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Drilling optimization of woven CFRP laminates under different tool wear conditions: a multi-objective design of experiments approach

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Abstract The cutting tool geometry is known to be an influential factor on damage induced during drilling of composite materials. Conversely, the geometry of the tool is affected under multiple drilling cycles due to highly abrasive nature of fibers. Building on earlier reports, the aim of this work is to create a better understanding of cutting parameters on the quality of drilled woven carbon fiber reinforced polymer (CFRP) laminates, given different tool wear conditions. Namely, a full factorial design of experiments has been conducted to quantify the significance of each process parameter (cutting velocity, feed rate and tool point angle), as well as their interactions, on the generation of entry- and exist- delaminations as well as the thrust force for different tool types. Finally, using a response surface methodology, a multi-objective optimization strategy has been presented to select optimum ranges of design parameters that can minimize the aforementioned output variables collectively. Such knowledge may be useful to explore further improvements toward defect-free drilling of woven CFRP composites.

Keywords CFRP composites, drilling, tool wear, multi-objective process optimization.

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1 Introduction

The application of Carbon Fiber Reinforced Polymer (CFRP) composites in modern industries is growing fast. Among different types of such materials, woven CFRPs have proven to be appealing material solutions in a broad range of applications, mainly 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 (Huang 2009; Santiuste et al. 2011; Teti 2002). Their conformability under different manufacturing methods is also agreeable.

In aircraft industries, CFRP composite parts are normally processed in near-net shapes. However, to achieve required dimensional tolerances, cured sub-components often need machining before assembly. Today, drilling is still among most common manufacturing processes used to join composites through mechanical joins like screws, rivets and bolts. (Santiuste et al. 2011). During drilling operation, however, composites are very prone to damage of different types, with delamination being the most major one as recognized by many other researchers (Teti 2002; Liu et al. 2012). This phenomenon is defined as inter-ply failure located on the entry and the exit of the drilled hole and is highly related to the choice of machining parameters as well as the drill geometry. On the other hand, the geometry of the drill bit is often worn over time due to the presence of hard fibers.

Earlier studies on the influence of cuttings parameters on delamination damage in drilling woven CFRP materials show that the cutting speed would be the least influential parameter (Heisel and Pfeifroth 2012). On the other hand, cutting speed has shown some slight influence on the cutting force. Instead, it has been shown that the feed rate is much more influential on both damage generation (delamination) and thrust force during drilling of composites (Shyha et al. 2009;

Davim and Reis 2003). As another cutting parameter, variation of the point angle of the drill bit has shown different results on the generation of delamination and cutting force. In general, it has been reported that increasing the point angle enhances the thrust force while the torque remains nearly constant (Heisel and Pfeifroth 2012). Increasing the point angle in conventional drills has also improved the quality of the hole in entry (less delamination), but it worsened the hole quality at the exit (Heisel and Pfeifroth 2012). The same effect has been observed at the entry of the hole in cross-ply composite materials with twist drill bits (Durão et al. 2010). In particular in the latter study, the thrust force was higher for 120° compared to 85° point angle bit, while delamination at the hole entry was lower for the former case (Durão et al. 2010). In another study it was observed that with a double-point angle drill bit, the hole diameter tolerance criterion is more critical at elevated feed rates than the exit delamination (Karpat et al. 2012).

Concerning worn drill bits, occasionally used in manufacturing of CFRPs, earlier studies have proven that the wear is mainly caused via tool abrasion by hard fibers (Mayuet et al. 2013). The abrasion of the tool geometry in conventional drill bits, as the number of machining cycles is increased, can increase the part delamination damage at the exit of the hole. For tests at high rotational speeds (10,000–15,000 rpm), the abrasive wear has been found to be more significant than chipping on the primary cutting edge (Rawat and Attia 2009). For both tools, coated and uncoated, it has been observed that the axial force is the main factor in increasing the tool wear at the cutting edge. Moreover, the contact length has a contribution in tool wear. In fact, relating to other cutting parameters, increasing the feed rate yields higher thrust forces and consequently a higher tool wear. Drill torque has been reported to be much less sensitive to wear compared to the thrust force (Iliescu et al. 2010).

Effect of specific features of the tool geometry, e.g., variation of cutting edge roundness due to abrasion, was studied in (Faraz et al. 2009) during drilling of woven CFRP materials. Both delamination and cutting forces presented a positive correlation with the cutting edge roundness. The influence of CER for orthogonal cutting has been studied previously by the third author and co-workers (Soldani et al. 2011). Other wear mechanisms reported for drilling CFRPs include the presence of chipping on the edge (Rawat and Attia 2009) and, to a more limited extend, the adhesion of the matrix to the cutting tool (Mayuet et al. 2013).

When compared to the above experimental works, numerical models on predicting delamination during composite drilling have been developed more recently (Soldani et al. 2011; Feito et al. 2014a; Phadnis et al. 2013). Some of these finite-element based models are aimed not only at estimating delamination, but also the torque and feed force, and their correlations with the underlying mechanical properties of the forming material at different (macro/meso/micro) scales.

1.1 Motivation of the present study

Limited ‘statistical’ studies have been carried out in the literature to gain more robust information regarding the individual and combined (interactive) effects of cutting parameters on different (multiple) drilling output variables, specially given the non-repeatable/random nature of such manufacturing process for composites. The recent studies on drilling optimization of FRP composites (e.g., (Sonkar et al. 2014; Abhishek et al. 2014)) did not verify if there is a statistical significance of process parameters (i.e., cause and effect/hypothesis testing) prior to applying a single or multi-objective optimization algorithm to minimize/maximize the process outputs via changes the input parameters. Pertinent to hypothesis testing, the study (Davim and Reis 2003) showed that with a significance level of 5 %, the cutting speed has a less influence on the peel-up, when compared to the effect of feed rate. However on push-out, contribution percentages of both of these cutting parameters were nearly the same under different tool geometries. For small drills, the study (Shyha et al. 2009) used an ANOVA analysis (Montgomery 2009) (with $\alpha=5$ %) using six input parameters. For the entry delamination, the drill type was found to be the only significant parameter, with no influence from cutting parameters. The point angle and feed rate were significant parameters on the thrust force, and the cutting speed and feed rate were influential on the resultant torque.

In the above statistical studies, however, interactions of cutting parameters were not taken into account. In addition, to the best of authors’ knowledge, it has not been shown how an optimum set of woven CFRP cutting parameters can be selected in order to optimize *multiple* process outputs of interest (e.g., the entry and exist delaminations as well as the thrust force simultaneously) and under different *tool wear conditions*. Generally speaking, an optimum set of parameters for a given single design objective such as entry delamination may not be coincident with that of another criterion such as exist delamination. These gaps constituted the main motivation of the present work. In addition to a brand new tool, two different types of tool wear types were considered: the flank wear (commonly identified in the literature as the dominant wear mode) and the cutting edge honing (resulting from the transition of the tool from new to used).

2 Experimental procedure

2.1 Workpiece material

Drilling tests were carried out on plates of 120 mm in length × 29 mm in width × 2.2 mm in thickness. Each ply is composed of 10 plies of plain woven CFRP with AS-4 fibres and 8552-epoxy manufactured by Hexcel Corporation. All the laminate plies have the same warp and weft fiber orientation (Fig. 1).

