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Deep Hole Drilling of Large-Diameter Titanium Alloy With a Novel Rotary Low-Frequency Vibration Device

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ABSTRACT Titanium alloy (Ti) has been widely used in aerospace industry due to excellent mechanical properties and the demands of Ti parts with a high length-to-diameter ratio and a large diameter are increasing. However, deep hole drilling of large-diameter Ti holes is usually both time-consuming and cost-consuming due to a series of problems such as unfavorable chip removal, helical structure on the hole surface, poor hole precision and severe tool wear. This paper reports on the cutting mechanism and experimental results of low-frequency vibration-assisted single-lip drilling (LFVASLD) of large-diameter Ti holes (Ø17mm) for the first time. In this paper, a novel rotary low-frequency vibration device was developed and the vibration generation mechanism was analyzed. Thereafter, the material removal mechanism of LFVASLD was established. Then, the comparative experiments between LFVASLD and conventional single-lip drilling (CSLD) of Ti were conducted. The experimental results show that, compared with CSLD, LFVASLD can significantly prolong the drilling depth by 9 times due to reduced tool wear and alleviate helical structure on the hole surface due to the separated cutting mode. Furthermore, the influence of drilling parameters in LFVASLD on hole quality were also investigated. It is concluded that, the LFVASLD method is suitable for deep hole drilling of large-diameter titanium alloy and the developed rotary low-frequency vibration device can be used as a machine tool accessory to significantly improve the processing capacity in the industrial practice.

INDEX TERMS Titanium alloy, deep hole drilling, low-frequency vibration-assisted drilling.

NOMENCLATURE

θ	inclination angle of the bearing (°)
e	eccentricity of the eccentric ball sleeve (mm)
φ	relative rotation angle of bearing inner and outer rings (°)
n_r	relative rotation speed between single-lip drill and outer hull (r/min)
n_{tool}	rotary speeds of the single-lip drill (r/min)
n_{hull}	rotary speeds of the outer hull (r/min)
$n_{\text{workpiece}}$	rotary speeds of the workpiece (r/min)
f	feed rate (mm/r)
α	angle of relative rotation between cutting edge and workpiece (°)
n	relative rotation speed between cutting tool and workpiece (r/min)
F	output frequency of rotary vibration system (Hz)
A	the output amplitude of rotary vibration system (mm)
a_p	cutting thickness of two consecutive turns of the cutting edge (mm)
K_A	the amplitude ratio, the ratio of the peak-to-valley amplitudes of vibration to the feed f
K_F	the frequency ratio, the ratio of vibration frequency to the relative rotational frequency

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I. INTRODUCTION

Titanium alloy (Ti) has been intensively used as the key components in aerospace, automotive, shipbuilding and petrochemical industries due to a variety of attractive properties such as high value of strength-to-weight ratio, excellent erosion resistance, high design flexibility etc. [1]–[3]. At present, the requirement of titanium alloy holes with a high length-to-diameter ratio (L/D>50) and a large diameter (D> Ø15mm) is increasing for airplanes and ships. Moreover, the narrow dimensional accuracy and high surface quality of the machined deep holes are usually required [4].

In the deep hole drilling process, a single-lip drill with an asymmetrical single-edged design is commonly employed [4]. The unfavorable long and continuous chips mixed with cutting fluid are ejected along the tool straight flute during deep hole drilling with a single-lip drill. As a result, chip jamming problem is easily induced, which can significantly deteriorate hole quality and reduce tool life as well as process efficiency. Hence, it is generally considered that chip removal during the single-lip drilling is the key factor for hole quality, tool wear and process stability in this process [5].

In order to achieve good chip breakage and removal in deep hole drilling, many researchers focused on optimizations of process parameter and tool geometry. Liu *et al.* [6] investigated chip morphologies at different cutting parameters during BTA drilling of Ti. However, the long and unfavorable chip forms were still generated at all cutting parameters. Nevertheless, a kind of narrow and long chips was successfully achieved by adjusting the distance of the drill cutting edges. Woon *et al.* [7] carried out an optimization of cooling design for the commercial single-lip drill based on a computational fluid dynamics model, which significantly improved chip evacuation. Tnay *et al.* [8] also investigated the effects of dub-off angle on chip evacuation in single-lip drilling. Besides, Biermann and Kirschner [9] optimized the single-lip drill geometry during drilling of small-diameter deep Inconel 718 holes and found the chip formation and removal were significantly improved by the optimized drill. Nevertheless, the improvement of chip removal rate by process and tool optimization in conventional single-lip drilling is still limited, due to the difficult control of chip formation in this process.

Recently, vibration-assisted drilling technique has been introduced to machine small-diameter deep holes due to the property of periodic intermittent cutting. Baghlani *et al.* [10] carried out the experiments of ultrasonic assisted deep hole drilling of Inconel 738LC (hole diameter Ø5mm and depth 50mm) with tungsten carbide twist drill. The experimental results demonstrated that, deep hole drilling of Inconel 738LC by conventional method was not possible due to fracture of drill bits. However, the ultrasonic assisted deep hole drilling can achieve better chip removal rate and better hole quality. Heisel *et al.* [11] developed a piezoelectric transducer and performed ultrasonic assisted deep hole drilling of ECu 57 with a small diameter (Ø5mm). The results showed that a higher surface quality and process stability can be achieved in ultrasonic drilling due to the favorable chip form and length, compared to conventional drilling. Nevertheless, the property of low amplitude of ultrasonic assisted machining caused by high inertia forces limits the application in the large diameter deep hole drilling because high load and long tool length can inevitably result in vibration losses at tool tip [12].

Low-frequency vibration-assisted drilling has also been introduced to machine deep holes with the advantages of high amplitude, easy realization of vibration and desirable drilling stability [13]. Bleicher *et al.* [14] investigated the influence of low-frequency and high-amplitude on the chip formation during vibration assisted single-lip drilling of age-hardened copper-zirconium (Ø0.94 and Ø1.84mm). In experiments, a piezo-driven vibration platform with vibration frequencies up to 500 Hz and amplitudes up to 30μm was employed. Experimental results indicated that the application of vibration-assistance at low frequencies and high amplitudes in single-lip drilling significantly improved chip breakage and removal, process characteristics and stability. Besides, low-frequency vibration-assistance drilling method has also been successfully used to drill conventional shallow CFRP/Ti stacked holes (L/D<2) by commercial mechanical tool holders [13], [15], [16]. However, up to now, a comprehensive investigation on low-frequency vibration-assisted deep hole drilling of large-diameter titanium alloy is still not available in the open literature. Moreover, neither the piezo-driven vibration platform nor commercial mechanical tool holders can be applied to the horizontal deep hole drilling machine tools, which are most commonly used for drilling deep hole parts. Therefore, in order to drill large-diameter deep hole of titanium alloy, it is urgent to develop a low-frequency vibration device, which can easily match the deep-hole drilling machine. The low frequency vibration device should have the characteristics of adjustable amplitude and frequency, stable vibration, and suitable for high load.

