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Impact of different parameters in the drilling of CFRPs with nanocrystalline diamond coated tools

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Abstract

The drilling process of composite materials, such as carbon fiber reinforced polymer (CFRP), constitutes a challenging task due to their inhomogeneous and anisotropic characteristics, besides the highly abrasive wear behaviour of their fibers. Accordingly, machining parameters should be carefully studied to optimize the process, leading to a better surface quality (avoiding defects in the CFRP) and to a lower wear behaviour of the cutting tool. This study proposed to test the drilling of a CFRP with a thermoplastic matrix using two different tool geometries (conventional and double-point angle drill) and varying two parameters, feed (f) and spindle speed (n), each one with two levels. It was concluded that the double-point angle drill with lower spindle speeds generates lower thrust force and torque values, as well as better hole quality. Higher spindle speeds combined with lower feeds result in fractured chips, in contrast with continuous chips for the other combinations.

Author Keywords. Drilling, CFRP, Tool Geometry, Spindle Speed, Feed, Surface Quality.

Type: Research Article

1. Introduction

Carbon fiber reinforced polymer (CFRP) is a composite material with excellent structural properties, combining the high strength of the carbon fibers with the flexibility and toughness of the matrix material (Geier, Davim, and Szalay 2019). Due to these characteristics, in addition to low weight, good damage tolerance, high strength, stiffness, and damping ability, as well as corrosion resistance, the application of CFRP has been increasing in high-tech industries such as the aerospace and automobile (Poór et al. 2021; Duboust et al. 2016). Nevertheless, this material presents some manufacturing challenges, as its inhomogeneous and anisotropic nature allied to the abrasive wear behaviour of its fibers leads to a high wear rate of the machining tools. This is the reason why diamond-coated tools have been increasingly used in this application, since their high hardness allows them to maintain a sharp cutting edge and reduce surface defects (Poór et al. 2021; Duboust et al. 2016). In spite of this, just choosing the right tool is not enough to avoid mechanical damage in drilling CFRP, for example delamination (at the drill's entry or exit within the material), the most problematic defect to arise in this process (Girot, Dau, and Gutiérrez-Orrantia 2017; Davim and Reis 2003). The exitply delamination, directly related to the drilling thrust force, is the one which occurs with more frequency, despite all precautions generally taken (Massoom and Kishawy 2019). As such, the solution stands by selecting the most suitable machining parameters and proper tool geometry in order to produce hole quality within the accepted boundaries (Aamir et al. 2019). The drilling parameters more studied in the literature to evaluate thrust force and torque are typically the spindle speed and the feed, as they have a greater impact on these outcomes (John et al. 2019; Faraz, Biermann, and Weinert 2009).

Shyha et al. (Shyha et al. 2009) drilled small holes in CFRP with 1.5 mm diameter uncoated drills with varying geometry, using statistical methods to evaluate the effect that drill geometry and the chosen conditions had on tool life and hole quality. They concluded that the step drill increased tool life, in contrast with the conventional twist drill, and that feed rate also had the most effect on the results, as a small increment in it led to a great variation on thrust force. Wang et al. (Wang et al. 2017) evaluated the effect of pilot drillings in CFRP, achieving a drilling pattern that reduced both the torque and thrust force, as well as eliminating delamination. Geng et al. (Geng et al. 2019) presented helical machining as a better method to obtain small-diameter CFRP holes than conventional drilling. An et al. (An et al. 2015) conducted orthogonal machining tests on CFRP comparing uncoated and diamond-coated carbide cutting tools, from which they observed that the latter were more suitable for the task, especially under high-speed cutting conditions. They also studied the influence of the tools' angles, stating that a large rake angle improves chip separation and, therefore, reduces the cutting force. Haeger et al. (Haeger et al. 2016) used non-destructive detection techniques to observe the delamination resulting from drilling in CFRP, namely optical inspection, ultrasonic testing, and computed tomography, which proved to be more efficient than the conventional methods. Xu et al. (Xu et al. 2018) proposed a series of adjusted damage criteria to assess CFRP drilling-induced defects, such as delamination, burrs, and tearing.

