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Analysis of Delamination Factor in Drilling of CFRP Composites Using Design of Experiments

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Abstract

The use of Carbon Fibre Reinforced Polymer (CFRP) composites has increased rapidly in recent times. Due to the complex cutting mechanism irregularities occur in the surface. The delamination factor should be minimized to obtain better surface quality. In this study, a CFRP composite material were drilled to experimentally minimize the delamination factor on the machined surfaces, using a drilling machine with different combinations of cutting parameters namely point angle, spindle speed, feed rate . Experimental results showed that the delamination factor increased rapidly with increasing spindle speed and lesser increase of delamination factor for feed rate and a very small change for point angle. In addition, analysis of variance (ANOVA) results clearly shows that the spindle speed was the most influential parameter affecting the delamination factor in drilling of CFRP composites. Response Surface Methodology (RSM) technique was adopted to optimize the responses and the relation between factors and response was plotted in 2D and 3D contour plots.

1. Introduction

CFRP composites are already made to near net shape and machining is carried out for deburring, trimming and to achieve contour shape accuracy [1]. In CFRP metal removal is conducted at lower rates because small cutting depths produce smaller and fewer cracks. Most of the metals are replaced by Carbon Fibre Reinforced Plastics (CFRP) composite because they are economic and have high strength. They have a wide variety of applications in automotive, aircraft, construction, spaceship, interior design, sports goods and sea vehicles industries due to their light weight, high modulus, specific strength, high resistance to corrosion and high fracture toughness [2]. The machining of composite is different from the conventional machining of metal due to the composite's anisotropic and non-homogeneous nature [3].CFRP composite materials are extremely abrasive when machined. Thus the selection of the cutting tool and the cutting parameters is very important in the machining process [4]. During the process of machining of CFRP laminates due to the action of machining force the composites tend to delaminate and in order to improve the dimensional accuracy, performance and production, the cutting conditions that influence delamination factor should be optimized. For achieving the desired machining force, it is necessary to understand the mechanisms of the material removal, and the kinetics of machining processes affecting the performance of the cutting tool [5]. The machinability of the composites is mainly dependent on the cutting parameters namely spindle speed, feed and depth of cut. Paulo Davim and Mata (2007) proposed a new machinability index for turning FRP materials using polycrystalline diamond (PCD) and cemented carbide (K15) cutting tools. According to the study it was found that PCD tools had better surface finish and specific cutting pressure than cemented carbides [6]. Paulo Davim et al [7] established that the cutting parameters (feed and dept of cut) influence the machining force, delamination, dimensional precision and surface roughness in two composites (Viapal VUP 9731 and ATLAC 382-05). The orthogonal Design of Experiments of Taguchi has been applied to investigate the **effect** of the fiber orientation, the tool rake angle, the **depth** of **cut**, and the tool edge radius. The induced damage can strongly affect the surface roughness (surface quality of the work pieces) and considerably limits the use of these **materials** in many industrial applications. Satisfactory numerical results have been found and a good correlation has been obtained compared to experimental trends. The results reveal that the interaction between some factors could be neglected and the obtained responses are greatly influenced by the fiber orientation and the **depth** of **cut** rather than the tool rake angle and the tool edge radius [8]. Machining of composite materials, have shown that the surface quality (surface roughness), and delamination factor is strongly dependent on cutting parameters, tool geometry and cutting forces. [9-13]. In this study, the experiments were carried out using RSM technique the machining force was observed for second order response surface and the validity of the experiment was checked using analysis of variance (ANOVA). The machining parameters namely point angle, spindle speed and feed rate were selected in order to analyze the delamination factor. Response Surface Methodology (RSM) is a sequential process which involves a series of mathematical and statistical techniques which is used to analyze the problems and produce the optimizing the responses. By experimentation and regression analysis the independent variables of a response model are found and in turn used to find out the optimal point of the response. The relationship between control factors and response can also be found and respective 2-D and 3-D plots could be generated.

