INFLUENCE OF TOOL GEOMETRY IN DRILLING CFRP

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Abstract
The influence of tool geometry in drilling woven CFRPs materials is analyzed in this paper. Three different point angles were tested with fresh tool and worn tool (honed edge). The results showed increasing feed forces when drilling with high point angles using worn tool. Delamination showed opposite trends with the variation of geometry at hole entry and exit for all cases. In addition, this damage has strong dependence with the feed rate and moderate in case of cutting speed. A numerical model for both geometries able to predict thrush force and delamination is presented.

1. Introduction

Fatigue and corrosion resistance, light weight and high specific stiffness and strength are characteristics of Carbon Fiber Reinforced Polymer (CFRP) composites. CFRPs have a wide range of high responsibility applications due to these properties [1]. Woven graphite fibre epoxy composites are significant materials in the family of CFRPs. This type of materials shows higher strength-to weight ratio, higher fracture toughness and excellent corrosion resistance properties compared to unidirectional composites.

The resultant component quality must be ensured in drilling operations in woven carbon composite CFRPs. Surface quality requirements need a suitable choice of both cutting parameters and tool geometry. Different cutting parameters and point angles were analyzed with different coated carbide drills [2, 3]. Feed was observed to be dominant causing workpiece damage. Hole diameter tolerance has been observed to be more critical than hole exit delamination at high feed rate during drilling. Whereas the drilling torque remains almost constant the thrust force increased with high point angles. Using high point angles the quality at the entrance of the hole was better than at the exit.

The tool wear has an obvious influence on the drill geometry. Because of wear progression the initial design of the fresh tool has been modified and thus the effective cutting geometry is varied. The evolution of wear is an influencing factor in the surface integrity. After the drilling tests under different cutting conditions Mayuet et al. [4] identified abrasion due to the presence of hard fibers to be the dominant wear mechanism. Adhesion of the matrix could be considered in second place, with much lower effect. These effects occur with different intensity depending on the cutting speed and the feed rate. In addition, delamination at the exit of the drill increase with the number of drill holes, due to drill wear. Shyha et al. [5] analyzed two drill geometries: conventional twisted and stepped drill. If the feed rate increased, a reduction of abrasive action with stepped drill it is observed because of the lower contact time. However the entry delamination factor is higher also when compared with twisted drill, raising the damage in 40%. Increases in feed rate have a growing impact around 15% in delamination. Opposite impact is found with point angle which reduces entry delamination when the point angle is modified from 118º to 140º.

Tool wear, also affects parameters involved in damage, such as thrust force [4]. In [6] experimental results showed that feed rate and tool wear were the most significant factors affecting the thrust force. The wear of uncoated and coated carbide tools was strongly related with contact length and axial force applied to the cutting edge.

Fracture (chipping) at the initiation of drilling process, subsequent abrasion and possibly adhesion of carbon were the main dominant wear mechanisms observed in high speed drilling (10,000–15,000 rpm) of woven graphite epoxy composites [7]. Abrasive wear on the flank face of the primary cutting edge, was stronger than the wear at the rake face.

Different geometries were also investigated to study cutting edge rounding (CER) and its correlation with the damage surfaces in woven materials [8]. It was found a correlation between delamination, drilling loads and cutting edge rounding in uncoated drills independent of their initial geometry. Numerical analysis of the influence of cutting edge radius in the elemental case of orthogonal cutting has been developed by the authors in [9].

Finite element modeling of the complex drilling process has recently achieved in [10, 11] for unidirectional laminates CFRP. In these works drilling was successfully reproduced including drill penetration in the workpiece, material failure and elements erosion. A recent paper developed by authors has compared this kind of models with a simplified model [12].

This paper presents an experimental analysis of the effect of drill point angle, honing at the edge, being one of the common wear modes in CFRP drilling, is considered. Thrust force and delamination at the entrance and exit of the hole have been evaluated. Also the effect of cutting parameters (cutting speed and feed rate), were studied. Finally a new FEM model has been developed for drilling and it has been validated in terms of thrust force and maximum delamination.

