Theoretical and experimental investigations of ultrasonic vibration–assisted boring for titanium alloy

Danni Lu · Yaoyao Shi · Pan Zhao

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Abstract
To effectively cope with the hard machinability challenges of hole caused by difficult-to-cut materials and high processing standards in aviation field, ultrasonic vibration–assisted boring (UB) methods with different modes are proposed. In this paper, the kinematics characteristics of UB were analyzed, the motion trajectory of tool was discussed. The comparison experiment of conventional boring and UB with longitudinal vibration and longitudinal-torsional vibration was performed to study the effect of ultrasonic field on the boring process, the influence of main parameters on boring force and surface roughness were investigated. The results show that UB can reduce boring force and surface roughness effectively, especially with the help of longitudinal-torsional vibration, compared with the conventional boring, the boring force could be reduced by 38.04–43.77%, and the surface roughness could be reduced by 25.48–41.47%. This study proves the feasibility of UB and provides theoretical and experimental reference for improving the surface quality of difficult-to-machine holes.

Keywords Ultrasonic vibration–assisted machining · Boring · Cutting force · Surface roughness

1 Introduction
Hole processing is one of the most common machining methods, the machining quality and efficiency influence the service performance, production cycle and production costs of the components directly [1, 2]. With the continuous progress of the field of aeronautics and astronautics, more and more holes are used for special purposes and requirements, such as the inner holes of some servo valve sleeves, action cylinders of aircrafts and transmission shafts. These kinds of holes have higher dimensional accuracy, contour accuracy and surface roughness requirements, and most parts of them involve difficult-to-cut material, which make hole processing (especially deep eyelet) much more difficult and extremely expensive [3–5].

Compared with “drilling-flaring-reaming” process, boring has stronger capability of error-correction, it can correct the axis error of the original hole and make the processed hole and the positioning surface maintain a higher position accuracy, it is a common processing method for precision hole parts and is also almost the only method for holes with larger diameter and higher size requirements [6]. Moreover, conventional boring methods have major drawbacks in the process of difficult-to-cut materials machining, such as difficult heat dissipation, hard chip removal, easy chatter, and large thermal deformation.

In view of the problem that the attitude cannot always be controlled when the tool deviates in conventional boring, Katsuki et al. [7] improved the boring cutter in three aspects and developed a practical laser-guided deep-hole boring cutter with a diameter of 110 mm to prevent hole deviation. Xiao et al. [8] proposed a novel approach to the machining condition monitoring of deep hole boring on the basis of the pseudo non-dyadic second-generation wavelet transform to achieve product quality control and tool cost reduction, and verified the effectiveness of this method through experiments. In view of the vibration phenomenon in the boring process, Dai et al. [9] developed a vibration-damping boring bar by changing the material, and the dynamic stiffness has been increased by 30% compared with the boring bar with hard alloy, the experiment results showed that there was still no obvious chatter in the cutting process and the
quality of the processed surface was improved. Matsubara et al. [10] have tried to suppress vibration of boring bar by use of piezoelectric actuators, but the control system is complicated on usual and difficult to be applied in the field of actual machining.

With the extensive application of ultrasonic vibration field in the machining process, many processing problems have been solved, especially for hard-cutting materials. Zhang et al. [11] conducted rotary ultrasonic drilling experiment on optical K9 glass with compressed air as a coolant and analyzed the effects of ultrasonic power, spindle speed, and feed rate on cutting force, surface roughness and ultrasonic power consumption. Li et al. [12] investigated the influence of the ultrasonic vibration on ceramic matrix composites, and found that the hole accuracy under ultrasonic vibration could be improved. Ding et al. [13] conducted rotary ultrasonic machining and conventional drilling tests with a diamond core drill on C/SiC composites, the effects of ultrasonic vibration on mechanical load and machining quality were studied by comparing the drilling force, torque, quality of holes exit and surface roughness of drilled holes between the two processes, and the results showed that the drilling force and torque under ultrasonic vibration were reduced by 23% and 47.6%, respectively. Lian et al. [14] have studied the effect of vibration on surface roughness by ultrasonic vibration–assisted micro-milling of Al6061, the results show that the relationship between vibration amplitude and surface roughness was not a simple negative correlation, but there was an optimal amplitude that made the surface roughness least. Xu et al. [15] investigated the chip formation mechanism and its influence on cutting forces during the elliptic vibration–assisted cutting of fiber-reinforced polymer composites and found that vibration minimize the fiber orientation effect on chip formation and cutting forces. Chern and Chang [16] investigated the effects of ultrasonic-assisted vibration cutting on the micro-milling quality of aluminum alloy on a two-dimensional vibrating worktable and found that slot oversize, displacement of slot center, and surface roughness could be improved by imposing vibration, and the result pointed out that the amplitude of the ultrasonic vibration is an important parameter which can be optimized to achieve good surface roughness. Xu et al. [17] designed a series of slot-milling experiments with vibration at different amplitudes and feed rates to explore the effects of vibration on the micro-milling, experiment results showed that milling force was effectively reduced by 12% and 17%, respectively, for aluminum alloy 6061T6 and titanium alloy TC4 compared with conventional micro-milling, the effect is much more obvious in titanium alloy processing; besides that, milling with vibration could lead to an improved machined surface and better machining accuracy. Li et al. [18] studied rotary ultrasonic–assisted drilling of titanium alloys utilized 8-facet drill under no cooling condition and confirmed the feasibility and superior cutting effects of the processing method, experiments found that ultrasonic-assisted drilling can greatly reduce the trouble and cost of deburring operations, the axial drilling force can be reduced by 19.07–20.09% compared with that of conventional drilling process.