The objectives of this work were to determine the influence of the feed and spindle speed on the drilling process of a thermoplastic matrix CFRP using diamond-coated drills with two different geometries, to evaluate the generated torques and thrust force, chip morphology, and delamination of the base material, comparing the results with the existing literature.

2. Materials and Methods

The used materials in this study can be divided into the base material and the cutting tools. The drilled material was a sample originated from a 16-ply 2x2 twill carbon fiber prepreg (CFRP) with a polyamide (PA 12) resin, of thermoplastic nature, with a 4 mm thickness. Conversely, the tools chosen for the experimental work were two kinds of twist drills, distinguishable by their different geometry: a conventional one, or single-point angle, and a double-point angle twist drill. Both of them possessed a first angle of 120°, a helix angle of 30°, and a diameter of 6 mm, besides a second point angle of 60° in the double-point angle drill. The drilling tools had a tungsten carbide-cobalt (WC-Co) substrate with 7% of Co content and were coated with nanocrystalline diamond to achieve better wear resistance.

For the experimental work drilling tests were performed using a HAAS VF2 CNC machine and a load cell. 8 holes were drilled in the same sample (Figure 1), 4 with each drill geometry. In these conditions, two spindle speeds (n) were tested (4000 and 8000 rpm), both combined with two feed (f) values (0.15 and 0.30 mm/rev). At the end of the experiments, it was possible to analyze the torque and thrust force values obtained for each case with a Kistler Type 9170A dynamometer and the respective data acquisition system, as well as evaluate the chips generated in the drilling process. The delamination that occurred in the CFRP was also assessed through x-ray tests. These were performed by a Satelec X-mind x-ray machine and a Kodak reflector after the drilled sample was immersed in a Diiodomethane contrasting fluid for the reveal of irregularities or discontinuities in the holes and surrounding zones.

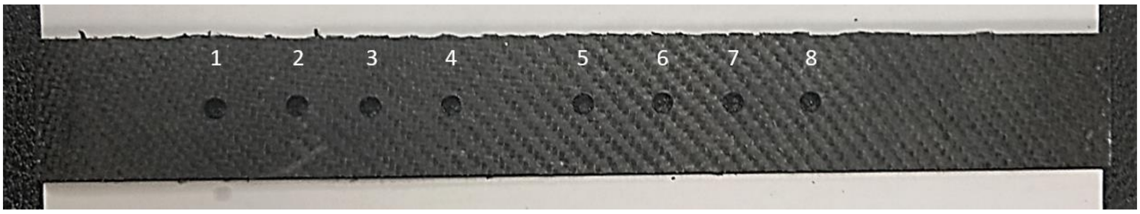

Figure 1: CFRP sample with its drilled holes

3. Results and Discussion

3.1. Drilling tests

After the drilling tests performed on the CFRP with the conditions already specified before, two different aspects were analyzed, the two primary categories into which drilling forces may be split up: torque and thrust force. The first one reflects the amount of force which is needed to twist the drill bit during the drilling process. On the other hand, the latter represents the tribological behaviour of the contact between the tool and the chip formed in the process. Table 1 presents both the parameters used in the experiments (spindle speed and feed) and the maximum values obtained for the thrust force and torque with each set of parameters.

	Hole	n (rpm)	f (mm/rev)	Max. Thrust Force (N)	Max. Torque (Nm)
Single-point angle drill	1	8000	0.15	73.73	1.17
	2	8000	0.30	111.82	0.93
	3	4000	0.15	118.16	0.44
	4	4000	0.30	255.37	0.54
Double-point angle drill	5	8000	0.15	84.96	0.54
	6	8000	0.30	76.17	0.68
	7	4000	0.15	73.73	0.39
	8	4000	0.30	80.08	0.44

Table 1: Drilling tests parameters and maximum thrust force/torque values obtained

3.1.1. Torque analysis

Figure 2 contains the graph corresponding to the torque analysis of the drilled holes.