In the present work, a mathematical model has been developed to predict the delamination factor of the CFRP using response surface method. The regression and graphical analysis of the data was collected using "Design Expert-9.0" software. The effect of cutting parameters on delamination factor was analyzed by the response surface plots. The validity of the model was checked by using analysis of variance "ANOVA" for finding significant parameters.

Table.2. Experimental parameters and their levels**.**

Level of parameters	Point angle (°)	Spindle speed (rpm)	Feed rate (mm/min)
1	100	500	50
2	118	1500	100
3	136	2500	150

2. Methods and materials

The main objective of the experimental work is the establishment of the correlations between cutting parameters and Delamination Factor (F_d), machining issues were performed under different cutting conditions on the CFRP composite material. The composite material used in the tests (epoxy matrix reinforced with 55% of carbon fiber), supplied by GALARK, was produced by autoclave with a fiber orientation of 0/90◦, as can be observed in figure 1. The experiments have been carried out in a laminate plate, made up with 12 alternating layers of fibers with 3mm of thickness, using a CNC drilling machine as shown in figure 3.

Figure.3. Solid carbide tool coated with PCD at tip.

3. Experimental procedure

The experiments were carried out in a CNC drilling machine. The sample was rigidly fixed to avoid vibrations. A three level rotatable central composite design was designed to analyze the influence of cutting parameters on the response independently .The Output response selected in this study is Delamination Factor (F_d).The measurement and calculation of response is based on the cutting parameters namely point angle, spindle speed and feed rate.

Autoclave process: High-performance CFRP laminates are usually manufactured widely using autoclave process with fibers reinforced epoxy systems. Composite materials manufactured by autoclave are particularly important for aerospace applications. A pressurized vessel is used in the above process to apply pressure and heat to both parts which are sealed in a vacuum bag. The process takes place in many stages. On the first stage, the impregnated carbon-fiber–epoxy material is carefully laid out on a table to ensure that fiber orientation is made according to the design requirements, where the prepreg material consists of unidirectional long carbon fibers in a partially cured epoxy matrix. On the second stage, the prepreg material are cut out into pieces and placed on top of each other on a shaped tool to form a laminate. The layers may be placed in different directions based on the desired strength pattern required. However the maximum strength is obtained by placing each layer parallel to the fibers. Once the required number of layers is placed properly, the tooling and the attached laminate are vacuum-bagged, for removing the entrapped air from the laminated part. Finally, the vacuum bag and the tooling is cured in an autoclave for final curing of the epoxy resin. After removed from the autoclave, the composite material is ready to undergo finishing operations [14].

Response surface methodology and experimental design: Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for modelling and analyzing of problems in which an output or response influenced by several variables and the goal is to find the correlation between the response and the variables. The steps involved in RSM technique are as follows: (i) designing a set of experiments for adequate and reliable measurement of the true mean response of interest, (ii) determination of mathematical model with best fits, (iii) finding the optimum set of experimental factors that produces maximum or minimum value of response, and (iv) representing the direct and interactive effects of process variables on the best parameters through two dimensional and three dimensional graphs. If all variables are assumed to be measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, \ldots, x_k) \qquad (1)$$

The goal is to optimize the response variable y. It is assumed that the independent variables are continuous and controllable by experiments with negligible errors. It is required to find a suitable approximation for the true functional relationship between independent variables and the response surface. Usually a second-order model is utilized in response surface methodology.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k} \beta_{ij} x_i x_j + \epsilon \qquad (2)$$

Where ε is a random error, β is the coefficients, which should be determined in the second-order model, are obtained by the least square method.

Owing to slightly wider ranges of the factors, it was decided to use a three level rotatable central composite design to optimize the experimental conditions. Rotatable central composite designs of second order have been found to be the most efficient tool in RSM to establish the mathematical relation of the response surface using the smallest possible number of experiments without losing its accuracy. In the present case, the size of the experiment is 30 for three machining parameters shown in table 3.

