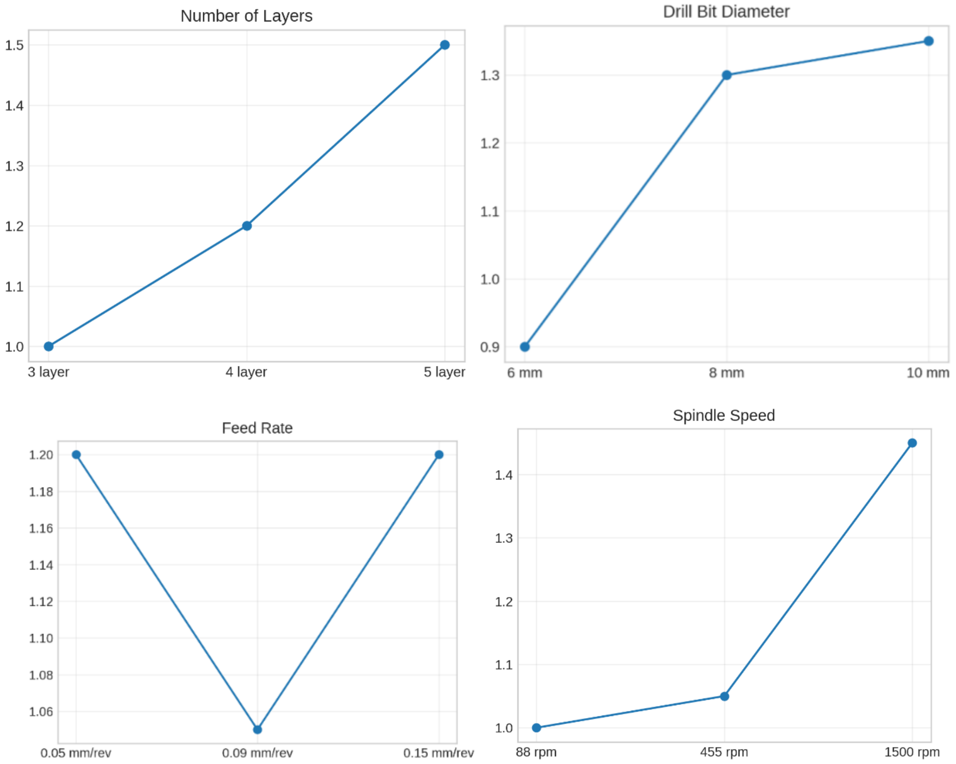


Figure 6. A lower S/N value is better on the exit side of the control factor and variation (level) in ramie woven composites

By using the optimal parameter settings, a diameter of 6 mm on a composite with 3 layers of reinforcement, a spindle speed of 88 rpm, and a feed rate of 0.09 mm/rev, the delamination factor can be predicted to be 1.031, representing a decrease of 10.42% from the average response. The signal-to-noise ratio calculation indicated that the drill bit diameter was the most sensitive factor influencing delamination changes. This sensitivity arises because an increase in the drill diameter enlarges the contact surface area and thrust force, which can initiate and propagate delamination between the composite layers. These findings are supported by Waseem et al. [14], who demonstrated that reducing the drill diameter significantly reduced delamination and enhanced the material's residual strength. Furthermore, the influence of the number of layers is significant, mainly because increasing the number of layers increases the composite's total thickness, mechanically enhancing resistance to cutting forces but also leading to the accumulation of interlayer stresses. Somaiah et al. [16] also showed that feed rate and thickness influence the size of the damage zone during drilling. Although spindle speed and feed rate are not the primary parameters, they still contribute to the local heat phenomenon and fiber exfoliation around the hole. The use of a moderate feed rate (0.09 mm/rev) helped maintain a stable cutting force and minimize matrix resin fracture, as reported by Tewani et al. [11] for drilling hybrid composites. The Taguchi method in this study not only improves efficiency by reducing the number of experiments but also provides a strong technical basis for decision-making in an environmentally friendly manufacturing process with minimal damage. From the Taguchi method analysis, the optimal parameters used on both the entry and exit sides of the drilling process were three layers, a diameter of 6 mm, a feed rate of 0.09 mm/rev, and a spindle speed of 88 rpm. The delamination value obtained can be reduced by 7.87% on the entry side and 10.42% on the exit side during the ramie woven composite drilling process.

