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Multi-objective optimization analysis of cutting parameters when drilling composite materials with special geometry drills.

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Abstract

The cutting tool geometry is strongly influencing damage induced during drilling of composite materials. The searching of new and optimum geometries reducing the damage on the laminates is still a challenge for the scientific community and industry. This study focuses on drilling woven CFRP laminates with four different tool geometries, analyzing the influence of the cutting parameters on the cutting forces and delamination damage. The work is divided in three phases; the first phase carries out a full factorial design of experiments conducted to quantify the significance of each process parameter as well as its interaction, on the generation of delamination at the hole entry and exit as well as the thrust force and torque. The second phase uses the response surface methodology (RSM) to establish the relationships between each output variable and the input variables based on ANOVA results. Finally, a multi-objective optimization strategy has been presented using the fitting equations to select optimum ranges of design parameters that can minimize collectively the aforementioned output variables. Ultimate objective is the process improvement toward negligible defects during drilling of woven CFRP composites.

Keywords: CFRP composites, Drilling, Drill bit, Multi-objective process optimization.

1 Introduction

In aerospace industry, increasing percentage of composite laminates is primarily used in highly responsibility structural components instead of metal alloys allowing for weight reduction. Different industrial sectors are increasing the use of woven CFRPs [1] due to their combined fatigue and corrosion resistance, light weight, high specific stiffness and strength properties, along with superior impact fracture toughness compared to unidirectional composites [2,3].

Although CFRPs are usually made close to the final shape of the component, drilling is commonly required prior to mechanical joining of high responsibility components [4]. The quality of the laminate is significantly affected by the action of machining forces (thrust force and torque) [5]. The tendency to delaminate of these materials is highly affected by the thrust force of the tool, which causes the separation of the plies of the laminate, especially the lower ones [6,7].

Earlier studies on the influence of cuttings parameters on delamination damage during drilling woven CFRP materials, showed that the feed rate is the parameter with most influence on the delamination and the thrust force [8,9]. On the other side, it has been shown, that the cutting speed would be the parameter with less influence on damage [6,7,10,11]. However, cutting speed has shown some slight influence on the cutting force [6,7,12]. As another relevant parameter, the choice of point angle of the drill bit has shown different influence in delamination and cutting forces. In general, it has been reported that increasing the point angle enhances the thrust force while the torque remains nearly constant. At the same time it improves the quality of the hole at the entry (less delamination), but it worsened the hole quality at the exit [5,10]. The same effect has been observed at the entry of the hole in cross-ply composite materials with twist drill bits [5,12]. Special attention must be paid to the double-point angle drill bits. For this case, achieving the hole diameter tolerance can be more critical than the exit delamination, especially when working at high feed rates [13].

Several authors support the importance of the drill bit geometry improving the quality of drilled holes (such as delamination reduction) in woven CFRP materials. Since conventional twist drill bit used in drilling of composite laminates without support plate provides a relatively high thrust force, it is difficult for this kind of geometry to obtain delamination-free hole [8,12,14–16]. To minimize the drilling-induced delamination of composite laminates, several special drill bits were developed, including step drill bit [2,3,12,15] brad drill bit [2,8,12,14,15], four flute drill bit [14,17], core drill bit [15,18] and step-core drill bit [19]. Between all geometries mentioned, it was proved that most of them reduced the thrust force during drilling process, but the core drill bit was the one with higher threshold of drilling feed rates without delamination because of its abrasive effect [20].

The main disadvantages of the experimental work are the high economic and time investment required. To face this problem, different methodologies have been proposed by several authors to obtain information in a fast and efficient way. Genetic algorithms haven been used to optimize the productivity and surface quality of the material [21] and the material removal rate according to cutting parameters [22]. Neuronal networks are also used to capture any complex input–output relationship [23–25]. However, the large number of experiments needed to carry out this methodology make it, in some cases, too expensive.

Despite the abundant amount of studies researching the influence of input variables, a limited number of statistical studies have been carried out in the literature. These studies provide robust information regarding individual and interactive effects of cutting parameters on multiple drilling output variables. Different multi-objective optimization methodologies have been used to establish the influence of different input process parameters in the surface quality and to find optimum machining conditions [26–30]. However, in these studies some information is missing. In some cases the statistical significance of process parameters, prior to applying a optimization algorithm to minimize/maximize the process outputs, is not verified [28,30]. In other cases, they are only focused on the damage delamination without considering the cutting forces. Finally, in the interaction factors are not taking into account in the ANOVA analysis [26,29] despite having demonstrated the influence of these interactions in some cases, e.g., in the evolution of wear [31].

It has not been shown in the mentioned studies, how an optimum set of cutting parameters (feed rate and cutting speed) can be selected in order to optimize multiple process outputs of interest simultaneously (e.g. exit delamination and thrust force) under one specific tool. An optimum set of parameters for a given single design objective, such as entry delamination, may not be coincident, with the optimum values of another criterion, such as exist delamination. These gaps constituted the main motivation of the present work in which four different tools are analyzed. This study is a continuation of a previous work carried out by the authors where the effect of the wear was analyzed for an helicoidal drill bit [31]. The results of both studies constitute a powerful analysis regarding the optimization of the woven CFRP laminates drilling process.

2 Experimental procedure

2.1 Workpiece material

The laminate is composed of 10 plies with a total thickness of 2.2 mm. Each ply is manufactured with AS-4 fibers and 8552- epoxy by Hexcel Corporation. Specimens of woven CFRP were cut on plates of 120 × 29 mm. Relevant mechanical properties provided by the manufacturer are shown in Table 1.

Table 1 Mechanical properties of the woven CFRP provided by Hexcel Corporation.

