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Research Article

CUTTING TOOL GEOMETRY IN THE DRILLING OF CFRP COMPOSITE PLATES AND TAGUCHI OPTIMISATION OF THE CUTTING PARAMETERS AFFECTING DELAMINATION

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ABSTRACT

It is possible to improve the hole quality by reducing the delamination which occurs in the drilling of carbon fibre reinforced plastic (CFRP) composite plates. For this study, carried out under dry machining conditions, the parameters included three different cutting speeds, three different feed rates and drill geometry involving three different point angles. The Taguchi L_9 orthogonal array experimental design was selected and the optimum cutting parameters and drill geometry for reducing the damage factor to a minimum were determined. The optimum test conditions were achieved using the parameter combination of 118° point angle, 30 m/min cutting speed and 0.06 mm/rev feed rate (A1B1C1). In addition, variance analysis (ANOVA) was conducted to determine the effect rate of the parameters on the damage factor. The variable having the greatest effect on the damage factor was found to be the point angle (47.66%), followed by the cutting speed (24.44%) and feed rate (19.82%). The conditions for minimising delamination damage in the drilling of the CFRP plates were optimised successfully by using the Taguchi test design.
Keywords: CFRP composite, drilling, delamination, design of experiments, ANOVA.

1. INTRODUCTION

Carbon fibre reinforced plastics (CFRPs) are found in widespread usage, especially in the aviation industry, where they are employed for structure parts in place of steel and aluminium. Furthermore, they are currently being used together with materials such as aluminium and titanium. In order to meet design requirements, CFRP materials are subjected to various machining processes, one of the most important of which is drilling. The drilling process is commonly applied to make it mechanically easier to connect CFRP plates with other parts. Along with the processing technology, studies done to improve drill quality are constantly increasing.

Optimisation is one of the most frequently applied methods for improving the outputs in the field of machining, as well as being used in all fields of engineering [1-4]. The tool material, tool geometry and cutting parameters all have a prominent role in minimising the delamination which occurs in the drilling of CFRP plates [5]. Optimisation of the cutting parameters to produce the minimum amount of delamination has been the subject of a great number of studies. In order to

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improve hole quality, determination of tool geometric values (e.g., point angle and helix angle) and sele ction of appropriate cutting parameters are both important [6-8]. Tsao and Chiu used drills having a special geometry in the drilling of CFRP plates. When analyzed, the experimental results revealed the chief factors affecting the thrust force to be the cutting speed, feed rate and the core of the special drill bit. This drill bit with the special geometry was shown to have the advantage of requiring lower cutting force, which resulted in less delamination and fiber accumulation and a high metal removal rate. Lower cutting speed and decreased cutting force and feed rate were recommended [9]. Iliescu et. al. evaluated the thrust force in the drilling of composite materials and examined the behaviour of coated and uncoated tools in improving hole quality and increasing tool life. A model was developed to explain the relation between the drilling parameters and tool wear. Experimental results showed that the feed rate, cutting speed and tool wear were the most important factors affecting the thrust force [10]. In another study, Karpat et al. investigated the effect of drill geometry having double point angles on drilling performance. Uncoated carbide and diamond-coated carbide drill bits were used in the experiments. Tool life tests were made and, based on the drill bit geometry, suitable drilling parameters were determined. As a result of the experiments, the feed rate was established as the most effective parameter on wear. In addition, the hole diameter tolerence at high feed rates was found to play a critical role, especially in the hole exits [11].

Holes of good quality improve assembly conditions and also play an important role in meeting other expectations involving the strength properties of the material under working conditions. The hole quality of CFRP materials is determined by the amount of damage that occurs following the drilling process. Examining the correlation of the damage factor with the cutting parameters and cutting tool geometry is an important step in the improvement of hole quality following the drilling process. Within this scope, drilling experiments were carried out by processing experimental plates in compliance with the Taguchi experimental design method. The optimum parameters were determined and their effect rate on the damage factor were revealed using analysis of variance (ANOVA).