This paper investigated the feasibility of low-frequency vibration-assisted single-lip drilling (LFVASLD) of large-diameter titanium alloy for the first time. A novel rotary low-frequency vibration device with adjustable frequency and amplitude was designed and the vibration generation mechanism was analyzed. And, the kinematic model of LFVASLD was established. Thereafter, a comparative experiment between LFVASLD and conventional single-lip deep hole drilling (CSLD) of Φ17mm Ti hole were conducted. Finally, the influence of drilling parameters including amplitude, vibration frequency, cutting speed and feed speed in LFVASLD on hole quality were also comprehensively investigated and the optimum parameters were obtained.

II. DEVELOPMENT OF A ROTARY LOW-FREQUENCY VIBRATION-ASSISTED DRILLING DEVICE

Generally, the current low-frequency vibrators are usually designed on the basics of the mechanical, hydro-mechanical, piezoelectric and electromagnetical principles. According to the previous studies, the low-frequency vibrator based on mechanical principle can achieve a more manageable stability under high load [12], [17]. However, the current commercial mechanical vibrators (e.g. MITIS tool holders) can only be applied on the vertical machining centers with limited output

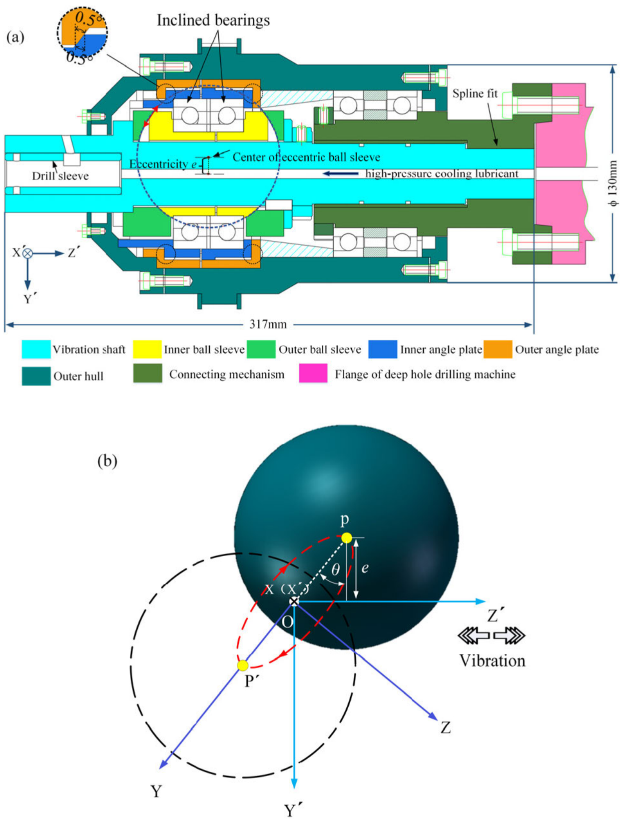

FIGURE 1. The illustration of (a) the structure and (b) the vibration generation mechanism of designed mechanical vibrator.

frequencies (e.g. oscillation/rev = 1.5 or 2.5) [16], [18]. For machining large-diameter deep Ti holes, the horizontal deep hole drilling special machine tools have to be used and more vibration parameters should be allowed in the industrial practice to achieve high hole quality and process efficiency. Therefore, it is urgent to develop a mechanical low-frequency vibration device for deep hole drilling machine tools, with adjustable amplitudes and frequencies for high load.

A. THE DESIGN OF MECHANICAL VIBRATOR

The schematic illustration of self-designed mechanical vibrator is shown in Fig.1(a). An innovative combination of an eccentric ball sleeve and two inclined angular contact ball bearings is set up to generate the low frequency axial vibration in the mechanical vibrator. The eccentric ball sleeve has a constant eccentricity of e while inclination angle θ of bearings is adjustable by adjusting the position between the inner and outer angle plates. When the inner and outer rings of the inclined bearing rotate relative to each other, the vibration shaft will generate an axial vibration. The amplitude value of the mechanical vibrator can be adjusted with the change of the inclination angle θ. Furthermore, the frequency of the mechanical vibrator can be adjusted freely by the change of relative speed of inner and outer rings of bearing during machining. In order to ensure the axial movement of the vibration shaft when it rotates, the vibration shaft connects the connecting mechanism by a spline.

The working principle of designed mechanical vibrator can be simplified as the movement of the eccentric ball sleeve. As shown in Fig. 1(b), two rectangular coordinates (i.e. O-XYZ and O-$X'Y'Z'$) with an origin O coincidence with the gravity center of two inclined bearings are established. The center point P of the eccentric ball sleeve rotates around Z axis in the XOY plane. Therefore, the movement path of the P in the O-XYZ can be written as follows:

$$\begin{cases} x = \dfrac{e}{cos\theta} sin\varphi \\ y = \dfrac{e}{\cos\theta} cos\varphi \\ z = 0 \end{cases} \tag{1}$$

where, θ is the inclination angle of the bearing, e is the eccentricity of the eccentric ball sleeve, φ is the relative rotation angle of bearing inner and outer rings.

Then, according to the transformation relation between the two coordinate systems, the movement path of the P in the O-$X'Y'Z'$ can be expressed as follows:

$$\begin{cases} x' = \dfrac{e}{cos\theta} sin\varphi \\ y' = ecos\theta \\ z' = etan\theta cos\varphi \end{cases} \tag{2}$$

It can be seen from the Eq. (2) that, besides the axial vibration, the non-axial vibration will also be generated when the inner and outer rings of the inclined bearing rotate relative to each other. However, the non-axial vibration can be eliminated by the relative swing of the inner and outer eccentric ball sleeves due to the support of outer hull. Therefore, the movements of the mechanical vibrator include the axial vibration of vibration shaft and the relative swing of inner and outer eccentric ball sleeves when the inner and outer rings of the inclined bearings rotate relative to each other. Moreover, the axial vibration will be not influenced by the relative swing of inner and outer eccentric ball sleeves because the center of the eccentric ball sleeves is constant.

