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Original Article

Investigation of the deformation and thrust forces generated during the drilling of GFRP composites

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ABSTRACT

Glass fiber-reinforced polymer (GFRP) composites are widely used in industry due to their advantageous properties, such as a high strength-to-weight ratio. However, during the preparatory processes for bolted or riveted joints, drilling operations often lead to delamination damage, which adversely affects the mechanical performance and reliability of these materials. In this study, the effects of different cutting speeds and feeds on thrust force and delamination damage during the drilling of GFRP composites were investigated. The maximum thrust forces generated during the hole drilling process were measured, and post-drilling deformations were examined. Mathematical models were developed using the response surface method (RSM) to predict thrust force and delamination under various cutting conditions determined by the selected drill geometry. The results of the analysis of variance (ANOVA) showed that the developed models were statistically significant with a confidence level of over 90%. It was found that feed is the dominant parameter influencing thrust force, whereas cutting speed plays a primary role in determining the extent of delamination. The results provide valuable insights for establishing optimum cutting conditions aimed at minimizing drilling damage in GFRP composite machining.

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INTRODUCTION

Glass fibre reinforced polymer (GFRP) composite materials, which are indispensable in engineering applications, are widely used in many industries such as wind turbine manufacturing, automotive, aerospace, and marine due to their lightweight nature and cost-effectiveness [1–3]. Although composite materials are generally manufactured in shapes close to the final geometry, machining operations such as drilling are often required to achieve assembly requirements or dimensional tolerances [3–5]. During the drilling process, problems such as delamination, fibre pull-out, fibre breakage, micro-cracks, and poor hole surface quality are encountered due to the layered and anisotropic structures of composite materials. These problems compromise material integrity, reduce strength, and may lead to parts being scrapped during the production process. Therefore, minimizing damage during drilling, specifically achieving high hole surface quality with minimal delamination and thrust force, is of critical importance. Deter-

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mining the optimum hole drilling parameters according to experimental designs by avoiding multiple experiments to determine the minimum damage is important in terms of time efficiency, cost reduction, and improved manufacturing quality [5–10].

Errors that occur after drilling are generally associated with factors such as incorrect drilling parameters, improper selection of the cutting tool, and thrust force. Numerous studies in the literature indicate that feed rate has a significant effect on delamination and thrust force [9,11–15]. These studies generally report that the thrust force and delamination increase with increasing feed or feed rate [5,9,10,16], while no significant increase or decrease is observed with increasing cutting speed [15,17–22]. The temperature increase in the hole region resulting from increasing cutting speed can cause local softening of the composite material, reducing the thrust force, alternatively may increase delamination due to undesirable effects such as fiber entanglement without softening [3]. Increasing the diameter of the cutting tool, one of the parameters affecting delamination and thrust force, increases delamination and thrust force [5]. Since the hole diameter is known during the assembly process, no change in the drill diameter is required. However, the effect of the drill tip geometry on delamination and thrust force is of critical importance. It has been reported that better results are obtained at lower point angles in the drilling of GFRP composite materials [9,23].

Various analysis and optimization methods are used to overcome processing difficulties, such as delamination in drilling operations, and to determine optimal drilling parameters. Abdul Nasir et al. [22] emphasized that feed rate, rather than cutting speed, is the dominant parameter affecting thrust force in the drilling of flax fiber composites. Ertürk et al. [20] investigated the drilling characteristics with different drill geometries, feed rates, and cutting speed parameters, and analyzed their experimental results using the response surface method. They reported that thrust force and cutting torque increased with increasing feed rate, while cutting speed had no significant effect. They also emphasized that the drill tip coating is a significant factor affecting the sample temperature during drilling.