However, based on the existing research, there has been relatively little research on ultrasonic vibration–assisted boring (UB), and no attention has been paid to UB under different vibration modes. In the pilot experiments, which focused on the performance of UB of the authors’ previous study, it was found that UB can obviously improve the quality of machined surface. In order to press the method into service, there is a dire need to study the processing mechanism of UB and the influence of ultrasonic vibration on machining process.

In this paper, the cutting characteristics of UB were analyzed, the kinematics characteristics and the motion trajectory of boring tool were discussed to understand the complexity of boring process with different ultrasonic vibration mode, the comparative experiments of conventional boring (CB), longitudinal ultrasonic vibration–assisted boring (L-UB), and longitudinal-torsional ultrasonic vibration–assisted boring(LT-UB) were conducted to study the influence of ultrasonic field on the boring force and surface roughness. Meanwhile, the influences of significant influential parameters on boring force and surface roughness were analyzed.

# 2 Mechanism of ultrasonic vibration assisted boring

## 2.1 The processing principle of UB

The machining mode of ultrasonic vibration–assisted machining is essentially different from conventional machining [19–21], the widely publicized case is that the additional ultrasonic vibration transforms the interaction between the workpiece and the tool from continuous into intermittent, which affects the cutting force and cutting heat during the processing, and further effectively improves the machining surface quality of the workpiece. As shown in Fig. 1, different machining methods correspond to different tool motion modes, the tool rotates around the spindle and keeps feeding in CB, the tool with vibration of ultrasonic frequency and low amplitude along the longitudinal direction in L-UB, while LT-UB has one more torsional vibration around the tool axis than L-UB, the movement of boring tool changes into a complex motion which is composed of feed motion, longitudinal and torsional ultrasonic vibration.
Kinematics analysis of boring tool in UB

In view of the above matching system, a coordinate system for trajectory analysis can be established. Look along the Z direction in Fig. 1, the projection of workpiece and tool on XOY plane is shown in Fig. 2, the eccentricity between the boring bar axis and the machining hole axis is \( e \) and the radius of the boring tool is \( r \), the radius of the machined hole is \( R \), \( (R = r + e) \). As shown in Fig. 2, the coordinate system O-XYZ is fixed to the boring tool, we take axis and the center of the coordinate, the coordinate system \( O_1-X_1Y_1Z_1 \) is fixed to the workpiece, we take axis of rotation and the center of the workpiece as the \( Z_1 \) axis and the origin of the coordinate. In L-UB process, the movement of the tool relative to the workpiece consists of a feed motion with a feed speed of \( u_f \), a rotation motion around the spindle at a circumferential speed of \( n \), and a reciprocating vibration with an amplitude \( A_z \) in Z direction. In the LT-UB process, the additional ultrasonic vibration includes longitudinal vibration with an amplitude of \( A_z \) along the Z direction and torsional vibration around the tool axis, the phase difference between the two different vibrations is \( \phi \).

The contact point between the boring tool and the workpiece is set to P, the influence of different machining methods on the processing process can be reflected from the trajectory of the point.

