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Study on the influence of fiber cutting angle on cutting force in ultrasonic assisted cutting CFRP disc

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Abstract

Carbon fiber reinforced plastics (CFRP) is a new type of composite material that is widely used in the aviation field, the influence mechanism of fiber cutting angle on cutting force is analyzed, a theoretical model of ultrasonic assisted cutting force for CFRP is established, ultrasonic assisted longitudinal-torsional cutting experiments of CFRP disc are carried out, and compared with normal cutting process. According to the experimental results, the radar map of the cutting force along the circumference of CFRP unidirectional laminates is established, which show that the cutting force can be reduced by ultrasonic assisted cutting compared with ordinary cutting. Under the three cutting modes, the fiber cutting angle has a great influence on the tangential force, and the radial force of the same fiber cutting angle is less than the tangential force, the maximum radial force appeared near the fiber cutting angle of 120°, while the minimum tangential force and the minimum radial force both appear near the parallel direction cutting at 0°. The research results can be used for reference in the processing of CFRP and other composite materials.

Keywords: Ultrasonic assisted cutting · Carbon fiber reinforced plastics · Fiber cutting angle · Cutting force

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0 Introduction

Compared with metal materials, carbon fiber reinforced plastics have been widely used in modern aerospace, military and other fields because of their excellent properties such as specific strength, high specific modulus, corrosion resistance and excellent heat resistance [1]. According to the relevant literature, CFRP has developed into the fourth largest aerospace structural component material after aluminum, steel and titanium, experts and scholars regard the ratio of CFRP in the total weight of the aircraft as one of the important indicators to measure the comprehensive performance of the aircraft [2,3]. The amount of composite materials used in the structure of large civil aircraft has risen from 4% of the overall mass of the aircraft in 1980 to 50% at present [4]. Take Boeing 787 as an example, its fuselage and wing connectors use a large number of CFRP laminates [5]. Of course, CFRP also has shortcomings, its anisotropy, low heat conductivity, low interlaminar bonding strength and brittleness make it a typical difficult-to-machine material [6]. Due to the preparation of CFRP using near-net forming process, while CFRP is mainly used in aircraft key hot-end components and high-end automotive brake systems and other key parts of high accuracy requirements, in order to make the component reach the geometric size and shape precision required by the part, the secondary processing after the material is formed is inevitable [7,8]. During the cutting process, the contact interface between the cutting edge and CFRP will be subjected to force-thermal coupling, resulting in a sharp deterioration of the machined interface, causing the quality and performance of the material to be seriously affected. [9]. Therefore, how to improve the processing quality of CFRP, and to reduce machining damage by reducing the stress in the cutting process is a problem that needs to be solved urgently.

In recent years, many scholars have carried out many corresponding studies on ultrasonic assisted processing, ultrasonic assisted machining is a new composite machining method [10]. Ultrasonic assisted cutting increases the periodic vibration in one or more directions on the basis of ordinary cutting, periodic contact and separation between tool and workpiece, periodic changes in velocity magnitude and direction, so that the processing process can achieve better results [11]. Wang et al. [12] performed ultrasonic milling tests on Vit1 block metallic glass, the results showed that compared with ordinary milling, the milling force in the feed direction of ultrasonic assisted milling was reduced by an average of 23%, and the axial resistance was reduced by an average of 31%, the tool wear was also significantly improved. Taghi et al. [13] performed ultrasonic assisted grinding experiments on material 42CrMo4, the results showed that ultrasonic assisted grinding can improve surface roughness, reduced grinding force and thermal damage compared to conventional grinding. Ma et al. [14] studied the influence of ultrasonic assisted milling on cutting force and surface roughness through experiments, the results showed that the cutting force decreased obviously after ultrasonic vibration was applied, under specific parameters, the surface roughness was also improved. Zhou et al. [15] conducted ultrasonic grinding experiments on silicon nitride ceramics, it was concluded that ultrasonic vibration can effectively improve the surface quality of machined materials. Through the above research findings of scholars, ultrasonic assisted processing has better processing effect than traditional processing, this article intends to introduce ultrasonic

assisted cutting to improve the surface quality of the hole wall.