2. Experimental work

2.1 Workpiece material

The material studied in this work is woven CFRP, based on AS-4 carbon fibre and 8552 epoxy matrix plies manufactured by Hexcel Composites. The specimens are composed by 10 plies with the same fiber orientation in all of them, and a total thickness of 2.2 mm. The characteristics and mechanical properties of this material are presented in Table 1.

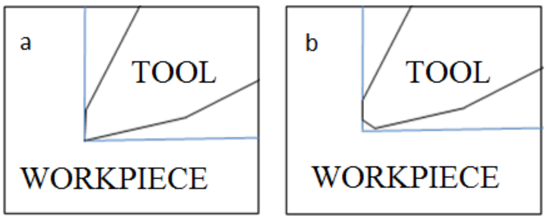
ρ	$E_1 = E_2$	E_3	υ_{12}	**Resin content**
1570 Kg/m^3	68 GPa	10 GPa	0.31	55.29%
$X_t = Y_t$	$X_c = Y_c$	S_t	$\varepsilon_1 = \varepsilon_2$	ε_3
793 MPa	860 MPa	98 MPa	0.025	0.05

Table 1. Mechanical properties of carbon-epoxy woven laminate.

2.2 Machining tests

Two different drill bit geometries (diameter 6 mm) were used with three values of point angle 90°, 118° and 140°; recommended by the manufacturer GUHRING for CFRP drilling. Two different stages concerning wear evolution were tested: fresh drill and honed edge with length equal to 0.05 mm (honed edge is related to chipping wear observed when drilling CFRP). The worn geometry was artificially generated using grinding.

The cutting tests were carried out on a B500 KONDIA machining center. A rotating cutting force dynamometer (Kistler 9123C) was used for the dynamic and quasi-static measurement of the thrust force F_y as well as of the drive moment M_z on the rotating tool. The drilling experiments were conducted without coolant and the cutting parameters from table 2.



Parameter	**Range**		
f [mm/rev]	0.05	0.1	0.15
V [m/min]	25	50	100

Figure 1. Edge geometry of the different tools used; (a) fresh tool and (d) honed edge tool and cutting parameters used in drilling tests: feed rate (*f)* and cutting speed (*V).*

The delamination factor (F_d) quantified as the ratio between the maximum diameter of delaminated area and the nominal diameter obtained from observation of images obtained with a stereo microscope (Optika SZR).

3. Description of the numerical model

This model involved a dynamic analysis including geometrical non-linearity and large deformations options. The problem was solved using an explicit integration scheme (ABAQUS/Explicit). The rotatory movement of the drill around the *y* axis and the feed rate in direction *y* were imposed. The model includes restriction to displacement in *z* direction in the base of the workpiece except inside a circumference with diameter 10 mm where it is free. On the other hand displacements were not allowed in the contour of the workpiece.

3.1 Drill and workpiece behavior

The drill was assumed to be rigid, with diameter equal to 6 mm and the tip angle equal to 118º. The carbon/epoxy woven laminate has been modeled as an orthotropic elastic material until failure. This kind of approach has been used before by López-Puente et al [13] for woven laminates. To model material failure, intra-laminar and inter-laminar damage mechanisms are defined. The first one has been implemented by means of a user subroutine (VUMAT). The second one has been taken into account using cohesive elements. This implementation of different failure mechanisms has been used in previous work of the authors [14].

Fiber failure: Woven laminates have fibers in orthogonal in-plane directions (1 and 2). Eq. (1) describes the failure in both directions:

$$d_{f1} = \begin{cases} \dfrac{\sigma_{11}}{X_t} & if \;\; \sigma_{11} > 0 \\ \dfrac{|\sigma_{11}|}{X_c} & if \;\; \sigma_{11} < 0 \end{cases} \qquad d_{f2} = \begin{cases} \dfrac{\sigma_{22}}{Y_t} & if \;\; \sigma_{22} > 0 \\ \dfrac{|\sigma_{22}|}{Y_c} & if \;\; \sigma_{22} < 0 \end{cases} \tag{1}$$

Where σ_{11} and σ_{22} are the stresses in the warp and fill direction respectively, X_t and X_c are the strengths of the composite laminate in tension and compression for the warp direction, and finally Y_t and Y_c are the strengths in tension and compression for the fill direction.

