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Original Article

A parametric study for drilling high quality holes on glass fiber composites

Sinan KESRİKLİOĞLU*, **Çağatay YILMAZ**

Department of Mechanical Engineering, Abdullah Gül University Faculty of Engineering, Kayseri, Türkiye

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ABSTRACT

The objective of this study is to investigate the effect of cutting parameters on the quality of holes drilled in a glass fiber reinforced thermoset polymer with the delamination factor defined as the ratio of intended hole diameter to the diameter of the maximum area which contains both hole and delaminated area. For this purpose, Taguchi's L9 orthogonal array was used to design the experiments and optimize the drilling parameters. 5 mm twist drill bits were used to drill the holes at various feeds and spindle speeds. The maximum diameters on the inlet and outlet sides of the holes drilled into the composite plates were then measured with an optical microscope to analyze the influence of the drilling parameters on the machining damage. The smallest delaminated area on the front and back sides of the composite plate was achieved with the lowest feed (0.05 mm/rev) for the drilling parameters used in this study. Even though the spindle speed was increased from 318 rpm to 2930 rpm at a constant feed of 0.05 mm/rev, it reduces the maximum diameter on the front and back sides by 9 μm and 266 μm, respectively. The obtained results showed that the material removal rates in the drilling of the glass fiber reinforced thermoset polymers can be increased significantly by setting the optimized process parameters without adversely affecting the hole quality.

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INTRODUCTION

Composite structures gain significant attention in the aerospace industry over the last decade due to their high specific strength, high specific modulus, and low cost when compared to their metallic counterparts. Although molding technique is used to produce near net shape composite structures, post processing (e.g., drilling) is still required to enable assembly with rivets and bolts. Drilling of composite structures is a complex process and needs special care to ensure the desired hole quality and dimension. The holes on the composite parts must be free of drilling-induced delamination and micro-crack to provide a good tensile and fatigue strength in the assemblies. A hole having an extremely large delamination area will reduce the fatigue life of the parts as well as cause an abrupt failure.

It can be seen from the literature that there are numerous studies on the machining of the glass fiber reinforced polymers (GFRPs) [1–6]. The effect of the feed, spindle speed, drill size, and fiber volume fraction on thrust force and torque generated during the drilling of random glass

***Corresponding author.**
*E-mail address: sinan.kesriklioglu@agu.edu.tr

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Table 1. Properties of composite used in this study

Tensile strength (S) [MPa]	Elastic modulus (*E*) [GPa]	Flexure strength (F) [MPa]	Density (ρ) [kg/m^3]	Volume fraction (v_f) [%]
1750	51.5	1500	1910	55

fiber reinforced polymeric composites was investigated. It was found that increasing the feed, drill size, and fiber volume fraction (>27.3%) causes an increase in the thrust force and torque [7]. The performance of cryogenic and dry drilling with TiAlN-coated carbide drill bit on the GFRPS was evaluated, but the experiments showed that cryogenic drilling was not able to improve the hole quality when compared to dry machining [8]. On the other hand, better drilling performances were observed with cryogenic cooling for carbon fiber reinforced polymers (CFRP) in other researches [9, 10].

Since the tool wear increases with the number of holes machined, the effect of wear on hole quality for high speed steels (HSS) drill bits was also studied [11]. Repeating experiments with the same tool showed that the critical number of holes that causes catastrophic wear (sudden drop in the performance of the tool) on the tool can be increased by super imposing vibration to drilling operation. Excessive tool wear occurred when drilling a number of 30 holes with the same drill bit with conventional drilling whereas it was at least 60 holes for the superimposed drilling [11]. The influence of drilling induced-damages on the tensile strength of unidirectional GFRP was also monitored. It was found that the tensile strength of the unidirectional GFRP diminishes with the area of drilling induced-damage [12]. Uncoated and TiAlN-coated twist drill bits were used in drilling of multidirectional and thick glass/epoxy composites. It was seen that uncoated tool performs better than the coated one with respect to the delamination and tool wear [13].

