NUMERICAL STUDY OF SPECIAL DRILL BIT FOR CFRP MATERIALS

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ABSTRACT

Drilling of composite materials is a widely used process in aeronautical assembly to join pieces of big structures. The growing use of these materials in the industry is mainly due to its excellent properties, especially for the case of Carbon Fiber Reinforced Polymers (CFRPs). However, the abrasive character of the fibres classifies this kind of materials as difficult to machine. The damage induced during the process decreases the life in service of the structure and, in some cases, generates the rejection of the component. In order to develop new tools able to estimate damage before machining, numerical models are presented as a good solution for industry. The FEM analysis makes easy to test new geometries and get quick information without carry out a high number of tests. The model presented in this work was validated for two different geometries, (conventional and step drill bits) and demonstrated its ability to predict thrust force and delamination for different values of feed rate and cutting speed. Finally, mechanistic equations and surface diagrams were developed to select optimum ranges of design parameters that can minimize the output variables.

1 INTRODUCTION

The use of Long Fibre Reinforced Polymers (LFRP) has increased in the industry during last years. The excellent mechanical properties of these materials compared with other conventional structural materials, make them a suitable option for high responsibility applications.

The Carbon Fibre Reinforced Polymer materials (CFRP) are specially used in aircraft industry. Usually the components are manufactured close to the final shape. However, for big structures, as airplanes, different parts are manufactured separately and joined using rivets or bolts. During this process, the abrasive character of fibres is presented as a disadvantage because of the damage induced with drilling operation. If the damage generated on the component is considerable, it can involve the rejection of the component and a huge economic loss for the company [1].

Among all defects found during drilling, delamination was reported as the most important damage reported on literature [2,3] because it can decreases the live in service of the component. The extension of this damage strongly depends on drilling geometry and cutting parameters as was analysed on previous studies [4,5]. At the same time, fresh drill geometry changes with cutting time due to wear progression modifying the geometry of the tool. As consequence the hole quality decreases as it has been analysed in the literature using mainly experimental approaches [3].

An interesting tool to reduce the number of tests and get a better understanding about drilling process is the use of 3D models based on finite elements methodology. Numerical analysis can be also used to optimize the drill bit geometry and to select adequately the process parameters in order to improve the hole quality. However, only a few works can be found in the literature in this field, [6,7]. This is mainly due to the high computational time and the complexity of the drill bit geometry. As a consequence some researchers developed simplify models considering the drill bit as a punch with the objective of reduce the computational time [8,9]. Even though this advantage, the main problem of this analysis is that this kind of models does not consider the spinning of the drill bit and the cut is not continuous. The authors have previously published a work with a discussion about the advantages and disadvantages between both models [10].

In this paper, a 3D numerical model is presented and validated with two geometries (helicoidal geometry and step geometry). Details of constitutive and contact modelling are given in the following sections. The model was used to estimated force and delamination for different cutting parameters. Finally, some mechanistic models were obtained supporting on simulations results.

2 EXPERIMENTAL PROCEDURE

In this section, the experimental equipment, including materials, tools and measurement systems used in the drilling tests are briefly described.

2.1 Material and drills

The material selected is CFRP bidirectional (woven) composed of 10 plies and a total thickness of 2.2 mm. The ply is based on AS-4 carbon fiber with direction X at 0º and 8552-epoxy matrix. The mechanical properties for the anisotropic composite are shown in Table 1 where E_i is elastic modulus in the direction *i*; υ_{12} is the poisson coefficient; G_{12} elastic modulus in shear directions; X_t, Y_t and S_t maximum tensile stress in longitudinal and shear directions, respectively; X_c and Y_c maximum compressive stress in longitudinal directions.

Property	Units	Value
E_1	[GPa]	68
E_2	[Gpa]	68
E_3	[Gpa]	10
ν_{12}	–	0.22
G_{12}	[GPa]	5
X_t	[MPa]	795
X_c	[MPa]	860
Y_t	[MPa]	795
Y_c	[MPa]	860
S_t	[MPa]	98

Table 1: Material properties.

