In this paper, a complex helicoids’ drill tip of “S” type chisel edge grinded with a three-parallel universal CNC grinding machine tool is carefully studied to obtain the optimum drill bit tip geometry parameters. The effects of experimental parameters, such as apex angle, chisel edge incline angle, and structure circumference rear angle, on the quality of the drilling hole and the machining force were studied from the orthogonal experiment compared with the ordinary drill bit. The range of technological parameters are confirmed which should be used during the drilling process of carbon fiber reinforced plastics (CFRP) in order to realize the reduction of cutting defects such as cutting force and spurs. The effect of spindle speed and feed on the drilling behaviour of the experiment using optimum complex helicoids’ drill tip is also analyzed. It is found that the feed has a great influence on the drilling axial force and the spindle speed has little influence on axial force, but great influence on torque.

1. Introduction

Carbon fiber reinforced plastics (CFRP) are characterized by lightweight, stiffness-to-weight ratios, high fracture toughness, and good heat resistance [1]. They have been widely used in airplanes, chemical machinery, communication, transportation, sport equipment, and textweave. However, there are many questions in drilling CFRP because of the most frequent defects, including delamination, fiber pull-out, interlaminar cracks, and thermal degradation after the drilling process. Drilling is the most commonly applied method in conventional machining, accounting for as much as 40% of all material removal processes. So drilling of CFRP has been taken as an important subject in the research field of machining. Due to heterogeneity and anisotropy of CFRP, the drilling principle is different from that in metal drilling. The drilling process of metal materials is mainly dominant by elastic-plastic deformation. The continuous drilling chip in metal materials’ machining cannot be formed in the CFRP process. König et al. [2] carried out experimental research on CFRP drilling in 1985 and concluded that excessively high feed rate during drilling would lead to defects such as delamination tearing at the drilling outlet. Chambers and Bishop [3] studied the drilling parameters of carbon fiber composites in 1995 and concluded that the drilling quality during CFRP drilling was mainly related to the properties of the matrix and the overall performance of the PCD tool. Chen [4] in 1997, by adopting different apex angles, chisel edge angles, and spiral angles of the drill point, conducted the drilling experiment of carbon fiber composite materials. They analyzed the effect of different drill tip geometry parameters on the drilling force and tear. Xu et al. [5] studied the CFRP material machining in terms of wear behavior and machining responses. Rawal et al. [6] detected the milling defects on CFRP structures using the sensor-based online quality monitoring system. Kumar and Verma [7] optimized the multiple response in machining (milling) of graphene oxide-doped EPOXY/CFRP composite using COCOSO-PCA. Furuki et al. [8] developed CBN electroplated end-mill combined cutting and grinding for precision machining of...
CFRP. Piquet et al. [9] analyzed the drilling damage in the thin carbon/epoxy laminate using special drills. Yuan et al. [10] investigated the grinding of carbon/epoxy composites using the electroplated CBN wheel with controlled abrasive clusters. Lin and Chen [11] explored the drilling process of the carbon fiber reinforced composite material at high speed. Wang et al. [12, 13] conducted the right-angle free cutting experiment of the one-way type and multiway type CFRP. The relation between the shear force and cutting force of the carbon fiber and resin matrix is obtained when the cutting speed direction and carbon fiber direction angle are in a certain range. Arola et al. [14, 15] used a CCD camera to observe the cutting process of CFRP and FRP composites, and the final observation results showed that the angle between the rake angle of the main cutting edge of the drill tip and the fiber direction had a great influence on the chip formation process during the cutting of fiber reinforced composites. Mihaï and Paul [16] analyzed the drilling process of fiber reinforced composites. Vijayan analyzed the influence of drilling parameters on the quality of the hole data acquisition card, data processing software FAS-4D-3, amplifier, analog/digital conversion board, special cable, instrument (Figure 3), FS-21/4A (four-channel) DC strain amplifier, analog/digital conversion board, special cable, data acquisition card, data processing software FAS-4D-3, and computer. The main purpose of this study is to find the increased by the joint action of the cutting edge and twist drill rake face, which has the effect of stripping the fiber layer upward during drilling CFRP. The effect on the inlet side of the drilled hole is particularly obvious, and the tear at the inlet side is mainly caused by $F_{z1}$. In the main cutting edge of the negative rake angle and chisel edge area, the cutting situation is worse, especially in the chisel edge; in this part, the linear velocity is low, the role of which is to roll up and smash the carbon fiber to chip, and the effect of this part of the structure on the CFRP in the drilling process mainly contains two parts of force, one is tangential force $F_{v2}$ along the tangent direction and the other is downward vertical axial force $F_{z2}$; these force components in the process of drilling accounted for 50%–60% of total axial force [19], to which both delamination and outlet tearing during drilling CFRP are directly related.