The axis movement of center P of eccentric ball sleeve results in vibration of mechanical vibrator. Therefore, the vibration equation of the mechanical vibrator can be expressed as follows:

$$Z(\varphi) = etan\theta cos\varphi \tag{3}$$

Additionally, according to the relative motion of bearing inner and outer rings, the φ can be expressed by the following equation:

$$\varphi = 2\pi \frac{n_r}{60} t = \frac{\pi n_r}{30} t \tag{4}$$

According to Eq. (3) and (4), the vibration equation of the mechanical vibrator can be expressed as follows:

$$Z(t) = etan\theta cos \frac{\pi n_r}{30} t \tag{5}$$

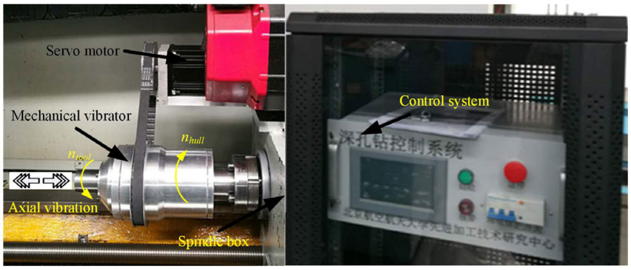

FIGURE 2. The rotary low-frequency vibration-assisted drilling device.

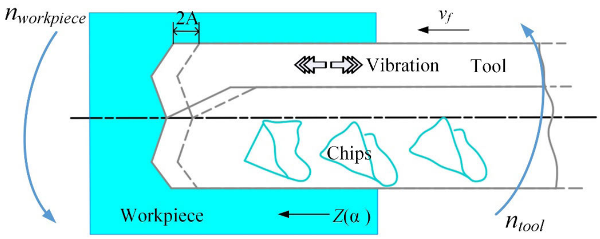

FIGURE 3. Schematic illustration of the drill motion in LFVASLD process.

where, $n_r = n_{tool} + n_{hull}$, n_{tool} and n_{hull} represent the rotary speeds of the single-lip drill and the outer hull, respectively, r/min, see Fig.2.

Therefore, the output amplitude (A) and frequency (F) of the mechanical vibrator are $etan\theta$ and $n_r/60$, respectively. Moreover, there are two typical advantages of the mechanical vibrator. On one hand, this frequency of the mechanical vibrator can be adjusted freely by the change of n_{hull} during machining according to different required chip shapes and drilling stages. On the other hand, the adjustment of vibration parameters does not influence the process stability because the rotary speed (n_{tool}) of single-lip drill is independent of outer hull speed (n_{hull}).

B. THE COMPOSITION OF DEVICE

As a key machine tool accessory, a rotary low-frequency vibration-assisted drilling device is comprised of a mechanical vibrator, a control system, a servo motor, as shown in Fig.2. The mechanical vibrator is connected with the spindle of a CNC deep hole drilling machine. The major functions of control system are to adjust the vibration frequency of mechanical system by control the speed and direction of servo motor rotation and to monitor the machining state.

III. ANALYSIS OF MATERIAL REMOVAL MECHANISM IN LFVASLD

During LFVASLD, a low-frequency axial vibration is applied on the tool end while it rotates and feeds to the workpiece. Thus, the material removal mechanism is changed. Fig. 3 schematically shows the tool-workpiece interaction in LFVASLD process realized by developed rotary vibration device in Section 2.

A kinematic model can be established to analyze the tool movement at different cutting parameters and vibration parameters, as follows:

$$Z(\alpha) = \frac{f}{2\pi}\alpha + etan\theta cos\left(\frac{60F}{n}\alpha\right) \tag{6}$$

where, f is the feed, mm/r, α is the angle of relative rotation between cutting edge and workpiece, n is the relative rotation speed between cutting tool and workpiece, r/min, $etan\theta$ is the output amplitude of developed rotary vibration system (half of peak-to-valley), mm, F is the output frequency of rotary vibration system, Hz.

Besides, the cutting thickness a_p of two consecutive turns of the cutting edge can be expressed as follows:

$$a_p = f + 2etan\theta sin\left(\frac{60F}{n}\pi\right) \cdot sin\left[\frac{60F}{n}(\alpha+\pi)\right] \tag{7}$$

According to Eq. (6) and (7), the tool motion and cutting thickness for LFVASLD is periodically changing. Fig. 4 illustrates the drilling depth and real-time cutting thickness in both CSLD and LFVASLD simulated by MATLAB software. In LFVASLD, the intermittent cutting mode can be significantly affected by two characteristic factors which are correlated with the cutting and vibration parameters. The first factor is the amplitude ratio K_A, defined as the ratio of the peak-to-valley amplitudes of vibration to the feed f, i.e. $K_A = 2A/f$. When $K_A \geq 1$, the chip breakage can be realized under proper conditions. However, if $K_A < 1$, no chip breakage can be achieved theoretically. The other factor is the frequency ratio K_F, defined as the ratio of vibration frequency to the relative rotational frequency, i.e. $K_F = 60F/n$. The frequency ratio K_F determines the intermittent cutting status between the cutting edge and workpiece.

When the parameters of vibration and cutting are selected properly, the intermittent cutting mode can be achieved, as shown in Fig. 4. During one vibration cycle, the cutting can be divided into cutting duration and separated duration. And the separated duration can be affected by the frequency ratio K_F. Even when K_F value is integer, the cutting depth a_p is fixed and the theoretical chip breaking cannot be achieved. Therefore, the theoretical chip breaking conditions in LFVASLD can be expressed as follows:

$$\begin{cases} K_F \neq INT \\ K_A \geq 1\ (i.e. f \leq 2etan\theta) \end{cases} \tag{8}$$

From the cutting duration to separating duration, the cutting edges are separated from the workpiece, which can bring a range of benefits for deep hole drilling, as illustrated in Fig. 5. Firstly, the chips can be broken completely, and the chip formation can be actively controlled by the cutting and vibration parameters. For deep hole drilling, the chip formation has a distinctly important effect on process productivity and stability [12]. Compared to the long spiral unfavorably formed chips, the smaller unit chips can be removed easily, and thus avoid chip congestion, sudden drill failure and chip scratching hole surface. Secondly, compared with CSLD, the cutting zone forms an instantaneous vacuum zone when the cutting edge is periodically separated from the workpiece