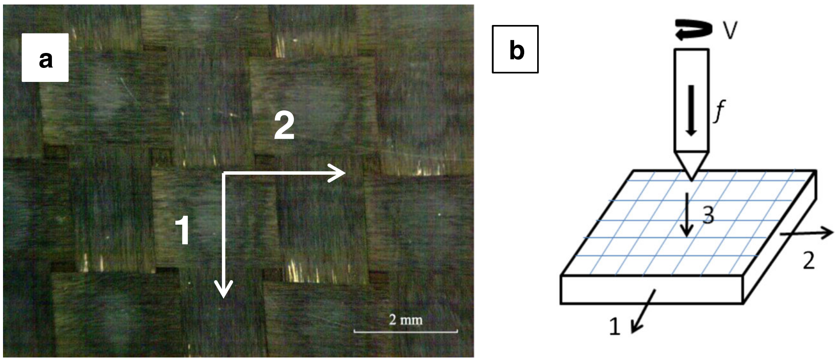


Fig. 1 Top view of the woven material showing directions 1 and 2 (**a**) and schematic view of the cutting test configuration including main directions of woven material (**b**)

Mechanical properties provided by the manufacturer are also shown in Table 1.

2.2 Drill tools and set-up

Uncoated helicoidal carbide drills recommended by manufacturer (GUHRING) for CFRP drilling were used. The tool nominal diameter was 6 mm with a 30° helix angle. Three different values of the point angle, 90°, 118° and 140°, were considered. In addition, three different conditions concerning tool wear were tested: a brand new drill, flank wear equal to 0.3 mm, and honed cutting edge with a length equal to 0.05 mm (see Fig. 2). These wear values were established according to the earlier tests by Faraz et al. (Faraz et al. 2009) in the case of flank wear, and by Rawat et al. (Rawat and Attia 2009) in the case of honed edge wear. The honed edge is an approximation to chipping wear observed in drilling CFRPs. These worn geometries were artificially generated on the drill bits using grinding process.

The drilling tests were carried out on a B500 KONDIA machining unit without coolant, while a Kistler dynamometer (9123C) was used to measure the induced thrust force, F_y. The drilling velocity V, feed rate f and point angle α were applied for each wear level (Fig. 3), resulting in a total of 81 tests. Upon drilling each sample, the damage intensity around the hole was identified as the ratio of the maximum damage diameter (D_{max}) to the nominal diameter (D_{nom}).

2.3 Analysis procedure

The statistical treatment of test data was made in three phases. The first phase was based on a full-factorial analysis of variance (ANOVA) (Montgomery 2009). The ANOVA analysis was specifically aimed to study the influence of the cutting parameters on quality of drilled parts under different tool geometries (wear levels). Interactions between drilling parameters were also considered to analyze whether they have any statistical relevance to the CFRP drilling process. In the second phase, based on the data from the factorial design, a response surface methodology (RSM) was implemented to establish input–output relations for the process variables and subsequently to locate the optimum drilling set-up given each response variable and tool wear level. For this RSM stage, the form of the relationships between each output response (thrust force, in- delamination and out- delamination) and the independent/process variables (point angle, feed rate and cutting speed) was unknown. Thus, the first step was to select a suitable approximation model between dependent and independent variables via testing p-value of different multiple regression models (Montgomery 2009). Due to anticipated nonlinear trends for all the study parameters, a general second-order approximation was needed (1), where $\beta_{0,}$ β_i, β_{ii} and β_{ij} are model constants and x_i and x_j are the cutting parameters (here k=3):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i}^{k} \beta_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} (\beta_1)_{ij} x_i x_j + \sum_{i=1}^{k-1} \sum_{j=2}^{k} (\beta_2)_{ij} x_i x_j^2 + \sum_{i=1}^{k-1} \sum_{j=2}^{k} (\beta_3)_{ij} x_i^2 x_j + \sum_{i=1}^{k-1} \sum_{j=2}^{k} (\beta_4)_{ij} x_i^2 x_j^2 \qquad (1)$$

Finally, once equations are fitted for each of the three tool wear levels, in the third phase, a 'multi-objective'

Table 1 Mechanical properties of the woven CFRP tested where ρ is the density; E_i elastic modulus in the in plane direction i; υ_{12} in plane Poisson's ratio; X_t, Y_t and S_t maximum tensile stress in the longitudinal and shear directions, respectively; X_c and Y_c maximum compressive stress in the longitudinal directions

Nominal fiber volume	ρ	E_1=E_2	E_3	υ_{12}	X_t=Y_t	X_c=Y_c	S_t
55.29 %	1570 Kg/m^3	68 GPa	10 GPa	0.31	793 MPa	860 MPa	98 MPa

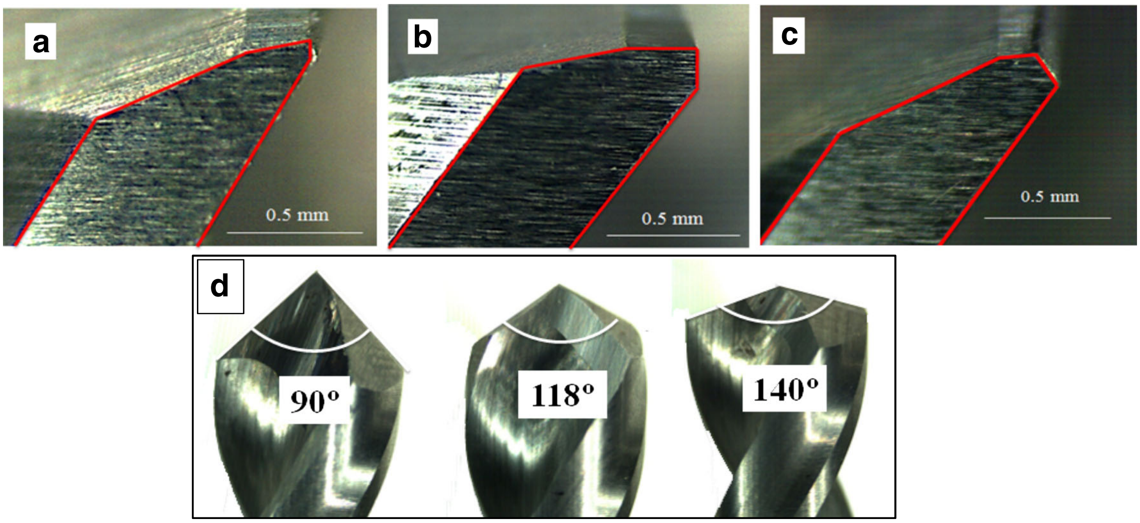


Fig. 2 Edge geometries of drill bits tested; **a** new tool, **b** honed edge tool, and **c** flank worn tool. Under each tool type, three point angles (90°, 118°, and 140°) were chosen as shown in **d** for the new tool case