In CB, there is no vibration applied to the boring tool, with the workpiece coordinate system \( O_1-X_1Y_1Z_1 \) as the reference system, the tool coordinate system \( O-XYZ \) rotates around the \( Z_1 \) axis, and the coordinate of P under the tool coordinate system O-XYZ is \((x, y, z)\), which is converted to the workpiece coordinate system \( O_1-X_1Y_1Z_1 \) as \((x_1, y_1, z_1)\), the motion trajectory of P can be expressed as follows:

\[
\begin{align*}
S_{x_1} &= (r + e) \cos \frac{\pi nt}{30} \\
S_{y_1} &= (r + e) \sin \frac{\pi nt}{30} \\
S_{z_1} &= u_f t
\end{align*}
\] (1)

When the longitudinal ultrasonic vibration is applied, the tool generates high frequency vibration along the axis of the tool bar, and the motion trajectory of P has been changed, it can be expressed as follows:

\[
\begin{align*}
S_{x_2} &= (r + e) \cos \frac{\pi nt}{30} + A_z \sin(2\pi f_z t + \phi) \\
S_{y_2} &= (r + e) \sin \frac{\pi nt}{30} + e \cos \frac{\pi nt}{30} \\
S_{z_2} &= A_z \sin(2\pi f_z t) + u_f t
\end{align*}
\] (2)

Where \( A_z \) is the amplitude of longitudinal ultrasonic vibration, \( \mu m, f_z \) is the frequency of longitudinal ultrasonic vibration, kHz.

In LT-UB, when composite vibration is applied to the processing, the mode of vibration in tool is not only longitudinal vibration along the axis of bar, but also torsional vibration along the tangential direction. The motion trajectory of P can be expressed as follows:

\[
\begin{align*}
S_{x_3} &= (r + e) \cos(\frac{\pi nt}{30} + A_\phi \sin(2\pi f_\phi t + \phi) + e \cos \frac{\pi nt}{30}) \\
S_{y_3} &= (r + e) \sin(\frac{\pi nt}{30} + A_\phi \sin(2\pi f_\phi t + \phi) + e \sin \frac{\pi nt}{30}) \\
S_{z_3} &= A_z \sin(2\pi f_z t) + u_f t
\end{align*}
\] (3)
Where $A_{\phi}$ is the amplitude of torsional ultrasonic vibration, $\mu m$, $f_{\phi}$ is the frequency of longitudinal ultrasonic vibration, kHz; $\phi$ is the phase difference between torsional vibration and longitudinal vibration.$^6$

### 2.3 Analysis of the effect of ultrasonic vibration in boring process

According to the trajectory model, the motion trajectory of tool under different machining process can be obtained. For simplicity, several major assumptions are made in the paper for research object:

1. The hardness of the tool is much greater than that of the workpiece, it is assumed here that the boring tool is rigid.
2. Ultrasonic vibration is kept in a stable condition during the boring process, in other words, once the amplitude and frequency are set, they remain unchanged.
3. The shape of the tool is invariable in machining process, that is, the integrity of the tool will not be damaged due to the machining state.
4. The influence of factors such as processing environment temperature and humidity on the tool action process can be ignored.

When ultrasonic frequency $f_c = f_{\phi} = 24$kHz, amplitude $A_{\phi} = A_{\phi} = 4\mu m$, and $\phi = 90^\circ$, feed rate $v_f = 0.01$mm/s, spindle speed $n = 140$ r/min, radius of the boring tool $r = 5$mm, eccentricity $e = 3$mm, the curve of tool trajectory under different machining process is obtained as shown in Fig. 3.

As shown in Fig. 3a, the motion trajectory of boring tool in CB is a spiral line formed by cutter along with the processing, both direction and size of the cutting angle and velocity are constant. Extremely different from in CB, when the ultrasonic vibration is applied, the motion trajectories of boring tool in UB are curve line and keep the actual cutting angle of tool constantly change, that means the tool contributes to the surface formation in a periodically changing manner. Especially in LT-UB, it will make the contact motion between the cutter and material to be processed change from traditional continuous to high-frequency intermittent, which is advantageous for reduction of the boring temperature and chip removal. Beyond that, the trajectory length of tool in UB is much longer than in CB, that means the tool could make a greater contribution to the chip travel in the same period of time, more material removal can be achieved.

