Theoretical Modeling and Experimental Verification of Rotating Ultrasonic Drilling

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ABSTRACT: Aiming at the problems of large drilling ability and serious wear of drill bit tool in the process of drilling, the connecting plate workpiece in the high strength engineering mechanical connection parts of carbon fiber reinforced composites is studied, and the theoretical model of ultrasonic drilling is established, and the simulation analysis is carried out by using the professional numerical calculation software MATLAB. The influence of the main parameters such as tool feed speed, spindle angular velocity and ultrasonic amplitude on the drilling force during ultrasonic drilling is studied, and the relevant parameters under the same working conditions of simulation are verified by experimental method. The simulation and experimental results show that with the increase of tool feed speed, the drilling force shows the trend of increasing gradually, and with the increase of spindle angular velocity and ultrasonic amplitude, the drilling force shows a decreasing trend, and the simulation value of maximum drilling force under different parameters is basically close to the experimental value, which verifies the correctness of the theoretical model. It provides theoretical basis and important reference for the improvement of the comprehensive performance and product quality of the ultrasonic drilling parts of carbon fiber reinforced composites, the popularization and application of the theoretical model of ultrasonic drilling, the optimization of ultrasonic drilling process parameters, and the ultrasonic processing and molding of composite materials.

1. Introduction
Carbon fiber reinforced composites are widely used in military, aerospace, construction, construction machinery and Automotive fields (1) (2) because of their advantages of light weight, high strength, high temperature resistance, corrosion resistance, good fatigue resistance, excellent anti-vibration performance and mechanical properties. With the increasing demands of construction machinery on component strength and performance, new refractory composite materials are widely used in their high strength components, such as key components of internal combustion engine for construction machinery, high strength connecting parts, key components in hydraulic systems, etc. (3). Carbon fiber material because of its unique high hardness and high strength and other mechanical characteristics make it more difficult to process, not only the workpiece processing heat, processing time, processing axial force and torque is large, and easy to cause more serious wear on the processing tools (4) (5). The wear of drilling tools will lead to the decrease of drilling quality, easy to tear at the orifice, high roughness and stratification and other processing defects, and at the same time will lead to too fast scrap of the tool, low processing efficiency and high economic costs (6). In view of the above problems, many scholars have put forward the method of ultrasonic vibration assisted processing to process the material, and some scholars have done the corresponding experimental research. The effects of rotational ultrasonic processing on the properties of brittle materials were studied by means of the experimental methods of Pei (7). Liu (8) and other believe that the ultrasonic cleaning effect of
RUEM can be beneficial to the improvement of cutting force in the processing process, can increase the service life of the tool and improve the accuracy of the machining hole, domestic scholars Wang Jinming (9) and other three kinds of superhard material tools for the milling of carbon fiber materials, The performance of different tools in the process is obtained. Chen Xiongbing of Dalian University of Technology and others (10) taking carbon fiber composites as the research object, the rotary ultrasonic milling technology is studied. Weinert K ET (11) The processing methods of composite C/c-sic materials were studied, Oliveria J.F.G and so on (12) studied and analyzed the grinding process challenges in industry. Although many scholars have carried on the correlation research to the composite material characteristic and its processing characteristic, has obtained the relatively fruitful achievement, has provided the important reference for the composite material characteristic improvement and the processing process optimization. However, there are few systematic researches on rotary ultrasonic drilling and so on, based on this, this paper takes the previous research object of carbon fiber reinforced composite high strength engineering mechanical connector as the research object, establishes its rotational ultrasonic drilling theory model, uses the professional numerical calculation software MATLAB to carry on the numerical calculation to it, The corresponding experimental verification is carried out under the same working conditions, which provides theoretical basis and guidance for the machining of high strength engineering mechanical components and carbon fiber reinforced composite materials, and also plays a great role in promoting the application and popularization of special machining of composites in engineering.

2. Rotary Ultrasonic drilling theoretical modeling

In the process of rotating ultrasonic drilling, the suspended abrasive particles in the liquid under the ultrasonic high frequency vibration of the drilling tool, with high speed and continuous impact on the workpiece drilling surface, so that the surface of the workpiece is subjected to a large pressure so that the deformation of the material, when the workpiece drilling and processing stress exceeds the strength limit of its material itself, The workpiece material will be damaged into a powder shape, thus removing the required workpiece material. The schematic diagram of rotary ultrasonic drilling is shown in Fig 1.