To simplify the calculation the natural values of input parameters are converted into coded values. The coded numbers for the variables used in tables are obtained from the following transformation equation:

$$X_i = [2X - (X_{max} + X_{min})] / [X_{max} - X_{min}/2] \qquad (3)$$

where, X_{max} is the upper level of the parameter, X_{min} is the lower level of the parameter and X_i is the required coded values of the parameter of any value of X from X_{min} to X_{max}.

Delamination factor:

Delamination factor is the ratio between maximum width of damage to the width of cut .The delamination factor has the control over the surface finish of the component .The results obtained through experiments are presented in Table 4 – 6.

Table.4. ANOVA for delamination

Source	Sum of squares	df	Mean square	F-value	p-value (Prob>F)	Effect	Percentage contribution
Model	0.37	9	0.041	16.44	<0.0001	Significant	88.09
A	0.044	1	0.044	17.49	0.0005	Insignificant	10.47
B	0.14	1	0.14	54.64	<0.0001	Significant	33.33
C	0.025	1	0.025	9.79	0.0053	Insignificant	5.95
AB	2.11E-003	1	2.11E-003	0.84	0.3704	Insignificant	0.50
AC	2.11E-003	1	2.11E-003	0.84	0.3704	Insignificant	0.50
BC	6.16E-003	1	6.16E-003	2.45	0.1333	Insignificant	1.46
A^2	9.16E-003	1	9.16E-003	3.64	0.0708	Insignificant	2.18
B^2	0.088	1	0.088	34.84	<0.0001	Significant	20.95
C^2	0.067	1	0.067	26.82	<0.0001	Significant	15.95
Error	0.050	20	2.51E-005				11.90
Total	0.42	29					

R^2 =0.8809, Adjusted R^2 =0.8273

Table.5. Response table for Delamination

Level	Point angle (°)	Spindle speed (rpm)	Feed rate (f), mm/rev
1	1.535	1.335	1.400
2	1.514	1.537	1.533
3	1.408	1.539	1.487
Delta	0.105	0.204	0.133
Rank	3	1	2

Table.6. Error table for delamination factor (F_d)

Run	Experimental F_d value	Calculated F_d value	Error (%)
1	1.601	1.59	0.687
2	1.629	1.559	4.297

3	1.601	1.59	0.687
4	1.351	1.402	-3.774
5	1.546	1.451	6.144
6	1.601	1.59	0.687
7	1.601	1.59	0.687
8	1.555	1.571	-1.028
9	1.601	1.59	0.687
10	1.351	1.402	-3.774
11	1.240	1.308	-5.480
12	1.481	1.513	-2.160
13	1.601	1.59	0.687
14	1.314	1.245	5.251
15	1.601	1.59	0.687
16	1.425	1.455	-2.105
17	1.240	1.308	-5.480
18	1.601	1.59	0.687
19	1.555	1.571	-1.028
20	1.611	1.613	-0.124
21	1.546	1.615	-4.463
22	1.342	1.347	-0.372
23	1.546	1.615	-4.463
24	1.601	1.59	0.687
25	1.481	1.513	-2.160
26	1.453	1.490	-2.546
27	1.601	1.59	0.687
28	1.333	1.285	3.600
29	1.453	1.490	-2.546
30	1.462	1.445	1.162

The delamination factor was calculated by the following procedure. The damage caused on the CFRP composite material was measured perpendicular to the feed rate with a shop microscope Mitutoyo TM-500, as can be observed in Figure 4.