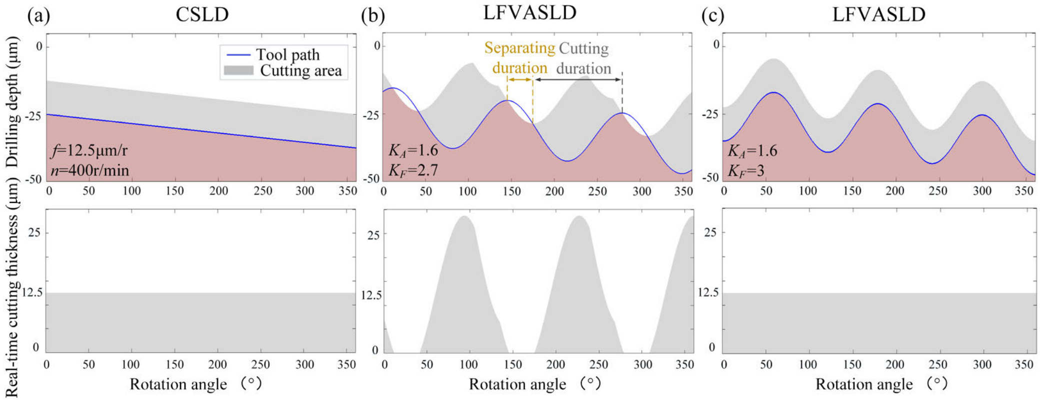

FIGURE 4. Simulation results for drilling depth and real-time cutting thickness at $f = 12.5\mu m$ $n = 400r/min$ in (a) CSLD; (b) LFVASLD with $K_A = 1.6$, $K_F = 2.7$; (c) LFVASLD with $K_A = 1.6$, $K_F = 3$.

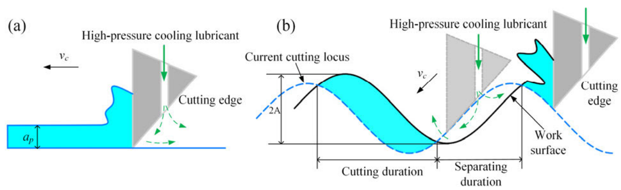

FIGURE 5. (a) CSLD and (b) Separated cutting mode realized in LFVASLD.

during LFVASLD. Under the negative pressure, the cutting fluid quickly enters the cutting zone and therefore the cutting edge can be fully cooled and lubricated (see Fig. 5). This not only reduces the cutting temperature, but also forms the surface oil film between the chip and the rake face, which can effectively decrease the tool wear. Finally, during the separating duration, the torsional and flexural vibrations of single-lip drill can be effectively suppressed and even eliminated, which improves the stability of drill and surface quality.

IV. EXPERIMENTS

A. EXPERIMENTAL SETUP

This experiments were conducted on a CNC deep hole drilling machine (ZK2104, Dezhou Precion Machine Tool Co., Ltd, China) with a fixed speed of 380 r/min for the spindle of workpiece end and a maximum spindle speed of 3000r/min for the spindle of tool end. The rotary low-frequency vibration-assisted drilling device was connected with the spindle of tool end. In order to effectively decrease the straightness deviation of hole, the operation mode of relative rotation of the workpiece and tool was applied during the experiments [12], as shown in Fig. 6. In addition, a drilling bush made of hardened steel was used to guide the single-lip drill at the initial stage of drilling.

B. PROPERTIES OF WORKPIECE MATERIALS AND TOOL

In the experiments, the annealed titanium alloy (Ti6Al4V) bars with a dimension of Ø30 × 250 (diameter × length, mm) supplied by Chengdu Aircraft Industrial (Group) Co., Ltd. were used as the workpieces. The material properties of

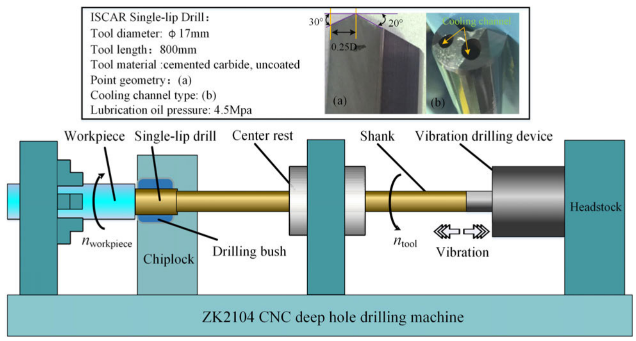

FIGURE 6. The schematic of LFVASLD of titanium alloy.

TABLE 1. Material properties of Ti6Al4V.

Property	Unit	Value
Density	kg/m^3	4510
Hardness	HRC	39
Elastic modulus	GPa	114
Poisson's ratio		0.34
Tensile strength	MPa	915
Yield strength	Mpa	845

Ti6Al4V are listed in Table 1. The tools used in the experiments are the solid carbide single-lip drills (ISCAR) with a diameter of 17mm, and drill point geometries are shown in Fig. 8.

C. EXPERIMENTAL CONDITIONS

The experimental procedures were divided into two steps. In the first step, a comparative experiment of LFVASLD and CSLD of Ti6Al4V were conducted with the same cutting parameters, and the experimental conditions were listed in Table 2. In order to compare the tool life of the two processes in the comparative experiment, the drilling depth was

TABLE 2. Comparative experiment conditions.

Process parameters	CSLD	LFVASLD
Tool	single-lip drill	single-lip drill
Oil pressure (Mpa)	4.5	4.5
Drilling hole diameter (mm)	17	17
Drilling depth (mm)	1000	1000
Vibration frequency (Hz)	0	18
Vibration amplitude A (μm)	0	25
Workpiece speed (r/min)	380	380
Spindle speed (r/min)	20	20
Feed speed (mm/min)	5	5

TABLE 3. Experiment conditions.

