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Diamond drilling of Carbon Fiber Reinforced Polymers: Influence of tool grit size and process parameters on workpiece delamination

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Abstract

The physical and mechanical properties of advanced composite materials promote their application in structural components for the aerospace and automotive sectors. However, limitations in their machinability are due to anisotropy/inhomogeneity, poor plastic deformation, and abrasive behavior. For CFRP drilling, the process efficiency is heavily influenced by cutting conditions and tool geometry. This paper reports the outcomes of experimental diamond drilling tests. A 4-mm thick carbon-epoxy composite laminate was machined. The plate was made of ten layers, in which the carbon fibers were intertwined at 90°. 6-mm diameter core drills were used. Core drills were characterized by an electroplated bond type and an AC32-H diamond grain type. Four different tool grit size ranges were tested: (1) 63/53 μm, (2) 125/106 μm, (3) 212/180 μm, and (4) 212/180 plus 63/53 μm. The results are reported in terms of workpiece delamination, thrust force, torque, and chip morphology. Overall, the results allow identifying the cutting conditions for the minimum drilling-induced delamination while retaining a satisfactory process productivity.

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Keywords: CFRP; Diamond drilling; Delamination; Cutting force

1. Introduction

Carbon Fiber Reinforced Polymers (CFRPs) are composite materials based on a polymer matrix reinforced with carbon fibers. These materials offer superior properties such as high strength-to-weight and stiffness-to-weight ratios, toughness, good corrosion-, creep-, fatigue-, and wear-resistance, low thermal expansion, and high vibration damping aptitude [1]. Such advantageous characteristics contributed to the wide diffusion of composite materials for structural components, especially in automotive, aeronautical, and aerospace industry [2]. Parts made of CFRPs are usually produced near-to-net shape, however additional machining operations are frequently required for assembly. The drilling of boreholes for rivets, bolts and screws represents one of the most common cutting operations. For instance, a single unit production of an Airbus A350 aircraft requires to drill up to 55,000 holes [3]. Therefore, the drilling process has to fulfill the requirements related with assembly needs and part quality specifications. Drilling is recognized as a complex process in which extrusion (by the drill chisel edge) and cutting (by the rotating cutting lips) coexist [4]. The inhomogeneity and anisotropy of composites cause the presence of damage in the region close to the drilled hole. The observed undesirable defects are fiber breakage, debonding, pull out, stress concentration, thermal damage, spalling, micro-cracking, and delamination [5]. Among these, drilling-induced delamination is a remarkable problem, which can imply the rejection (up to 60%) of aircraft components affected by such a defect [6]. As reviewed in [6, 7], in the last years, several papers aimed to understand the CFRP drilling mechanisms have been published. A particular focus was given on the effects of process parameter variation and tool material/geometry on the damaged area around the drilled holes, also by developing analytical and statistical models [5, 8]. In order to reduce delamination, lower values of feed rate have been suggested by many authors [4, 5, 9-12].

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Vice versa, conflicting results were given with respect to the cutting speed variation. When increasing the cutting speed, the delamination factor at the hole entrance was found to increase by Davim and Reis [11], to decrease by Phadnis [12], or it did not show any significant variation in the study by Abrão and co-authors [9]. In addition, when increasing the cutting speed, the delamination factor at the hole exit was found to increase by Davim and Reis [11], to decrease by Palanikumar [13], or to have a parabolic dependence on such variable (with a minimum point) by Marques et al. [4]. Many authors [3, 10, 14-16] investigated the influence of process parameters on thrust force and torque, since they are expected to directly affect the quality of the machined hole. According to Turki et al. [14], the reduction of the thrust force is one of the most effective ways to decrease the risk of damage. Feed has a greater influence than that of spindle speed on thrust force and torque. Therefore, a low feed rate is suggested during drilling of carbon/epoxy composites in order to lower thrust force and torque as well as to limit the presence of defects.

Several authors [5, 9, 10, 17-19] investigated the influence of tool geometry and/or material on drilling performance and delamination. Besides standard twist drills, tool geometries can vary among ‘brad & spur’ (or candle stick) drills, core drills, dagger drills, drills with multiple flutes, ‘one shot’ drills, saw drills, step drills, step-core- and core-special drills, and twist drills with double point angle [20]. The peculiar distribution of cutting forces exchanged with the workpiece can be identified as the main difference between the tools. In particular, core drills show advantages with respect to conventional twist drills due to the different application area and magnitude of the thrust force [21]. Twist drills are characterized by the chisel edge of the drill point that pushes aside the material during the tool penetration into the material. Moreover, the thrust force for core drills is approximable as a distributed circular load. This load distribution is expected to reduce the delamination risk, achieving a better hole quality.

