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Tool wear and induced damage in CFRP drilling with step and double point angle drill bits

J. Fernández-Pérez*, J. L. Cantero, J. Díaz-Álvarez and M. H. Miguélez

Department of Mechanical Engineering, Universidad Carlos III de Madrid, Avda. Universidad 30, Leganés, Madrid 28911, Spain

Abstract

Drilling operations on Carbon Fiber Reinforced Plastics (CFRP) have become crucial for the manufacturing process of multiple components on the aerospace industry. The main objective of this research is to develop a comparative analysis between a step geometry drill bit, currently used in the aerospace industry for drilling processes in CFRP with a hole diameter of 9.54 mm, and the double point angle geometry. The tool material is tungsten carbide with a diamond coating. The performance of each cutting geometry is assessed based on the type of tool wear, the evolution of the thrust force and cutting torque and the onset of machining induced damage on the test specimens. Although the main wear mechanism suffered by both tools was very similar, it was observed a remarkable influence of the cutting geometry on the tool wear evolution and the associated thrust force. This different performance also affected the onset of the machining induced damage.

Keywords: composites drilling; diamond coated carbide; wear mechanism; macining induced damage

1. Introduction

The use of composite materials has increased remarkably during the last decade and nowadays it is a key element of multiple industries, especially the aerospace. Nowadays, these materials play a crucial role in aerospace secto reaching more than 50% of the structural weight of some aircraft [1]. Carbon Fiber Reinforced Plastics (CFRP) are the most popular in the aerospace industry due to its superior strength-to-weight ratio and stiffness. CFRPs ar

* Corresponding author. Tel.: +34 916248873;
E-mail address: jfperez@pa.uc3m.es

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characterized by its excellent specific mechanical properties, corrosion resistance and that they are commonly manufactured near net shape.

For assembly purposes, machining processes are unavoidable, mainly drilling operations for further mechanical joining. The low machinability of the composite materials, combined with the restrictive quality requirements demanded by the aerospace industry, impose a noticeable complexity to perform the drilling operations with competitive costs per operation and cycle time.

CFRPs are heterogeneous materials made of two phases: the matrix and the reinforcements or fibers. Both have different properties which influences the behavior during machining and can affect the surface and dimensional quality of the hole [2]. Furthermore, the fluctuation of the cutting forces produced during the machining process and the abrasiveness of the carbon reinforcements impose severe requirements to the cutting tools.

Another factor to take into account is the susceptibility of composite materials to suffer machining induced damage. This may deteriorate the individual properties of the component and affect the structural integrity and reliability of the mechanical joint [3]. The main types of defects are delamination, uncut fibers, hole surface damage, and thermal degradation. [4]. Delamination is the most critical and common type of machining induced damage and there are multiple studies focused on analyzing strategies to suppress or delay delamination onset [5].

Tungsten carbides (WC) are extensively used as cutting tool material for drilling operations in composite materials. They are very stiff, have a high modulus of elasticity and very good wear resistance leading to good economic performance [6]. Masuda et al. studied the failure of cemented tungsten carbide-cobalt tools during composites machining and they concluded that, in the ranges analyzed in the study, as WC grain size increases, tool wear rate decreases, in spite of a reduction in tool hardness and that a decrease in Co content leads to a decrease in tool wear rate [7].

Xin Wang et al. compared the performance of uncoated carbide tools with respect to diamond coated and AlTiN coated. In the uncoated tool, they found a rapid dulling of the cutting edge, dominated by edge rounding wear which was mitigated with the application of the diamond coating. The AlTiN coated drills showed no visible improvement over the uncoated carbide drill, despite of their higher hardness [8]. On the other hand, Sheikh-Ahmad and Sridhar found that the wear mechanism was a combination of chipping and delamination of the diamond coating layer and further abrasion of the substrate. Similar results were reported by Fernández-Pérez et al. [9]. Xinchang Wang et al. [10] also studied the influence of diamond films on carbide tools and they found improvements in wear resistance, lifetime and machining quality in the long-duration drilling process.

