Optimizing Cutting Parameters for Minimizing Drilling-Induced Delamination Damage in CFRP Composites

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Abstract. Due to its remarkable mechanical qualities, composites are now widely used in unconventional industries, particularly aircraft. During assembly, drilling CFRP composite elements is a common activity, and choosing the right process parameters and geometry is essential to prevent drilling-related damage like delamination. This has led to the creation of a mathematical model that forecasts the required thrust force at which delamination occurs, taking into account the thermo-mechanical stresses and mixed failure mode in the separation area for unidirectional composites.The procedure is divided into three steps: i) an Experimental drilling thrust force study; (ii) an analysis of how scheduling the feed rate and fibre orientation can reduce delamination. It was discovered that only changing the feed rate is insufficient to prevent delamination. This research will look at drilling CFRP composites' performance optimization strategies. The study concentrates on crucial performance traits such as thrust, torque, average hole roughness, and delamination factor (both at the entry and exit). The objective is to identify the ideal machining settings that can successfully balance these aspects.

Keywords: Carbon Fibre Reinforced Polymer (CFRP) · thrust force · torque · delamination

1 Introduction

The use of composite materials has rapidly increased in recent years and is being utilized in a variety of unconventional industries, particularly the aerospace sector. They compete well with other materials in a variety of applications because to their distinctive mechanical qualities, which include a high strength-to-weight ratio and corrosion resistance. One of the most common operations in the assembly of composite materials is drilling, and choosing the right process parameters and geometry is crucial in minimizing damage caused by drilling, such as delamination. Research has been conducted that predicts the required thrust force at which separation begins and considers the thermo-mechanical loads in the separation region for unidirectional composites.

The goal of the current research is to better understand how to drill carbon fibre-reinforced plastic (CFRP) composites while optimizing machining performance. This

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entails assessing the effect of process performance characteristics on the drilled hole, such as load (thrust), torque, roughness average, and delamination factor. The objective is to find the best machining parameters that can concurrently meet these response qualities.

2 Literature Review

M.P. Groover [1], Lopresto, V., Caggiano, A., &Teti [2] and D. Arola, M. Ramulu, D.H. Wang et al. [3] Machining CFRP composite materials is a difficult task. As a result, an adequate mechanism that takes fibre orientation and chip creation into consideration is required, and identifying optimal processing conditions is critical. Using chip preparation procedures, Koplev et al. [4] investigate the machining of CFRP. Caggiano et al. [5] methods involved in machining FRP composites. Takeyama et al. [6] provided a chip formation theory in the orthogonal FRP cutting model. Bhatnagar et al. [7] performed a shear test and provided a model for predicting cutting force. Zhang et al. [8] studied the cutting of CFRP using finite element analysis and split the cutting zone into three parts. Kishawy et al. [9] created an energy-based model to estimate cutting forces in orthogonal metal matrix composite cutting, Pramanik et al. [10] developed a model for forecasting the cutting forces of metal matrix composites. Guo, Q. Wen, H. Gao, Y.J. Bao, and others[11] Cutting force is an important factor in affecting the quality of holes drilled in carbon-fibre-reinforced plastic composites. Gopala et al. [12] created an orthogonal cut-ting finite element model in unidirectional FRP. Durao et al. [13] developed a 3D finite element model to investigate damage and delamination in fiber-reinforced composites. According to M. Ocnarescu, P. Spanu, A. Vlase, C. Opran, et al. [14]. The poor surface quality, 60% of drilled composite components are rejected. According to Zitoune et al.[15]'s research, chip ejection impacts the hole's entry and exit during composite hole drilling. Wern et al. [16] also looked at the effect of feed rate and observed that drilling damage in composites is related to both the feed rate and the drill geometry. Tsao et al. [17] conducted studies with feed rates of 0.1, 0.2, and 0.3 mm/rev, Kim et al. [18] came to a similar conclusion. Davim et al. [19] investigated feed rate and spindle speed at 0.05, 0.1, and 0.2 mm/rev feed rates and spindle speeds of 3500, 4500, and 5500 rpm.