Quan and Zhong [18] highlighted that core drills (with and without plated diamond coating) show advantages in terms of reduced tool costs, higher tool life, and better machined hole quality in comparison to High Speed Steel (HSS) drills. Low feed rates, high spindle speeds, and high pressure cooling conditions (applying water or air) were recommended in order to improve hole quality when drilling composites with core drills. Tsao and Chiu [19] developed compound core-special drills in order to minimize the problems related to the chip removal clog when using core drills. Such tools are composed of an outer tool (core drill) and an inner tool (twist drill, saw drill, or candlestick drill). Drilling of CFRP can be improved when using core-special drills with respect to standard core drills due to lower thrust force, delamination and chip clogging, as well as higher chip removal. Core drills are made with metal-bond polycrystalline diamond (PCD) particles, so that the cutting mechanism is similar to a grinding operation. Core drills are mainly characterized by the grit size of the particles and the thickness of the hollow tube. Tsao and Hocheng [22] compared the performance of core drills with grit sizes of 100, 200, and 400 sieve mesh, and thicknesses of 0.8, 1.0, and 2.0 mm, by varying the feed rate and the spindle speed in CFRP drilling. The grit size was found to be the most significant variable among the four control factors, while the drill thickness showed only a limited influence. Generally, the choice of grit size depends on the feed and the desired hole quality. In addition, Tsao [23] tested other core drills with grit sizes of 60, 80, and 100 sieve mesh, and thicknesses of 1.0, 1.5 and 2.0 mm. The experimental results indicated that (in those specific cases) the thickness had a significant impact on the overall drilling performance, so the lowest thickness was suggested to minimize thrust force and surface roughness. In this scenario, the present paper is focused on CFRP drilling by using diamond core drills with different tool grit sizes. The discussion of the results in terms of hole delamination at varying of the process parameters, such as cutting speed and feed rate, is supported by the measurements of thrust force and torque. The aim of the study is to identify the cutting conditions which can ensure the minimum drilling-induced delamination while retaining a satisfactory process productivity.

2. Experimental set-up

Drilling tests were performed on a 3-axis Cortini M500/F1 vertical CNC milling machine characterized by continuously variable spindle speed up to 8000 rpm and peak power of 3.7 kW. Details concerning the experimental setup as well as the measured outcomes are given in the following.

2.1. Workpiece material

A 4-mm thick carbon-epoxy composite laminate was machined. The plate was made of ten 0.4-mm thick layers, in which the carbon fibers were intertwined at 90°. Table 1 lists the main properties of the CFRP plate (as provided by the material supplier).

Table 1. Workpiece material properties (from technical data sheet).

Matrix	Resin system	EPIKOTE^{TM} Resin 04695-1
	Density at 20°C	1.17 ± 0.02 g/cm^3
	Viscosity at 25°C	9000 ± 1000 mPa·s
Hardener	Curing Agent	EPIKURE^{TM} 05357
	Density	0.98 ± 0.02 g/cm^3
	Viscosity at 25°C	40 ± 20 mPa·s
Reinforcement	Type	Carbon Fiber
	Fabric weight	400 g/m^2
	Filaments/tow	6K
	Weave type	Twill K2/2 (Style 402)

2.2. Tool geometries

For diamond drilling, 6-mm diameter core drills were used (Figure 1). Core drills are characterized by an electroplated bond type and an AC32-H diamond grain type. Four different tool grit size ranges were tested: (1) 63/53 μm, (2) 125/106 μm, (3) 212/180 μm, and (4) 212/180 plus 63/53 μm (according to the ISO 565 standard). The latter code (4) refers to core drills made of a 212/180 μm diamond substrate plus an external layer of 63/53 μm. Such peculiar tool design is expected to modify the cutting behaviour, since the main cutting work should be performed by the larger grains, whereas the fine external grains should provide a better calibration of hole diameter and roughness [24].

