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Research Article

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Study on surface Morphology of 7075 aluminum alloy deep hole by two-dimensional ultrasonic elliptical vibration turning

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Abstract: In order to obtain 7075 aluminum alloy deep hole tube parts with better surface quality, the two-dimensional ultrasonic elliptical vibration turning (2D-UEVT) was studied. The tool tip trajectory model and the surface roughness model of 2D-UEVT deep hole were established. It was found that 2D-UEVT could obtain lower surface roughness than common turning (CT) through analyzing the theoretical model. Finally, the effects of turning parameters and acoustic parameters on surface morphology were studied by four-factor four-level orthogonal test. The experimental results indicated that the surface roughness Ra value decreased in different degrees after the 2D-UEVT. However, various turning parameters and acoustic parameters had different effects on the reduction of Ra. With the increase of the feed rate and spindle speed, the surface roughness Ra shows a trend of decreasing first and then increasing. With the increase of ultrasonic amplitude, the Ra displayed increasing first and then decreasing. The influence of cutting depth on the roughness is not significant. The results demonstrated that better surface texture and surface quality can be obtained with lower feed rate, medium ultrasonic amplitude and spindle speed.

Keywords: Two-dimensional ultrasonic vibration turning; 7075 aluminum alloy; Single excitation elliptical vibration turning tool; Surface roughness; Micro-texture

1 Introduction

7075 aluminum alloy has superior tensile strength, good mechanical properties and good corrosion resistance in 7 series aluminum alloys [1]. However, due to its large plasticity, easy deformation and other characteristics, it is difficult to guarantee the surface quality and accuracy after machining with ordinary deep hole turning methods [2,3], which seriously hinders the further development of aviation and other related technical equipment [4]. The shortage of advanced deep hole processing technology and equipment will seriously restrict the high-quality development of China's manufacturing industry. Therefore, the research on 7075 aluminum alloy deep hole processing technology and equipment is of great significance [5,7].

Ultrasonic elliptical vibration turning is a processing method of high-frequency intermittent vibration cutting by using a specific ultrasonic vibration system to apply ultrasonic vibration signals to tools or workpieces, so that the moving trajectory of cutting edges in the cutting process becomes high-frequency elliptical vibration [8]. Ultrasonic machining is a
non-traditional special cutting technology. In a vibration cycle, the effective cutting time of the tool is very short, the complete separation of the tool from the workpiece and chip takes about 80% of the time. It can effectively reduce tool wear, extend tool life, reduce cutting force and cutting heat [9], effectively improve the surface accuracy of the workpiece to be machined [10], and improve the stability of the part system [11]. In recent years, many scholars at home and abroad have done a lot of research on 2D ultrasonic elliptical vibration machining technology and equipment. Tong et al. [12] designed a single excitation ultrasonic elliptical vibration system. Through experiments, it was found that aluminum alloy can obtain the best surface morphology when cutting with appropriate ultrasonic amplitude and low feed speed. Based on the principle of ultrasonic elliptical vibration turning, Zhou et al. [13] designed a single excitation ultrasonic elliptical vibration turning device with a frequency of 60kHz, and compared the results of ordinary turning and ultrasonic elliptical vibration turning, and found that the elliptical vibration cutting effect is obviously superior to ordinary turning. In order to improve the machining efficiency of ultrasonic elliptical vibration cutting, Yin et al. [14] designed an ultrasonic elliptical vibration cutting device with multi-level amplification function, which effectively improved the output amplitude. Liu et al. [15] used ultrasonic vibration cutting system to conduct ordinary cutting and vibration cutting tests on 7075 aluminum alloy. The results showed that there is an optimal cutting speed for vibration cutting, the cutting force of ordinary cutting is significantly higher than that of vibration cutting, and the stability of vibration cutting system is higher.