3 Material Methods

3.1 Method Used for Specimen

A 150 $\pm$ 5 mm $\times$ 105 $\pm$ 5 mm $\times$ 4 $\pm$ 0.5 mm CFRP material (specimen) that was made utilizing the hand lay-up process and orientated at 30°, 45° and 60° (3 specimens)was used for the trials. Alternating layers of carbon fibre with epoxy resin that had undergone made as the panel. The trials were carried out using a computer numerical control drilling machine, and the drilling parameters employed in them are reported in Table 2.

3.2 Experimental Drilling Process for CFRP Material

Preparing the materials through hand lay-up, the CFRP material is manufactured, and it is then cured in accordance with the manufacturer's instructions. Three specimens with fibre orientations of 30°, 45°, and 60° were manufactured for the panel, which is constructed of alternating layers of carbon fibre and epoxy resin. The drilling machine is set up with the proper fixtures and tools to hold the specimen firmly. The drilling settings are selected in accordance with the Table 2's experimental design. The specimen is drilled in accordance with the drilling parameters specified in the design. The drilled holes are examined for delamination. The delamination factor is measured and recorded at the hole's entry and exit. The data gathered during the experiment is examined and reported in a Table 3 to determine the influence of the drilling parameters on the thrust force, torque, and delamination factor at entry and exit. Delamination is a prevalent problem in composite materials, and utilizing a design of experiment (DOE) method, there are numerous techniques to reduce delamination at the entry and exit of a drilled hole. There are various elements that might lead to composite material delamination during drilling.Once the factors have been determined, we must establish the range of each factor that will be utilized in the DOE. Establish the drilling procedure in accordance with the DOE plan. An experiment in accordance with the DOE plan, measuring the delamination factor at the entry and exit of each hole.To find the elements that substantially impact delimitation, analyze the data using statistical approaches such as analysis of variance (ANOVA) or regression analysis. Using the processes outlined above, we may apply a DOE strategy to reduce delamination during composite material drilling entrance and exit.

The drilling experiment's input parameters are the drilling machine's speed, the feed rate, and the fibre orientation of the CFRP material. The thrust force in kN, torque in kN-mm, delamination factor at entrance, and delamination factor at exit of the drilled hole are among the output metrics. During each drilling experiment, these parameters are measured and recorded, and the results are evaluated to determine the ideal drilling settings for reducing delamination damage in CFRP composites.

3.3 Techniques for Determining Output Parameters

A drill Tool Dynamometer used to measure thrust force. The dynamometer is mounted in the machine spindle to measure the axial force generated during drilling. While drilling, the thrust force may be recorded constantly, and the data can be utilised to determine the average force, peak force, and force variation. The thrust force resulting from drilling was examined in the experiment. As drilling conditions, three distinct rotating speeds (1000, 1200, and 1400 rpm) and three different feed rates (100, 150, and 200 mm/rev) were investigated for different orientation of specimen. The outcomes were compared using the same feed rate.

Torque can also be measured with a dynamometer. The dynamometer is mounted in the spindle and measures rotational force when drilling. Torque data may be used to compute average torque, maximum torque, and torque variance.

Delamination factor at the entrance (push-down delamination or thrust delamination): This sort of delamination happens as the drill bit compresses the top layer of

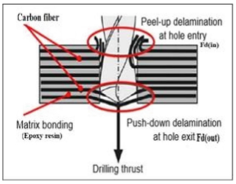

Fig. 1. Types of delamination's

the composite material. The delamination factor at the entrance can be determined by viewing the drilled hole with a microscope or scanning electron microscope (Scanning Electron Microscope). As indicated in Fig. 1, the delamination factor may be calculated by measuring the area of delamination and dividing it by the total drilling area.

