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Study of axial cutting forces and delamination phenomenon in drilling of carbon fiber composites

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Abstract

With this study we intend to relate the cutting conditions and the tool wear with the shearing forces appeared and the phenomenon of the delamination when we mechanized composite materials reinforced with carbon fiber (CFRP). In this case, we will focus on the drilling operation, because the most used to join pieces of these materials are usually screws and rivets, and drilling is necessary.

Keywords: Cutting forces; drilling; delamination; CFRP.

1. Introduction

Nowadays, fiber reinforced composites have become very important because they achieve good mechanical properties with very low density, achieving the lightening of all types of machinery, aircraft or vehicles. But these types of materials are expensive and difficult to machine because they are abrasive and the chip in the form of powder represents a potential risk to the health of people. Even so, their use is increasing and more and more frequently we can find them in more applications and devices.

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When assembling pieces of CFRP, the most used method is the use of screws or rivets, for which the hole must have good geometric characteristics. Otherwise, the tolerances required for assembly should be greater, and forces and stresses may appear on the screws, causing premature failure of the assembly.

In addition, the abrasive character of the material will cause the cutting edge of the tool to wear rapidly [1], breaking the fibers instead of cutting them, and thus splintering the material. The greater the wear of the tool, the higher the temperature reached inside the workpiece, and the material can degrade. This behavior is similar to that produced in other types of materials, such as metal materials [2], and has the same consequences: surface integrity, residual stresses, alteration of machined surfaces, thermally affected areas, etc. which will affect the life of the part, inducing a fatigue failure [3-6]. There are also forces that overcome the cohesion between the different layers, appearing the phenomenon of delamination. This makes it vital to control the wear of the tool, and always use the appropriate compounds and geometries to achieve a quality and competitive production process.

There have been previously published more studies of carbon fiber drilling and its associated defects, mainly delamination [7-13].

In this case, we want to compare the results obtained when drilling a carbon fiber board used in the aeronautical industry, using different speeds of rotation of the tool, therefore, different cutting speeds, and different feed rates.

2. Experimental procedure

The experiment consisted in drilling a carbon fiber plate with a series of drills, under different cutting conditions. Dry machining is used with the aim of evaluating the most critical conditions.

The CFRP plate that was used was similar to those used in the manufacture of aircraft. It consisted of unidirectional carbon fiber-epoxy pre-impregnated layers, with fibers at 45° between the different layers and 4 mm thickness. This prepreg has an epoxy rate of 34%, density of 297 g/m2 and a cure temperature of 185 °C. The last layer had a special treatment to decrease the delamination at the exit (push-out), reason why in this study we focused on the delamination to the entrance (peel-up).

To evaluate the behavior of the tool as it was wearing, with each drill 30 holes were made, in sets of 5, and with 3 different advances. The three drills were of the Gühring brand, 6 mm in diameter and were HSS cobalt-coated. Commercial references were HSCO5524 and HSCO1261. The difference between them is in the angles of the tips, which were 118° and 130° respectively. These tools were not specific for drilling carbon fiber, but were used to observe the results obtained, and to be able to study if their use is profitable, since the cost is five times inferior to one specific for carbon fiber.

The machine with which the drills were made is an NC model A-16, equipped with a TNC control Heidenhain 355, by means of which the drills to be executed and their positioning were programmed, automatically, thus achieving a repetitive process. The cutting conditions were taken based on previous experiences, because the tools are not specific to mechanize this type of materials.

The equipment used to measure shear forces includes a Kistler 9124 rotary dynamometer to measure the three force components associated with a reference system attached to a cutting tool, and a 12-bit multichannel data acquisition system Wave Book 512 type (IOtech), with a Simultaneous Samples & Hold card, which allows high-speed sampling and reduces the gap between acquisition channels. Data processing is performed using DasyLab V.8 software from National Instruments.

The measurements of the diameters were made by an optical microscope coupled to a computer, and the images were processed by Deltec Vision software. Each diameter was determined by taking 10 points, and the software itself implements an algorithm to determine the diameter, by the least squares method. Chen [14] defined the delamination factor (Fd) as the quotient of the maximum diameter of the zone affected by the drill (Dmax) between the nominal diameter of the drilled hole (D), i.e. the diameter of the drill, as the equation indicates:

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

We only focused on the peel-up delamination, that is to say, the one produced by introducing the tool into the material, because as we mentioned, the plate had treatment to avoid the push-out delamination (at the exit), and we quantified it using the Factor defined by Chen.