It is an important aspect to study the cutting mechanism of CFRP, force is the source of various physical phenomena in the cutting process [16]. In order to reveal the removal mechanism of CFRP cutting process and clarify the role of CFRP in the cutting process between tool and fiber, matrix and interface, many scholars have established a single fiber cutting model by analyzing the stress state of CFRP in recent years, which is of great significance to the study of cutting force in the cutting process. Hocheng et al [17] studied the influence of different forms of drilling tools on delamination, and compared with twist drill. Shyha [18] believed that bit form and feed rate were the main factors affecting drilling damage. Işık [19] conducted orthogonal cutting experiments with unidirectional glass fiber reinforced matrix composite, the relationship between machined surface roughness and tool geometry parameters, cutting speed, cutting depth and other parameters were studied. Later, Işık et al. [20] proposed a new method for optimizing cutting parameters, and by making holes in braided composite materials, the correctness of the optimization parameter method was verified. Zhang et al. [21] conducted right angle cutting experiments on unidirectional laminates, the results showed that the sub surface damage of materials was closely related to the fiber direction angle, and the resilience of materials was also affected by the fiber direction angle. Arola et al [22,23] through orthogonal cutting tests on fiber reinforced matrix composites, based on the results it was concluded that the fiber orientation angle contributed the most to the effect of cutting forces and chips, followed by the geometric angle of the tool, and the least effect was on the cutting parameters. In summary, many scholars have carried out a lot of research on CFRP at present, and basically revealed the removal mechanism in the cutting process of CFRP. However, most of the research focus on the optimization of parameters and the development and optimization of new tools, while ignoring the important research direction of changing the fracture form of reinforcing fiber in CFRP by cutting process. Ultrasonic vibration is added to the main cutting edge during ultrasonic assisted cutting of CFRP, the cutting edge gathers great energy to make the carbon fiber reach the shear strength limit instantly, so that the fiber is cut off before bending occurs, which is bound to affect the material removal mechanism in the cutting process, therefore, this research direction should be paid attention to.

The structure of this paper is as follows: In the first section, the influence of longitudinal-torsional ultrasonic assisted cutting on CFRP material removal is analyzed from the perspective of theoretical modeling. The second section introduces the experimental conditions and scheme of CFRP disk cutting experiment. In the third section, the experimental results are analyzed and discussed. Finally, the research conclusion is given in the fourth section.

1 Theoretical analysis model of ultrasonic assisted cutting CFRP material

In this section, the motion model after the decomposition of the cutting behavior of the vertical orthogonal cutting CFRP unidirectional material, namely $\theta=90^\circ$ cutting edge, is

analyzed, the force equation of fiber deformation is established, the tangential force and radial force models are obtained, then the debonding position of matrix fiber is obtained accurately the influence of ultrasonic vibration on material removal is revealed. Suppose y direction is the cutting direction of single cutting edge, x direction is along the direction of fiber.

Fig. 1 shows that when the tool is subjected to torsional ultrasonic vibration, cutting principle diagram of 90° orthogonal cutting CFRP single fiber. Define the coordinate system as xoy , assume that the top of the original position of the cut fiber is the origin o of the coordinate, y axis is consistent with the cutting direction, x axis is consistent with the fiber direction, suppose the vibration frequency is f , the ultrasonic amplitude is A , point A is the contact point between the cutting edge of the tool and the fiber, the feed rate of the tool is V_c , δ is the distance between the bottom of the tool and the actual processed fiber, the radius of the arc of the tool is r_e , and the diameter of the fiber is r_f .

