Research on drilling CFRP laminate with a thin woven glass fiber surface layer using plane rake–faced twist drill

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Abstract

The delamination produced during drilling CFRP will affect its structural strength seriously. Delamination is closely related to the thrust force during drilling, which is closely related to the tool, so it is particularly important to choose the tools with appropriate geometric structure. Many scholars used tools with different geometric structure to drill CFRP, and then conducted the drilling damage analyses and drilling mechanism researches. It finally came to a conclusion that a drill with a special structure had certain advantages compared with a common twist drill in the drilling process. A new type of plane rake–faced twist drill was used to drill the CFRP laminate with a thin-woven glass fiber surface layer. Experimental results showed that the plane rake–faced twist drill along cutting edge had a constant reference rake angle value, which caused the plane rake–faced twist drill generated smaller thrust force and less drilling damage than the common twist drill. As the reference rake angle of the plane rake–faced twist drill increased, the thrust force and drilling damage decreased. It was revealed the inhibition of the thin-woven glass fiber surface layer on the drilling damage at entrance and exit. Finally, it was proposed that when the plane rake–faced twist drill was used to drill CFRP laminate with a thin-woven glass fiber surface, 46° reference rake angle should be selected.

Keywords CFRP · Plane rake–faced twist drill · Reference rake angle · Thrust force · Drilling damage

1 Introduction

Carbon fiber–reinforced polymer (CFRP) composite is an excellent structural composite material composed of high-strength carbon fiber and flexible matrix material. Carbon fiber composite materials have high strength and stiffness to weight ratio properties, relatively low density, high damping capacity, great dimensional stability, and strong corrosion resistance. Therefore, CFRPs have been widely used in many high-tech industries. In order to increase the thrust-to-weight ratio of civil aviation aircraft, the use of composite materials was increased in the fuselage to reduce its weight while considering the strength, thereby improving economy. CFRP can and will in the future contribute more than 50% of the structural mass of an aircraft [1–3].

While CFRP composite has various advantages, the cutting mechanism is quite different from a traditional material cutting mechanism due to its anisotropy and high wear resistance. Therefore, the manufacturing processing of CFRP composite has become the main reason for its limited application [4]. For traditional drilling CFRP composite, there is damage such as interlayer delamination and uncut fibers, matrix melting, and fiber cracks, which make it particularly difficult to analyze its drilling performance [5]. In the composite material manufacturing industry, traditional drilling is the main method for making composite material holes. Holes need to be drilled during assembling the aircraft structure. The quality of assembly mechanical joints such as bolted connections, rivet connections, and pin connections are highly dependent on the quality of drilling [6].

A large number of researchers had used different drilling tools to conduct experiments and analyzed the cutting performance of different tools and the machinability of CFRP. Some researchers mainly used different types of tools, such as brad
and spur drill, step drill, and dagger drill for CFRP drilling experiments. These tools were quite different from common twist drills in terms of geometric structure, to a certain extent, they had better cutting performance. For example, brad and spur drills showed excellent performance results during drilling fiber–reinforced materials. Due to the cut-push effect (the drill first cuts the last layer of the composite, then pushes this layer off) of sharp flank cutting edges, the number of uncut fibers as well as delamination could be minimized [7]. The dagger drill (one-shot drill) was a special double-point angle twist drill with four straight grooves. Compared with common twist drill, it had bigger thrust force. However, it exhibited better drilling performance than a common twist drill. In other words, the damage area of burrs and delamination factor were lower [8]. The step drill was used to drill a pilot hole with a smaller diameter drill bit firstly and then a larger diameter cutting edge was used for reaming, so that the delamination effect of the chisel edge could be minimized, thereby achieving smaller drilling damage. Qiu et al. [9] used twist drills and step drills to conduct drilling experiments on CFRP. The effect of the ratio of the minimum diameter \( D_1 \) to the maximum diameter \( D \) of the step drill on the cutting force and the damage of the hole wall was studied. The results showed that step drills had better cutting performance than common twist drills and a smaller maximum thrust and damage area were produced on the hole wall.

Other researchers mainly used twist drills with different geometries to drill CFRP. For example, the twist drills with different chisel edge, drill point angle, or rake face were used during drilling CFRP. Wang et al. [10] used the standard twist drill (ST), the drill with a shorter chisel edge and a larger point angle (130°) (SCE-LPA), the drill with a short S-shape chisel edge and a larger point angle (130°) (SSCE-LPA), along with the drill with double point angles (90° and 140°) and a shorter chisel edge (SCE-DPA) to conduct drilling experiments. The research results showed that the tools with shorter chisel edge (SCE-LPA, SSCE-LPA, SCE-DPA) could provide smaller thrust force than the ST, which could fully ensure better drilling quality. It was also verified that the conclusive factor of drilling quality was a tool structure rather than diamond coating. The change to the point angle mainly referred to double-point angle twist drills. When the drill point angle was the same as that of the common twist drill, a smaller thrust force value and small delamination damage were produced, which was due to the double-point angle twist drill had a smaller second drill point angle value. At the same time, they also had better wear resistance [11]. Therefore, the use of appropriate tools is particularly important to reduce the defects of drilling.