As you know from Figure 1, the diamond drilling tool rotates at a certain speed, while applying the ultrasonic vibration frequency of the 20-25kHz in the direction of the coordinate Y axis, and the diamond drilling cutter processes the machined workpiece on the plane along the Y axis to make the upper and lower feed movement. The motion trajectory of particles on diamond drilling tools can be expressed by equations (1):

\[
\begin{align*}
X &= R \cos(wt) \\
Y &= R \sin(wt) \\
Z &= A \sin(2\pi f t) + v_f \cdot t
\end{align*}
\]

Among them: R is the diamond drilling tool radius; A is the amplitude of ultrasonic vibration; w is the rotation angle speed of diamond drilling tool; Feed speed for diamond drilling tool; f is ultrasonic vibration frequency; t is the action time.
According to the Hertz fracture theory model, the drilling and cutting tools can be obtained during each vibration cycle, and the maximum impact depth formed is \( s \):

\[
s = \left[ \frac{9 \times (F/n)^2 \times (1 - x^2)^2}{8 \times d \times E^2} \right]^{1/2}
\]

(2)

Among them: \( F \) is the contact force between the drilling tool and the processing workpiece; \( n \) is the number of effective media on the end surface of the drilling tool; \( D_d \) medium diameter; \( E \) is the elastic modulus of drilling machining workpiece; \( \lambda \) is Poisson ratio of the workpiece for drilling.

In the ultrasonic drilling process, the instantaneous impact force \( p(t) \) obtained by the combined effect of the average impact force and the static load \( F_j \) on the processing surface of the drilled workpiece is:

\[
p(t) = F(t) + F_j = \frac{4 \pi^2 M \cdot A_z \cdot f^2 \cdot \cos(2\pi f t)}{\Delta T} + F_j
\]

(3)

Among them: \( M \) is removal rate of brittle fracture during rotary ultrasonic drilling hard brittle material; \( A_z \) is diamond drilling tool and workpiece contact area; \( \Delta T \) is effective use of time.

The maximum impact \( p_{\text{max}} \) of a single effective medium \( n_y \) can be obtained as:

\[
p_{\text{max}} = \frac{1}{n_y} \left( \frac{4 \pi^2 M \cdot A_z \cdot f^2 \cdot \cos(2\pi f t)}{\Delta T} + F_j \right)
\]

(4)

When \( p_{\text{max}} > P_{\text{max}}, \) the workpiece produces brittle cracks, which leads to the rupture of the workpiece in the ultrasonic drilling process to achieve the purpose of processing.

In ultrasonic drilling process, the contact force between the single abrasive and the workpiece is set to be when the grinding material is pressed into the workpiece to a maximum depth \( s \). In an ultrasonic vibration period, the impulse force \( F_c \) of diamond drilling tool and workpiece is equal to that of drilling contact force. The relationship between the maximum impact force \( p_{\text{max}} \) and the drilling contact force \( F_c \) can be obtained as follows:

\[
F_c \Delta T = \frac{p_{\text{max}}}{f}
\]

(5)

In the process of rotary ultrasonic drilling, the length of transverse cracks produced on the surface of diamond abrasive stamping workpiece is \( L \) and depth \( H \) respectively:

\[
L = k_1 \left( \frac{F_c}{n K_{IC}} \right)^{1/2}
\]

(6)

\[
C = k_2 \left( \frac{F_c}{n H V} \right)^{1/2}
\]

(7)

Among them: \( K_{IC} \) is the fracture toughness of the material, its value is obtained by indentation test; \( H V \) is the strength of the material, the value is obtained by indentation test; \( k_1 \) and \( k_2 \) are proportional constant, calculated by multiple sets of indentation tests.

According to indentation fracture mechanics, the relationship between the maximum impact force and the maximum impact depth of diamond abrasive particles can be obtained as:

\[
\frac{F_c}{n} = \frac{1}{2} \xi s^2 \tan \left( \frac{\alpha_0}{2} \right) H V
\]

(8)

Among them: \( \xi \) is Vickers head geometry factor, related to the geometry and material of the pressure head, generally take \( \xi = 1.854 \); \( \alpha_0 \) is the cone angle of the Vitis tetrahedral pressure head.