Drilling holes on aerospace grade GFRP parts is a significant process because a single jet engine aircraft can has up to 100.000 holes for fasteners and a commercial passenger transport aircraft can has holes up to 1.000.000 [7]. A safe flight of aircraft can only be achieved when all the drilled parts of an aircraft structure are intact. For that purpose, in this study, the drilling performance of HSS twist drill bit on an aerospace-grade GFRP was evaluated under different machining parameters. The effect of feeds and spindle speeds on the quality of drilled holes was assessed by measuring the delamination factors with an optical microscope. Taguchi and regression analysis were then performed to find the least significant parameter affecting the size of delaminated area around the hole in the drilling operation. This paper also provides expressions to calculate the delamination factors on the front and back sides of the glass fiber reinforced thermoset polymers with the spindle speeds and feeds.

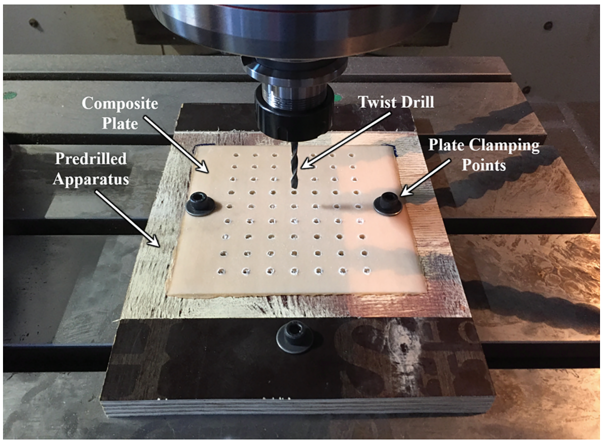

Figure 1. Experimental setup.

MATERIAL AND METHODS

A unidirectional (fibers aligned only in one direction) glass fiber reinforced epoxy plate with ten layers of glass fiber was used to show the contribution of the drilling parameters and determine the optimum machining conditions. The composite plate has a total thickness of 2.8 mm and a square shape with sides 160 mm. The tensile strength (S) and tensile elastic modulus (E), flexure strength (F), density (ρ), and volume fraction (v_f) of composite used in this study were determined according to ASM D 3039, ASTM D 790, ASTM D 792, ASTM D 2734 standards, respectively, and listed in Table 1.

Dilling tests were performed on a 3 axis CNC mill (*Hannsa YL 1000 B*) under dry cutting conditions. A wooden plate was first attached on the table of CNC mill as shown in Figure 1 and the front surface of it were faced with an indexable end mill to obtain a flat surface so that the holes machined are perpendicular to the surface of composite plates. Since the large size and nonplanar surfaces of the composite structures used in aerospace applications do not allow using a backup support easily, the holes with a diameter of 10 mm were drilled on the wooden plate so that the back side of the composite plate has a uniform support and free space for all the drilling tests. The glass fiber reinforced composite was secured on the pre-machined wooden plates with two M8 Socket head cap screws with washers to make a stable drilling operation and avoid the damages due to workpiece movement.

High speed steel twist drills with a diameter of 5 mm (*EVAR DIN 338/R-N*) were used in all machining tests. It has a point angle of 118 degrees and a helix angle of 30 de-

Table 2. Factors and levels in the experimental tests

Parameters	Level 1	Level 2	Level 3
Speed [rpm]	318	1146	2930
Feed [mm/rev]	0.050	0.150	0.300

Table 3. Taguchi L9 full factorial design and corresponding material removal rates

Test#	Speed (rpm)	Feed (mm/rev)	Speed (*N*) (rpm)	Feed (*f*) (mm/rev)	MRR (mm^3/min)
1	1	1	318	0.050	312
2	1	2	318	0.150	937
3	1	3	318	0.300	1873
4	2	1	1146	0.050	1125
5	2	2	1146	0.150	3375
6	2	3	1146	0.300	6750
7	3	1	2930	0.050	2877
8	3	2	2930	0.150	8630
9	3	3	2930	0.300	17259

