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Comparative analysis of PCD drill designs during drilling of CFRP laminates

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Abstract

As a result of increased use of CFRPs in the aerospace industry, the machining of CFRPs has been studied extensively. The majority of these studies consider drilling of CFRPs, since it is the most common process in the machining of structural parts used in aircraft. It has been shown that drilling process parameters and drill geometry significantly influence the quality of holes. In this study, a systematic approach has been used to compare the influence of drill geometry on process outputs such as drilling forces, torques and tool wear. Custom-made double point angle polycrystalline diamond (PCD) drills from the same manufacturer were used in the experiments. The advantage of this approach is that it eliminates the drill material and edge preparation effects on the experimental measurements, thus helps reveal the influence of drill geometry on the process outputs. The pros and cons of different drill designs are discussed and an appropriate design is identified for the drilling of thick CFRP laminate considered in this study.

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Keywords: Drilling; fiber reinforced plastics; diamond tool

1. Introduction

Carbon fiber reinforced plastics (CFRP) possess desirable material properties such as high strength to weight ratio, high resistance to corrosion, and low thermal expansion. In addition, composite parts are produced near net shape, which results in fewer process steps when compared with metallic parts. Some drilling and finish milling operations are still necessary in order to bring the CFRP parts to their final shapes. However, CFRPs are known to be difficult to cut due to the abrasive nature of carbon fibers and the low thermal conductivity of the polymer matrix. Therefore, drills wear out rapidly and consequently increase the forces acting on the laminate during drilling and cause CFRP plies to separate from each other, which is known as delamination. Drilling process parameters, drill geometry, and drill tool material must be carefully selected in order to prevent delamination, which hinders the load-carrying capability of the CFRP structural parts. The most important process parameter affecting delamination is the drilling feed rate; its selection is closely related to drill geometry, which is the subject of this paper.

Drilling of CFRPs has been studied extensively. In general, it is recommended to keep feed low to keep thrust forces low and rotational speed high to obtain better productivity. However, low feed increases the total distance the drill travels while drilling the hole and hence interaction with the CFRP material and higher speed increases the temperatures during drilling. These conditions yield to rapid wear of the drills and eventually leads to delamination. Delamination is closely related to thrust forces at the hole exit. König et al. [1] defined the term "critical thrust force," as a limit value of thrust force beyond which delamination initiates. Hocheng and Dharan [2] and Zhang et al. [3] developed analytical models to predict the critical thrust force. Hocheng and Tsao [4] investigated different types of drills in terms of their delamination performance and concluded that successful drill designs are those which distribute the loads to the periphery rather than to

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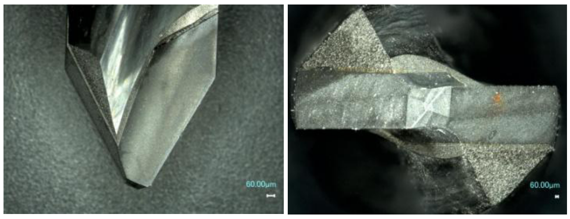
the hole centre. Abrao et al. [5] compared four different drill designs and identified a favourable drill design where cutting action takes place at the outer diameter of the tool. Shyha et al. [6] performed a statistical analysis to identify the ideal conditions for drilling CFRPs and found that drill geometry and feed rate are the two main factors affecting the drilling operation. Durao et al. [7] compared five different drill designs and found the one with 120° tip angle as the best performer. Karpat et al. [8] studied drilling of fabric woven type CFRP laminates using uncoated and diamond coated carbide drills having the same drill geometry. The diamond coated carbide drills significantly outperformed the uncoated carbide drills, and they perform well as long as the diamond coating is intact. Park et al. [9] investigated the hybrid drilling of CFRP and titanium alloys with PCD drills. They observed less titanium adhesion in PCD drills, but chipping of PCD cutting edges is a major concern. Recently, Karpat et al. [10] compared performances of different PCD drills while drilling CFRPs and investigated the trade-offs in drill geometries through experimental analysis of drilling forces and torques. While comparing different drill designs, it is beneficial to base the comparison to analytical models of drilling. Due to the complexity of the drilling process, mechanistic modelling approaches have been used to model drilling forces and torques. Lazar and Xirouchakis [11] made an extensive review of existing mechanistic drilling models in the literature and also introduced a new mechanistic model to predict drilling forces. Meng et al. [12] proposed a new model by considering the force fluctuations due to varying fiber directions during the drilling process. In a recent study, Karpat et al. [13] proposed a mechanistic drilling model for double point angle PCD drills where cutting force coefficients are represented as a function of fiber direction.