2. EXPERIMENTAL PROCEDURE

2.1. Material and equipment

For the experiments, the CFRP plates (145 × 80 × 5 mm) were formed using the hand lay-up technique with vacuum bagging (0.1-0.2 mbar) and cured in an autoclave for 5 h at 80 °C. Hexion L160 epoxy resin and its hardener LR 160 (at a ratio of 28%) were included in the CFRP plates and Frekote 770 NC was used as the mould release agent. One of the composite plates is shown in Figure 1.

Figure 1. CFRP composite plate.

The plates were composed of 12-layered woven carbon fibre fabric. The mechanical and physical properties of the CFRP composite plate are shown in Table 1.

Table 1. The physical and mechanical properties of the CFRP composite plates.

Properties	Value
Thermal Coefficient of Expansion	2.1×10^{-6} K^{-1}
Compressive Strength	570 MPa
Density	1.6 g/cm^3
Shear Modulus	5 GPa
Shear Strength	90 MPa
Tensile Strength	600 MPa
Fibre Volume	50%
Modulus of Elasticity	70 GPa

Uncoated carbide tools of standard geometry, 8 mm in diameter and having three different point angles (118º, 130° and 140º) were used in the experiments. The carbide drill bits (TaeguTec) had a 118° point angle and a 30º helix angle, with some being ground down to 130° and 140º point angles. Figure 2 shows a drill bit photo and the geometrical dimensions of a bit with a 118º point angle.

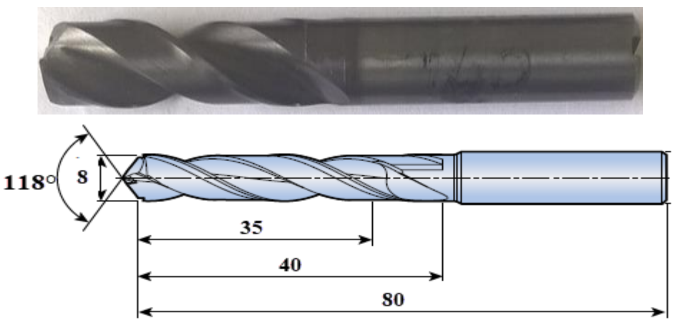


Figure 2. Drill bit photo and geometrical dimensions of a bit with a 118º point angle.

The experiments were carried out on a DELTA SEIKI CNC - 1050 A – CNC vertical processing centre having 11 kW motor power and maximum 10 000 rpm spindle. The CFRP composite plates were fastened onto the machine with the tool clamp and drilled using drill bits having point angles of 118°, 130° and 140°. All experiments were performed under dry machining conditions. The cutting parameters were prepared to comply with the Taguchi L_9 array, as shown in Table 2.

Table 2. The cutting parameters used in the tests

Drill bit material	Point angle (ε), °	Cutting speed (Vc), m/min	Feed rate (f_n), mm/rev
Uncoated Carbide	118	30	0.06
	130	60	0.08
	140	90	0.1

The drilling experiments were carried out with the plates held rigidly by the machine tool clamp which was fixed to the benchtop. The experimental setup is shown in Figure 3.