Fiber volume	ρ	E_1=E_2	E_3
55.29 %	1570 Kg/m3	68 GPa	10 GPa
υ_{12}	X_t=Y_t	X_c=Y_c	S_t
0.31	793 MPa	860 MPa	98 MPa

2.2 Drills tools and experimental set-up

Four uncoated carbide drills with different geometry manufactured by GUHRING are selected. For all tools, nominal diameter is 6 mm. The point angle, the helix angle and the clearance angle are presented in Table 2 where a picture of each geometry is showed.

Table 2 Geometrical parameters of the drilling tools.

Geometry	**Helicoidal**	**Brad center**	**Step**	**Reamer**
Diameter	6 mm 	6 mm 	6 mm 4 mm 	6 mm 
Point angle	118°	90°	110°	20°
Helix angle	40°	30°	20°	0°
Clearance angle	9°	9°	9°	9°

The drilling tests were carried out on a B500 KONDIA machining unit without coolant. A Kistler dynamometer was used to measure the thrust force (in drill axis direction) and the Torque (Fig. 1). A discrete range of cutting parameters was selected following the recommendation of the drill manufacturer (see Table 3).

Table 3 Range of cutting parameters.

Parameter	**Range**		
Cutting speed (m/min)	25	50	100
Feed rate (mm/rev)	0.05	0.10	0.15

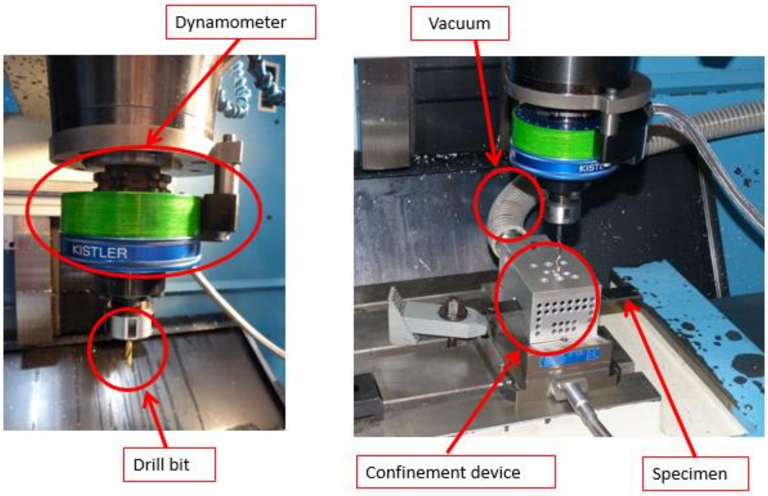
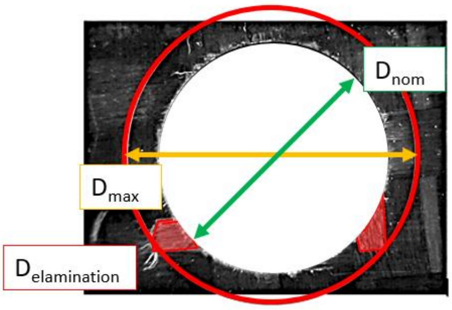


Fig. 1 Experimental set-up device.

2.3 Delamination measurement

The damage intensity around the hole entry and exit was quantified through the delamination factor (F_d). This value is defined at the ratio between the maximum diameter of delaminated area and the nominal diameter of the hole as can be seen in Fig. 2. The images of the machined hole were obtained with a stereo microscope Optika SZR.



$$F_D = \frac{D_{max}}{D_{nom}}$$

Fig. 2 Measure of the delamination factor (F_d).

3 Data analysis procedure

The statistical study is presented in this section. The analysis can be divided in in three steps as follow:

The first step is based on a full-factorial analysis of variance (ANOVA) specifically aimed to study the influence of the cutting parameters on cutting forces and delamination extension under different tool geometries. The analysis includes Interactions between cutting factors and the second order of the factors.

The second step is based on the response surface methodology (RSM) to establish the relationships between each output variable (cutting forces, delamination at both hole entry and exit) and the independent variables (feed rate and cutting speed) based on ANOVA results. Subsequently, approximation model between dependent and independent variables were tested based on the p-value of different multiple regression models. Due to anticipated nonlinear trends for all the study parameters, a general quadratic order approximation following equation (1) was used as the main model, where β_0, β_i, β_{ii} and β_{ij} are model constants and x_i and x_j are the cutting parameters (here k=2):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} \beta_{ij} x_i x_j \quad (1)$$

The final step consists of 'multi-objective' optimization methodology to identify a set of cutting parameters that can simultaneously minimize the thrust force, toque, in-delamination, and out-delamination responses. More specifically, for each geometry, the multi-objective regression model is defined by summing the four individual response equations fitted from step two following equation (2). The cutting forces are normalized by the maximum thrust force and the maximum torque. The equation is also weighted with the ω_i factors to reflect the relative importance of the four responses. The optimum solution of cutting parameters for fixed weights values is calculated minimizing the equation.

$$y = w_1 \cdot \frac{F_t(V,f)}{F_{max}} + w_2 \cdot \frac{T(V,f)}{T_{max}} + w_3 \cdot F_{d-IN}(V,f) + w_4 \cdot F_{d-OUT}(V,f) \quad (2)$$

Table 4 ANOVA results for the thrust force (significant factors: *p*-value<0.05).