The goal of this study is to investigate the influence of different PCD drill geometries on process outputs such as drilling forces, torques, tool wear, and delamination. To this end, experiments were conducted with three different custom-made double point angle PCD drills. Drills were prepared by the same tool manufacturer from the same PCD material. Total drilling power is calculated and wear of different drills is used to compare drill designs.

2. Experimental setup

All the experimental work in this study was conducted under industrial conditions using a machining centre specifically designed for CFRP machining. Experiments were performed under wet conditions. An aluminum back-up plate with 8 mm diameter holes was used to support the CFRP laminate. A Kistler 9123 rotating dynamometer was used to measure the drilling forces and torques. Drilling tests used intermediate modulus laminates of 9 mm thickness, with fiber directions repeating in a sequence of 0°/45°/90°/135° with two layers of 45° and 135° laminates on the top and bottom surfaces. The laminate has 59% fiber volume with 2690 MPa tensile strength. Three different PCD drill designs were used in the experiments as shown in Figure 1. Drills have flat faces. The advantage of selecting flat face drills is that it simplifies the analysis of drilling since no helix angle exists on the PCD drill. Drills are coded as D1, D2, and D3. The drills are fabricated to have the same chisel edge length. The diameter of the drills are 6.4 mm. The edge radius of all the drills are measured to be around 10 μm as shown in Figure 2. A laser scanning microscope (Keyence VKX 110) was used to measure the edge radius values.



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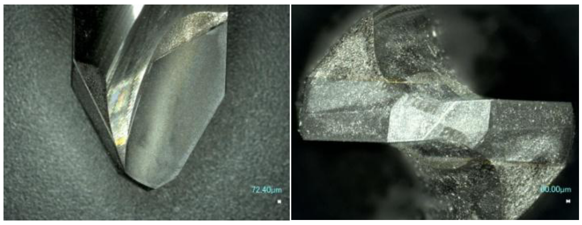

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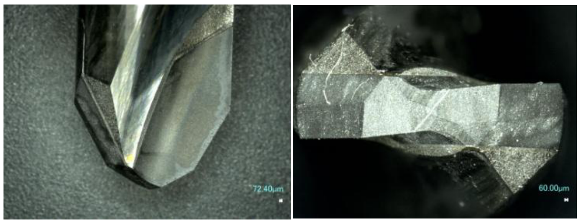

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Fig. 1. Double point angle drill geometries (a) D1, b) D2, c) D3.

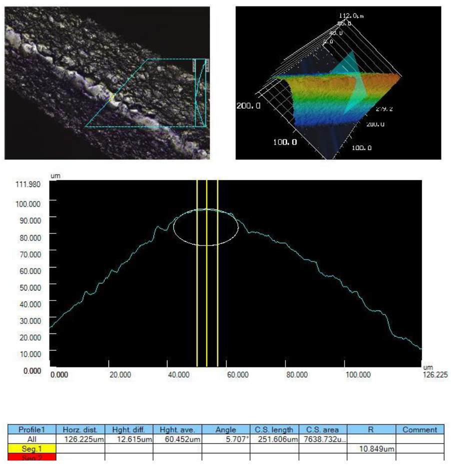


Fig. 2. Edge radius measurement of the drill.

3. Double point angle drill design

A generalized design for flat face double point angle PCD drills is shown in Figure 3. In this figure; *O'-O* represents the chisel edge region, *OA* shows the primary drilling region, *AB* shows the secondary drilling region, and *BC* shows the tertiary drilling region. In this study, only the length of the primary drilling edge is considered as variable. The total height (*H*) of the PCD is constant, therefore the lengths of *AB* and *BC* depends on primary edge length *OA*. The length and angle of the chisel edge are represented with R_c and γ, respectively. The tool tip angles corresponding to primary and secondary drilling regions are shown with p_1 (60°) and p_2 (30°). Table 1 summarizes the actual tool geometry measurements performed by using Keyence VHX 1000 digital microscope.