Process parameters	LFVASLD
Tool	single-lip drill
Oil pressure (Mpa)	4.5
Drilling hole diameter (mm)	17
Drilling depth (mm)	250
Vibration frequency (Hz)	10, 14, 18, 22, 26
Vibration amplitude A (mm)	0.01mm, 0.02mm, 0.025mm, 0.03mm, 0.05mm
workpiece speed (r/min)	380
Spindle speed (r/min)	20, 50, 80, 110, 140
Feed speed (mm/min)	5, 7, 9, 11, 13

set to 1000mm. In the second step, the influences of process parameters in LFVASLD of Ti6Al4V on hole quality were investigated to determine the suitable drilling parameters, the experimental conditions were listed in table 3. To avoid the tool life decrease induced by the high cutting speed during experiments, the lower spindle speed was chose due to the ZK2104 deep hole machine with a fixed workpiece speed of 380r/min. In addition, the experiments were carried out at room condition and the output amplitudes of LFVASLD system were measured before and after each experiment. The measured results showed that the values of amplitude were almost stable, which indicated that temperature rise in the hull during drilling had limited effect on the output amplitude at room conditions.

After drilling, the Ti6Al4V bar was cut into 5 parts with 50mm length perpendicular to the hole axis and the measurements were made at each section. The hole diameter, roundness, hole surface roughness were measured by a coordinate measuring machine (CENTURY 977, Beijing Precision Engineering Institute, China) with 1 μm resolution and a surface tester (Talysurf 50, Taylor Hobson, England), respectively.

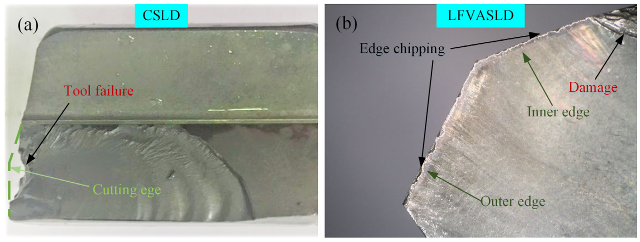

FIGURE 7. A comparison of tool wear conditions between (a) CSLD and (b) LFVASLD.

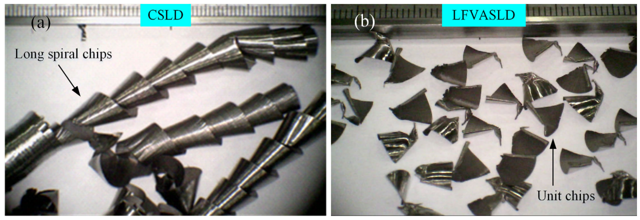

FIGURE 8. A comparison of Ti6Al4Vchips between (a) CSLD and (b) LFVASLD.

The morphologies of chips, tools and hole surfaces were also observed with a digital camera optical microscope.

V. RESULTS AND DISCUSSION

A. THE COMPARATIVE EXPERIMENTS BETWEEN LFVASLD AND CSLD

1) TOOL WEAR AND CHIP MORPHOLOGY

Fig.7 shows the wear conditions of single-lip drill during CSLD and LFVASLD of Ti6Al4V. In CSLD, when the drilling depth reached 110mm, the shank of single-lip drill shook violently and the processing sound was harsh. It indicated the CSLD process lost stability due to chip blockage in the chip flute or tool failure, as a result, the CSLD process must be stopped. After tool retraction, severe tool wear in term of cutting edge fracture was observed and the worn single-lip drill cannot be used in the following experiments, as shown in Fig. 7(a). This suggests that CSLD process is not competent for machining larger-diameter titanium alloy deep holes.

Fig. 7(b) shows the tool wear condition after a drilling depth of 1000mm for LFVASLD. It can be seen that just slight edge chipping on both the outer and inner cutting edges occurred, and the closer to the outer corner, the more serious edge chipping is. Besides, obvious damage on the center of single-lip drill was observed in LFVASLD, which is probably induced by the vibration shock effect. Nevertheless, this worn single-lip drill still has cutting ability. The comparison of tool wear between CSLD and LFVASLD suggests that the significant improved cutting performance in terms of nine times of cutting depth and less tool wear extent can be achieved in LFVASLD.

Fig. 8 shows the chip morphologies obtained in CSLD and LFVASLD. The unfavorably long spiral chips were formed in CSLD, which have a negative effect on the process efficiency,

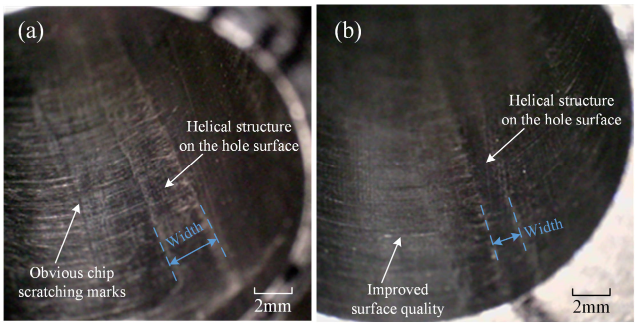

FIGURE 9. The helical structures on the hole surface in (a) CSLD and (b) LFVASLD at about 50mm drilling depth.

stability and hole surface integrity, as shown in Fig. 8(a). Fig. 8(b) shows the chip forms in LFVASLD. Compared with the long spiral chips in CSLD, chip breakage was achieved in LFVASLD due to the separated cutting characteristics. The unit chips with small volume can be easily removed, and are less harmful to the produced hole surface and the tool during their continuous evacuation along the flute of tool. As a result, significantly improved process efficiency and stability due to the excellent chip evacuation conditions can be achieved in LFVASLD of larger-diameter titanium alloy deep holes. Similarly, the excellent chip evacuation is also considered as the main cause to improve process stability and avoid tool failure in LFVASLD of small diameter hole of copper-zirconium material [14].

The results in Fig. 7 and Fig. 8 indicate that the processing capacity of the machine tool was significantly improved due to the use of LFVASLD system. The main reasons can be attributed to the lower cutting force and temperature resulted from the separated cutting characteristics, and excellent chip evacuation conditions achieved in LFVASLD which improved the process stability. The phenomenon and mechanism of cutting force and temperature reduction in low-frequency vibration-assisted drilling have been verified by experiments by many researchers [14], [16], [17].

2) HOLE SURFACE MORPHOLOGY

Due to the low tool rigidity, caused by high length-to-diameter ratios and the alongside V-shaped chip flute of the single-lip drill, the tool vibration is easily induced during drilling. According to the previous study, the flexural vibration of single-lip drill induced a helical structure on the hole surface, while the torsional vibration of single-lip drill only produced radial chatter marks at the hole bottom, which had no obvious effect on the surface quality [1], [19], [20]. Therefore, the helical structure on the hole surface produced by CSLD and LFVASLD was observed and compared in this section.