Karimi et al. [24] investigated the effects of the nanomaterial content in the composite structure, drill diameter, feed rate, and cutting speed on drilling conditions. According to ANOVA results, they emphasized that the effect of drill diameter on delamination is negligible, while feed rate has the most significant effect. They concluded that there was a significant interaction between the feed rate and the cutting speed. Karaca [25] investigated the effects of cutting speed, feed rate, and drill tip angle on exit delamination and emphasised that cutting speed has no significant effect, while feed rate and drill tip angle strongly influence the delamination factor. Also, the study reported that low feed rates combined with small tip angles yield minimal deformation. Shanmugam et al. [26] investigated the effects of drill bit angle, feed rate, and cutting speed on thrust force, delamination, and burr formation. They reported that thrust force increases with higher feed rates and cutting speeds and that a 118° drill tip angle results in lower thrust forces. ANOVA results showed that thrust force is influenced primarily by cutting speed, followed by feed rate and drill tip angle, while delamination is significantly affected by feed rate. Kalita et al. [14] examined the effects of material thickness, drill diameter, cutting speed, and feed rate, each at three levels, on delamination. They concluded that delamination decreases with increasing material thickness and decreasing feed rate. While feed rate had a dominant effect on delamination, cutting speed had no significant effect. To determine the minimum delamination factor, they employed Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), emphasising that both methods converged to the same optimal solution, although PSO achieved faster performance. Behera et al. [27] investigated the entry delamination factor and surface roughness values (Ra-Rq) using the parameters of material thickness, drill diameter, cutting speed, and feed rate during the drilling process. Using artificial neural networks (ANN), they established predictive relationships and analyzed the results. Experimental findings indicated that feed rate is the most influential parameter for both output responses. They concluded that delamination decreased with increasing material thickness and decreasing feed rate, while surface roughness increased with higher feed rate. Spindle speed was found to have no significant effect. Xu et al. [21] investigated drilling experiments using different feed rates, cutting speeds, and drill bits (double-edged and dagger-drills). Xu et al. [21] conducted drilling experiments using different feed rates, cutting speeds, and drill bits (double-edged and dagger-drills). They examined the effects of the parameters on cutting forces, machining temperatures, and delamination as a result of the drilling process. They noted that cutting speed had no significant effect on thrust force, but plays a major role in temperature generation. They also demonstrated that drilling could be performed without delamination using a double-point-angle drill. Biruk-Urban et al. [28] investigated the effects of cutting speed and feed rate on drilling four different types of GFRP composites, each with varying fiber weight fractions and fiber type (Twill and Plain). They emphasized that Fz, a cutting force component, is significantly affected by the feed rate, and that Fz increases with increasing feed rate. They recommended the use of Twill-type fibers. Abd-Elwahed [4] investigated torque and delamination by machining woven glass fiber-reinforced epoxy composites at different laminate thicknesses, feed rates, and cutting speeds. The results were modeled and evaluated using the response surface methodology (RSM) and artificial neural networks (ANN). By enhancing ANN training with particle swarm optimization (PSO), the prediction performance of the models was improved. The study highlighted that low feed rates and high cutting speeds lead to optimal values for torque and delamination.

Generally, low cutting speeds and feeds/feed rates are recommended to minimize delamination. Although previous research has addressed various drilling problems with GFRP composites, a comprehensive understanding of drilling behavior and damage mechanisms has not yet been fully established in the industry.

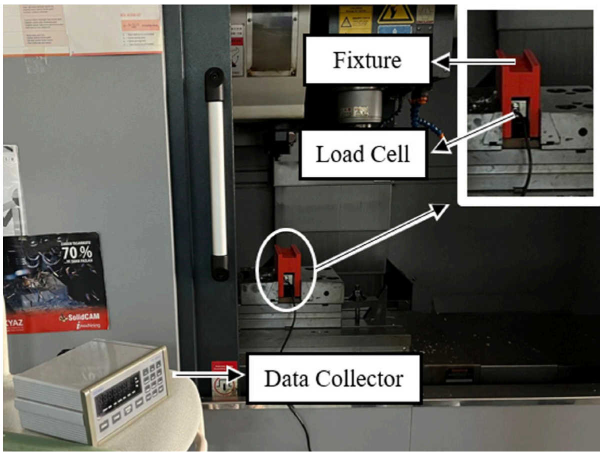


Figure 1. Experimental system.

Figure 2. SDC drill bit.

Table 1. Cutting parameters and levels

Parameters	Levels
Cutting Speed – V_c (m/min)	80 – 100 – 120
Feed – f (mm/rev)	0.05 – 0.0625 – 0.075 – 0.0875 – 0.1

In this study, the effects of cutting speed and feed on delamination and cutting forces (thrust force) were investigated during drilling 10 mm diameter holes using an SDC drill bit in the drilling process of GFRP composite materials. Drilling experiments were conducted at five different feeds and three different cutting speeds. As output responses, delamination, hole taper, and thrust force were evaluated. Analysis of variance was performed, and mathematical models were developed using the response surface method. By examining the effects of input parameters on output values, optimum cutting parameters for improved hole quality in GFRP drilling were determined using RSM combined with the desirability function approach. Comparsion with experimental results confirmed the strong predictive capability of the developed models.