Two drill bits have been tested with a nominal diameter equal to 6 mm: a conventional drill bit and a new step drill with a length of step equal 6.6 mm and a section change from 4 mm to 6 mm (the stepped geometries in the literature usually present a section change higher than 2 mm). Figure 1 shows the dimensions of both tools. They are based on CW substrate without coating and tested in fresh conditions. The manufacturing company was Guhring, Inc. [11].

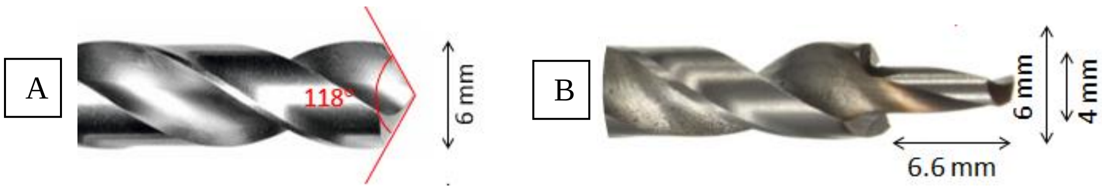

Figure 1: Helicoidal drill bit (A) and step drill bit (B)

2.2 Machining tests

The drilling tests were carried out on a machining centre (B500 KONDIA) equipped with a rotating dynamometer (Kistler 9123C) used to measure the thrust force during machining. None lubricant was used and the plates did not present a pre-drilled hole. Table 2 shows the values of the range recommend for the cutting parameters by the tool manufacturer.

Parameter		Range	
f (mm/rev)	0.05	0.1	0.15
V(m/min)	25	50	100

Table 2: Cutting parameters range.

A supporting back plate was used during drilling tests with the main of diminish delamination damage. The plate includes a drilled hole with 10 mm diameter. This procedure is commonly used in industry.

The delamination factor (F_d) was used to quantify the delamination damage. This parameter is defined as the ratio between the maximum diameter of delaminated area and the nominal diameter of the hole (Equation 1). This factor is the most used in literature due to its simplicity. Both diameters were measured using an optical microscope (Optika SZR).

$$F_d = D_{max}/D_{nom} \tag{1}$$

3 NUMERICAL MODEL

3.1 Implementation of the drill bits

Both tools were drawn in a CAD software, and imported to ABAQUS [12]. Both drills were assumed rigid with nominal diameter equal to 6 mm. For the case of the step drill bit, the first section has a diameter equal to 4 mm. The feed rate and rotatory movement were imposed over the geometry.

3.2 Implementation of the workpiece

Each ply of the CFRP workpiece was modelled using two kinds of elements: wedge elements close to the drill entrance and hexagonal elements far from this zone. The first kinds of elements are classified as C3D6R with six nodes. The minimum size is fixed in 0.2 mm. For the second case, the elements are defined as C3D8R with 8 nodes and reduced integration. The minimum size is 1 mm. For all plies, only one element is located along the thickness. The properties are the same as Table 1.

Cohesive plies have been included in the model to measure the delamination damage. These plies have the same meshing strategy mentioned for the CFRP material but with 5 microns of thickness (1 element per ply). Each ply is located between two layers of CFRP material.

Finally, to reproduce the boundary conditions of experiments, the displacement of the workpiece in Z direction was restricted at the base except for the zone inside a circumference with 10 mm diameter where it is free. All the conditions mentioned, can be seen in the Figure 2.