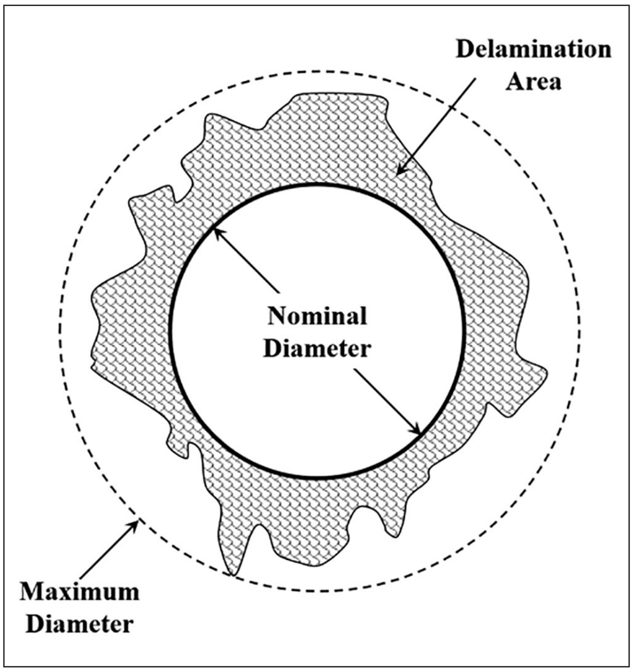

Figure 2. Calculation of delamination factor.

grees. In order to study the effects of cutting parameters on machining induced damages, three levels of rotational speed and feed were determined based on the minimum and maximum values used in the literature and initial observations for drilling glass fiber reinforced composite plates with HSS twist drill bits, and listed in Table 2.

A full factorial design of Taguchi L9 orthogonal array was selected to analyze the contribution of cutting parameters to the final hole dimensions, and ensure that all levels of all parameters are considered equally for a higher accuracy. Table 3 shows the rotational drilling speeds and feeds used in the experiments, and calculated material removal rates for each cutting sets. Material removal rates in the drilling operation are expressed by

$$MRR = \frac{\pi D_t^2 N f}{4} \tag{1}$$

where D_t is the diameter of the twist drill bit, N is the spindle speed and f is the feed. Since a high volume of material removal is desired to increase the efficiency of the machining process (i.e. drilling), all the experimental designs will enable to optimize the drilling operation for minimal hole damage. It should be noted that a new tool was used for each cutting set to avoid the effect of tool wear on hole damage. Each set of experiments was also repeated seven times to show reliable trends in the results.

As stated in the introduction part, delamination is a significant problem in the drilling of composite structures. It is caused by fiber pull out during the rotation of the tool and fiber-matrix debonding due to the thrust forces acting on the layers of composites as well as the thermal damage and cracks. Therefore, a delamination factor is defined to evaluate the damage size based on the maximum diameter as shown in Figure 2. It is calculated as the ratio of the maximum diameter to nominal diameter. In this research, the glass fiber composite plate was drilled with the parameters listed in Table 3 and the front and back side of the holes were imaged by an optical motorized microscope (*Zeiss AXIO Imager.M2m*) to measure the maximum diameter. All the results are discussed in the subsequent section.

RESULTS AND DISCUSSION

A total of sixty three drilling tests were carried out to investigate the effect of spindle speeds and feeds on the hole damage. Figure 3 shows the glass fiber reinforced composite plate after all the drilling tests. Among the nine different sets of drilling parameters, the most severe damages were observed on the front and back sides of the drilling test number 9 which has the highest material removal rate tested in this study.