Luan et al. [16] studied the surface quality and morphology characteristics of 7075-T6 aluminum alloy in unidirectional ultrasonic vibration turning, and obtained the cutting parameters of excellent machined surfaces. Zhang et al. [17] designed a spiral groove type single excitation ultrasonic turning device for 3D curved surfaces based on the principle of ultrasonic turning of 3D curved surfaces, and explained the specific method of realizing the vibration trajectory of 3D curved surfaces of turning tools. Hara Keisuke et al. [18] conducted friction experiments on stainless steel pins in order to evaluate the tribological properties of ultrasonic vibration assisted turning textured surfaces. The results show that the friction coefficient and its fluctuation of ultrasonic vibration assisted turning surface are lower than those of conventional turning surface. Liu et al. [19] conducted a single excitation 2D elliptical vibration turning test on 7075 aluminum alloy. The results show that compared with common turning, the roughness of 2D ultrasonic vibration turning has been greatly reduced, and the turning surface has uniform grooved micro-structures. Yuan et al. [20] studied the surface micro texture characteristics of aluminum alloy in ultrasonic elliptical assisted machining, and found that the geometric size, profile height and surface roughness Ra of micro texture grooves will change regularly with the change of speed and feed speed. Zhang et al. [21] applied ultrasonic vibration to the deep-hole boring process, and carried out experiments such as roughness measurement and surface topography observation of machined surfaces. The results demonstrate that ultrasonic vibration boring can effectively overcome the chip block problem, reduce the hole diameter error and surface roughness and suppress the cutting chatter, and improve the machining quality of deep-hole boring. Jiao et al. [22] carried out ordinary and ultrasonic turning tests on the guide mirror tube parts of ultra-thin wall precision camera. The results show that under the same conditions, the surface roughness of ultrasonic turning is nearly 30% lower than that of ordinary cutting.

At present, The two-dimensional ultrasonic elliptical vibration turning mostly synthesizes the required multi-dimensional vibration through single vibration in different directions [23]. During machining, the shape of cutting edge motion in 2D ultrasonic elliptical vibration turning is affected by the phase difference, amplitude, feed speed and tool
shape generated by two-phase excitation [24]. In this experiment, a 2D ultrasonic elliptical vibration turning tool with a single excitation asymmetric structure is used, and a special asymmetric structure of the cutter bar is used to transform the single excitation ultrasonic vibration of the tool body into two-dimensional ultrasonic vibration at the tool tip, so as to achieve 2D ultrasonic vibration deep hole turning.

In this paper, Based on the characteristics of ultrasonic elliptical vibration and the formation mechanism of the machined surface, the 7075 aluminum alloy deep hole turning test was carried out using the single excitation asymmetric ultrasonic elliptical vibration turning tool. The surface roughness and surface morphology after the 2D ultrasonic elliptical vibration deep hole turning were studied, and the influence of cutting parameters and acoustic parameters on the surface roughness and surface morphology of deep holes in the actual machining process was revealed.

2 Theoretical analysis

2.1 2D ultrasonic vibration turning deep-hole model

Fig.1 shows a simplified model of the 2D ultrasonic vibration turning deep-hole system. When the ultrasonic vibration turning deep holes, the tool is periodically excited by high frequency vibration in the two directions of \( X \), \( Y \) and \( Z \), which makes the tool tip motion trajectory more complex compared with common turning under the action of two excitation sources.

![Fig. 1 Two-dimensional ultrasonic vibration turning inner hole model](image)

\[ \begin{align*}
X(t) &= nf_r t/60 \\
Y(t) &= (r + a_p) \cos(2\pi nt/60) \\
Z(t) &= (r + a_p) \sin(2\pi nt/60)
\end{align*} \tag{2-1} \]

Where, \( X \) is the feed direction displacement; \( Y \) is the cutting depth direction; \( Z \) is the cutting speed direction displacement; \( r \) is the radius of the deep hole; \( f_r \) is the feed rate; \( a_p \) is the cutting depth; \( t \) is the cutting time; \( n \) is the spindle speed.