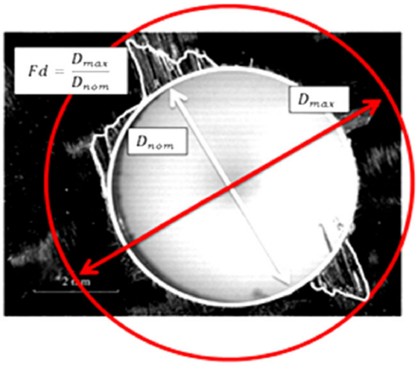
optimization model was employed to identify a set of cutting parameters that can minimize the thrust force, in-delamination, and out-delamination responses, at the same time. More specifically, for each tool wear level, the multi-objective regression model (2) was defined by summing the three individual response equations fitted from phase 2. In the multi-objective model, which is also normalized and weighted, F_t (θ,V,f) is the prediction equation for the thrust force, F_{max} is the maximum thrust force reached during tests for a given tool wear condition, $F_{d\text{-}in}$ (θ,V,f) is the prediction equation for in-delamination, $F_{d\text{-}out}$ (θ,V,f) is the predict equation for out-delamination, and ω_1, ω_2 and ω_3 are the weighting factors.

$$y=\omega_1\cdot\frac{F_t(\theta,V,f)}{F_{max}}+\omega_2\cdot F_{d-in}\,(\theta,V,f)+\omega_3\cdot F_{d-out}\,(\theta,V,f) \qquad (2)$$

To find the multi-objective optimum point for each tool wear level, the weighting factors can be selected by an expert designer to reflect the relative importance of the three criteria (responses). Subsequently (2) can be minimized. For a non-expert designer, however, a sensitivity analysis of weights should be carried out before making a final decision (these practical notions are discussed further in Section 3.5).

Fig. 3 Schematic of delamination under each combination of process parameters. Note that the same full factorial design has been implemented for three wear levels (as a fourth factor)

α (°)	V (m/min)	f (mm/rev)	Set-Up
90	25	0.05	1
		0.1	2
		0.15	3
	50	0.05	4
		0.1	5
		0.15	6
	100	0.05	7
		0.1	8
		0.15	9
118	25	0.05	10
		0.1	11
		0.15	12
	50	0.05	13
		0.1	14
		0.15	15
	100	0.05	16
		0.1	17
		0.15	18
140	25	0.05	19
		0.1	20
		0.15	21
	50	0.05	22
		0.1	23
		0.15	24
	100	0.05	25
		0.1	26
		0.15	27



3 Results and discussion

The raw experimental data for thrust force, in- and out- delaminations under tested drilling configurations were previously published in the study (Feito et al. 2014b). This work is directly focused on statistical evaluation of main and interaction factor effects as well as the multi-objective optimization process under different tool wear levels.

3.1 Thrust force

Table 2 shows the results obtained from the ANOVA analysis on the thrust force response. It is observed that only two of the three cutting parameters are related to the thrust force, namely the point angle and the feed rate, independently of the tool geometry (i.e., p-value<0.05 for all three wear levels). The relative percentage contributions of these factors, however, change when the wear level increases on the drill bit; for the new tool the feed rate has the main influence (57.46 %). On contrary, the point angle is the dominant factor controlling the thrust force in the case of the flank worn tool (84.74 %). Honed edge tool shows comparable contributions of the two factors. *These results suggest that as the tool bit is worn due to drilling cycles, under a given feed rate, a significant increase of thrust force may be experienced.*

Cutting speed did not show a statistically significant influence on the thrust force for any tool case (p-value>0.05). However, based on Table 2, for the case of new tool it has a slight influence in combination with other significant parameters (namely, the interaction factor BC). The influence of this interaction is relatively low for the case of new tool (2.75 %), which practically means it is not as important as the point angle factor. Similarly, for both worn tools, the interaction factor AC has marginally contributed to the variation of thrust force (less than 2 %).

3.2 Entry delamination

For the case of entry delamination or peel up, the ANOVA results are shown in Table 3. The feed rate indicates the maximum contribution for all tool types. It is interesting that for the worn tools, this factor contribution increases by ~25 % for the flank wear tool and ~65 % for the honed edge tool, compared to the new tool. *This suggests that as the drill bit is worn, the same feed rate can cause less entry delamination in the CFRP laminate (or in a different way, to avoid excessive*

Table 2 ANOVA results for the thrust force (highlighted rows indicate significant factors with a p-value<5 %)

	Factor	Sum of squares	DF	Mean square	F-Value	p-value	Contribution of SS_{Mean}	Significance
New Tool	Point angle (A)	2987.512	2	1493.756	141.2005	5.76E-07	37.23 %	Very High
	Cutting speed (B)	52.82743	2	26.41372	2.496812	0.143694	0.66 %	Insignificant
	Feed rate (C)	4610.603	2	2305.301	217.9135	1.06E-07	57.46 %	Very High
	AB	136.0129	4	34.00323	3.214228	0.075016	0.85 %	Insignificant
	AC	126.1262	4	31.53156	2.980588	0.088243	0.79 %	Insignificant
	BC	441.957	4	110.4892	10.44423	0.002907	2.75 %	Very Low
	Residual	84.6318	8	10.57898	–	–	0.26 %	–
	Total	8439.67	26	–	–	–	100 %	–
Honed Edge Tool	Point angle (A)	100141.9	2	50070.96	128.6085	8.28E-07	47.41 %	Very High
	Cutting Speed (B)	1630.257	2	815.1283	2.093678	0.185662	0.77 %	Insignificant
	Feed rate (C)	100965.8	2	50482.9	129.6666	8.02E-07	47.80 %	Very High
	AB	4616.701	4	1154.175	2.964528	0.089253	1.09 %	Insignificant
	AC	8287.652	4	2071.913	5.321761	0.021754	1.96 %	Very Low
	BC	2486.189	4	621.5472	1.59646	0.265445	0.59 %	Insignificant
	Residual	3114.628	8	389.3284	–	–	0.37 %	–
	Total	221243.2	26	–	–	–	100 %	–
Flank Wear Tool	Point angle (A)	854,889	2	427444.5	1061.95	1.98E-10	84.74 %	Very High
	Cutting Speed (B)	2382.996	2	1191.498	2.960176	0.109083	0.24 %	Insignificant
	Feed rate (C)	140944.2	2	70472.11	175.082	2.49E-07	13.97 %	Very High
	AB	3903.594	4	975.8985	2.424537	0.133259	0.19 %	Insignificant
	AC	12656.36	4	3164.09	7.860916	0.007088	0.63 %	Very Low
	BC	3113.887	4	778.4717	1.934047	0.198154	0.15 %	Insignificant
	Residual	3220.073	8	402.5091	–	–	0.08 %	–
	Total	1,021,110	26	–	–	–	100 %	–

Table 3 ANOVA results for in-delamination (highlighted rows indicate significant factors with a p-value<5 %)

