Precise Design of Drill Structure Based on Cutting Force Distribution Along Cutting Edge in CFRP Drilling

Xin-Yi Qiu

Hunan University of Science and Technology

Peng-Nan Li (✉ pnli@hnust.edu.cn)

Hunan University of Science and Technology

Chang-Ping Li

Hunan University of Science and Technology

Qiu-Lin Niu

Hunan University of Science and Technology

Shu-Jian Li

Hunan University of Science and Technology

Tae Jo Ko

Hunan University of Science and Technology

Research Article

Keywords: CFRP, drill geometric, precise design, cutting force model

Posted Date: October 5th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-940504/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Precise design of drill structure based on cutting force distribution along cutting edge in CFRP drilling

Xin-Yi Qiu^a, Peng-Nan Li^{a,*}, Chang-Ping Li^a, Qiu-Lin Niu^a, Shu-Jian Li^a, Tae Jo Ko^{a, b, *}

^a College of Mechanical and Electrical Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

^b School of Mechanical Engineering, Yeungnam University, 214-1 Daedong, Gyeongsan, Gyeongbuk 712-749, South Korea

* Corresponding author.

E-mail: pnli@hnust.edu.cn (Pengnan Li)

E-mail: tjko@yu.ac.kr (Tae Jo Ko)

Abstract

At present, the problems that need to be solved urgently in CFRP drilling are delamination and tool wear, which are closely related to the distribution of cutting force on the cutting edge. The aim of this paper is to present a method to analyze the cutting force distribution on the main cutting edge of the drill. This method applies to the analysis of the drilling performance of double point angle (DPA) drill and to optimize the step drill structure for CFRP drilling. Both of these applications prove the correctness of the analysis method. According to the calculation model of the rake angle of the main cutting edge of the twist drill and the cutting force prediction model, the distribution model of the cutting force on the main cutting edge is established. This method reveals the basic reason why the thrust force increases linearly when a single main cutting edge cuts into the workpiece. In the process of analyzing the drilling performance of the DPA drill, the edge force coefficient is used to represent the thrust force, and the application environment of the drill with a different structure is analyzed. Based on the distribution characteristics of the axial force on the main cutting edge, the step ratio of the step drill is optimized. This method can optimize the step ratio of the step drill. This method can be employed to optimize the step ratio of any structure step drill.

Keywords:

CFRP; drill geometric; precise design; cutting force model;

1 Introduction

The proportion of carbon fiber reinforced polymer composites (CFRP) used in the new

generation of aircraft have reached 50%, because it can reduce the weight of the structural components, resist corrosion and bear high loads. However, CFRP is difficult to machine because of its continuity, inhomogeneity and anisotropy, as well as its strong abrasion during machining processing [1, 2]. Therefore, the choice of cutting tools and processing parameters are very important in cutting such materials [3, 4].

Drilling is the most common mechanical work in the processing of CFRP parts. Common damage in CFRP drilling process includes delamination, burr, fiber pullout and matrix damage. Delamination seriously affects the performance of parts, which are the most serious damage, so it must be avoided. Delamination and surface quality are affected by cutting speed, feed rate and tool performance (geometric, matrix materials and tool wear). The importance of tool geometry parameters in reducing delamination has been confirmed by many scholars. Piquet et al. [5] recommended multi-edged drills with point angle of 118 deg and small front-angle which can increase the tool-workpiece contact length.

Drill is a common tool for hole making, and the typical representative is the twist drill. Many drills are developed on the basis of a twist drill, such as DPA drill and step drill. The cutting edge of twist drill mainly includes chisel edge, main cutting edge and auxiliary cutting edge, among which the chisel edge and main cutting edge play a major cutting role. The cutting edge directly contacts with the workpiece and removes material to form the machined surface, and also determines the tool's drilling performance [6, 7]. In order to obtain ideal hole quality, it is necessary to understand the physical mechanism of material removal and the influence of machining process dynamics on the performance of cutting tools. So far, most models for predicting thrust and torque are based on the isotropy of workpiece material [8-10].