Crushing matrix failure: Two different parameters are proposed in this damage mechanism, one in plane direction Eq. (2) and the other one in the through-thickness direction Eq. (3).

$$d_{m12} = \left| \frac{\sigma_{12}}{S_{12}} \right| \tag{2}$$

$$d_{m3} = \frac{1}{4}\left(\frac{\sigma_{33}}{Z_c}\right)^2 + \frac{Z_c \cdot \sigma_{33}}{4S_{13}S_{23}} + \left|\frac{\sigma_{33}}{Z_c}\right| + \max\left[\left(\frac{\sigma_{13}}{S_{13}}\right)^2, \left(\frac{\sigma_{23}}{S_{23}}\right)^2\right] \tag{3}$$

Where σ_{ij} are components of the stress tensor, S_{12}, S_{13} and S_{23} are the shear strengths in the three different planes and finally Z_c is the strength in the through-thickness direction under compression. The Eq. (3) applies only when $\sigma_{33} < 0$.

Delamination: The cohesive elements are based on a constitutive response in terms of a traction-separation law. To define the law it is necessary to specify the linear elastic behavior by means of the correspondent stiffness (K_{nn}, K_{ss} and K_{tt}). In this work, a quadratic nominal stress criterion for the damage initiation, similar to Eq. (4), has been chosen where t_n, t_s and t_t are the strengths of the cohesive interface in the normal and in the two shear directions respectively. This last equation is applied if one of conditions on Eq. (5) is reached, where Z_t is the laminate strength under tension in the through thickness direction.

$$\left(\frac{\sigma_{33}}{t_n}\right)^2 + \left(\frac{\sigma_{13}}{t_s}\right)^2 + \left(\frac{\sigma_{23}}{t_t}\right)^2 \geq 1 \tag{4}$$

$$\sigma_{33} \geq Z_t \;\; or \;\; \sqrt{\sigma_{12}^2 + \sigma_{13}^2} \geq S_{23} \tag{5}$$

The damage evolution law is a potential law type based on energies as Eq. (6) in which α = 1 and G_n, G_s and G_t are the released rates energies in the three aforementioned directions, $G^C{}_n$; $G^C{}_s$ and $G^C{}_t$ are the critical values of the released rates energies. The properties that have been used are shown in Table 3.

$$\left(\frac{G_n}{G_n^C}\right)^{\alpha} + \left(\frac{G_s}{G_s^C}\right)^{\alpha} + \left(\frac{G_t}{G_t^C}\right)^{\alpha} \geq 1 \quad (6)$$

K_{nn}	$K_{ss}=K_{tt}$	t_n	$t_s=t_t$	G_n	$G_s=G_t$
2 GPa/mm	1.5 G Pa/mm	11 MPa	45 MPa	0.6 J/m^2	1.8 J/m^2

Table 3. Parameters for the cohesive interface.

3.2 Finite element meshing

Each ply was modelled at the zone close to the drill entrance using solid elements C3D6R (wedge elements) with six nodes to minimize the dependence of the results with mesh orientation in the laminate plane. One element is imposed along the thickness. Minimum element size was 0.2 mm. Far from to the drill entrance zone hexagonal elements C3D8R with 8 nodes and reduced integration were used, with minimum element size around 1mm. Delamination is modeled by means of cohesive elements. Small thickness was assigned to the interface (50 microns) in order to improve numerical behavior when elevated deformations are reached during calculation. Meshing strategy in the plane 1-2 was the same as that used in the ply, with one element along the thickness (direction 3).

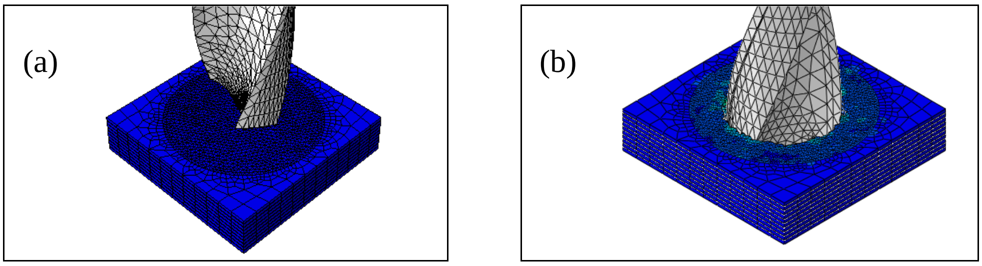


Figure 2. Drill simulation; (a) Initial and (d) finish position.