Delamination factor at exit (peel-up delamination): Delamination that happens at the drill bit's exit point is referred to as pull-up delamination or peel-up delamination. The delamination factor at the exit may be assessed using the same procedures as the delamination factor at the entry. As illustrated in Figs. 1, 2, the drilled hole is examined under a microscope to determine the area of delamination and the overall drilled area (Fig. 3).

The MINITAB software was used to carry out the following techniques to optimize the machining parameters: i) Design of Experiments; ii) Analysis of Variance (ANOVA); iii) Taguchi; and iv) Regression Analysis.

Table 1 lists the parameters of the CFRP specimen as well as information regarding its manufacturing procedure.

Fig. 2: Experimental set-up

Fig. 3: Drill bit of 5 mm

Table 1: CFRP plate specifications

Parameters/technique	Value(s)
Density	02 gm/cm^3
Fibre orientations	30°, 45°, 60°
Fibre and matrix % ratio	fibre:resin = 60:40
Preparation technique	hand lay-up

4 Design of Experiments (DOE)

Drilling activities were performed using a drilling machine in this investigation. Using the Taguchi method, a series of tests were carried out to ascertain the response measures. The research focused on the influence of drilling settings on response parameters (Figs. 4 and 5).

Table 2 depicts how these variables will be modified at different levels during the experiment to study their impact on the CFRP specimen.

Table 3 shows the experimental findings for various values of speed, feed, and fibre orientation, as well as the related values of Thrust, Torque, Fd(in) (delamination at entry), and Fd(out) (delamination at exit).

According to the response Table 4, the feed of the cutting tool has the biggest delta value among the other parameters, which means it has a higher effect on surface roughness than the other inputs. The main effects plots for the S/N ratio the and main effects

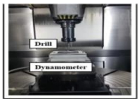

Fig. 4: Experimental set for CFRP specimen

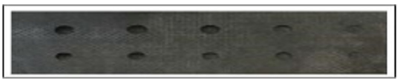

Fig. 5: Specimens after performing drilling

Table 2: Domain of experiments

Parameters (Notation)	Unit	Level 1	Level 2	Level 3
Drill Speed (N)	Rpm	1000	1200	1400
Feed rate (f)	mm/min	100	150	200
Fibre Orientation	angle	30	45	60

Table 3: The experiment's design (L27 Orthogonal Array)

Speed Rpm	Feed in mm/min	Fiber Orientation (angle)	Thrust kN	Torque kN-mm	Fd(in)	Fd(out)
1000	100	30	0.054	0.37	1.068	1.072
1000	100	45	0.0525	0.5105	1.327	1.194
1000	100	60	0.059	0.4475	1.553	1.2985
1000	150	30	0.051	0.28	1.054	1.065
1000	150	45	0.065	0.4	1.315	1.17
1000	150	60	0.066	0.22	1.523	1.295
1000	200	30	0.049	0.26	1.049	1.058
1000	200	45	0.424	0.31	1.305	1.197
1000	200	60	0.093	0.355	1.558	1.319
1200	100	30	0.056	1.02	1.065	1.077
1200	100	45	0.0635	0.46	1.328	1.192
1200	100	60	0.139	0.425	1.549	1.3015
1200	150	30	0.062	0.46	1.065	1.055
1200	150	45	0.104	0.37	1.288	1.22
1200	150	60	0.109	0.55775	1.562	1.2905
1200	200	30	0.053	0.44	1.078	1.077
1200	200	45	0.0785	0.18	1.312	1.209
1200	200	60	0.087	0.8475	1.545	1.295
1400	100	30	0.035	0.61	1.08	1.053
1400	100	45	0.059	0.28	1.318	1.187
1400	100	60	0.068	0.2875	1.557	1.301
1400	150	30	0.129	0.33	1.055	1.08
1400	150	45	0.08	0.395	1.285	1.181
1400	150	60	0.071	0.295	1.552	1.271
1400	200	30	0.19	0.38	1.058	1.089
1400	200	45	0.135	0.295	1.305	1.195
1400	200	60	0.073	1.0125	1.565	1.307

plot for means both support the response table for S/N ratios. The required amounts for the input parameters can be determined using these charts and the response table.