The cutting force generated by the chisel edge accounts for half of the total thrust force [11, 12]. Therefore, delamination is mainly caused by chisel edge. In order to reduce delamination, it is necessary to reduce the axial force that generates by the chisel edge. Shortening the chisel edge length (drilling with grinding chisel) and selecting appropriate drill bit (step drill) are effective methods. The step ratio of the step drill determines the final influence of the chisel edge on delamination. However, the determination of step ratio has always been a key point. Tsao [13, 14] pointed out that the critical thrust force of step drill was smaller when the step drill was subjected to bending. Isbilir and Ghassemieh [15] analyzed the drilling performance of step drill in CFRP

drilling by 3D finite element simulation. They pointed out that the axial force and torque decrease with the step ratio. Qiu et al. [16, 17] carried out CFRP drilling experiments with different step ratios step drills, and obtained the step ratio from 0.3 to 0.75 in the theory of critical delamination force. Within this range, the step drill could effectively remove the impact of the chisel edge on the exit damage. However, the above studies are all carried out under the fixed drill geometry parameters (diameter, helix angel, chisel edge length, point angle, etc.), lacking of universal and systematic research.

Karpat et al. [18-20] used the edge force coefficient to characterize the thrust force on straight main cutting edge, analyzed the impact of tool geometry on drilling performance, and studied the drill performance of DPA drill. They claimed that the thrust force increases linearly with the depth of the main cutting edge cutting into the workpiece, but the fundamental cause is not clear. In previous studies, it was found that DPA drill has better drilling performance in CFRP drilling. Krishnaraj et al. [21] drilled composite materials at high spindle speed to study the influence of the tool geometry. Their report indicated that DPA drill could achieve better surface quality than standard twist drills. The DPA drill can obtain better surface integrity, especially, when the length of the primary cutting edge (L_1) is equal to the length of the secondary cutting edge (L_2) [21, 22]. Zitoune et al. [23] considered that when the ratio (L_1/L_2) was 3.1, the thrust force of DPA drill was smaller in CFRP drilling. That just says the longer primary cutting edge produced smaller thrust force. However, Karpat et al. [18, 19] believed that the shorter secondary cutting edge could obtain better quality, and pointed out that the workpiece material properties, processing conditions and tool structure must be considered in the parameter selection process. It can be observed that the conclusions of the above scholars based on the experimental methods are not consistent. Also, the cutting force on the cutting edge is associated with cutting environment (cutting parameters, tool geometry, etc.). Therefore, it is very important to study the relationship of cutting force on the main cutting edge with processing parameters and tool geometry for the application and development of DPA drills.

The purpose of this paper is to introduce a method to analyze the cutting force distribution on the main cutting edge of the drill. With that, the drilling performance and application environment of the DPA drill are analyzed, and the step ratio of step drill is optimized. Firstly, the analysis method is used to analyze the rake angle of each point on the main cutting edge of the drill.

According to Zhang's force model in CFRP cutting, the relationship between rake angle and cutting force is established to reveal the fundamental reason why the thrust force increases almost linearly when the straight main cutting edge cuts in. Then, according to the characteristics of the thrust force on the straight-edge drill, the edge force coefficient is defined to characterize the thrust force, and the drilling performance of the DPA drill is studied, and the step ratio of the step drill is optimized. The analytical model and examples provide the basis for the accurate design of drill bit.

2 Theoretical analysis model of the cutting force

2.1 Rake angle analysis

During the cut in process of the main cutting edge of the twist drill, the rake angle is always changing, so it is very important to understand the change rule of the rake angle with the position of each point on the edge. The twist drill main cutting edge is straight, and the rake angle γ_0 of each point on the main edge can be calculated or measured. The diagram of twist drill structure shows in Fig.1.

According to Ref [24], the rake angle of each point on the main cutting edge can be indicated as following:

$$tg\gamma_0 = \frac{\frac{r}{R}tg\beta_0\sqrt{1+tg^2\phi_0\left(\frac{r^2-r_0^2}{r^2}\right)}}{tg\phi_0\frac{\sqrt{r^2-r_0^2}}{r}} + \frac{-r_0}{\sqrt{r^2-r_0^2}} \cdot \frac{1}{\sqrt{1+tg^2\phi_0\left(\frac{r^2-r_0^2}{r^2}\right)}} \quad (1)$$

where, R is the drill radius, r is the radius of the position of the point. β_0 is the helix angle, $2\phi_0$ is the original point angle, and r_0 is the drill core half thickness.