In 2D ultrasonic elliptical vibration inner hole turning, in addition to rotating and feeding relative to the workpiece, the tool also has ultrasonic vibration in \( X \) and \( Z \) directions. The vibration equation is as follows:
\[
\begin{align*}
X(t) &= A_x \sin(2\pi ft + \theta) \\
Z(t) &= A_z \sin(2\pi ft)
\end{align*}
\]

(2-2)

Where, \(A_x\), \(A_z\) are amplitudes in X and Z directions, and \(\theta\) is the phase differences in X and Z directions. Because the single excitation elliptical vibration turning tool is used in this test, so \(\theta\) is a fixed value in theory.

Joint equations (2-1) and (2-2), the motion equation of cutting edge for 2D elliptical vibration turning deep holes is:

\[
\begin{align*}
X(t) &= (r + a_p) \cos(2\pi nt/60) + A_x \sin(2\pi ft + \theta) \\
Y(t) &= nft/60 \\
Z(t) &= (r + a_p) \sin(2\pi nt/60) + A_z \cos(2\pi ft)
\end{align*}
\]

(2-3)

Through MATLAB calculation, the Cutting edge trajectory model of 2D-UEVT and CT is obtained, as shown in Fig.2.

![Fig. 2 Cutting edge trajectory model of 2D-UEVT and CT](image)

By comparing the Cutting edge trajectory of CT and 2D-UEVT, it can be found that the trajectory of 2D-UEVT is a spiral rising curve. There are obvious elliptical vibration trajectories, and the cutting edge motion trajectories of 2D-UEVT has a partial rotation overlap phenomenon. At this time, the vibration speed of the cutting edge is synthesized by the vibration speed components \(V_x\) and \(V_z\) added in the X and Z directions. This vibration state leads to the periodic separation and contact between the tool and the workpiece, which changing the traditional continuous machining state. It makes chips break more easily, and has a positive effect on reducing cutting force, cutting heat, tool wear and improving surface quality.

### 2.3 Surface Roughness Modeling of 2D Ultrasonic Vibration Deep Hole Turning

#### 2.3.1 Surface roughness modeling of CT

Surface roughness is one of the important factors to measure the quality of deep hole machining. In common turning, the tool extrudes and shears the rotating workpiece with a certain feed rate, so that the material on the machined surface can be removed and a groove is formed on the machined surface. In an ideal state, the surface morphology of deep hole turning is shown in Fig.3, and the surface morphology is a periodic circular arc groove.
Fig. 3 Ideal surface topography for deep hole turning

Extract the contour curve in the feed direction, as shown in Fig. 4. It can be seen from the geometric relationship that:

\[ R^2 = (R - h_{\text{max}})^2 + \left( \frac{f_r}{2} \right)^2 \]  \hspace{1cm} (2-4)

Where, \( R \) is the tool tip arc radius.

Fig. 4 Feed direction contour curve

In actual machining, \( h_{\text{max}} \ll R \), so the maximum height of residual area \( h_{\text{max}} \) is:

\[ h_{\text{max}} = R - \sqrt{R^2 - \frac{f_r^2}{4}} \]  \hspace{1cm} (2-5)

Due to the extrusion friction between the tool and the material, micro-plastic deformation and a small amount of elastic recovery can be caused on the workpiece, thus producing the plastic flow height difference \( \Delta h \) on the processed surface. The plastic flow height difference \( \Delta h \) can be expressed by the following formula:

\[ \Delta h = h_p - h_e \]

Where, \( h_e \) is the elastic recovery height of the workpiece; \( h_p \) is the plastic deformation depth of the workpiece.

According to the molecular-mechanical friction theory in Kragelsky's friction theory [25], the plastic deformation depth of the workpiece \( h_p \) can be expressed as:

\[ h_p = 2R \left( 1 - \frac{0.33H}{\sigma_m} \right) \]  \hspace{1cm} (2-6)

According to Hertz's elastic contact theory [26]:

\[ h_e = \left( \frac{9p}{16E^2R} \right)^{\frac{1}{3}} \]  \hspace{1cm} (2-7)

The influence value of microplastic deformation on surface roughness of machined surface can be obtained from the above formula[27]:

\[ \Delta h = 2R \left( 1 - \frac{0.33h}{\sigma_m} \right) - \left( \frac{9p}{16E^2R} \right)^{\frac{1}{3}} \]  \hspace{1cm} (2-8)
Where, $p$ is the pressure perpendicular to the machined surface; $E$ is the elastic modulus of the workpiece; $H$ is the hardness of the workpiece; $\sigma_m$ is the flow stress of the workpiece.