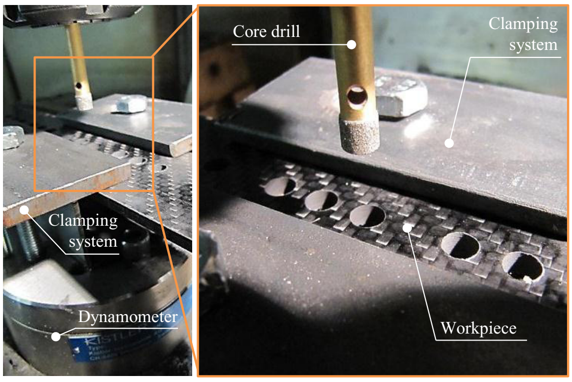


Fig. 1. A detail of the experimental setup.

2.3. Experimental plan

The experimental plan is detailed in Table 2: cutting speed, feed rate, and grit size range are the three studied factors. Two levels for cutting speed and feed rate as well as four levels for the grit size range have been considered. A total of 16 drilling test combinations have been executed by using core drills. In order to reduce the accidental and statistical errors all the experiments have been executed three times, in random order, for each cutting condition. Every hole has been machined with a new tool. The cutting speed range has been chosen according to the typical values applied by various researchers when using core drills [17, 22, 23]. Cutting speeds higher than 63 m/min were only suggested by Quan et al. [18] for the drilling-grinding of CFRPs, when applying water or air to remove chips and cool the tools. The actual results could be compared with those achieved with standard 6-mm diameter, 140° point angle, TiAlN PVD-coated carbide twist drills, that were formerly published by the Authors in [20].

Table 2. Experimental plan.

Level	Cutting speed v_c (m/min)	Feed f (mm/rev)	Grit size g (µm)
1	30	0.02	63/53
2	40	0.06	125/106
3	-	-	212/180
4	-	-	212/180 + 63/53

Cutting force and torque were measured by means of a Kistler (type 9272) four-component dynamometer, connected to a Kistler (type 5019) multichannel charge amplifier. The CFRP samples were clamped on the dynamometer top plate by means of a rigid C-shaped fixture allowing the execution of through holes. In addition, the workpiece was repositioned during the tests in order to be aligned with the central axis of the sensor. Data were acquired at a sampling frequency of 5 kHz for each channel, and were analysed by using a dedicated application developed in LabView. Hole delamination was measured by means of a stereo-microscope Leica MS5 (up to 40× magnification) equipped with a Leica DFC280 high-resolution camera for image acquisition. The camera was connected to a computer equipped with the Leica Qwin software for picture analysis and delamination assessment. Chip morphology was observed by keeping the same setup.

3. Results and discussion

Results are presented and discussed hereafter with respect to cutting force and torque (in Section 3.1), hole delamination (Section 3.2), and chip morphology (Section 3.3). In addition, comments concerning the core drilling process drawbacks are given in Section 3.4.

3.1. Cutting force and torque

Figure 2 shows the trends of thrust force versus cutting length for the three repetitions of all the experimental trials performed with the 212/180 + 63/53 µm grit size tool. Similar trends were observed when using the other core drills. A decrease in thrust force has been noticed in the steady-state region (i.e., between the tool/workpiece engagement and dis-engagement transients) when increasing the cutting length.

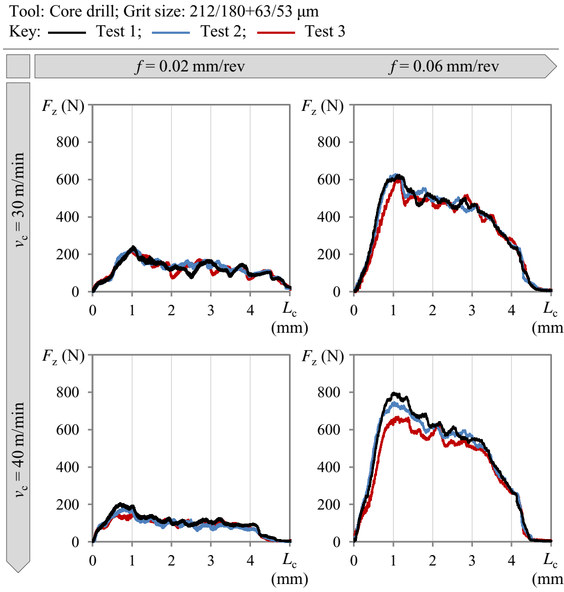


Fig. 2. Thrust force F_z versus cutting length L_c as a function of cutting speed v_c and feed rate f. Three tests for each cutting condition are shown.