Taking twist drill as an example, the drill parameters are set as following. $R=3$ mm, $2\phi_0=120$ deg, $r_0=0.525$ mm, $\beta_0=35$ deg. Fig.2 shows the variation curve of the rake angle of the main cutting edge according to formula (1). The change curve is consistent with literature [25]. The rake angle increases sharply with r/R (see Fig.2). When $r/R=0.2$ increases to $r/R=0.3$, the rake angle changes from -52.5 deg to 0 deg. When r/R is greater than 0.30, the rake angle changes very slowly. When $r/R=0.3$ increases to $r/R=1$, the rake angle changes from 0 deg to 37.38 deg. The rake angle of the chisel edge is -54 deg to -60 deg [24].

Fig.1 Diagram of twist drill structure

Fig.2 Variation of rake angle on the main cutting edge of the twist drill

2.2 Analysis of cutting force on the main cutting edge

This section is based on Zhang' cutting force model [26] at the fiber cutting angle 0-90 deg. Fig.3 is a diagram of cutting force when θ is less than 90 deg. The first region starts at the starting point tool tip in the experiment, the second region includes all areas below the tool tip, and the third region starts at the lowest point of the tool. It is assumed that the total cutting force is in the sum of the cutting forces of the three regions.

Fig.3 Cutting force diagram of three regions

First region. In this region, chip separation is no different from normal orthogonal cutting with sharp cutters. According to the analysis of Fig. 3(a), the following formula can be obtained:

$$\begin{cases} F_{y1} = \tau_1 \cdot h \cdot a_c \cdot \frac{\cos \varphi \cdot \tan(\varphi + \beta - \gamma_0) - \sin \varphi}{\frac{\tau_1}{\tau_2} \cdot \cos(\theta - \varphi) \cdot \sin \theta - \sin(\theta - \varphi) \cdot \cos \theta} \\ F_{z1} = \tau_1 \cdot h \cdot a_c \cdot \frac{\sin \varphi \cdot \tan(\varphi + \beta - \gamma_0) + \cos \varphi}{\frac{\tau_1}{\tau_2} \cdot \cos(\theta - \varphi) \cdot \sin \theta - \sin(\theta - \varphi) \cdot \cos \theta} \end{cases} \quad (2)$$

where, F_{y1} and F_{z1} are shown in Fig.3(a). θ is the fiber cutting angle. τ_1 and τ_2 are the shear strength of workpiece materials along AC and BC directions, respectively. h is the workpiece thickness. φ is the shear plane angle. a_c is the cutting depth. β is the friction angle of rake surface. γ_0 is the rake angle. Because CFRP is typical brittle material in cutting, so the material deformation coefficient is set to 1. According to the general shear angle calculation:

$$\varphi \approx \arctan\left(\frac{\cos \gamma_0}{1 - \sin \gamma_0}\right) \quad (3)$$

Second region. The deformation in the second region is contribute by the tool tip. This part of the tool tip can be regarded as a cylindrical indenter (see Fig.3(b)). Applying the model of indentation in semi-cylindrical contact, the force acting on the tool tip at indentation can be

counted by half of the force acting on AB and BC. So

$$\begin{cases} F_{y2} = K \cdot \frac{(b_1^2 + b_2^2) \cdot \pi \cdot E^* \cdot h}{8 \cdot r_e} \cdot (\cos \theta - \mu \cdot \sin \theta) \\ F_{z2} = K \cdot \frac{(b_1^2 + b_2^2) \cdot \pi \cdot E^* \cdot h}{8 \cdot r_e} \cdot (\sin \theta + \mu \cdot \cos \theta) \end{cases} \quad (4)$$

where, $b_1 = r_e \cdot \sin \theta$, $b_2 = r_e \cdot \cos \theta$. μ is the friction coefficient. K is a function of the direction of the fibers, which is determined by experiments. Effective modulus of elasticity E^* is defined as

$$E^* = \frac{E}{1 - \nu^2}, \quad E \text{ is the modulus of elasticity in OP direction of workpiece material. } h \text{ is the}$$

thickness of the workpiece. r_e is the tip radius. b_1 and b_2 are the lengths of contact arcs AB and BC.

Third region. The contact force in this area is mainly generated by the springback of the workpiece material. Supposing the springback is complete (see Fig.3(c)). The cutting force in the third region is obtained as following

$$\begin{cases} F_{y3} = \frac{1}{2} \cdot r_e \cdot E_3 \cdot h \cdot (1 - \mu \cdot \cos \alpha \cdot \sin \alpha) \\ F_{z3} = \frac{1}{2} \cdot r_e \cdot E_3 \cdot h \cdot \cos^2 \alpha \end{cases} \quad (5)$$

α is the flank angle. E_3 is the effective modulus of the workpiece material in the third region. The material in this area becomes more fragile after deformation in the second region. Therefore, this effective modulus must be less than the elastic modulus of the original workpiece material.

