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ORIGINAL ARTICLE

Experimental study on surface generation in vibration-assisted micro-milling of glass

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Abstract Micro-milling of glass is a technique to fabricate micro-optics with complex geometry using a defined cutting edge. This paper presents the experimental study on the surface generation in vibration-assisted micro-milling of a BK-7 optical glass. A piezoelectric-actuated 2D vibration stage with flexure design is developed to apply vibration assistance on the workpiece in the micro-milling process. The effects of vibration direction, vibration amplitude and frequency on the surface roughness and profile are determined from a series of vibration-assisted micro-milling experiments. It is concluded that the vibration applied in normal direction has a major effect on the improvement of surface quality. The vibration assistance enhances the brittle-ductile transition of glass material and therefore reduces the damage on the machined surface. Higher vibration frequencies improve the surface quality by reducing the waviness on the surface.

Keywords Micro milling · Vibration · Surface · Glass

1 Introduction

Precision machining of glass is applied for the fabrication of micro-optics with complex geometry in the industrial areas such as astronomy, biomedical, defense, energy and lithography. Geometric accuracy and surface quality are critical factors to achieve desired functioning performance of the optical components. Grinding, polishing and lapping are traditionally used to machine glass materials. However, these processes are time consuming, and the geometric accuracy is not guaranteed due to a non-deterministic material removal process [1]. In addition, polishing can cause subsurface damage up to 0.5 μm on the finished surface because of the free particles in the abrasive slurry [2]. Therefore, new techniques for machining complex optics with high efficiency are required.

Micro-milling is capable of generating high slope freeform surface with a micron-level geometric feature using a defined cutting edge. Different from metallic materials for which plastic deformation is the dominant material removal mechanism in the machining process, glass is a brittle material with low fracture toughness and high hardness [3]. The cutting load causes brittle fracture of glass and generates crack on the machined surface, which is detrimental to the quality of the optical components. However, it has been demonstrated that when the uncut chip thickness is below a critical value, the material deformation goes through the brittle-ductile transition and a crack-free surface is achieved. Experimental studies on milling glass showed that feed rate and tool diameter are the key parameters which govern the brittle-ductile transition of glass material [4, 5]. An analytical model based on fracture mechanics principle was proposed to determine the critical feed rate in ductile-mode milling of glass [6]. The brittle-ductile deformation of glass in the machining process also depends on stress and temperature in the material deformation zone [7], cutting speed [8] and tool edge radius [9].

Vibration-assisted cutting applies high frequency and small amplitude of displacement between the tool and the workpiece in addition to the original feed motion. It was originally developed for turning process by exciting the cutting tool at its natural frequency using piezo-actuators. The added vibration changes the fundamental mechanism of chip formation and surface generation in the cutting process [10–13]. It is shown that when the maximum vibrating speed exceeded about ten

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times the cutting speed, the critical depth of cut corresponding to ductile deformation mode increased by around sevenfold [13]. Vibration-assisted cutting has been applied on milling process for a few metallic materials, including aluminium 6061 [14–16], nickel-based super alloy [17], hardened tool steel [18], stainless steel [19–21] and hard aluminium [22]. Adding vibration assistance on the milling process has the advantages of reducing cutting force [19, 20, 23], decreasing tool wear rate [17, 18, 21, 24], minimizing burr formation [24, 25] and improving surface finish [18, 20, 23, 24, 26, 27]. However, the cutting performance highly depends on the cutting conditions and vibration assistance parameters.

This paper presents the first study on the vibration-assisted micro-milling of glass material. Different from the vibration-assisted turning process presented in the literature, the milling process involves varying uncut chip thicknesses due to the high speed rotation of milling tool, and the machining dynamics includes forced vibration, regenerative vibration and externally applied vibration assistance. This paper conducts an experimental investigation on the fundamental mechanism of surface generation in vibration-assisted micro-milling of glass. A 2D vibration stage with adjustable vibration amplitude and frequency is developed. The effects of the vibration direction, amplitude and frequency on the surface roughness and damage are investigated. It is concluded that the vibration applied in normal direction enhances the brittle-ductile transition of glass workpiece material and decreases the surface roughness by reducing the waviness on the machined surface. The amplitude and frequency of the applied vibration have major effects on the surface property.