Fig. 1 Schematic diagram of ultrasonic assisted machining CFRP

Before establishing the cutting force model for ultrasonic assisted cutting of a single fiber, the following assumptions are made:

- (1) No shear failure occurred before fiber fracture;
- (2) There is no tensile or compressive deformation in the matrix resin;
- (3) The contact area between cutting edge and fiber conforms to Hertz contact principle;
- (4) Fiber deformation is not affected by fiber normal stress.

Based on the above assumptions, the force on a single fiber during ultrasonic assisted cutting is shown in Fig. 2, where the upper right side of the cut fiber is deformed by the

tangential force f_{Ay} from the cutting edge of the tool, and the lower right side of the fiber is subjected to the adhesion force P_b from the matrix interface because the fiber is not bonded to the matrix, while the left side of the entire cut fiber is supported by the composite material to resist the force deformation on the right side of the fiber.

(1) Tangential force

According to the above analysis, it is found that the stress of the fiber cut is very similar to that of the elastic foundation beam, the support given to the fiber by the fiber back composite can be thought of as consisting of a number of independent springs, in this case, the composite material can be equivalent to a uniform matrix fiber element, its equivalent elastic modulus is k_m , can be expressed as [23]:

$$k_m = \frac{0.95E_m}{1-\nu_m^2} \left[\frac{r_f^4 E_m}{E_f I_f (1-\nu_m^2)} \right]^{0.108} \quad (1)$$

E_m is the equivalent Young's modulus of matrix fiber element, ν_m is the poisson's ratio of cross section of matrix to fiber element, E_f is axial modulus of fiber, I_f is the moment of inertia of the fiber, $I_f = \pi r_f^4 / 64$, r_f is the diameter of fiber.

Fig. 2 Stress on a single fiber

Refer to the foundation model in Winkler, in the model shown in Fig. 2, assuming point A is the contact point between the cutter and the fiber, point B is the corresponding point of actual cutting depth, point E is the boundary point of adhesion between fiber and resin, point C is the other end of the fiber which is at infinity, the cutting parameters, tool parameters and fiber diameter are further introduced into the model, the tool is fed at the speed of V_c , the

cutting depth is h , δ is the distance between the bottom of the tool and the actual processed fiber, the radius of the tool is r_e , and the diameter of the fiber is r_f , when the cutting force is greater than the limit of resin and interface adhesion, The fiber will produce bending deformation in y direction, namely deflection $w(x)$.

In the following discussion, define concentrated load f_{Ay} as positive to the left, uniform load P_b and foundation reaction P_m as positive to the right, the uniformly distributed load causes the micro segment to be anticlockwise positive, the deflection $w(x)$ is positive to the left, angular displacement ρ becomes positive counterclockwise. According to Winkler's hypothesis and deformation condition of elastic foundation beam, the reaction force of the composite material on the fiber is proportional to the deflection of the point, namely:

$$P_m(x) = w(x)k_m \quad (2)$$

In the right part of the fiber without debonding, the fiber is subjected to the bonding resistance P_b of the matrix and interface, at the point E of debonding, P_b should be equal to the bonding strength ρ_b of the resin. If the length of fiber microunit is selected, the bond resistance P_b on the microunit can be calculated according to Formula (3):

$$P_b = k_b w(x) \quad (3)$$

In summary, it can be seen from the mechanical model that the debonding point E is the cut-off point, and the cut carbon fiber supported by the composite material can be divided into two parts: one is the debonding cracking part subjected to the external load, namely the OE section, and the other is the non-debonding part subjected to the uniform load P_b , namely the EC section. According to the relationship between force and reaction force, tangential cutting force can be expressed as:

$$f_{Ay} = k_m w(x) \Big|_0^{h-r_e+l} + (k_m + k_b) w(x) \Big|_{h-r_e+l}^{+\infty} \quad (4)$$

(2) Radial force

In Fig. 3 force model of fiber, cutting force f_{Ax} represents the sliding friction between the fiber and the tool, when the tool is processed with additional torsional vibration, in fact, a high frequency vibration speed is added to the tool in the feed direction, lead to a contact-separate-contact phenomenon between the tool and the fiber, the radial force in the x direction is analyzed below.