The total cutting force F_y and F_z are equal to the sum forces in the corresponding parts of the three regions, which can be expressed as following:

$$\begin{cases} F_y = F_{y1} + F_{y2} + F_{y3} \\ F_z = F_{z1} + F_{z2} + F_{z3} \end{cases} \quad (6)$$

The parameters of T800 in this paper are $\tau_1=98$ MPa, $\tau_2=80$ MPa, $\beta=15^\circ$, $\mu=0.15$, $E=9.28$ GPa, $\nu=0.34$, $h=1$ mm, $a_c=0.05$ mm and $E_3=0.6E$. The cutting forces are analyzed when the fiber cutting angle are 30 deg, 60 deg and 90 deg.

According to the change of rake angle, the value of formula (6) is obtained, and the relationship curve between rake angle and cutting force is drawn (see Fig.4). The cutting force decreases sharply with the rake angle. The cutting force decreases slowly when the rake angle is

greater than 0 deg. Therefore, when the rake angle is greater than 0 deg, the change of rake angle has little effect on cutting force.

Fig.4 Effect of rake angle on cutting force

Fig.5(a) is an orthogonal cutting sketch, and Fig.5(b) is a cutting sketch of the main cutting edge of the drill. The oblique cutting of the main cutting edge is evolved from the orthogonal cutting. By analyzing the orthogonal cutting, the characteristics of oblique cutting can be inferred. Lazar et al. [10] also analyzed the cutting force on the main cutting edge by establishing the relationship between drilling and oblique. Therefore, the following section will analyze oblique cutting by means of orthogonal cutting.

Fig.5 The cutting sketch of orthogonal cutting and main cutting edge cutting

The relationship between r/R and rake angle is also obtained according to formula (1). Then the relationship between r/R and cutting force per unit length (mm) is drawn (see Fig.6). When r/R is less than 0.3, the per unit length (mm) of cutting force decreases sharply with the increase of r/R . When r/R is more than 0.3, the per unit length of cutting force decreases slowly with a small reduction. According to Fig.6, the rapidity reduction stage of cutting force is a small section of the

main cutting edge near both ends of the chisel edge, and the corresponding rake angle of the cutting edge is less than 0 deg. It is difficult to distinguish the cutting force in this region, which is linked to the cutting force on the chisel edge of the thrust force curve. This section of the main cutting edge caused a large impact on thrust force, so it can also be classified as a chisel edge. From ref [27], it can be known that the influence of cutting speed on cutting force can be ignored. So, the change of cutting force per unit length (mm) of the main cutting edge is small, which is the fundamental reason why the thrust force of the straight main cutting edge drill increases linearly when it cuts in.

Fig.6 The curve of relation between r/R and cutting force

3 Analysis of drilling performance of DPA drill

3.1 Experimental designs

The material of the workpiece is T800S/250F with a thickness of 5 mm. The drills used in the tests were ground on a tool grinder (ANCA RX7) with cemented carbide bars. Fig.7 shows photos of the drill T1 and drilling experiment site. The DPA drill parameters can be seen in Fig.8 and Tab.1. The cutting parameters of the spindle speeds (n) are 1500, 3500 and 5500 r/min, and the feed rates (f) are 0.01, 0.02, 0.03, 0.04 and 0.05 mm/r. The experiments were finished on KVC800/1 center. The cutting force is recorded with a dynamometer (Kistler 9253B23).

Fig.7 Photos of the drill T1 and drilling experiment site

Fig.8 Structural parameters of DPA drill

Tab.1 Geometric parameters of T1

Diameter	The first point angle	The second point angle	Chisel edge length	Helix angle	L_1	L_2	L_2/L_1
6 mm	120 deg	70 deg	0.153 mm	35 deg	1.9 mm	1.05 mm	0.55

3.2 Analysis of thrust force

3.2.1 Force analysis of cutting edge

Fig. 9 is the schematic diagram of cutting force distribution on cutting edge of the DPA drill. F_{ch} , F_1 and F_2 represent the force on cutting edge (see Fig.9). Fig.10 shows the time-varying curve of the drilling thrust force for DPA drill. OC, CA and AB are the stages of chisel edge, primary

cutting edge and secondary cutting edge cutting-in stage, respectively.