In the process of common turning, when the microplastic deformation and elastic deformation are taken as the main factors affecting the surface roughness, the surface roughness of the common turning deep hole is:

$$R_a = \left( R - \sqrt{R^2 - \left( \frac{p}{2} \right)^2} \right) + \left[ 2R \left( 1 - \frac{0.33H}{\sigma_m} \right) - \left( \frac{9p}{16E^2R} \right)^{1/3} \right]$$

\[ (2-9) \]

2.3.2 Surface roughness modeling of 2D-UEVT

Fig.5 shows the ideal surface morphology of 2D ultrasonic vibration deep hole turning. The research object is two consecutive cutting cycles in the process of 2D ultrasonic vibration deep hole turning. Its model is shown in Fig. 6.

![Fig. 5 2D-UEVT surface morphology](image)

The ellipse in the $oxy$ plane is the tool tip trajectory of the current cutting cycle, and the ellipse in the $oX_1y_1$ plane is the cutting trajectory of the next cutting cycle. Combined with the elliptical shape formula, the residual height in the cutting direction is:

$$\hat{h} = \frac{A_t}{2} \sqrt{1 - \left( \frac{v_F}{fA_c} \right)^2}$$

\[ (2-10) \]

$$R_{th} = \frac{A_t}{2} \left( 1 - \sqrt{1 - \left( \frac{v_F}{fA_c} \right)^2} \right) = \frac{A_t}{2} \left( 1 - \sqrt{1 - \left( \frac{1}{fA_c/v_F} \right)^2} \right)$$

\[ (2-11) \]

Where, $\hat{h}$ is the distance between the intersection of the two periodic elliptical trajectories and the x-axis; $A_t$ and $A_c$ are twice the amplitudes in Y and X axis directions, respectively.

In cutting, the speed ratio is defined as the ratio of cutting speed to the maximum vibration speed, that is:

$$SR = \frac{V_F}{2\pi fA}$$

\[ (2-12) \]

When $SR < 1$, the tool and workpiece can be separated. When $SR \geq 1$, the tool and workpiece separation will weaken or even disappear. When $SR < 1$, $fA_c/v_F > 1$, which can be obtained by Taylor series transformation. When $SR \gg 1$, the residual height is approximately:

$$R_{th} \approx \frac{A_t}{4} \left( \frac{1}{fA_c/v_F} \right)^2 = \frac{1}{4} \frac{A_t}{A_c^2} \left( \frac{v_F}{f} \right)^2$$

\[ (2-13) \]
In ultrasonic vibration machining, due to the introduction of ultrasonic excitation signal, a variable cutting acceleration will be added to the tool. The radial acceleration \(a_x(t)\) when vibrating along the \(X\) direction can be obtained by taking the derivative of formula (2-3):

\[
a_x(t) = -A_x(2\pi ft)^2 \sin(2\pi ft)
\] (2-14)

Then the impact force in \(X\) direction is:

\[
F_x = ma_x = -A_xm(2\pi ft)^2 \sin(2\pi ft)
\] (2-15)

Where, \(f\) is the ultrasonic vibration frequency and \(A_x\) is the ultrasonic amplitude in \(X\) direction.

The radial force on the machined surface during ultrasonic machining is:

\[
p' = p + F_x = p - A_xm(2\pi ft)^2 \sin(2\pi ft)
\] (2-16)

The height difference of plastic flow generated on the machined surface during ultrasonic machining \(\Delta h\) is:

\[
\Delta h = 2R \left(1 - \frac{0.33h}{\sigma_m} \right) - \left(\frac{9}{16} \frac{p - A_xm(2\pi ft)^2 \sin(2\pi ft)}{E^2R}\right)^{\frac{1}{3}}
\]