MATERIALS AND METHODS

In this study, drilling operations using a special SDC series drill bit were performed on glass fiber–reinforced polymer (GFRP) composite materials that were commercially manufactured using the vacuum infusion method. The GFRP composites were produced by GENBA using a 16-ply vacuum infusion method using 0/90° plain woven fabrics. The manufactured composites were cut into specimens with dimensions of 8.6 × 35 × 200 mm using a water-jet cutting to prepare them for experimentation. Drilling experiments operations were conducted on a LER VQ-75 CNC vertical machining center with a spindle motor power of 20 kW and a spindle speed range of 50-11000 rpm (Fig. 1). An MDS10000SDC3-coded drill bit with a diameter of Ø10 mm (Fig. 2) was used in the experiments, which were conducted under air cooling conditions. The study was conducted using a Multilevel Factorial experimental design with three different cutting speeds and five different feeds as cutting parameters, and a total of 15 experiments were conducted (Table 1). The flowchart of the experimental study is presented in Figure 3.

To ensure accurate measurement of the thrust force during drilling, a protective fixture was designed to isolate the load cell from external factors (Fig. 4). The thrust forces generated during the drilling process (Fig. 5), performed at different levels and parameters, were measured using an MS Cell SS300 series load cell with a capacity of 500 kg. Delamination occurring on the upper surface of the specimens after drilling was examined using a Dino-Lite Pro AM4000 series digital microscope equipped with a 1.3-megapixel camera.

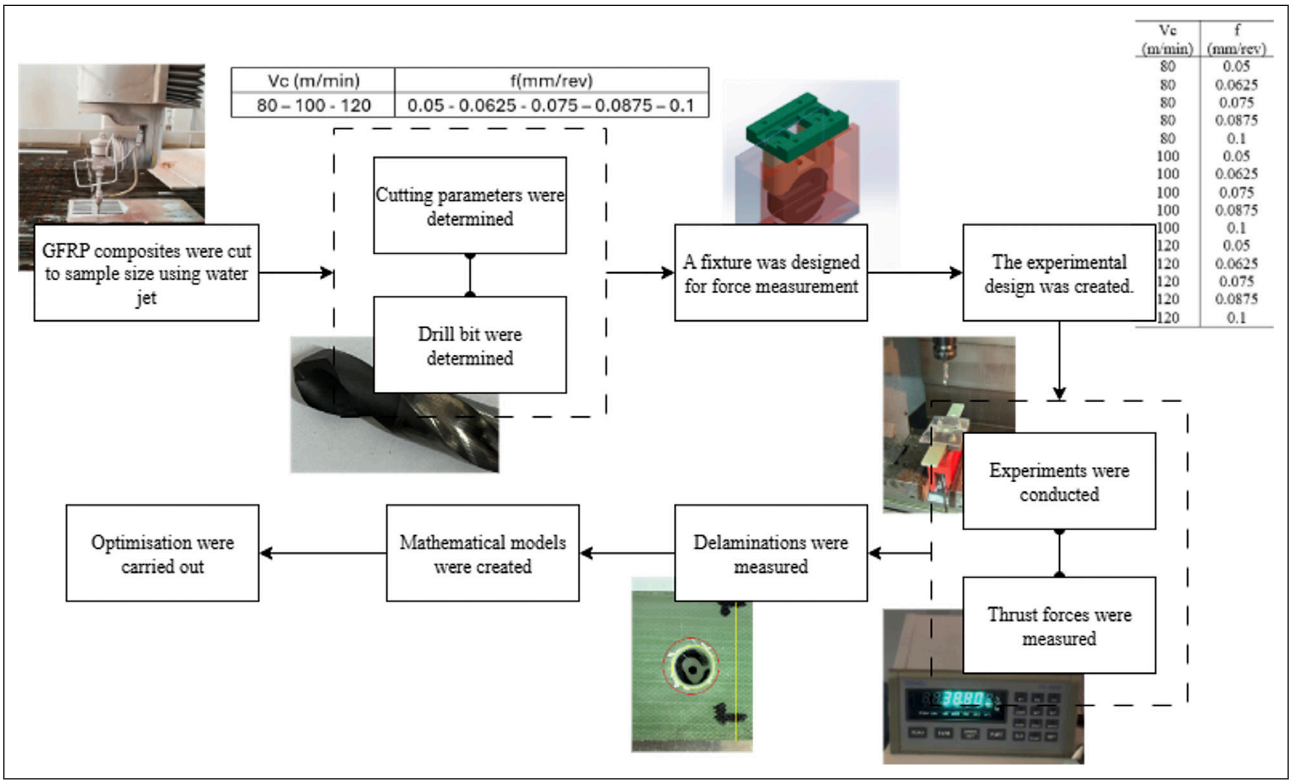
As a result of the experiments, variance analysis was applied to investigate the effects of input parameters on delamination, hole taper (conicity), and thrust force. The aim was to determine the cutting speed and feed values that minimize delamination, hole taper, and thrust force. Due to the limited number of experimental data points, optimization was performed using the RSM combined with the Desirability Function approach, which is suitable for small datasets [29].

