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An experimental study on processing performance of rotary ultrasonic drilling of K9 glass

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Abstract. Rotary ultrasonic machining process, regarded as one of the effective processing methods for hard-brittle materials, is introduced into drilling K9 glass in this paper. The effective cutting velocity, cutting depth, and cutting length of single diamond particle are determined by analyzing the kinematics characteristic of diamond tool in rotary ultrasonic drilling (RUD). Experiments are conducted to study the influences of process variables (spindle speed, feedrate) on cutting force, chipping size, and surface roughness in RUD. As comparison study, the processing performances between RUD and diamond drilling are also discussed. The experimental results show that the RUD process can significantly reduce cutting force and the value of chippings size, which inferred that RUD process can improve machining efficiency and make the machining cost lower. It is also concluded that the effective cutting depth of diamond particles is the main factor for surface roughness in RUD of K9 glass.

Introduction

K9 glass is known as an excellent performance optical material that is widely used in optics, aerospace, electronics, thermodynamics, chemical industry and so on [1]. It possesses many desirable qualities, such as high strength, hardness, thermal resistance, corrosion resistance, and oxidation resistance. However, it is one of the most difficult-to-machine materials due to its mechanical characteristics. Their utilization potentials, however, can be realized fully as critical products only with development of appropriate advanced machining technology [2].

Rotary ultrasonic machining (RUM), a hybrid machining process that combines diamond grinding and ultrasonic machining, is regarded as a relatively cost-effective, environment-benign machining method for machining hard-to-machine materials (such as glass, advanced ceramics, ceramic matrix composites, silicon carbide (SiC), titanium alloys and so on) [3, 4]. Since the birth of RUM in 1960s, a large number of experimental and theoretical investigations have been conducted to study the RUM process. Figure 1 illustrates the rotary ultrasonic drilling (RUD) process.

Cutting forces are important parameters to better understand the cutting process since they are directly related to tool wear, cutting temperatures and surface integrity [5, 6]. Chippings are the key barrier of drilling high-quality holes on hard-brittle materials (such as glass, advanced ceramics). In general, the lower the values of chipping size are, the better the quality of machined holes will be [7]. In this paper, experiments are conducted to study the influences of process variables (spindle speed, feedrate) on cutting force, chipping size, and surface roughness in RUD of K9 glass. The investigation also includes a comparison between RUD and diamond drilling.

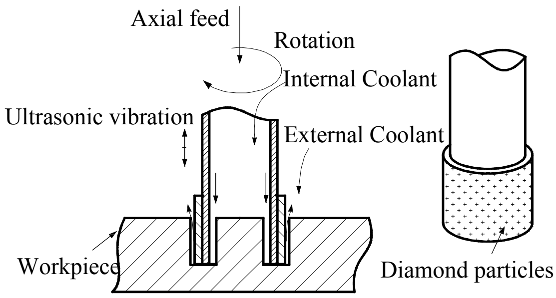
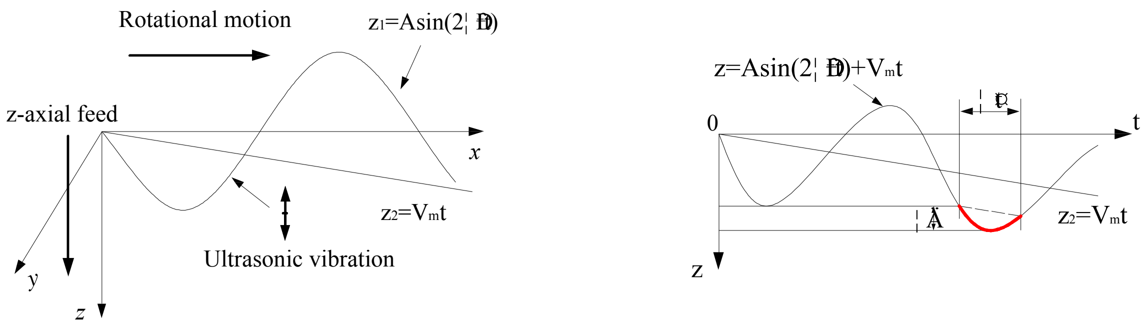


Figure 1. Illustration of rotary ultrasonic drilling.

Characteristic analysis of rotary ultrasonic drilling

Since the RUD process combines diamond drilling and ultrasonic machining, its material removal mechanism is a hybrid that includes hammering, abrasion, and extraction. As shown in Fig. 1, the motion of the diamond particle or the tip of diamond tool is a hybrid that includes rotational motion, ultrasonic vibration and *z*-axis direction feed. The three-dimensional coordinate system used to represent the hybrid motion is illustrated in Fig. 2 (a). The ultrasonic vibration that means the sine curve is in the *x*-*z* plane or *y*-*z* plane. The rotational motion is in the *x*-*y* plane. Figure 2 (b) shows *z*-axial direction movement principle of RUD, where Δt is the period of time during that the particle is contact with the workpiece, and δ is the cutting depth.