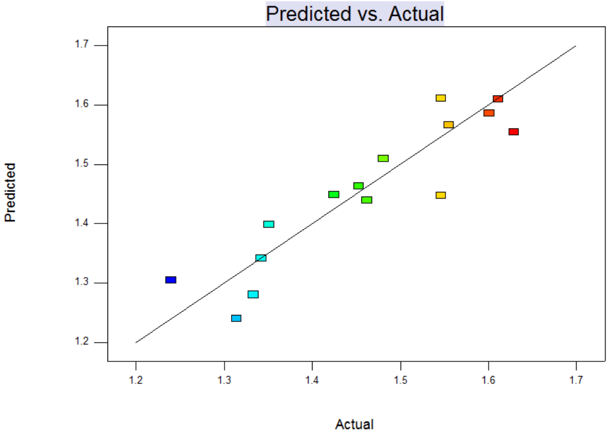

Figure.4. Correlation graph for delamination factor(F_d)

The composite material was positioned and fixed on the XY stage carbon of the microscope, and then the alignment of an initial measuring point with one of the cross-hairs was made on the machined feature. Moving the XY stage carbon by turning the micrometer head with a Digital Counter to the final point with the same cross-hair has been measured the damage (maximum width). After the measurement of the maximum width of damage (W_{max}) suffered by the material, the damage normally assigned by delamination factor (F_d) was determined. This factor is defined as the quotient between the maximum width of damage (W_{max}), and the width of cut (W). The value of delamination factor (F_d) can be obtained by the following equation:

$$F_d = W_{max} / W \qquad (4)$$

Where, W_{max} is the maximum width of damage in mm and W is the width of cut in mm

4. Results and discussions

The delamination factor of the sample was found out through the experiment from the following tables. The relationship between delamination factor and the cutting parameters namely point angle, spindle speed and feed rate are drawn separately and can be seen in Fig 5.