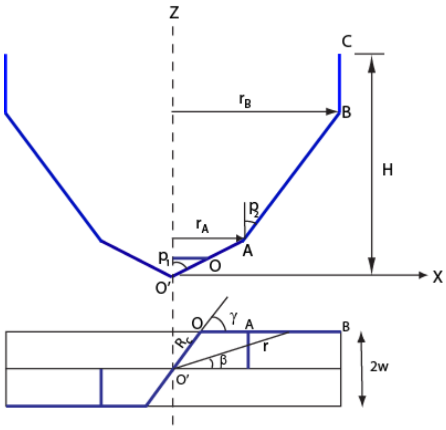


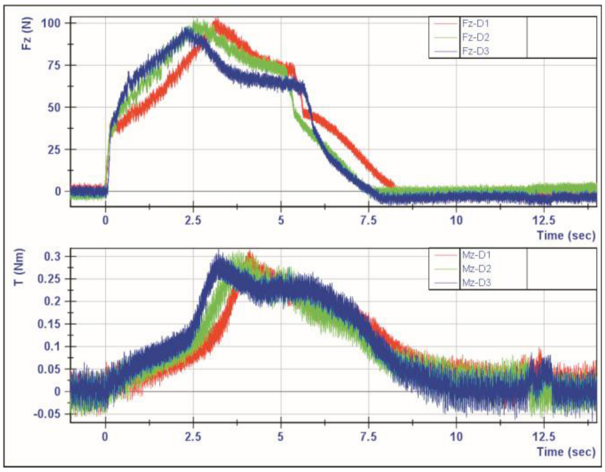
Fig. 3. Generalized double tip point angle PCD drill geometry.

Table 1. Tool geometry measurements.

Drill	OA (μm)	AB (μm)	P_1°	P_2°	Rc (μm)	γ°
D1	141	5180	60	30	1300	50
D2	915	3827	60	30	1300	50
D3	1455	2914	60	30	1300	50

4. Investigation of drilling thrust forces and torques

Figure 4 shows the variation of thrust force and torque measurements for a double point angle drill at two different feeds. Since the drill geometry and drilling feed rate is known, the time points corresponding to progression of the drill can be identified as shown in Figure 4b for drill D3. The thrust force increases as the drill moves inside the hole (0-t_1) and reaches its peak value when point B enters the hole (t_2). The torque reaches its peak value when the tertiary drilling region (BC) fully enters the hole (t_3). Rubbing action between the drill and the material is responsible for the increase in torque but the tertiary drilling region also performs as a reamer. An interesting observation is that drill geometry does not influence the peak thrust forces and torques, but it influences the time history and the progression of the forces and torques. Based on this observation, it is decided to calculate the total drilling power for each drill design since it requires the integration of progression of thrust force and torque with respect to time. The total drilling power corresponding to each drilling section can be calculated separately for each drill design.



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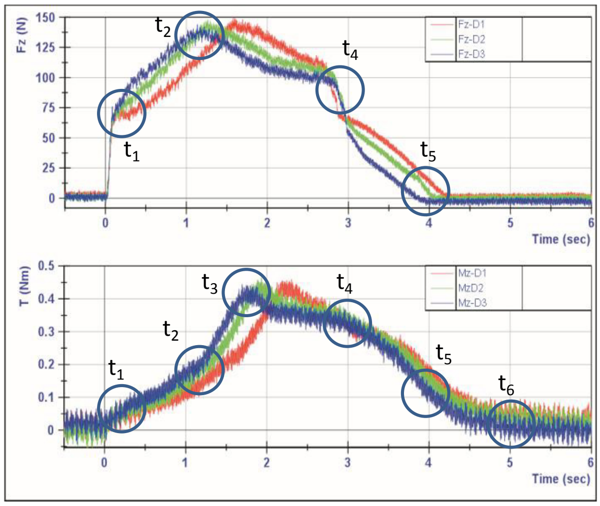

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Fig. 4. Thrust force and torque measurements at 5000 rpm: a) 20 μm/rev feed, b) 40 μm/rev feed.