As can be clearly seen from Figure 3, the glass fibers were not cut on the backside of the composite for all drilling conditions with HSS twist drills. This is because the plate is not supported completely, and/or the thrust force was higher than the interface strength between matrix and fiber although the speed and feed were as low as 318 rpm and 0.050 mm/rev, respectively. In addition to the visual assessments of the hole quality, the maximum diameters on the front and back sides were measured to quantitatively investigate the parameter effects on hole damage size. Figure 4 shows the maximum delamination size on the front and back sides

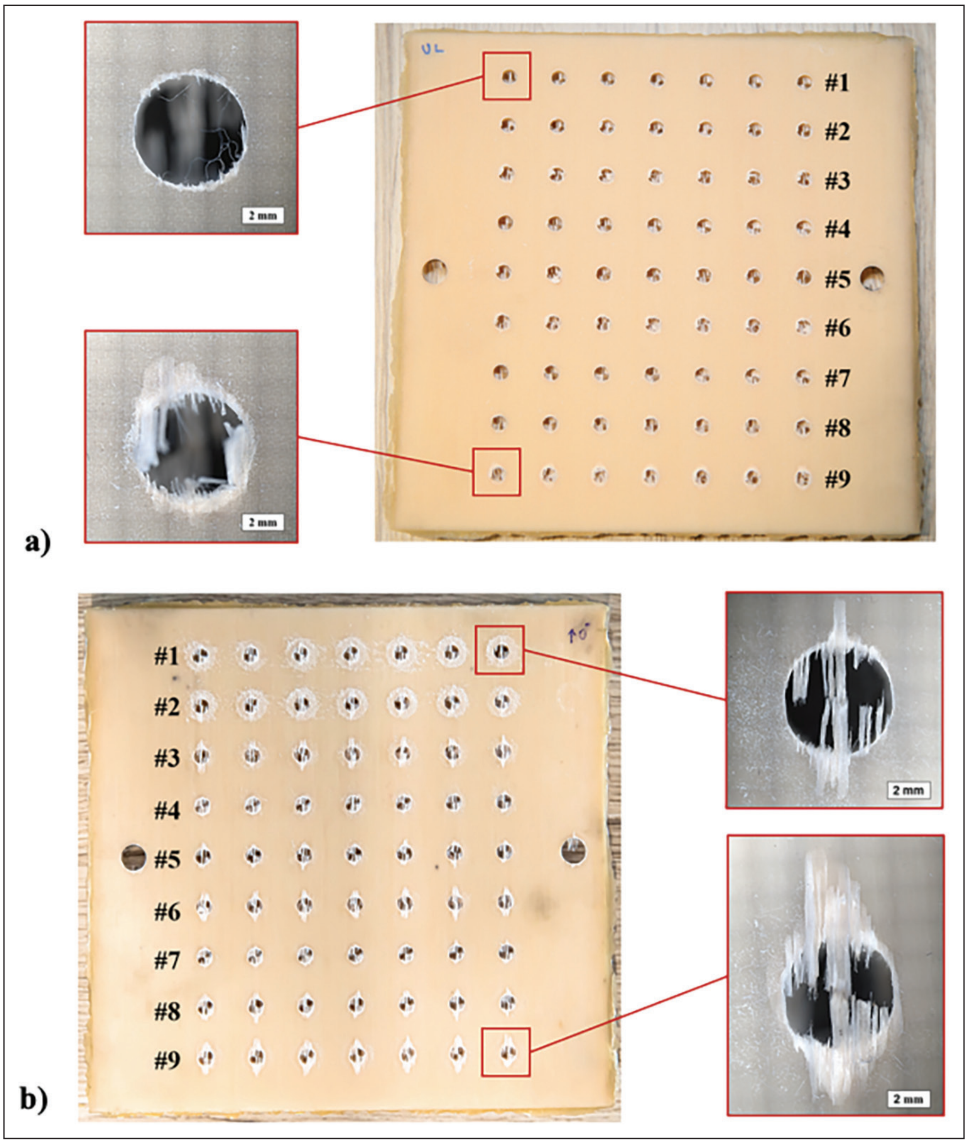

Figure 3. **(a)** Front and **(b)** back sides of the glass fiber reinforced composite plates after drilling tests.