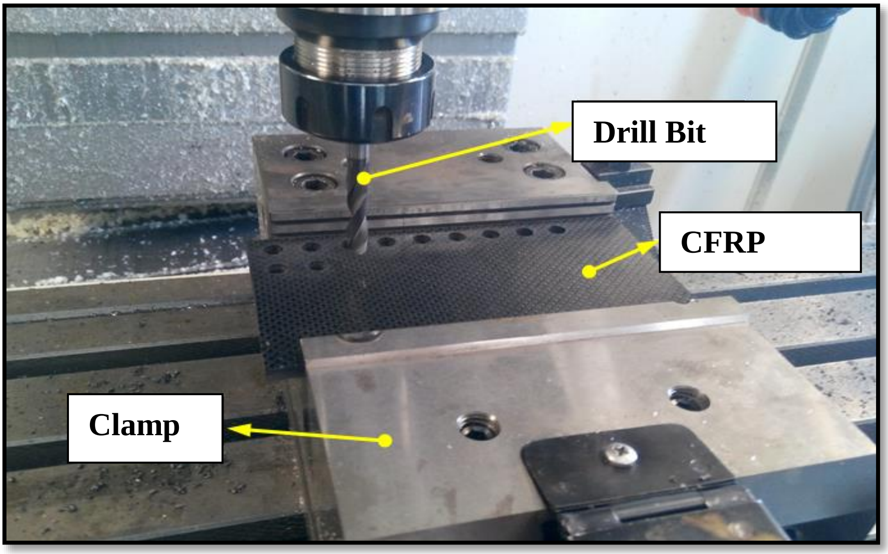


Figure 3. Experimental setup.

2.2. Determination of the damage factor

The establishment of the maximum damage diameter (D_m) is of vital importance in the determination of the damage factor (D_f). In order to find the maximum damage diameter (D_m), a line is drawn through the centre of the circle (hole), passing through the areas on both sides where the maximum damage is distributed. In the determination of D_m, the values X_1 and X_2, express the maximum damage on each side of the hole where the line passes through its centre. The maximum damage was calculated using Equation (1) and the damage factor was calculated using Equation (2) [12].

$$D_m = X_1+X_2+D \quad (1)$$

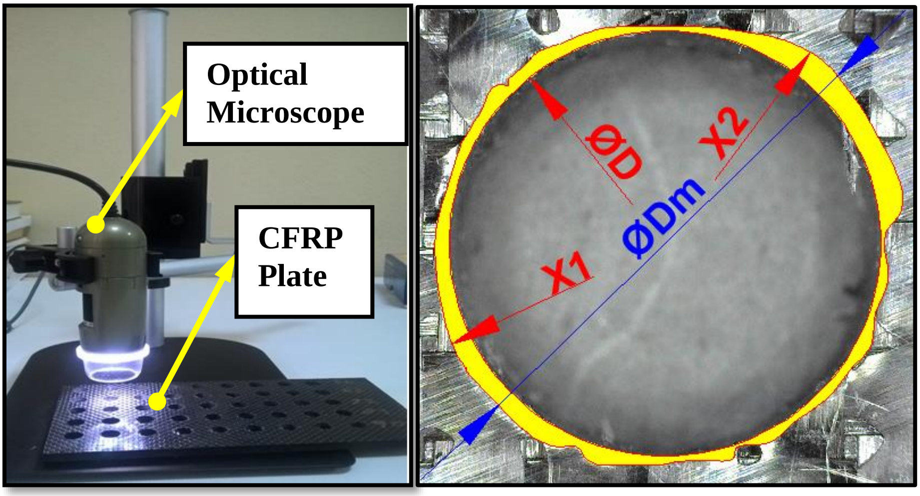
$$D_f = \frac{Dm}{D} \quad (2)$$

A toolmakers microscope was utilised to visualise the damage to the entrance of the hole. The optical (toolmakers) microscope and damage determination process are shown in Figure 4. The damage determined for a hole, measured as D, X_1 and X_2 , can be seen in Figure 4(b).

3. TAGUCHI EXPERIMENTAL DESIGN

The Taguchi method enables the reduction of the number of experimental trials by using determined arrays. Far from being just a test design technique, the Taguchi method is an extremely beneficial technique for high-quality system design. On the other hand, by decreasing the number of the tests, the interaction between the factors are ignored to a certain extent [13]. In order to evaluate the results, a statistical performance measurement known as the signal/noise (S/N) ratio is used. The results obtained from the tests are changed into the S/N ratio and an evaluation is made. The S signifies the signal factor in the ratio, and N signifies the noise factors

[14]. The uncontrollable (noise) factors are those which cause the functional characteristics of the product to deviate from the target value, i.e., result in poor quality [15].



(a) (b)

Figure 4. Scanning the hole damage: (a) Optical (toolmakers) microscope; (b) Measuring the scanned damage.

In the study, the cutting parameters and cutting tool geometry (point angle) were optimised for the damage factor occurring in the drilling of the CFRP composite plates. The cutting speed, feed rate and point angle were set as variables. There were three different levels for each variable and thus, the Taguchi method L_9 vertical array was selected. The variables and their levels are given in Table 3.