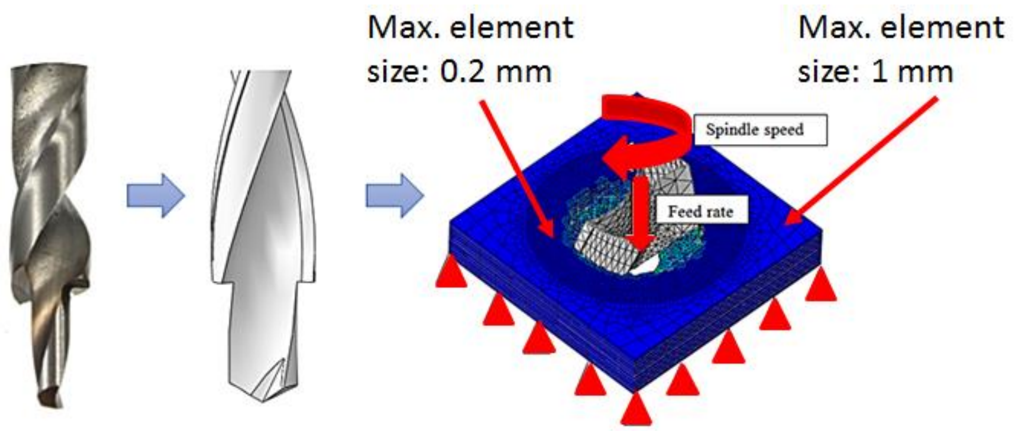

Figure 2: Boundary conditions of the model for the drill bit (A) and the workpiece (B) and mesh dimensions.

3.3 Damage models

In this section the intra-laminar and inter-laminar damages used are described. For intra-laminar damage, a VUMAT subroutine based on Hou criteria [13] was defined to control the element erosion. Equations 2 and 3 describe the fiber failure in first and second directions, and Equations 4 corresponds to crushing matrix failure mode in the ply plane and Equation 5 through thickness. The variable damage for each case *d* ranges from 0 (no damage) to 1 (fully broken). The subroutine evaluates the strain tensor after each time increment, and when one of the components reaches the value 1, the stress components involved in the failure definition (fiber or matrix failure) are set to zero.

$$d_{f1}\begin{cases}\dfrac{\sigma_{11}}{X_t} \; if\ \sigma_{11} > 0\\ \dfrac{|\sigma_{11}|}{X_c} \; if\ \sigma_{11} < 0\end{cases} \tag{2}$$

$$d_{f2}\begin{cases}\dfrac{\sigma_{22}}{Y} \; if\ \sigma_{22} > 0\\ \dfrac{|\sigma_{22}|}{Y_c} \; if\ \sigma_{22} < 0\end{cases} \tag{3}$$

$$d_{m12} = \left|\frac{\sigma_{12}}{S_{12}}\right| \tag{4}$$

$$d_{m3} = \frac{1}{4}\left(\frac{\sigma_{33}}{Z_x}\right)^2 + \frac{Z_c \cdot \sigma_{33}}{4S_{13}S_{23}} + \left|\frac{\sigma_{33}}{Z_c}\right| + max\left[\left(\frac{\sigma_{13}}{S_{13}}\right)^2, \left(\frac{\sigma_{23}}{S_{23}}\right)^2\right] \tag{5}$$

In the equations, σ_{ij} are the components of the stress tensor, X_t and X_c are the strengths of the composite laminate in tension and compression for the warp direction, and Y_t and Y_c are the strengths in tension and compression for the fill direction. S_{12}, S_{13} and S_{23} are the shear strengths in the three different planes and Z_c is the strength in the through-thickness direction under compression. All the values of these constants are summarizing in the previous Table 1.

The inter-laminar damage was modeled using cohesive elements. The linear elastic behavior of the traction–separation law for this kind of elements is defined by means of the respective stiffness, whose values are presented in Table 3. The damage initiation is implemented by a quadratic nominal stress criterion, similar to Equation 6, where t_n, t_s and t_t are the strengths of the cohesive interface in the normal and in shear directions respectively (values in Table 3). The damage evolution follows the Equation 7, a potential law characterized by α=1. G_n, G_s and G_t are the released rate energy in the three directions and $G^C{}_n$, $G^C{}_s$ and $G^C{}_t$ the critical values of the released rate energy.

