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Influence of Special Tool Geometry in Drilling Woven CFRPs Materials

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Abstract

Machining processes of Carbon Fiber Reinforced Polymer (CFRP) are commonly required in order to achieve final assembly specifications. Despite the good mechanical properties of this kind of materials, they are hard to be machined due to the presence of hard particles; delamination, fiber pull-out and matrix thermal degradation are usually observed during its machining. Drilling operations are required before mechanical joining of the CFRP components. The actual interest in reducing delamination rests in the fact that it is the most serious damage found during drilling. In this work, a comparative study of three special geometries under different cutting conditions is presented. Thrust force and torque were monitoring during drilling tests and delamination extension was quantified. Results showed that a good drill tip geometry and feed rate selection is fundamental to reduce delamination damages.

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Keywords: Drilling; CFRP; woven; delamination.

1. Introduction

Although composite components are manufactured close to the final shape, they usually require machining operations in order to achieve dimensional tolerances and assembly specifications. This is the case of Carbon Fiber

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Reinforce Polymers usually used in aerospace industry to manufacture huge lightweight structures due to high strength-to weight ratio, high fracture toughness and excellent corrosion resistance properties [1].

The most common process to perform holes is through drilling processes. But, due to the abrasive character of carbon fibers and the high temperatures reached during the process, the final result is not always satisfactory. This complex process frequently goes in detriment of surface quality and usually decreases holes performance. One of the negative consequences of drilling operations is the delamination damage. This phenomenon is mainly related with machining parameters and drill geometry. A brief summary of different studies carried out to enhance drilling process on woven CFRP is presented in the following paragraphs.

Davim et al. [2] established a correlation between cutting parameters and delamination for helical and Brad & Spur drills with 5 mm diameter. The experiments showed for both geometries that cutting parameters had a strong influence on the delamination at the entrance for 3 mm thickness woven; however cutting velocity was the major influencing factor in exit delamination. On the other hand it was proved that Brad & Spur drills produced less delamination in the CFRP composite laminate than the Straight Shank drill.

For the same material, Grillo et al. [3] carried out a similar study with Spur, Helicoidal and Four Floute drills. No delamination was found using Spur drills, getting the best results with a spindle speed of 6750 rpm and a feed rate of 2025 mm/min. For higher feed rates, delamination was observed at the entrance.

Hocheng et al. [4] tested Saw, Stick, Core and Step drills. All the holes were made in a thick woven laminate (6 mm). It was proved that exit delamination can be reduced if a drill with a small chisel edge is used (saw and core drills).

Tsao [5] focused on the study of Step-Core drills. The main advantage of this kind of drills is the fact that thrust force is distributed towards the drill periphery during drilling operations. 4 mm thickness material was selected and the conclusions emphasized that thrust force of various Step-Core drills increases when the diameter ratio decreases and the feed rate increases. A combination of high diameter ratio, low feed rate and high speed improved the delamination damage.

The same author compared in other study Step and Non-Step Core-drills using the same material [6]. In that case, a relative motion between the inner and outer parts of the drill was imposed. As a result, a combination between high negative relative motion and low feed rate were recommended in order to reduce delamination damage.

Lazar et al. [7] compared two different materials: CFRP and GFRP woven with a total thickness of 10 mm each one. A Tapered drill, 8-Facet drill and 2-Facet Twist drill were selected to be tested. CFRP showed similar machinability despite the superior mechanical properties over GFRP. Maximum thrust force measured for CFRP material was only a 3% higher than maximum reached for Glass fibers and a 20% in case of torque. Results showed that spindle speed had an enormous importance, especially on the value of the torque mainly due to the vibrations.

Conventional and stepped drills with and without TiN coated were compared by Shyha et al. [8]. All the tools were manufactured in Tungsten carbide (WC) with a diameter equal to 1.5 mm. The total material thickness was 3 mm. During the study, the most of the drills experienced catastrophic failure at high feed rate level (0.4 mm/rev). This was attributed to a drill strength reduction associated to the small diameter of the pilot segment of the tool. To reduce the feed force, the use of uncoated stepped drill with 140° point angle and high feed rate was recommended.

Finally Murphy et al. [9] studied the influence of titanium nitride (TiN) and diamond-like carbon (DLC) coatings with high-performance tungsten carbide (WC) drills. The nominal diameter was 6.35 mm. The geometry selected was a four straight flutes single pass drill. The material used was a combination between woven and unidirectional plies with a total thickness of 4 mm. Results proved that torque and thrust force increased with the tool life but also the flank wear. The wear rate was reduced between the holes 5-7. This fact may correspond to the transition between primary and secondary wear zones in this kind of drills and consequently generate a change in the thrust forces and the torque. No benefit was found in the use of coatings when machining carbon-epoxy composites.