Table 3. Variables and levels.

Variables	Codes	Levels		
Point angle (ε), °	A	118	130	140
Cutting speed (Vc), m/min	B	30	60	90
Feed rate (f_n), mm/rev	C	0.06	0.08	0.1

Because the best hole quality is achieved by the reduction of the damage factor, the 'Smallest is Best' S/N equation was used. The 'Smallest is Best' performance characteristic is given in Equation (3):

$$S/N = -10\,.\log\left(\frac{1}{n}\,.\;\sum_{i=1}^{n} Y_i^2\right) \tag{3}$$

In Equation (3), *Y* signifies the damage factor and *n* signifes the number of the test. The effect levels of the variables on the damage factor were determined by applying ANOVA to the test results. Minitab 18 software was employed for the variance analysis at a 95% confidence interval.

4. RESULTS AND DISCUSSION

Table 4 shows the damage factor (D_f) data for the holes drilled in the CFRP composite plates according to the Taguchi L_9 vertical array and the S/N data calculated according to the 'Smallest is Best' performance characteristic.

Table 4. S/N ratios and damage factor data according to L_9 vertical array

Test No	A	B	C	Df	$\eta_{Df\ (dB)}$
1	118	30	0.06	1.014	-0.12076
2	118	60	0.08	1.048	-0.40723
3	118	90	0.10	1.060	-0.50612
4	130	30	0.08	1.071	-0.59579
5	130	60	0.10	1.062	-0.52249
6	130	90	0.06	1.075	-0.62817
7	140	30	0.10	1.097	-0.80413
8	140	60	0.06	1.089	-0.74056
9	140	90	0.08	1.288	-2.19832

Figure 5 shows the interactions of the S/N ratios calculated for the damage factor. Here, the nonlinear display in the feed rate was thought to occur due to the gaps in the microstructure of the CFRP composite material. A number of these gaps can cause variations like this in the experimental results and can give an idea of the production quality of the plate.

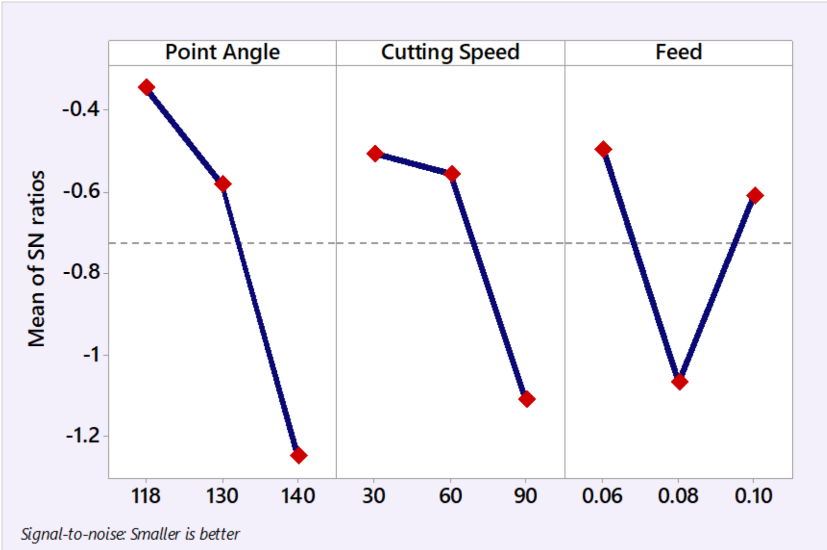


Figure 5. Main effect graphic showing S/N ratios for the damage factor.

The S/N response table in Table 5 shows the effect of all the variables on the damage factor.

Table 5. S/N response table.

Level	**A**	**B**	**C**
1	1.041	1.061	1.059
2	1.069	1.066	1.136
3	1.158	1.141	1.073
Delta	0.117	0.080	0.076
Rank	1	2	3

When Figure 5 and Table 5 are taken into consideration, it can be seen that the variable which had the greatest impact on D_f was the point angle (A), followed by the cutting speed (B), and the feed rate (C). The variables of cutting speed (B) and feed rate (C) affected each other in approximate values.