Such evidence has already been discussed by Wang et al. [25], who provided a comprehensive explanation concerning the FRP drilling process mechanics. A reduction in thrust force while increasing the drilling depth could be due to the gradual reduction of the uncut thickness of the composite laminate, since the presence of cracks, elastic deformation, and bend deflection might promote the material removal mechanism as well as the occurrence of fracture and fiber separation. Also, the heat due to the cutting process is expected to be localized in the workpiece material close to the tool tip, due to the low thermal conductivity of the epoxy matrix. The increase in temperature reduces the mechanical strength of the workpiece as well as the cutting forces [25]. The drilling torque, vice versa, showed an increasing trend as the drilling depth increased (i.e., when increasing the tool-workpiece contact), until reaching the full tool-workpiece engagement. Per each hole, the steady-state average values of thrust force and torque were computed (within the range 1.0-3.5 mm, with reference to Figure 2), and the results are reported in Figure 3*a* and 3*b*, respectively. Each bar of the histograms represents the average value computed from the three test repetitions under the same cutting condition. The error bars define the maximum and the minimum values.

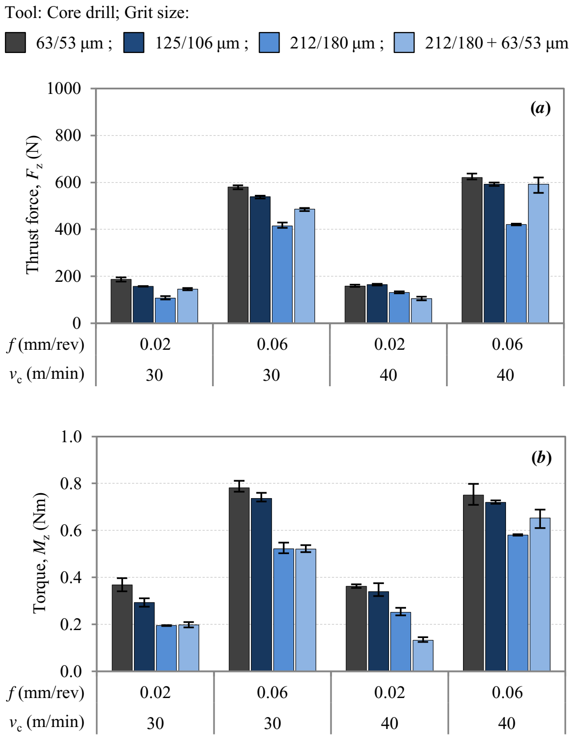


Fig. 3. Average thrust force (*a*) and torque (*b*) when drilling with core drills.

Feed rate is the main cutting parameter that influenced the thrust force trend. No or poorly significant variations of the thrust force were induced by the cutting speed change. Lower thrust force values were achieved when using tools with the coarsest grit size range of diamond particles. Core drills with grit size range of 212/180 µm were found to be the most advantageous in order to reduce the drilling thrust force. Core drills with the double layer of diamond particles (i.e., 212/180 + 63/53 µm) reached intermediate results between the standard core drills with the finest (i.e., 63/53 µm) or the coarsest (i.e., 212/180 µm) grit size range. The drilling torque follows the same behavior of the thrust force with respect to process parameters variation (within the tested range). It is worth pointing out that the 212/180 + 63/53 µm grit size tools minimized thrust force and torque when feed and cutting speed were 0.02 mm/rev and 40 m/min, respectively. Overall, lower feed rates and higher cutting speeds could be suggested when drilling CFRPs.

3.2. Hole delamination

The hole delamination was observed by means of the Leica MS5 optical microscope. Figure 4*a* and 4*b* show pictures of the hole entry and the hole exit, respectively, acquired for the tests carried out with the 212/180 grit size tool. Uncut plies have been observed at the hole exit, especially for the holes drilled at higher process parameters. The CFRP plate is made of ten 0.4-mm thick layers. When the tool tip reaches the last ply, the thrust force can exceed the adhesive bonding between adjacent layers, increasing the push-down delamination.

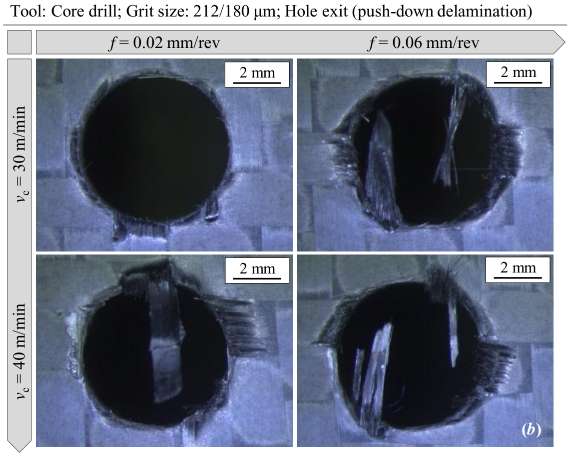


Fig. 4. Peel-up (*a*) and push-down (*b*) delamination.