There are different analysis of the influence of drill bit geometry on the process performance. Qiu et al. [11] concluded, based on experimental results, that the hole entry quality of the step drills are better than that machined with twist drill. The ratio between the diameter of the two steps has a great influence on the hole exit quality and the factor of 0.5 retrieved the best results under the large processing parameters. Feito et al. [12] presented a comparative study of three special geometries: brad and spur, reamer and step. Results showed that, 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.

Another common geometry is the double tip angle. Karpat et al. [13] analyzed the influence of double point angle drill geometry on drilling performance through an experimental approach. High feed rate drilling experiments are observed to be favorable in terms of drill wear. Feed is observed to be more important than cutting speed, and the upper limit of feed is dictated by the drill design, the rigidity of the machine drill and the associated machining induced damage. Hole diameter variation due to drill wear is monitored to determine drill life. At high feeds, hole diameter tolerance is observed to be more critical than hole exit delamination during drilling of fabric woven CFRP laminates. On the other hand, Kuo et al. [14] analyzed the tool wear on double-point and multi-facet drills with diamond coatings. The double-point geometry showed chipping and delamination of the diamond-coated layer while on the multi-facet drill progressive abrasion wear, scoring and severe abrasion were found on the different faces. Zitoune et al. [15] also studied the double cone drill geometry using carbide drills. They have stated that double cone drills generated less thrust force and less damage on the test specimens compared to standard twist drills.

Regarding the analysis of alternative cutting geometries on large diameters there is limited information in the literature [16]. Most of the bolts and rivets used on industry and studied in the literature have a diameter between 3/16 and 5/16 inchs, so hole diameters over 8 mm are referred as large diameters. There are some studies focusing on the influence of the cutting parameters in the performance of drilling process in composite materials with tool diameters between 8 and 13 mm, but the cutting geometry is not specified and there is no information about the tool wear [17] [18]. Tsao et al. [19] also analyzed the influence of the cutting parameters on large diameters, 8, 10 and 12 mm, and they tested high speed steel tools with different geometries: twist, candle stick and saw. They have found that the candle stick drill and the saw drill caused smaller delamination factor than twist drill, but tool wear suffered by each tool was not described. Khashaba et al. [20] compared the performance of cemented carbide drills with a diameter of 8 mm and 13 mm when drilling woven E-glass fiber-reinforced epoxy composite laminates. They found that the thrust force was 75% higher for the larger diameter which is related to higher peel-up and push-out delamination. However, the 8 mm drill diameter produced holes with greater surface roughness than the 13 mm.

The main objective of this manuscript is to enhance one-shot strategy drilling process on large diameter tools of carbon fiber reinforced plastics by studying the performance of diamond coated carbide drill bits with non-conventional geometries: double tip angle and step. For this purpose, the thrust force and the cutting torque were analyzed, as well as the relation between the evolution of the tool wear and the machining induced damage.

Drilling operations on composite materials for large diameter bolts and rivets suppose a significant percentage of the total manufacturing process cost of some aerospace components, so the optimization of these machining operations can have a remarkable impact on real industrial processes.

2. Experimental set-up

The experimental tests were conducted on a CNC equipped with a vacuum for chip aspiration. This system allows to perform the test in safety conditions (avoiding the dispersion of the carbon dust produced during drilling) and to position the specimens. The equipment used was:

- 3 axis CNC machine KONDIA B500 with hydraulic toolholders ISO40.
- Aspiration system Nilfisk S2B with a cyclonic filter, an antistatic filter, and a microfilter.
- Rotative piezoelectric dynamometer Kistler 9123C to measure the thrust force and the cutting torque
- Optical microscope OPTIKA SZR and a scanning electron microscope (SEM) Philips XL-30 for tool wear progression analysis.