(a) (b)

Figure 2. Illustration of the movement properties of rotary ultrasonic drilling: (a) The hybrid motion of the diamond particle; (b) z-axial direction movement principle.

The motion trajectory of each diamond particle in RUD can be properly described with the following equation

$$S_{RUD}(t) = \begin{bmatrix} r \cdot \sin(\omega t) \\ r \cdot \cos(\omega t) \\ A \cdot \sin(2\pi f t) + V_m t \end{bmatrix} \tag{1}$$

where r is the rotational radius of the diamond particles; A is the ultrasonic vibration amplitude; f is the ultrasonic vibration frequency; ω is the angular velocity of the diamond particles; V_{m} is the feedrates in *z*-axis direction; t is the processing time.

According to equation (1), the hybrid velocity of each diamond particle in RUD is derived as

$$V_{RUD} = \frac{dS_{RUD}(t)}{dt} = \begin{bmatrix} r \cdot \omega \cos(\omega t) \\ -r \cdot \omega \sin(\omega t) \\ 2\pi f A \cdot \cos(2\pi f t) + V_m \end{bmatrix} \tag{2}$$

A similar method used to present the velocity of each diamond particle in diamond drilling is described as

$$V_{\text{Diamond drilling}} = \begin{bmatrix} r \cdot \omega \cos(\omega t) \\ -r \cdot \omega \sin(\omega t) \\ V_m \end{bmatrix} \tag{3}$$

With equation (1), (2), (3) and Fig. 2 (b), it can be concluded that the effective cutting length, cutting velocity and cutting depth of single particle in RUD are higher than the features of diamond drilling at the same machining conditions, which will make the RUD process have better processing performance (such as smaller cutting force, higher material remove rate, etc.).

Experimental conditions and procedure

Experiments are conducted on a rotary ultrasonic machine (DMG Ultrasonic 50, Germany). It mainly consists of an ultrasonic spindle system, a numerical control machining system, and a coolant system. The diamond tool processes the workpiece along z-axis direction of the machine at a constant feedrate. The frequency is 20.5 kHz and the power is 18W used in the experiments through testing the resonant effect of diamond cutting tool and spindle. Then the amplitude is tested by the laser fiber vibrometer (Polytec, Germany) that is 10 μm.

The diamond core drill with outer and inner diameters of 10 mm and 8 mm respectively, which consists of metal-bonded diamond particles of mesh size from 120 μm to 140 μm. The workpiece is K9 glass. The sample size is 70 mm × 35 mm × 14 mm. The workpieces are pasted on the fixture that is drilled 4 holes. The diameter of the drilled holes is 16 mm, which are prepared for machining the workpieces and observing the machined holes quality. The grinding fluid (Blaser, Switzerland) is used as internal coolant and external coolant.

The cutting force along the feedrate is measured by a KISTLER 9257B dynamometer (Kistler Instrument Corp, Switzerland). The sampling frequency is 1000 Hz. The mean value of the entire cutting force curve in the tool axial direction is chosen to represent the cutting force in this study. Surface roughness of the machined surfaces is measured along the feed direction by talysurf (Talysurf 5P-120, Rank Taylor Hobson Corporation, British) that can examine surface roughness, surface waviness, etc. The tested range is set as 4mm in the middle of the machined surface. The average surface roughness (Ra) is considered as the surface roughness in this study.

Table 1 shows the processing conditions. Two tests are conducted under each test condition. The process becomes diamond drilling when the ultrasonic vibration is turned off. Two important process variables were studied in this research:

Spindle speed: rotational speed of diamond core drill.

Feedrate: feedrate of diamond core drill toward the workpiece.

Table 1. Experiment conditions

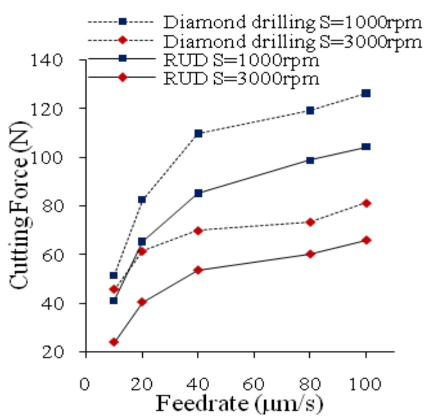
Process variable	Unit	Value
Spindle speed	rpm	1000, 3000
Feedrate	μm/s	10, 20, 40, 80, 100
Ultrasonic Frequency	kHz	20.5
Ultrasonic power	W	18
Ultrasonic amplitude	μm	10