In the work process, the drilling knife has an effective action time of:
\[ \Delta T = \frac{s}{2Af} \]  

(9)

Combined with the motion mode of diamond abrasive, the removal rate of brittle fracture removal \( M \) can be obtained when rotating ultrasonic drilling hard brittle materials:

\[ M = 2nLHf \]  

(10)

From this it can be deduced that the material removal rate under feed speed \( v_f \) conditions is:

\[ M = \pi v_f \left( R^2 - R_{in}^2 \right) \]  

(11)

Among them: \( R_{in} \) is diamond drilling tool inner radius.

In the vertical (5)-(11) formula, when it can be calculated that the rotary ultrasonic constant feed rate drilling hard brittle material, the mathematical model of the material brittle fracture removal is:

\[
F = k \left[ \frac{2K_{in}^2 HV^{\frac{3}{2}} \left( R^2 - R_{in}^2 \right)^{\frac{3}{8}}}{k_1 k_2 \tan \left( \frac{\alpha_m}{2} \right) R_{in}^{\frac{1}{2}}} \right]^{\frac{6}{7}} \left[ \frac{2\pi v_f n^6}{wA} \right]^{\frac{6}{7}}
\]  

(12)

Among them: \( k \) is correction coefficient of drilling force, the drilling test was carried out and the linear regression method was used to obtain it; \( R_{in} \) is rotation diameter of the diamond abrasive.

From formula (12), it can be seen that when the rotary ultrasonic constant feed rate drills hard brittle materials, the parameters such as tool feed speed, Spindle angular speed, diamond tool abrasive number, and ultrasonic amplitude affect the drilling force. Moreover, the tool feed speed and spindle angle speed have great influence on the cutting force. The drilling force increases with the increase of feed speed, and the increase rate decreases with the increase of feed speed. With the increase of the angular velocity of the spindle, the change range decreases with the increase of the spindle speed. In the theory of this study and experimental research, the main parameters of tool feed speed, Spindle angular velocity, ultrasonic amplitude and so on are emphasized.

3. Experimental equipment materials methods and conditions

The main equipment used for ultrasound assisted processing is ultrasonic 65 equipment in the WMG high-value equipment processing center, which is produced by German DMG/MORI SEIKI. The remaining equipment and instruments include charge amplifiers YE5850, A/D converters and computers; The tool's wear measurement equipment includes a body vision microscope, image scale software Image Measure and JEOLJSM-6380 LV scanning electron microscope. The experimental workpieces and main equipment are shown in Fig 2.

Fig 2: Test parts and main test equipment

As can be seen from Fig 2, the ultrasonic driver is installed on the tool cage and produces a certain frequency of ultrasonic vibration through the piezoelectric effect, ultrasonic vibration through the tool feed direction oscillation overlay to achieve the impact on the tool. The material used in drilling experiments is isotropic epoxy resin-based carbon fiber reinforced composites, the volume fraction of carbon fiber is 65%, and its material properties are shown in table 1.

| Setting | Tensile Strength/M Pa | Tensile modulus/GPa | Density/(g.cm\(^{-3}\)) |
|---------|-----------------------|---------------------|------------------------|
| Value   | 4300                  | 145                 | 1.44                    |
Machining workpiece for carbon fiber reinforced composites high strength engineering machinery connecting parts of the connecting plate, the drill bit for the nickel-based electroplating diamond drilling knife, the outer diameter of the tool is 8 mm, the inner diameter of 1 mm, the thickness of the wall is D126 (120/140), the particle size of the diamond abrasive particles is, the ultrasonic frequency of rotational ultrasonic processing is The ultrasonic power is 17.5 W, the ultrasonic amplitude is 5-15 um, the spindle angular velocity is 2000\(\pi\)-8000\(\pi\)rad/min, and the feed speed is 10-100um/s. The measurement of cutting force in the test is done by the Kistler 9257B Dynamic force measuring system produced by Kistler Instrument Corporation. In order to enhance the reliability of the test data, three Tests were carried out on each set of process parameters and the average value was taken as the experimental results when the test was carried out.

4. SIMULATION ANALYSIS AND EXPERIMENTAL VERIFICATION

4.1 Simulation analysis

According to the theoretical model established above, the theoretical model is calculated by using MATLAB, a professional numerical calculation software, and the distribution of drilling force under the parameters of feed speed, spindle angular velocity and ultrasonic amplitude of different tools is shown in Figures 3, 4 and 5, respectively.