4. Results and discussion

4.1 Thrust force

The maximum level of thrust force obtained during drilling tests is presented in Fig. 3. It is possible to observe the negligible influence of the point angle on thrust force in comparison with worn tool when fresh drill is tested since the projection of the resultant force in the axial direction is the same for all point angles. The increment of feed lead to thrust force increment (values of thrust force between 50 and 150 N for all cases tested). However, the variation of the cutting speed has no significant effect on thrush force.

In the case of honing tools it is observed a clear growing tendency with the increment of point angle. In that case, the force increases around 50% regardless of the value of cutting speed tested. Nevertheless, low feed per revolution (0.05 mm/rev) show lower increases in feed force than high feed per revolution (0.15 mm/rev) when the point angles grow up. Raising the feed with same point angle leads to an increment around 85% in thrush force. It is clear that the wear strongly increases the effect of the feed and the point angle on thrust force.

For new tool has been observed decreasing values of the torque when the point angle is increased from 90º to 118º and slight increment when it changes from 118º to 140º. For worn tool the trend is the opposite and maximum values of the torque are observed for the point angle 118º.

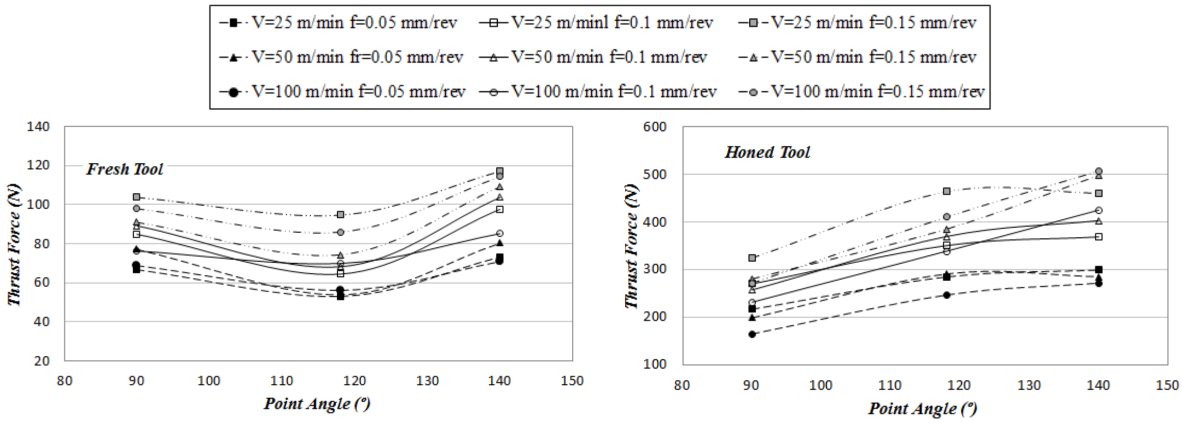


Figure 3. Thrust force variation for both geometries.

4.2 Delamination

The diameter was measured after each drilling test using a micrometer (Mitotuyo 368-101). Nominal value equal to 6 mm was measured in all cases; deviation of the measurements was 6 ± 0.12 mm.

Delamination is presented in Fig.4 in a range for all the tests with the cutting conditions specified before. Entrance delamination factor increases with point angle for both geometries. This trend is in agreement with the thrust force enhancement. For fresh tool this behavior, it is not the same at the exit. Slight decrease in delamination factor is observed with 118º point angle. This fact has been found before for multi-layer CFRP [15].

