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Energy based investigation of process parameters while drilling carbon fiber reinforced polymers

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Abstract

Carbon fiber reinforced polymers (CFRPs) are widely used in the aerospace industry due to their light weight, high strength, and low thermal conductivity. Drilling is a critical process that affects the quality of CFRP parts. This work studies the influence of process parameters on delamination and tool wear. Polycrystalline diamond helical drills are used in the experiments. It has been shown that drilling energy calculations can be used to set appropriate feed and speed parameters and for increasing drilling performance of CFRPs. The results also indicate the importance of thermal modeling of CFRP laminate for better understanding of the drilling process.

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Keywords: Drilling; carbon fiber reinforced polymer materials; carbide tools; tool wear; delamination; thrust force

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1. Introduction

Carbon fiber reinforced polymers (CFRPs) have become a widely used material in the aerospace industry due to their superior material properties. Drilling of CFRPs is a critical process in terms of delamination. It has been shown that delamination is closely related to drilling process parameters, tool geometry, and tool wear [1, 2, 3]. Due to the abrasive nature of carbon fibers and the low thermal conductivity of the polymer matrix, rapid tool wear is a common problem in drilling of CFRP laminates. As the cutting edges of the drills wear out, forces increase, which leads to quality problems inside the hole and at the exit of the hole.

Many studies have been conducted to understand the relationship between process parameters and delamination while drilling CFRPs [4, 5, 6]. It has been observed that in order to keep thrust forces low at the hole exit, feed must be set low. It has also been observed that rotational speed does not influence the drilling forces significantly. Therefore, a high rotational speed is set in order to obtain an acceptable feed rate in the drilling process. However, especially when drilling thick CFRP laminates, setting a low feed increases the interaction time of the tool and the material, which results in rapid tool wear. Therefore, diamond coated carbide and polycrystalline diamond (PCD) are widely adopted tool materials used to drill thick CFRP laminates [7, 8, 9]. This study uses PCD drills in the twist drill form that have recently become available in the market.

Recent studies have shown the importance of thermal modeling while drilling CFRP laminates [10, 11]. The changes in temperatures inside the hole affects the material properties of the polymers. The resin system, fiber content, and sequence of laminate are important factors that must be considered in the models. In this study, drilling energy is calculated and compared for two different PCD drills. Thrust force and torque measurements are used to calculate the instantaneous power for different feed and rotational speed values. The work related to the movement of the drill can be assumed to convert into heat energy, which results in rising temperature inside the hole.

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2. Experimental setup and drill geometry

A unidirectional CFRP plate with 11 mm thickness was used in the drilling experiments. There are 72 layers in total with repeating laminate configuration of 0˚-45°-90˚-135°. Two additional CFRP layers of ±45˚ were laid at the top and bottom surfaces of the laminate. The carbon fiber content is 59%. A CNC milling machine is used to conduct drilling experiments. A back plate made from aluminum with 8 mm diameter holes was used to support holes from behind. The experimental setup and CFRP plate are shown in Fig. 1. Thrust force and torque measurements were made by using a rotational dynamometer and its charge amplifier (Kistler 9123, Kistler 5223). Experiments were performed under wet drilling conditions.

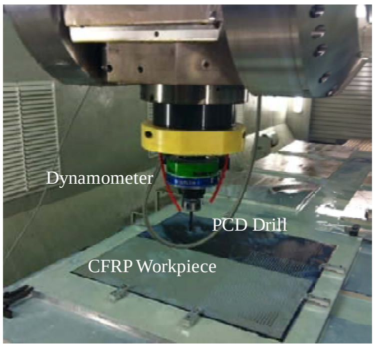
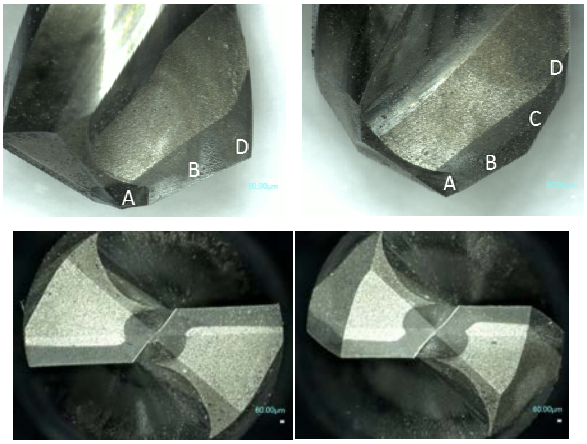


Fig 1. Experimental setup.