3.2 Analysis of Variance

Like the Taguchi method, analysis using the ANOVA method also requires control factors and variations (levels). From the control factors and variations (levels), we obtain the contributions from the entry and exit sides, as shown in Tables 6 and 7. Table 6 shows that the largest contributor to the entry-side delamination factor is drill diameter, accounting for 70.1%. In addition to the diameter, the number of layers and spindle speed were also quite influential, with contributions of 11.3% and 7.9%, respectively, while the feed rate contributed the least, at only 0.5%. This confirms previous findings that geometric parameters are the primary determinants in generating high thrust forces and interlayer damage. Karthick et al. [15] reported that drill diameter is the most influential parameter on thrust force and delamination when drilling CFRP composites with carbide drills. Table 6 also indicates that the error from research using the ANOVA method was 10.2%. This error arises from the number of samples used for each control factor and variation (level), which was 7. In this case, a larger number of test samples led to a higher error rate. Figure 8 compares the contributions of each control factor with the error at the entry side of the drain. Unlike the exit side of the digging, the contribution of each control factor is more evenly distributed than on the entry side, which is predominantly influenced by the drilling diameter. This is evident from the results, which show the percentage contributions of each control factor: 20.6% for the number of layers, 44.8% for the drilling diameter, 3.9% for the feed rate, and 24.1% for the spindle speed. Similar to the entry side, the control factor with the largest contribution was the drilling diameter (44.8%), whereas the smallest was the feed rate

(3.9%). The error from the exit side of the digging is 6.6%. Figure 9 compares the contributions of each control factor with the error on the exit side. Additionally, the p-values for the main factors were statistically significant at the 95% confidence level, and the low error values (<10%) indicated that the constructed experimental model had high validity. Consequently, the ANOVA in this study provides a robust mathematical and statistical justification for establishing the process parameters most critical to composite integrity after drilling. The study further supports these results from Somaiah et al. [16] and Waseem et al. [14], which indicated that changes in diameter directly influence the compressive zone and delamination potential in natural and hybrid composites.

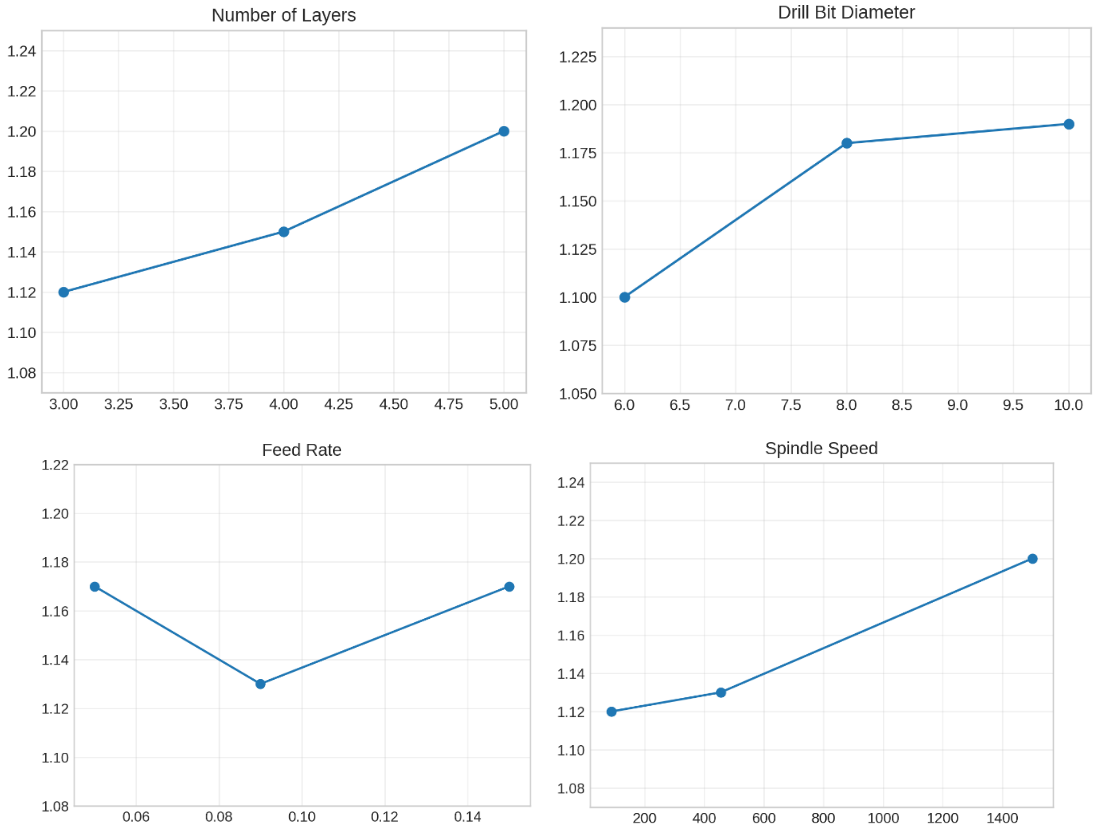


Figure 7. Mean values of the exit side for the control factor and the variation level in ramie woven fabric composites

