A STATISTICAL APPROACH TO THE MECHANICAL CHARACTERISTICS OF COMPOSITE DRILLING

Tadeght Mohammed[1], Bendifallah Mourad[2], Abdelkrim Mourad[1], Belloufi Abderrahim[1], Mezoudj Mourad[1]

1Laboratoire de Mécanique Appliquée et Systèmes Energétiques, Faculté des Sciences Appliquées, Université Kasdi Merbah Ouargla, Algérie.

[2]Center of Research in Mechanics, CRM, Constantine, Algeria

E-mail: belloufi.abderrahim@univ-ouargla.dz

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***ABSTRACT**: This work examines the effects of different drilling parameters on mechanical properties, using spindle speed (360, 700 and 1400 rpm) as an example, feed rate (0.15, 0.25, and 0.40 mm/rev), and tool diameter (4, 6, and 9 mm) on delamination factors when drilling composite materials, with a focus on the cutting process and its impact on material integrity. The experiments were performed using HSS drills, and the experimental design was formulated based on the effects of different drilling parameters were evaluated using a variance model (ANOVA).*

The results obtained will assist manufacturers in selecting the optimal machining conditions to enhance machinability for newly developed materials in the industry.

***KEYWORDS**: composites. Drilling. Delamination. ANOVA. RSM.*

1 INTRODUCTION

Researchers are currently focusing on developing materials and improving their strength using natural fibers. Natural fibers can serve as reinforcements or fillers (Kannan & Thangaraju, 2022; Lee et al., 2021; Singh et al., 2018). Among the various plant fibers, jute fibers are particularly notable for their potential to reinforce polymer matrices as an ideal solution for glass fiber composites (Maiti et al., 2022). jute fiber based composites are primarily used in systems and applications in the broad engineering sector, including joinery and safety systems in electrical cabinets(Akter et al., 2024). It can also be found in vehicle manufacturing and transportation media, such as car interior panels, truck floors and used as pallets (Jensen, 2017). In recent years, interest in biomaterials has grown due to the need to preserve nature and human health.

The primary advantages of composites include their low pollutant emissions, cost-effectiveness, low density, and enhanced energy recovery. Additionally, they possess desirable properties such as non-abrasiveness and biodegradability (Nasir et al., 2015; Rajmohan & Palanikumar, 2013; Sathishkumar et al., 2022), making them a sustainable choice in response to environmental and economic concerns (Belaadi et al., 2013; Belaadi, Bezazi, Bourchak, et al., 2014; Lefeuvre et al., 2015). Among the most important advantages is the fact that it is widely available and abundant, which encourages its exploitation in the form of natural fibers.

However, the difficulties encountered in manufacturing these composites due to the nature of their variable and non-homogeneous properties create an obstacle to large-scale production(Amroune et al., 2015; Belaadi, Bezazi, Maache, et al., 2014; Benítez et al., 2013; Chaitanya & Singh, 2018; De Olveira et al., 2018; De Rosa et al., 2010).Despite the significant technical development of non-conventional machines, drilling remains the most widely used manufacturing process in the composites industry. Numerous research studies have been carried out into the drilling behavior of synthetic fiber composites (glass, carbon, aramid, etc.) (Baley, 2002; Bezazi et al., 2014; Goudenhooft et al., 2019; Manimaran et al., 2018; Resende et al., 2019). Several parameters influence the drilling process, such as the choice of drill and cutting conditions (Dobah et al., 2016; Feito et al., 2014; Wei et al., 2016). In the industrial sector, it is generally necessary to drill holes and circles to different, strict geometric tolerances. Choosing the best cutting parameters for drilling requires either experimental or theoretical techniques such as optimization methods (Azuan et al., 2012; Baraheni et al., 2021; Kanagaraju et al., 2016; Virk et al., 2011).

2 MATERIALS AND METHODS

The drilling tests were carried out on Bakelite which is an organically filled phenolic casting material reinforced with cotton fibre to improve breaking strength.

Table 1. Design of experiments

No	Factors	Notation	Levels		
			-1	0	+1
1	Spindle speed (rev/min)	N	360	700	1400
2	Feed rate (mm/tr)	f	0.15	0.25	0.40
3	Drill diameter (mm)	d	4	9	10

For this study, Bakelite samples were drilled using a radial drill to measure the damage they had sustained (fig 1). The composite used in this work was a rectangular plate 90 mm long, 50 mm wide and 10 mm thick.