When considering the influence of elastic deformation and micro plastic deformation on surface roughness, the surface roughness of deep holes is:

\[
R_{a'} = R_{th} + \Delta h
\]

\[
= \left(\frac{A}{4}\right) \left(\frac{v_F}{f A_c}\right)^2 + \left[2R \left(1 - \frac{0.33h}{\sigma_m} \right) - \left(\frac{9}{16} \frac{p' - A_xm(2\pi ft)^2 \sin(2\pi ft)}{E^2R}\right)^{\frac{1}{3}}\right]
\]

(2-17)

2.3.3 Simulation of surface roughness

Based on the above theoretical model of surface roughness, take ultrasonic frequency \(f=20\text{KHz}\), ultrasonic amplitude \(A=3\mu m\), spindle speed \(n=600\text{r/min}\), feed rate \(f_r=0.15\text{mm/r}\). Use MATLAB software to program and calculate, and the results are shown in Fig. 7.
As shown in Fig.7, the surface roughness value of 2D-UEVT is much less than that of CT. The theoretical amplitude of the residual height on the surface of CT is the same, and the residual height formed on the surface of 2D-UEVT shows periodic fluctuations. It shows that 2D-UEVT is more conducive to the formation of micro texture on the processed surface, thus affecting the quality of the machined surface.

3 Test device and method

3.1 Test device

The CNC lathe CK6140 was used for the experiment of two-dimensional ultrasonic elliptical vibration turning 7075 aluminum alloy deep hole. The 2D-UEVT tool is installed and fixed on the tool holder of the machine tool. The turning tool and the ultrasonic generator are connected by cables. The electrical signal generated by the power supply is transmitted to the transducer inside the 2D-UEVT tool to generate the required vibration signal. One end of the workpiece is fixed with a three jaw chuck, and the other end is fixed with a tool rest. As the wall thickness of 7075 aluminum alloy tube is only 5mm, if it is directly clamped on the three jaw chuck, excessive clamping force will cause deformation of the workpiece, and too small clamping force will cause instability of the workpiece axis, which will affect the test results. Therefore, an auxiliary support washer is used at the three jaw chuck end to clamp and protect the workpiece, so that the excessive clamping force does not directly act on the workpiece and will not cause deformation impact on the workpiece. Because the length of the workpiece is 430mm, there will be a large swing when rotating, so the workpiece is axially fixed with the tool rest at the turning end. The test platform is shown in Fig.8-1, and the workpiece is shown in Fig.8-2.
The type of turning tool used in the test is DCGT070204-AK, and the specific parameters are shown in Tab.1. The workpiece is 7075 aluminum alloy tube, with an inner diameter $\phi = 70 \text{mm}$, a wall thickness of $h_0 = 5 \text{mm}$, and a length of $L_0 = 430 \text{mm}$. The depth diameter ratio of the workpiece is $L_0/\phi = 6.14 > 5$. The workpiece is a deep hole.

\begin{tabular}{|c|c|c|c|c|}
\hline
material & Cemented carbide & \\
\hline
Anterior horn/(°) & 0 & \\
Posterior angle/(°) & 7 & \\
Tip radius/mm & 0.4 & \\
Knife tip angle/(°) & 55 & \\
Principal deflection angle/(°) & 62.5 & \\
Blade inclination/(°) & 0 & \\
\hline
\end{tabular}

In order to study the influence of ultrasonic amplitude, cutting depth, Spindle speed and feed rate on the machined surface, an orthogonal test scheme is designed as shown in Tab.2.

\begin{tabular}{|c|c|c|c|c|}
\hline
levels & $f_r (\text{mm/r})$ & $n (\text{mm/r})$ & $a_p (\text{mm})$ & $A (\mu\text{m})$ \\
\hline
1 & 0.05 & 200 & 0.1 & 1 \\
2 & 0.1 & 400 & 0.15 & 2 \\
3 & 0.15 & 600 & 0.2 & 3 \\
4 & 0.2 & 800 & 0.25 & 4 \\
\hline
\end{tabular}