Table 5 explain the analysis, we must select the S/N ratio that, at a given level of an input parameter, is the lowest among the others. From the aforementioned plots and response table, it is clear that level-1 for cutting speed, level-3 for feed, and level-2 and level-1 is for fibre orientation.

Table 4: For Signal-Noise Ratios: smaller is better (thrust)

Level	Speed	Feed	Fiber orientation
1	22.56	24.30	23.71
2	22.00	22.11	20.71
3	21.59	19.74	21.72
Delta	0.97	4.56	3.00
Rank	3	1	2

Table 5: Analysis of variance push down delamination (fd(in))

Level	Speed	Feed	Fiber orientation	Level	Speed	Feed	Fiber orientation
1	-2.2134	-2.28	-0.5348	1	-1.4473	-1.4550	-0.5835
2	-2.2467	-2.174	-2.3397	2	-1.4894	-1.4178	-1.5387
3	-2.2295	-2.229	-3.8151	3	-1.4481	-1.5120	-2.2625
Delta	0.0333	0.112	3.2803	Delta	0.0421	0.0943	1.6790
Rank	3	2	1	Rank	3	2	1

Table 6: Analysis of variance peel up delamination (fd(out))

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% of Contribution
Speed	2	4.242	4.242	2.121	0.14	0.869	0.837
Feed	2	93.645	93.645	46.822	3.15	0.098	18.48
Fiber orientation	2	42.018	42.018	21.009	1.41	0.298	8.294
Speed*Feed	4	88.974	88.974	22.243	1.50	0.290	17.56
Speed*Fiber orientation	4	8.515	8.515	22.129	1.49	0.292	1.68
Feed*Fiber orientation	4	70.264	70.264	17.566		0.388	13.86
Residual error	8	118.942	118.942	14.868			
Total	26	506.6					

The machining parameters consist of speed, feed, and fiber orientation. Among these parameters, fiber orientation has the most significant impact, followed by feed and speed. Tables 6, 7, and 8 indicate the importance and contribution of speed, feed,

Table 7: Analysis of Variance (Fd(in)) for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Of contribution
Speed	2	0.0050	0.0050	0.0025	0.33	0.728	0.0102
Feed	2	0.0564	0.0564	0.0282	3.73	0.072	1.156
Fiber Orientation	2	48.5841	48.5841	24.2920	3212.08	0.000	99.62
Speed*Feed	4	0.0088	0.0088	0.0022	0.29	0.875	0.018
Speed*Fiber orientation	4	0.0301	0.0301	0.0075	1.00	0.462	0.061
Feed*Fiber orientation	4	0.0208	0.0208	0.0052	0.69	0.621	0.042
Residual Error	8	0.0605	0.0605	0.0076			
Total	26	48.7657					

Table 8: Analysis of Variance (Fd(out)) for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Of Contribution
Speed	2	0.0104	0.0104	0.00522	0.38	0.693	0.08
Feed	2	0.0406	0.0406	0.02028	1.50	0.280	0.312
Fiber orientation	2	12.7654	12.7654	6.38270	470.89	0.000	98.2
Speed*Feed	4	0.0162	0.0162	0.00406	0.30	0.871	0.124
Speed*Fiber orientation	4	0.0473	0.0473	0.01182	0.87	0.521	0.363
Feed*Fiber orientation	4	0.0100	0.0100	0.00249	0.18	0.940	0.0769
Residual Error	8	0.1084	0.1084	0.01355			
Total	26	12.9983					

and fibre orientation, as well as their interactions, in explaining variation in the Thrust, delamination at the entrance (fd(in)), and delamination at exit (fd(out)) variables.

Explain The major influences plot shows that the Fibre orientation, feed, and cutting speed plot is growing in trend, with the SN value increasing from level 1 to level 3. When feed progresses from level 1 to level 3, the feed plot exhibits the same rising trend for the SN value.