The output delamination value (Fd) is used to estimate the resulting damage reduction. The output factor is determined using formula (1):

$$Fd = Dmax/D (1)$$

Dmax, indicating the maximum measurement of the damaged zone, and D the actual diameter of the drilling.

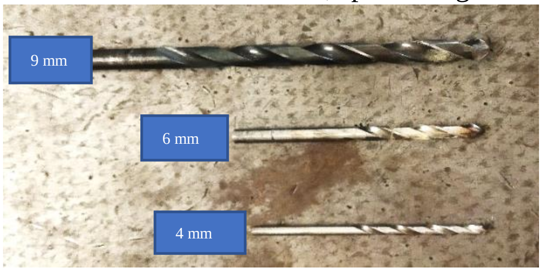
Table 2 Specifications for the machine

Spindle Speed 40–1400 rev/min
Feed rates f (mm/tr) = 0.08 – 0.40
Table size 800 × 360 mm

The drilling operation is executed using a radial drill with different parameter variations fiq.1.

Fig. 1 machines used

The experiments were executed with HSS drills of three different diameters, producing different



results fiq.2.

Fig. 2 Tools used

In this study, the structure of the experimental delamination device was evaluated after the drilling process fiq.3.

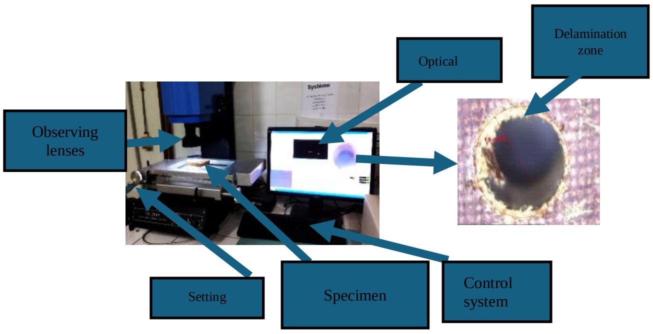


Fig. 3 Visual measuring system

3 STATISTICAL ANALYSES OF DRILLING

In this research, delamination was evaluated following the drilling process. A factorial design approach was A factorial design approach was employed to test the effect of feed rate (f) and spindle speed (N) on the delamination effect, selecting the three drilling tool diameters to be tested in the different experiments. The milling settings selected included the machining parameters assessed using a complete factorial design (L27) of 33, incorporating real independent process variables to provide comprehensive insights into the delamination behavior. The measured responses (outputs) results are given on Table 3

Table 3 Factors related to the effects of delamination

Drill diameter mm		Feed rate mm/min	Spindle speed rev/min	Fd = Dmax/D
1	4	0.15	360	1,107
2		0.25	360	1,094
3		0.40	360	1,134
4		0.15	700	1,073

5		0.25	700	1,082
6		0.40	700	1,093
7		0.15	1400	1,054
8		0.25	1400	1,069
9		0.40	1400	1,096
10		0.15	360	1,604
11		0.25	360	1,622
12		0.40	360	1,630
13		0.15	700	1,595
14	6	0.25	700	1,599
15		0.40	700	1,621
16		0.15	1400	1,550
17		0.25	1400	1,579
18		0.40	1400	1,602
19		0.15	360	2,386
20		0.25	360	2,427
21		0.40	360	2,499
22		0.15	700	2,353
23	9	0.25	700	2,280
24		0.40	700	2,497
25		0.15	1400	2,157
26		0.25	1400	2,313
27		0.40	1400	2,467

3.1. Effect of Drilling Parameters on Delamination Factor

Our experimental study revealed that certain drilling conditions significantly affect hole appearance and quality. Specifically, debonding occurs due to the feed rate (f) and spindle speed (N), with more pronounced disbanding on the outlet face compared to the entry face. Thus, the analysis above concentrates on delamination occurring at the end of the drilling hole. Many research results confirm that delamination is greater on the exit face of the hole compared to the entry face. Figure 5 illustrates the drilling process after drilling using feed rates of 0.15, 0.25 and 0.40 mm/rev with spindle speeds of 360 rpm. In addition, figure 4 demonstrates delamination around the holes, influenced by the parameters of the cut. So, for a drill with a small diameter of 4 mm and the choice of a speed of 0.15 mm/rev and 360 rpm of displacement and a rotational speed respectively indicated in table 2, we obtain a delamination value of 1.107 at the drill exit. Thus, we obtain a delamination value of 1.134 for the choice of a speed of 360 rpm of rotational speed and 0.4 mm/rev displacement of a speed. To assess the delamination occurring during the experimental drilling trials, we have plotted characteristic curves that show the influence from feed rate (f), tool speed (N) and drill diameter on the factor of delamination (Fd). near the hole exits. Fd was measured for holes drilled with various HSS drills of diameters 4 mm, 6 mm, and 9 mm under specific cutting conditions.