Fig. 9 shows the helical structures on hole surface at about 50mm drilling depth for CSLD (n = 400r/min, v_f = 5mm/min) and LFVASLD (n = 400r/min, v_f = 5mm/min, F = 18Hz, A = 25μm). It can be seen that, the width of helical structure achieved in LFVASLD is less than that achieved in CSLD. At about 90mm drilling depth, as shown in Fig. 10, the helical structure on hole surface in CSLD still exists, but it has disappeared in LFVASLD. This suggests that the flexural vibration of single-lip drill can be effectively suppressed at low-frequency vibration-assistance support, as analyzed in material removal mechanism. Additionally, the chip scratching marks on the hole surface, formed by the long spiral unfavorably chips, in CSLD, were more obvious, compared to in LFVASLD, as shown in Figs. 9 and 10. This significantly decreased the surface quality of holes.

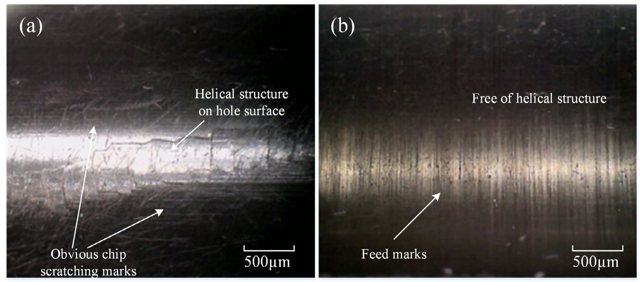

FIGURE 10. The hole surface morphologies in (a) CSLD and (b) LFVASLD at about 90mm drilling depth.

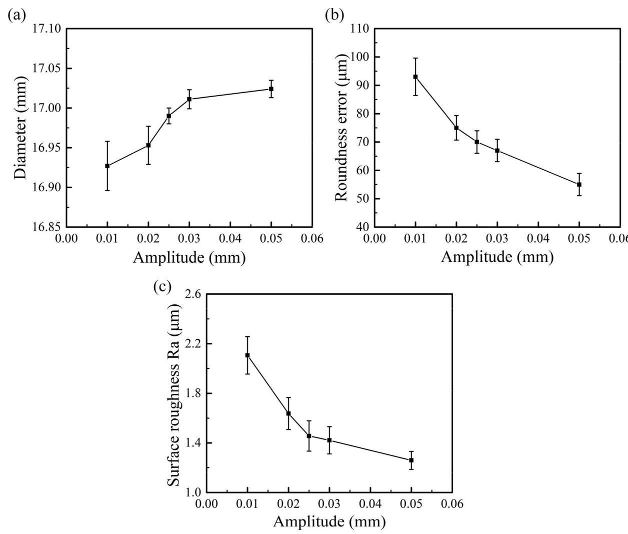

FIGURE 11. Influence of amplitude on (a) hole diameter accuracy, (b) hole roundness error and (c) hole surface roughness (n = 400r/min, v_f = 5mm/min, F = 18Hz, A = 0.01mm, 0.02mm, 0.025mm, 0.03 mm, 0.05mm).

B. THE INFLUENCE OF PROCESS PARAMETERS ON HOLE ACCURACY AND SURFACE ROUGHNESS IN LFVASLD

1) THE INFLUENCE OF VIBRATION AMPLITUDE AND FEED SPEED

Figs. 11 and 12 show the influence of vibration amplitude and feed speed on hole diameter accuracy, roundness error and surface roughness, respectively in LFVASLD. It can be observed that the values of roundness error and surface roughness of hole decrease with the increase of vibration amplitude, while the values increase with the increase of feed speed. According to the definition of K_A, i.e. $K_A = 2A/f$, the value of K_A increases with the increase of amplitude and

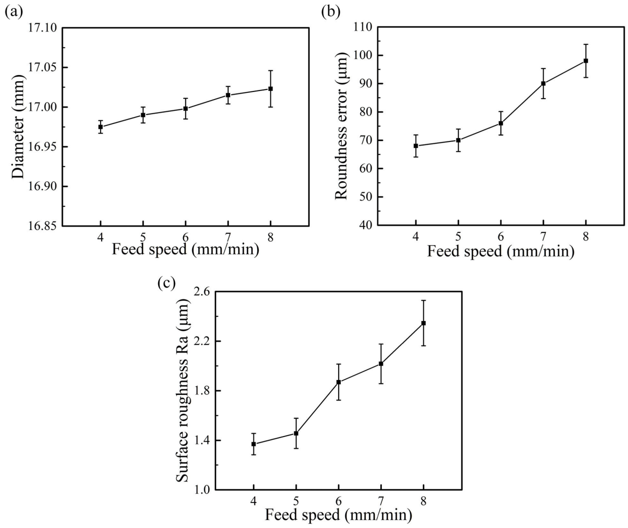

FIGURE 12. Influence of feed speed on (a) hole diameter accuracy, (b) roundness error and (c) surface roughness ($n = 400$r/min, $A = 0.025$mm, $F = 18$Hz, $v_f = 4$mm/min, 5mm/min, 6mm/min, 7mm/min, 8mm/min).

decreases with the increase of feed. The experimental results suggests that, the larger K_A is, the better surface quality and roundness of the hole are. The reason can be attributed that, the separating duration in a vibration cycle increases, as the value of K_A increases, which means that more better separated cutting effect can be achieved. This significantly improves the recovery of the drill deviation, which suppress or even eliminates the torsional and flexural vibrations of single-lip drill. Also, the cooling and lubrication of high pressure lubrication oil to cutting area can be improved obviously. In addition, the increase of K_A can effectively improve the smoothing effect of margin and guide pads, and thus improves the roundness and surface roughness of hole.