Fig.9 Cutting forces on cutting edge of the DPA drill

Fig.10 Time-varying curve of thrust force at $n=3500$ r/min, $f=0.02$ mm/r

According to the above analysis, the following relationships can be obtained:

$$F_Z = F_{ch} + 2F_1 + 2F_2 \quad (7)$$

$$2F_1 = F_A - F_{ch} \quad (8)$$

$$2F_2 = F_B - F_A \quad (9)$$

where, k_1 is the edge force coefficient on l_1 , k_2 is the edge force coefficient on l_2 . The tool diameter is D and the radius is R .

$$F_1 = k_1 \cdot l_1, \quad F_2 = k_2 \cdot l_2 \quad (10)$$

$$F_Z = F_{ch} + 2k_1 \cdot l_1 + 2k_2 \cdot l_2 \quad (11)$$

$$R = \frac{l}{2} + \sin \delta \cdot l_1 + \sin \delta_1 \cdot l_2 \quad (12)$$

$$\begin{aligned} F_Z &= F_{ch} + 2k_1 \cdot l_1 + 2k_2 \cdot \left(\frac{R - \frac{l}{2} - \sin \delta \cdot l_1}{\sin \delta_1} \right) \\ &= F_{ch} + \left(2k_1 - \frac{2k_2 \cdot \sin \delta}{\sin \delta_1} \right) \cdot l_1 + \frac{2k_2 \cdot \left(R - \frac{l}{2} \right)}{\sin \delta_1} \end{aligned} \quad (13)$$

In order to obtain a smaller thrust force F_z under the same processing parameters, it is necessary to judge $k_1 - \frac{k_2 \cdot \sin \delta}{\sin \delta_1}$ or $\frac{k_1}{k_2} - \frac{\sin \delta}{\sin \delta_1}$ the positive and negative.

When $\frac{k_1}{k_2} - \frac{\sin \delta}{\sin \delta_1} > 0$, the smaller the l_1 is, the smaller the thrust force is.

When $\frac{k_1}{k_2} - \frac{\sin \delta}{\sin \delta_1} < 0$, the larger the l_1 is, the smaller the thrust force is.

In this case, $\delta=60$ deg, $\beta=35$ deg, $\sin \delta / \sin \delta_1 = 1.51$, so it is only needed to judge the relationship between k_1/k_2 and 1.51. When k_1/k_2 is greater than 1.51, the smaller l_1 causes the smaller thrust force. When k_1/k_2 is smaller than 1.51, the longer l_1 causes the smaller thrust force.

3.2.2 Thrust force

Fig.11 shows the relationship between the cutting force (F_{ch} , F_1 , F_2 and F_z) and the processing parameters. The cutting forces (F_{ch} , F_1 , F_2 and F_z) increase with feed rate. However, the influence of the spindle speed on the thrust force can be ignoring at large feed rate.

(c) F_2

(d) F_z

Fig.11 Relations between thrust force and machining parameters

3.2.3 Edge force coefficient

Fig.12 represents the relationship between edge force coefficient and cutting parameters. From the graph, there is a close relationship between k_1 , k_2 , k_1/k_2 and cutting parameters (spindle speed and feed). The coefficients k_1 and k_2 increase with the feed rate, but decrease with the spindle speed. The change trend is consistent with that of thrust force with cutting parameters. The relationship between k_1/k_2 and cutting parameters can be seen in Fig.12(c). k_1/k_2 decreases with the feed rate. And, it increases with the spindle speed, but the variation range is small. In Fig.12(c), a shadow plane of $k_1/k_2=1.51$ has been given. Under the shadow plane, namely, the thrust force of the drill with longer primary cutting edge is smaller at feed rate great than 0.04 mm/r. Above the shadow plane, namely, the thrust force of the drill with longer secondary cutting edge is smaller at smaller feed rate (less than 0.04 mm/r).

(a) k_1

(b) k_2

(c) k_1/k_2

Fig. 12 The relationship between edge force coefficient and cutting parameters

The relationship model between k_1/k_2 and processing parameters was obtained by regression analysis (see formula (14)). In the case of given a specific DPA drill, the value of k_1/k_2 is calculated according to the prediction model. Then, compared it with $\sin\alpha/\sin\alpha_1$, the appropriate range of processing parameters can be selected.

$$k_1 / k_2 = 0.0297 \cdot n^{0.2725} \cdot f^{-0.4956} \quad (14)$$

3.3 Verification experiments

In order to verify the above conclusions, drill bit T2 is designed. The structure parameters of T2 are shown in Tab. 2. The cutting parameters are the same with T1. The thrust forces of T1 and T2 are compared as shown in Fig. 13. The predicted value of k_1/k_2 is given in the figure. When k_1/k_2 is less than 1.51, the thrust force of T1 is greater than that of T2. However, when k_1/k_2 is greater than 1.51, the thrust force of T2 is greater than that of T1. This conclusion is consistent with the above conclusions, which verify the correctness of the deduction process and the k_1/k_2 prediction model.