3.2 Test method

The laser displacement sensor (LKG10) produced by KEYENCE Company is used for amplitude measurement, and the sampling frequency is 50kHz. Adjust the frequency of the ultrasonic generator to the frequency range matching the natural frequency of the 2D ultrasonic vibration turning tool, and measure the amplitude and trajectory of the 2D ultrasonic vibration turning tool. The ultra-depth of field microscope VHX-2000 was used to observe the micro topography of the deep hole turning surface of the workpiece, and the BRUKER GTK white light interferometer was used to measure the surface parameters of the workpiece, with a sampling area of $350 \times 475 \mu\text{m}$, the sampling parameter is $5000 \mu\text{m/s}$, and the sampling interval is $10 \mu\text{m}$. Select 5 measuring points for each machined surface, and calculate the average value as the measurement result.
4 Test results and analysis

4.1 2D ultrasonic vibration turning tool trajectory measurement

The amplitude of the designed turning tool was measured by KEYENCE’s laser displacement sensor (LK-G10). Fig. 9 (a) shows a set of displacement waveforms obtained by measurement. Import the measured amplitude data into ORIGIN software for analysis, as shown in Fig.9 (b), it can be seen that the actual vibration trajectory is approximately elliptical.

![Fig. 9 (a) Ultrasonic amplitude test results](image1)

![Fig. 9 (b) The vibration trajectory of the tool](image2)

4.2 Influence of turning parameters on surface roughness

Because the machined surface is the inner surface of aluminum alloy tube, the workpiece should be cut before measuring the surface roughness. As shown in Fig.10, the BRUKER GTK white light interferometer was used to measure the roughness and observe the surface topography of the cut workpiece surface. The results are shown in Tab.3.

![Fig.10 Observations of the scene](image3)

<table>
<thead>
<tr>
<th>Test number</th>
<th>$f_r$ (mm/r)</th>
<th>$n$ (mm/r)</th>
<th>$a_p$ (mm)</th>
<th>$A$ (μm)</th>
<th>$Ra$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>0.05</td>
<td>200</td>
<td>0.1</td>
<td>1</td>
<td>0.941</td>
</tr>
<tr>
<td>T-2</td>
<td>0.05</td>
<td>400</td>
<td>0.15</td>
<td>2</td>
<td>1.283</td>
</tr>
<tr>
<td>T-3</td>
<td>0.05</td>
<td>600</td>
<td>0.2</td>
<td>3</td>
<td>0.776</td>
</tr>
<tr>
<td>T-4</td>
<td>0.05</td>
<td>800</td>
<td>0.25</td>
<td>4</td>
<td>0.981</td>
</tr>
<tr>
<td>T-5</td>
<td>0.1</td>
<td>200</td>
<td>0.2</td>
<td>2</td>
<td>0.735</td>
</tr>
<tr>
<td>T-6</td>
<td>0.1</td>
<td>400</td>
<td>0.25</td>
<td>1</td>
<td>0.612</td>
</tr>
<tr>
<td>T-7</td>
<td>0.1</td>
<td>600</td>
<td>0.1</td>
<td>3</td>
<td>0.382</td>
</tr>
<tr>
<td>T-8</td>
<td>0.1</td>
<td>800</td>
<td>0.15</td>
<td>4</td>
<td>0.58</td>
</tr>
<tr>
<td>T-9</td>
<td>0.15</td>
<td>200</td>
<td>0.25</td>
<td>3</td>
<td>0.716</td>
</tr>
<tr>
<td>T-10</td>
<td>0.15</td>
<td>400</td>
<td>0.2</td>
<td>4</td>
<td>0.507</td>
</tr>
<tr>
<td>T-11</td>
<td>0.15</td>
<td>600</td>
<td>0.15</td>
<td>1</td>
<td>0.753</td>
</tr>
</tbody>
</table>
In order to explore the influence of different processing parameters and acoustic parameters on the machined surface roughness, range analysis and variance analysis were conducted on the data in Tab.3. The results are shown in Tab.4 and Tab. 5.

Fig.11 is drawn based on the range analysis results, and the optimal processing parameter can be obtained as $f_r = 0.1\text{mm}/r$, $n = 600 \text{r/min}$, $A = 4 \mu\text{m}$, $a_p = 0.1\text{mm}$.

