Analyses of Burr and Exit Thrust Force of Ultrasonic-Assisted Micro-Drilling

Guangjun Chen, Jinkai Xu, Jingdong Wang, Jiaqi Wang, Huadong Yu*

Ministry of Education Key Laboratory for Cross-Scale Micro and Nano Manufacturing, Changchun University of Science and Technology, Changchun, Jilin Prov., 130022, China
yuhuadong@cust.edu.cn

Abstract. With the development trend of miniaturization of product production, ultrasonic assisted micro-drilling technology (UAMD) is more widely used in micro-hole processing due to its unique advantages. In this paper, the effect of 20 kHz harmonic vibration on the exit burr of micro-hole during UAMD has been studied. Based on the self-designed micro-hole drilling cell, a series of experiments have been carried out on the typical difficult-to-process material 30CrNiMo8. The experimental results show that compared with the conventional micro-drilling (CMD), the burr of the hole is well suppressed in the UAMD process, and the height of the burr is reduced by about 27.3%. The manufactured micro-hole exit burr is relatively neat. While in CMD, the exit burr is deformed greatly, the fracture is obvious, and the exit thrust force is generally larger than that in UAMD.

1. Introduction
Ultrasonic assisted micro-drilling technology (UAMD) is widely used in micro-hole manufacturing of various difficult-to-machine materials. Different from conventional micro-drilling technology (CMD), the principle of UAMD is to apply additional harmonic vibration to the axial feed direction, besides the axial feed movement. The additional harmonic vibration makes the micro-drilling change from continuous to discontinuous, which can improve the cutting environment and brings a series of advantages, such as improving heat dissipation conditions [1], reducing tool wear [2], increasing tool life [3] and surface finish [4] and so on.

Sun et al. studied the drilling temperature when using ultrasonic assisted drilling on bones. Experimental results show that ultrasonic-assisted drilling has a promoting effect on reducing temperature, improving surface roughness and reducing drilling torque [5]. Lv et al. analysed the formation of burr at the hole entrance of BK7 glass in the UAMD process. Experimental results show that in UAMD, the propagation of transverse cracks in BK7 glass is suppressed and the quality of the hole entrance is improved [6]. Onawumi et al. conducted conventional drilling and ultrasonic-assisted drilling experiments on carbon fiber reinforced materials, and the results showed that the exit burr height, drilling temperature and torque of the hole were greatly reduced under high-frequency vibration [7]. Azarhoushang and Akbari (2007) pointed out that ultrasonic-assisted drilling can not only improve the surface roughness of the workpiece and increase the roundness of the inner hole, but also inhibit the wear of the drill, and significantly improve the hole size smoothness of Inconel 738LC [8]. The burr of the micro-hole is an important indicator for evaluating the quality of the hole [9], and it has a vital impact on the assembly and working process of micro-parts. In a typical drilling process,
the thin layer of material at the end of the hole loses its resilience under the action of the drill chisel. As the cutting edge continues to deepen, the cutter relieving phenomenon intensifies. With the increase of the reserved material, the thin layer of material at the end of the hole will be plastically deformed, tearing, and becoming burrs along the circumference. When ultrasonic vibration is applied, the intermittent vibration causes the tool to produce an impact on the material, resulting in a change in the formation mechanism of micro-hole burrs. In this paper, 20 kHz ultrasonic vibration is applied in the micro-hole drilling process. The 0.25 mm micro twist drill is used to fabricate micro-holes on 30CrNiMo8 material. According to the change of the exit burr shape and the exit thrust force, the effect of ultrasonic vibration on the exit burr of the micro-hole is studied.

2. Experimental setup
The experiment was completed by the designed UAMD unit. The spindle is fixed on the feed stage, and the micro drill is fixed on the spindle by collet (1/8) and the nut (ER8). The vibration is realized by the transducer at the resonance frequency, and the excitation signal is provided by the ultrasonic generator. The measurement of force data is realized by Kistler Type 9256C dynamometer and the date is evaluated and processed by Dyno Ware 2825A. The schematic of ultrasonic unit is shown in figure 1. The workpiece material is a typical high-strength hard-to-machine material. The experimental parameters are shown in Table 1. The experiment under the same parameters was performed 3 times.