The base material of the CFRP laminates used in the experiment is epoxy resin, and the reinforcing material is carbon fiber, which is made of multidirectional braided prepreg cloth laid in layers. The specific conditions of the CFRP laminates are shown in Table 1.

The CFRP is a braided composite material, which is composed of multilayer 0°/90° interwoven prepreg cloth laid layer by layer. The tool adopted is an ordinary high-speed steel drill bit produced by Haliang Cutting Tool Factory (China); the complex helical surface grinding method is used to grind the drill tip. The drill tip grinding machine is a three-parallel universal joint CNC grinding machine independently developed by Northeastern University (China). It is equipped with control system PCI-1234U, as shown in Figure 2. This machine tool can theoretically grind the complex helicoid drilling point of any parameter.

The drilling experimental platform is composed of a drilling test bed and a drilling force measurement system. The drilling test bench (Figure 3) is a Z3040 radial drilling machine, whose maximum speed is 2000 r/min and feed is 0.04–3.2 mm/r. The drilling force measuring system is composed of SDC series precision drilling force measuring instrument (Figure 3), FS-21/4A (four-channel) DC strain amplifier, analog/digital conversion board, special cable, data acquisition card, data processing software FAS-4D-3, and computer. The main purpose of this study is to find the...
3. Experimental Results and Analysis of Drill Tip Geometric Parameters

Under the process parameters of speed \( n = 800 \text{ r/min} \) and feed \( f = 0.04 \text{ mm/r} \), drill tips with different geometrical parameters were used to carry out single-factor drilling comparison experiments.

Table 1: The properties of CFRP.

| Reinforcing material | Carbon fiber |
|----------------------|--------------|
| **Base material**    | Epoxy        |
| **Layer form**       | 0°/90° weaving prepreg cloth |
| **Fiber volume fraction (%)** | 60 |
| **Thickness (mm)**   | 5            |
| **Length (mm)**      | 400          |
| **Width (mm)**       | 400          |

3.1. Influence of Drill Apex Angle on Drilling Force and Tear.

With the standard twist drill apex angle 118° as the reference, 100°, 110°, 115°, 120°, 125°, 130°, 140°, and 150° were selected as the apex angle value, respectively, the rear angle value is 10°, and the chisel edge incline angle value for grinding is 60°. The grinding drill bit shape is shown in Figure 4.

The apex angle of the drill tip is mainly determined by the angle between the grinding wheel axis and the drill tip axis. Under the condition that the process parameters are the spindle speed of 800 r/min and the feed rate of 0.04 mm/r, eight drill bits with different vertices are used for drilling, respectively. Figure 5 shows the pictures of the hole inlet and outlet after drilling with several bits.