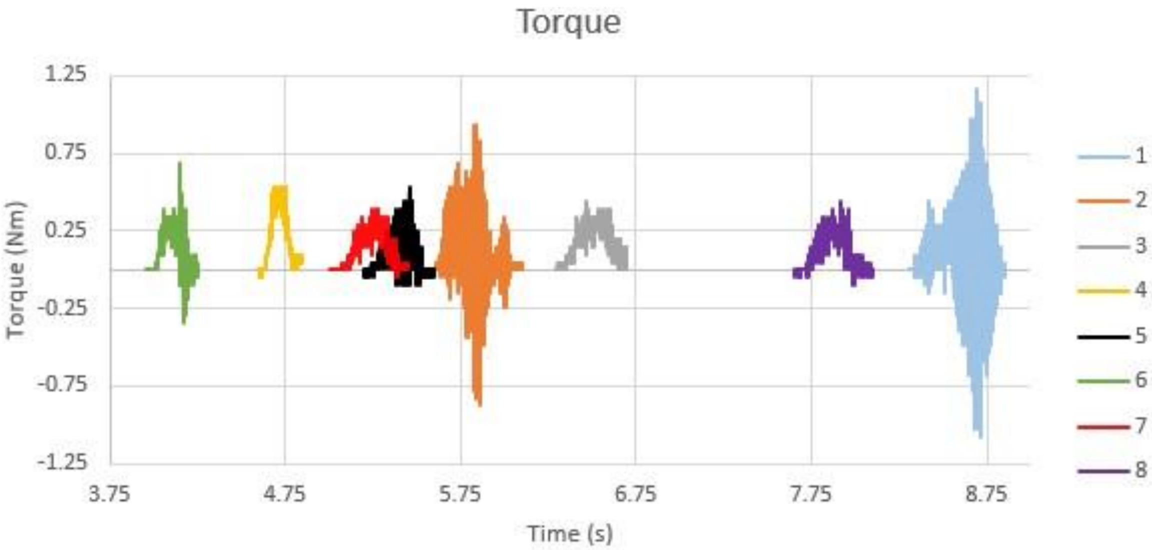

Figure 2: Torque graph of the drilled holes

By the torque graphics obtained for the different tests, the single-point angle drill generated much higher torques than the double-point tool, which was expected, since it has only one cutting edge, in contrast to the two in the second case, therefore it needs more force to twist the drill bit during the drilling process. Furthermore, and through the assessment of Table 1, the highest torques were obtained for the spindle speeds of 8000 rpm, revealing that lower spindle speeds are more beneficial. In spite of this, the feed didn't show a significant impact on the variation of the torque values. The negative torque values correspond to the withdrawal of the tool from the hole, and are more prominent when the spindle speed is higher.

Fernández-Pérez et al. (Fernández-Pérez et al. 2021) observed, in their study, that torque increases with the increment of feed for the same cutting speed values, which also occurs for the tests performed here, except for the single-point angle drill at high spindle speeds. A possible explanation for this can be that, with this geometry, at high spindle speeds, higher feeds don't need so much force to twist the drill bit; however, with more tests performed more than once with the same parameters, a more statistically significant set of data can be obtained and a conclusion to this can be better drawn.

3.1.2. Thrust force analysis

In Figure 3, the graph containing the thrust force variations during each drilling test for the 8 holes is observable.