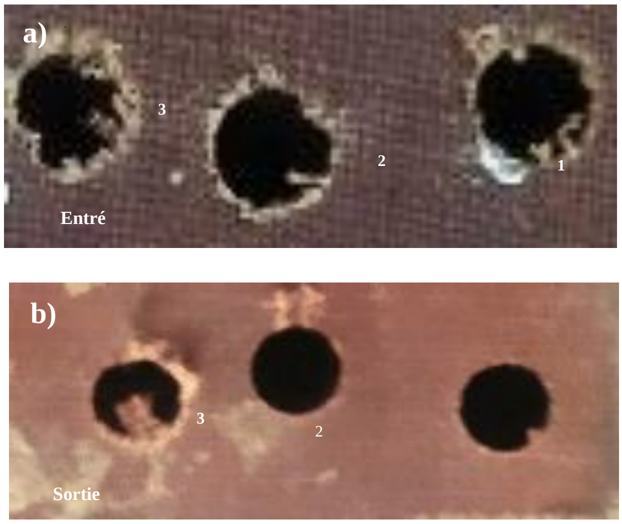


Fig. 4 Typical holes drilled on the sample: a) input) output

4 RESULTS AND DISCUSSION

The parts were drilled within the cutting parameters indicated above. All holes were compared in terms of delamination factor. Table 3 shows the combination of three different delamination factor values for each composite hole, with different spindle speeds and feeds, as well as different hole diameters.

From Table 3, the delamination effect factors indicate that feed speed plays a bigger part in the delamination process than spindle speed. Higher feed speeds also increase the delamination factor, while higher spindle speeds reduce it. At a feed speed of 0.15 mm/min, the delamination factor was approximately 3% lower compared to a feed speed of 0.4 mm/min, and around 5% lower at a spindle speed of 1400 rpm compared to 360 rpm

Conversely, the drill diameter was found to significantly influence the delamination factor. This study shows that smaller drill diameters result in less delamination compared to larger ones. For instance, in selecting the workpiece drilled with a 4 mm diameter tool cutter, at a tool advance speed of

0.15 mm/min and a tool cutting spindle speed of 560 rpm, delamination was reduced by around 31% compared to the workpiece drilled with a 6 mm diameter tool cutter, and by around 54% compared to the workpiece drilled with a 9 mm diameter tool cutter. These results indicate that the optimum cutting parameters are as follows (spindle speed of 1440 rpm, feed rate of 0.15 mm/min and drill bit diameter of 4 mm).

Thus, we can see that the findings of this work are consistent with earlier investigations conducted, for example, by Zohir et al(Tabet et al., 2021).

At about the identical moment, Lotfi et al (Aamir et al., 2020). demonstrate that an increase in machining tool speed reduces drilling cuttings to a minimum, while a higher feed speed, while a higher feed speed significantly increases the debonding factor.

4.1 Methodology for response surface

The response surface method (RSM) consists of a series of mathematical techniques used to model and evaluate a situation where the response studied is impacted by several different variables, with the goal of optimizing this response. The aim is to identify the optimal value of the response based on the influence of these variables (Lotfi et al., 2020; Rajendran et al., 2024).