Tab.2 Geometric parameters of T2

Diameter	The first point angle	The second point angle	Chisel edge length	Helix angle	L_1	L_2	L_2/L_1
6 mm	120 deg	70 deg	0.153 mm	35 deg	1.2 mm	2.2 mm	1.83

Fig.13 Thrust force comparison between drill T1 and T2

4 Step ratio optimization of step drill

4.1 Thrust force

According to the relationship between rake angle and cutting force, and considering the rake angle of each point on the main cutting edge of the drill, it can be inferred that the thrust force will be greatly reduced by removing the part which has negative rake angle. Fig.14 shows the drill structure of twist drill and step drill. Point P is the point where the rake angle is 0 deg, and also is the boundary point between positive and negative rake angle of the main cutting edge. PQ section has the negative rake angle. D_{r0} is the diameter of Point P. Therefore, when the diameter of the first stage is greater than D_{r0} (that is to say, the ratio of step drill is greater than D_{r0}/D), the effect of the negative rake angle cutting edge can be effectively removed. In this case (the twist drill structure parameters show in section 1), when the step ratio is greater than 0.3, the influence of chisel edge on pushing can be effectively removed. This result is consistent with Qiu's [16] conclusions.

Fig.14 Diagram of drill structure

A twist drill and a step drill (step ratio 0.3) were used to finish CFRP drilling tests. The drill's structure parameters are consistent with section 1. The time-varying curves of thrust forces have been shown in Fig.15. Compared with twist drill, the maximum thrust force of step drill is 30.4% less. Fig.15(f) shows that Point P' is the maximum thrust force in the first drilling stage of step drill. Point P (see Fig.14(b)) on the primary cutting edge of step drill corresponds to Point P' (see Fig.15(f)). The thrust force curve of step drill coincides with that of the twist drill before Point P'. The thrust force increases rapidly due to the chisel edge and the part of main cutting edge with negative rake angle. After Point P', the thrust force of twist drill continues to increase, but the increasing speed slows down. The reason is that the rake angle of the main cutting edge after Point P' is greater than 0 deg, and the cutting force is relatively small.

(a) Hole 2

(b) Hole 4

(c) Hole 6

(d) Hole 8

(e) Hole 10

(f) Hole 10

Fig.15 The time-varying curve of the thrust force ($n=3500$ r/min, $f=0.04$ mm/r)

4.2 Exit damage

The processing quality of import and export was tested by digital microscope. The hole entrance burr and delamination of the two drill bits are few. On the contrary, obvious burr and delamination were found at the exit. Tab.3 shows the hole exit morphology. It can be seen from the table that in the first five holes, the holes drilled by twist drill appeared accidental tearing phenomenon, while step drill shows good cutting performance. Burrs occurred at the seventh hole and becomes serious as more holes were drilled. Compared with twist drill, the burrs caused by step drill were less.

Tab.3 Hole exit morphology

Hole	Twist drill	Step drill	Hole	Twist drill	Step drill
1			9

The delamination factor F_d was used to evaluate the push-out delamination at the hole exit [28]. It described by the following equation:

$$F_d = D_{max} / D_{norm} \quad (16)$$

Fig. 16 shows F_d variations of two drill bits. Compared with twist drill, step drill causes less delamination damage. The decrease in delamination should be attributed to two factors. One is that, the thrust force produced by step drill is obviously reduced (see Fig.15). Then, the secondary drill bit can effectively remove the damage caused by the primary drill bit [16].