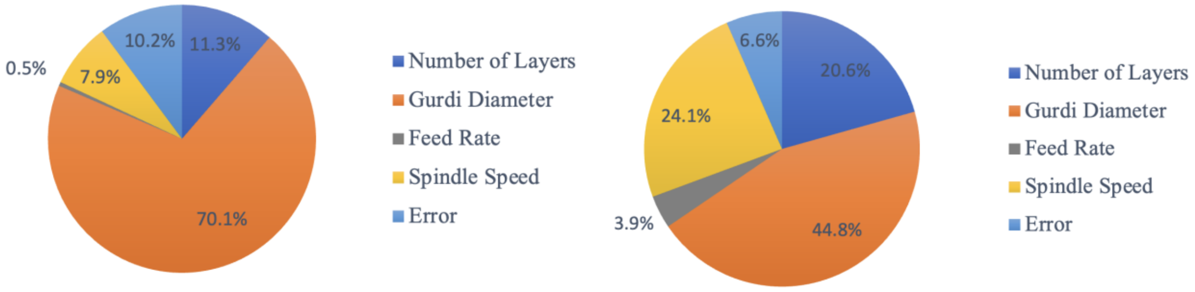
Table 6. Contribution of each entry-side factor

Source	Degree of Freedom	Adj SS	Adj MS	F	P	Cont	% Contribution
A	2	0.01422	0.00711	30.07	Significant	11.3	11.3%
B	2	0.08797	0.04398	185.9	Significant	70.1	70.1%
C	2	0.00059	0.00030	1.26	Insignificant	0.5	0.5%
D	2	0.00986	0.00493	20.85	Significant	7.9	7.9%
Error	54	0.01277	0.00024	-	-	10.2	10.2%
Total	62	-	-	-	-	100.0	100.0%

The findings of this study are highly relevant to the industrial application of natural fiber composite materials, particularly in the automotive, construction, and sustainable structural design sectors. As shown in Figure 8, the ANOVA analysis revealed that drill diameter is the most dominant factor affecting delamination damage on both the entry and exit sides, accounting for up to 44.8%**.** This reinforces the importance of optimizing tool geometry to maintain mechanical integrity and minimize structural weakening during machining. In contrast, the feed rate, although often considered a crucial parameter, contributed the least (3.9%), suggesting that within the selected experimental range, surface damage is more sensitive to drill geometry than to feed variations. The spindle speed, with a moderate contribution of 24.1%, continued to play a substantial role in affecting fiber pull-out and interfacial matrix failure. These findings align with prior research by Somaiah et al. [16], which indicated that increased drilling-induced damage is correlated with reduced tensile strength and durability in perforated composites [17, 18]. Our findings on thrust force trends are consistent with Fard et al. [8], who reported that higher feed rates increased delamination in hemp composites. However, the magnitude of delamination observed in the woven ramie/epoxy is lower, likely because the tighter fiber architecture provides improved crack resistance. Unlike Waseem et al. [14], who found spindle speed as the dominant parameter in CFRP drilling, our study indicates that feed rate plays a more critical role in woven ramie composites. This difference may arise from the lower stiffness and greater susceptibility to matrix debonding of natural fibers. The results of this study confirmed that drill bit diameter is the most dominant factor influencing delamination (contributing up to 44.8%), followed by the number of layers and spindle speed. This finding agrees with recent studies on natural fiber composites such as coir, sisal, and nettle, which also reported that larger drill diameters increase the thrust force and delamination, while higher spindle speeds can improve the hole quality under certain machining conditions [19-21]. For example, drilling of epoxy laminates showed that a slightly larger tool diameter, combined with a high spindle speed, reduced delamination and improved dimensional accuracy [22-24]. These comparisons reinforce the conclusion of the present study that tool geometry, particularly drill diameter, plays a decisive role in distributing cutting forces and suppressing fiber pull-out during drilling of woven ramie/epoxy composites.