K_n	$K_{ss}= K_{nn}$	$G^C{}_n$	$G^C{}_s=G^C{}_t$	t_n	$t_s=t_t$
2 GPa/mm	1.5 GPa/mm	0.6 J/m^2	1.8 J/m^2	11 MPa	45 MPa

Table 3: Cohesive interface parameters.

$$\left(\frac{\sigma_{33}}{t_n}\right)^2 + \left(\frac{\sigma_s}{t_s}\right)^2 + \left(\frac{\sigma_t}{t_t}\right)^2 \geq 1 \tag{6}$$

$$\left(\frac{G_n}{G_n^C}\right)^\alpha + \left(\frac{G_s}{G_s^C}\right)^\alpha + \left(\frac{G_t}{G_t^C}\right)^\alpha \geq 1 \tag{7}$$

4 VALIDATION

The model was validated for both geometries, through the comparison with experimental results. Figures 3 A and C show the thrust force and delamination results in case of helicoidal drill bit. The maximum deviations were 7.7% and 2.6% respectively. Results for the step geometry are presented in

Figures 3 B and D. In this case the errors are around 11.3% and 3.5% for thrust force and delamination. All figures shows reasonable accuracy when predicting the axial force and the damage and it can be observed very good predicted results in shape and trending.

In most cases the model tend to overestimates the results so it is important to highlight that this model is conservative.