From Figure 6, it can be seen that the change of the size of the apex angle has a significant influence on the tearing at the inlet and outlet. On the inlet side, the tear defects are relatively small, and the tear factor decreases first and then increases with the increase of the apex angle, and the minimum is near the apex angle 130°. The main reason is that, with the increment of the apex angle, drilling axial force also increase, which, thus, would enhance the extrusion of the fiber layer. However, at the same time, the rake angle of the drill bit main cutting edge also increases; then, the cutting edge becomes sharper, and the carbon fiber can be instantaneously cut off, which can reduce the inlet tear. On the outlet side, it can be clearly seen that the tear defect is larger than that in the inlet side, and the influence of the apex angle on the outlet side is also greater than that on the inlet side. However, the change behavior of the total defect is similar to that on the inlet side. The tear factor also decreases first, then increases with the increase of the apex angle, and reaches the minimum near the apex angle 125°. This is because that, with the decrease of the apex angle, the axial force is reduced. The rake angle of the main cutting edge is correspondingly decreased, and the drilling cutting edge is not sharp. Consequently, the carbon fiber cannot be instantaneously cut off. With the increase of the apex angle, although the main cutting edge rake angle increased, the cutting edges became sharper. And, the cutting edge of concave shape would cut off the carbon fiber easily, but the increase of the apex angle makes drilling axial force increase.

The push effect of the drill tip to the outlet of the raw fiber layer is very severe, which causes the fierce outlet side tear. Figure 7 shows the behaviour of the influence of the apex angle of the drill tip on the drilling axial force and torque in the case of the structure’s circumferential rear angle \( a_{fc} = 10° \) and chisel edge incline angle \( \psi = 60° \). As can be seen from the above relationship graph, when the drill point structural circumferential rear angle and chisel edge bevel angle are constant, with the increase of the drill apex angle, axial force has been increased in the approximately linear form; the main reason is that, with the increment of the apex angle, the rake angle and rear angle of the drill tip chisel edge are less, while drilling axial force is mainly concentrated on the chisel edge; as both the chisel edge bevel angles decrease, the scraping extrusion effect of the drilling chisel edge on the material becomes more severe, which will lead to the increase of axial force.

It also can be seen that, with the increment of the apex angle, the torque is decreased. The reason is that, with the increment of the apex angle, the length of the main cutting edge decreases; under the same processing parameters, the material to be cut by the drill bit per processing round is...
reduced; at the same time, along with the rising of the apex angle, the main cutting edge of the rake angle increases; the cutting edges is sharper, which reduces the drilling torque. By analyzing the apex angle on the inlet and outlet, the influence of drilling force, considering the effect of the inlet tear, is significantly less than the tear of outlet, so it is needed to consider the quality of the outlet when choosing the best apex angle; at the same time, considering the strength of the drill tip, on the premise of guaranteeing the quality of drilling, the larger apex angle is chosen; this drill bit is of high intensity and longer life. The best apex angle value is chosen as 125°.

3.2. Influence of Chisel Edge Bevel Angle of Drill Tip on Drilling Force and Tear. The chisel edge bevel angle is a geometric parameter that is sensitive to the grinding parameters. 50°, 60°, 70°, and 80° are, respectively, taken as the chisel edge bevel angle; 125° is selected as the apex angle value, and 10° is selected as the structure circumferential rear angle for grinding. The grinding drill bit shape is shown in Figure 8. Figure 9 shows some pictures of the hole inlets and outlets after the drill bits have been drilled.

Figure 10 shows the curve of the influence of the chisel edge angle of the drill tip on the tear factor at the outlet and inlet in the case of the apex angle $\psi = 125^\circ$ and the structure circumference rear angle $a_{fc} = 10^\circ$. Clearly, with the increase of the chisel edge angle, the outlet and inlet of tear factor increase with the decrease firstly and then increase; the main reason is that, with the increase of the chisel edge angle, the horizontal angle of cutting edge and chisel edge angle are also increased, which makes the chisel edge sharper; the extrusion effect of the chisel edge to the processed materials is reduced, but the horizontal blade angle is too small, which will cause the chisel edge too long; then, the drilling axial force increases, which is not helpful for the drilling of CFRP. Figure 11 is the curve of the influence of the chisel edge incline angle of the drill tip on the drilling axial force and