for all cutting conditions. It was found that the damage on the back side was much higher than the front side for all drilling combinations although the trends are similar. Lowest delamination was observed at a spindle speed of 1146 rpm and feed of 0.050 mm/rev. The measurements from the back side also significantly deviate by 1036 μm at a feed of 0.150 mm/rev while they are smaller on the front side. It could be because of the ratio between the fiber layer thickness and axial uncut chip thickness. As expected, increasing the cutting speeds causes severe damages in the drilling of composite structures. However, Taguchi analysis will show, but it is also clear in Figure 4 and 4b that the magnitudes of the hole damage are similar at a feed of 0.050 mm/rev for all rotational speeds used in the experiments since the twist drill needs at least several rotations to pass one glass fiber in the composite plate. Therefore, increasing the spindle speed

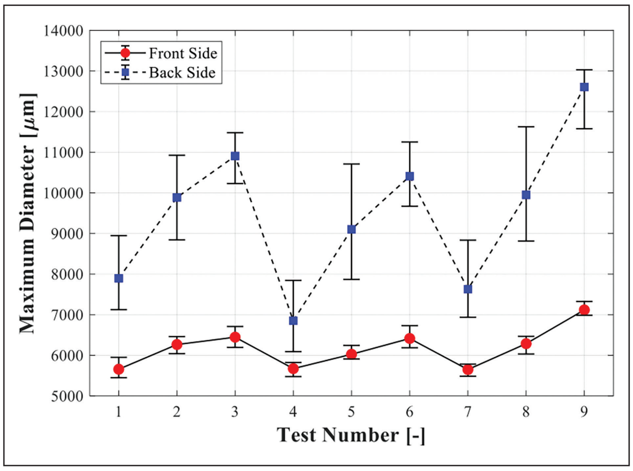

Figure 4. Maximum damaged size on the **(a)** front and **(b)** back sides of the composite plate.