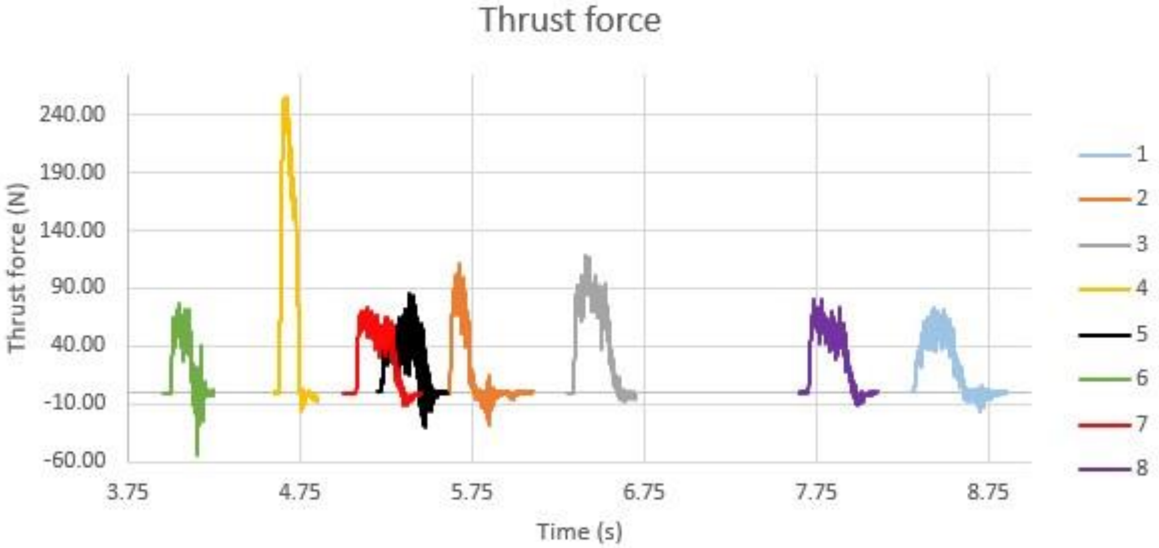

Figure 3: Thrust force graph of the drilled holes

By the observation of the thrust force graph, one curve clearly stands out, number 4, with a maximum of 255.37 N (Table 1). This occurred because of a problem in the analysis, where the tool broke due to excessive vibrations and, thus, it cannot be considered. Other than that, higher thrust force values were registered for the single-point angle drill, for the same reasons as in the torque situation. According to the chosen parameters, although in the double-point angle drill all four holes present close thrust forces, the lowest and better values were obtained for both high spindle speed and feed (6), or both low spindle speed and feed (7). The negative values represent the tool-chip contact when removing the drill after the experiment.

Feito et al. (Feito et al. 2018) performed an experimental analysis of a step drill performance for the drilling of woven CFRPs, from which they could observe that the thrust force and torque reduced when using the step drill compared to the conventional drill. This is in accordance with this study, where the optimized geometry is more valuable to the result.

3.2. Chip morphology

The assessment of the chips after a machining operation can unveil a great deal about the machined material when subjected to determined conditions, namely its fragile or ductile behaviour based on the used parameters, or its morphology according to the chosen tool's geometry. Figure 4 shows the chips which were obtained after the CFRP drilling tests.