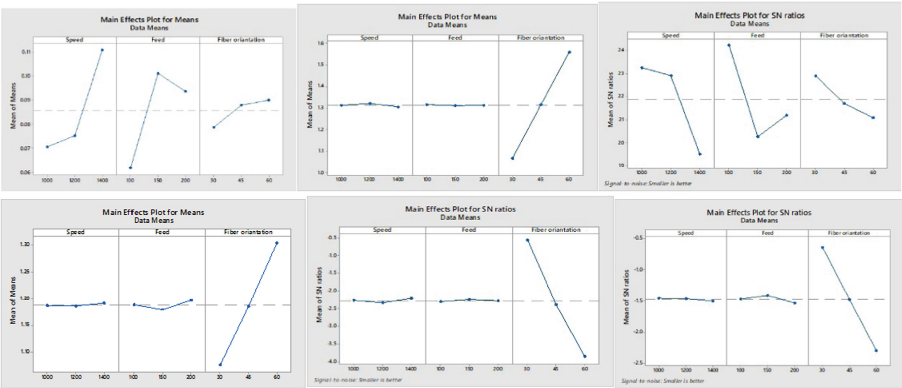

Fig. 6: Main Effects Plot For S/N Ratios

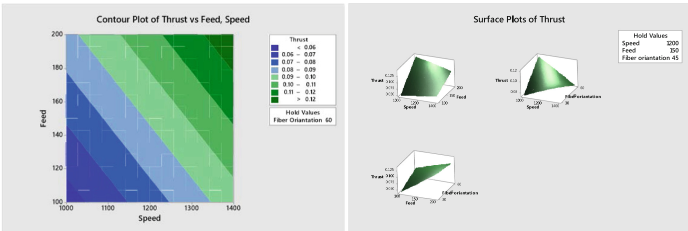

Fig. 7: Contour plots at various fiber orientations and (b) surface plots of Thrust

4.1 Contour Analysis

Contour plots are a visualization tool used to demonstrate the relationship between three input variables and a specific output parameter. They provide a visual representation of how changes in the input variables affect the output. Colored contour bands show the range of response values.

Figure 7, 8 and 9 demonstrates Finally, at various levels and conditions, a smaller area of contour plots and surface plots is chosen for reducing thrust and delamination during the entrance and exit.

Figure 10 depicts predicted values for the given point of operation are as follows: the speed (N) is 100rpm, the feed (f) is 116.203mm/min, and the fiber orientation is 30°. At this operating point, the responses observed are as follows: the thrust is 0.035kg, the Fd(in) is 10695, and the Fd(out) is 1.0677 from Fig. 10.

5 Results and Conclusions

1) According to the Taguchi technique of optimization, thrust is the key response factor for fibre orientation and feed and speed and is explained in percentage contribution from Tables 6, 7 and 8.