![Figure 4: The shape of blade-grounded drills. (a) $\psi = 100^\circ$. (b) $\psi = 110^\circ$. (c) $\psi = 115^\circ$. (d) $\psi = 120^\circ$. (e) $\psi = 125^\circ$. (f) $\psi = 130^\circ$. (g) $\psi = 140^\circ$. (h) $\psi = 150^\circ$.](image-url)
torque in the case of the apex angle $2\phi = 125^\circ$ and the structural circumferential rear angle $\alpha_{fc} = 10^\circ$. As can be seen from the above relationship graph, under the condition that the drill structural circumferential rear angle and chisel edge angle are constant, with the increase of the drilling chisel edge angle, drilling axial force increases gradually; this is mainly because that, with the increase of the chisel edge angle, the rake angle and rear angle of the chisel edge are reduced; when the chisel edge wedges into the workpiece, it does not become sharp; although the chisel edge at the same time gets shorter, but it would not make influence as big as the former one, so the tendency of the axial force increases.

For torque, it can be seen that, with the increase of the chisel edge angle, drilling torque is gradually reduced; this is mainly because with the increase of the chisel edge angle, the chisel edge gets shorter; although the chisel edge is less sharper than it was when the chisel edge incline angle was smaller, the scraping extrusion effect on the material during the drilling process would increase, so the torque would present a decreasing trend, but because the chisel edge is very short, the corresponding torque is small, so there is less influence to the overall torque of the drill tip. By analyzing the influence of different chisel edge incline angles on the hole inlet, outlet, and drilling force and comprehensively...
considering the influence of the chisel edge bevel angle on the axial force and the hole inlet and outlet, the optimal chisel edge bevel angle is determined to be $60^\circ$.

3.3. Influence of the Circumferential Rear Angle of the Drill Tip Structure on Drilling Force and Tearing. $5^\circ$, $10^\circ$, and $15^\circ$ were selected as the structure circumferential rear angle, $125^\circ$ as the apex angle value, and $60^\circ$ as the chisel edge bevel angle value for grinding, and the grinding parameters and the shape of the grinding drill bit are shown in Figure 12.

Figure 13 is a picture of the hole inlet and outlet after several drill bits have been drilled.

Figure 14 shows the influence curve of the size of the circumferential rear angle of the drilling tip structure on the tear factor at the inlet in the case of apex angle $2\phi = 125^\circ$ and chisel edge bevel angle $\psi = 60^\circ$. Due to the drill tip structure circumferential rear angle, the apex angle and chisel edge bevel angle are different; their change will only affect the sharp degree of the cutting edges and will not impact other parameters of the drill tip; therefore, it can be seen from the diagram, along with the rising of the drill point structural circumferential rear angle, the tear factor of inlet and outlet has been reduced; this is mainly because the main cutting edge becomes more sharp, and the cutting off effect of carbon fiber is enhanced. However, at the structure’s circumference rear angle, the tearing at the outlet appeared abnormal, which was mainly due to the fact that the drill material used in the experiment was high-speed steel, and the main cutting edge wore too fast when drilling CFRP, and the main cutting edge of the drill tip became blunt before a hole was finished. Figure 15 shows the curve of the influence of the size of the circumferential rear angle of the drilling tip structure on the drilling force in the case of apex angle $2\phi = 125^\circ$ and chisel edge bevel angle $\psi = 60^\circ$. It can be seen clearly from the figure that along with the increasing of the drill point structural circumferential rear angle, the drilling torque and axial force are reduced; this is mainly because of the increase of the structure circumferential rear angle which leads to the main cutting edge becoming more sharp; in the drilling of carbon fiber, the cut off effect is enhanced. The drilling torque is mainly focused on the main cutting edge, and axial force is mainly concentrated on the chisel edge, so the effect of the structure circumferential rear angle on torque is greater than the chisel edge angle. Through the above analysis, it is found that, with the increase of the circumference rear angle of the structure, both the tearing and drilling force at the inlet and outlet of the drilling hole are decreased. Therefore, the circumference rear angle of the structure should be larger, but this will lead to the wear of the main cutting edge of the drilling tip too fast. After comprehensive consideration, the optimal structure circumference rear angle is set as $10^\circ$.