	Factor	Sum of Squares	DF	Mean Square	F-Value	P-Value	Contribution of SS_{Mean}	Significance
New Tool	Point angle (A)	0.065	2	0.032	9.52	0.0077	29.02 %	Very High
	Cutting speed (B)	0.033	2	0.017	4.89	0.041	15.42 %	Very Low
	Feed rate (C)	0.084	2	0.042	12.36	0.0036	38.08 %	Very High
	AB	0.036	4	8.88E-03	2.62	0.115	8.05 %	Insignificant
	AC	5.51E-03	4	1.38E-03	0.41	0.7997	1.25 %	Insignificant
	BC	0.023	4	5.63E-03	1.66	0.2507	5.11 %	Insignificant
	Residual	0.027	8	3.39E-03	–	–	3.08 %	–
	Total	0.27	26	–	–	–	100 %	–
Honed Edge Tool	Point angle (A)	0.012424	2	0.006212	4.47461	0.049632	15.81 %	Very Low
	Cutting Speed (B)	0.00102	2	0.00051	0.367472	0.70359	1.30 %	Insignificant
	Feed rate (C)	0.049492	2	0.024746	17.82488	0.001128	62.97 %	Very High
	AB	0.01759	4	0.004397	3.167539	0.077453	11.19 %	Very Low
	AC	0.004056	4	0.001014	0.73044	0.595901	2.58 %	Insignificant
	BC	0.004126	4	0.001032	0.743089	0.588804	2.62 %	Insignificant
	Residual	0.011106	8	0.00139	–	–	3.53 %	–
	Total	0.099816	26	–	–	–	100 %	–
Flank Wear Tool	Point angle (A)	0.007143	2	0.003571	8.12755	0.011834	21.91 %	Very Low
	Cutting Speed (B)	0.005743	2	0.002872	6.534943	0.020783	17.62 %	Very Low
	Feed rate (C)	0.015629	2	0.007814	17.78385	0.001137	47.94 %	Very High
	AB	0.002455	4	0.000614	1.396736	0.317881	3.77 %	Insignificant
	AC	0.001022	4	0.000256	0.58161	0.684819	1.57 %	Insignificant
	BC	0.002935	4	0.000734	1.669933	0.248746	4.50 %	Insignificant
	Residual	0.003515	8	0.000439	–	–	2.70 %	–
	Total	0.038442	26	–	–	–	100 %	–

delamination, the feed rate should be low for new tools); see also (Feito et al. 2014b). Regarding the rest of parameters, the new and flank wear tools have almost the same sensitivity to the point angle (29.02 vs. 21.91 %) followed by the cutting speed (15.42 vs. 17.62 %). Results for the honed edge tool, however, show a different behaviour. The feed rate has a huge influence on the entry delamination (62.97 %) followed by the point angle (~15.81 %), while the cutting speed is no longer significant in this case. Finally, it can be observed that while the p-values for all interaction factors are greater than 0.05 (i.e., statistically insignificant), their contribution for factors such as AB under the honed edge tool is calculated as high as 11.19 %. This is partly because the random error (residual) for the entry delamination measurement has been relatively high (~3.5 %) when compared to the other responses.

3.3 Exit delamination

The last output parameter individually analyzed is the exit delamination or push out. Table 4 shows the corresponding ANOVA. All the three drilling parameters are significant for the exist-delamination using the new tool and flank worn tools. In both tool cases, the point angle is the most influential factor (~40 % contribution). As the tool is worn, the exit delamination generally increases. This high contribution of point angle on the exit pdelamination is opposite to the entry delamination based on results in Section 3.2, where the feed rate had the highest contribution. *This suggests that for these tool bits, given that the interaction AC is trivial in both Tables 2 and 3, designers may use the feed rate effect to better control (lower) the extension of in-delamination, while using the point angle effect to better control (lower) the exist delamination.* It is also interesting that for the new tool and flank worn tool, the cutting speed is influential on the exist delamination, in contrast to Sections 3.1 & 3.2.

For the case of honed edge tool, similar to the entry delamination case, the point angle and feed rate become significant, but not the cutting speed. However, for this tool the contribution of feed rate is higher than point angle, when compared to the new tool and flank worn tools. Generally, as reviewed in Section 1, lower feed rates and higher point angles result in lower in-delamination. However, as will be shown in Section 3.5, there are several conflicts in such trends under other criterion (e.g., minimization of exit-delamination),

Table 4 ANOVA results for out delamination (highlighted rows indicate significant factors with a *p*-value<5 %)

	Factor	Sum of Squares	DF	Mean Square	*F*-Value	*P*-Value	Contribution of SS_{Mean}	Significance
New Tool	Point angle (A)	0.058	2	0.029	23.91	0.0004	41.82 %	Very High
	Cutting speed (B)	0.013	2	6.27E-03	5.21	0.0356	9.04 %	Very Low
	Feed rate (C)	0.025	2	0.012	10.29	0.0061	17.31 %	Very High
	AB	0.062	4	0.015	12.82	0.0015	21.63 %	Very High
	AC	7.79E-03	4	1.95E-03	1.62	0.2603	2.81 %	Insignificant
	BC	0.016	4	3.92E-03	3.26	0.0729	5.65 %	Insignificant
	Residual	9.63E-03	8	1.20E-03	–	–	1.74 %	–
	Total	0.19	26	–	–	–	100 %	–
Honed Edge Tool	Point angle (A)	0.147998	2	0.073999	11.95297	0.003953	34.31 %	Very High
	Cutting Speed (B)	0.016753	2	0.008376	1.353034	0.311774	3.88 %	Insignificant
	Feed rate (C)	0.202589	2	0.101295	16.36206	0.001489	46.97 %	Very High
	AB	0.090622	4	0.022655	3.659526	0.045933	10.50 %	Low
	AC	0.004073	4	0.001018	0.164477	0.950542	0.47 %	Insignificant
	BC	0.00859	4	0.002148	0.346889	0.839234	1.00 %	Insignificant
	Residual	0.049527	8	0.006191	–	–	2.87 %	–
	Total	0.520152	26	–	–	–	100 %	–
Flank Wear Tool	Point angle (A)	0.117941	2	0.05897	24.15872	0.000407	43.52 %	Very High
	Cutting Speed (B)	0.070968	2	0.035484	14.53698	0.002168	26.19 %	Very High
	Feed rate (C)	0.042954	2	0.021477	8.798636	0.009541	15.85 %	Very High
	AB	0.052622	4	0.013155	5.389433	0.021022	9.71 %	Low
	AC	0.005614	4	0.001404	0.574982	0.688994	1.04 %	Insignificant
	BC	0.010285	4	0.002571	1.053368	0.438097	1.90 %	Insignificant
	Residual	0.019528	8	0.002441	–	–	1.80 %	Insignificant
	Total	0.319912	26	–	–	–	100 %	–

hence justifying the need for a 'multi-objective' optimization approach. Finally, it is evident from Table 4 that *the exit delamination is more sensitive to the tool geometry condition (wear) and is a more complex response to minimize* (e.g., notice the effect of *AB* interaction which is not negligible in this case under all tool types; the other two interactions (AC and BC), however, seem insignificant with a maximum influence of 5.7 %).

3.4 Regressions

The correlation between the cutting factors (cutting speed, feed rate and point angle) and the dependant variables (thrust force, peel-up delamination and push-out delamination) were obtained using multiple linear regression and test data from designed experiment as in Figs. 3, 4 and 5. The fitted equations are presented in Table 5 where F_t represent the thrust force, $F_{d\text{-}in}$ the entry delamination, $F_{d\text{-}out}$ the exit delamination, θ the point angle, V the cutting speed and f the feed rate. The higher-order interactions have been included to improve the accuracy of the predictions. All the fits presented a statistically significant R^2 value.