Geometry	Source	Sum of Squares	DF	Mean square	*F*-value	*P*-value	Contribution	Significance
Helicoidal	A-*V*	0.00156817	1	0.00156817	2.9993E-05	0.99597418	0%	Insignificant
	B-*f*	1342.87028	1	1342.87028	25.6836928	0.01483301	85%	High
	AB	17.087488	1	17.087488	0.32681473	0.60756592	1%	Insignificant
	A²	52.7430561	1	52.7430561	1.00876195	0.3891986	3%	Insignificant
	B²	9.32400139	1	9.32400139	0.17833054	0.70125002	1%	Insignificant
	Residual	156.854814	3	52.2849379	-	-	10%	-
	Total	1578.88121	8	-	-	-	-	-
Step	A-*V*	8.59206667	1	8.59206667	0.18073656	0.69939195	0%	Insignificant
	B-*f*	2398.10684	1	2398.10684	50.4448569	0.00574234	63%	High
	AB	1.57714405	1	1.57714405	0.03317567	0.86708393	0%	Insignificant
	A²	1229.69304	1	1229.69304	25.8669415	0.01468881	32%	Medium
	B²	27.60245	1	27.60245	0.58062536	0.50149699	1%	Insignificant
	Residual	142.617523	3	47.5391742	-	-	4%	-
	Total	3808.18906	8	-	-	-	-	-
Brad	A-*V*	1750.1876	1	1750.1876	115.917025	0.00171366	23%	Medium
	B-*f*	5584.03634	1	5584.03634	369.837428	0.00030707	72%	High
	AB	333.134137	1	333.134137	22.0638737	0.01825012	4%	Low
	A²	0.0486881	1	0.0486881	0.00322467	0.95828606	0%	Insignificant
	B²	5.31271339	1	5.31271339	0.35186738	0.59480518	0%	Insignificant
	Residual	45.2958726	3	15.0986242	-	-	1%	-
	Total	7718.01536	8	-	-	-	-	-
Reamer	A-*V*	1148.94146	1	1148.94146	41.8653215	0.00749118	16%	Low
	B-*f*	5347.90429	1	5347.90429	194.867832	0.00079597	74%	High
	AB	629.11588	1	629.11588	22.9238298	0.01732686	9%	Low
	A²	5.80766486	1	5.80766486	0.21162067	0.67679178	0%	Insignificant
	B²	0.000648	1	0.000648	2.3612E-05	0.99642799	0%	Insignificant
	Residual	82.3312533	3	27.4437511	-	-	1%	-
	Total	7214.1012	8	-	-	-	-	-

4 Results and discussion

Details of the experimental data recorded during drilling tests can be found in a previous work of the authors [2]. The present study advances in the treatment of data of cutting forces and delamination through the statistical evaluation of main and interaction factor effects as well as the multi-objective optimization process under different tool geometries.

4.1 Thrust force

Table 4 shows the results obtained from the ANOVA analysis on the thrust force response. It is observed that feed rate is the parameter the most influencing parameter on the thrust force, independently of the tool geometry (*p*-value<0.05). The relative percentage contributions of this factor, however, change with the geometry; for the Helicoidal drill the feed rate has the main influence (85 %) and cutting speed is negligible. On contrary, for the brad point tool, this factor increases its influence until 23% reducing the feed rate at 72%.

Cutting speed did not show a statistically significant influence on the thrust force for Helicoidal and Step tools (*p*-value>0.05). However, based on Table 4, for the cases of Brad tool and Reamer tool it has a slight influence in combination with feed rate (namely, the interaction factor AB). The influence of this interaction is relatively low (23% and 16% relatively). However, it cannot be negligible because a significant increase of thrust force may be experienced with the variation of the cutting speed. It is important to put in relief that the quadratic term of this parameter presents a significant contribution for the case of Step geometry (32%).

4.2 Torque

ANOVA results for torque are presented in Table 5. For all cases, feed rate is the most influencing parameter as it was discussed in the previous analysis for thrust force (*p*-value<0.05). However, the relative percentage contribution of this factor is lower than thrust force case reaching a minimum level of 50% on case of Reamer drill bit.

The influence of the first order cutting speed term is negligible for the cases of helicoidal, step and reamer tools. However, is relevant the influence of the second order term of the parameter, especially for the reamer geometry with the contribution reaches almost a 40%. Also, the interaction with the feed rate is relevant for helicoidal and Reamer drill bits. This confirms again that the quadratic and interaction terms cannot be discarded from the model.

4.3 Entry delamination

ANOVA results for the case of entry delamination (peel up) are presented in Table 6. For all cases except for the Brad tool, the cutting speed presents a high contribution, being in some cases equal or more important than the contribution of the feed rate. It is worth to note that the Helicoidal drill bit presents the highest contribution (73%) considering that cutting speed was not significant in the cutting forces analysis. This suggests that despite the low influence of cutting speed on thrust force and torque, it is relevant in the delamination generated at the top ply of the laminate. Feed rate is also, in a minor way, significant for the three geometries mentioned.

Brad drill is the only geometry that presents an opposite contribution of the factors compared to the rest of the tools. The feed rate has a huge influence on the entry delamination (56%) being more sensitive than cutting speed (25%).