By the comparison of Fig. 3b, c, the effect on machining trajectories of different ultrasonic vibration modes were known as greatly different, it can be seen from the local projection of the trajectory on the L-Z plane, L represents arc length of tool, the trajectory is sinusoidal curve and oval under longitudinal mode and longitudinal-torsional mode, respectively. Corresponding to the actual processing, no matter the mode, non-linear machining trajectory will invest cutting tool with a periodic drag effect on the chip, which will be beneficial to the chip breaking in a relatively closed machining space. In addition, the boring tool under LT-UB shows a “separation characteristic,” oval trajectory under composite vibration will make the tool periodically retreat relative to the cutting direction in the machining process, further lead to a separation of the tool from the chip and the material to be processed which can make better performance in force reduction and wear alleviation. Another notable feature is the overlapping characteristic of the trajectories in LT-UB, boring tool can conduct a repeated removal effect on the workpiece material, at the same time, the increasing degree of cutting length is more prominent.

![Fig. 3](image) The trajectory of boring tool a CB, b L-UB, c LT-UB

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As stated above, the machining mode has been fundamentally changed by applying ultrasonic vibration to the boring process, the continuous processing in the macro view is actually high-frequency intermittent processing in the micro view, it brings a series of benefits to the machining process and the surfaces formation.

Further research on the trajectory description formula, the influence of ultrasonic parameters on the boring process also can be obtained. As shown in Fig. 4, in terms of vibration mode, frequency and amplitude, when the different mode vibration act on the tool together, their influence on the machining process is not single but interactive. As far as their respective outstanding functions are concerned, the increase of frequency will increase the contact time between the cutting tool and the workpiece, that is to say, the cutting tool has more contact times with the workpiece per unit time, as shown in Fig. 4a, it can help the cutting fluid play a greater role, and provide conditions for further thermal damage reducing and chip accumulation. As shown in Fig. 4b, with the increase of the longitudinal amplitude, the cutting length of the tool is increased, and the impact effect applied to the material to be processed caused by vibration increases correspondingly. Longer cutting length and impact effect to the machining process will allow for more effective material removal. Through the simulated image shown in Fig. 4c, we can see that the introduction of torsional vibration not only further grows the cutting length, but also keeps the trajectory present a state of interlacing, increase the torsional amplitude will cause more denser trajectory interleaving. The trajectory under compound vibration is longer than that under single longitudinal vibration, which is helpful to improve the machining efficiency obviously. The interleaving of the trajectories make the material removal of the workpiece surface more uniform and complete, which also greatly reduce the surface roughness, thus improving the quality of the workpiece.

3 Experimental methodology

3.1 Experimental setup

All experiments were performed on a modified lathe (BOCHI MACHINE TOOL - HK63) with an ultrasonic vibration-assisted boring system, it can facilitate the switch between UB and CB by turning the ultrasonic generator on or off and avoid assembly errors. A chute is arranged at a specific position of the transformer to realize the conversion from single longitudinal vibration to longitudinal-torsional composite vibration, this method avoids the problem of transducer replacement and matching, it has been used by Wang et al. [25]. This structure makes use of phenomena that the reflection and refraction of waves when they pass through the material.
through different media. The vibration in a single direction produces two components at the position of the chute, one along the axial direction of the transformer and the other along the circumferential direction of the transformer. The width of the chute is far less than the wavelength of sound waves, so the waves will be superimposed repeatedly at the chute after conversion, resulting in a composite vibration mode at the end of the transformer.

Figure 5 shows the experimental setup, ultrasonic generator applies electrical energy to a piezoelectric transducer, in which the piezo-ceramic rings generate high-frequency low-amplitude mechanical vibration, then it is transferred to the amplitude transformer to realize amplification and mode conversion, the generator’s fixed frequency is 24 kHz. The modified lathe can realize stepless speed regulation in the range of 0–2000 r/min, and the feed speed can realize stepless speed regulation in the range of 0–10 mm/min. According to boring process and materials, the coated cemented carbide tool is selected as the processing tool in the test, and the type of boring tip is TCGT090202L-K 1125.

### 3.2 The boring conditions

In this study, the material of workpiece for boring test is Ti-6Al-4 V, which is good at comprehensive mechanical properties but sensitive to surface damages and defects; it is a typical difficult-to-machine material with a wide range of applications, especially in aviation field [22–24]. Its chemical composition is listed in Table 1.

Several experiments were carried out by varying the levels of cutting speed, feed rate, depth of cut, and vibration amplitude, the values of each parameter were listed in Table 2, the experiment was carried out by single factor test and designed with four factors and three levels. The amplitude of vibration was controlled by adjusting the output powers of the ultrasonic generator, according to the description of the equipment, we measure the amplitudes by using displacement sensors and Z101-G dual-channel vibration measuring instrument in the experiment, found that the amplitude increases with the increase of output power at resonance frequency, so the output power was used to represent the amplitude.