Table 6 shows results of a set of validation experiments that were performed at new design points to assess the predictably of identified regression equations in Table 5. The maximum relative difference between the experimental value and the predicted value was 9.7 % for the thrust force, 4.9 % for entry delamination, and 3.3 % for the exit delamination, providing a good confidence level regarding the applicability of the prediction equations.

3.5 Optimization process

Table 7 presents the optimum solution that minimizes each dependent variable separately (i.e., single objective optimization). In this table, 'A' columns refer to the best solutions obtained from a 'discrete' single-objective optimization, i.e., using only tested configurations with the select levels of point angle {90°, 118°, 140°}, cutting speed {25 m/min, 50 m/min, 100 m/min}and feed rate {0.05 mm/rev, 0.1 mm/rev, 0.15 mm/rev}. These single-objective optimum points are also marked as circles in Figs. 4, 5 and 6 (indicating that the optimum solution can change in the design space from one response to another and/or between different tool conditions).

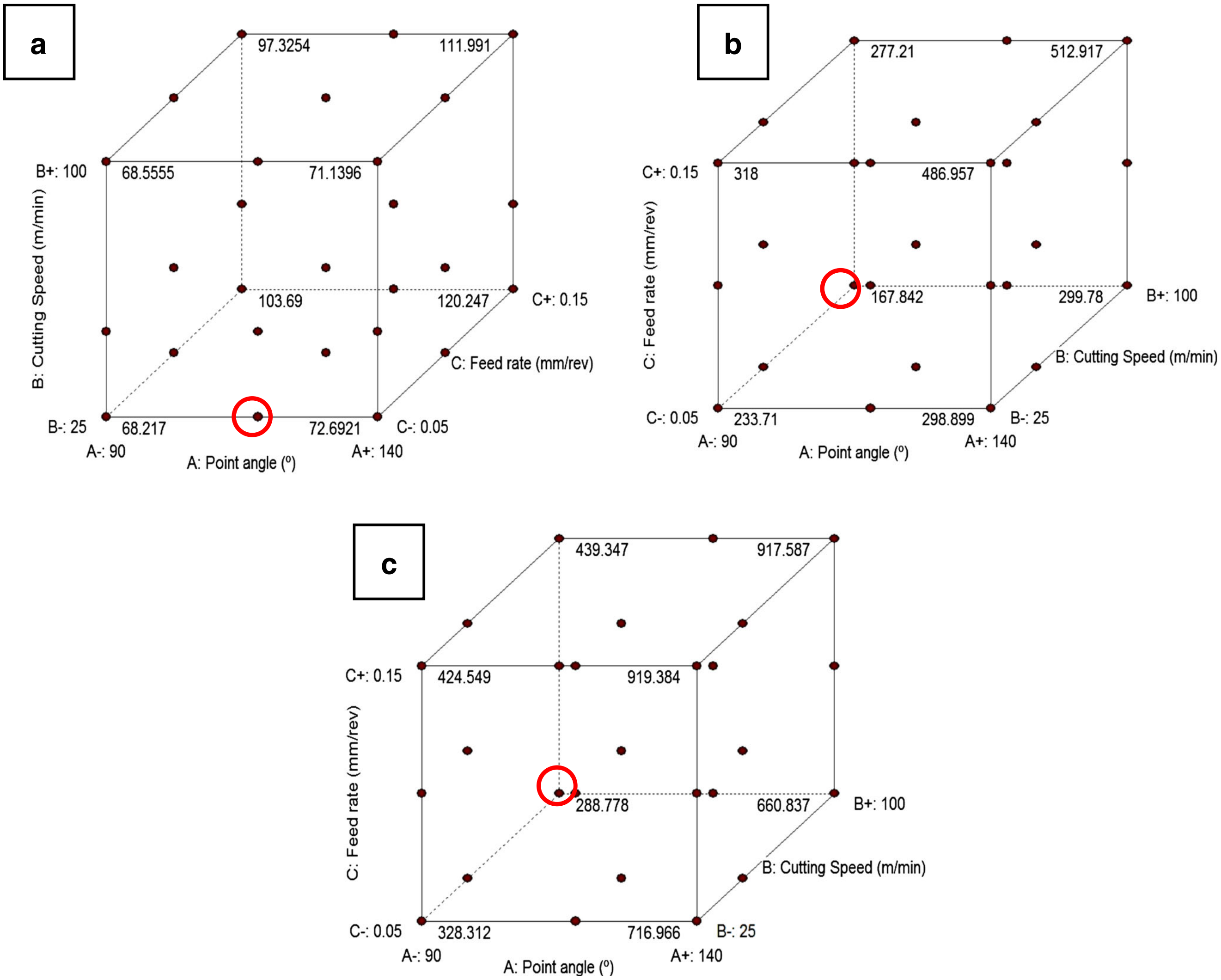


Fig. 4 Variation of the thrust force for **a** the new tool, **b** honed edged tool, and **c** flank wear tool as a function of cutting variables

Columns 'B' in Table 7 refer to the 'continuous' optimization solutions via minimizing the fitted equations (RSM approach) in Table 5, based on the continuous ranges of independent variables: point angle [90–140°], cutting speed [25 m/min-100 m/min] and feed rate [0.05 mm/rev–0.15 mm/rev].

Table 7, it can be observed that for a given tool wear condition, the optimum set of cutting parameters changes notably from one response variable to another (e.g., for a new tool, the continuous optimum solution of point angle is 114° for thrust force, 90° for peel-up, and 107° for push out criteria). Such conflicts point to the fact that there is no unique solution that can minimize all the criteria perfectly, hence the need for a weighted multi-objective optimization to arrive at an overall optimum solution. Nevertheless, from Table 7 it can be said that, in general, low feed rates are desirable for most cases.

Table 8 presents the multi-objective optimization results under different weighting factor combinations according to (2). The weight associated to each response variable defines the relative importance of corresponding criterion to the designer. In the first attempt, the three design criteria (output variables) were assumed to have an equal importance ($\omega_1=\omega_2=\omega_3=1$). For the second scenario, only in- and out-delaminations are assumed to have high weights ($\omega_1 < \omega_2=\omega_3$). For the last case, only the exit delamination is considered to be highly important for the designer, on account of the fact that it is normally more severe than the entry de-lamination in practice ($\omega_1 = \omega_2 < \omega_3$). From results in Table 8, for all weighting cases, *a low feed rate is recommended for all tool wear conditions*. The latter recommendation can also be noticed from the general performance trends shown in Fig. 7. Multi-objective optimum value of point angle changes between the tool conditions, but within a limited range of 90°–120°