RESULTS AND DISCUSSION

Drilling GFRP composites, widely used in industry, is difficult due to delamination. Regions affected by delamination a reduction in material strength [1], which can lead to assembly errors, non-compliance with tolerance requirements, and ultimately the rejection of manufactured parts or failure to meet the design specifications. These problems were controlled by optimizing cutting parameters to achieve minimum delamination and thrust force.

The results of the thrust force, delamination factor, and hole taper, resulting from feed and cutting speeds, are shown in Figure 6. It was observed that decreasing the feed resulted in a reduction in thrust force, delamination factor, and hole taper. The delamination factor and hole taper also decreased with decreasing cutting speed. While the thrust force was low at the upper and lower cutting speed values, the thrust force was high at the middle cutting speed values. Variance analysis was preferred to examine the relationship between the input parameters and the output responses.

Analysis of Variance (ANOVA) is a statistical analysis technique used to determine the significance of independent variables, called input parameters, on the output responses obtained because of the input parameters. ANOVA



Vc (m/min)	f(mm/rev)
80 – 100 - 120	0.05 - 0.0625 - 0.075 – 0.0875 – 0.1

Vc (m/min)	f (mm/rev)
80	0.05
80	0.0625
80	0.075
80	0.0875
80	0.1
100	0.05
100	0.0625
100	0.075
100	0.0875
100	0.1
120	0.05
120	0.0625
120	0.075
120	0.0875
120	0.1

Figure 3. Flowchart.

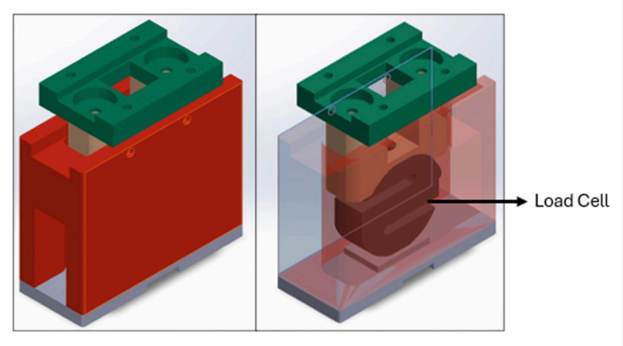


Figure 4. Load cell protective fixture.

determines the effect ratios of input parameters on output responses. It also determines whether there is a significant relationship between input parameters and output responses [30]. Variance analysis at a 95% confidence level for thrust force, delamination factor, and hole taper is presented in Table 2. The table includes the percentage contributions and p-values for individual parameters and their interactions. P-values lower than 0.05 indicate that the corresponding parameter has a statistically significant effect on the output response.

Examination of the ANOVA results indicated that both cutting speed and feed have a significant effect on thrust force, delamination, and hole taper. Feed was the most effective parameter on thrust force, whereas cutting speed had a greater effect on delamination and hole taper. Mahesh et al. [31] also reported in their study that cutting speed was the most effective parameter on delamination and that cutting speed had a greater impact on taper than feed.

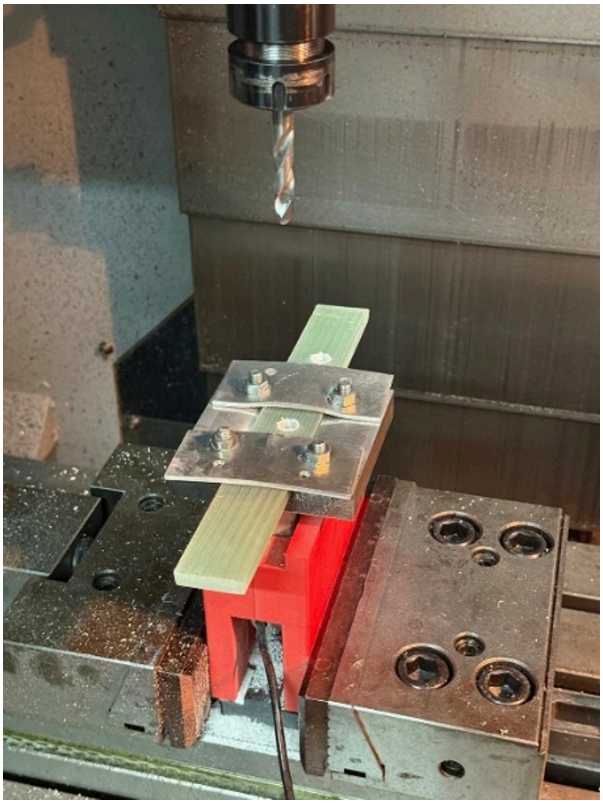


Figure 5. Test sample.