Table 7. Contribution of each exit-side factor

Source	Degree of Freedom	Adj SS	Adj MS	F	P	Cont	% Contribution
A	2	0.04304	0.02152	84.80	Significant	20.6	20.6%
B	2	0.09352	0.04676	184.25	Significant	44.8	44.8%
C	2	0.00808	0.00404	15.92	Significant	3.9	3.9%
D	2	0.05022	0.02511	98.95	Significant	24.1	24.1%
Error	54	0.01370	0.00025	-	-	6.6	6.6%
Total	62	-	-	-	-	100.0	100.0%



(a) Drill entry side (b) Drill exit side

Figure 8. Contribution of each control factor to the drill entry and exit side

Although this study primarily focused on delamination, literature indicates that drilling-induced damage directly affects the residual mechanical performance of composites. Increased delamination is associated with reduced tensile strength, fatigue resistance, and long-term durability of the perforated laminates [25-27]. The findings of this study suggest that maintaining an optimal drill diameter and selecting a spindle speed within an appropriate range can mitigate delamination, thereby preserving the post-drilling tensile and fatigue performance of woven ramie/epoxy composites. This implication is critical, since natural fiber composites are increasingly used in structural applications where hole-making is unavoidable. From an industrial standpoint, these results provide practical guidelines for the machining of natural fiber composites. In the automotive and aerospace industries, where lightweight components with mechanical fasteners are common, optimizing drill geometry is essential to ensure reliable joint performance. Recent studies on hybrid jute–palm composites have also highlighted the importance of drilling parameter optimization to ensure hole quality and structural integrity in lightweight applications [23-24, 28]. Similarly, in the construction sector, woven ramie/epoxy composites can serve as eco-friendly alternatives to synthetic FRPs in load-bearing or modular systems, provided that machining-induced damage is controlled. By demonstrating the parameter dominance hierarchy starting from drill diameter, number of layers, and spindle speed, this study delivers actionable insights for industries transitioning toward sustainable composite solutions. Conversely, the limitations of this study, such as the neglect of the point angle and drill material, highlight areas for further investigation. Future research could incorporate additional variables, such as tool wear and temperature variations during drilling, and numerical modeling to predict spatially distributed damage zones [17-18]. The Taguchi method demonstrated effectiveness in identifying the optimal parameter configuration, whereas ANOVA quantitatively illustrated the contribution level of each parameter. This research acts as a reference for developing a more accurate and eco-friendly machining process for natural fiber composites [29-30].

4. Conclusions

This study successfully identified the drilling parameters that influence delamination damage in woven ramie/epoxy resin composites using the Taguchi method and analysis of variance. The drill bit diameter was found to be the most critical factor, contributing 70.1% on the entry side and 44.8% on the exit side of the hole. The optimal parameter combination with three layers, a 6 mm drill diameter, a spindle speed of 88 rpm, and a feed rate of 0.09 mm/rev, reduced delamination by 7.87% on the entry side and 10.42% on the exit side. The Taguchi method proved effective in minimizing the number of trials while identifying parameter settings that significantly reduced delamination, whereas ANOVA quantified the relative contribution of each factor. These results underscore the importance of controlling tool geometry and machining parameters to maintain the mechanical integrity of natural fiber composites. Beyond the experimental outcomes, this research has broader industrial relevance. These findings provide practical guidelines for industries such as automotive, aerospace, and construction, where natural fiber composites are increasingly adopted as lightweight and sustainable alternatives to synthetic FRPs. By demonstrating how optimized drilling can maintain structural reliability while minimizing damage, this study contributes to the development of eco-friendly manufacturing practices in the field.

Ultimately, the insights gained in this study can serve as a reference for establishing sustainable machining standards that support the global shift toward greener materials and environmentally responsible engineering solutions.

Acknowledgements

The authors would like to thank the Applied Mechanics Laboratory Officers of the Faculty of Mechanical Engineering, Hasanuddin University, Indonesia. We would like to thank Yunita Feby Ramadhany for her help with the manuscript and for taking the time to review it.

Funding

This study was not supported by any grants from funding bodies in the public, private, or not-for-profit sectors.

Declaration of Competing Interest

The author declares no conflicts of interest.

CRediT Authorship Contribution Statement

T. Zulkifli (Conceptualization; Formal analysis; Writing-original draft; Writing-review & editing; Supervision)
Z. Djafar (Methodology; Data curation; Resources)
M. Massaguni (Investigation; Software; Visualisation)

Availability of Data and Materials

The data supporting this study’s findings are available on request from the corresponding author.

Ethics Declarations

This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations

The authors stated that generative AI was not used to generate content, ideas, or theories. We have just utilized AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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