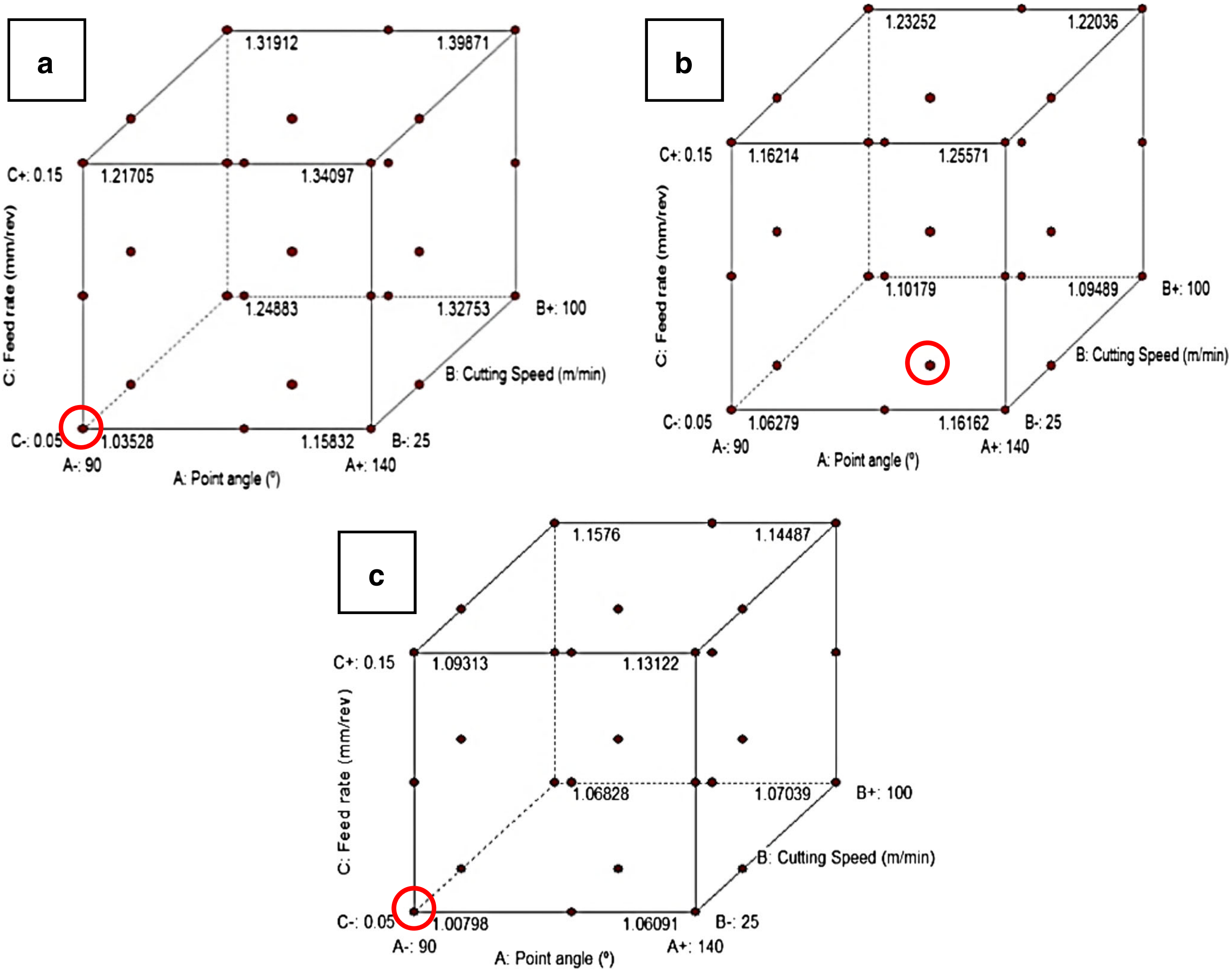


Fig. 5 Variation of the entry delamination for **a** the new tool, **b** honed edged tool, and **c** flank wear tool as a function of cutting variables

Table 5 Regression equations for thrust force, peel up, and push responses out for different tool geometries

	Fitted equations	R^2
New Tool	$F_t = 504.2035 - 8.9386\theta - 0.03889V + 976.7025f + 0.0354\theta V - 4.8606\theta f - 23.5586Vf + 0.0381\theta^2 - 0.0122V^2 + 505.3006f^2 - 0.0001\theta^2 V + 0.045\theta^2 f - 1.6567e{-}5\theta V^2 - 15.3854\theta f^2 + 0.1404V^2 f + 25.5897Vf^2$	0.96
	$F_{d\ in} = -5.7535 + 0.1125\theta + 0.0598V + 95.6124f - 0.0008\theta V - 1.5999\theta f - 0.0905Vf - 0.0005\theta^2 - 5.288e{-}5V^2 - 4442.823f^2 + 3.627e{-}6\theta^2 V + 0.0072\theta^2 f + 7.5553\theta f^2 + 0.3783Vf^2 - 0.0342\theta^2 f^2$	0.87
	$F_{d\ out} = 1.5158 - 0.0109\theta + 0.1163V - 27.4703f - 0.002\theta V + 0.7454\theta f - 0.5047Vf + 1.75e{-}5\theta^2 - 0.0009V^2 + 185.86667f^2 + 1.076e{-}5\theta^2 V - 0.0034\theta^2 f + 1.6e{-}5\theta V^2 - 4.3705\theta f^2 + 0.0035V^2 f + 2.2533Vf^2 - 8.53e{-}8\theta^2 V^2 + 0.0195\theta^2 f^2 - 0.0151\theta^2 f^2$	0.95
Honed edge Tool	$F_t = 233.8026 - 0.1789\theta - 2.6474V - 1108.5187f + 0.0178\theta V + 20.7536\theta f + 3.3438Vf$	0.96
	$F_{d\ in} = -2.76332 + 0.0623\theta + 0.1877V - 20.2656f - 0.003\theta V + 0.4477\theta f - 0.2832Vf - 0.0003\theta^2 - 0.0013V^2 + 157.2017f^2 + 1.2e{-}5\theta^2 V - 0.0018\theta^2 f + 2.1e{-}5\theta V^2 - 3.2388\theta f^2 + 0.00241V^2 f + 1.6152Vf^2 - 9.07e{-}8\theta^2 V^2 + 0.0133\theta^2 f^2 - 0.0132V^2 f^2$	0.89
	$F_{dout} = -4.9926 + 0.1169\theta + 0.3191V - 75.5488f - 0.006\theta V + 1.338\theta f + 0.0681Vf - 0.0005\theta^2 - 0.0021V^2 + 390.0332f^2 + 2.73e{-}5\theta 2V - 0.0057\theta^2 f + 3.85e{-}5\theta V^2 - 6.8446\theta f^2 + 0.0001V^2 f - 0.2157Vf^2 - 1.754e{-}7\theta^2 V^2 + 0.0291\theta^2 f^2 - 0.0011V^2 f^2$	0.90
Flank wear Tool	$Ft = -311.5443 + 6.8219\theta - 0.4910V - 1129.9914f - 0.0044\theta V + 21.2362\theta f + 7.2443Vf$	0.98
	$F_{d\ in} = 0.9156 - 0.0029\theta + 0.0064V + 4.7056f + 3.1956e{-}5\theta V - 0.0435\theta f - 0.0713Vf + 1.294e{-}5\theta^2 - 4.12e{-}5V^2 + 6.5013f^2 - 1.364e{-}7\theta^2 V + 0.0003\theta^2 f - 1.13e{-}7\theta V^2 - 0.1603\theta f^2 + 0.0004V^2 f + 0.1286Vf^2$	0.90
	$F_{d\ out} = -6.4478 + 0.1299\theta + 0.39225V - 42.4574f - 0.0067\theta V + 0.8083\theta f - 0.213Vf - 0.0005\theta^2 - 0.003V^2 + 240.2445f^2 + 2.82e{-}5\theta^2 V - 0.003\theta^2 f + 5.11e{-}5\theta V^2 - 4.3768\theta f^2 + 0.0023V^2 f + 0.758Vf^2 - 2.15e{-}7\theta^2 V^2 + 0.0168\theta^2 f^2 - 0.009V^2 f^2$	0.93