The delamination factor (F_d), which is defined as the ratio between the maximum diameter of the delaminated zone (D_{max}) and the hole nominal diameter ($d = 6$ mm), was assessed for each test. The histograms in Figure 5*a* and 5*b* plot the average values computed by considering the three repetitions for all the cutting conditions, both at the hole entry (peel-up delamination) and at the hole exit (push-down delamination), while the error bars highlight the interval of variation of the results. The delamination factor at the hole exit (push-down) is much more higher than that at the hole entry (peel-up). Moreover, the error bars are wider for the delamination factor at the hole exit. The differences among the results obtained with the applied diamond grain sizes did not allow to achieve a clear correlation between the delamination at hole entry and the tool type. By contrast, the delamination factor values at the hole exit appear to be lower when using the coarsest grit size (212/180) or the double layer of diamond particles (212/180 + 63/53).

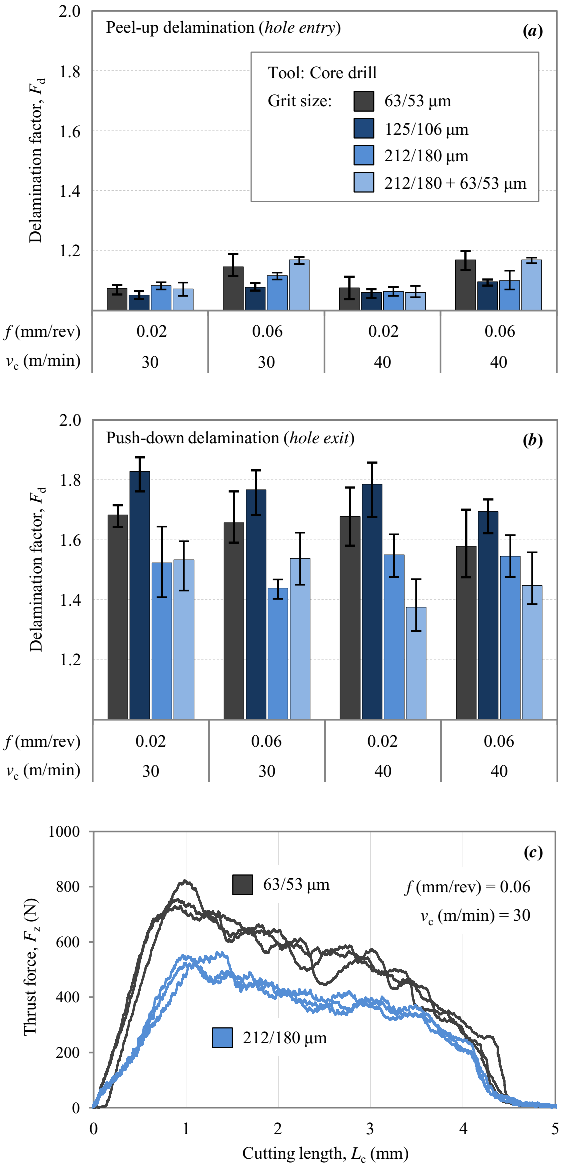
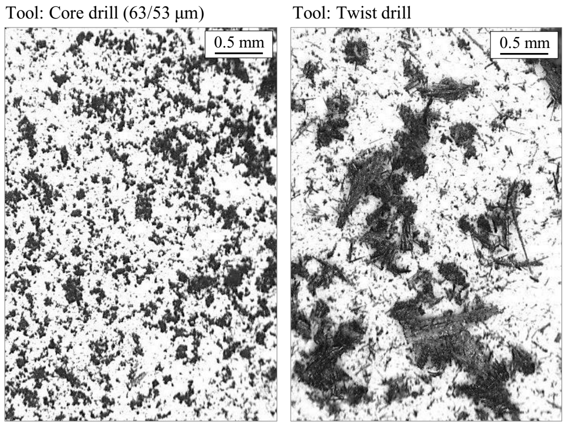


Fig. 5. Peel-up (*a*) and push-down (*b*) delamination results, with reference to thrust force trends (*c*).