![Fig. 3 Drilling force at different tool feed speed and spindle angular velocity](image1)

Fig. 3 Drilling force at different tool feed speed and spindle angular velocity

Fig. 3 is an ultrasonic amplitude of 10um, different tool feed speed, spindle angular velocity under the drilling force. As you know from Figure 3, with the increase of tool feed speed, the drilling force shows a gradual increase trend, and with the increase of spindle angular velocity, the drilling force shows a decreasing trend, and the change trend of the former is greater than that of the latter. The above phenomenon is caused by the increase of tool feed speed, the increase of drilling resistance, while the angular velocity of spindle increases, and the drilling resistance decreases gradually.

![Fig. 4 Drilling force of different tool feed speed and ultrasonic amplitude](image2)

Fig. 4 Drilling force of different tool feed speed and ultrasonic amplitude

Fig. 4 is the spindle angular velocity of 5000\(\pi\)rad/min, different tool feed speed, ultrasonic amplitude under the drilling force. As you know from Figure 4, with the increase of tool feed speed, the drilling force shows a gradual increase trend, and with the increase of ultrasonic amplitude, the drilling force shows a decreasing trend, and the former change trend is greater than that of the latter. The reason for the above phenomenon is that the ultrasonic amplitude increases and the drilling resistance decreases gradually.

Fig. 5 is a tool feed speed of 55um/s, different spindle angular velocity, ultrasonic amplitude under the drilling force. As you know from Figure 5, with the increase of the angular velocity of the spindle, the drilling force shows a decreasing trend, but with the increase of ultrasonic amplitude, the drilling force shows a decreasing trend, and the change trend of the former is greater than that of the latter.
4.2 Experimental verification

In order to verify the correctness of the theoretical model and simulation, the experiment is carried out under the same working conditions as the above simulation analysis. The experimental results are shown in Figure 6 and 7 below. Fig. 6 is the drilling force at a ultrasonic amplitude of 10um, different spindle angular velocity and tool feed speed. As you know from Figure 6, with the increase of the angular velocity of the spindle, the drilling force shows a decreasing trend, and with the increase of the feed speed of the cutter, the drilling force shows a gradual increase trend, which is basically consistent with the trend of simulation analysis above, and the maximum value of simulation and experiment is 518N and 525N respectively, which verifies the correctness of simulation.

Fig. 6 Drilling force at angular velocity and tool feed speed of different spindle

Fig. 7 is the spindle angular velocity of 5000πrad/min, different ultrasonic amplitude, tool feed speed under the drilling force. As can be seen from Figure 7, with the increase of ultrasonic amplitude, drilling force shows a decreasing trend, with the increase of tool feed speed, drilling force is gradually increasing the trend, and the trend of simulation analysis above is basically the same, and the simulation and experimental maximum values are 528N, 545N, the two are relatively close, verify the correctness of the simulation.

Fig. 7 Drilling force at different ultrasonic amplitude and tool feed speed

The comprehensive study shows that the carbon fiber reinforced composites are related to the main parameters such as tool feed speed, spindle angular velocity and ultrasonic amplitude in ultrasonic
drilling process, among which the tool feed speed has the greatest influence, and the spindle angular velocity and ultrasonic amplitude have great influence on it. The simulation results of theoretical modeling are basically consistent with the experimental results, and the correctness of the theoretical model is verified, in order to obtain the machining parts with excellent performance, it is necessary to study the comprehensive influence of its related parameters in more depth.

5. CONCLUSIONS
Taking the connecting plate workpiece in the high strength engineering mechanical connection parts of carbon fiber reinforced composites as the research object, the theoretical analysis model of ultrasonic drilling is established, and the influence of the main parameters such as tool feed speed, spindle angular velocity and ultrasonic amplitude on the drilling force is studied by simulation combined with experiment, and the results show that with the increase of tool feed speed, the drilling force shows a gradual increase trend, and with the increase of spindle angular velocity and ultrasonic amplitude, the drilling force shows a decreasing trend. Through theoretical and experimental methods, the influence of ultrasonic drilling main parameters on the drilling and processing of carbon fiber reinforced composite workpiece is studied, which provides an important basis and reference for the machining and forming of carbon fiber reinforced composite materials, the optimization of ultrasonic drilling process parameters and their popularization and application.

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