The tool feed rate is V_c , the speed of additional ultrasonic vibration in the feed direction is V_t , then the relative speed between the fiber and the tool is:

$$V_{t\hat{c}} = V_c + V_t = V_c + 2\pi f \cdot a \cos(2\pi ft) \quad (5)$$

Suppose $\hat{v} = 2\pi f \cdot a$, then:

$$f_{Ax} = \mu f_{Ay} \left[\text{sgn}(V_t + \hat{v} \cos(2\pi ft)) + \text{sgn}(V_t - \hat{v} \cos(2\pi ft)) \right] \quad (6)$$

It can be obtained in one vibration cycle that:

$$\begin{aligned} \bar{f}_{Ax} &= \frac{1}{T} \int_0^T f_{Ax}(t) dt = \frac{1}{2\pi} \mu f_{Ay} \int_0^{2\pi} \left[\text{sgn}(V_t + \hat{v} \cos(2\pi ft)) + \right. \\ &\quad \left. \text{sgn}(V_t - \hat{v} \cos(2\pi ft)) \right] dt \\ &= \frac{1}{\pi} \mu f_{Ay} \int_0^{2\pi} \text{sgn}(V_t - \hat{v} \cos(2\pi ft)) dt \end{aligned} \quad (7)$$

When $V_c > \hat{v}$. The velocity is always in the positive direction of the y axis, and the tool moves in one direction. At this point there is continuous contact between the tool and the fiber, and the magnitude and direction of the frictional force is constant. Act as $f_{Ax} = \mu f_{Ay}$.

When $V_c < \hat{v}$. The speed is partly positive and partly negative in a cycle, at this time, contact-separation-contact occurs between the tool and the fiber, and the magnitude of friction will be a variable.

The solution of equation (7) can be obtained:

$$\bar{f}_{Ax} = \begin{cases} \frac{\mu f_{Ay}}{\pi} \arcsin\left(\frac{V_c}{\hat{v}}\right), & V_c < \hat{v} \\ \mu f_{Ay}, & V_c > \hat{v} \end{cases} \quad (8)$$

Fig. 3 shows the relationship between speed and radial force. It can be seen from the figure that the radial force in ultrasonic vibration processing is always not greater than that in traditional processing. According to the above analysis, the cutting force of cutting CFRP single fiber with torsional vibration added by the tool can be expressed by Formula (4) and Formula (8).

Fig. 3 Curve of friction force during torsional vibration of tool

2 Experimental conditions and scheme

T300 CFRP unidirectional laminate is selected as the test material, the thickness is 5mm with 40 layers. In order to better simulate the orthogonal cutting experiment of $0^\circ \sim 180^\circ \sim 360^\circ$ full fiber cutting angle, the workpiece material is machined into CFRP unidirectional laminated plate disk with diameter of 100mm. In order to ensure the uniformity of fiber adhesion strength, remove 1.5mm on both sides of the disk and 2mm on the circumference, so that a boss with 2mm thickness and 2mm height is formed on the circumference of the CFRP disk, in the preparation of the disk, a 2mm notch is processed on its circumference with a milling cutter to mark the position of each cutting angle. The shape of the workpiece material is shown in Fig. 4. Table 1 shows the components of CFRP (T300-12K/AG80), table 2 shows the physical/mechanical properties of workpiece materials. The tool used in the test is a diamond PCD lathe blade with a blunt edge radius of 5-10 μ m, basically consistent with the diameter of a single fiber, as shown in Fig. 4(c).