As shown in Tab.5, it can be seen that the mean square error of the cutting depth is smaller than the mean square error of the error, that is $0.008582 < 0.010699$, which indicates that the cutting depth has a relatively small impact on the machined surface roughness Ra and should be classified as error. Therefore, it is necessary to recalculate the degrees of freedom, mean square deviation and the sum of squares of deviations. The recalculated degree of freedom becomes 6, and the sum of squares of the total error is 0.057782, so the mean square deviation of the recalculated error is 0.00963.

Check the table, $F_{0.05}(3,6) = 4.76$, $F_{0.01}(3,6) = 9.78$. $F_{f_r} =11.164683 > 4.76$, $F_A = 6.483327 > 4.76$, $F_n = 5.068586 > 4.76$. Therefore, for the significance level $\alpha = 0.05$, the factors that affect the surface roughness of deep holes from large to small are: feed rate, Ultrasonic amplitude, Spindle speed, cutting depth.

---

### Tab.4 Range analysis of Ra

<table>
<thead>
<tr>
<th>levels</th>
<th>Spindle speed</th>
<th>Feed rate</th>
<th>Cutting depth</th>
<th>Ultrasonic amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>0.77343</td>
<td>0.99489</td>
<td>0.72788</td>
<td>0.72788</td>
</tr>
<tr>
<td>K2</td>
<td>0.76405</td>
<td>0.57713</td>
<td>0.82925</td>
<td>0.93305</td>
</tr>
<tr>
<td>K3</td>
<td>0.67263</td>
<td>0.72725</td>
<td>0.73538</td>
<td>0.68175</td>
</tr>
<tr>
<td>K4</td>
<td>0.85445</td>
<td>0.76532</td>
<td>0.77206</td>
<td>0.64238</td>
</tr>
<tr>
<td>range</td>
<td>0.18181</td>
<td>0.41775</td>
<td>0.10137</td>
<td>0.29068</td>
</tr>
</tbody>
</table>

### Tab.5 Ra variance analysis

<table>
<thead>
<tr>
<th>factors</th>
<th>sum of squares of deviations</th>
<th>freedom</th>
<th>Mean square error</th>
<th>F ratio</th>
<th>significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>0.066395</td>
<td>3</td>
<td>0.022132</td>
<td>5.068586</td>
<td>0.282873</td>
</tr>
<tr>
<td>$f_r$</td>
<td>0.358238</td>
<td>3</td>
<td>0.119452</td>
<td>11.164683</td>
<td>0.039010</td>
</tr>
<tr>
<td>$a_p$</td>
<td>0.025715</td>
<td>3</td>
<td>0.008582</td>
<td>0.802137</td>
<td>0.569756</td>
</tr>
<tr>
<td>$A$</td>
<td>0.208012</td>
<td>3</td>
<td>0.69364</td>
<td>6.483327</td>
<td>0.079521</td>
</tr>
<tr>
<td>Error</td>
<td>0.032067</td>
<td>3</td>
<td>0.010699</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$F_{0.05}(3,6) = 4.76$, $F_{0.01}(3,6) = 9.78$

It can be seen from Fig.11 that: (1) With the increase of the feed rate, the surface roughness Ra showed a trend of decreasing first and then increasing. When the feed rate increases, the material removal rate per unit time increases, and
the residue after turning will also increase. Incomplete material removal is easy to occur on the machined surface, resulting in poor quality of the machined surface. Therefore, selecting the appropriate feed rate during machining can significantly reduce the surface roughness;

(2) With the increase of spindle speed, the surface roughness Ra showed a trend of first decreasing, then increasing. When the speed reaches 600 \( r/min \), the surface roughness reaches the minimum value. According to the analysis of equation (2-12), this was because the cutting speed increases with the increase of spindle speed. When the cutting speed exceeds the critical cutting speed, \( SR > 1 \), the ultrasonic separation phenomenon will be weakened, and the effect of ultrasonic turning will also be weakened. At this time, the two-dimensional ultrasonic vibration turning will be weakened into one-dimensional longitudinal ultrasonic vibration turning, resulting in the increased roughness of the machined surface;