Two different helical PCD drills, both with 6.4 mm diameter, were used in the experiments as shown in Fig. 2. Both drills (M1 and M2) have 30° helix angle and 120° tip angle. Drill M2 has a double point angle (120°- 60°). The drills have the same chisel edge design. Different sections along the cutting edges of the drills are identified as A, B, C, and D as shown in Fig. 2.



(a) (b)

Fig 2. Helical drill geometries. a) M1, b) M2.

3. Calculation of energy during drilling

Table 1 shows the experimental drilling conditions used in this study. The feed rate is fixed at 100 mm/min in order to keep drilling time the same for each drill. Three different levels of rotational speed values are considered and three different feed values are used to fix the feed rate at the same level in all experiments. Three holes were drilled under each condition. Fig. 3 shows the thrust force and torque measurements for each condition for drills M1 and M2.

Table 1. Experimental drilling conditions

Experiment	Rotational Speed N (rpm)	Cutting Speed (m/min)	Feed f (μm/rev)	Feed rate f_r (mm/min)
1	5000	100	20	100
2	4000	80	25	100
3	3300	67	30	100

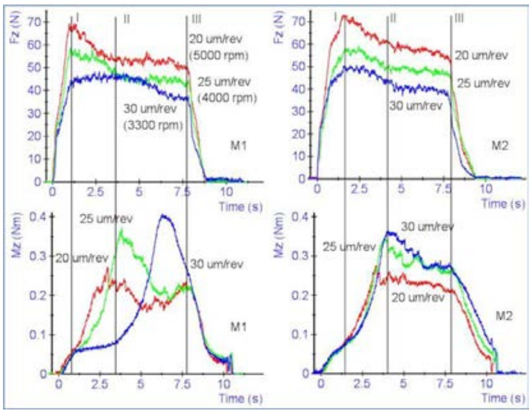


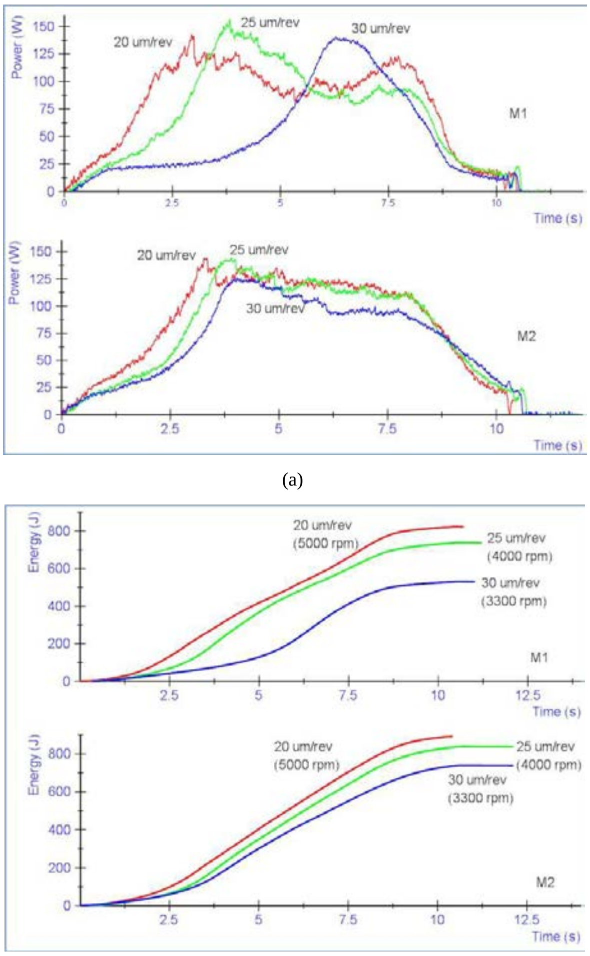
Fig 3. Measured thrust forces (F_z) and torques (M_z) for M1 and M2 as a function of process parameters.