4.1. Variance analysis (ANOVA)

A variance analysis was performed in order to determine the effect of the variables on the damage factor. The ANOVA results are shown in Table 6.

Table 6. ANOVA results for the damage factor (D_f.)

Source	Degree of Freedom	Sum of Squares (*SS*)	Mean of Squares (*MS*)	*F*	*P*	*PCR* (%)
A	2	1.3147	0.6573	5.91	0.145	47.66
B	2	0.6743	0.3372	3.03	0.248	24.44
C	2	0.5468	0.2734	2.46	0.289	19.82
Residual Error	2	0.2225	0.1112			8.06
Total	8	2.7582				100

The *P* values (the significance level of each variable over the results), the total of the sum of squares, the mean of the squares, the F values and percent rates are seen in Table 5. The variable which had the greatest effect on the damage factor was the point angle, at the rate of 47.66%, followed by, respectively, the cutting speed (24.44%) and feed rate (19.82%). The main effect graphic (Fig. 5) and the S/N response values stated in Table 5 verified the ANOVA results. The effects of the parameters of point angle and cutting speed on the damage factor are shown in Figure 6.

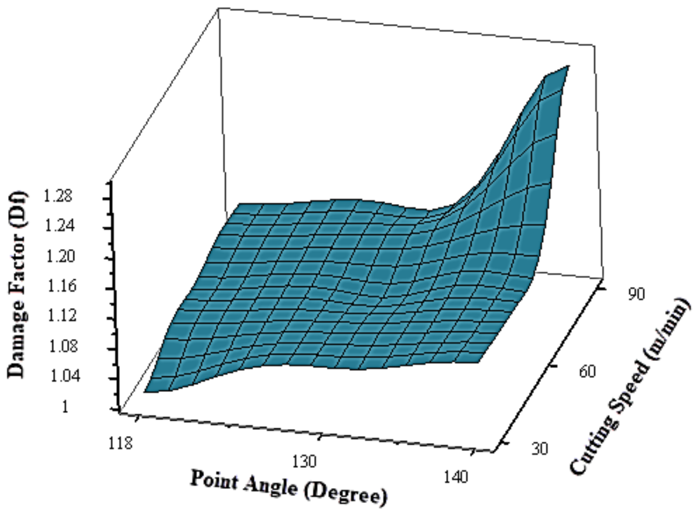


Figure 6. The effect of the parameters of point angle and cutting speed on the damage factor.

The last process which should be done in the optimisation process is the performance of verifying experimental tests to validate the optimisation. Although the parameter group which gives the optimal damage factor as a result of Taguchi optimisation may sometimes be one of the current tests, it may occasionally be one other than those conducted [16]. In this study, the optimum result for the damage factor was achieved under the A1B1C1 experimental conditions, which were among those included in the expiremental tests. For this reason, there was no need to conduct verification tests.

5. CONCLUSION

In this study, CFRP composite plates were drilled using different cutting parameters with drill bits of standard geometry having different point angles, and the hole damage which occurred was evaluated by the Taguchi optimisation method. With this method, time and cost were kept at a minimum by reducing the number of tests required. By applying the variance analysis to the test results, the levels of the cutting parameters effective on the damage factor were determined. At the end of the evaluations, the findings included:

- After Taguchi analyses, the optimum damage factor obtained was 1.014 with the test parameter combination of 118° point angle, 30 m/min cutting speed and 0.06 mm/rev feed rate (A1B1C1).
- The ANOVA results showed the parameter having the greatest effect on the damage factor to be the point angle (A) (47.66%), followed by the cutting speed (B) (24.44%) and lastly, the feed rate (C) (19.82%).
- In the light of the experimental results, the damage factor was reduced with decreased cutting speed, feed rate and point angle.

The Taguchi method optimisation of the drillhole damage occurring in the CFRP composite plates was applied successfully.

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