Table 1 Composition of CFRP laminates

Reinforced material	Matrix material	Density (g/cm ³)	Fiber volume fraction (%)	Average fiber diameter (cm)
T300	AG80	1.76	60	7

Table 2 CFRP mechanical/physical properties

Tensile strength (Mpa)	Tensile modulus (Gpa)	Elongation (%)
3530	230	1.5

The experiment is carried out on SPHERE360 ultra-precision diamond lathe, in the experiment, Kistler9257B piezoelectric dynamometer (natural frequency 2.3kHz) is used to measure the dynamic cutting force during the machining process, cutting force data are recorded by multi-channel charge amplifier and corresponding data acquisition system, AE sensors are used to collect and monitor the processing status and fiber fracture. The ultrasonic vibration system used in the experiment includes: 35kHz ultrasonic generator, piezoelectric ceramic transducer, and one-dimensional vibration conical horn designed according to the experiment requirements. The experimental field of ultrasonic assisted orthogonal cutting CFRP disc is shown in Fig. 4. In order to simulate the vibration of the main cutting edge of the tool in contact with the fiber in the process of longitudinal-torsional ultrasonic assisted drilling, in this experiment, longitudinal-torsional ultrasonic assisted cutting CFRP is decomposed into: (a) Tool additional longitudinal ultrasonic vibration (LDVA); (b) Tool additional torsional ultrasonic vibration (TDVA).

Fig 4 Ultrasonic assisted orthogonal cutting CFRP disk test device and test tool

Fig. 5(a) shows the experimental design scheme of machining CFRP disks with longitudinal vibration added by cutting tools, the workpiece is fixed on the spindle of the lathe by fastening bolts to minimize vibration error during processing, in order to ensure the stiffness of the material, the outer circle of CFRP disc should not be too large, which is about 10mm in this experimental. Machining the cylindrical shell of the ultrasonic vibration system into a plane, bolted to the dynamometer, the dynamometer is fixed on the work table, the blade shank of the diamond blade is connected with the horn, the acoustic emission sensors are bonded to the upper and lower sides of the cutter shank using the coupling agent Vaseline. When placing the longitudinal ultrasonic vibration device and dynamometer, the x direction of the dynamometer should be parallel to the x direction of the lathe. The unidirectional CFRP disk workpiece rotates with the spindle during machining, the ultrasonic device drives the tool head to vibrate in the x direction of the lathe. Finally, the cutting angle of fiber changes periodically from 0° to 180° to 360° , the cutting path is shown in Fig. 5(b).

(a) Machining sketch chart

(b)

Cutting path

Fig. 5 CFRP disc with longitudinal vibration machining

Fig. 6 shows the experimental design of CFRP disc processed by ultrasonic vibration with additional torsion of the tool. The CFRP disc workpiece is fixed on the spindle of the lathe by fastening nut. In order to ensure the stiffness of the workpiece, the suspension of CFRP disc is no more than 10mm. The ultrasonic device is vertically fixed on the dynamometer, which is fixed on the work table. The x direction of the dynamometer is parallel to the x direction of the lathe table. During the processing, the ultrasonic device drives the tool to vibrate along the z direction of the machine tool, and the disk workpiece rotates along the spindle. Finally, the cutting angle of the fiber changes periodically from 0° to 180° to 360° . The cutting path is shown in Fig. 6(b).

(a)

Machining

sketch

chart

(b) Cutting path

Fig. 6 CFRP disc with torsion vibration machining

According to the actual processing conditions, ultrasonic assisted orthogonal cutting of CFRP unidirectional laminates with three different machining methods: traditional processing, tool additional torsional vibration and tool additional longitudinal vibration, in order to avoid the influence of the repeated use of CFRP unidirectional laminates on the experimental structure, the machined surface of the disc workpiece needs to be trimmed before the start of each set of experiments. In addition, new blades need to be replaced in time to prevent tool wear from affecting the processing results.

Experiment is divided into three groups according to different processing way, after the

experiment, the machined surface morphology of the CFRP disk circumference is observed using the Keyence VHX ultra-depth-of-field 3D microscopic system manufactured in Japan, the workpiece can be rotated during observation, to obtain the machined surface morphology of any fiber angle, a set of data is measured at each interval of 5° fiber cutting angle.