Until now, there are few researches studying on the twist drill with change rake face. Armarego et al. [12] proposed the way to obtain one new type of the plane rake–faced twist drill by grinding the rake face of a common twist drill. The tool had also been verified through experiments that it had better drilling performance than common twist drill, but this research mainly aimed at the drilling of aluminum alloy. There were few studies about the plane rake–faced twist drill was used to drill CFRP laminate; the characteristic of low drilling damage is unknown. In this paper, the plane rake–faced twist drills with a different reference rake angle and a common twist drill were used to drill CFRP laminate with a thin-woven glass fiber surface layer. The purpose was to study the characteristic of low drilling damage with the plane rake–faced twist drill, and the influence of plane rake–faced twist drills with different reference rake angle on the drilling quality at the drilling entrance and exit of CFRP laminate with a thin-woven glass fiber surface layer. In addition, the effect of the thin-woven glass fiber on the drilling damage at the entrance and exit of the drilling hole was disclosed.

## 2 Geometrical analysis of drilling tool

The plane rake–faced twist drill as shown in Fig. 1 was made through modifying the rake face of the common twist drill to a plane rake face with a disc-shaped-grinding wheel on a precision numerical control grinding machine. During grinding, the reference rake angle at the outer corner of lip was used as the benchmark to make the entire cutting edge produce a constant reference rake angle. The reference rake angle at each point along the cutting edge is defined as follows: the angle between a plane parallel to the drill axis containing the lip and the tangent to the flute surface at the point in question, projected in a plane normal to the lip. The plane parallel to the axial direction and containing the cutting edge is called \( P_f \), and the tangential plane of the helix surface at different points on the cutting edge is called \( P_h \). The plane \( P_f \) of different points on the cutting edge is the same and unchanged. As the radius increasing, the helix angle of the common twist drill gradually increases, and the plane \( P_h \) changes, so that the angle between the plane \( P_f \) and the plane \( P_h \) in the normal plane \( P_n \) increases at each point. It means that the reference rake angle gradually increases along the cutting edge. When the common twist drill is grinded to a plane rake–faced twist drill, the plane \( P_h \) of each point on the cutting edge coincides, so that there is a constant reference rake angle at different radius of the main cutting edge.

The width of the plane rake face of grinding is subjected to certain restrictions. On the one hand, when the width of the ground plane rake face is over large, the strength of cutting edge will decrease and the life span of tool will be sharply reduced. On the other hand, if the width of the plane rake face...
is too small, the cutting performance is not excellent enough. Therefore, the width of the plane rake face is determined by considering the contact length between the tool and the chip, rather than significantly reducing the cutting edge strength. For smooth chip disposal, the width $Y$ of the plane rake face should be larger than the maximum tool-chip contact length $h_{\text{max}}$ [13].

$$h_{\text{max}} = \frac{t}{0.6}$$  \hspace{1cm} (1)

where $t$ is the undeformed chip thickness. In the lip region of a drilling operation, $t$ can be given by [14]

$$t = \frac{f \cdot \sin \phi \cdot \cos \varepsilon}{2}$$  \hspace{1cm} (2)

$f$ represents the feed per revolution, which is related to the speed and feed. $P$ represents the half drill point angle. $\varepsilon$ represents the velocity angle.

2.1 Fundamental geometry on the lips

Figure 2 shows the geometrical relationships between various fundamental drill angels at one lip of a plane rake–faced drill. $P_r$ represents the reference plane of point $M$, $P_n$ represents the cutting plane, $P_n'$ represents the normal plane of point $M$. In addition, OA represents the intersecting line of the plane $P_f$ and the normal plane $P_n$, OB represents the intersecting line of the plane $P_r$ and the normal plane $P_n'$. OC represents the intersecting line of the plane rake face and the normal plane $P_n'$. According to the definition of reference rake angle, the included angle between OA and OC mean reference rake angle. The normal rake angle is defined as the projection of reference plane and rake face on normal plane, that is, the included angle between OB and OC. It can be given by the following formula:

$$\gamma_n = \gamma_{\text{ref}} - \varepsilon = \gamma_{\text{ref}0} - \varepsilon$$  \hspace{1cm} (3)
\[ e \] represents the velocity angle, which is defined as follows: the angle between the work velocity and the normal to a plane parallel to the drill axis containing the lip, projected in a plane normal to the lip. According to the geometric relationship in Fig. 2, it is equivalent to the angle between OA and OB, which can be expressed by the following formula:

\[ \tan e = \tan \omega \cos \rho \]  

where \( \omega \) is the web angle at point \( M \) with radius \( r \), \( W \) represents the half of the drill web thickness and is given by the following:

\[ \omega = \sin^{-1} \left( \frac{W}{r} \right) \]  

\( \lambda_x \) represents the inclination angle, which is the included angle between the normal plane and the cutting speed \( V_w \) in the cutting plane. It is given by the following:

\[ \lambda = \sin^{-1}(\sin \omega \sin \rho) \]  