This evidence follows the slight decrease in cutting forces (i.e., in Figure 5*c* the results of the three repetitions for each cutting condition are shown). When the thrust force increases, the delamination factor increases too. The delamination factor at hole entry increases when increasing the feed from 0.02 to 0.06 mm/rev. The slight increase in cutting speed from 30 to 40 m/min did not affect the results. The delamination factor at hole exit does not seem to be influenced by the process parameter variations. However, the delamination factor involves only the maximum diameter of the delamination zone (D_{max}). In many cases, even for comparable values of D_{max}, when increasing the feed, it is possible to notice an increase in the damaged area affected by delamination. In addition, the plies of the external layer at the hole exit are usually not removed at higher feeds by the cutting process. Finally, with respect to the previous results achieved when using twist drills under comparable cutting conditions [20], for the core drills the push-down delamination appears to be higher, while the peel-up delamination was comparable (or, in some cases, even lower).

3.3. Chip morphology

The chips obtained when diamond drilling were in the form of a fine powder (with a characteristic dimension smaller than that of the chips produced by conventional twist drills under equal process parameters, as shown in Figure 6). This is due to the chip removal mechanism that is closer to that of a grinding process [18]. In the actual tests, chip morphology was not clearly affected by variations in process parameters or tool grit size.


Tool: Core drill (63/53 µm)

Tool: Twist drill

Fig. 6. Chip morphology for v_c = 30 m/min and f = 0.06 mm/rev.

3.4. Potential drawbacks for core drilling

The results presented and discussed in the previous paragraphs refer to the holes all drilled with a fresh tool. In case of multiple-hole drilling operations, the tool's internal hollow geometry might be obstructed by the cut disks of workpiece material, as shown in Figure 7. This prevents the tool to work properly, causing a progressive increase in thrust force (Figure 7*a*) and huge delamination at hole exit (Figure

7*c,d*). In order to solve such problem, which penalizes the process automation, Tsao [8] designed a step-core drill that executes the drilling process in two subsequent cycles.

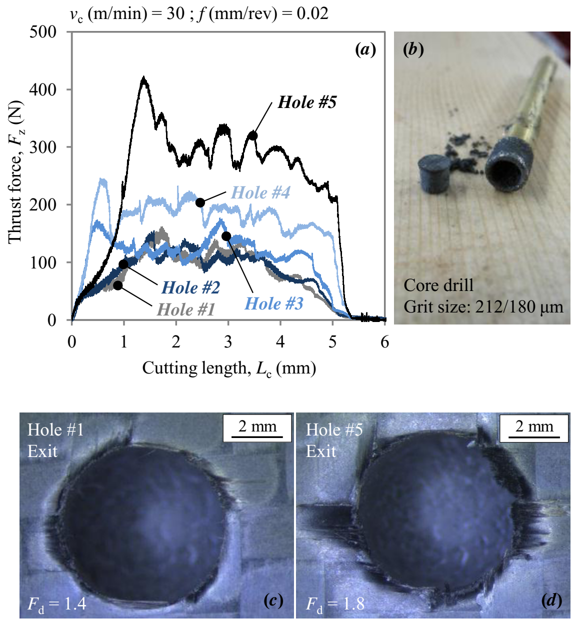


Fig. 7. Thrust force increase (*a*) due to tool obstruction (*b*) and effects on push-down delamination (*c*, *d*).

4. Conclusions

A better understanding concerning the influence of process parameters and tool geometry on CFRP drilling performance is required, aiming to improve the surface quality/integrity of the machined holes. Besides conventional twist drills, several special drills such as core drills, step drills, brad point drills, multiple-flute drills, and straight-flute drills have been developed over the years to reduce the drilling-induced delamination. In this paper, the diamond core drilling of composite laminates made of a thermoset epoxy-based polymer matrix reinforced with carbon fibers has been studied. Four different tool grit size ranges were tested, namely (1) 63/53 µm, (2) 125/106 µm, (3) 212/180 µm, and (4) 212/180 plus 63/53 µm. Tests were executed at varying of cutting speed and feed rate and the results were discussed in terms of delamination factor, thrust force, drilling torque and chip morphology. Feed rate was found to have a significant impact on delamination and thrust force. Core drills coated with the coarsest diamond particles achieved better results in term of delamination, thrust force, and torque in comparison to the tools coated with finer diamond particles. Further studies are needed to optimize the tool geometries in order to enhance the automated process productivity and the tool performance with respect to conventional twist drills.

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