In this work a new study with special geometries is presented: Brad-Center drill, a special Step drill bit (from 4 mm to 6 mm step diameter) and a new designed of Reamer drill bit untested in previous works. Thrust force, torque, and damage delamination were measured and compared for the three cases. Results showed that select a good tool geometry is the most important factor to avoid the delamination damage. It was proved that the influence of cutting parameters on delamination is variable, depending on the geometry selected and feed rate has not always a proportional influence on the thrust force.

2. Experimental Procedure

2.1. Material

Coupons cut in 180 mm x 29 mm have been used to carry out the experimental tests. Each coupon is composed by 10 plies with a total thickness of 2.2 mm. The mechanical properties of the CFRP material are showed in Table 1 where E_i is elastic modulus in the direction i; υ_{ij} Poisson coefficient; G_{ij} elastic modulus in shear directions; X_t, Y_t and St maximum tensile stress in longitudinal and shear directions respectively; X_c and Y_c maximum compressive stress in longitudinal directions.

Table 1. Mechanical properties for woven material [10]

ρ	E1= E2	E3	υ12	G12	Xt = Yt	Xc = Yc	St
1570 Kg/m3	68 GPa	10 GPa	0.31	5GPa	793 MPa	860 MPa	98 MPa

2.2. Tools

The geometries chosen for the present study were three: a Brad-Center drill (typically used for drilling wood materials), a Step drill with a change of section from 4 mm to 6 mm and a new design of Reamer drill untested in previous works (Figure 1). All the drill bits were uncoated and have a nominal diameter equal to 6 mm. The selected manufacturing company was GUHRING.

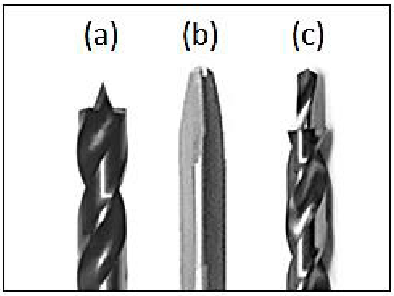

Fig. 1. Drill geometries: (a) Brad; (b) Reamer and (c) Step

2.3. Setup

A machining center equipped with a rotating dynamometer was used to carry out all drilling tests. The cutting forces were acquired with an acquisition data card. In order to characterize the delamination factor, the equation 1 was used, where D_0 is the nominal diameter of the hole (6 mm) and D_{max} is the maximum diameter of the delamination zone observed with an optical stereo microscope (Optika SZR).

$$F_d = \frac{D_{\max}}{D_0} \tag{1}$$

The tests were carried out without coolant to avoid the composite contamination with the cutting fluid. Also a vacuum was used to avoid the fiber dust escapes from the special drilling device to the air. The cutting parameters were chosen among common values used in the industry, those were recommended by the manufacturing company GHURING. They can be observed in Table 2.

Table 2. Cutting parameters selected for the test

Nominal diameter (mm)	6
Cutting Speed (m/min)	25, 50, 100
Feed Rate (mm/rev)	0.05, 0.10, 0.15

3. Results and Discussion

Thrust force, torque and damage delamination were measure during tests and the register signal was treated and analyzed. The tool was new for all cases.

3.1. Thrust Force & Torque

Figure 2 (a) shows the variation of thrust force with feed rate for the studied three geometries under different cutting speeds. For all cases, the force considered was the maximum force which involves delamination damage (in the case of Step drill, the force measured in the second section and in case of reamer the force produced when the conical edges are cutting).

For Brad drill bit, the influence of the cutting parameters is clear. The thrust force increases with feed rate and decreases with cutting speed. For the others two geometries, thrust force is not affected by the increment in the feed rate and a minimum effect of the cutting speed is found in the same indicator. The lowest forces are reached with Reamer drills being the highest with Brad drills.