### Table 1 Chemical composition of Ti-6Al-4 V titanium alloy

| Element | Al  | V    | Fe   | Si  | C   | N   | H    | O    | Other |
|---------|-----|------|------|-----|-----|-----|------|------|-------|
| Wt pct  | 5.5–6.5 | 3.5–4.5 | 0.08 | ≤0.15 | ≤0.10 | ≤0.05 | ≤0.01 | ≤0.20 | 0.11  |
3.3 Cutting force and surface roughness measurements

Investigations were carried out into the comparison of UB and CB, the effect of main parameters on boring force and surface roughness was studied. In order to achieve reliable data, each test was repeated three times and a final value was obtained by averaging the obtained results, the boring tool was dressed after each group of the tests.

As shown in Fig. 6, the boring force was measured by Kistler 9257B three-way dynamometer, the sampling frequency is 5000 Hz per channel, the matching equipment is 5070A charge amplifier and SIRIUSi-STG8 data collector. Three-dimensional surface topography was measured by a MarSurf XR 20 surface measuring station, produced by MahrCo. Ltd. The arithmetic mean of the surface roughness, Ra, was calculated using the surface profile information.

4 Results and discussion

4.1 Analysis of boring force

Cutting force is not only an important reference indicator in machining performance, but also the foundation of flutter prediction and surface topography estimate, the influence of each parameter on the boring force under different methods is shown in Fig. 7. Taken as a whole, it can be seen that the force in UB is lower than in CB under the same processing conditions and reduced by 38.04% and 43.77% respectively, in L-UB and LT-UB compared with in CB. It is mainly due to the impact action of the tool which can make the material removal becomes easier and the separation effect which can improve the closed cutting environment in the machining process. Furthermore, composite vibration has a better effect on force reduction, more thorough separation effect will cause a reduction of cutting resistance and dispersion of cutting heat which can jointly affect the reduction of the average cutting force in the machining process.

From Fig. 7a, it can be seen that the amplitude has obvious influence on the cutting force, with the increase of amplitude, the cutting force decreases firstly and then increases at 37.8 W. Combined with the above theory analysis, as the amplitude of vibration increases, the cutting force and impact effect enhances, chip breaking and cutting fluid utilization are better, especially in LT-UB. However, with the increase of the excitation voltage, the thermal power of the piezoelectric vibrator will increase rapidly, disturbing the natural frequency of the transducer and causing a reduction of the amplitude, thus adversely affecting the machining process. Therefore, with the precondition of piezoelectric transducer working properly, the amplitude of the vibration system can be selected to a higher value.

It can be seen from Fig. 7b that the cutting force gradually increases with the increase of the rotating speed, especially in Fp and Fc, the inhibition effect gradually weakens with the increase of rotational speed. This may be due to the fact that with the increase of rotating speed, the trajectory of cutting tools gently flat, and the original advantages of vibration polishing will be gradually weakened and even disappeared. Besides that, in order to avoid the deformation and chatter of the boring bar caused by excessive rotating speed, the smaller rotating speed should be considered on the premise of ensuring the necessary effect.

| Parameters          | Unit | Values       |
|---------------------|------|--------------|
| Rotating speed      | r/min| 300 300 380 460 540 |
| Feed rate           | mm/min| 0.1 0.1 0.14 0.18 0.22  |
| Depth of cut        | mm   | 0.02 0.02 0.03 0.04 0.05  |
| Amplitude (output powers) | W | 0 23.2 28.6 33 37.8  |
The cutting depth and the feed rate jointly determine the size of the cutting layer, thus affecting the cutting force. It is found through experiments that the cutting force gradually increases with the increase of the cutting depth and the feed rate. From Fig. 7c, it can be seen that the cutting depth has a great influence on $F_p$ and $F_c$, and the composite vibration has a greater influence on $F_p$. From Fig. 7d, it can be seen that the feed speed has significant influence on the component forces in three directions. This may be down to the increase of cutting layer thickness and tool load which is caused by the increase of the cutting depth and feed speed. In addition, the separation characteristic in LT-UB is weakened with the increase of the two parameters, the cutting force is further increased.