(3) With the increasing of ultrasonic amplitude, the surface roughness Ra showed a trend of increasing first and then decreasing. When the ultrasonic amplitude \( A = 4 \mu m \), the surface roughness Ra is the minimum. The reason for this phenomenon was that when the ultrasonic amplitude is small, the smaller ultrasonic amplitude has no obvious effect on the surface dressing. With the increase of the ultrasonic amplitude, the elliptical vibration also increases correspondingly. The periodic separation and contact between the tool and the workpiece will make the tool produce periodic ironing and dressing on the machined surface in the feed direction, so that the surface quality was improved;

(4) The influence of cutting depth on roughness is not significant.

![Fig. 11 Effect of machining parameters on surface roughness](image)

4.3 Influence of turning parameters on surface micro-texture

The workpiece after ultrasonic cleaning was observed by VHX-2000 ultra-depth of field microscope, and the surface micro morphology of common turning deep hole and 2D ultrasonic vibration turning deep hole was compared and analyzed. As shown in Fig.12. Where (a) and (b) are the surface topography of common turning deep holes, and (c) and (d) are the surface topography of 2D ultrasonic elliptical vibration turning deep holes. It can be seen that the surface microstructures of common turning deep hole after machining presents a furrow shape, and the lines are messy, with obvious scratches, furrows, tears and other defects; The surface microstructures machined by 2D ultrasonic elliptical vibration turning has regular micro texture with uniform distribution.
In order to observe the processed surface topography more finely, the BRUKER GTK white light interferometer was used to observe the surface topography of the deep hole. As shown in Fig. 13. The plough phenomenon on the surface of common turning is irregular, with obvious defects such as scaling, scratches, furrow and tear. There are regular groove like microstructures on the surface of deep holes machined by 2D ultrasonic vibration, which are uniformly distributed. Through the analysis and simulation of the cutting edge motion trajectory, it can be seen that it is precisely because the unique motion characteristics of 2D ultrasonic vibration turning change the motion trajectory of the cutting edge, making the cutting edge periodically contact---separate with the workpiece, which can form a unique micro texture morphology on the machined surface.
5 Conclusion

In this paper, a single excited asymmetric 2D elliptical vibration turning tool was used to analyze its elliptical vibration principle and the motion trajectory of the tool tip for deep hole turning. A theoretical model of the surface roughness of 2D ultrasonic vibration turning deep hole was established. The orthogonal 2D ultrasonic vibration cutting experiment and the contrast experiment between 2D ultrasonic vibration turning and common turning were carried out, and the following conclusions were obtained:

(1) By measuring the vibration trajectory of 2D ultrasonic vibration turning tool, the elliptical vibration trajectory of 2D ultrasonic vibration turning tool with single excitation is verified, and the trajectory presents a regular elliptical shape.

(2) By comparing the simulation results of surface roughness, it is found that the surface roughness value of 2D ultrasonic vibration turning deep hole is far less than that of common turning. Moreover, the residual height formed on the machined surface by 2D ultrasonic vibration deep hole turning fluctuates periodically. It shows that 2D ultrasonic vibration turning is more conducive to the formation of micro texture on the machined surface.

(3) The optimal processing parameters were obtained by range analysis of the orthogonal test results: \( f_r = 0.1 \text{mm/r}, n = 600 \text{r/min}, A = 4 \text{\mu m}, a_p = 0.1 \text{mm}. \) Through the analysis of the test results, it is found that the influence of each factor on the surface roughness of deep hole is in the following order: feed rate, ultrasonic amplitude, spindle speed, cutting depth.

(4) Through the research on the surface morphology of 7075 aluminum alloy tube after deep hole machining, it is found that compared with the burr and plough cut marks on the surface of common deep hole machining workpiece, the ultrasonic cutting workpiece surface has uniform texture and regular groove like micro-texture.

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Declarations

Ethical approval  This paper is new. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal as well.
Consent to participate  Not applicable

Consent to publish  Not applicable

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