3.4. Comparison between the Best Geometric Parameters of Grinding Drill Tips with Ordinary Drill Tips. According to the best geometrical parameters determined in the above sections, the edge grinding bit with apex angle $2\phi = 125^\circ$, rear angle $\alpha = 10^\circ$, and chisel edge bevel angle $\psi = 60^\circ$ is used to conduct the drilling experiment on comparison with the standard high-speed steel twist drill. Under the condition of the spindle speed of 800 r/min and the feed of 0.04 mm/r, two tools were used to drill, and the axial force and machining quality were compared.

It can be seen from Table 2 that, under the same process parameters, the axial force of the complex helicoidal drill tip with the best geometric parameters is 28% lower than that of the ordinary twist drill. Figure 16 shows the inlet and outlet of the hole drilled using a complex helicoidal drill point with the best geometry and an ordinary drill bit.

It can be clearly seen from the above figure that, under the same process parameters, the drilling quality of the drill bit sharpened by the helicoid drill tip sharpening method is significantly better than that of the ordinary drill bit during the drilling processing of CFRP.

3.5. Improvement of Drill Tip Structure. The best drill bit tip geometry parameters of the complex helicoid drill bit to machining CFRP is obtained through the above experiment. With the optimal geometric parameters of the complex helical drill bit in drilling CFRP laminated plates, good effect can be achieved, but a closer examination at the hole outlet reveals that there is a slight tear. Therefore, the drill tip is partially improved. In the process of drill grinding, the complex helicoidal drill tips are double-edge sharpened according to the characteristics of Bickford drill tips [20]. The sharpened drill tips are shown in Figure 17.

The effect comparison after drilling is shown in Figure 18.

It can be seen from Figure 18 that the drilling effect of the double edge drill bit at the outlet is better than the drill tip of the single edge. This is because there is a relatively sharp angle at the connecting area between the main cutting edges; therefore, it is easy to squeeze out scraps with burr generated. However, the drill tip of the double edge angle is shaped through secondary grinding, which makes the connecting angle between the main cutting edge and edge area become bigger, which can effectively reduce the burr at the export; at the same time, due...
to the main cutting edge of the double edge angle of the drill tip becoming longer, the load on unit cutting length in the case of the double edge angle tool tip is smaller than that of the single edge angle tool tip. This is because the main cutting edge of the double edge tool tip becomes longer. In addition, drilling heat is less which is helpful for drill tip cooling.
Because the chisel edge rake angle of the complex helical surface drill tip grinded by the flat grinding wheel is still small, basically it is the same as the normal drill tip, the shaped grinding wheel of the circular arc angle edge is adopted to grind the drill tip in order to reduce the chisel edge angle of the drill tip and increase the rake angle. This would make the chisel edge more sharp during the drilling process. In addition, the extrusion of the chisel edge to the CFRP is decreased; therefore, the tear generated by the chisel edge is decreased. The sharpened drill tip is shown in Figure 19, and Figure 20 is the comparison of the effect after drilling.

The effect comparison after drilling is shown in Figure 20.

4. Experimental Study on Drilling Process Parameters

Both the geometric parameters of the drill tip and the experimental parameters during drilling have a great influence on the quality of the CFRP hole. It is of great significance to select the appropriate experimental parameters for the quality of the hole and the life of the tool. Hereby,
experimental process and results are introduced and analyzed, and the influence of process parameters on drilling force and drilling quality is obtained. On this basis, the regression analysis of drilling force and the observation of drilling surface quality are carried out. The material used in the experiment is CFRP. The experiment tool adopts the carbide twist drill with diameter $\phi 6$, and other experimental equipment is the same as the equipment used aforementioned.

The main purpose of this experiment is to study the effect of drilling process parameters on CFRP drilling quality and determine the process range that should be taken in processing CFRP laminates by analyzing the influence of drilling process parameters on hole quality. In the drilling process, the parameters affecting the drilling quality are the spindle speed and feed per rotation. The influence of feed per rotation is bigger than that of the spindle speed. In the selection of the experimental parameters, the spindle speed range is wider. The feed per rotation is set relatively small. So it can comprehensively reflect the effect of spindle rotation and feed per rotation on drilling force and machining quality. The number of experimental groups was designed according to the orthogonal experimental table $L_{16}(4^2 \times 2^3)$, and a total of 16 groups of experiments were carried out. The spindle speed was selected as 500 r/min, 800 r/min, 1250 r/min, and 2000 r/min. The feed per revolution during drilling was selected as 0.04 mm/r, 0.06 mm/r, 0.1 mm/r, and 0.13 mm/r. The experimental parameters are shown in Table 3.