2.1. Materials

The test specimens studied in this manuscript are currently used in industry and are part of multiple structural elements of commercial aircraft.

They were made of carbon fiber reinforced polymer composed by multiple unidirectional layers with different orientations covered in the upper part by an epoxy preinpregnated copper foil and in the lower part with a prepreg made from a glass fiber fabric preimpregnated with epoxy. The thickness of the test specimen was 14.5 mm.

2.2. Cutting tools and cutting parameters

The tools tested are right-hand twisted drill bits made of carbides and diamond coated. A layout of the cutting geometries can be seen in Figure 1 and the main dimensional features are detailed in Table 1. They were manufactured by HAM Praizision according to the procedures and dimensions specified by Airbus Getafe.

The step drill bit shown in Figure 1.a, is the cutting geometry currently used in the industry for this application and hole diameter. It has two cutting edges with a secondary cutting edge diameter of 9.54 mm and a primary diameter of 8.2 mm. The distance from the tip of the tool to the secondary diameter (from O to B' according to the nomenclature used in Figure 1) is 7.1 mm and the point angle of both cutting edges is 90 degrees. The tip of the tool has a split point geometry.

On the other hand, the double point angle geometry, shown in Figure 1.b, has also two cutting edges with a diameter of 9.54 mm. The first point angle from the tip is 130º and the second point angle is 60º and it also has a split point geometry.

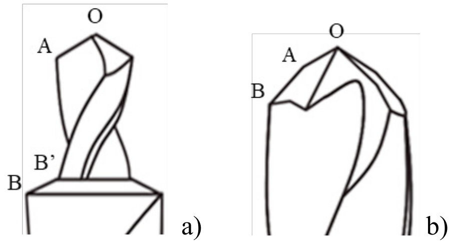

Fig. 1. (a) Step drill bit; (b) Double point angle drill bit. Adapted from [21].

Table 1. Tools dimensional information.

Tool geometry	Step geometry	Double tip angle geometry
Diameter (mm) – first stage (A)	8.1	5.8
Diameter (mm) – second stage (B)	9.54	9.54
Point angle (º) – first stage (OA)	90	130
Point angle (º) – second stage (AB)	90	60
Helix angle (º)	40	40

The cutting parameters analyzed in this document, shown in Table 2, are generally used on the industry, so they are representative of the composite drilling processes in order to compare the performance of both cutting geometries. Furthermore, the machining was carried out in dry conditions. For each test, 285 holes were made, which corresponds to a cutting time accumulated on the cutting edges of 24.75 min. These values are representative of the tool life currently defined in the industry for this application.

Table 2. Cutting parameters analyzed.

Rotation speed [rev/min]	Cutting speed [m/min]	Feed rate [mm/min]	Feed [mm/rev]
1668	50	167	0.10

3. Results

The performance of the drilling process was assessed based on the tool wear suffered and its influence on the evolution of the thrust force and cutting torque as well as the deterioration of the hole quality, in the form of delamination at the exit of the hole.

3.1. Tool wear analysis

The tool wear found on diamond coated carbide tools used to be determined by the proper adhesion between the coating and the substrate. Generally, small and localized detachments of the diamond coating, produced by fragile breaks, are found close to the cutting edge in the rake surface which leaves the carbide substrate exposed. A detailed representation of this phenomenon can be seen in the zoomed view of Figure 3.b. Afterwards the strong abrasiveness of the carbon fibers produces severe flank wear on the exposed substrate.