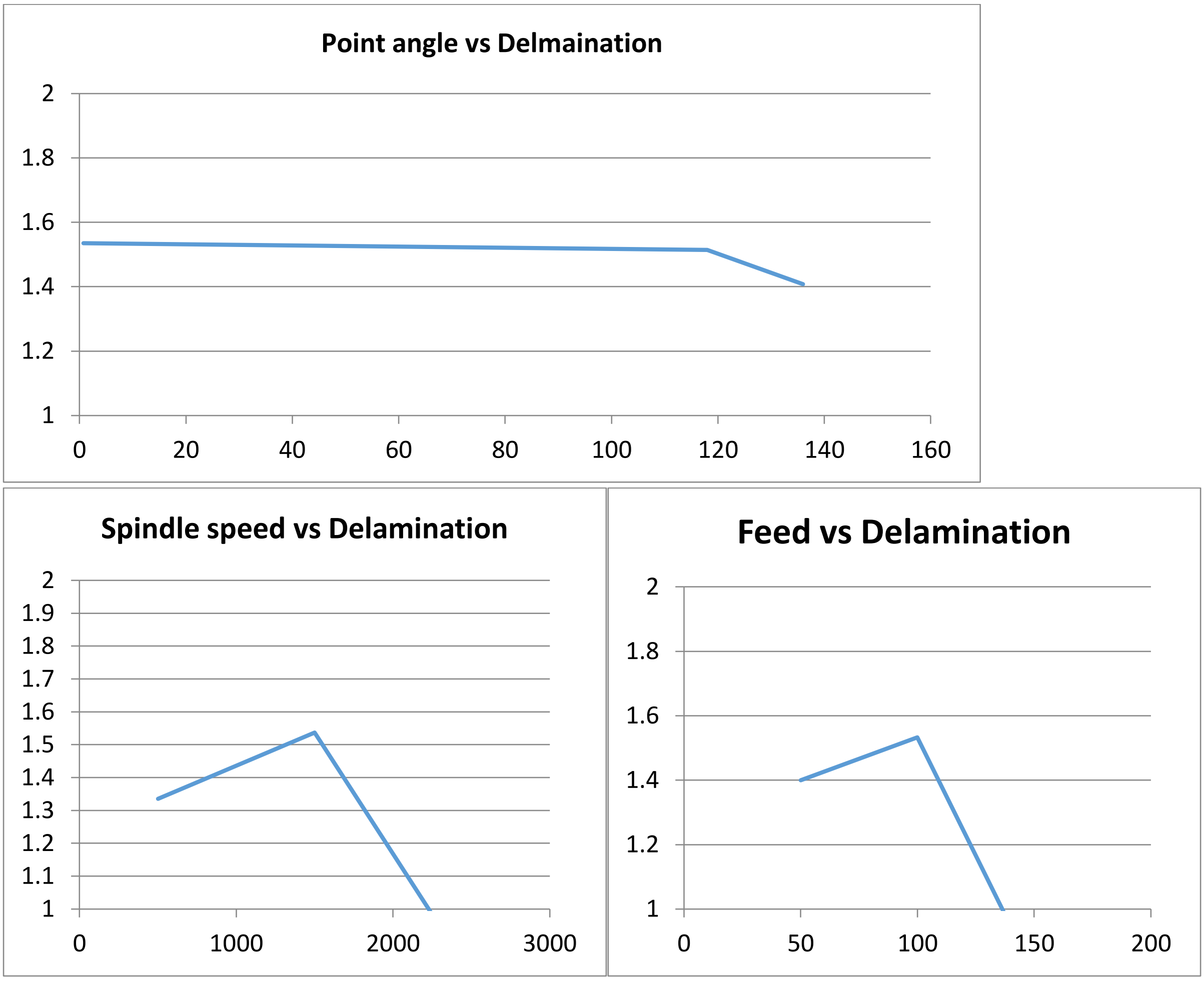

Figure.5. Illustration of factor effects on Delamination factor (F_d)

It is known that the cutting mechanism in CFRP composites is due to the combination of plastic deformation, shearing, and bending rupture. The occurrence of the above mechanisms depends on the flexibility, orientation, and toughness of the fibers. These constitute a surface texture on the work piece. The chips formed from machining of CFRP composites are discontinuous types in powder form. During the machining of CFRP composites, the tool continuously encounters alternating matrix and fiber materials, whose response to machining can vary greatly. Normally, in machining of CFRP, the tool encounters a low temperature soft epoxy matrix and brittle glass fibers. Due to the above facts, achieving a low machining force with good surface finish is a tedious job [15]. Spindle speed is the prominent factor which influences the delamination factor. Delamination factor increases rapidly with increase in spindle speed. Spindle speed is the cutting parameter which affects delamination factor the most and it is designated with the rank 1 based on the delta value of the three cutting parameters. Spindle speed is the more influential than feed and point angle for the delamination factor[16]. Feed also to an extent influences the delamination factor. The delamination factor increases with the increase in feed. Feed is ranked 2 as per its delta value. It does not affect delamination factor largely like spindle speed but it has a reasonable impact on delamination factor. Point angle is the factor which has negligible effect on delamination factor and is ranked 3 based on its delta value. It has very minimal impact on delamination factor. The analysis of variance is done for the three parameters and it is noted to have a 88% level of confidence. The ANOVA table is also drawn for the delamination factor (F_d) during the machining of CFRP. From the analysis it clear that the significant factors that delamination factor is spindle speed. The effect of feed and point angle are considered insignificant compared to spindle speed .The design was analyzed by response surface analysis and the following relation was established.

Final Equation in Terms of Actual Factors:

Delamination Factor =

+1.58593

-0.052440 * Point Angle

+0.092685 * Spindle Speed
+0.039231 * Feed Rate
-0.016250 * Point Angle * Spindle Speed
-0.016250 * Point Angle * Feed Rate
-0.027750 * Spindle Speed * Feed Rate
-0.024370 * Point Angle^2
-0.075370 * Spindle Speed^2
-0.066120 * Feed Rate ^2

5. Conclusion

The research presents findings based on parameters influencing delamination factor draws the following conclusions. Delamination factor increases with the increase of spindle speed and feed. Delamination factor decreases with increasing point angle. Spindle speed has the most physically dominant influence on the delamination factor followed by feed. A mathematical model was successfully developed to determine the delamination factor of the CFRP composites. The second order response surface model was developed and validated by conformation test by error analysis which was found to be within the allowable error limits. RSM technique was useful to find the influence of the cutting parameters on the delamination factor and ANOVA was useful in finding analysis of variance.

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