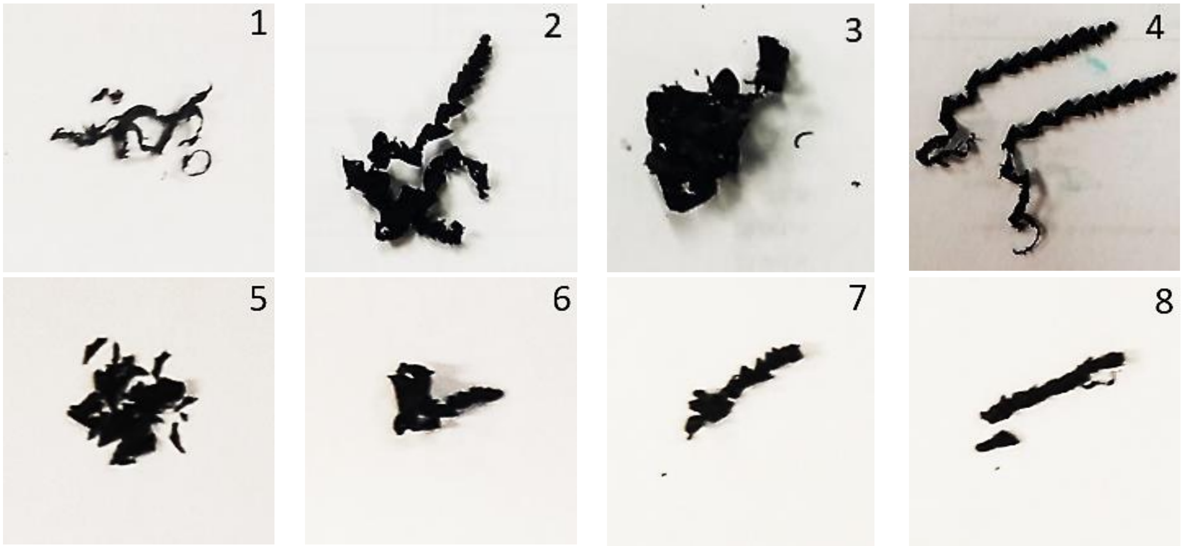

Figure 4: Chips obtained from the drilling tests

From an inspection of the chips, it can be stated that the tool's geometry has a great influence on them, as with the double-point angle drill, the chips stick together, promoting an easier evacuation through the tool's helix space. On the other hand, with the single-point angle drill the chips have more tendency to separate from one another, resulting in a higher probability of causing damage to the tool, increasing its wear, and also to the base material. This is explained by the additional angle in the second case, which makes the tool perform a better cut, i.e., originating united chips.

Considering the used parameters, it can be clearly seen that the combination of higher spindle speeds (8000 rpm) with lower feeds (0.15 mm/rev), in cases 1 and 5, results in fractured chips, a bad outcome, as this may create the same problems stated before. Additionally, lower values for the tested parameters result in more continuous and easier-to-evacuate chips.

Hrechuk et al. (Hrechuk et al. 2018) performed a chip analysis after CFRP drilling in two different components: fibers and matrix particles, correlating them with tool wear. The conclusion was drawn that the fibers length increased with tool wear, and the matrix particles showed grinding for lower feeds, which is in accordance with the present study.

3.3. Delamination assessment (x-ray images)

The x-ray images (Figure 5) for each of the holes made it possible to observe them in detail, as well as possible signs of delamination. Although the images are predominantly dark, because of the composite's matrix, the white areas, representant of the fibers, are clearly visible, being the zones where to look for discontinuities caused by the drills.