In order to simulate the working conditions, as was done in the aeronautical industry, the drills were made at a minimum distance from each other of twice the diameter. This prevents holes from influencing others. The sequence of drills carried out was as follows: keeping constant the speed of rotation of the spindle, five holes were realized with an intermediate feed rate. Subsequently, five more holes were drilled with a 50% higher feed rate, and finally, five more holes were drilled with a feed rate of 50% lower, and the sequence was repeated again, thus achieving the 30 holes per drill.

In Table 1 we can see the cutting conditions used in each series and with each drill.

Table 1. Cutting conditions.

Parameter	HSCO5524	HSCO5524	HSCO1261
Diameter (mm)	6	6	6
Tip angle (°)	118	118	130
Cutting speed (m/min)	61	16	16
Spindle speed (rpm)	3240	865	865
Feed rate (mm/min)	300	80	80
Feed rate (mm/rev)	0,10	0,10	0,10

3. Results and discussion

3.1 HSCO5524 – 3000 rpm drill

If we analyze the results obtained as the tool was worn, as shown in Fig. 1, we can see how the forces grow between the series of medium and high advances, and decrease between the series of high and low advances, although series of low advances were made later, that is, with the most worn tool.

If we compare the series made with equal advances, we see clearly the increase in shear forces, due only to the wear of the tool, since all other factors remain the same.

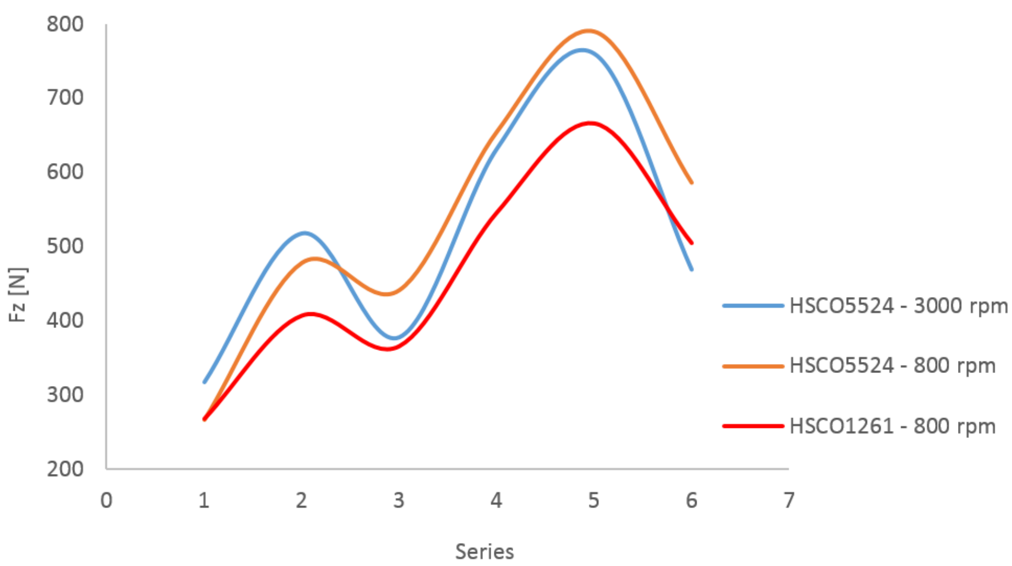

Fig. 1. Cutting forces.

As shown in Table 2, in each series, we see how the forces between the first and last drill of the first series increase, much more than in the others, where the values obtained are more similar to each other.

Table 2. Results for HSCO5524 - 3000 rpm.

Parameter	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
FZmax (N)	316,91	517,92	377,58	632,12	760,85	468,96
Increase between drills 1 and 5 (%)	95,95	9,50	10,99	6,31	1,34	6,95
Increase with respect to identical series (%)				109,88	47,01	24,30

With these cutting conditions, we observe a very pronounced wear in the first series, while in the following, it is smaller, as we observe increases of forces between the first and last drill of the very small series.

In the last series, the tool is already too much worn, so the increase in wear is not as great as it should, because it can no longer wear out.

3.2 HSCO5524 – 800 rpm drill

In this drill, the behavior is similar to that analyzed in the previous section. The difference is in the values obtained of the forces and in the increments suffered between series.

In this case, in the first three series there is an evident increase of forces between the first and last bore, and values similar to each other for the following three series.