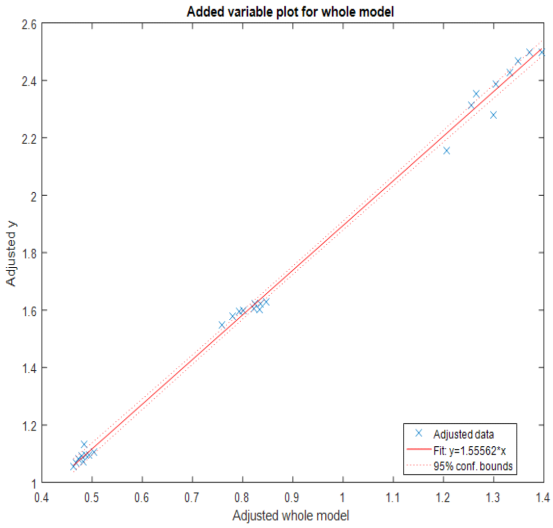
RSM involves three main components: Initial steps include experimental design, to define the factors governing the measurement of the experiences and the collected information; and the empirical conception, designed to assess the relationship between the results and the different variables; and finally optimization, which uses the empirical model to identify the optimal response value. These models are applicable for optimizing, simulating, or predicting the behavior of processes, such as drilling metal matrix hybrid composites, particularly in experimental settings (Khuri & Mukhopadhyay, 2010).

In this experiment, a complete factorial design of the RSM method was used for design obtained a quadratic design with 27 experiments. The operating levels and increments values of the independent variables (feed rate (f), spindle speed (N) and bore diameter (d)) are given in Table 6. Using the design of experiments given in Table 5, we developed a series of empirical second-order equations of the response variable (delamination factor) in relation to the independent variables, as illustrated using the following equation (2). In this study, the mathematical equation of the linear regression is calculated with MATLAB and is given by:

$$\begin{aligned} Y = {} & 0.33943 + 0.22747.* x1 + -1.2592.* x2 \\ & + -0.00012787.* x3 + 0.13669. \\ & * x1.* x2 \pm 1.7154e-05.* x1. \\ & * x3 + 0.00030547.* x2.* x3 \\ & + 0.00057037.* x1.^2 + 0.87407. \\ & * x2.^2 + 5.0707e-08.* x3.^2 \quad (2) \end{aligned}$$

The result of the proportion of variance of the response variable is given:

$R^2 = 0.9971$



Fiq. 5 Graphical representations of variables for the entire model

In conclusion, the graph of variables shows an independent factor important in explaining the degree of variance of the dependent factor, and that the fit of the model appears sound.

The fitted model was verified using the sequential P-value and coefficient of determination R2 as illustrated in the table below.

Table 6 ANOVA to check fitted model

	1 Estimation	2 SE	3 tStat	4 pValue
1 (inter.)	0.3394	0.148	2.2937	0.0348
2x1	0.22747	0. 343	6.6398	4.1782 e-06
3x2	-1.2592	0.6037	2.0858	0.0524
4x3	-1.2787e-04	1.3154 e-04	0.9721	0.3446

5x1 :x2	0.1367	0.0327	4.1790	6.2958 e-04
6x1 :x3	1.7154e-05	7.7618 e-06	-2.2101	0.0411
7x2 :x3	3.0547e-04	1.5524 e-04	1.9678	0.0656
8x1 ^2	5.7037e-04	0.0025	0.2321	0.8192
9x2 ^2	0.8741	0.9831	0.8891	0.3863
10x3 ^2	5.0707e-08	6.2766 e-08	0.8079	0.4303

4.2 Analysis of Variance (ANOVA) for the Delamination Factor

The variance (ANOVA) is analyzed and applied to test the model fit,the results of the ANOVA test are in the table below.

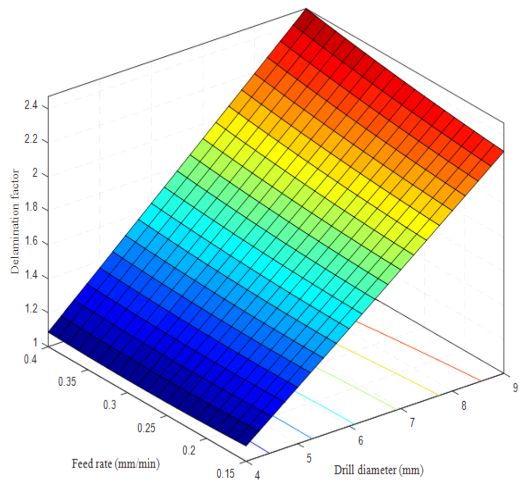
Table 7 Results of the ANOVA

	1 SumSq	2 DF	3 MeanSq	4 F	5 pValue
1x1	7.5505	1	7.5505	5.864 4e+03	5.0017 e-23
2x2	0.0339	1	0.0339	26.29 79	8.3880 e-05
3x3	0.0202	1	0.0202	15.72 09	0.0010
4x1:x2	0.0225	1	0.0225	17.46 37	6.2958 e-04
5x1:x3	0.0063	1	0.0063	4.884 5	0.0411
6x2:x3	0.0050	1	0.0050	3.872 2	0.0656
7x1^2	6.9345 e-05	1	6.9345e-05	0.053 9	0.8192
8x2 ^2	0.0010	1	0.0010	0.790 5	0.3863
9x3 ^2	8.4031 e-04	1	8.4031e-04	0.652 7	0.4303
10 Error	0.0219	17	0.0013	1	0.5000