Table 5 ANOVA results for the torque (significant factors: *p*-value<0.05

Geometry	Source	Sum of Squares	DF	Mean square	*F*-value	*P*-value	Contribution	Significance
Helicoidal	A-*V*	80.0810667	1	80.0810667	0.67187791	0.47245628	1%	Insignificant
	B-*f*	3732.68472	1	3732.68472	31.3171205	0.01127193	70%	High
	AB	1134.76652	1	1134.76652	9.52065937	0.05390078	21%	Medium
	A²	34.2724667	1	34.2724667	0.28754504	0.62900964	1%	Insignificant
	B²	1.21160556	1	1.21160556	0.01016534	0.92605119	0%	Insignificant
	Residual	357.569725	3	119.189908	-	-	7%	-
	Total	5340.58611	8	-	-	-	-	-
Step	A- *V*	29.8820167	1	29.8820167	4.07579588	0.13680673	1%	Insignificant
	B-*f*	4372.27823	1	4372.27823	596.362481	0.00015052	82%	High
	AB	53.4085762	1	53.4085762	7.28473106	0.07384705	1%	Insignificant
	A²	516.461867	1	516.461867	70.4434768	0.00354771	10%	Low
	B²	323.766422	1	323.766422	44.1605352	0.00694387	6%	Insignificant
	Residual	21.9947349	3	7.33157831	-	-	0%	-
	Total	5317.79185	8	-	-	-	-	-
Brad	A- *V*	1514.9526	1	1514.9526	22.067234	0.01824635	16%	Low
	B-*f*	7061.31436	1	7061.31436	102.85713	0.00204232	76%	High
	AB	44.9975048	1	44.9975048	0.65544656	0.4774273	0%	Insignificant
	A²	409.781336	1	409.781336	5.96899243	0.09224055	4%	Insignificant
	B²	28.4258	1	28.4258	0.41405835	0.56572345	0%	Insignificant
	Residual	205.955029	3	68.6516762	-	-	2%	-
	Total	9265.42663	8	-	-	-	-	-
Reamer	A- *V*	42.5068167	1	42.5068167	1.30173946	0.33672603	0%	Insignificant
	B-*f*	4630.025	1	4630.025	141.791052	0.00127374	50%	High
	AB	806.310268	1	806.310268	24.6926488	0.0156555	9%	Low
	A²	3624.958	1	3624.958	111.011627	0.00182604	39%	Medium
	B²	4.08027222	1	4.08027222	0.12495528	0.74710292	0%	Insignificant
	Residual	97.9615766	3	32.6538589	-	-	1%	-
	Total	9205.84194	3	32.6538589	-	-	-	-

4.4 Exit delamination

The last output parameter individually analyzed is the exit delamination (push out). Table 7 shows the corresponding ANOVA. For Helicoidal, Step and Brad tools, both cutting parameters are significant for the exit-delamination (*p*-vale<0.05). For all cases, the feed rate is the most influential factor (59-79 % contribution).

Exit delamination is generally higher than entry delamination because thrust force directly affects it [3,32]. The parameters contribution on the exit delamination is, in general, opposite to the entry delamination based on results in Section 4.3, where the cutting speed presented the highest contribution. It is worth to note that for Helicoidal tool and Step tool, the cutting speed is influential on the exit delamination, in contrast to observations described in Sections 4.1 & 4.2. For the case of Reamer tool, only the cutting speed become significant.

Table 6 ANOVA results for the entry delamination (significant factors: p-value<0.05).

Geometry	Source	Sum of Squares	DF	Mean square	F-value	P-value	Contribution	Significance
Helicoidal	A-V	0.01926667	1	0.01926667	213.745964	0.000694	73%	High
	B-f	0.00366669	1	0.00366669	40.6785294	0.00780304	14%	Medium
	AB	0.00046045	1	0.00046045	5.10826675	0.10891113	2%	Insignificant
	A²	0.0024381	1	0.0024381	27.0484265	0.01381265	9%	Low
	B²	0.0003858	1	0.0003858	4.28012392	0.13038612	1%	Insignificant
	Residual	0.00027041	3	9.0138E-05	-	-	1%	-
	Total	0.02648812	8	-	-	-	-	-
Step	A-V	0.01126667	1	0.01126667	27.9724138	0.01318642	42%	High
	B-f	0.01128289	1	0.01128289	28.0127042	0.01316019	42%	High
	AB	0.00145833	1	0.00145833	3.62068966	0.15320658	5%	Insignificant
	A²	0.00040238	1	0.00040238	0.99901478	0.39120601	1%	Insignificant
	B²	0.00125	1	0.00125	3.10344828	0.1763405	5%	Insignificant
	Residual	0.00120833	3	0.00040278	-	-	4%	-
	Total	0.02686861	8	-	-	-	-	-
Brad	A-V	0.0216	1	0.0216	25.056928	0.01534452	25%	Medium
	B-f	0.04908289	1	0.04908289	56.9382667	0.00482575	56%	High
	AB	0.000525	1	0.000525	0.60902256	0.49207073	1%	Insignificant
	A²	0.00619286	1	0.00619286	7.18398036	0.07503011	7%	Insignificant
	B²	0.00802222	1	0.00802222	9.30612245	0.05540206	9%	Low
	Residual	0.00258611	3	0.00086204	-	-	3%	-
	Total	0.08800909	8	-	-	-	-	-
Reamer	A-V	0.00106667	1	0.00106667	23.373913	0.01687424	56%	High
	B-f	0.00052801	1	0.00052801	11.5702517	0.04241432	28%	Medium
	AB	9.6429E-05	1	9.6429E-05	2.11304348	0.24201369	5%	Insignificant
	A²	3.8095E-05	1	3.8095E-05	0.83478261	0.42826342	2%	Insignificant
	B²	5E-05	1	5E-05	1.09565217	0.37212576	3%	Insignificant
	Residual	0.0001369	3	4.5635E-05	-	-	7%	-
	Total	0.0019161	8	-	-	-	-	-

4.5 Regressions

The fitted equations are presented in Table 8 where V represents the cutting speed and f the feed rate. The correlation between the cutting factors and the output variables (thrust force, torque, entry delamination and exit delamination) was obtained using multiple linear regression and experimental data. The second order terms and interaction between factors have been included to improve the accuracy of the predictions based on the ANOVA results. All the fits presented a statistically significant R^2 value.

Figs. 3-6 show the response surface diagrams for output variables based on the fitting equations of Table 8. For each geometry, the continuous range of the cutting parameters is used: f [0.05 mm/rev–0.15 mm/rev] and V [25 m/min-100 m/min]. These diagrams are very efficient for a rapid estimation of the output variables. It can be observed how the evolution of the entry and exit delamination is similar for the cases of Helicoidal and Step drills, while Brad and Reamer tools present an opposite behavior between them. The graphics also provide a visual information about the evolution of the cutting forces; while the evolution of thrust force is lineal for almost all cases, torque tends to be more parabolic.