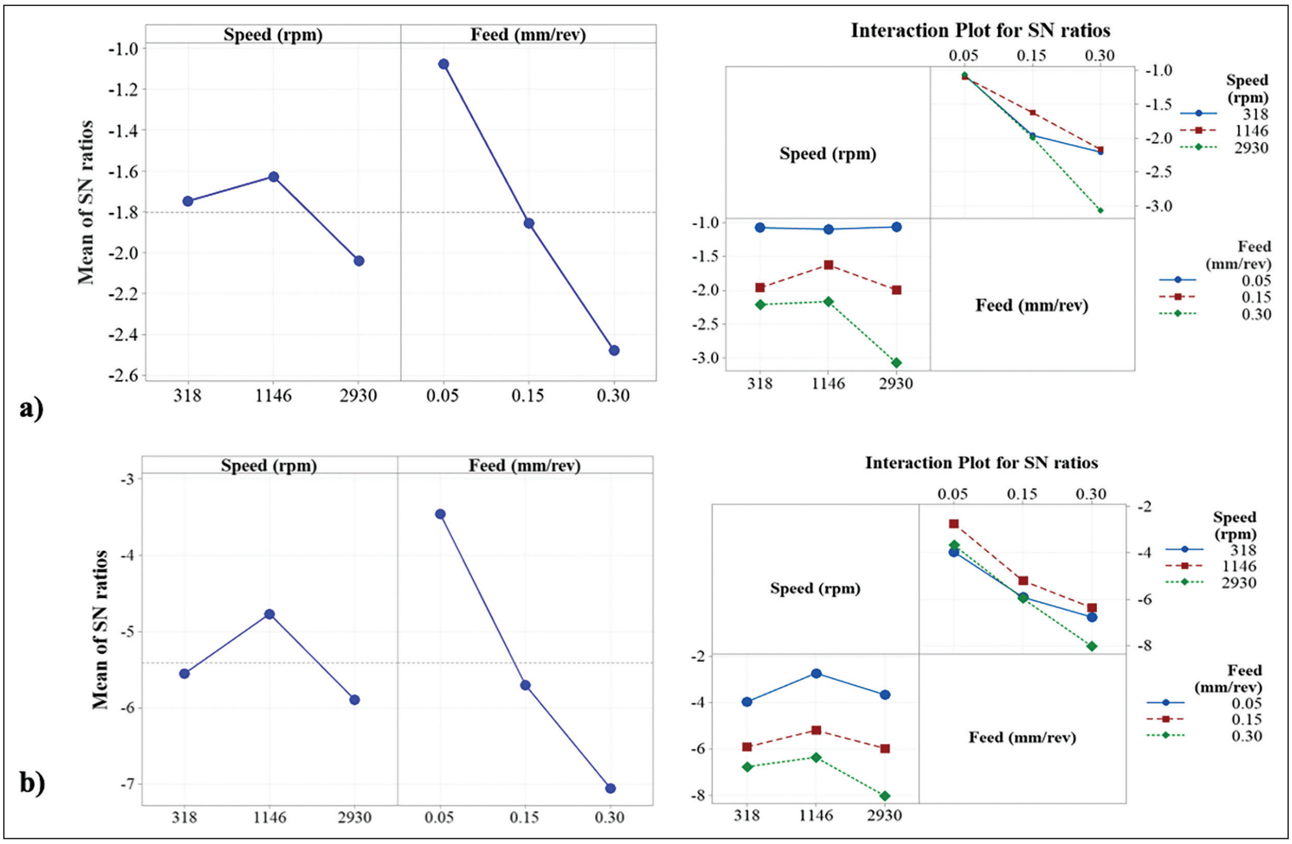

Figure 5. Effects of drilling parameters on the S/N ratio for the delamination factors on the **(a)** front and **(b)** back sides of the composite plate.

from 318 rpm to 2930 rpm at a constant feed of 0.050 mm/rev, increases the material removal rates in the drilling operation by 2564 mm^3/min and also achieves a reduction in the delamination size on the front and back side by only 9 μm and 266 μm, respectively. It should be noted that the maximum damage on the back side of the plate where the twist drill bit exits is greater than the diameter of the holes (10 mm) machined to the wooden backing plates for a feed of 0.300 mm/rev. Therefore, the damage size could be even larger if the holes on the wooden plate were drilled with a larger tool. Since 5 mm drill bits were used in composite machining, the authors were not anticipated that the delamination would be greater than twice the diameter of twist drills. Since the hole damage exceeding twice the nominal diameter is unacceptable in the aerospace industry, it is not necessary to perform further experiments to find the actual damage size for the set of drilling parameter.

Taguchi analysis was performed in a statistical analysis software (Minitab [14]) to determine the relative importance of the drilling parameters to the delamination factor. In this type of analysis, all factors are varied simultaneously instead of changing one factor at a time and keeping the other at a nominal value. Since a smaller delamination factor is desired, "smaller-is-better" signal to noise (S/N) ratio characteristics was selected in the analysis and it is given by

$$S/N = -10 * log(\Sigma(Y^2)/n)) \qquad (2)$$

where Y is the maximum diameter for the nth test in that trial and n is the number of tests in the factor level combination. Figures 5a and 5b show the control factor effects on the S/N ratios for delamination rate in the drilling of glass fiber composites with HSS twist drills. Although the influence of spindle speed and feed show similar trends for both sides of the composite plate, the magnitude of the mean S/N ratio is approximately three times larger for the back side. As can be seen from the interaction plots in Figure 5, the feed has a detrimental impact on the delamination size whereas spindle speed has minimal effect on the response. Therefore, in an efficient manner, the feed should be kept at 0.050 mm/rev while the spindle speed was set as high as possible when drilling glass fiber composites with HSS twist drill bits. It should be noted that these results might be particular to the fiber layer thickness used in this study. Using a constant feed to thickness ratio could increase the agreement between these findings and future experiments.