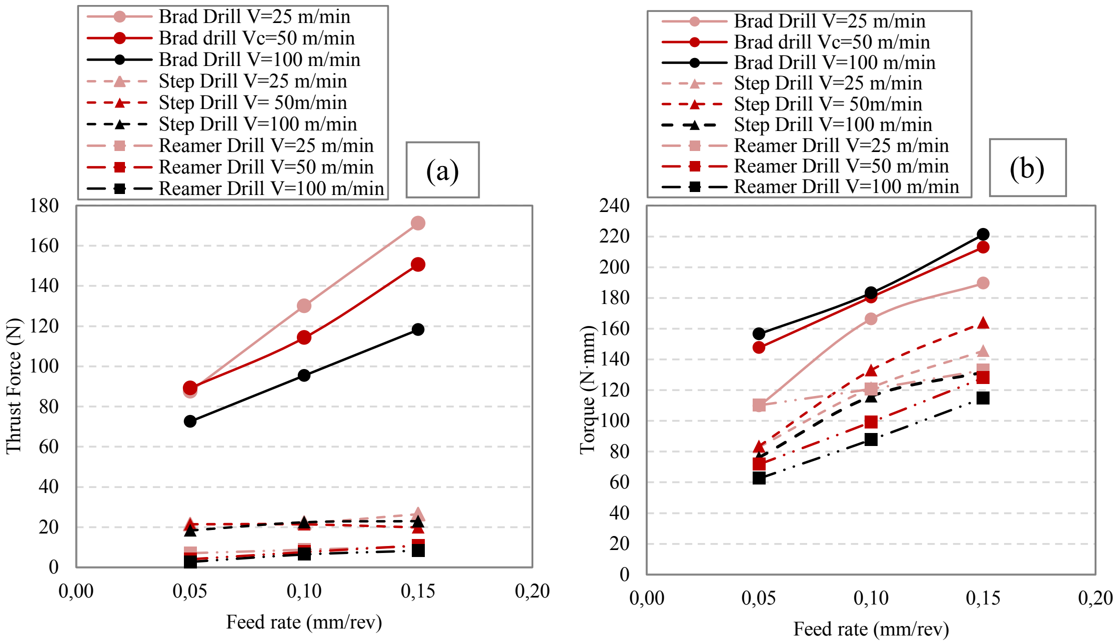

Fig. 2. Variation of thrust force (a) and torque (b) with feed rate and cutting speed for the three different geometries

The evolution of torque with feed rate is represented in Figure 2 (b). It is interesting to remark that, in contrast with thrust force, torque has a positive trending for all cases. It must be noted the differences in the results for the used drill. While torque from Brad drill increases with cutting speed, the opposite effect is observed for Step and Reamer drills. Finally, the lowest values of torque are reached using Reamer drill, as same as feed force, whereas the highest one is observed for Brad drill.

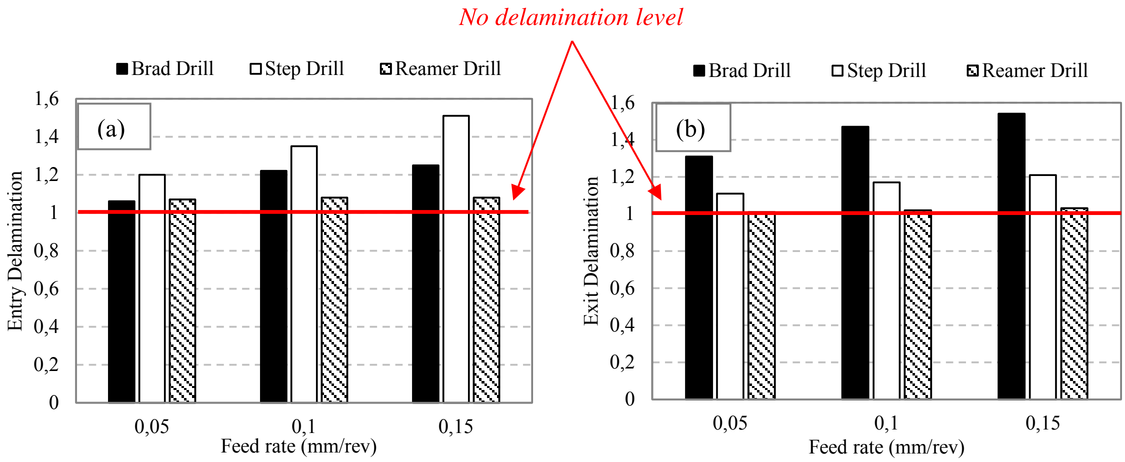

Fig. 3. Variation of entry (a) and exit (b) delamination with feed rate for the geometries tested (*V*=100 m/min)

3.2. Entry & Exit Delamination

Figure 3 shows results for entry (a) and exit (b) delamination. In this case, the influence of cutting speed can be neglected and it has not been presented due to the fact of being not as high as the influence of feed rate.

The feed rate has a strong influence on Brad and Step drills. For the first case (Brad drill) the presence of peel-up is lower than push-out. Change the feed rate from 0.05 mm/rev to 0.15 mm/rev produces an increment of 17.5 % on delamination factor. This percent is similar for entry and exit damage.

In case of Step drills, entry damage is higher than exit damage for all the considered feed rates. Entry delamination factor increases in a 25.8% and exit delamination factor in a 9%. It can be observed that the influence of this geometry on the hole entry is more severe than on the hole exit.