Table 7 ANOVA results for the exit delamination (significant factors: *p*-value<0.05).

Geometry	Source	Sum of Squares	DF	Mean square	*F*-value	*P*-value	Contribution	Significance
Helicoidal	A-*V*	0.00056067	1	0.00056067	1655.71875	3.2662E-05	12%	Low
	B-*f*	0.0037689	1	0.0037689	11130.0395	1.8775E-06	79%	High
	AB	7.619E-07	1	7.619E-07	2.25	0.23058387	0%	Insignificant
	A²	1.6095E-05	1	1.6095E-05	47.53125	0.00625243	0%	Insignificant
	B²	0.00043022	1	0.00043022	1270.5	4.856E-05	9%	Low
	Residual	1.0159E-06	3	3.3862E-07	-	-	0%	-
	Total	0.00477766	8	-	-	-	-	-
Step	A-*V*	0.0054	1	0.0054	76.7368421	0.00313297	32%	Medium
	B-*f*	0.01064737	1	0.01064737	151.304709	0.00115732	63%	High
	AB	0.00023333	1	0.00023333	3.31578947	0.16616612	1%	Insignificant
	A²	0.00034286	1	0.00034286	4.87218045	0.11438924	2%	Insignificant
	B²	0.00013889	1	0.00013889	1.97368421	0.25469893	1%	Insignificant
	Residual	0.00021111	3	7.037E-05	-	-	1%	-
	Total	0.01697356	8	-	-	-	-	-
Brad	A-*V*	0.0294	1	0.0294	24.9959514	0.01539586	35%	Medium
	B-*f*	0.0496609	1	0.0496609	42.2218197	0.00740153	59%	High
	AB	0.00107143	1	0.00107143	0.91093117	0.41027898	1%	Insignificant
	A²	0.00034286	1	0.00034286	0.29149798	0.62676379	0%	Insignificant
	B²	0	1	0	0	1	0%	Insignificant
	Residual	0.00352857	3	0.00117619	-	-	4%	-
	Total	0.08400376	8	-	-	-	-	-
Reamer	A-*V*	0.0024	1	0.0024	39.3365854	0.00818262	77%	High
	B-*f*	0.00012223	1	0.00012223	2.00333761	0.25190356	4%	Insignificant
	AB	5.0298E-05	1	5.0298E-05	0.82439024	0.43083704	2%	Insignificant
	A²	0.0002625	1	0.0002625	4.30243902	0.12971583	8%	Insignificant
	B²	0.0001125	1	0.0001125	1.84390244	0.26760074	4%	Insignificant
	Residual	0.00018304	3	6.1012E-05	-	-	6%	-
	Total	0.00313056	8	-	-	-	-	-

4.6 Optimization process

Table 9 shows the results from single objective optimization. Cutting speed and fees rate are the optimum solution that minimizes each dependent variable separately. In this table, '*A*' columns refer to the best solution obtained using only tested configurations with the selected levels of cutting speed (25 m/min, 50 m/min, 100 m/min) and feed rate (0.05 mm/rev, 0.1 mm/rev, 0.15mm/rev). On the other hand, '*B*' Columns refer to the optimum solutions based on the continuous ranges of independent variables: cutting speed [25 m/min-100 m/min] and feed rate [0.05 mm/rev–0.15 mm/rev].

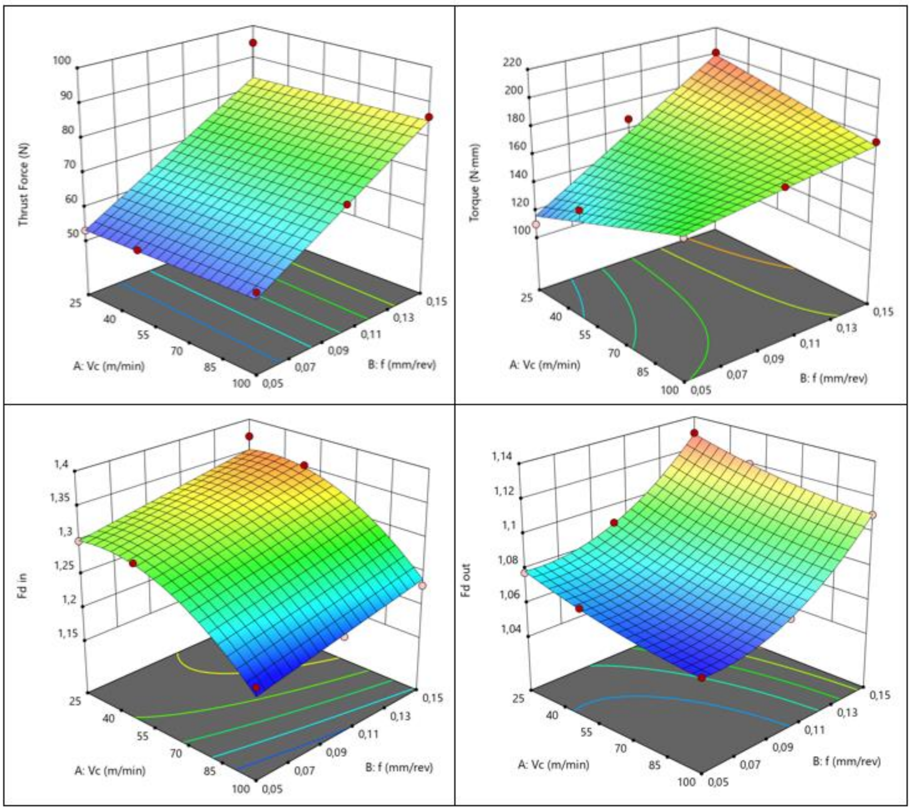


Fig. 3 Response surface diagrams for helicoidal geometry.