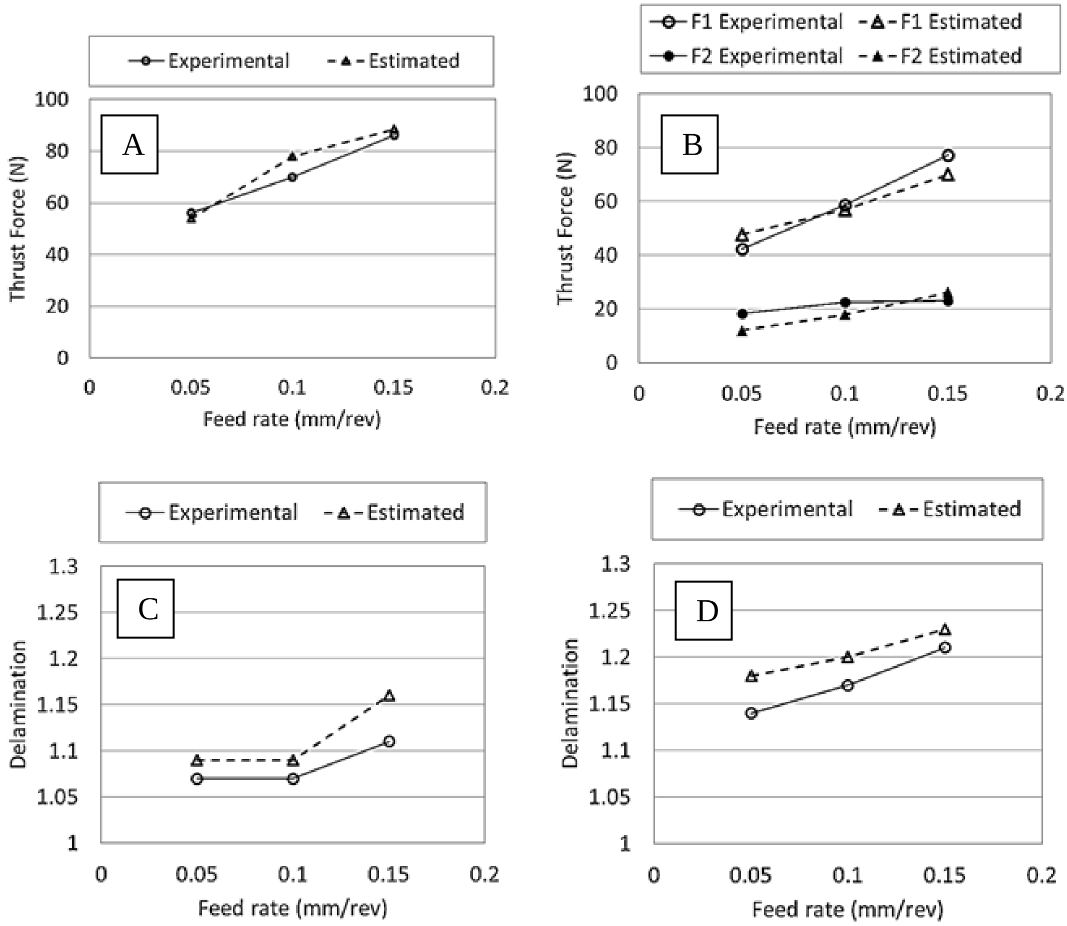

Figure 3: Comparison between experimental and numerical results for the case of conventional geometry (A-thrust force, C-delamination) and step geometry (B-thrust force, D-delamination).

5 ANALYSIS RESULTS

Once the model is validated, a parametric analysis was carried out in order to study the influence of the cutting parameters and the geometry in thrust force and delamination factor.

Results for thrust force are presented in Figure 4. It can be observed that feed rate is the most influential factor for both geometries. However, the influence of cutting speed depends of the feed rate range selected as can be seen in Figure 4 A where cutting speed is negligible at low feed rates but it is not when this parameter increases. In the Figure 4 B the feed force is presented for the first and second sections of the step drill bit. With this special geometry, part of the damage generated in the material with the first section is eliminated with the material removed with the second section. At the same time, the previous hole decreases the thrust force.

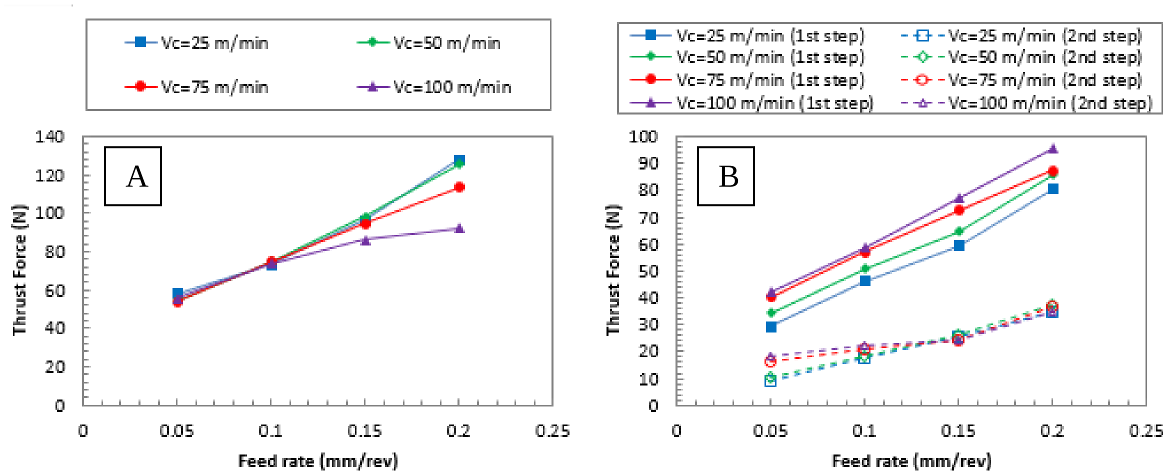

Figure 4: Thrust force evolution for helicoidal geometry (A) and step geometry (B).

Figure 5 shows the evolution of delamination with feed rate for both cases. Feed rate has a positive influence on delamination as can be seen with the creasing evolution of damage. The influence of the cutting speed is more relevant for the step geometry than for the helicoidal, where this parameter has low influence. It can be observed that for this geometry is more convenient to work with low cutting speed and low feed rates.