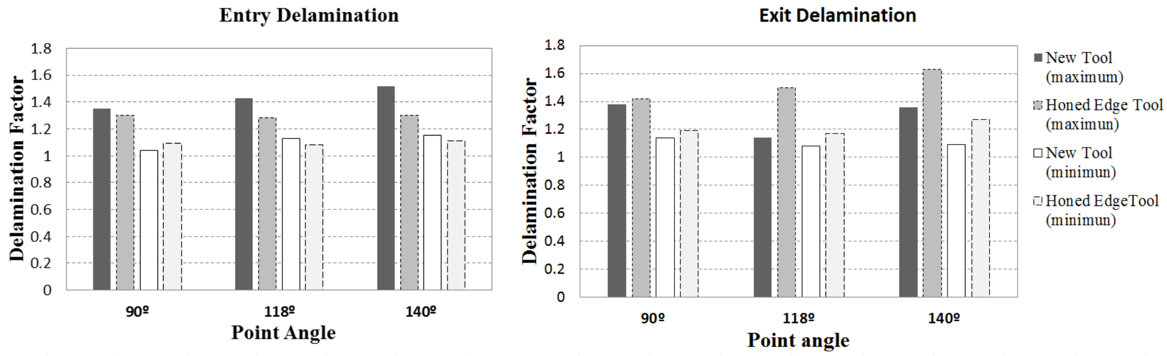


Figure 4. Maximun and minimum delamination at hole entry and exit for both geometries.

Opposite trends are observed when compared the influence of wear at the entrance and exit delamination. Honed drills lead to slightly increased entrance delamination until 1.3 in maximum cases. There is a minimum delamination factor, observed even for fresh tool that is not possible to be avoided in the range between 1.08-1.18.

On the other hand exit delamination increased with wear. This fact is related to the increment of the thrust force, which is higher with wear progression. Delamination at the exit for honed is higher than delamination with fresh tool that never reach values higher than 1.38. The minimum exit delamination is for all the cases higher than the minimum found for entry delamination.

When the cutting edges of drill bit make contact with the material a peeling force through the slope of the drill results in separate the plies from each other. When the edge starts to wear, this force decrease due to the geometry is going flattering. This fact elevates the thrust force but decreases the peel force, what results into reduce the peel up and elevate the push out mechanisms.

4.3 Model validation

The complete model was validated through the comparison with experimental results provided for cutting speed equal 100 m/min and 118º point angle. The model was validated in terms of thrust force and maximum delamination. Table 5 shows reasonable accuracy when predicting these parameters. The thrust force prediction for fresh tool is better than honed tool. In all cases prediction error is not higher than 5%. On the other hand delamination prediction is also higher in the model than in experimental with a maximum deviation of 4.5%. This model is therefore conservative in predicting delamination. Thus the model could be used as simulation tool for prediction of variable related to surface integrity.

Geometry	Feed rate (mm/rev)	Experimental thrust force (N)	Estimated thrust force (N)	Experimental delamination	Estimated delamination
Fresh Tool	0.05	56.2	53.9	1.07	1.09
	0.1	69.93	77.97	1.07	1.09
	0.15	86.2	88.4	1.11	1.16
Honed Tool	0.05	246.2	209.8	1.19	1.23
	0.1	338.5	322.7	1.28	1.3
	0.15	410.12	392.6	1.37	1.4

Table 3. Experimental and numerical results for thrust force and delamination. (V = 100 m/min).

5. Conclusions

In this work the effect of discrete machining parameters and worn geometry on thrust force and delamination in drilling of a woven composite laminate was investigated both experimentally and numerically.

Point angle has no strong influence when drilling with fresh tool. Honed edge tool (related to chipping wear), shows linear growing tendency on thrust forces with a variation of point angles from 90º to 140º. The increment of feed leads to increasing thrust force in all cases and for all values of point angle.

In general, entry and exit delamination factor was below 1.6. The trend of delamination factor is to increase with the point angle due to the enhancement of thrust force. For all cases analyzed, exit delamination is higher than entry delamination. Entry delamination factor is lower for honed wear geometry, due to reduction in peel up force produced by sharp cutting edge. The same geometry has opposite effect at hole exit causing the highest delamination as a consequence of enhanced thrust forces.

Finally The FE model predicted the drilling thrust force with reasonable accuracy when compared to experimental results. The use of cohesive zone elements between the adjacent plies in the model of composite laminate predicts also maximum delamination slightly over-estimated, giving a conservative prediction of damage.

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