Figures 2 (frontal view of both drill bits) and 3 (detailed view of the second stage cutting edge corner for both drill geometries) show a comparison of the condition of the tools after 285 holes (which corresponds to a representative value of the tool life currently used in the industry for these applications).The step geometry has suffered strong flank wear on the first stage, which extension increases uniformly from the tip of the tool to the corner of the first stage main cutting edge (reaching up to 0.4 mm after 285 holes), owning to the higher cutting speed of this region, which induces higher abrasion. The second stage also suffered flank wear produced by the coating detachment from the rake surface, but the extension of the damage is smaller. In this region, the flank wear after 285 holes had an extension of 0.2 mm as it can be seen in Figure 3.a

On the other hand, the double point angle geometry have suffered the combination of diamond coating localized detachments by fragile breaks on the rake surface followed by severe abrasion of the carbide substrate exposed. In this case, the extension of the flank wear is more uniform and continuous from the tip of the tool up to the corner of the second stage main cutting edge. The maximum extension of the flank wear reached around 0.14 mm and it was produced on the corner of the main cutting edge (Figure 3.b).

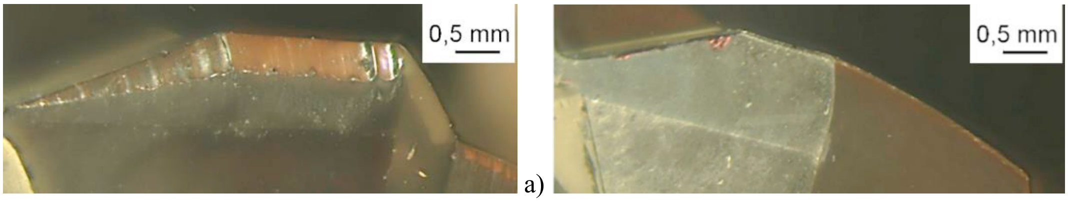

Fig. 2. Frontal view of the tools after 285 holes; (a) Step drill bit; (b) Double point angle drill bit.

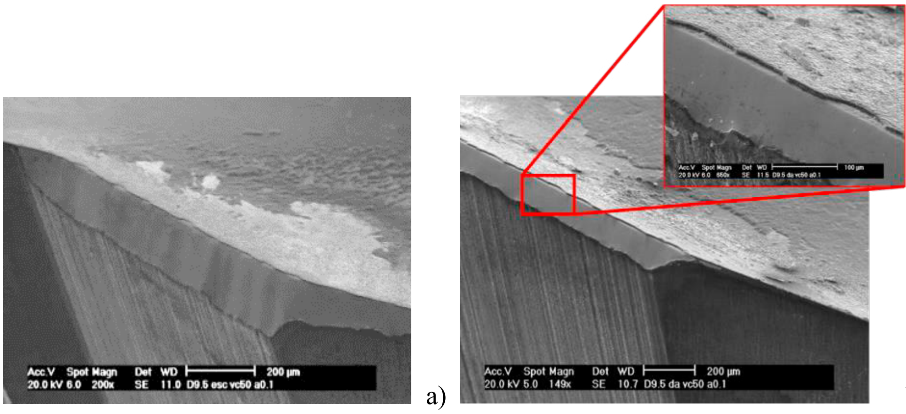

Fig. 3. Detailed view of the main cutting edge corner of the secondary stages of the tools after 285 holes; (a) Step drill bit; (b) Double point angle drill bit. The amplification view of Figure 3.b shows the fragile breaks of the diamond coating on the rake surface close to the cutting edge.

The differences in wear modes in each drill bit can be explained by the following features related with the cutting geometry of each tool, which may have a combined influence:

- Tool tip angle. The double tip angle tool has suffered less wear on the second stage cutting edge (corresponding to a 60 degrees angle.) The smaller tip angle leads to a longer cutting edge which allows to distribute the cutting stresses in a higher edge length. Furthermore, even the feed is maintained, there is a reduction in the average chip thickness for smaller point angles which reduces the wear on the cutting edges [15].
- Cutting edge orientation angle with respect to the line which crosses the center of rotation of the drill bit. It can be seen in Figure 2.b that the second stage cutting edge of the double point angle tool (cutting edge AB) produces a very oblique cutting condition (the angle between the cutting velocity and the cutting edge is noticeable smaller than 90 degrees). This leads to a smaller tool wear owning to an attenuation of the abrasive character of the fibers.
- Continuous length of the active cutting edge. In the step geometry there is a noticeable difference between the flank wear extension suffered by the first and the second stages. A longer cutting edge removes a significative amount of material at the same time, affecting several layers with different fiber orientations, which may enhance tool wear. On the other hand, the secondary step has a lower cutting edge length so the amount of layers being cut at the same time is smaller, leading to a smaller tool wear.