From formulas (3), (4), and (5), it can be seen that as the radius increases, the web angle \( \omega \) gradually decreases. With the decrease of the web angle \( \omega \), the velocity angle \( e \) also decreases, which leads to an increase in the normal rake angle. The reference rake angle of common twist drill along the lip can be by [14]

\[ \gamma_{\text{ref}} = \tan^{-1} \left( \frac{\tan \delta \cos \omega}{\sin \rho - \tan \delta \sin \omega \cos \rho} \right) \]  

where \( \delta \) represents the helix angle of each point on the cutting edge. The helix angle of common twist drill gradually increases as the radius of the main cutting edge increasing. That is, the reference rake angle increases as the radius of the main cutting edge increasing, and so does the normal rake angle. But when the plane rake–faced drill is produced after grinding the curved rake face to a plane rake face, the helix angle \( \delta \) at each point is equal to the helix angle \( \delta_0 \) at the outsider diameter. At the same time, the reference rake angle \( \gamma_{\text{ref}} \) is also equal to the reference rake angle at the outer corner of lips \( \gamma_{\text{ref}0} \), that is, \( \delta = \delta_0 \), \( \gamma_{\text{ref}} = \gamma_{\text{ref}0} \). Finally, the normal rake angle of each point on the cutting edge of the plane rake–faced twist drill is larger than that of the common twist drill. Compared with common twist drill, the plane rake–face twist drill had larger normal rake angle along the main cutting edge, so the smaller thrust force was generated [15]. The cutting behavior also increased with the increase of a normal rake angle [16]. Therefore, with the decrease of thrust force and the improvement of cutting behavior, the plane rake–faced twist drill had better drilling quality.

### 3 Drilling experiment

#### 3.1 Experiment set up

The experiment was carried out on CNC machine tool (model: JMTT-CK6136). The mobile platform of CNC machine tool provided movement in \( X \)- and \( Z \)-directions. The precision moving platform was installed on the CNC machine tool and the movement of clamped material in the \( Y \)-direction was controlled by the corresponding controller, so the movement of material in three directions was satisfied. The thrust force was measured through a strain dynamometer installed on the back of the material. The strain dynamometer was manufactured by Touch Technology Co., Ltd. The WKDS93 multifunctional dynamic signal test and analysis system including data capture, amplifier, data display, and data analysis was used to collect thrust force signals. The tool was fixed on a high-speed main spindle at the end of the CNC machine tool and the speed was precisely controlled by frequency converter. The entire experimental platform is shown in Fig. 3. After drilling, an optical microscope and an electron microscope (model: Hitachi S-3400N) were used.

#### 3.2 Workpiece material and drilling tools

In this paper, the CFRP laminate with a thin-woven glass fiber surface layer was similar to that used in literature [17]. The uppermost and the lowermost layers of CFRP laminate had woven glass fibers layers with the thickness of 0.09 mm. The laying sequence is shown in Fig. 4 and the size is 75mm×65mm×6.18mm. The main parameters of internal carbon fiber laminate are shown in Table 1.

In this paper, one common twist drill and seven plane rake–faced twist drills with different reference rake angle at the outer corner of lips made in Changzhou Kenbo Tool Factory were used to drill CFRP laminate with the thin-woven glass fiber surface layer. The tools were numbered, as shown in Table 2. The reference rake angle at the outer corner of lips of common twist drill is 30°, and that of seven plane rake–faced twist drills are range from 26° to 50°. Except for reference rake angle at the outer corner of lips, other geometric parameters were the same, such as the half point angle \( P=60^\circ \), the width of the plane rake face \( Y=0.45 \text{ mm} \), the rounded cutting edge radius \( r_e=7 \mu \text{m} \), diameter \( d=6 \text{ mm} \), and clearance angle \( \alpha=30^\circ \). In the process of drilling, the speed was 2000 rpm, and the feed was 100 mm/min.

#### 3.3 Damage factor

In this paper, delamination factor was defined as the ratio of maximum diameter \( (D_{\text{max}}) \) of drilled hole surface damage area to the standard diameter of drilled hole \( (D) \), which was a traditional delamination damage factor \( (F_d) \) as shown in Fig.
5. The optical microscope was used to accurately compare the delamination factor among the holes drilled by different tools. The traditional delamination damage factor is shown in equation (8).

\[ F_a = \frac{D_{\text{max}}}{D} \]  

(8)

4 Results and discussion

4.1 Thrust force analysis

The rake face of common twist drill was changed from curved to plane through grinding, resulting in the generation of the plane rake–faced twist drill. The main cutting edge of the plane rake–faced twist drill could be regarded as many micro-elements of inclined cutting. The inclination angles at each point of plane rake–faced twist drill were the same as that of common twist drill before grinding [14]. The forces of plane rake–faced twist drill and common twist drill were similar. As shown in Fig. 6, \( F_{\text{th}} \) represents total thrust force, \( F_{\text{chit}} \) represents the thrust force generated by chisel edge. \( F_{\text{lipth}} \) represents the thrust force generated by main cutting edge. The relationship between them is as follows:

\[ F_{\text{th}} = F_{\text{chit}} + F_{\text{lipth}} \]  

(9)

Each tool was tested twice under the same parameters and the average value of two test results was calculated. The thrust force value for each experiment was the average of thrust force when the main cutting edge was steadily drilling. The typical thrust force signals recorded during drilling are shown in Fig. 7. Figure 7(a) is a typical thrust force signal during drilling with a common twist drill whose reference rake angle at the outer corner of lips is 30°. Figure 7(b) is a typical thrust force signal during drilling with a plane rake–faced twist drill whose reference rake angle at the outer corner of lips is 30°.