It must be noted that the thrust force significantly decreases during drilling (t_2-t_4) probably due to thermal softening of the polymer matrix. In the exit region (beyond t_4), thrust force decreases rapidly as the chisel edge and primary drilling edge leave the hole. The rate of decrease in torque is lower since the secondary and tertiary cutting edges would still be in contact with the material. The torque decreases continuously until the drill completely leaves the material. The thrust force at the hole exit (at time t_4) is critical in terms of delamination. The measurements reveal that thrust forces at the exit decrease as the primary drilling edge length increases. Considering that the peak forces are almost equal, it may be stated that the drill with longer primary drilling edge builds up more heat energy in front of the drill, leading to softening of the material. However, this heat energy would affect the tool wear and, if excessive, would burn the polymer matrix during drilling. Calculation of drilling power at different stages of drilling would also help to assess this situation.

5. Drilling power based assessment of drill geometries

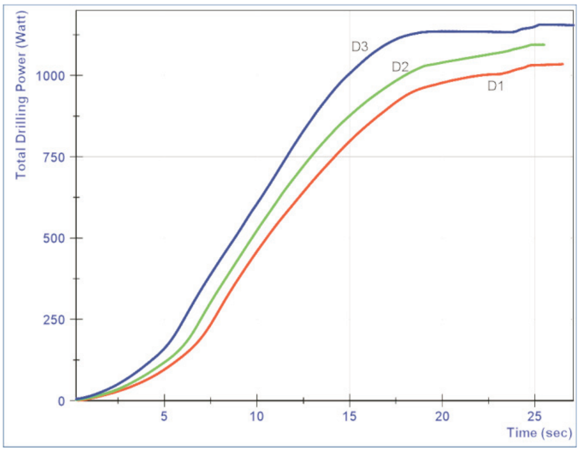
It is assumed that the total energy is spent on fracturing the carbon fibers, separating the polymer matrix from the laminate in the form of powders, and overcoming friction at the tool material interfaces. The total drilling power (P) can be written as the summation of power related to thrust force (P_{FZ}) and torque (P_{MZ}) as shown in Equation 1, which can be determined by taking the integral of the thrust force and torque curves with respect to time. Thrust force and torque measurements are multiplied with the feed rate and rotational speed, respectively.

$$P = P_{Fz} + P_{Mz} \quad (1)$$

$$P_{Fz} = \left[\int_0^{t_5} F_z(t) f N dt \right]$$

$$P_{Mz} = \left[\int_0^{t_6} M_z(t) N \frac{2\pi}{60} dt \right]$$

The drilling feed rates used in this study (50-250 mm/min) are quite small compared to drilling cutting speed (5000 rpm or 100 m/min). Therefore, the contribution of thrust force to total drilling power is negligible, and, only the contribution of torque is considered in the analysis. The data collected during drilling experiments has been filtered with a low pass filter then transferred and analyzed with National Instruments DIAdem Software (http://www.ni.com/diadem/). The integrals were calculated numerically using this software. Figure 5a shows the comparison of total drilling power for each drill corresponding to 10 µm/rev feed value and Figure 5b shows the drilling power calculations as a function of feed. The drilling power calculated for drill D1 is lower compared to others at all feed values. As primary drilling edge length (*OA*) increases, total drilling power also increases. The results imply that the torque intensity on the secondary drilling edge becomes larger as primary edge length gets longer. As feed increases, the total drilling power decreases drastically from 10 to 20 µm/rev. It must be noted that 10 µm/rev feed is equal to radius of the tool's cutting edge (Figure 2). The decrease of total drilling power from 20 to 40 µm/rev is small which indicates an increase in torque intensities especially on the secondary drilling edges. The critical feed value after which delamination was observed at the hole exits as observed from experiments is 30 µm/rev for sharp drills.