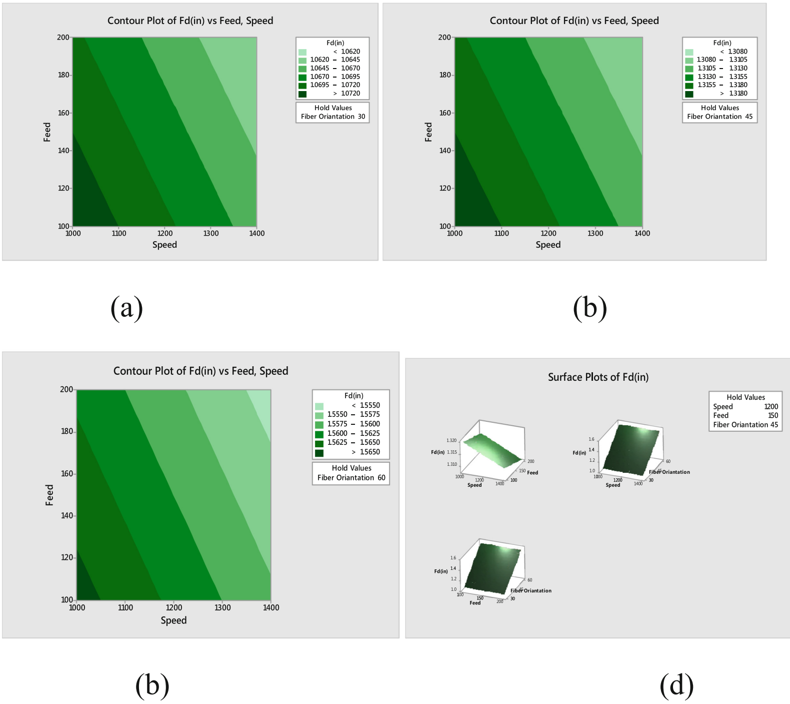

Fig. 8: Contour plots at various fiber orientations (a, b, c) and (d) Surface plots of Fd (in)

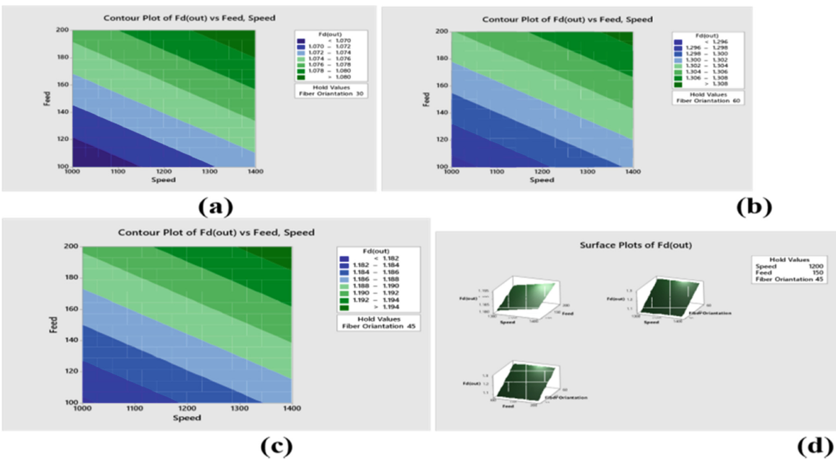

Fig. 9: Contour plots at various fiber orientations (a, b, c) and (d) Surface plots of Fd (out)

Table 9: Predicted values at speed, feed and Fiber Orientation

Variable	Setting
speed	1000
feed	100
Fiber orientation	30

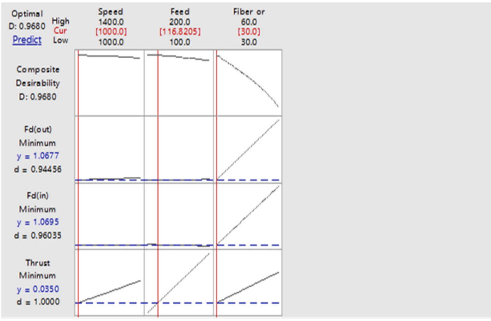

Fig. 10: Optimization plot

2) By taking into account various combinations of the three accessible input parameters, contour plots were made to study the interactions between the input parameters and their effect on the output parameters, such as thrust, peel-up delamination, and push-down delamination from Tables 7, 8 and 9.
3) The results show that for the thrust parameter, feed has the highest effect at 18%, followed by fiber orientation at 8.2%, and speed at 0.8%. On the other hand, for the Delamination factor at entry, fiber orientation has the highest effect at 99.62%, followed by feed at 1.15%, and speed at 0.01%. For the Delamination factor at exit, fiber orientation still has the highest effect at 98.2%, followed by feed at 0.312%, and speed at 0.08% from Table 7, 8 and 9.
4) The predicted values for the given point of operation are as follows: the speed (N) is 100rpm, the feed (f) is 116.203mm/min, and the fiber orientation is 30°. At this operating point, the responses observed are as follows: the thrust is 0.035kg, the Fd(in) is 10695, and the Fd(out) is 1.0677 from Fig. 10.

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