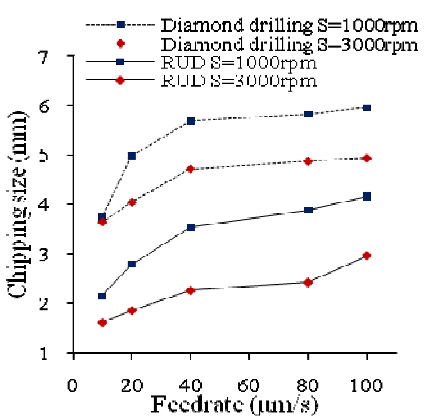
Experimental results and discussion

Comparison of cutting force. Figure 3 shows the comparison of cutting force between RUD and diamond drilling. Compared with diamond drilling, it shows that cutting forces are reduced significantly in RUD process. It also tells that cutting force will decrease as spindle speed increases and will increase with the increase of feedrate. According to the tangent of the curves, it can be concluded that the effect of feedrate on cutting force is much stronger at lower spindle speed. As described in Section 2, the effective machining length and velocity of diamond particle in RUD are higher than the performance of diamond drilling at the same machining conditions, which is a main reason for the reduction of cutting force in RUD. Moreover, plenty of micro-cracks are generated in the machining workpiece surface with ultrasonically hammering of the diamond particle, which make contribution to the reduction of cutting force. Since a lower level of cutting forces will result in the considerable reduction in tool wear, it can be concluded that RUD process will reduce the wear of the diamond tools and extend the life of diamond tools. If the cutting force in RUD process is set at the same with that obtained by diamond drilling, the processing efficiency will be improved with RUD through increasing feedrate.

Comparison of chipping size. In hard-brittle materials drilling process, the features of chippings are regarded as the important criteria to evaluate the holes quality. Figure 4 illustrates the comparison of chipping size for RUD process and diamond drilling. It shows that the values of chipping sizes in RUD are smaller than that processed by diamond drilling. It also shows that the values of chipping sizes will decrease as spindle speed increases and will increase with the increase of feedrate. It is concluded that the effects of feedrate on chipping size is much stronger at lower spindle speed. Compared with the diamond drilling process, it proves that the values of chipping sizes are reduced and the cost of process is lower in RUD process.

Comparison of surface roughness. Figure 5 shows the comparison of surface roughness between RUD and diamond drilling. It tells that the surface roughness of RUD process is slightly higher than that obtained in diamond drilling. As shown in Fig. 5, it tells that surface roughness will increase with the increase of feedrate. It also presents that there is a decreased trend of surface roughness as spindle speed increases. As displayed in Fig. 2 (b), the effective machining depth of diamond particle in RUD is higher than the performance of diamond drilling at the same machining conditions that is inferred that the movement features of diamond particles in RUD process affect the machined surface quality. It can be concluded that the effective cutting depth of diamond particles is the main factor for surface roughness in RUD of K9 glass.





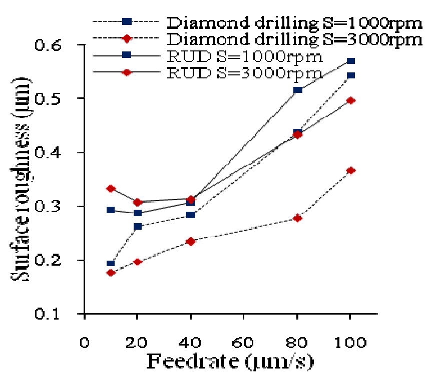


Figure 3. Comparison of cutting force. Figure 4. Comparison of chipping size. Figure 5. Comparison of roughness.

Conclusions

This paper discusses the kinematic characteristics of diamond particles in RUD. It studies the influences of process variables on cutting force, chipping size, and hole inside surface roughness in RUD of K9 glass. As a comparison study, it also investigates the processing performance between RUD process and diamond drilling. The following conclusions can be drawn through this research:

(1) The experimental results show that spindle speed and feedrate have significant effects on the processing performance in RUD process. It presents that cutting force and the value of chipping size will decrease as spindle speed increases and will increase with the increase of feedrate, and surface roughness will increase with the increase of feedrate. It is concluded that the effects of feedrate on cutting force and chipping size are much stronger at lower spindle speed in RUD process.

(2) Compared with the diamond drilling process, the RUD process can significantly reduce the cutting forces and the values of chippings sizes, which can improve machining efficiency and make the machining cost lower in K9 glass processing. The surface roughness of RUD process is higher than that obtained in diamond drilling, which is concluded that the effective cutting depth of diamond particles is the main factor for surface roughness in RUD of K9 glass.

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