3.2. Cutting forces and torque

The evolution of the cutting forces during the drilling process shows important information about the performance of each cutting geometry. Figures 4 and 5 show the evolution of the thrust force and the cutting torque through the first hole and the hole 285 for both cutting geometries.

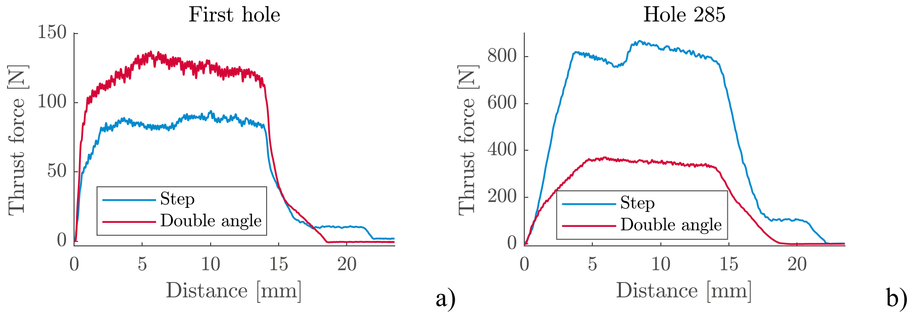

Fig. 4. Thrust force evolution produced with the step (blue line) and the double point angle (red line) drill bits; (a) First hole; (b) Hole 285.

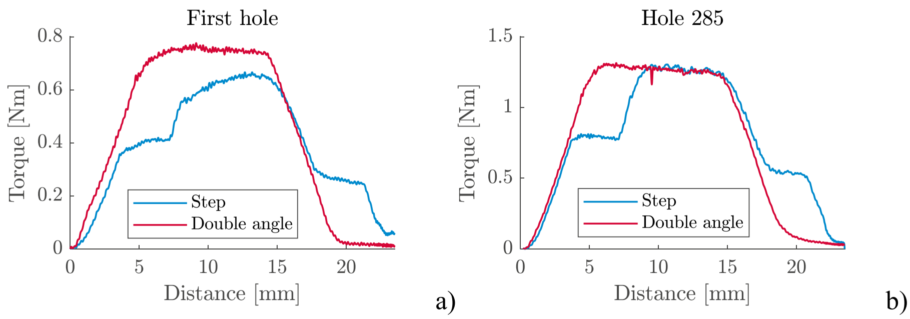

Fig. 5. Cutting torque evolution produced with the step (blue line) and the double point angle (red line) drill bits; (a) First hole; (b) Hole 285.

It can be seen that in the first hole (Figure 4.a), the double point angle produces higher thrust force due to the larger point angle of the first stage. The maximum thrust force reached with the step geometry is 90 N while the maximum with the double point angles is 135 N. However, as the tool wear progresses the step geometry suffers higher flank wear on the main cutting edge of the first stage which produces a huge increment on the thrust force, reaching 860 N after 285 holes, which is 9.5 times higher than with the fresh tool. On the other hand, the thrust force produced after 285 holes with the double point angle tool increases 2.7 times from the first hole, reaching 370 N. This big difference on thrust force increment with the tool wear is aligned with the wear extension found on each tool.

The cutting torque is very similar for both cutting geometries during the first hole as it can be seen in Figure 5.a, being slightly higher in the double point angle geometry due to the larger tip angle of the first stage. The maximum torque obtained with the step and the double point angle were 0.66 Nm and 0.77 Nm respectively. As the tool wear increases, the maximum cutting torque produced during hole 285 with both tools reaches 1.31 Nm. Compared with the fresh tool, this value is 2 times higher for the step geometry and 1.7 times higher for the double point angle.