Figure 6 shows the delamination factors as a function of spindle speed and feeds in the drilling of the glass fiber reinforced composite. Regardless of the rate of spindle speeds, the lowest feed produces the minimum damage around the machined holes. Therefore, the spindle speed should be increased more than the feed to maximize the material remov-

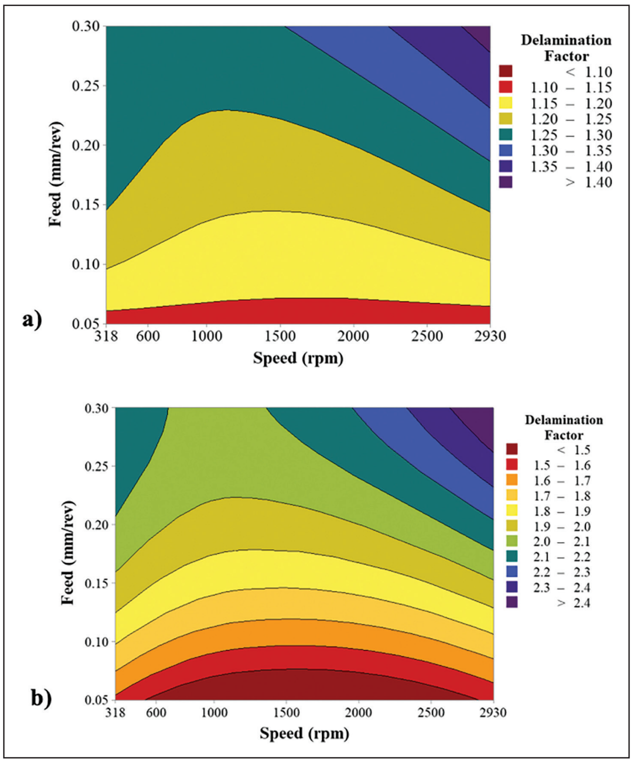

Figure 6. Delamination factor as a function of drilling parameters on the **(a)** front and **(b)** back sides of the composite plate.

al rate. On the other hand, the influence of the spindle speed and feed is almost similar for a feed above 0.200 mm/rev.

Regression analysis was also performed in Minitab to obtain the percentage contribution of the drilling parameters to the delamination size, and provide an expression for the operators and researchers working in the drilling glass fiber composites. In the regression analysis, the p-values of rotational speed were 0.177 and 0.297 for the models of the front and back sides, respectively while it is 0.001 in both regression models for the feed. For the front side, the percentage contribution of the spindle speed was predicted by 5.9 while it was 78.9 for the feed with a total error of 15.2 %. Moreover, the contribution of the speed was decreased by half on the back side model. This analysis also shows that the spindle speed should be increased instead of the feed to minimize the delamination area. In a linear regression analysis in Minitab, the delamination factors (DF) on the front and back side can be expressed as

$$DF_{Front\ Side} = 1.0735 + 0.000020\ x\ Speed + 0.786\ x\ Feed \quad (3)$$

$$DF_{Back\ Side} = 1.312 + 0.000055\ x\ Speed + 3.011\ x\ Feed \quad (4)$$

where the speeds are in revolution per min and feeds are millimeters per revolutions. Within the levels used in the experiments, the equation 3 and 4 estimate the delamination factors with maximum errors of approximately 5% for the front side and 11% for the back side in the drilling of the aerospace-grade glass fiber reinforced thermoset polymers.

CONCLUSIONS

An aerospace-grade glass fiber reinforced polymer was drilled with high-speed steel tools to investigate the effect of cutting parameters on the damage size. Taguchi method was applied to design the set of experiments and each set was repeated seven times with the same twist drill bit. A motorized optical microscope was used to qualitatively compare the influence of cutting parameters on the delamination area as well as measuring the size of damage on both sides of the composite plate. It was observed that for all drilling conditions, the delamination area was smaller on the front side than the back side where the drill bits exit although they show similar trends. Statistical analysis revealed that the spindle speed has low impact on the drilling induced delamination at low feed conditions, and the material removal rate in the drilling process of the composite plates can be increased by nine times with a minimal change in the delamination area. Regression analysis was also performed to obtain expressions for the prediction of damage size. With these equations, the delamination factor can be estimated with a maximum error of 15%.

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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

Sinan Kesriklioğlu: Conceptualization, machining tests, image processing, statistical analysis, original draft preparation, review and editing.

Çağatay Yılmaz: Conceptualization, composite plate fabrication, image processing, original draft preparation, review and editing.

Conflict of Interest

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

Ethics

There are no ethical issues with the publication of this manuscript.

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