The results of the variance analysis (ANOVA), derived from factor experiments, provide indications of the importance of individual and interacting factors controlling the process. In this table, you'll find information on degrees of freedom, sum of squares, mean square-values, probability and proportion of contribution respectively (DF,SS,MS,F,Prob,Contr. %) the relationship between each factor and their interactions. To calculate the mean square, divide the sum of the squares by the degrees of freedom (MS =SS/DF), then find the value of the proportion (F), which generally represents the mean squared error of the experimental error. In the context of a robust design, the value of F allows for a qualitative assessment of the relative impact of factors. A high F value indicates that a specific factor has a significant effect on experimental error variance. Thus, the higher the F-value, the greater the influence of the corresponding factor on the process response. Additionally, a smaller P-value indicates a higher statistical significance of that factor on the response (Dutta et al., 2019). The linear factors (f, N and d) in shown in Table 7, the squared factors (N × N and d × d) being significant, but using very low P-values (Prob. 0.05), the remaining coefficients are not significant (Prob. 0.05). Based on the data in Table 7, The spindle speed (N) and drill diameter (d) have a smaller impact on delamination in treated composites, compared to those with a major effect on delamination, the factor with the greatest and most significant impact on delamination is feed speed (f).

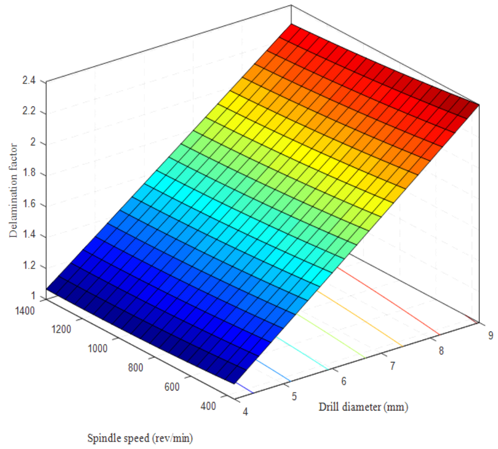
4.3 Delamination factor diagram

According to the graph, the feed speed and drill diameter is increased results in a higher delamination factor. Therefore, for best results (lower delamination), it may be advisable to use lower feed speeds and smaller drill diameters.

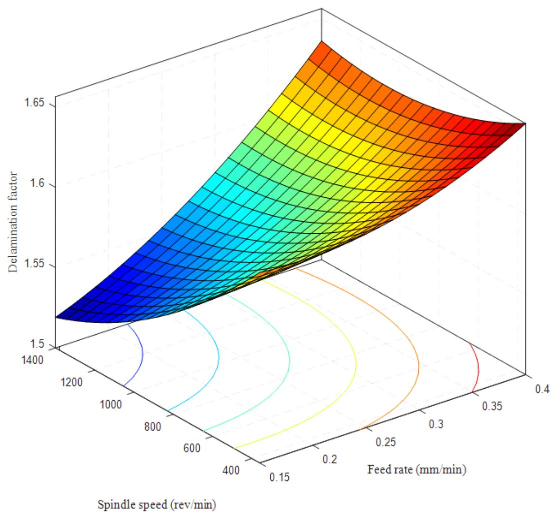


Fiq.6 Graph of delamination as a function of advance and drilling diameter

To minimize the delamination factor and reduce damage during the process, both spindle speed and drill diameter should be decreased. Higher spindle speeds and larger drill diameters result in a higher delamination factor, as indicated by surface elevation and a change from blue to red.



Fiq.7 Delamination factor depending on cutting speed and hole diameter



Fiq.8 Graph of delamination as a function of advance and tool speed.

To minimize damage and reduce the delamination factor, it is recommended to reduce tool speed and its advance to low levels. tool speed and his advance that higher tend to increase delamination, as evidenced by the elevated surface and red-colored areas.