In view of the great difference in values of the thrust force, we can ensure that the tool produces a marked wear, especially up to the third series. From this moment on, wear plays a secondary role.

Table 3. Results for HSCO5524 - 800 rpm.

Parameter	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
FZmax (N)	266,56	478,02	441,26	654,56	789,76	586,08
Increase between drills 1 and 5 (%)	96,88	19,35	20,19	4,85	4,25	8,74
Increase with respect to identical series (%)				158,13	65,62	33,15

Between series with medium advance and with low advance, the latter present greater forces, due only to the wear of the tool, because for equal wear, we should have obtained smaller forces for the low advances.

In the series with smaller feed rates, we can observe greater strength increases between holes, so that there will be greater influence of the wear with low feed rates.

3.3 HSCO1261 – 800 rpm drill

As in the previous cases, we obtain a similar behavior, appreciating quickly the wear of the tool especially in the first series.

Table 4. Results for HSCO1261 - 800 rpm.

Parameter	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
FZmax (N)	268,04	407,18	365,98	546,00	666,38	505,02
Increase between drills 1 and 5 (%)	46,03	6,28	19,36	4,70	3,29	11,44
Increase with respect to identical series (%)	--	--	--	106,82	63,70	38,16

In this drill we see that there is greater wear in the low advances compared to the previous ones, due to the geometry of the tool. It is also seen that in the first series the bit undergoes much less wear than in the previous experiments, the increase of forces being 50% lower than in the HSCO5524 bit at 800 rpm, i.e., equal cutting conditions. If we compare the forces obtained between these two tools, we see that the values for HSCO1261 are smaller, so there will also be minor wear.

We cannot compare the results with HSCO5524 at 3000 rpm, as there are no equal cutting conditions.

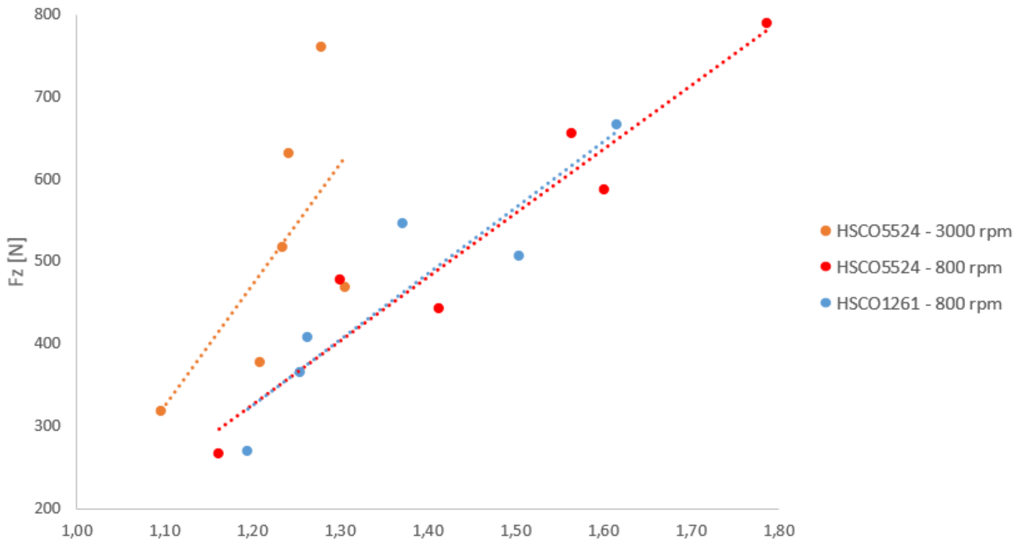

Fig. 2. Delamination factor.

The delamination factors obtained for the different series have been represented in Fig. 2, as a function of the obtained cutting forces. It is observed that in all the series, to greater values the force, greater delamination in the piece.

4. Conclusions

Under the same cutting conditions, a lower cutting speed is obtained for lower feed rate, but the wear of the tool appears faster. Also less delamination is obtained in the piece.

For a greater turning speed, a lower tool wear and a less delamination are obtained.

The geometry of the bit has influence on how the wear and damage to the workpiece are produced, obtaining smaller forces and smaller delaminations for the tool with greater tip angle.

At some point, the wear of the tool no longer plays an important role.

For smaller feed speeds, lower cutting forces and less delamination are observed at the inlet of the drill bit in the workpiece.

We have obtained large tool wear in all circumstances, so it is not cost effective to drill CFRP with non-specific tools for these materials.

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