2 Experimental

2.1 Machining mechanism of vibration-assisted milling process

In this study, the vibration assistance is applied on the workpiece by piezoelectric actuators for the micro-milling process. Figure 1 shows the schematics of micro-milling with vibration assistance in normal (Y) and feed (X) directions, as well as the chip formation mechanism in the orthogonal representation. When the vibration is provided in the normal direction, the tool edge has a vertical displacement relative to the workpiece; therefore, the surface generation is influenced by the tool's indention beside the shearing mechanism. When the vibration is applied in the feed direction, the relative motion between the tool and workpiece is only in the cutting direction, and the surface generation is dominated by the burnishing effect when the tool's bottom edge rubs on the surface.

Figure 2 shows the tool tip trajectory with respect to the workpiece when the vibration assistance is provided in the normal direction. The solid curve is a combination of original tool tip motion (dashed line) and high-frequency vibration motion in normal direction. In vibration-assisted micro-milling process, the tool edge radius is comparable with the amplitude of the assisted vibration, and the surface is generated when the tool edge indents into the workpiece. The shaded area in Fig. 2 shows the indentation volume. The indentation increases the hydrostatic pressure in the material deformation zone. As reported by M. Yoshino et al. [28], the hydrostatic pressure enhances the brittle-ductile transition of brittle material. Therefore, the experimental study in this paper is to test the hypothesis that the improvement of surface quality is a result of brittle-ductile transition due to the indentation of the tool edge into the workpiece when the vibration assistance is applied.

2.2 Design of a 2D vibration stage

A piezoelectric-driven 2D vibration stage with a parallel kinematic scheme based on flexure design was developed, as shown in Fig. 3. The vibration assistance in the micro-milling process is provided to the workpiece which is fixed on the vibration stage. A Physik Instrument piezoelectric actuator (model: P844.10) with a maximum travel range of 15 μm and a frequency range of 18 kHz is employed. The maximum pushing force of the actuator is 3000 N. The tip of the piezoelectric actuator vibrates with the frequency provided

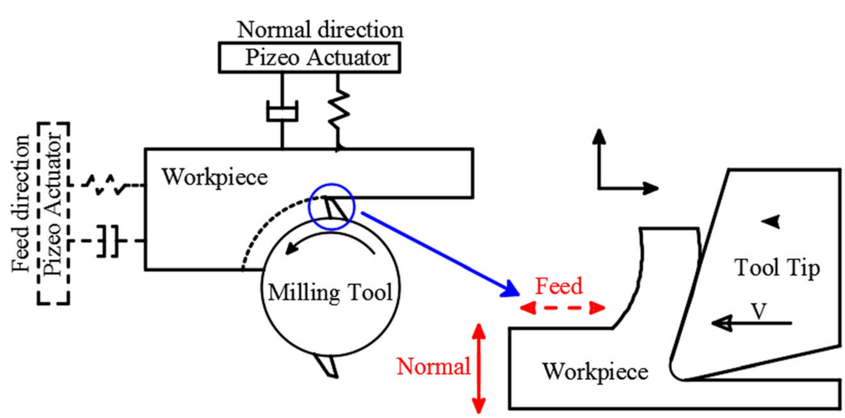

Fig. 1 Schematics of micro-milling with vibration assistance in normal (*solid line*) and feed (*dashed line*) directions

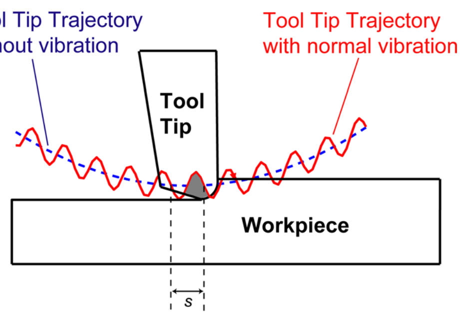

Fig. 2 Tool tip trajectory with respect to the workpiece with vibration assistance in normal direction

by the power amplifier, which has a maximum output of 20 V. The flexure structure is designed to amplify the actuator's tip displacement at the centre of the stage.