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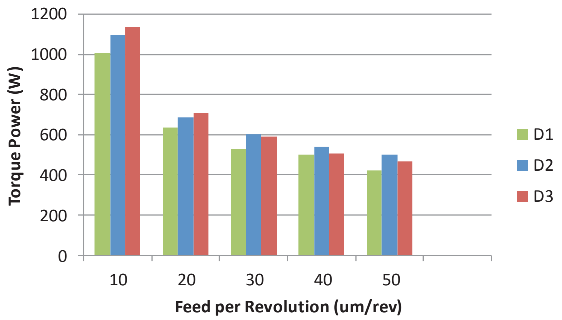

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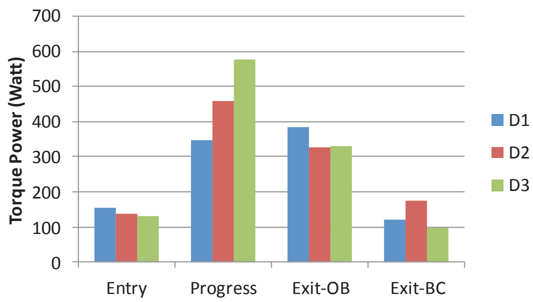
Fig. 5. a) Total drilling torque power at 10 µm/rev feed, b) Total drilling power as a function of feed.

The drilling process is divided into four sections as Entry (0-t_2), Progress (t_2-t_4), Exit-OB (t_4-t_5), and Exit-BC (t_5-t_6). Figure 6a shows the breakdown of the power calculations at each section for 10 µm/rev feed and Figure 6b shows the same breakdown for 20 µm/rev.



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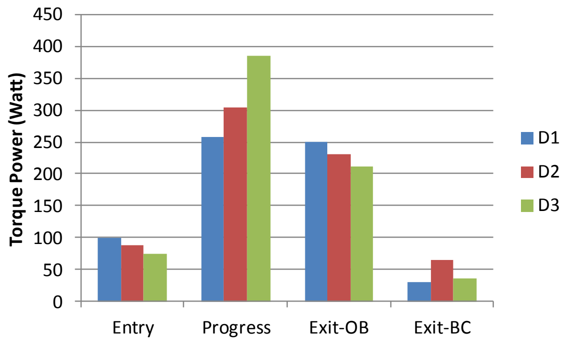

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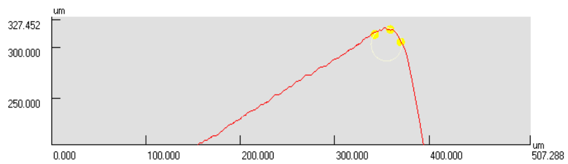
Fig. 6. Distribution of torque power at different stages of drilling at: (a) 10 µm/rev, (b) 20 µm/rev feed values.

It may be stated that, at the tested drilling conditions, drill geometry D1 is better in terms of chip/powder evacuation than other drill geometries. Assuming that heat builds up on the drill during Progress section, temperatures on the drill D1 would be lower compared to others. Considering the difficulties related to temperature measurements during drilling, it is decided to test each drill under the same drilling conditions for the same number of holes and investigate the resulting wear on the edges of the drills. The results is given in the next section.

6. Investigation of tool wear

Due to the abrasive nature of carbon fibers, rapid tool wear is common while drilling CFRPs. When PCD drills are used, wear is observed in the form of edge rounding. As drills wear out, thrust forces and torques increase, leading to poor hole quality. Drills D1, D2, and D3 were tested under the same drilling conditions (N=5000 rpm, 50 mm/min feed rate) and 66 holes were drilled with each drill. A new set of drills was used at the beginning of these experiments. The edge radii of primary and secondary drilling edges were measured before (as shown in Figure 2) and after the experiments. Figures 7 and 8 show each drill's edge profile measurements using a laser scanning microscope.



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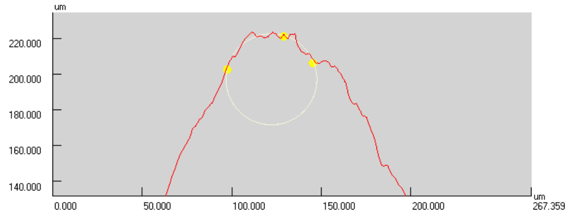