4.4 Optimization of cutting conditions

The PSO method was used to solve the following optimization problem:

Min Y = 0.33943 + 0.22747.* x1 + -1.2592. * x2 + -0.00012787.* x3+ 0.13669.*x1.*x2 +-1.7154e-05.* x1.*x3 + 0.00030547.*x2.*x3 + 0.00057037.*x1.^2 + 0.87407.*x2.^2 + 5.0707e-08.*x3.^2;

Sous les contraintes

4<x1<9;

0.15<x2<0.4;

360<x3<1400 ;

The PSO algorithm was implemented in Matlab and the algorithm's excusions gave us the following solution:

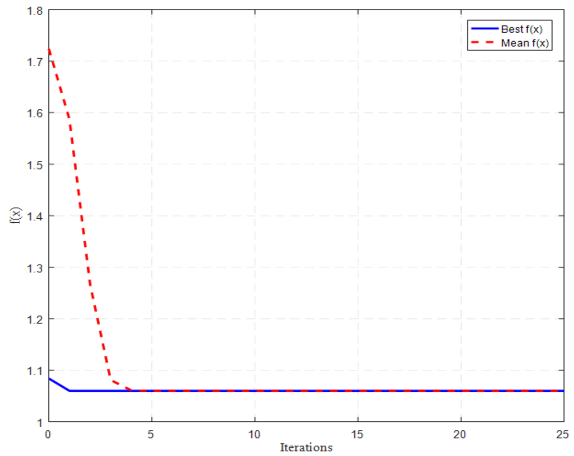
The PSO (Particle Swarm Optimization) algorithm was implemented using MATLAB to solve this optimization problem. During its execution, the algorithm went through an iterative process where particles, potentially representing solutions, were updated according to their own best solution found and the best solution found by the other particles in the swarm. After several iterations, the algorithm converged on an optimal solution, or one close to the global optimum. At the end of the run, the resulting solution was analyzed and evaluated. Algorithm parameters such as number of particles, convergence speed and stopping criteria were adjusted to achieve optimum performance. The resulting solution was used to solve the given optimization problem, providing a valuable answer or recommendation for the situation under study.

x1 = 4

x2 = 0.16291

x3 = 1400

The minimum Y value is 1.0595



Fiq.9 optimization result

The diagram can be used to illustrate the performance of an adaptive process (such as genetic algorithms) or any other optimization algorithm in which best and average values are tracked over time.

5 CONCLUSION

In this article, the drilling behavior of composites was investigated for the first time, using drilling tools with different cutting parameters. The influence of machining parameters, namely spindle and feed speeds, as well as drilling diameter, on the drilling process was evaluated in terms of delamination factor.

The following conclusions were drawn:

In effect, increasing the delamination factor rises due to the value of the feed rate, this factor decreases when cutting speed is increased, contrary to what Baraheni et al. stated(Dutta et al., 2019)[36], where the delamination value is almost uninfluenced by the cutting speed, smaller drill diameters caused less delamination than larger diameters . The delamination factor ranges from a maximum value of approximately 1.98 to a minimum value of around 1.01. The Optimum drilling quality in terms of delamination was achieved using a 1440 rpm drilling spindle speed with a drill diameter of 4 mm and a feeding frequency of 0.4 mm/min.

Increasing tool rotation speed reduces the tool-fiber interaction time at each increment, and this explains the observed reduced delamination factor. Importantly, the level of delamination varies with variations in the tool feed speed and the drill diameter, both of which have a significant impact on delamination. In addition, the value of the penetration force increases at higher feed rates and larger drill diameters, whereas it decreases at relatively elevated spindle speeds. Therefore, a similar force-torque tendency is maintained, with maximum force at relatively low spindle speeds and minimum force at medium and high spindle speeds.

From the experimental analysis, it can be concluded that low feed speeds and high feed speeds with high moderate spindle speeds are better suited to composite(bakilite) drilling, as they reduce drilling-induced damage.

The three-dimensional response surface plots clearly show that it is possible to find non-linear responses between system parameters and machinability parameters, confirming the chosen quadratic model. According to the results, the experimental and predicted factors for delamination were perfectly equivalent, resulting in a good ratio of the determination coefficients (R^2 = 0.9971). Settings optimal for minimizing Fd levels included a spindle advance speed of 0.16291 mm/min, machining spindle speed of 1440 rpm as well as drilling diameter of 4 mm.

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