The step geometry requires to drill deeper to perform the same hole since the second stage is further from the tip of the tool. In this case, the cycle time with the step drill bit is 18% longer, compared with the double point angle.

Figure 6 shows the evolution of the thrust force (Figure 6.a) and the cutting torque (Figure 6.b) with the tool wear. In both cases it increases with a linear behavior. However, it can be seen that the increment on the thrust force with the step drill bit is bigger than with the double point angle due to the big differences on the flank wear extension. On the other hand, the cutting torque increases linearly but with a very similar behavior for both geometries since the main wear mechanism suffered (coating breaks and flank wear) barely affects the geometry of the main cutting edge.

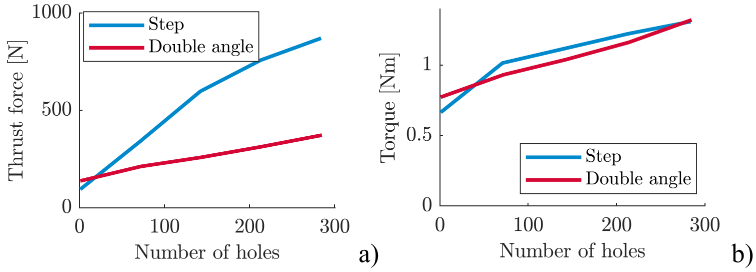

Fig. 6. (a) Thrust force evolution with the number of holes; (b) Cutting torque evolution with the number of holes.

3.3. Machining induced damage

The main type of machining induced damage found was delamination at the exit of the hole. It was quantified through the delamination factor, which represents the ratio of the delamination extension, measured in diameter, over the nominal diameter of the hole.

Figure 7 shows the evolution of the delamination factor versus the number of holes. With the step geometry, the onset machining induce damage occurs after 19 holes, while with the double angle it occurs after 65 holes. This can be explained by the flank wear extension suffered by each drill bit geometry, which produces a very different evolution of the thrust force with the number of holes (Figure 6.a).

Once the delamination factor reaches values between 1.4 – 1.5, although the tool wear progresses, the delamination factor stabilizes and does not longer increase with the same rate. For the step geometry, the stabilization point is reached after 70 holes while for the double point, it is produced after 200 holes.

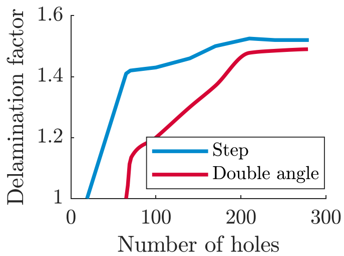

Fig. 7. Delamination factor evolution with the number of holes.

4. Conclusions

Step and double point angle geometries were tested on diamond coated carbide drill bits with a diameter of 9.54 mm during CFRPs drilling. The main wear mechanism observed in both tools was a combination of localized detachments of the diamond coating near the cutting edge on the rake surface followed by severe flank wear of the exposed substrate. However, owning to a combination of several geometrical features of each drill bit (point angle, cutting edge orientation angle with respect to the line which crosses the center of rotation of the drill bit and continuous length of the active cutting edge), the extension of the flank wear on the step drill bit, mainly on the cutting edge of the first stage, is larger than that observed for the double point angle.

This difference produces higher increment of the thrust force with the number of holes for the step drill bit. On the other hand, the cutting torque evolution with the number of holes is very similar for both cutting geometries since the main wear mechanism observed (flank wear) barely affects the cutting torque.

Finally, it was found out that the double point angle delays the machining induced damage onset at the exit of the hole. This geometry also delayed the number of holes at which the stabilization of the delamination factor is produced.

The characterization of the tool wear and its influence on the machining induced damage of non-conventional drill bit geometries enhance drilling processes in terms on cost per hole and cycle time.

Acknowledgements

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