![Figure 1. The schematic of UAMD unit.](image)

![Figure 2. The displacement curve along the feed direction.](image)

| Process parameters         | Value          |
|----------------------------|----------------|
| Radius ($R$)               | 0.125 mm       |
| Vibration amplitude ($a$)  | 0.6 μm         |
| Vibration frequency ($f$)  | 20 kHz         |
| Rotation speed ($n$)       | 20000 rev/min  |
| Feed rate ($f_r$)          | 0.008 mm/rev   |
| Workpiece material         | 30CrNiMo8      |
| Coolant condition          | Water          |

The dynamic trajectory of the main cutting edges is mainly determined by the geometric and cutting parameters. When the feed motion and high-frequency vibration are simultaneously applied in the axial direction, the displacement and velocity of a certain point on the micro drill along the feed direction can be expressed as.

$$u(t) = a\sin(2\pi ft) + f_rnt / 60$$

(1)
\[ \dot{u}(t) = 2a\pi f \cos(2\pi ft) + \frac{f_r n}{60} \]  

(2)

where \( a \) and \( f \) is the ultrasonic vibration amplitude (\( \mu m \)) and frequency (Hz), respectively. \( f_r \) is the feed rate, \( \text{mm/rev} \), \( n \) represents the rotation speed, \( \text{rev/min} \).

Under high frequency vibration, the displacement curve of the micro drill along the feed direction is shown in figure 2. The extra ultrasonic harmonic energy has an impact effect on the material during the cutting process, which can further improve the destructiveness of the main cutting edge to the material and achieve the purpose of removing the material.

3. Results and discussions

The burr height of the hole is the main methods to characterize the burr defect. A confocal microscope is used to measure the three-dimensional characteristics of the hole exit burr to obtain the burr height data. The obtained morphology of the micro-hole exit burr and cross-sectional height are shown in figure 3.

![Figure 3. Burr and cross-sectional height in UAMD (a) and CMD (b) a=6\mu m, f_r=0.008\mu m/rev, n=20000rpm.](image)

According to Figure 3, the burr height of the micro-hole obtained by UAMD is greatly reduced, about 27.3\%, 20 \( \mu m \), while in CMD, the burr height is about 27.5 \( \mu m \). The decrease in burr height is due to the release of harmonic energy to the thin material at the bottom of the micro hole. Under high-frequency vibration, the material is quickly impacted by the cutting edge, and the elastic-plastic transition time of the material is shortened, which makes the material is quickly removed and the extension length of the material becomes shorter. However, in CMD the cutter relieving phenomenon is more serious due to the feed movement of the tool. The thin material at the bottom of the hole is deformed due to the feed motion of the tool, and the elasto-plastic conversion time is longer than that of UAMD. The tearing of the material leads to a long plastic deformation time and large deformation of the remaining material.

In order to obtain a more detailed morphology of the exit burr, a scanning electron microscope (SEM) was used to obtain a clear morphology of the exit burr, as shown in figure 4. According to figure 4, it can be seen that the micro-holes obtained by applying ultrasonic vibration have relatively neat holes, the fracture of the burrs is small, and the width of the fracture area is about 4.3 \( \mu m \). In CMD, the burr fracture area is larger, about 13.1 \( \mu m \), and the tear marks on the inner surface of the micro-hole after the burr fracture is very clear. In CMD, the larger tearing area is caused by the accumulation of
materials and plastic deformation caused by the cutter relieving phenomenon. Eventually the material reaches the failure limit and tears occur. This means that, in CMD, when the material at the end of the micro-hole fails, the cutter relieving phenomenon of the chisel blade will gradually increase the exit thrust force.

According to UAMD and CMD force data of the entire drilling process obtained by the dynamometer, the exit thrust force when the micro-drill goes through the workpiece is obtained. Three experiments were carried out under the same parameters. The error bars represent the distribution of force data. Figure 5 shows the exit thrust force at different rotation speeds and feed rates.

![Figure 4. SEM morphology of the exit burr UAMD (a) and CMD (b).](image)

Figure 5. The exit thrust force in UAMD (a) and CMD (b). $a=6$ and $0 \, \mu m, f_r=0.004-0.02 \, \mu m/rev$, $n=5000-25000 \, rpm$.

According to figure 5, with the change of rotation speed and feed rate, the exit thrust force in UAMD is always smaller than that in CMD. When the rotation speed changes, it is about 20%. When the feed rate changes, it is about 20%. In the UAMD process, the exit thrust force on the thin material at the bottom of the micro-hole is generally smaller that in the CMD, which makes the thin material at the bottom be removed by the impact of harmonic-like force. In CMD, the material has always been subjected to a large thrust force, which causes the material to be removed in the form of slow elasto-plastic deformation, causing the chips and the material around the micro-hole to tear.
4. Conclusions
In this paper, the exit burr and exit thrust force in UAMD was studied. The experimental results show that in the UAMD process, the height of the exit burr is well suppressed. Compared with CMD, the height of the exit burr is reduced by 27.3%, and the burr is neater. In CMD, the exit burr is deformed greatly, the fracture is obvious, and the exit thrust force is generally larger than that of UAMD.

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Acknowledgments
This work was supported by China-EU H2020 International Science and Technology Cooperation Programme (FabSurFWAR Nos.2016YFE0112100), Jilin Province Science and Technology Development Program Supported Project (No.20180201057GX, Z20190101005JH, 20200401070GX).