Table 6 Comparison between validation experiments and estimated values by regression equations

Tool type	Point angle (°)	Cutting speed (m/min)	Feed rate (mm/rev)	Thrust Force		Entry Delamination		Exit Delamination	
				Experimental	Estimated	Experimental	Estimated	Experimental	Estimated
New Tool	118	75	0.1	119.10	117.62	1.22	1.28	1.14	1.12
	118	75	0.2	187.70	171.15	1.26	1.30	1.27	1.23
Honed Tool	118	75	0.1	290.86	320.79	1.06	1.09	1.29	1.31
	118	75	0.2	438.26	469.91	1.10	1.12	1.33	1.35
Flank Wear Tool	118	75	0.1	638.86	612.60	1.07	1.10	1.22	1.25
	118	75	0.2	804.28	801.52	1.12	1.11	1.22	1.20

(i.e., low to medium point angles are recommended for overall optimization of CFRP drilling under different tool conditions). For more detailed design guidelines, *when the geometry of the drill bit deteriorates due to the wear process, subsequent drillings with smaller point angles (90°–100°) would be theoretically preferred, whereas for new tools (no wear) a medium range point angle (100°–120°) is optimum.* Optimum level of cutting speed is well varied depending on the given tool geometry. *If the wear is found on the drill bit on the honed edge, it would be recommended to continue the drilling with an increased cutting speed (~100 m/min in the current study) as compared to the flank wear as well as the new tool conditions where generally a lower cutting speed is suitable to avoid the entry and exit delaminations.* Recall that according to sensitivity results in Table 2, the thrust force is not affected as much by the cutting speed.

Finally, Table 9 shows an example of comparison between average exit delamination measured and the damage estimated using the optimum set of parameters for the case of $\omega1=\omega2<\omega3$. In the optimized drilling set-up, the delamination has been reduced by 13.73–26.36 % depending on the tool condition.

4 Conclusions

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

Feed rate and point angle are the factors with highest influence on the thrust force. When the tool is new, the point angle is the most influent parameter. When the tool geometry changes due to wear, the feed rate becomes more important. Cutting speed is not a relevant factor on the thrust force.

Feed rate is the most important factor on the entry delamination for new tool and flank worn tool. Opposite to this, point angle has a strong influence on the exist delamination. Cutting speed is significant for both delamination cases but its influence is generally low, when compared to other cutting parameters. Honed edge tool shows a notably different behaviour that the other tool cases. Feed rate is the most influence for this kind of wear condition, either for in-delamination or out-delamination.

The single optimization of the three output responses showed that under different drilling set-ups a low feed rate (0.05 mm/rev) is most frequently preferred. Point angles in a range of 90° to 114° are recommended to

Table 7 Cutting parameters for the case of discrete (A columns) and continuous (B columns) optimizations of each response variable separately (note: optimum solutions may not be extrapolated to ranges outside those tested)

		Thrust Force		Peel-Up		Push-Out	
		A	B	A	B	A	B
New tool	Point angle (°)	118	114	90	90	118	107
	Cutting Speed (m/min)	25	25	25	25	100	69
	Feed Rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.09
Honed Edge tool	Point angle (°)	90	90	118	116	118	106
	Cutting Speed (m/min)	100	100	50	73	100	98
	Feed Rate (mm/rev)	0.05	0.05	0.05	0.05	0.05	0.05
Flank Wear tool	Point angle (°)	90	90	90	92	118	113
	Cutting Speed (m/min)	100	100	25	25	50	65
	Feed Rate (mm/rev)	0.05	0.05	0.05	0.05	0.15	0.15

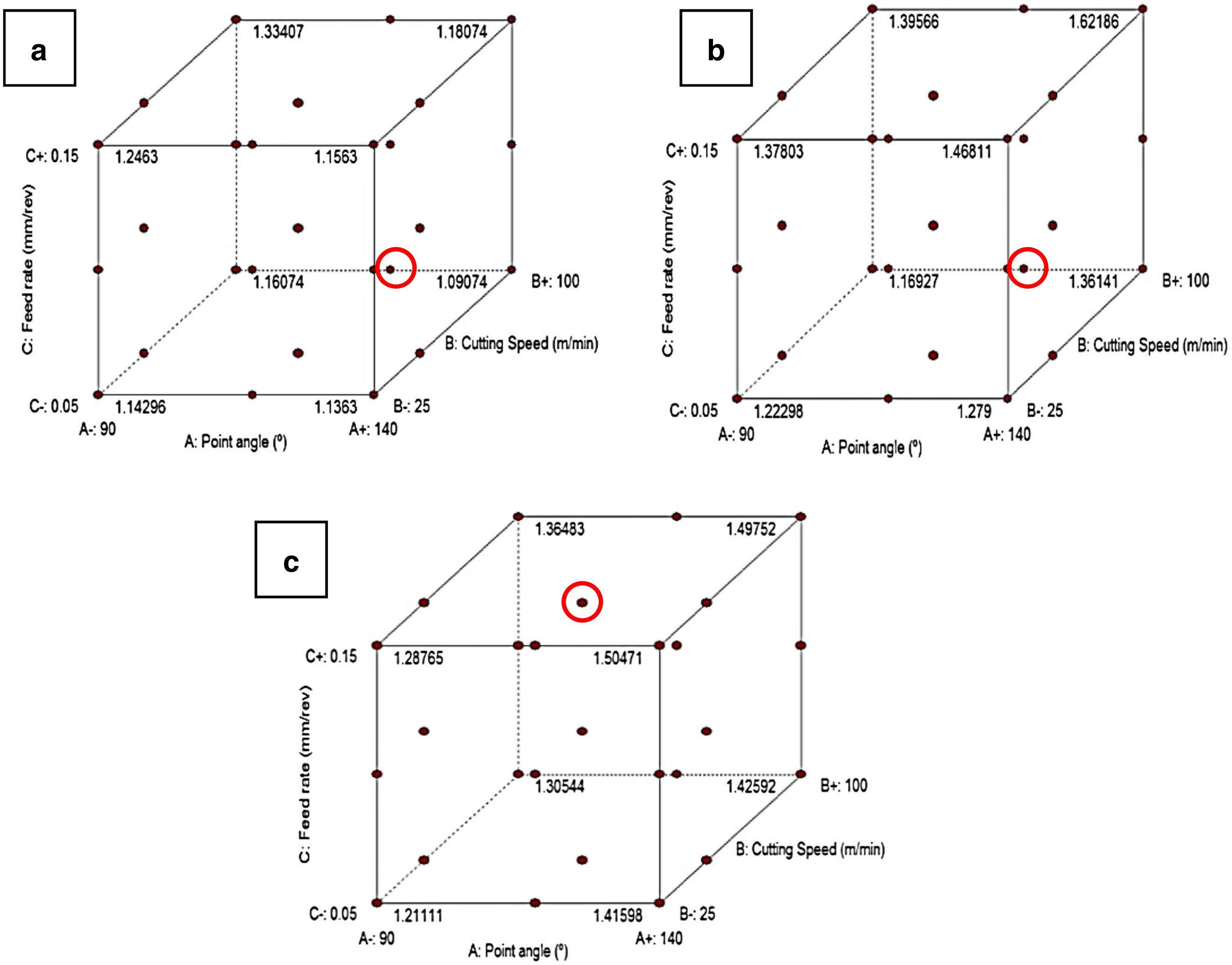


Fig. 6 Variation of the exit delamination for **a** the new tool, **b** honed edged tool, and **c** flank wear tool as a function of cutting variables