The response surface method is an empirical modeling approach used to determine the relationship between different input parameters and output responses [30, 32].

Table 2. ANOVA results for thrust force, delamination factor, and hole taper

Output	**Fz**		**Df**		**C**	
Source	**Contribution**	**P-Value**	**Contribution**	**P-Value**	**Contribution**	**P-Value**
Model	98.77%	0.000	94.89%	0.000	91.87%	0.000
Linear	70.23%	0.000	50.13%	0.000	39.88%	0.000
V_c (m/min)	5.42%	0.000	33.61%	0.000	28.66%	0.000
f (mm/rev)	64.81%	0.000	16.52%	0.000	11.22%	0.006
Square	23.38%	0.000	13.33%	0.003	25.81%	0.002
V_c (m/min)*V_c (m/min)	22.96%	0.000	13.30%	0.001	25.72%	0.000
f (mm/rev)*f (mm/rev)	0.43%	0.110	0.04%	0.807	0.09%	0.754
2-Way Interaction	5.16%	0.000	31.42%	0.000	26.18%	0.000
V_c (m/min)*f (mm/rev)	5.16%	0.000	31.42%	0.000	26.18%	0.000
Error	1.23%		5.11%		8.13%	
Total	100.00%		100.00%		100.00%	

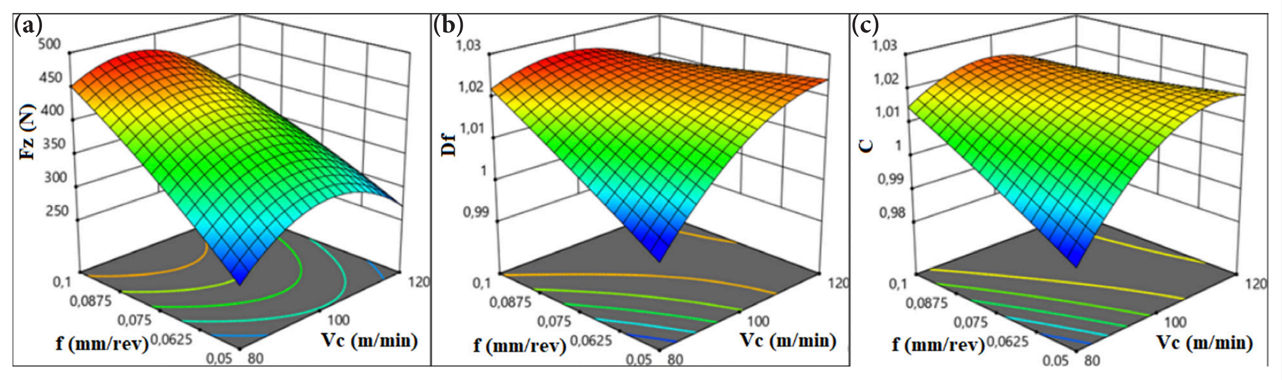


Figure 6. Flowchart.

In order to determine the effects of feed and cutting speed factors, second-order mathematical models were developed using the response surface methodology for the outputs of thrust force, delamination, and hole taper. Based on the experimental data, Equation 1, Equation 2, and Equation 3 represent the relationship function between the input parameters and the measured outputs. Where ε represents unexplained experimental errors.

Output function for the thrust force:

$$Fz=f(Vc,f)+\varepsilon \tag{1}$$

Output function for the delamination factor:

$$Df=f(Vc,f)+\varepsilon \tag{2}$$

Output function for the hole taper:

$$C=f(Vc,f)+\varepsilon \tag{3}$$

The second-order equations based on the Response Surface Method are given in Equation 4, Equation 5, and Equation 6.

$$Fz=\beta_0+\beta_1.V_c+\beta_2.f+\beta_3.V_c.V_c+\beta_4.f.f+\beta_5.f.V_c \tag{4}$$

$$Df=\beta_0+\beta_1.V_c+\beta_2.f+\beta_3.V_c.V_c+\beta_4.f.f+\beta_5.f.V_c \tag{5}$$

$$C={}_0+\beta_1.V_c+\beta_2.f+\beta_3.V_c.V_c+\beta_4.f.f+\beta_5.f.V_c \tag{6}$$

The regression equations with a confidence interval of 95% have a confidence level of 98.77%, 94.89%, and 91.87%, respectively. The regression equations generated using the Response Surface Method are given in Equation 7, Equation 8, and Equation 9.