Comparing the plane rake–faced twist drill with common twist drill, it could be seen from Fig. 7(b) that the thrust force increased to a smaller value \( B_1 \) firstly, and then it steadily increased to peak value \( B_2 \) when the entire main cutting edge participated in drilling. However, when the chisel edge of a common twist drill participated in drilling, the thrust force increased to a larger value \( A_1 \). Then, the main cutting edge of a common twist drill gradually participated in drilling, the thrust force unsteadily increased to a larger peak value \( A_2 \). The reason for the different drilling process between the plane rake–faced twist drill and common twist drill was that reference rake angles of common twist drill along the main cutting edge changed. While, the reference rake angles of the plane rake–faced twist drill along the main cutting edge were constant. So, the thrust force curve of common twist drill fluctuated obviously and there was an inflection point, as shown in Fig. 7(a). However, the thrust force curve of the plane rake–faced twist drill was smooth. At the same time, the plane rake–faced twist drill had a smaller thrust force peak \( B_2 \) than common twist drill. There were two main reasons for this. On the one hand, the chisel edge (near the main cutting edge) could

| Parameters      | Values                  |
|-----------------|-------------------------|
| Laying          | [0°–45° 90° 45°]_SS     |
| Fiber density   | 1.81 g/cm³              |
| Fiber volume fraction | 65%                  |
| Thickness       | 6 mm                    |

Table 1  Carbon fiber–reinforced plastic
be eliminated through grinding. During this process, it did not reduce the actual length and change the rake angle of chisel edge, so it is usually called “point relieving.” This phenomenon had been proved to have a significant effect on reducing peak thrust force [14]. On the other hand, compared with a common twist drill, the plane rake–faced twist drill had a larger reference rake angle at the same position of the main cutting edge. The increase of reference rake angle could reduce thrust force, and it could also improve the cutting performance of the tool during drilling CFRP laminate with thin-woven glass fiber surface layer.

The average of thrust force when the main cutting edge was steadily drilling for each drill is shown in Fig. 8. For plane rake–faced twist drills with different reference rake angles, the thrust force and the thrust force decreasing amplitude are shown in Fig. 8. The decreasing amplitude is calculated by the following formula:

\[
Am_{n+1} = \frac{F_n - F_{n+1}}{F_n} \times 100% 
\]  

(10)

where \( Am_{n+1} \) represents the decreasing amplitude about thrust force of tool No.\( T_{Pn+1} \) compared to that of tool No.\( T_{Pn} \). \( F_n \) represents the thrust force value of tool No.\( T_{Pn} \). \( F_{n+1} \) represents the thrust force value of tool No.\( T_{P(n+1)} \), \( n=2...7 \).

The thrust forces of the common twist drill and plane rake–faced twist drill were analyzed when their reference rake angle at the outer corner of lips was 30°. It could be seen from Fig. 8 that the plane rake–faced twist drill had a smaller thrust force than the common twist drill, and the thrust force of plane rake–faced twist drill reduced by 34.3% compared to that of the common twist drill. It could be seen from Fig. 9 that the plane rake–faced twist drill had smaller push down delamination factor than the common twist drill with the same reference rake angle of the outer corner of lips. The main reason for the smaller push down delamination factor of the plane rake–faced twist drill was that its reduction of thrust force caused the decline of pushing effect. In addition, the cutting performance of main cutting edge was improved, which led to less drilling damage. It showed that the plane rake–faced twist drill had the characteristic of low drilling damage.

It could be seen from Fig. 8 that as the reference rake angle increased from 26° to 50°, the thrust force decreased from 115.53 to 55.62N. The decreasing amplitude of thrust force was 51.8%. It showed that the reference rake angle of the plane rake–faced twist drill affected thrust force significantly.

The decreasing amplitudes of thrust force about the plane rake–faced twist drills with different reference rake angle were calculated. It was found that the decreasing amplitude of thrust force gradually decreased with the increase of the reference rake. It could be seen from Fig. 8 that as the reference rake angle increases, the thrust force changed relatively smooth and the decreasing amplitude of thrust force reduces from 25 to 1%. It showed that the reduction of thrust force was more limited as the reference rake angle increased to a certain value. As shown in Fig. 9, as the reference rake angle increases, the push down delamination factor decreased significantly when the reference rake angle was not more than 46°. A small push down delamination factor was obtained when the reference rake angle was increased to 46°.
rake angle was 46°. When the reference rake angle was 50°, the reduction of push down delamination would be limited. In addition, the plane rake–faced twist drill with too large reference rake angle always has a risk of tool wear. It means that it is not necessary to blindly select tools with large reference rake angle in order to get small delamination damage.