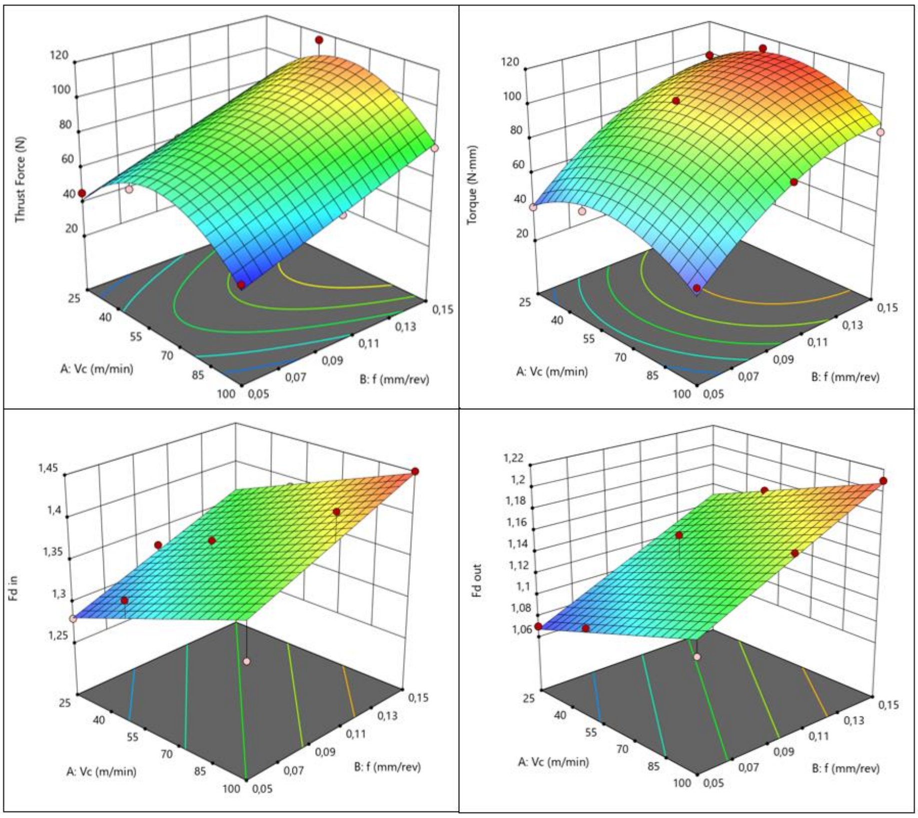


Fig. 4 Response surface diagrams for step geometry.

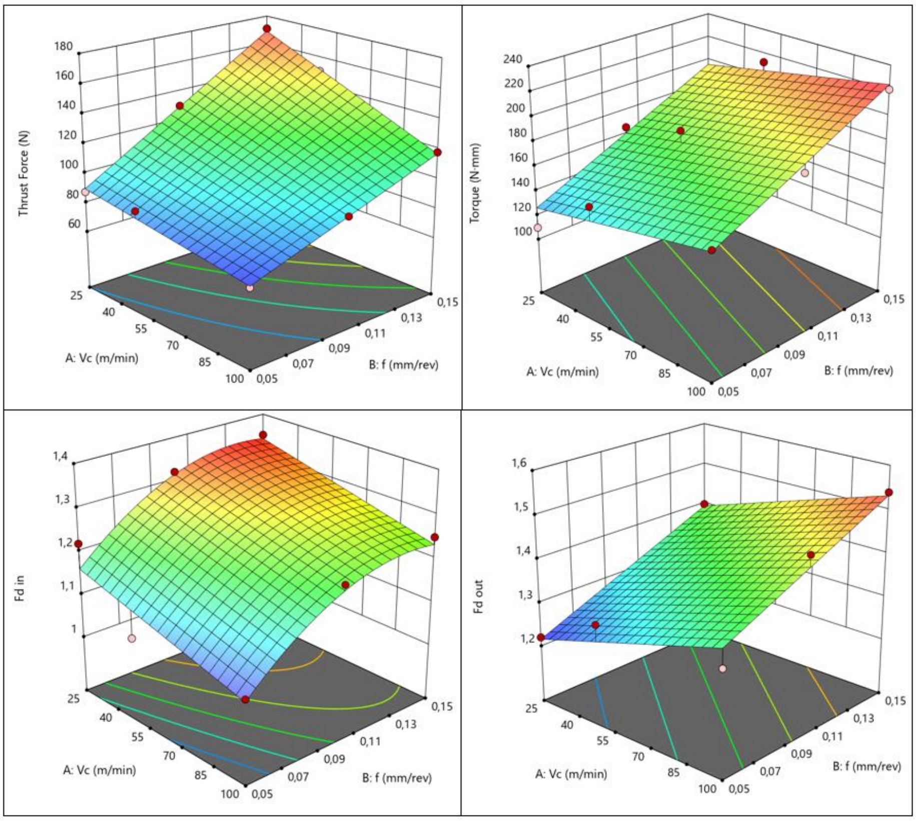


Fig. 5 Response surface diagrams for brad center geometry.