Finally, delamination of Reamer drill shows no damage at exit and lower tan 1.1 for entry case with no influence of feed rate. For all cases, the damage found surrounded the hole is the minimum of the three tested geometries with delamination factor very close to 1.

3.3. ANOVA analysis of delamination

The following Tables (3 and 4) show the results of ANOVA analysis for entry and exit delamination respectively. The results are commented on the next paragraphs.

For the peel-up, spindle speed and feed rate are relevant (F-ratio>6.94, P-value <0.05). In general, the contribution of the feed rate is higher than the cutting speed (for Brad and Step drills). Noticed that for the case of reamer drill, cutting speed is the only significant factor and its influence is about 58%.

On the other hand, push out presents similar conclusions. All the factor are significant in case of Brad and Step drills (F-ratio>6.94, P-value <0.05). Feed rate presents a very high contribution (between 60-69 %) which makes it the most influential cutting parameter. The reamer drill case has not been analyzed for exit delamination due to no delamination was found.

Notice that the error associated to the table for each output has less contribution than the significant factors.

Table 3. ANOVA results for entry delamination (peel-up)

	Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	Contribution
Brad Drill	V (m/min)	2.43E-02	2	1.21E-02	15.61	0.0129	29.5%
	f(mm/rev)	5.66E-02	2	2.83E-02	36.4	0.0027	68.7%
	Error:	3.11E-03	4	7.78E-04	-	-	1.9%
	Total:	8.40E-02	8	4.12E-02	-	-	-
Step Drill	V (m/min)	1.13E-02	2	5.63E-03	8.45	0.0366	46.4%
	f(mm/rev)	1.17E-02	2	5.83E-03	8.75	0.0346	48.1%
	Error:	2.67E-03	4	6.67E-04	-	-	5.5%
	Total:	2.56E-02	8	1.21E-02	-	-	-
Reamer Drill	V (m/min)	1.07E-03	2	5.33E-04	9.14	0.0322	58.2%
	f(mm/rev)	6.50E-04	2	3.25E-04	5.57	0.0698	35.5%
	Error:	2.33E-04	4	5.83E-05	-	-	6.4%
	Total:	1.95E-03	8	9.17E-04	-	-	-

Df: Degrees of freedom; F Ratio: F-test value F(α=5%)=6.94; P-Value: P-test value (Significant at the 5% level).

Table 4. ANOVA results for exit delamination (push-out)

	Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value	Contribution
Brad Drill	V (m/min)	2.96E-02	2	1.48E-02	12.87	0.0181	36.8%
	f(mm/rev)	4.86E-02	2	2.43E-02	21.13	0.0075	60.4%
	Error:	4.60E-03	4	1.15E-03	-	-	2.9%
	Total:	8.28E-02	8	4.03E-02	-	-	-
Step Drill	V (m/min)	4.87E-03	2	2.43E-03	14.6	0.0145	29.2%
	f(mm/rev)	1.15E-02	2	5.73E-03	34.4	0.003	68.8%
	Error:	6.67E-04	4	1.67E-04	-	-	2.0%
	Total:	1.70E-02	8	8.33E-03	-	-	-

Df: Degrees of freedom; F Ratio: F-test value F(α=5%)=6.94; P-Value: P-test value (Significant at the 5% level).

4. Conclusions

The influence of three special geometries under different cutting conditions has been analysed in this work. A Carbon Fiber Reinforced Polymer in woven configuration has been selected. The selected geometries included new designs as the case of Reamer drill. The analysis included an ANOVA study to observe the impact of the different parameters and its contribution. The main conclusions are presented in the next paragraphs:

The influence of the feed rate is only remarkable for Brad drill, where the thrust force and torque increase as feed rate increases. Reamer and Step drill are highly affected by the feed rate in terms of torque, being that effect negligible in the thrust force.

On the other hand, increasing the cutting speed, in general, decreases the cutting forces. This influence is more relevant for torque than for thrust force, especially for the cases of Step and Reamer drills for which it is almost depreciable.

In terms of delamination, Reamer drill showed the best results, with a delamination factor very close to one in both sides of the hole. The low influence of machining parameters for this tool makes it the best option to work with high cutting parameters values. The delamination tendency for the other two drills increases with feed rate. Step drill is the only one which presents an entry delamination higher than exit delamination. Brad drill is the worst geometry for all cases, being the cutting forces and delamination damages the highest.

Finally the ANOVA analysis showed that feed rate is the cutting parameter which has the highest statistic influence on peel-up, and also push-out in Brad and Step drill cases. For Reamer drill, only cutting speed has influence and its contribution is 58% in case of thrust force and 88% for torque.

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