| No. of drill | $\gamma_{\text{ref}}$ | Drill |
|--------------|-----------------|-------|
| $T_{C}$      | 30°             | ![Image](image1.jpg) |
| $T_{P1}$     | 26°             | ![Image](image2.jpg) |
| $T_{P2}$     | 30°             | ![Image](image3.jpg) |
| $T_{P3}$     | 34°             | ![Image](image4.jpg) |
| $T_{P4}$     | 38°             | ![Image](image5.jpg) |
| $T_{P5}$     | 42°             | ![Image](image6.jpg) |
| $T_{P6}$     | 46°             | ![Image](image7.jpg) |
| $T_{P7}$     | 50°             | ![Image](image8.jpg) |

Table 2  Geometric angles for plane rake–faced twist drills and common twist drill

4.2 Comparison of damage between common twist drill and plane rake–faced twist drill

In order to describe the damage around drilling entrance and exit more accurately, the entrance and exit was divided into 4 regions, each of them was corresponding to a quarter circle. The fiber cutting angle $\theta$ is defined as the angle between cutting speed direction and the fiber orientation of unidirectional carbon fiber layer near the thin-woven glass fiber layer, as shown in Fig. 10. At first, the four regions at entrance were numbered in Fig. 10(a), and the numbers of four regions at exit in Fig. 10(b) were corresponding to that in Fig. 10(a).
When the fiber cutting angle is $0^\circ < \theta < 90^\circ$, it is defined as along cutting region, such as regions I and III in Fig. 10(a). When the fiber cutting angle is $90^\circ < \theta < 180^\circ$, it is defined as against cutting region, such as regions II and IV in Fig. 10(a).

Table 3 shows the surface morphology of drilling entrance and exit of seven plane rake–faced twist drills and one common twist drill. The region division of drilling entrance and exit in Table 3 corresponds to that in Fig. 10. The $0^\circ$ fiber orientation in Table 3 is defined the fiber orientation of unidirectional CFRP layer near the thin-woven glass fiber layer. It could be seen from Table 3 that the burrs distribution at the drilling exit typically exhibited symmetrical regional characteristic on the hole periphery, which might be caused by the fiber orientation symmetry relatively to the hole center [18]. The direction of burrs existing at the drilling exit was the same as the fiber orientation of unidirectional CFRP layer near the thin-woven glass fiber layer, which was similar to the burrs distribution at the drilling exit when drilling unidirectional CFRP [19]. It showed that the damage of drilling exit and entrance in this paper was mainly affected by the unidirectional CFRP layer near the thin-woven glass fiber layer.

The plane rake–faced twist drill with $30^\circ$ reference rake angle was obtained by grinding the rake face of a common twist drill with $30^\circ$ reference rake angle at the outer corner of lips. At the outer corner of main cutting edge, the plane rake–faced twist drill and common twist drill had the same reference rake angle and geometries. Along the main cutting edge of common twist drill from drill bits center to its outer corner of lip, the reference rake angle gradually increased from a negative value to a positive value, and the contribution of thrust force generated by main cutting edge to total thrust force decreased. In particular, the thrust force generated by main cutting edge close to outer corner was negative, which was upward peeling force [20]. Compared with common twist drill, the plane rake–faced twist drill had a larger reference rake angle at the same position of the main cutting edge. Therefore, the entire main cutting edge of the plane rake–faced twist drill could generate larger peeling force than that of the common twist drill. At the same time, as the reference rake angle increases, the cutting performance of the entire
main cutting edge of the plane rake–faced twist drill will be improved.

As shown in Table 3 for drilling entrance, it could be seen that the plane rake–faced twist drill with 30° reference rake angle had smaller peeling delamination than of the common twist drill. The plane rake–faced twist drill had not only higher peeling force, but also excellent cutting behavior. The common twist drill had smaller peeling force, but it would result in worse damage at entrance than the plane rake–faced twist drill due to its bad cutting performance. It indicated that the peeling delamination of drilling entrance was not just affected by the peeling force of the entire main cutting edge, but by the cutting behavior of the entire main cutting edge. At the exit of drilling, it could be seen that the plane rake–faced twist drill had less overhanging burrs than common twist drill when the reference rake angle at the outer corner of lips was the same. In Fig. 9, it is further shown that the plane rake–faced twist drill caused less delamination damage of drilling exit than of the common twist drill. Therefore, it showed that when the reference rake angle at the outer corner

**Table 3** The hole entrance surface and hole exit surface drilled by seven plan rake–faced twist drills and one common twist drill

| No.of Drill | Entrance | Exit |
|-------------|----------|------|
| TC          | ![Image](TCEntrance.png) | ![Image](TCExit.png) |
| TP1         | ![Image](TP1Entrance.png) | ![Image](TP1Exit.png) |
| TP2         | ![Image](TP2Entrance.png) | ![Image](TP2Exit.png) |
| TP3         | ![Image](TP3Entrance.png) | ![Image](TP3Exit.png) |
| TP4         | ![Image](TP4Entrance.png) | ![Image](TP4Exit.png) |
| TP5         | ![Image](TP5Entrance.png) | ![Image](TP5Exit.png) |
| TP6         | ![Image](TP6Entrance.png) | ![Image](TP6Exit.png) |
| TP7         | ![Image](TP7Entrance.png) | ![Image](TP7Exit.png) |

Fig. 10 Definition of fiber cutting angle. **a** Entrance. **b** Exit
of lips was the same, the plane rake–faced twist drill could obtain smaller delamination damage of drilling entrance and exit of CFRP with a thin-woven glass fiber layer than of the common twist drill.