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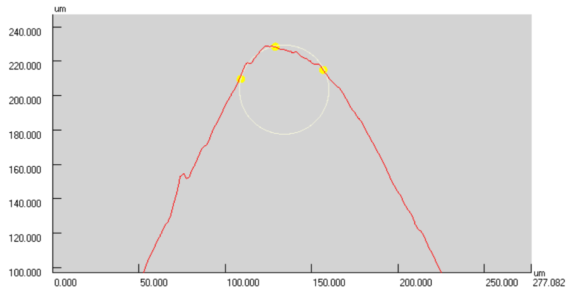

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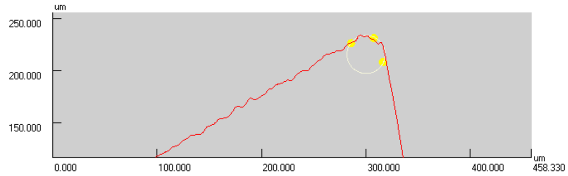
Fig. 7. Laser scanning microscope profiles of primary drilling edges a) D1, b) D2, c) D3.



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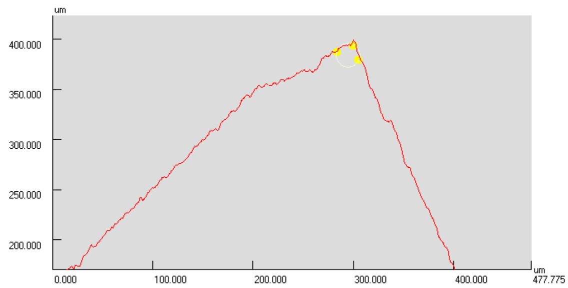

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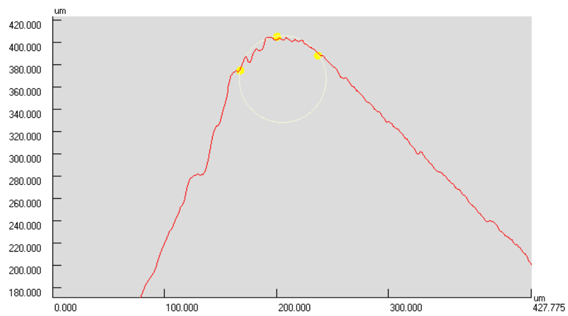

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Fig. 8. Laser scanning microscope profiles of secondary drilling edges. a) D1, b) D2, c) D3.

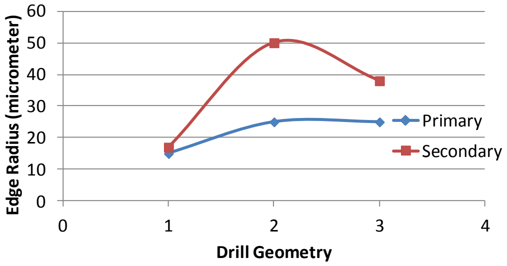

Fig. 9. Edge rounding as a function of drill geometry.

Figure 9 summarizes the edge radius measurements where the tool wear was measured in the form of edge rounding as a function of drill geometry. Increasing edge rounding indicates that the tool wears out faster under the same drilling conditions. This finding is in accordance with our predictions based on drilling power calculations in the previous section. The wear on the secondary drilling edge is larger than on the primary drilling edge which is related to the higher torque intensity on the secondary drilling edge. In Figure 8b, tool wear is observed as flank wear. As a result, due to the edge sharpening effect, the edge radius is actually measured as 13 µm. However, for comparison an equivalent edge radius is measured which assumes a value of 50 µm for D2 in Figure 9.

7. Conclusions

This experimental study reveals the importance of drill geometry specific to the CFRP laminate being drilled. Based on drilling power calculations and tool wear investigations, drill design D1 with short primary drilling edge length yields better performance at low feeds. Although long primary edge length yields lower thrust forces at the hole exit when the tool is sharp, these drills wear out faster and hence yield a poor performance during drilling process. The results also reveal that using higher feeds with lower cutting speed decrease the total power during drilling and would improve tool life without affecting the productivity, however, this improvement is limited by the critical thrust force. For drilling thick CFRP laminates, variable feed rate drilling method seems to be appropriate. The results demonstrate the importance of thermal modeling of CFRP drilling process based on analytically predicted drilling thrust forces and torques. These models can be used to select suitable drilling conditions and to improve drill designs.

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