Fig. 16 Delamination factor variation of the two drill bits

5 Conclusions

Firstly, the analysis method is used to analyze the rake angle of each point on the main cutting edge of the drill. According to Zhang's cutting force model in CFRP cutting, the impact of

the rake angle on the cutting force is analyzed to reveal the fundamental reason why the thrust force increases almost linearly when the straight main cutting edge cuts in. Then, according to the characteristics of the drilling thrust force of the straight-edge drill, the edge force coefficient is used to represent the thrust force, and the drilling performance of the DPA drill is studied, and the step ratio of the step drill is optimized. The main conclusions can be drawn as following:

(1) The cutting force decreases sharply with the rake angle when the rake angle is less than 0 deg. When the rake angle is greater than 0 deg, the cutting force changes little with increasing of the rake angle. The area of negative rake angle on the main cutting edge is close to the chisel edge, and its range is small. Therefore, the change of cutting force on per unit length (1 mm) of the main cutting edge at different positions is very small in CFRP drilling, which is the fundamental reason why the cutting force increases linearly when a single main cutting edge cuts in.

(2) During the analysis of DPA drill, the edge force coefficient is used to characterize the thrust force. It is found that when k_1/k_2 is greater than $\sin\delta/\sin\delta_1$, the shorter the primary cutting edge produces smaller thrust force. However, when k_1/k_2 is less than $\sin\delta/\sin\delta_1$, the longer the primary cutting edge generates smaller thrust force.

(3) The spindle speed and feed rate have a great effect on k_1 , k_2 and k_1/k_2 , among which the feed rate has a greater impact. k_1/k_2 decreases with the feed rate, while it slightly increases with the spindle speed. Therefore, the thrust force of the DPA drill with shorter primary cutting edge is smaller at lower feed rate, but the thrust force of the drill with longer primary cutting edge is smaller at larger feed rate. The DPA drill with longer primary cutting edge is recommended to obtain higher processing efficiency.

(4) When a step drill's first stage is used to replace the cutting edge with the negative rake angle (the diameter here is D_{r0}), its thrust force reduce greatly. Therefore, when the step ratio of step drill is larger than D_{r0}/D , the effect of the chisel edge on the push-out delamination can be effectively removed. This method can be employed to optimize the step ratio of any structure step drill.

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Agree to publish.

Authors' contributions

Xin-yi Qiu: Investigation, writing of original draft, and project administration.

Peng-Nan Li: Reviewing, editing, and funding acquisition.

Chang-ping Li: Reviewing, formal analysis, and editing.

Qiu-Lin Niu: Reviewing, and editing.

Shu-Jian Li: Reviewing, visualization, and editing.

Tae Jo Ko: Supervision, resources, and reviewing.

Acknowledgements

The work is supported by the National Natural Science Foundation of China (No.52105442, No. 51775184, No. 51975208, No. 51905169).

Conflicts of interest

We confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

References

- [1] Li HN, Wang JP, Wu CQ, Zhao YJ, Xu J, Liu X, Zhu WQ (2020) Damage behaviors of unidirectional CFRP in orthogonal cutting: A comparison between single- and multiple-pass strategies. *Composites Part B: Engineering* 185:107774
- [2] Li S, Zhan L, Chang T (2018) Numerical simulation and experimental studies of mandrel effect on flow-compaction behavior of CFRP hat-shaped structure during curing process. *Archives of Civil and Mechanical*