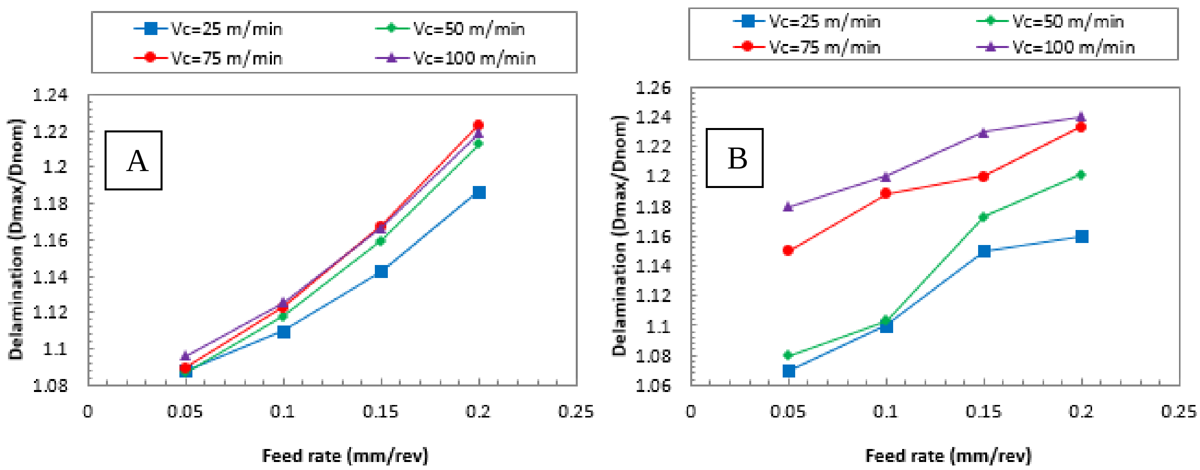

Figure 5: Delamination evolution for helicoidal geometry (A) and step geometry (B).

The numerical results obtained from the simulations allowed the adjustment of a mechanistic expression relating both thrust force and delamination factor with feed rate and cutting speed (see Tables 4 and 5). All models have a R^2 higher than 0.9 so we can conclude that the predictive models are adequate.

Drill bit	*Parameter*	*Equation*	R^2
	Thrust Force (N)	$71.92 - 0.9585V - 271.63f + 14.6184Vf + 0.0056V^2 + 2592f^2 - 0.0653V^2f - 37.736Vf^2$	0.96
	Delamination	$1.0981 - 0.001V - 0.2075f + 0.0146Vf + 8E\text{-}6V^2 + 2.25f^2 - 0.0001V^2f$	0.92

Table 4: Prediction equations for helicoidal geometry.

Drill bit	*Parameter*	*Equation*	R^2
	Thrust Force 1 (N)	$10.60875 + 265.35f + 0.213494V + 0.210592fV + 224.2f^2 - 0.0003388V^2$	0.99
	Thrust Force 2 (N)	$-0.73062 + 90.94f + 0.22942V - 1.04928fV + 473.6f^2 - 4.46e\text{-}4V^2$	0.97
	Delamination	$1.00687+0.66167f+1.23e\text{-}3V$	0.93

Table 5: Prediction equations for step geometry.

The mechanistic expressions were used to generate surface predictions in function of cutting parameters (feed rate and cutting speed) able to estimate the output variables graphically and see the evolution of the force when the cutting parameters change. Figure 6 presents the graphics for both tools. It can be seen how the geometry has a high influence not only in the values but also in the evolution of this values.

For the case of conventional drill bit, low cutting speed and high feed rate generates the highest thrust force, while for step geometry the high values are reached with high feed rates independent of the cutting speed.

Delamination also evolves positively with feed rate and reaches the highest value with mediums cutting speeds for the helicoidal case. The maximum delamination generated with step geometry is reached with high feed rates and high cutting speeds.