The dynamic property of the vibration stage is critical to the capability of vibration provided to the micro-milling operation. In order to identify the dynamic property of the vibration stage, the frequency of the input voltage to the amplifier is swept up to 11 kHz, and a Lion Precision displacement sensor CPL-290 with a bandwidth of 15 kHz and a resolution of 0.25 nm is used to measure the displacement of the vibration stage. When the frequency of the input voltage goes beyond 11 kHz, the allowable input voltage drops down significantly, and then the output signal of the amplifier is distorted. The frequency response functions of the vibration stage in the *X* and *Y* directions are shown in Fig. 4. It is found that the stage displacement is amplified in the frequency range of 5–11 kHz. Under each frequency, the relationship between the displacement and the input voltage is calibrated. In the micro-milling experiment, the maximum input voltage is constrained to ensure a linear displacement-voltage relationship.

3 Results and discussion

The vibration-assisted micro-milling experiment is conducted on a MDA precision micro-machining centre with a

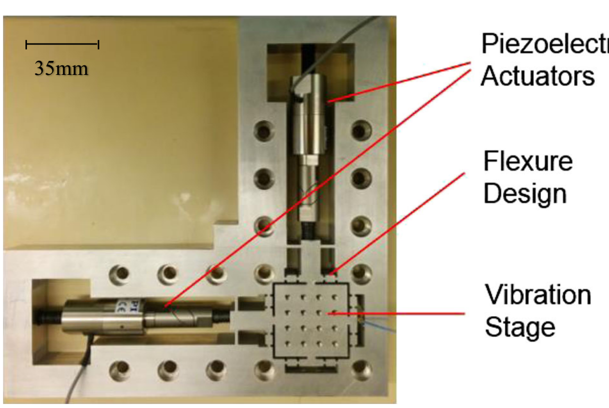

Fig. 3 2D vibration-assisted stage

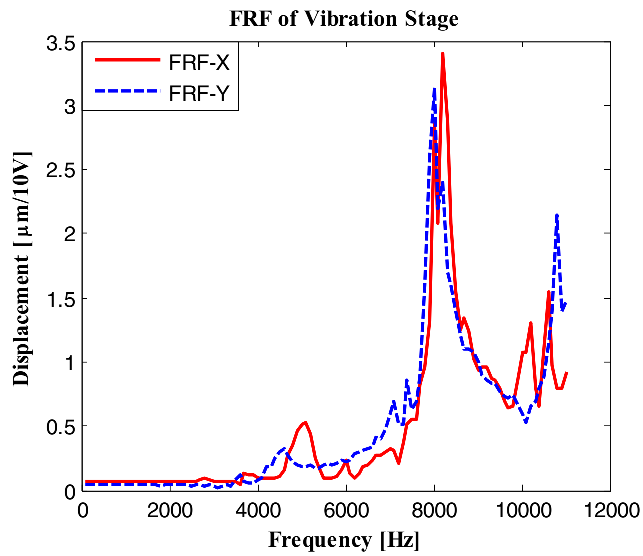

Fig. 4 Frequency response function of the vibration stage

maximum spindle speed of 60,000 rpm. A two-flute diamond-coated micro-end mill (MICROCUT) with a diameter of 3.175 mm and a helix angle of 30° is used. The workpiece is BK-7 uncoated optical glass. The cutting conditions of the experiment are listed in Table 1. A range of amplitudes and frequencies of the vibration assistance are applied to investigate the effect of external vibration on the surface quality. If the uncut chip thickness exceeds the critical value which corresponds to the brittle-ductile transition of the glass material, micro-crack is generated on the machined surface. The uncut chip thickness in the milling process is determined by the radial depth of cut and the feed rate. In this study, different values of feed rate and radial depth of cut are applied. The spindle speed and axial depth of cut are kept constant. For each cutting parameter, micro-milling tests are conducted under three vibration assistance conditions: no applied vibration, vibration in normal direction and vibration in feed direction. Cutting tool edge is checked under an optical microscope after each test to avoid severe tool wear. All the tests have been conducted three times to ensure repeatability of the results. A Mitutoyo surface roughness tester SJ-210 and a Nanovea optical confocal microscope are used to characterize the quality of the machined surface.