In terms of thrust forces (F_z), similar values were measured for both drills. The drill M2 reaches peak force slightly later due to its different point angle in the secondary cutting edge. With increasing feed and decreasing rotational speed, thrust forces decrease for both M1 and M2. Thrust forces decrease as the drill proceeds in the hole, which corresponds to regions between I and II as shown in Fig. 3. While thrust forces decrease, a significant increase in torque was observed. Torque measurements reach their peak value at II except for drill M1 at experimental condition 3. After this point, torque measurements decrease and thrust force measurements remain almost constant until the drill reaches region III, where the drill tip reaches the bottom of the hole. Measured thrust force and torque measurements are used to calculate power as shown in Fig. 4(a). The forces acting on the drill in x-y directions are neglected due to their relatively low values of 5-6 N. Drilling energy (*E*) can be calculated by integrating the power terms with respect to time using Eq. (1) where the first term considers the influence of thrust force (F_z) and feed rate ($f.N$) and the second term considers the influence of torque

(M_z) and rotational speed (N) [12]. In Eq. (1), t_f and t_m correspond to end of drilling operation time values for thrust force and torque, respectively. It can be seen in Eq. (1) that rotational speed has a significant influence on the calculation of drilling power, which justifies using the same feed rate in drilling experiments.

$$E=\left[\int_0^{t_f} F_z(t) fN dt\right]+\left[\int_0^{tm} M_z(t) N \frac{2\pi}{60} dt\right] \quad (1)$$

Fig. 4(b) shows the energy calculation for drills M1 and M2 for each drilling condition. With increasing feed and decreasing rotational speed, drilling energy decreases. Table 2 compares drilling energy calculations for each drill. The difference gets larger as feed is increased and rotational speed is decreased.



(a)

(b)

Fig 4. (a) Power and (b) energy as a function of feed and rotational speed.

Table 2. Drilling energy (J) for each experimental condition.

	Exp. 1	Exp. 2	Exp. 3
M1	818	731	524
M2	886	835	739
M1/M2	0,978	0,875	0,7

The percentage of energy flowing into the workpiece (q) can be calculated by Eq. 2 [10] where η is the heat partition ratio. For CFRP material, it is estimated to be 20–50% [11].

$$q=\frac{\eta.P}{Area} \quad (2)$$

In Eq. (2), the swept area of the cutting edges in one revolution defines the heat flux (W/mm^2) and P represents the instantaneous drilling power (W). The swept area per revolution of drill M1 is 0.67 of the swept area of drill M2. Therefore, although larger values for drilling energy for M2 were calculated, the heat flux is expected to be lower for drill M2. Based on these calculations, temperature rise inside the hole for M2 is expected to be lower. Decreasing thrust force with increasing feed and decreasing rotational speed imply the influence of temperature distribution inside the hole. As rotational speed decreases, the contribution of torque to total drilling power decreases and lower temperatures are expected. It must be noted that, as feed increases, the effective rake angle in drilling operation also increases, which eases material removal. Temperature increase inside the hole during drilling may result in softening of the polymer which may decrease the thrust forces. The torque values at the hole exit for drill M1 are slightly smaller than they are for the drill M2. However, for drill M1, at 30 μm/rev feed, the trend of torque measurements changes compared to lower feed values. A large torque peak value shifted to a later point in time may indicate the difficulty of chip/powder evacuation (clogging) and/or increased contact of outer drill edge with the hole.