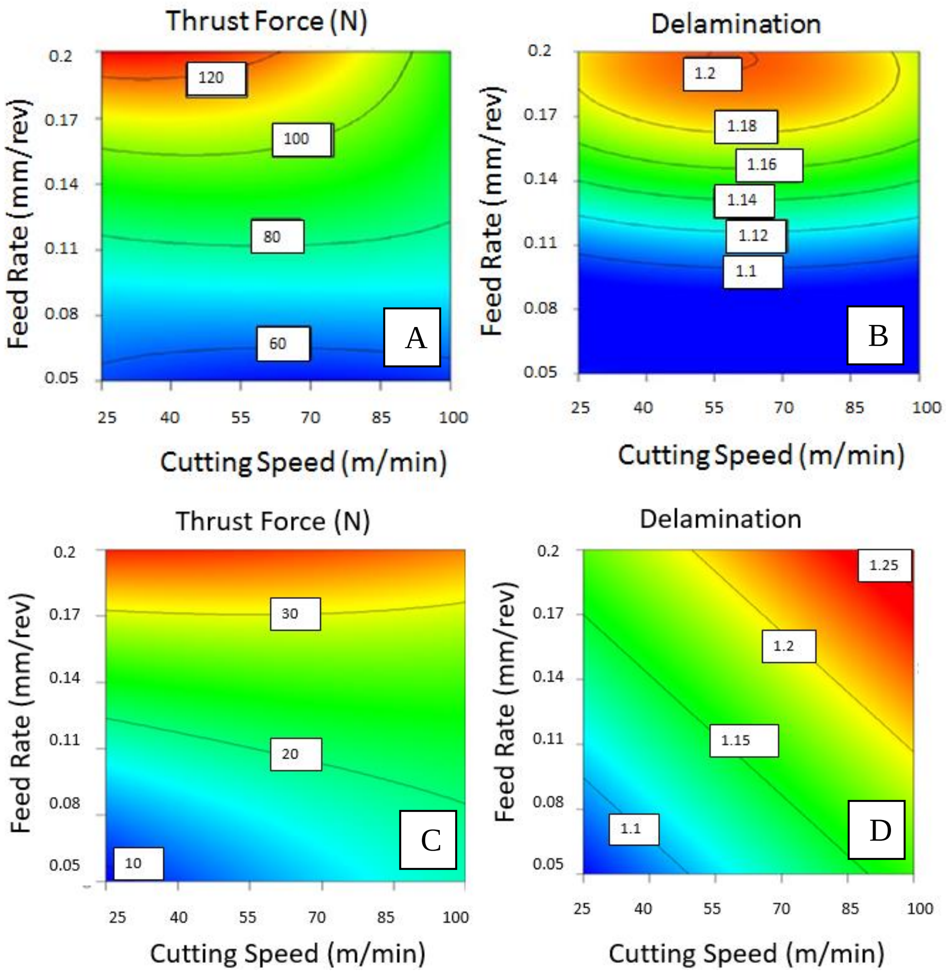

Figure 6: Prediction surfaces for thrust force and delamination for both geometries tested: helicoidal tool (A, B) and step tool (C, D).

9 CONCLUSIONS

This study presents a numerical analysis based on a 3D model developed to predict the responses of CFRP woven laminates under drilling machining. The model was validated for two tool, conventional geometry and step geometry, in terms of delamination and axial force comparing numerical results with experiments. This tool allows having a better understanding of the drilling process without a huge number of tests. It is possible to extend the proposed modelling scheme to new geometries and wear modes.

A parametrical study to analyse the influence of the cutting conditions (feed rate and cutting speed) based on optimization methodology was carried out for both geometries supported by model results. It was concluded that the influence of the feed rate and the cutting speed (with lower influence) is positive and direct. The analysis also proved that step geometry reduces the thrust force and the damage compared with conventional geometries when a low feed rate and cutting speed are selected.

Finally an optimisation methodology to generate mechanistic models for rapid estimation of output parameters (thrust force and delamination) was developed. The expressions and surface diagrams presented in the results allow predicting, for example, the delamination for a couple of cutting parameters, (feed rate and cutting speed). The applicability of this kind of tools in industry is very useful because of its simplicity. However it is important to note the necessity of carry out some previous work, both experimental and numerical, priory required to develop these type of mechanistic models with applicability in industrial environment.

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