The grinding edge parameters of the cemented carbide twist drill are the optimal geometric parameters ($2\phi_0 = 125^\circ$, structure circumferential rear angle $a_{fc} = 10^\circ$, and chisel edge incline angle $\psi = 60^\circ$) obtained in the previous part. The data collection is still taken the average value when the drilling process reaches a steady state. The average value of two drilling holes drilled under each process parameter and the orthogonal experimental results are shown in Table 4.

It can be clearly seen from the results in the table that axial force and torque vary greatly under different process parameters, and it is found that the increase of feed and the decrease of rotation speed will increase the axial force and torque.

4.1. Analysis of Drilling Force. Drilling force is one of the most important phenomena produced in the process of drilling, and drilling force can be used as an important evaluation parameter of drilling parameters. The influence of process parameters on drilling force is analyzed, which is helpful to the selection of process parameters. Figures 21 and 22 show the change curves of drilling force corresponding to different feed rates when drilling CFRP with twist drill. It is easy to see that both axial force and torque increase with the increase of the feed rate when drilling CFRP. This is because the greater the feed, the greater the area of the fiber layer cut by the drill tip and the greater the axial force and torque. On the contrary, the larger the area of the fiber layer cut by the drill tip, the smaller the deformation of the fiber layer, which will reduce the drilling force to some extent, but this is only an indirect effect. From the general trend, the axial force and torque increase with the increase of the feed.

It can be seen from Figures 21 and 22 that, with the increase of rotational speed, cutting force has a tendency of decreasing; this is mainly due to the fact that, with the increase of rotational speed, the extrusion deformation of the carbon fiber layer will decrease. The carbon fiber can cut off in an instant, and it will reduce drilling force. However, the influence of the rotational speed on drilling
Figure 16: Comparison of two drills. (a) By ordinary drill tip. (b) By complex helicoidal drill.

Figure 17: Double point angle drill.

Figure 18: Outlet quality comparison. (a) Original sets. (b) Improved sets.

Figure 19: The improved drill.

Figure 20: Comparison of two holes. (a) Original sets. (b) Improved sets.
force is small, much smaller than the influence of feeding. It can be seen by force curves, in the process parameters, the effect of feed per rotation on the axial force is relatively significant, which is almost proportional. The effect of the spindle speed on the torque is large. The method of regression analysis was adopted to fit the experience formula of the axial force and torque. According to the commonly used experience formula [22] for drilling axial force and torque, the fitting of the exponential form was carried out. Firstly, the original form of the drilling axial force and torque equation is set as

\[ F = C_F \cdot n^{X_F} \cdot f^{Y_F}, \]

\[ M = C_M \cdot n^{X_M} \cdot f^{Y_M}, \]

where \( F \) is the axial force, \( M \) is the torque, \( n \) represents the spindle speed, \( f \) represents feed per rotation, \( C_F \) and \( C_M \) are the parameters relative to the nature of the processed material itself and drilling conditions, and \( X_F, X_M, Y_F, \) and \( Y_M \) are the feed and the index of the rotation speed, respectively. It should be emphasized that, since drill bits of the same diameter were used in this experiment, the influence of

| Table 3: The parameter of the orthogonal array. |
|------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| \( n \) (r/min) | 500 | 800 | 1250 | 2000 | 500 | 800 | 1250 | 2000 | 500 | 800 | 1250 | 2000 |
| \( F \) (mm/r)  | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.06 | 0.06 | 0.06 | 0.1 | 0.1 | 0.1 | 0.1 |