4. Investigating the tool wear and hole exit quality

After drilling three holes with each drill for all conditions shown in Table 1, the cutting edges are investigated with the laser scanning microscope (Keyence VKX 110). The edge radius of upsharp cutting edge was measured as 5 μm. Fig. 5(a) shows the edge rounding in drill M2. Edge rounding at the chisel edge is measured to be the same for both drills. However, the edge rounding in the primary, secondary, and tertiary drilling edges (shown as A, B, C, and D in Fig. 1) of M1 and M2 are measured to be different. The measurements are shown in Fig. 5(b). Due to its double point angle design, drill M2 manages to keep edge rounding lower at the secondary and tertiary edges compared to M1. The edge rounding values are due to combined effect of torque and temperature distributions along the drill's cutting edge, which affect the mechanics of machining the workpiece.

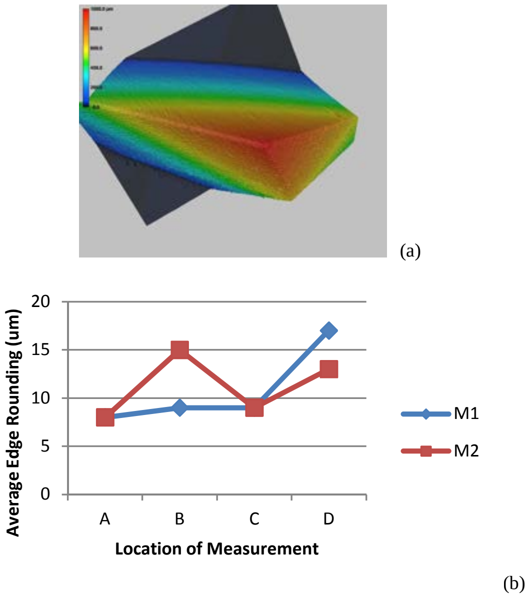
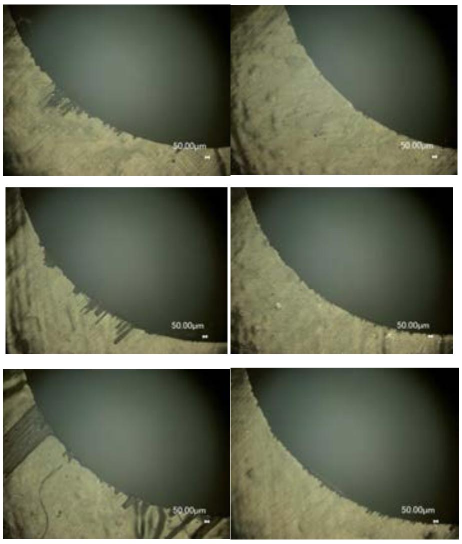


Fig 5. a) Edge rounding along the cutting edge, b) Variation of edge rounding values (A, B, C, D shown in Fig 2).

In order to investigate the influence of force, torque, and tool wear on the hole quality, the exit side of the holes are examined under the optical microscope. Fig. 6 shows the hole exit pictures corresponding to 45° laminate direction, which is known to be sensitive to edge conditions and drilling thrust force and torque values.



(a) (b)

Fig 6. Hole exit quality at three different cutting conditions. a) M1, b) M2 (From top to bottom: Exp 3-2-1).

Drill M2 produces hole exits with no significant problems at all conditions. Although drill M1 yielded lower thrust force and torque value at 20 and 25 μm/rev feed values, hole exits with this drill have quality problems as shown in Fig. 6. The conditions of the edges at hole exit, which also influences torque measurements, seem to affect the process. Additional long term drilling tests must be conducted for further verification of these observations.

6. Conclusions

This study performed drilling energy calculations under varying feed and rotational speed conditions. The results reveal the importance of the drill geometry on process outputs. The drilling power calculations were used to estimate the heat flux flowing into the workpiece, which affects the temperature distribution inside the hole during drilling. The results indicate that energy calculations may be affected by temperature distributions, which in turn affects the material properties of the polymer matrix. Tool wear is observed in the form of edge rounding which varies along the cutting edge of the drill. The condition of the drills' edge seems to be more influential than the thrust force measurements on the hole exit quality.

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