4.3 Damage mechanism analysis of different plane rake–faced twist drills

4.3.1 Entrance damage analysis

Figure 11 shows the micro morphology of typical drilling entrance about different plane rake–faced twist drills. As the reference rake angle of the plane rake–faced twist drill increases, the damage in along cutting region and against cutting region of entrance generally decreased. But when the reference rake angle was larger than 42°, the damage of drilling entrance in against cutting region increased as shown in Fig. 11(c), 11(e), and 11(g), and the damage reduction of drilling entrance in along cutting region was not significant as shown in Fig. 11(d), 11(f), and 11(h). When the reference rake angle was the same, the damage of against cutting region II was more serious than that of along cutting region III. Taking the entrance damage produced by the plane rake–faced twist drill with 26° reference rake angle as an example, the cavities caused by compression-induced stress in the against cutting region of entrance extended to the hole periphery longer than that caused by tensile-induced stress in along cutting region of entrance, seen Fig. 11 (a) and (b). The study of Wang et al. [23] believed that in terms of basic mechanical properties, the longitudinal tensile strength, transverse shear strength, and transverse compression strength of the fiber are always much higher than the bonding strength between the fiber and matrix. Therefore, in the along cutting region of drilling exit, the fiber/matrix interface debonding damage appeared under the pushing behavior of thrust force, resulting in the fibers of unidirectional CFRP layer near the thin-woven glass fiber layer became too soft. When the lowermost carbon fibers were cut by the main cutting edge, it could not provide great support in the against cutting region. It could not provide great support and circumferential cutting behavior at the drilling exit. Therefore, when the reference rake angle of the plane rake–faced twist drill was larger than 42°, the surface quality at entrance reduced owing to larger peeling force. Therefore, when the reference rake angles were larger than 42°, the surface quality at entrance was significantly affected by peeling force. In order to obtain best surface quality at entrance, it was recommended to use a plane rake–faced twist drill with a reference rake angle of 42°.

4.3.2 Exit damage analysis

As shown in Table 3, the overhanging burrs were existing in all the along cutting regions of drilling exits. However, the overhanging burrs only existed in the against cutting region of drilling exit when the reference rake angle of the plane rake–faced twist drill was 26° and 30°. With the increase of the reference rake angle of the plane rake–faced twist drill was larger than 46°, the overhanging burrs increased in the along cutting region of drilling exit. When the reference rake angle of the plane rake–faced twist drill was larger than 46°, the burrs increased in the along cutting region of drilling exit. The burrs also firstly decreased in the against cutting region of drilling exit with the increase of reference rake angle of the plane rake–faced twist drill. When the reference rake angle of the plane rake–faced twist drill increased to 38°, there was no burr damage in the against cutting region of drilling exit. When the reference rake angle of was 50°, the tiny burrs appeared. Therefore, it is recommended to use a plane rake–faced twist drill with 46° reference rake angle from the point of view of drilling exit burrs.

The existence of burrs was associated with axial pushing effect and circumferential cutting behavior at the drilling exit. Hintze et al. [22] pointed out that due to fibers or fiber bundles could repeatedly avoid the tool during its feed motion, thus the fibers or fiber bundles were bent either in the laminate plane or perpendicular to it. The fibers would not be broken if the bending did not reach its transverse fracture strength. Jia et al. [23] believed that in terms of basic mechanical properties, the longitudinal tensile strength, transverse shear strength, and transverse compression strength of the fiber are always much higher than the bonding strength between the fiber and matrix. Therefore, in the along cutting region of drilling exit, the fiber/matrix interface debonding damage appeared under the pushing behavior of thrust force, resulting in the fibers of unidirectional CFRP layer near the thin-woven glass fiber layer became too soft. When the lowermost carbon fibers were cut by the main cutting edge, it could not provide compressive shear stress, so the lowermost carbon fibers would suffer from large axial bending deformation under the continuous downward feed of the plane rake–faced twist drill. It would reduce the transverse cutting stress of fibers in the contact area, which would lead to less fibers break. Therefore,
the existence of burrs was greatly influenced by axial pushing in the along cutting region of drilling exit. Xu et al. [24] showed that the burr defect occurred in the against cutting region of drilling exit. It might attribute to that
the bending-dominated failure mode governed the chip separation in this region. In the against cutting region of drilling exit, the bending-dominated chip separation mode made the circumferential bending deformation of the lowermost carbon fiber more complex than that in the along cutting region. At the same time, the axial pushing made carbon fibers lose the support of matrix, causing the axial bending of lowermost carbon fibers. Under the combined action of axial bending and circumferential bending, the fibers would appear more serious bending deformation. In the against cutting region of drilling exit, the stress concentration mainly appeared at the maximum curvature point of fiber bending deformation below the cutting edge. When the bending stress of fibers reached the bending strength, bending fracture would happen. When the bending stress of fibers did not reach the bending strength, they were pressed below the clearance face of the drill until the drilling process was completed. It resulted that the fibers were not separated from workpiece and finally burrs were formed.