It can be also seen from the Figs. 11 and 12 that, the value of hole diameter increases with the increase of amplitude or the increase of feed speed. However, in Fig.11 (a), with the increase of amplitude, the hole diameter was much closer to the nominal drill diameter of 17 mm and more stable, compared to those obtained in high feed speed (Fig.12 (a)). This suggests that high amplitude can result in better process effect than high feed speed in LFVASLD. The reason can be attributed to the increase of amplitude can effectively improve the cutting ability of cutting edge and the smoothing effect of margin and guide pads, which decrease the resilience of the machined surface and rub feed marks of the machined surface, and thus increase the hole diameter. The mechanism for the improvement of cutting ability and smoothing effect at higher amplitude has also been found in conventional low-frequency vibration-assisted drilling of aluminum alloy by Zhang and Wang [21] and ultrasonic vibration-assisted drilling of titanium alloy by Li *et al.* [22]. However, the reason of hole diameter increase with the increase of feed speed is weakening of the separated cutting effect of LFVASLD, which easily induce the instability of single-lip drill and

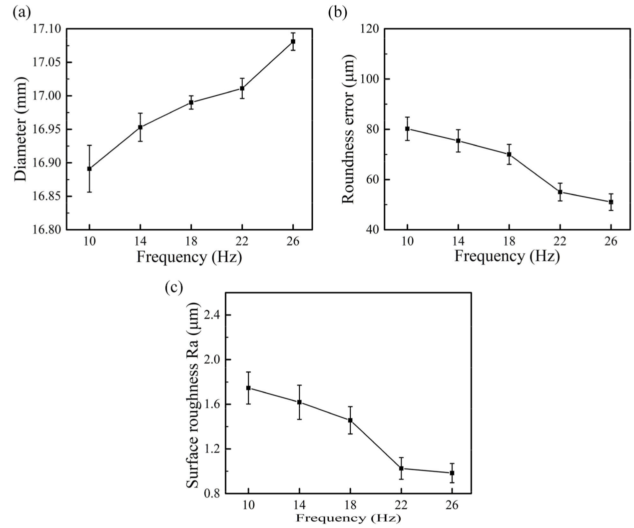

FIGURE 13. Influence of frequency on (a) hole diameter accuracy, (b) roundness error and (c) surface roughness ($n = 400$r/m, $v_f = 5$mm/min, $A = 0.025$mm, $F = 10$Hz, 14Hz, 18Hz, 22Hz, 26Hz).

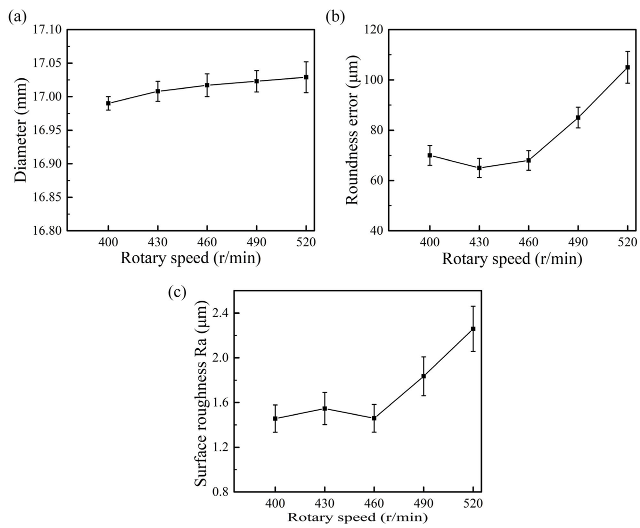

FIGURE 14. Influence of rotary speed on (a) hole diameter accuracy, (b) roundness error and (c) surface roughness ($v_f = 5$mm/min, $A = 0.025$mm, $F = 18$Hz, $n = 400$r/min, 430r/min, 460r/min, 490r/min, 520r/min).

aggravate the tool wear. Even, the feed speed is too large, resulting in $K_A < 1$, the separated cutting effect will disappear in LFVASLD.

2) THE INFLUENCE OF VIBRATION FREQUENCY AND ROTARY SPEED

Figs. 13 and 14 show the influence of vibration frequency and rotary speed on hole diameter accuracy, roundness error and surface roughness in LFVASLD, respectively. It can be observed that, the values of roundness error and surface roughness of hole decrease with the increase of vibration frequency, while the values almost increase with the increase of rotary speed. According to the definition of K_F, i.e. $K_F = 60F/n$, the value of K_F increases with the increase of frequency and decreases with the increase of rotary speed. The experimental results suggests that, the larger K_F is, the better surface quality and roundness of the hole can be obtained. The reason can be attributed that, the separating numbers between tool and workpiece in one rotation of single-lip drill increases, as the value of K_F increases. This can significantly decrease the chips size, which improves chip removal rate, and thus improves the process stability and reduces chip damage to hole surface. In addition, the increase of K_F can also effectively improve the smoothing numbers of margin and guide pads on machined surface, and thus improves the roundness and surface roughness of hole.

It can be also seen from the Figs. 13 and 14 that, the value of hole diameter increases with the increase of vibration frequency or the increase of rotary speed. However, in Fig.13 (a), with the increase of frequency, the hole diameter was more stable, compared to those obtained in high rotary speed (Fig.14 (a)). This suggests that high frequency can result in better process stability than high rotary speed in LFVASLD. The reason can be attributed to the increase of frequency can effectively improve separating numbers in one rotation of single-lip drill, between tool and workpiece. This increases smoothing numbers of margin and guide pads on hole surface at one rotation, which decrease the resilience of the machined surface, and thus increase the hole diameter. However, the reason of hole diameter increase with the increase of rotary speed is weakening of the separated cutting effect of LFVASLD, and the instability of single-lip drill induced by the high rotary speed.

The above experiment on influence of drilling parameters on hole quality in LFVASLD indicates that, on the basis of satisfying chip breaking conditions (see Eq. 8), it is suggested to select a lower spindle speed, proper feed speed, a higher frequency and amplitude to achieve higher hole quality in LFVASLD of Ti6Al4V in the industrial practice.

VI. CONCLUSION

In the paper, an innovation LFVASLD device was developed firstly, and then its feasibility was verified by the comparative experiments. According to the comparative experimental results, the process and device of LFVASLD were a proper and promising, for machining deep hole of Ti, to achieve a favorable chip form, high hole quality and productivity in the industrial practice. The main conclusions can be drawn as follows:

(1) This paper, for the first time, developed an innovational LFVASLD device with adjustable frequency and amplitude, and the vibration generation mechanism was analyzed. Besides, the material removal mechanism of LFVASLD was also analyzed.

(2) Compared with CSLD of Ti6Al4V, tool wear conditions in LFVASLD were significantly alleviated, thus, the drilling depth can be prolonged by 9 times. Moreover, a favorable unit chip, short and thin helical structures on the hole surface, higher the process productivity and stability could be also achieved in LFVASLD. In addition, the processing capacity of the machine tool was significantly improved due to the use of LFVASLD system.

(3) In the industrial practice, to achieve higher hole quality in LFVASLD of Ti6Al4V, the lower rotary and feed speed, the higher frequency and amplitude should be selected, according to chip breaking conditions and the results of the process parameters influence experiment.