$$Fz=-1787+35.01*V_c+10241*f-0.1609*V_c^2-15829*f^2-49.83*f*V_c \tag{7}$$

$$Df=0.6979+0.004646*V_c+1.866*f-0.000016*V_c^2-0.59*f^2-0.01589*f*V_c \tag{8}$$

$$C=0.5567+0.00714*V_c+2.171*f-0.000027*V_c^2-1.19*f^2-0.018*f*V_c \tag{9}$$

Table 3. Explanatory power of models

Output Respose	**R^2 (%)**	**R^2 adj (%)**	**R^2 pred (%)**
Thrust Force - Fz (N)	98.95	98.37	96.52
Delamination factor - Df	95.75	93.39	87.96
Hole taper (conicity) - C	93.9	90.52	74.97

When the relationships between the input parameters (independent variable) and the output values (dependent variable) were examined, the coefficient of determination (R^2) for the explanatory power of the models was found to be 98.95% for thrust force, 95.75% for delamination factor, and 93.9% for hole taper. The predictive capability of the models was determined as 96.52% for thrust force, 87.96% for delamination factor, and 74.97% for hole taper (Table 3).

Table 4. The objective/target and importance levels of optimization

Output / response	Objective	Target value	Upper limit value	Degree of importance
Fz	Minimize	262.908	478.728	2
Df	Minimize	1	1.026	5
C	Minimize	1	1.027	4

Table 5. Combined desirability optimization outputs

Combined desirability	Vc (m/min)	f (mm/rev)	Fz (N)	Df	C
1	80	0.05	257.504	0.997≅1	0.987≅1

A statistically significant relationship was observed between the input parameters and the output responses.

The high-reliability mathematical models developed in this study enable the prediction of thrust force and the resulting deformation during drilling within the defined drill bit and parameter ranges, without conducting experiments.

Increasing the feed rate from 0.05 mm/rev to 0.1 mm/rev led to a substantial rise in thrust force from 262 N to 478 N. This trend agrees well with results commonly reported in the literature; however, the absolute force levels are higher than those in some studies due to differences in specimen thickness and drill diameter. For example, Vankanti and Ganta reported a maximum thrust force of approximately 78 N when drilling 4 mm thick GFRP laminates using a 10 mm HSS drill [33], whereas the minimum thrust force measured in the present study was 262 N, primarily due to the more than twofold increase in laminate thickness (8.6 mm). Similarly, Abrão et al. [5] reported thrust force values of around 140 N for 2.5 mm thick GFRP laminates drilled with 5 mm diameter tools. In contrast, Latha et al. [34] observed thrust forces of up to 270 N using different drill geometries, which closely match the lower thrust force levels obtained in this study.

The delamination factor values obtained in the present study range from 0.999 to 1.026, indicating markedly superior hole quality compared to previously reported results. For instance, Rubio et al. [35] reported delamination factors between 1.151 and 2.143, while Kilickap [17] and Babu et al. [36] documented minimum values of 1.11 and 1.06, respectively. Importantly, even the maximum delamination factor in this study (1.026) remains below these reported minimum values, demonstrating the effectiveness of the SDC-type drill geometry in suppressing delamination. These results are comparable to the low delamination factor of 1.006 reported by Mohan et al. [37] under optimized conditions and indicate a stable drilling performance under the selected parameter ranges.

The Desirability Function approach is a multi-objective optimization technique commonly used for industrial problems with limited data sets. The purpose of multiple response optimization is to determine the conditions that yield the optimal values of the output (response) variables with respect to the indipendent variables. In this method, individual desirability functions are defined for each response. Three different performance outputs were evaluated within the scope of the study: thrust force, delamination factor, and hole taper. Because minimizing output values is crucial, optimization was performed using the " smaller is better" approach for all criteria.

The desirability value (di) for each output value was normalized between 0 and 1. The desirability value can assume values of 0, between 0 and 1, or 1. If the response value is less than the minimum value, the desirability value is di=1. If the response value is greater than the maximum value, the desirability value is di=0. If the response value is between the minimum and maximum values, the desirability value is between 0 and 1. The overall or combined desirability (D) evaluates how input parameters optimize a set of responses. Combined desirability is the weighted geometric mean of the individual desirability for the results, that is, the responses (Equation 10).

$$D = (d_1^{w1} * d_2^{w2} * \dots * d_n^{wn})^{1/w} \qquad (10)$$

Here, n represents the number of response values, w represents the sum of the individual weights, where the sum of the weights equals one. The weight determines how the desirability is distributed between the lower or upper limits and the target value.