4.2 Surface roughness analysis of the workpiece

The surface roughness of each workpiece at the measuring position is listed in Fig. 8, it is apparent that the surface roughness in UB is lower than in CB and reduced by 25.48% and 41.47% in L-UB and LT-UB, respectively. The existence of torsional vibration makes the tool repeatedly act on the surface of workpiece material, the polishing-like effect can effectively reduce the residual height of the machined surface, which greatly reduces the surface roughness value. In addition, the fluctuation of Ra's value in UB is much smaller than in CB, it demonstrates that the surface defects of the workpiece decrease obviously with the introducing of ultrasonic vibration and its flatness gets better under the same conditions.
As shown in Fig. 8a, with the increase of amplitude, Ra decreases firstly and then increases at 37.8 W. The surface roughness decreased the most at 33 W which decreased by 48.15% and 56.79% under L-UB and LT-UB, respectively, compared with CB. In the previous analysis, as the amplitude increases, the impact effect is stronger and chip breaking is easier, the cutting force decreases significantly, thus the surface roughness value decreases accordingly. In addition, it is worth noting that the amplitude of ultrasonic vibration cannot be continuously increased without restriction, excessive amplitude will pose a threat to the rigidity of the cutting system, and the influence of amplitude on the tool tip trajectory is very complex, therefore, increasing the amplitude on the basis of ensuring the stability of the machining system is conducive to improving the machining quality.

It can be seen from Fig. 8b that the surface roughness value of the machined surface gradually increases with the increase of the rotation speed. With the addition of ultrasonic vibration, chip breaking is easier and the tool deformation is harder, the surface quality of boring is improved. However, the increase of rotating speed makes the cutting force significantly increase, the stiffness of the cutting system is affected and the tool will also be deformed in severe cases. On the other hand, with the continuous increase of speed, the machining process gradually tends to be unstable, the optimization effect of vibration is weakened and gradually lost, then the surface roughness increases.
As Fig. 8c, d shows, the surface roughness increased with the increase of the cutting depth and feed rate. As the depth of cut grew, the increased cutting force and temperature destabilized the boring process and further lead to the decline of surface quality significantly, greater cutting depth will cause great resistance to vibration which further limits the reduction of surface roughness. During the UB manufacturing process, higher feed rate implied longer travel of the tool in the feed direction, more obvious tool wear will lead to a high surface roughness value.

5 Conclusions

In this investigation, the kinematic analysis of UB is carried out, the motion trajectory equations of the boring tool in CB, L-UB, and LT-UB are derived. Besides, the comparison experiment and analytical research of different boring methods are performed to study the influence of ultrasonic field on the boring process, the influence of main parameters on boring force and surface roughness are analyzed. The main contributions of this paper are demonstrated as follows:

1. The trajectory of L-UB and LT-UB is sinusoidal curve and oval, respectively, the actual cutting angle of tool constantly changes, and the trajectory length of tool in UB is much longer than in CB.
2. Further simulation and analysis have shown that nonlinear machining trajectory of UB will invest cutting tool with a periodic drag effect, the oval trajectory under composite vibration will make the tool periodically retreat relative to the cutting direction and keep the trajectories present a state of interlacing.
3. The increase of frequency will increase the contact time between the cutting tool and the workpiece, the increase of the longitudinal amplitude will increase the cutting length of the tool and the impact effect applied to the material to be processed, and the increase of the torsional amplitude will cause denser trajectory interlacing.
4. The cutting force and surface roughness under UB is smaller and more stable than CB, the improvement effect of LT-UB is more obvious than L-UB. Compared with CB, boring forces reduced by 38.04% and 43.77% in L-UB and LT-UB, respectively, surface roughness reduced by 25.48% and 41.47% in L-UB and LT-UB, respectively.
5. In UB, boring force increases with the increase of spindle speed, feed rate and depth of cutting, decreases firstly and then increases with the increase of the vibration amplitude. Surface roughness increases with the increase of spindle speed, feed rate and depth of cutting, decreases with the increase of the vibration amplitude.

This study proves the feasibility of UB and provides theoretical and experimental reference for improving the boring quality of difficult-to-machine holes. It is not advisable to increase the amplitude blindly in pursuit of better surface machining, further research on the interaction of various factors is needed in the future study.

Author contribution Danni Lu designed the framework of the thesis, carried out the experiments, and provided data analysis, Yaoqiao Shi contributed to the main idea of this paper, Pan Zhao participated in the writing of this paper.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate Not applicable.

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Conflict of interest The authors declare no competing interests.

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