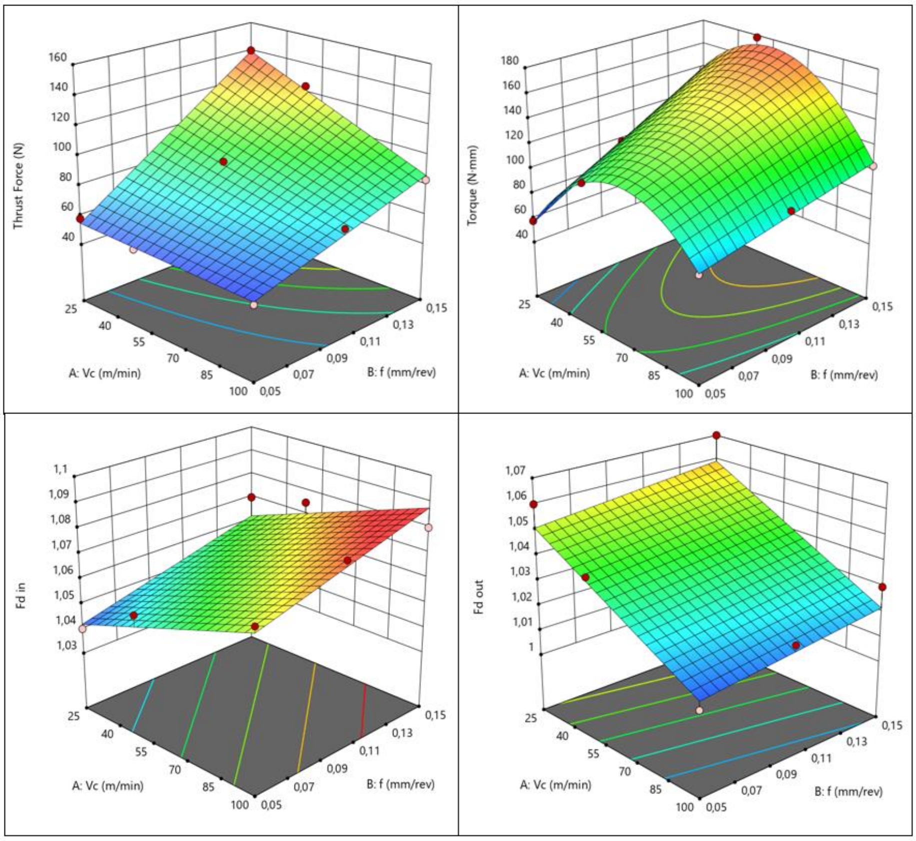


Fig. 6 Response surface diagrams for reamer geometry.

Minimizing the fitted equations (RSM approach) from Table 8, it can be observed that for a given tool geometry, the optimum set of cutting parameters changes notably from one response variable to another. E.g., for Helicoidal tool, the continuous optimum solution of cutting speed is 25 m/min for thrust force and 95 m/min for exit delamination. Such conflicts point put in relief the fact that there is no unique solution that can minimize all the criteria perfectly. For this reason, it becomes necessary a weighted multi-objective optimization, to reach at an overall optimum solution. Nevertheless, from Table 9 it can be concluded that, in general, low feed rates are desirable.

Table 8 Regression equations for thrust force, peel up, and push responses out for different tool geometries

Geometry	Parameter	Prediction equation	R^2
Helicoidal	Thrust Force	$y=37.5053+0.0145\cdot V+306.3767\cdot f$	0.85
	Torque	$y=49.6467+0.9916\cdot V+1054.6\cdot f-8.8211\cdot V\cdot f$	0.93
	Fd-in	$y=1.2411+2.0444e\text{-}4\cdot V+0.5222\cdot f-2.8444e\text{-}5\cdot V^2$	0.96
	Fd-out	$y=1.1098-5.4667e\text{-}4\cdot V-0.6667\cdot f+5.8667\cdot V^2+5.8667\cdot f^2$	0.99
Step	Thrust Force	$y=-28.3878+2.4932\cdot V+404.7667\cdot f-2.0201e\text{-}2\cdot V^2$	0.95
	Torque	$y=-55.812+1.5769\cdot V+1570.5333\cdot f-1.3092e\text{-}2\cdot V^2-5089.3333\cdot f^2$	0.98
	Fd_{in}	$y=1.2117+1.1143e\text{-}3\cdot V+0.8333\cdot f$	0.83
	Fd_{out}	$y=1.0067+7.619e\text{-}4\cdot V+0.8333\cdot f$	0.94
Brad	Thrust Force	$y=49.437+2.2958e\text{-}2\cdot V+914.28\cdot f-4.7795\cdot V\cdot f$	0.99
	Torque	$y=81.895+0.3821\cdot V+699.5333\cdot f$	0.92
	Fd_{in}	$Y=0.9172-1.4381e\text{-}3\cdot V+6.8667\cdot f-25.3333\cdot f^2$	0.89
	Fd_{out}	$y=1.08+1.8286e\text{-}3\cdot V+1.8\cdot f$	0.94
Reamer	Thrust Force	$y=5.1313+0.2828\cdot V+1012.91\cdot f-6.5681\cdot V\cdot f$	0.98
	Torque	$y=-89.4094+5.008\cdot V+1025.25\cdot \text{f}-7.4357\cdot V\cdot f-3.4684e\text{-}2\cdot V^2$	0.98
	Fd_{in}	$y=1.0233+3.4290e\text{-}4\cdot V+0.2\cdot f$	0.84
	Fd_{out}	$1.0591667-0.0005\cdot \text{V}+0.0833333\cdot \text{f}$	0.79

Table 9 Cutting parameters for the case of discrete (A columns) and continuous (B columns) optimizations of each response variable separately.