In this study, the three output variables were evaluated simultaneously, and a single optimization model based on the combined desirability function was employed to determine the optimal levels of the input parameters. The targets and objectives were selected separately for each output to accurately determine the effects on the combined desirability. The objective was to minimize the output parameter value. The target values were selected as the minimum of the output values. The weight value can vary between 0.1 and 10 to determine the importance of reaching the target value [38, 39]. During the optimization, the importance levels of the delamination factor and hole taper were set higher than the importance levels of the thrust force. The importance of the parameters was kept high because delamination causes a decrease in the strength of the material, and hole taper causes inconsistency in tolerance values. The objective during optimization was to minimize all output values, and the target was to have no delamination and taper, i.e., that the delamination and taper outputs be equal to one (Table 4).

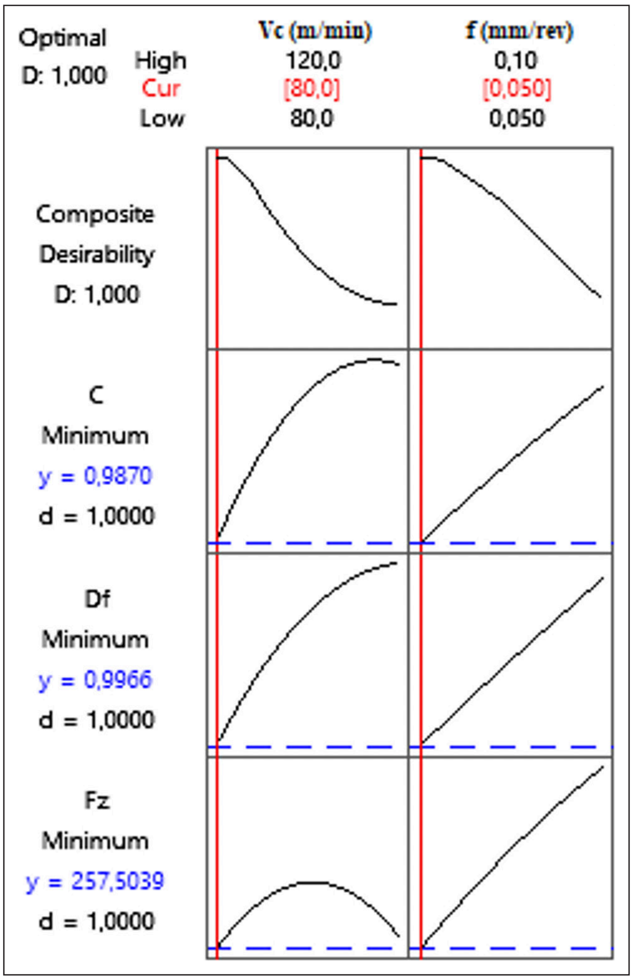


Figure 7. Influence plots for optimization of GFRP composite drilling using desirability function.

As a result of the optimization carried out using the defined objectives, targets, and importance weights, the combined desirability value was obtained as 1. A combined desirability value equal to or close to 1 indicates that all optimization criteria were achieved at the target values or at levels better than the targets [30, 40]. This demonstrates that the selected parameter combination represents an optimal point for multi-response optimization. It was observed that minimum cutting speed and feed values provide minimum thrust force, delamination factor, and hole taper. Gemi et al. [7] Abdul Nasir et al. [22] and also reported that the thrust force was lower with decreasing feed, while Kilickap et al. [17] emphasized that lower delamination occurred with low feed and cutting speed, and Shyha et al. [41] emphasized that decreasing feed decreased damage at the entry and exit. The optimum result was obtained at a cutting speed of 80 m/min and a feed value of 0.05 mm/rev. The thrust force was 257.504 N, and the delamination factor and hole taper values were ≅1 (Table 5).

Figure 7 shows the effects of the drilling parameters on individual output values and a set of output values (combined desirability) in the drilling process of a glass fiber-reinforced polymer composite using a desirability function. A linear relationship is observed between feed and the output values, indicating that an increase in feed results in higher values of thrust force, delamination factor, and hole taper. An increase in cutting speed led to a linear increase in hole taper and delamination factor, whereas the thrust force observed a parabolic trend. In the studies by Abd-Elwahed [4] and Birik-Urban et al. [16] a linear increase in thrust force was observed with increasing feed rate, while cutting speed showed lower thrust force values at all levels except at the mid-range level. Similarly, Işık et al. [15] reported a linear relationship between feed rate and cutting force, with lower cutting force observed at the non-linear mid-range level cutting speed. The relatively low influence of cutting speed on thrust force may be attributed to differences in drill geometry and the selected parameter levels, which can result in a non-linear effect. Within the range of the determined parameter levels, it is observed that if the cutting speed is too high or too low, a lower thrust force will be produced. The optimum thrust force occurred at the lowest cutting speed. The three-dimensional graphs of the experimental results clearly match the effect graphs for optimization (Fig. 6, 7).