| Table 4: The measurement data of the orthogonal experiment. |
|------------------|------------------|------------------|------------------|
| Feed rate (mm/r) | Spindle speed (r/min) | Axial force \( F_z \) (N) | Torque \( M \) (N·m) |
| 0.04             | 500              | 52.83            | 0.15            |
| 0.04             | 500              | 60.52            | 0.13            |
| 0.04             | 500              | 66.63            | 0.11            |
| 0.04             | 500              | 72.43            | 0.10            |
| 0.06             | 800              | 94.82            | 0.20            |
| 0.06             | 800              | 111.01           | 0.17            |
| 0.06             | 800              | 120.11           | 0.15            |
| 0.06             | 800              | 129.63           | 0.13            |
| 0.1              | 1250             | 114.21           | 0.26            |
| 0.1              | 1250             | 130.23           | 0.23            |
| 0.1              | 1250             | 144.35           | 0.20            |
| 0.1              | 1250             | 156.09           | 0.18            |
| 0.13             | 2000             | 125.41           | 0.35            |
| 0.13             | 2000             | 144.12           | 0.31            |
| 0.13             | 2000             | 157.81           | 0.28            |
| 0.13             | 2000             | 171.19           | 0.24            |

Figure 21: Axial force at the varying experimental parameter.
the drill bit diameter on axial force and torque was not considered in the calculation of the empirical formula. The fitting results are shown in Table 5.

In order to verify the empirical formula obtained, the formula is tested using the $F$ method, which is to test the significance of the equation directly from the empirical formula results according to the square sum decomposition formula. After analysis, it can be obtained as follows: $F_{\text{feed-axialforce}} = 0.013$, $F_{\text{speed-axialforce}} = 21.553$, $F_{\text{speed-torque}} = 4.645$, and $F_{\text{feed-torque}} = 0.418$. After looking up the $F$ distribution table, it can be obtained as follows: $F_{0.1}(3, 15) = 21.553$, $F_{0.05}(3, 15) = 3.29$, and $F_{0.01}(3, 15) = 5.42$. Then, $F_{\text{feed-axialforce}} > F_{0.1}(3, 15)$ and $F_{0.05}(3, 15) < F_{\text{speed-torque}} < F_{0.01}(3, 15)$. It is found that the feed has a highly significant influence on the axial force, while the axial force change caused by the spindle speed is very small. Spindle speed has a significant effect on the torque, and the change of torque caused by the feed is small.

4.2. Influence of Process Parameters on Hole Inlet/Outlet Tearing. Figure 23 shows the influence curve of rotating speed and feed rate on the tear factor at the drilling hole inlet when drilling CFRP with complex helicoidal drill tips. As can be seen from the change of the curve in the figure, when the speed $n$ is constant, the tear factor at the hole inlet increases with the increase of the feed $f$; when the feed $f$ is constant, the tear factor at the hole inlet tends to decrease with the increase of the speed $n$, but the influence of the speed $n$ on the tear at the inlet is significantly smaller than that of the feed $f$. It can be concluded that the small feed or high speed can ensure the quality of the drilling hole inlet. Figure 24 shows the influence curve of rotating speed and feed rate on the tear factor at the outlet of the drill hole when drilling CFRP with complex helicoidal drill tips. It can be seen clearly that the influence of speed and feed on the hole outlet tear is bigger than that on the inlet, when the rotational speed $n$ is constant; with the increase of feeding $f$, the tear factors at the outlet also increase with a fast growing speed. This is mainly due to the fact that the increase of feed has caused the rapid increase of axial force, leading to tear at the outlet. When the feed rate is constant, with the increase of speed $n$, the outlet tear is decreasing, but the decreasing trend is not obvious, which is far less than the effect of the feed rate on the tear. Through the above analysis, it is concluded that when drilling CFRP, it is necessary to ensure a small feed and a high speed in order to get a high-quality drill hole.