The axial pushing generated by drill existed along the whole hole circumference at the drilling exit. According to the research of Bonnet et al. [25], it showed that the drilling exit delamination damage was mainly concentrated in the along cutting region and the position near 0°/180° fiber cutting angle. The local thrust force in the along cutting region of drilling exit was larger than that in the against cutting region of drilling exit. It further made the axial pushing effect in the along cutting region of exit was larger compared to that in the against cutting region of drilling exit, which resulted in more serious burrs damage. Therefore, when the reference rake angle of the plane rake–faced twist drill were the same, the burrs distribution in the along cutting region of drilling exit was much more than that in the against cutting region of drilling exit.

As shown in Fig. 12, the against cutting region was divided into two situations, when the fiber cutting angle \( \theta \geq 90° + \gamma_n \), the rake face contacted with fibers firstly, then the fibers were bent and deformed through the action of rake face. Its crack extension was more complicated than that in the along cutting region of exit. When the drill continues to cut along the hole circumference, the pressure from rake face increased and then the tensile failure of fibers and compressive shear failure occurred. This situation was mainly based on the bending fracture of fibers. When the fiber cutting angle \( \theta < 90° + \gamma_n \), the cutting edge firstly contacted with fiber, and the compressive and shear extrusion fracture was generated in vertical fiber direction. The fibers were sheared off by cutting edge in local contact area and then the fractured fibers were pushed by the rake face along the circumferential cutting direction. Next, it moved outward along the fiber direction and then was separated from the material to form chips. This situation was mainly dominated by the compression shear fracture of fibers.

From Equation (3), it could be seen that the reference rake angle of the plane rake–faced twist drill was positively correlated with the normal rake angle. In the along cutting region, due to the fiber cutting angles \( \theta \) always satisfied \( \theta < 90° + \gamma_n \), so the increase of the reference rake angle did not change the shear-dominated fiber fracture mode. It was further showed that the reduction of damage in the along cutting region of drilling exit was mainly influenced by the reduction of thrust force, but not by the fiber fracture mode.

In the against cutting region of drilling exit, when the fiber cutting angle remained unchanged, the pushing along the circumferential cutting direction was decreased with the increase of normal rake angle \( \gamma_n \), as shown in Fig. 12. Before the bending stress of fibers reached bending strength, the cutting edge contacted with the fibers in local contact area to generate compressive shear load, which caused the shear failure of fibers. Therefore, the shearing effect of drill was enhanced and the bending effect was weakened when \( \theta < 90° + \gamma_n \) in the against cutting region. The cutting performance was getting better as the reference rake angle increases. In addition, the thrust force gradually decreased with the increase of the reference rake angle of plane rake–faced twist drill in the Fig. 8. Therefore, as the increase of the reference rake angle of the plane rake–faced twist drill, the damage in the against cutting region of drilling exit reduced by the combined action of thrust force and cutting performance. As shown in Fig. 13(a), 13(b), and 13(c), with the increase of the reference rake angle, the drilling quality at the position with the same fiber cutting angle in against cutting region II of drilling exit improved.

The plane rake–faced twist drill with 50° reference rake angle generated worse drilling quality compared to the plane rake–faced twist drill with 46° reference rake angle as shown in Fig. 13(c) and 13(d). At the same time, the burrs damage increased when the reference rake angle of plane rake–faced twist drill was larger than 46° as shown Table 3. It was due to serious tool wear of the plane rake–faced twist drill with 50° reference rake angle. The plane rake–faced twist drill with 50° reference rake angle could achieve the fiber shearing and chip disposal easily, but there was serious tool wear and edge chipping phenomenon as shown in Fig. 14. The serious tool wear would increase the main cutting edge radius of the planar rake.
rake–faced twist drill. With the increase of the cutting edge radius of the plane rake–faced twist drill, the fiber fracture mode for the fiber cutting angle $\theta < 90^\circ + \gamma_n$ would change from a shearing-dominated fiber fracture mode to the bending-dominated fiber fracture mode, leading to fiber deflect without being broken [26]. So, in order to obtain low damage at exit, it was recommended to use a plane rake–faced twist drill with a reference rake angle of 46°.

4.4 The effect of thin-woven surface on damage

The CFRP laminate surface was a thin-woven glass fibers layer. As shown in Fig. 4, the orientation of glass fibers in a woven surface was 0°/90°. Rahme et al. [17] proposed that added a woven glass fiber layer at the bottom of workpiece increased the critical thrust force and then decreased delamination.