minimize the trust force, while it will help avoiding delaminations to a specific extent. When the tool geometry is affected by the wear, however, increasing the cutting speed would keep the response values low, hence maintaining the drilling quality. Peel-up decreases with choosing medium point angles (90°–116°) and low cutting speeds (25 m/min). The opposite effect was found for push-out where higher point angles (107°–113°) and higher cutting speeds (69 m/min–98 m/min) would improve the results; this observation is also in alignment with the earlier reports (Heisel and Pfeifroth 2012; Feito et al. 2014b) and suggest that depending on the wear type and/or a particular design objective, the cutting parameters can be changed to maximize the process quality. However, this may be viewed as a complex paradigm for practical applications, leading to the following multi-objective/overall optimization results.

Table 8 Multi-objective optimum set of cutting parameters for different tool wear conditions tested

	ω_1	ω_2	ω_3	Point angle (°)	Cutting Speed (m/min)	Feed Rate (mm/rev)
New Tool	1	1	1	108	25	0.05
	0.2	1	1	101	25	0.05
	0.2	0.2	1	119	100	0.07
Honed Edge Tool	1	1	1	90	100	0.05
	0.2	1	1	109	87	0.05
	0.2	0.2	1	106	98	0.05
Flank Wear Tool	1	1	1	90	25	0.05
	0.2	1	1	90	25	0.05
	0.2	0.2	1	113	63	0.15

4.1 Overall recommendation

From a multi-objective, practical optimization perspective, considering Fig. 7 and that a manufacturer would

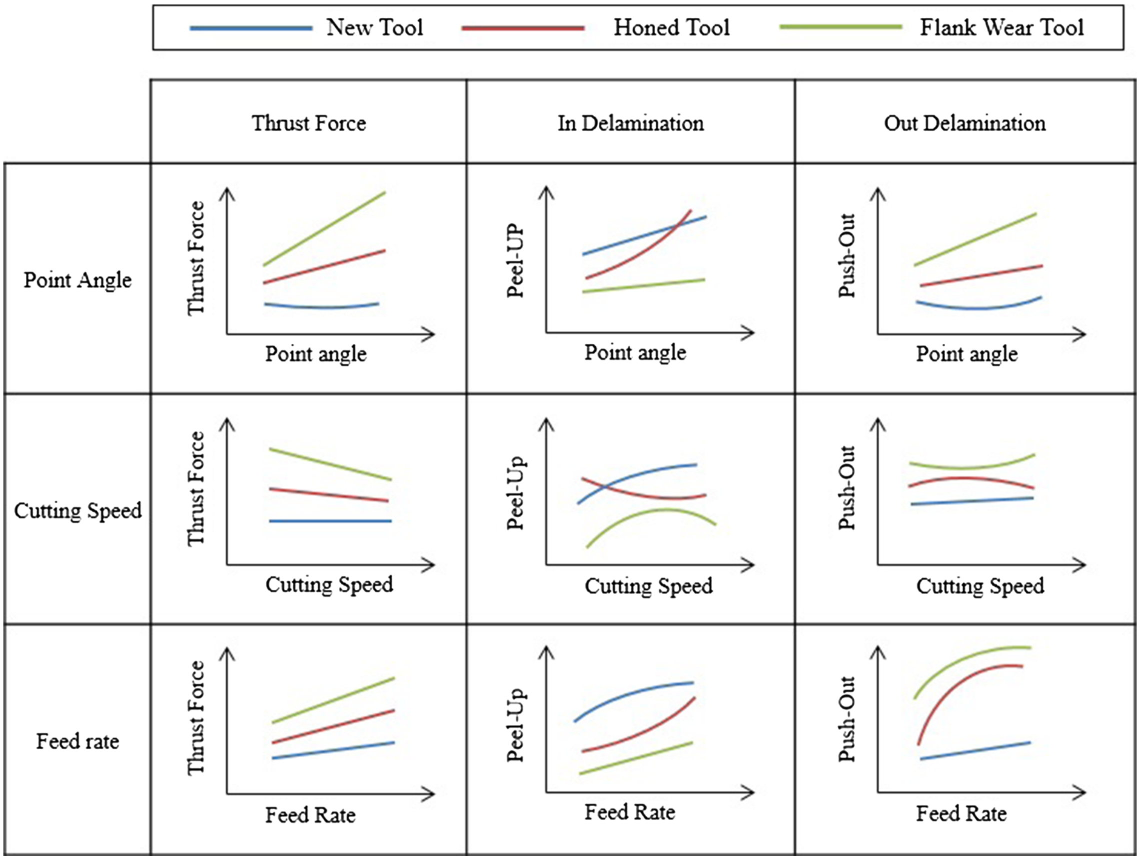


Fig. 7 Overall variation of the CFRP drilling quality with the drill point angle, cutting speed and feed rate, under different wear conditions (trends have been plotted based on test data in (Feito et al. 2014b))

normally prefer to choose one tool in the beginning and use it until its failure, a low feed rate would be recommended (~0.05 mm/rev) for CFRP drillings. A choice of low point angle in the range of 90°–108° is recommended to reduce delamination as the geometry will change due to wear phenomenon. Only the cutting speed would be the one parameter that should be modified from ~25 m/min to ~100 m/min when the wear increases on the drill bit, especially for the honed edge wear case. The drilling parameter interactions, overall, did not show a dominant statistical significance under different measured responses and hence the aforementioned individual factors may be employed independently to control the quality of drilled composite parts.

Future study may include the experimental valuation of optimization results under different tool wear conditions, along with evaluation of the effect of part thickness and/or use of other types of composite materials/fiber architectures. As well, further development and validation of advanced nu-merical models of composites drilling, e.g., (Faraz et al. 2009; Soldani et al. 2011; Feito et al. 2014a), may be conducted using experimental data, along with an in-depth understanding of the macro/meso level mechanisms that correlate to cutting parameters and lead to damage during the process. Eventually using such models, new/customized drilling tools may be de-veloped for composites. The effect of curing/post curing of polymeric composite samples can be another area of future study to evaluate to which extent it may affect the drilling quality for CFRPs.

Table 9 Comparison between average exit delamination observed during measurements and the estimated delamination under optimum drilling parameters in Table 7 for the case of $\omega_1=\omega_2=0.2$, $\omega_3=1$

	Average experimental delamination (Fig. 3)	Estimated delamination with optimized set-up	Relative difference (improvement)
New Tool	1.16	1.02	13.73 %
Flank Wear Tool	1.39	1.10	26.36 %
Honed Edge Tool	1.37	1.13	21.24 %

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