4.3. Fiber Fracture Morphology and Microstructure of Cutting Surface. After the CFRP hole was processed, the surface of the CFRP hole was observed by a variable focus optical microscope, and the microstructure of the hole surface, the fracture morphology, and the failure mechanism of carbon fiber were analyzed. Considering that this test material is a bidirectional woven carbon fiber laminate, the two sides of the holes are symmetrical, so only one quarter of the hole surface is observed to obtain a complete picture of the entire hole surface. Because the adjustable range of lens of the microscope is limited, in order to conveniently and efficiently observe the specimen hole wall surface, the size of the sample must be limited in a certain range, so before observation, the drilling hole is cut into small pieces, which needs to be cleaned before observation. Figure 25 shows the observed samples.

Table 5: The fitting results of axial force and torque.

| Fitting variable | Value | Correlation coefficient | Error (%) |
|------------------|-------|-------------------------|-----------|
| $C_F$            | 190.331 | —                       | —         |
| $X_F$            | 0.022  | 85.1                    | 3.2       |
| $Y_F$            | 0.398  | 100                     | —         |
| $C_M$            | 7.693  | —                       | —         |
| $X_M$            | 0.465  | 100                     | 16.3      |
| $Y_M$            | 0.261  | 99.7                    | —         |
Figure 26 shows the morphology of the inner wall of the hole observed by the microscope. In this case, the process parameters are the rotational speed $n = 2000 \text{ r/min}$ and the feed speed $f = 0.04 \text{ mm/r}$. Due to the high-speed rotation of the drill bit, the resin matrix of the cutting part was daubed on the machined surface. The resin-coated part of the hole wall looks very smooth due to the fact that the fiber fracture was wrapped, while the part without being resin-coated looks rough because its surface composition is fiber fracture and resin matrix of the fiber layer. The outlet and inlet of the hole are relatively less resin coated, so the rough part is more. It can be also found from the observation of the hole wall surface that the roughness in different location holes is also not identical. The main reason is that the fiber fracture forms are different.

Figure 27 shows the hole wall morphology at several typical angles under high magnification, in which Figure 27(a) shows the hole wall morphology when the angle between the fiber direction and the cutting direction is 0° and 90°, Figure 27(b) shows the hole wall morphology when the angle between the fiber direction and the cutting direction is 45°, and Figure 27(c) shows the hole wall morphology when the angle between the fiber direction and the cutting direction is 135°. When the intersection angle is 0°, because the separation deformation between layers occurs here, most fibers are not cut off, and the hole wall is very smooth. When the intersection angle is 90°, the fibers are all cut off from the root by the cutting edge, and the exposed part of the fracture is very little, which looks smooth in the overall topography. When the intersection angle is 45°, the fracture part is longer than that of the direction of 90°, but the fracture is neat, and the quality is good in the overall topography. However, when the intersection angle is 135°, because the cutting form here is bending shear, the exposed part of the fracture is uneven and looks very rough on the hole wall. This also reveals that when the angle between the fiber direction and the cutting direction is between 0° and 90°, the cutting mode belongs to “straight cutting,” and the surface quality after drilling is smooth. When the fiber direction is between 90° and 180°, the cutting mode belongs to “inverse cutting,” and the surface quality after drilling is rough [23].
5. Conclusion

This work mainly focuses on the drilling experiment of CFRP using the complex helicoid drill tip. The preliminary conclusions can be drawn as follows:

1. Under the same process parameters, the best geometrical parameters of the complex helical surface drill tip for CFRP laminates are the apex angle $2\phi = 125^\circ$, chisel edge bevel angle $\psi = 60^\circ$, and circumferential rear angle $\psi = 60^\circ$. The complex helical surface drill tip with the best geometrical parameters can achieve a good effect during the drilling process of CFRP laminates compared with the ordinary drill bit.

2. By using the same geometrical parameters of the drill tip at different speeds and feeds, it is found that the feed has a great influence on the drilling axial force, and the drilling of CFRP has a great influence on the tearing at the outlet. The spindle speed has little influence on the axial force, but great influence on torque.

3. The drilling hole wall of CFRP is mainly composed of the resin matrix coating part and the fiber fracture part, and the hole wall surface in the “procut” area is smooth, while the hole wall surface in the “anticut” area is rough.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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