Engineering 18: 1386-1400

- [3] Yu Z, Li C, Qiu X, Park KM, Ko TJ (2020) Study on damage in carbon fiber reinforced plastic drilling using step cutting mechanism drill. *Journal of Alloys and Compounds* 826. DOI: 10.1016/j.jallcom.2020.154058
- [4] Yu Z, Li C, Kurniawan R, Park KM, Ko TJ (2019) Drill bit with a helical groove edge for clean drilling of carbon fiber-reinforced plastic. *Journal of Materials Processing Technology* 274. DOI: 10.1016/j.jmatprotec.2019.116291
- [5] Piquet R, Ferret B, Lachaud F, Swider P (2000) Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills. *Composites Part A: Applied Science and Manufacturing* 31: 1107–1115.
- [6] Henerichs M, Voß R, Harsch D, Kuster F, Wegener K (2014) Tool Life Time Extension with Nano-crystalline Diamond Coatings for Drilling Carbon-fibre Reinforced Plastics (CFRP). *Procedia CIRP* 24: 125-129.
- [7] Sheikh-Ahmad JY, Dhuttargaon M, Cheraghi H (2017) New tool life criterion for delamination free milling of CFRP. *The International Journal of Advanced Manufacturing Technology* 9–12: 1-13.
- [8] Faraz A, Biermann D, Weinert K (2009) Cutting edge rounding: an innovative tool wear criterion in drilling CFRP composite laminates. *International Journal of Machine Tools and Manufacture* 49: 1185–1196.
- [9] Hinze W, Hartmann D, Schutte C (2011) Occurrence and propagation of delamination during machining of carbon fibre reinforced plastics (CFRP)—an experimental study. *Composites Science and Technology* 71: 1719–1726.
- [10] Lazar MB, Xirouchakis P (2013) Mechanical load distribution along the main cutting edges in drilling. *Journal of Materials Processing Technology* 213: 245-260.
- [11] Zitoune R, Collombet F (2007) Numerical prediction of the thrust force responsible of delamination during the drilling of the long-fibre composite structures. *Composites Part A: Applied Science and Manufacturing* 38: 858-899.
- [12] Feito N, López-Puente J, Santiuste C, Miguélez MH (2014) Numerical prediction of delamination in CFRP drilling. *Composite Structures* 108: 677-683.
- [13] Tsao CC, Hocheng H (2003) The effect of chisel length and associated pilot hole on delamination when drilling composite materials. *International Journal of Machine Tools and Manufacture* 43: 1087-1092.
- [14] Tsao CC (2012) Effect of induced bending moment (IBM) on critical thrust force for delamination in step drilling of composites. *International Journal of Machine Tools and Manufacture* 59: 1-5.
- [15] Isbilir O, Ghassemieh E (2013) Numerical investigation of the effects of drill geometry on drilling induced delamination of carbon fiber reinforced composites. *Composite Structures* 105: 126–133.

- [16] Qiu X, Li P, Li C, Niu Q, Chen A, Ouyang P, Ko TJ (2018) Study on chisel edge drilling behavior and step drill structure on delamination in drilling CFRP. *Composite Structures* 203: 404–413.
- [17] Qiu X, Li P, Li C, Niu Q, Chen A, Ouyang P, Ko TJ (2018) Influence of machining parameters and tool structure on cutting force and hole wall damage in drilling CFRP with stepped drills. *The International Journal of Advanced Manufacturing Technology* 97: 857–865.
- [18] Karpaz Y, Bahtiyar O (2015) Tool geometry based prediction of critical thrust force while drilling carbon fiber reinforced polymers. *Advances in Manufacturing* 3: 300-308.
- [19] Karpaz Y, Bahtiyar O, Değ er B, Bilgin K (2014) A mechanistic approach to investigate drilling of UD-CFRP laminates with PCD drills. *CIRP Annals* 63: 81-84.
- [20] Karpaz Y, Değ er B, Bahtiyar O (2014) Experimental evaluation of polycrystalline diamond tool geometries while drilling carbon fiber-reinforced plastics. *The International Journal of Advanced Manufacturing Technology* 71: 1295-1307.
- [21] Krishnaraj V, Vijayarangan S, Suresh G (2005) An investigation on High speed drilling of GFRP. *Indian Journal of Engineering and Materials Sciences* 12: 189-196.
- [22] Zitoune R, El Mansori M, Krishnaraj V (2013) Tribo-functional Design of Double Cone Drill Implications in Tool Wear During Drilling of Copper mesh/CFRP/Woven ply. *Wear* 302: 1560-1567.
- [23] Zitoune R, Vijayan K, Bouacif SA, Francis C (2014) Design of double cone twist drill geometry to improve the holes quality while drilling in multi-stack made of CFRP/Al. *ASME 2014 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers 2014.
- [24] Group drilling team of Beijing Yongding machinery plant. *Group drilling*. Shanghai scientific and technical publishers, 1982.
- [25] Strenkowski JS, Hsieh CC, Shih AJ (2004) An analytical finite element technique for predicting thrust force and torque in drilling. *International Journal of Machine Tools and Manufacture* 44: 1413-1421.
- [26] Zhang LC, Zhang H, Wang X (2011) A new mechanics model for predicting the forces of cutting unidirectional fiber-reinforced composites. *Mach Sci Technol* 5: 293-305. (in Chinese)
- [27] Wang CY, Chen YH, An QL, Cai XJ, Ming WW, Chen M (2015) Drilling temperature and hole quality in drilling of CFRP/aluminum stacks using diamond coated drill. *International Journal of Precision Engineering and Manufacturing* 16: 1689-1697.
- [28] Chen WC (1997) Some experimental investigations in the drilling of carbon fiber- reinforced plastic (CFRP) composite laminates. *International Journal of Machine Tools and Manufacture* 37 :1097-1108.