Gemi et al. [7] and Xu et al. [10] highlighted the importance of drill type in their studies. The drill bits affect delamination at both the entry and exit of the hole. The SDC-type cutting inserts used in this study contribute to the reduction of delamination by reducing the thrust force due to their three-point angles. In addition, the short cutting-edge length, suitable helix angle, and optimized flute geometry of the SDC-type drills limited heat generation, resulting in longer tool life and a stable drilling process [42]. No fiber pull-out or splintering issues were observed during drilling.

Although the present study provides meaningful insights into the optimization of drilling parameters for GFRP composites using RSM and desirability function analysis, certain limitations should be acknowledged. The experimental investigation was restricted to a special drill geometry and a specific GFRP laminate configuration. As a result, the potential effects of different drill point angles, tool coatings, and laminate stacking sequences on thrust force, delamination behavior, and hole quality were not investigated. Therefore, the generalization of the obtained results to other tool designs or composite configurations should be approached with caution. Future studies may extend the current framework by conducting comparative drilling experiments using various drill geometries, such as brad-point, step, or coated drills, as well as GFRP laminates with different fiber orientations and stacking sequences. Moreover, a comparative assessment of holes produced with the same nominal diameter using alternative machining techniques, including abrasive water jet cutting, could provide valuable insights into the differences in damage mechanisms, delamination characteristics, and overall hole quality. Such comprehensive investigations would contribute to a deeper understanding of machining-induced damage in composite materials and enhance the broader applicability of the findings reported in this study.

CONCLUSIONS

In this study, the drilling of glass fiber-reinforced polymer composite materials using air-cooled special drill bits at different cutting speeds and feed parameters was experimentally investigated. The thrust force generated during the drilling process and the resulting hole deformation damage were examined, and the optimum cutting parameters were determined.

The cutting parameters have a significant effect on thrust force, delamination factor, and hole taper. While the effect of cutting speed on the thrust force is relatively low, the effect of feed is considerably high. The thrust force increases with increasing feed. At a cutting speed of 80 m/min, a 50% increase in feed led to a 35.8% increase in thrust force. At 100 m/min, the same feed increase resulted in a 20.1% rise, and at 120 m/min, a 29.1% increase in thrust force was observed. Conversely, at a feed of 0.05 mm/rev, increasing cutting speed from 80 to 120 m/min (a 25% increase) resulted in a 26.1% rise in thrust force. For feeds of 0.0675, 0.075, 0.0875, and 0.1 mm/rev, the corresponding increases were 19.6%, 11.5%, 7%, and 7%, respectively. Increasing cutting speed from 80 to 120 m/min (50% increase) did not significantly affect thrust force at lower feeds, while at higher feeds, a reduction of approximately 18% was observed. Within the specified parameter range, thrust force was observed to be low at both the lowest and highest cutting speed values. However, the minimum thrust force was obtained at the lowest cutting speed values.

Cutting speed has a greater effect on the delamination factor than feed. Analysis results indicate that the effects of cutting speed and the interaction of cutting speed and feed on the delamination factor are quite high and similar. This also demonstrates the interrelationship of cutting parameters. Minimum delamination was achieved at low cutting speed and feeds.

The effect of cutting parameters on hole taper is similar to that observed for the delamination factor. Cutting speed has a greater effect than feed, and the effects of cutting speed and the interaction of cutting speed and feed on the delamination factor are quite high and similar. Minimum hole taper difference was obtained at low cutting speed and feeds.

The developed models at a 95% confidence interval exhibited reliability levels of 98.95% for thrust force, 95.75% for delamination factor, and 93.9% for hole taper, indicating strong statistical significance. The models are found to be highly significant. The predictive capability of the models was 96.52% for thrust force, 87.96% for delamination factor, and 74.97% for hole taper. These results confirm the high predictive performance of the developed models for the selected parameter ranges.

Optimization using the defined objectives, targets, and importance weights resulted in a combined desirability value of 1. A combined desirability value equal to or close to 1 indicates that all optimization criteria were achieved at or better than the specified target values. As a result of the optimization using the desirability function, the optimum result was achieved at the lowest cutting speed of 80 m/min and the lowest feed of 0.05 mm/rev within the level ranges.

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Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Yunus Emre Nehri: Investigation, Experimental Design, Optimization, Validation, Writing.

Mert Şener: Optimization, Validation, Writing, Original Draft Preparation.

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Ali Oral: Methodology, Review, Editing.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethics

The study presented in this paper does not have any ethical issues or no ethical approval was needed to conduct the investigation. The study is not patented or a trade secret of GENBA Group (Balıkesir, Turkey), where Mr. Osman Talha Dinçer is employed.

Statement on the Use of Artificial Intelligence

Artificial intelligence was not used in the preparation of the article.

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