Geometry	Cutting parameter	Thrust Force (N)		Torque (N·mm)		Fd_{in}		Fd_{out}	
		A	B	A	B	A	B	A	B
Helicoidal	Cutting speed (m/min)	25	25	25	25	100	99.35	100	94.49
	Feed rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.062	0.05	0.062
Step	Cutting speed (m/min)	25	100	100	100	25	25	25	27.28
	Feed rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.051
Brad	Cutting speed (m/min)	100	100	25	25	100	68.98	25	25.84
	Feed rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.052	0.05	0.051
Reamer	Cutting speed (m/min)	100	100	25	25.13	25	25	100	100
	Feed rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table 10 presents the multi-objective optimization results under different weighting factor combinations according to equation (2). The weight associated to each response variable defines the relative importance of the corresponding criterion to the designer. Four scenarios are study:

1. In the first attempt, the four design criteria (output variables) were assumed to have equal importance (ω_1=ω_2=ω_3=ω_4=1) and the minimum value of all of them is searched.
2. For the second scenario, the weight of torque is reduced because of between the two cutting forces, is the one that least affects the quality of drilled holes. (ω_2<ω_1= ω_3=ω_4=1)
3. For the third scenario, only in- and out-delamination are assumed to have high weights (ω_3=ω_4=1).
4. The fourth case considers only the entry delamination is considered to be relevant to minimize (ω_1=ω_2=ω_4<ω_3)
5. For the last case, only a high weight is assigned to out-delamination, on account of the fact that it is normally more severe than entry delamination in practice (ω_1=ω_2=ω_3<ω_4).

From results in Table 10, for all study cases, low feed rate is recommended. For helicoidal and step geometries the optimum values are the same for the five scenarios. This result is conditioned by the fact that in-delamination and out-delamination follow the same trending in function of cutting parameters as can be seen in the surfaces of Figs 2 and 3. The recommended values for cutting speed are 96 m/min for the helicoidal drill bit and 25 m/min for the step drill bit.

Table 10 Multi-objective optimum set of cutting parameters for different geometries tested.

Geometry	w_1	w_2	w_3	w_4	V (m/min)	f(mm/rev)	T_f (N)	T (N·mm)	Fd_{in}	Fd_{out}
Helicoidal	1	1	1	1	96.39	0.05	54.22	155.44	1.20	1.06
	1	0.2	1	1	96.39	0.05	54.22	155.44	1.20	1.06
	0.2	0.2	1	1	96.39	0.05	54.22	155.44	1.20	1.06
	0.2	0.2	1	0.2	96.39	0.05	54.22	155.44	1.20	1.06
	0.2	0.2	0.2	1	96.39	0.05	54.22	155.44	1.20	1.06
Step	1	1	1	1	25.00	0.05	41.56	41.23	1.28	1.07
	1	0.2	1	1	25.00	0.05	41.56	41.23	1.28	1.07
	0.2	0.2	1	1	25.00	0.05	41.56	41.23	1.28	1.07
	0.2	0.2	1	0.2	25.00	0.05	41.56	41.23	1.28	1.07
	0.2	0.2	0.2	1	25.00	0.05	41.56	41.23	1.28	1.07
Brad	1	1	1	1	56.12	0.05	83.03	138.31	1.07	1.27
	1	0.2	1	1	62.79	0.05	81.59	140.86	1.06	1.28
	0.2	0.2	1	1	60.01	0.05	82.19	139.80	1.07	1.28
	0.2	0.2	0.2	1	27.65	0.05	89.17	127.44	1.18	1.22
	0.2	0.2	1	0.2	62.79	0.05	81.59	140.87	1.06	1.28
Reamer	1	1	1	1	25.56	0.05	54.61	57.69	1.04	1.05
	1	0.2	1	1	56.98	0.05	53.18	113.42	1.05	1.04
	0.2	0.2	1	1	54.69	0.05	53.28	111.67	1.05	1.04
	0.2	0.2	1	0.2	25.00	0.05	54.64	56.08	1.04	1.05
	0.2	0.2	0.2	1	100.00	0.05	51.22	78.64	1.07	1.01

Brad and Reamer tools present a different behavior. In these cases, the cutting values changes in function of the objective fixed, e.g., to minimize the entry delamination, a low cutting speed is desirable. However, to minimize the exit delamination a high cutting speed is better option. Usually the objective is to diminish the damage at both sides of the laminate, thus the user should decide which scenario is the best option for each case.

These results complement the information published in a previous work by the authors [31], where the effect of the wear was studied. In that analysis, the optimum cutting parameters were modified by the evolution of the wear. Conclusions led to an overall recommendation about modifying the cutting speed to keep good drilling quality.

5 Conclusions

Based on the factorial design and optimization study presented in this work on CFRP drilling, the following conclusions could be drawn:

Feed rate is the factor with highest influence on the cutting forces and exit-delamination. On the other side, the cutting speed is the most significant factor in in-delamination. This conclusion is independent of the geometry. This suggests that designers may use the feed rate effect to control the extension of out-delamination, while using the point angle effect to reduce the in-delamination.

The second order and interaction factors must be included in the ANOVA analysis. It was proved that for some tools, they cannot be neglected and can present a relevant significance. Including these factors in the fitting equations improves the prediction of the output variables.

The single optimization of the four output responses showed that under different drilling set-ups a low feed rate (0.05 mm/rev) is most frequently preferred. The cutting speed should be selected according to the geometry. On one side, high cutting speed values would be a good choice for the Reamer and Helicoidal geometries due to the out-damage reduction. On the other side, low values are recommended for Step and Brad geometries. The in-delamination follows the same trend in Helicoidal and Step tools. However, Bard and Reamer geometries reduce the damage with opposite values of cutting speed. This may be viewed as a complex paradigm for practical applications that can be solved through the multi-objective optimization.

Based on the results from a multi-objective analysis to reduce the damage at the entry and the exit of the laminate, low feed rates and medium cutting speed values (55-60 m/min) are recommended for Brad and Reamer drill bits. Helicoidal drill bit decreases the damage with high cutting speed (96 m/min) and Step drill bit with low cutting speed (25 m/min). Among all the study geometries, Reamer tool is the best option since it generates minimum delamination.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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