REFERENCES

[1] V. P. Astakhov, "The mechanisms of bell mouth formation in gundrilling when the drill rotates and the workpiece is stationary. Part 2: The second stage of drill entrance," *Int. J. Mach. Tools Manuf.*, vol. 42, pp. 1145–1152, Aug. 2002.

[2] D. Biermann, M. Heilmann, and M. Kirschner, "Analysis of the influence of tool geometry on surface integrity in single-lip deep hole drilling with small diameters," *Procedia Eng.*, vol. 19, pp. 16–21, Nov. 2011.

[3] C. H. Che-Haron, "Tool life and surface integrity in turning titanium alloy," *J. Mater. Process. Technol.*, vol. 118, pp. 231–237, Dec. 2001.

[4] L. Li, H. Xue, and P. Wu, "Experimental study on the axis line deflection of Ti6A14V titanium alloy in gun-drilling process," *IOP Conf., Mater. Sci. Eng.*, vol. 301, Jan. 2018, Art. no. 012012.

[5] S. V. Kirsanov and A. S. Babaev, "Study of accuracy and surface roughness of holes in comparative testing of small diameters gun drills," *IOP Conf., Mater. Sci. Eng.*, vol. 66, no. 1, 2014, Art. no. 012030.

[6] Z. Liu, Y. Liu, X. Han, and W. Zheng, "Study on super-long deep-hole drilling of titanium alloy," *J. Appl. Biomaterials Funct. Mater.*, vol. 16, pp. 150–156, Jan. 2018.

[7] K. S. Woon, G. L. Tnay, M. Rahman, S. Wan, and S. H. Yeo, "A computational fluid dynamics (CFD) model for effective coolant application in deep hole gundrilling," *Int. J. Mach. Tools Manuf.*, vol. 113, pp. 10–18, Feb. 2017.

[8] G. L. Tnay, S. Wan, K. S. Woon, and S. H. Yeo, "The effects of dub-off angle on chip evacuation in single-lip deep hole gun drilling," *Int. J. Mach. Tools Manuf.*, vol. 108, pp. 66–73, Sep. 2016.

[9] D. Biermann and M. Kirschner, "Experimental investigations on single-lip deep hole drilling of superalloy Inconel 718 with small diameters," *J. Manuf. Process.*, vol. 20, pp. 332–339, Oct. 2015.

[10] V. Baghlani, P. Mehbudi, J. Akbari, E. Z. Nezhad, A. A. D. Sarhan, and A. M. S. Hamouda, "An optimization technique on ultrasonic and cutting parameters for drilling and deep drilling of nickel-based high-strength Inconel 738LC superalloy with deeper and higher hole quality," *Int. J. Adv. Manuf. Technol.*, vol. 82, pp. 877–888, Feb. 2016.

[11] U. Heisel, J. Wallaschek, R. Eisseler, and C. Potthast, "Ultrasonic deep hole drilling in electrolytic copper ECu 57," *CIRP Ann.*, vol. 57, no. 1, pp. 53–56, 2008.

[12] D. Biermann, F. Bleicher, U. Heisel, F. Klocke, H.-C. Möhring, and A. Shih, "Deep hole drilling," *CIRP Ann.*, vol. 67, no. 2, pp. 673–694, 2018.

[13] O. Pecat and E. Brinksmeier, "Tool wear analyses in low frequency vibration assisted drilling of CFRP/Ti6Al4V stack material," *Procedia CIRP*, vol. 14, pp. 142–147, Mar. 2014.

[14] F. Bleicher, M. Reiter, and J. Brier, "Increase of chip removal rate in single-lip deep hole drilling at small diameters by low-frequency vibration support," *CIRP Ann.*, vol. 68, no. 1, pp. 93–96, 2019.

[15] R. Hussein, A. Sadek, M. A. Elbestawi, and M. H. Attia, "Surface and microstructure characterization of low-frequency vibration-assisted drilling of Ti6Al4V," *Int. J. Adv. Manuf. Technol.*, vol. 103, pp. 1443–1457, Jul. 2019.

[16] C. Li, J. Xu, M. Chen, Q. An, M. El Mansori, and F. Ren, "Tool wear processes in low frequency vibration assisted drilling of CFRP/Ti6Al4V stacks with forced air-cooling," *Wear*, vols. 426–427, pp. 1616–1623, Apr. 2019.

[17] F. Bleicher, G. Wiesinger, C. Kumpf, D. Finkeldei, C. Baumann, and C. Lechner, "Vibration assisted drilling of CFRP/metal stacks at low frequencies and high amplitudes," *Prod. Eng.*, vol. 12, no. 2, pp. 289–296, 2018.

[18] D. Geng, Y. Liu, Z. Shao, Z. Lu, J. Cai, X. Li, X. Jiang, and D. Zhang, "Delamination formation, evaluation and suppression during drilling of composite laminates: A review," *J. Compos. Struct.*, vol. 216, pp. 168–186, May 2019.

[19] N. Raabe, D. Enk, D. Biermann, and C. Weihs, "Dynamic disturbances in BTA deep-hole drilling: Modelling chatter and spiralling as regenerative effects," in *Proc. Adv. Data Anal., Data Handling Bus. Intell.-Conf. Gesellschaft Für Klassifikation Ev, Joint Conf. Brit. Classification Soc.*, 2009.

[20] K. Matsuzaki, T. Ryu, A. Sueoka, and K. Tsukamoto, "Theoretical and experimental study on rifling mark generating phenomena in BTA deep hole drilling process (generating mechanism and countermeasure)," *Int. J. Mach. Tools Manuf.*, vol. 88, pp. 194–205, Jan. 2015.

[21] D. Zhang and L. Wang, "Investigation of chip in vibration drilling," *Int. J. Mach. Tools Manuf.*, vol. 38, no. 3, pp. 165–176, Feb. 1998.

[22] Z. Li, D. Zhang, X. Jiang, W. Qin, and D. Geng, "Study on rotary ultrasonic-assisted drilling of titanium alloys (Ti6Al4V) using 8-facet drill under no cooling condition," *Int. J. Adv. Manuf. Technol.*, vol. 90, pp. 3249–3264, Jun. 2017.

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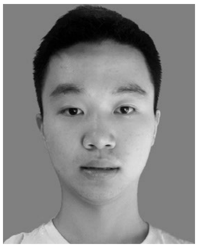

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