Turki et al. [27] believed that the initial damage of the drilling entrance was mainly the fiber/matrix interface fracture and matrix fracture, resulting in the propagation of cracks over a larger distance. When the fibers were not cut, burrs and delamination were formed. In this paper, there was no burr damage at the drilling entrance, but just slight delamination was generated. It was attributed to the delamination inhibition given by the thin-woven glass fiber layer. In the against cutting region of drilling entrance, the 0° oriented carbon fibers on uppermost layer were subjected to upward force including peeling force and bending-induced stresses [28, 29]. As shown in the rectangular region of Fig. 15(a), the 90° oriented glass fibers in a woven layer suppressed the bending-induced

Fig. 13 Micro morphology at the exit surface of tool drilling hole. a 26° against fiber cutting region. b 42° against fiber cutting region. c 46° against fiber cutting region. d 50° against fiber cutting region

Fig. 14 Micro morphology of tipping about the plane rake–faced twist drill with 50° reference rake angle
force and peeling force of 0° oriented carbon fibers on the uppermost layer. When the stress generated by resultant force of bending-induced force and peeling force exceeded the shear strength of 90° oriented glass fibers, cracks continued to extend through the 90° oriented glass fibers. As shown in Fig. 15(b), in the along cutting region of drilling entrance, the 0° oriented carbon fiber on uppermost layer was only subjected to the peeling force. Therefore, in the along cutting region of drilling entrance, the shear strength of 90° oriented glass fibers in the woven layer was sufficient to only resist the upward stress generated by the peeling force of 0° oriented carbon fiber on the uppermost layer, which inhibited the peeling delamination. The thin-woven glass fiber layer on the surface of CFRP laminate had the inhibition effect on peeling delamination at drilling entrance.

The thin-woven glass fibers layer also had a certain degree of delamination suppression effect at the drilling exit. Figure 16(a) and 16(b) showed the drilling exit morphology about the plane rake–faced twist drill with 30° reference rake angle, which was corresponding to that in the entrance regions II and III shown in Fig. 15. As shown in Fig. 16(a), the propagating distance of cracks along the lowermost layer of 0° carbon fiber orientation was longer than the cracks along the uppermost layer of 0° carbon fiber orientation in Fig. 15(a). Like the entrance, the bending-induced stress also existed in the against cutting region of drilling exit. In addition, there was a large axial pushing at the drilling exit. In the against cutting region of drilling exit, the 90° oriented glass fiber was difficult to inhibit the propagation of cracks along the lowermost layer of 0° carbon fiber orientation due to the existence of bending-induced force and thrust force. Compared to the along cutting region of drilling entrance, the thrust force in the along cutting region of drilling exit was much bigger than the peeling force. As shown in Fig. 15(b) and 16(b), the cracks propagating distance of the drilling exit was longer than that of the drilling entrance. Therefore, the glass fiber in the thin-woven layer only had a certain inhibition effect on push down delamination at the drilling exit.

5 Conclusions

In this paper, one common twist drill and seven plane rake–faced twist drills with different reference rake angle were used to drill CFRP with a thin-woven glass fiber layer. The characteristic of low drilling damage with the plane rake–faced twist drill compared with the common twist drill was studied. In addition, the effect of the plane rake–faced twist drills with a different reference rake angle, and the thin-woven glass fiber surface on the drilling quality of drilling entrance and exit of CFRP laminate with the thin-woven glass fiber surface layer were also studied. Some conclusions can be drawn.
The addition of a thin-woven glass fiber layer on the plane rake–faced twist drill could generate smaller thrust force. Due to the constant value of the reference rake angle of plane rake–faced twist drill, the increase of thrust force was more stable when the main cutting edge was gradually drilled into the drilling entrance. The thrust force decreased with the increase of reference rake angles, but when the reference rake angles increased from 46° to 50°, the decreasing amplitude of thrust force was only 1%. Therefore, the reduction of thrust force was limited when the reference rake angle of plane rake–faced twist drill increased to a larger value.

The drilling entrance damage produced by plane rake–faced twist drill and common twist drill at the same reference rake angle at the outer corner of lips were compared. It was revealed that the drilling entrance damage was not just influenced by the peeling force of the entire cutting edge, also by the cutting behavior of the entire cutting edge. The drilling entrance damage produced by plane rake–faced twist drill was less than that of the common twist drill. Compared the push down delamination factor of drilling exit, it showed that the push down delamination factor generated by a plane rake–faced twist drill was smaller than that generated by the common twist drill. Therefore, the plane rake–faced twist drill had the characteristic of low drilling damage compared to common twist drill.

When the plane rake–faced twist drill was used to drill CFRP with a thin-woven glass fiber layer, the drilling surface quality at the entrance was influenced by the combination of cutting behavior and peeling force. When the reference rake angle of plane rake faced twist drill was 42°, the best surface quality of drilling entrance was achieved. The damage in the along cutting regions and against cutting region at drilling exit reduced by the combined action of thrust force and cutting performance, and the best drilling quality at exit was achieved when the reference rake angle was 46°.

The addition of a thin-woven glass fiber layer on the CFRP laminate surface could inhibit the peeling delamination well at drilling entrance, and it could also have a certain inhibiting effect on push down delamination at drilling exit.

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Declarations

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