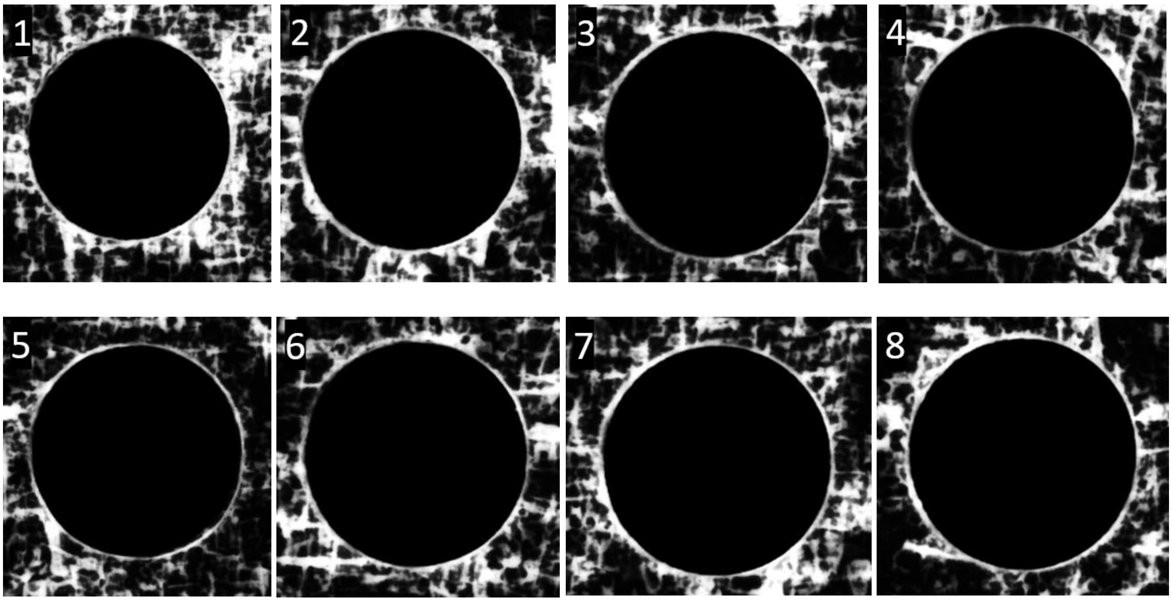

Figure 5: X-ray images of the drilled holes

As the CFRP sample used for the tests had a thermoplastic matrix, with the heat generated from the contact of the tool with the material during the process, after the drilling ended, the composite fibers rearranged themselves and, thus, no great delamination was possible to be observed. Nevertheless, small surface quality issues can be seen in the x-ray images, since some holes are not perfectly round.

In the case of the single-point angle drill, neither of the holes have shown a perfect circularity, with fiber damage mainly in their left side, explained by the lesser ability of this tool to cut the fibers compared to its competitor, as it only has one cutting edge, being more restricted. In hole number 1, this issue is even more problematic, with the inner diameter being more damaged in its upper left corner, meaning that higher spindle speeds are not favorable. For the double-point angle drill, only holes number 6 and 7 present a slight problem in their left side, which means that both the combination of the highest values and the lowest ones affect the hole's quality, concluding that a balance in the parameters is ideal.

Xu et al. (Xu, An, and Chen 2014) also compared two different tool geometries in drilling CFRP with diamond-coated drills, and reached the conclusion that the special-geometric dagger drill was more effective in terms of better hole quality than the standard twist drill, proving that, once more, optimized geometries possess a better performance. Feito et al. (Feito et al. 2018) also observed that delamination was reduced with the improved drill geometry, but only for low feed rates, whereas in this study higher feed rates resulted in better hole quality.

4. Conclusions and future works

This paper aimed to study how variables such as the spindle speed and the feed could affect a thermoplastic matrix CFRP's drilling process, as well as the influence of the diamond-coated drills' geometry on factors such as torque and thrust force, obtained chips and composite delamination. From the experimental work performed, it can be stated that:

- The double-point angle drill, due to its additional cutting edge, has a much better cutting performance than the single-point angle drill, achieving lower torques and thrust forces, therefore it develops lower wear, besides resulting in better hole quality;
- Lower spindle speeds (4000 rpm) contribute to lower torque values, with the feed not having a significant influence in this variable. As for the thrust force, the best values are obtained when the spindle speed and feed are both high or both low;

- Higher spindle speeds (8000 rpm) combined with lower feeds (0.15 mm/rev) generate fractured chips, which are not beneficial to the drilling process, since they may damage more both the drill and the material. The best chips (continuous and not separated) arise from the double-point angle drill and lower spindle speeds (4000 rpm);
- Considering all the aspects, the best combination of parameters from the ones studied to optimize the CFRP drilling process is the use of a diamond-coated double-point angle drill with low feeds and low spindle speeds, with the latter possessing a greater impact on the final outcome.

As future works, in a following paper, the holes in this manuscript will be evaluated by an image analysis software, so that a more precise assessment of the holes' quality and their delamination can be performed, using techniques with a higher reliability and effectiveness. Additionally, after these preliminary tests, a bigger experimental database can be obtained through the repetition of the test holes more than once, to perform a statistical analysis and draw more complete conclusions regarding this process.

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