3 Analysis and discussion of experimental results

The cutting process is shown in Fig. 7. The tangential force f_{Ax} and radial force f_{Ay} of cutting force are F_z and F_y output by the dynamometer, and the F_x output by the dynamometer is contributed by the feed of the tool. The size of F_x of CFRP unidirectional lamination plate is almost unchanged within one week of rotation.

Fig.7 Cutting force and dynamometer direction

Fig. 8 radar diagram of tangent force and radial force changing with cutting angle of fiber with same cutting tool, same cutting parameter ($n=276\text{r/min}$, $A=6\mu\text{m}$, $F=35\text{kHz}$,) and different processing technology. As can be seen from Fig. 8(a), the tangential force f_{Ax} fluctuates obviously under the influence of different fiber cutting angles, in the first quadrant the tangential force is generally small, mostly below 40N, the tangential force in the first quadrant increases slowly with the increase of cutting angle, near the fiber cutting angle of 90° , the tangential force of the three processing methods all reached a significant peak. In the second quadrant, the directionality of the tangential force between $100^\circ\sim 130^\circ$ of the traditional machining and the additional longitudinal vibration of the tool is not obvious. The traditional tangential force remains around 70N, the tangential force of the additional longitudinal vibration of the tool is maintained near 65N. However, the tangential force of the additional torsional vibration of the tool still fluctuates in a large range in this interval, the tangential force on both sides of the peak 52N at 100° decays rapidly, and the directivity is still obvious.

Fig.8 Radar diagram of cutting force changing with "θ"

According to the symmetry of cutting fiber angle, it can be found in Fig. 8(a) that the tangential force in the third quadrant and fourth quadrant shows the same change law as that in the first and second quadrant. Therefore, it can be seen that the introduction of ultrasonic reduces the magnitude of tangential force to different degrees. Compared with traditional machining, when the tool is attached with torsional vibration, the tangential force is reduced by about 20~30N. When the tool is attached with longitudinal vibration, the amplitude of tangential force is not significantly reduced compared with traditional machining.

Fig. 8(b) shows the radar diagram of radial force f_{Ay} changes under the influence of different fiber cutting angles. The radial force of the same fiber cutting angle is smaller than the tangential force. The radial forces in the second and fourth quadrants are obviously larger than those in the first and third quadrants. However, the cutting angle of the maximum radial force is around 120°, while the minimum radial force still appears in the parallel cutting process of 0°. In contrast to the tangential force, in the whole process of circumferential machining, the minimum radial force is processed by the tool with longitudinal vibration, and the radial force of this method is not more than 35N.

4 Conclusions

The ultrasonic assisted orthogonal cutting experiment of CFRP unidirectional laminated plate is completed, the cutting force spectrum of unidirectional laminates along the cutting angle distribution of circumferential fiber is established, and the influence law of different machining modes and cutting angle on cutting force is obtained. The main conclusions are as follows:

- (1) The addition of ultrasonic can reduce the tangential force in different degrees.

Compared with the traditional machining tools, when additional torsional vibration is added, the tangential force is reduced by about 20~30N, and the change of tangential force of additional longitudinal vibration of tool is not obvious.

(2) The directionality of radial force is more significant than that of tangential force, radial force is less than tangential force at the same fiber cutting angle.

(3) No matter what processing method, the position of the maximum tangential force appears near the vertical cutting, the fiber cutting angle at the position where the maximum radial force appears is about 120°, the minimum tangential force and the minimum radial force appear near the parallel cutting direction of 0°.

(4) During the whole circumferential cutting process, the contribution ratio of radial force and tangential force to total cutting force is closely related to the cutting angle, in the second and fourth quadrants, the contribution rate of tangential force is larger, while in the first and third quadrants, the contribution ratio of tangential force and radial force is basically the same.

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