Table 1 Cutting conditions

Vibration assistance	Frequency (kHz)	5, 7, 8, 9, 11
	Amplitude (μm)	1.0, 1.2, 2.0, 4.0
Feed rate (μm/tooth)		0.4, 0.5
Radial depth of cut (μm)		15, 25
Spindle speed (rpm)		10,000
Axial depth of cut (mm)		1.0

3.1 Effect of vibration direction and amplitude on surface roughness

Figure 5 shows the surface roughness results when the amplitudes of applied vibration are 1, 2 and 4 μm. Maximum, minimum and average values of the repeated results under each vibration assistance condition are plotted. Table 2 lists the calculated standard deviation of the measured results. A small feed rate of 0.5 μm/tooth is selected to ensure a ductile deformation-dominated cutting mode. Under each vibration amplitude, the Ra values with no external vibration and vibration applied in normal and feed directions are compared. When the vibration amplitude is 1 μm, the difference of Ra under the three vibration conditions is less than 2 %, showing that the vibration assistance under a small amplitude is not effective. When the vibration amplitude increases to 2 and 4 μm, a better surface quality is achieved with the vibration assistance. When the vibration assistance is applied in normal direction, the Ra value reduces by 45 % when the vibration amplitude increases from 1 to 4 μm. However, the surface roughness does not change extensively for the vibration applied in feed direction. Therefore, it is concluded that the vibration assistance in normal direction is the main factor for the improvement of the surface quality. Furthermore, it is found that the Ra values reduce asymptotically with the increase of the vibration amplitude in normal vibration mode. It is because a higher vibration amplitude results in a higher hydrostatic pressure in the tertiary deformation zone and therefore enables plastic deformation of glass material instead of brittle fracture.

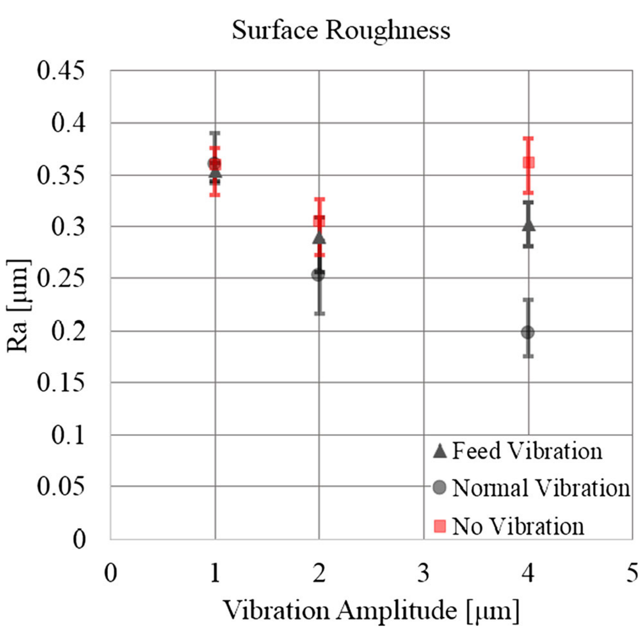

Fig. 5 Surface roughness with vibration amplitude (frequency 8 kHz, feed rate 0.5 μm/tooth, radial depth of cut 15 μm)

Table 2 Standard deviation of surface roughness results with vibration amplitude (μm)

Vibration assistance condition	Vibration amplitude (μm)		
	1	2	4
No vibration	0.016	0.020	0.020
Feed vibration	0.006	0.020	0.014
Normal vibration	0.017	0.024	0.017

3.2 Effect of vibration frequency on surface roughness

Figure 6 shows the surface roughness results with respect to the frequency of the vibration assistance at constant vibration amplitude. Table 3 lists the standard deviation of measured results corresponding to each vibration condition. The frequency range of 5 to 11 kHz is applied. Based on the calibrated FRF of the vibration stage, the vibration displacement at 5 kHz is minimum, and it has the highest amplitude of 1.2 μm in the linear vibration range. Therefore, a constant vibration amplitude of 1.2 μm is applied at all frequencies by adjusting the out voltage of the amplifier.

It is found that the surface roughness reduces asymptotically when the frequency of applied vibration increases, and the average Ra value decreases by 38 % when the frequency of the vibration assistance increases from 5 to 11 kHz. As shown in Fig. 2, the vibration frequency influences the travel distance of the tool tip at each vibration cycle, defined as:

$$s = v \cdot \frac{1}{f} \tag{1}$$

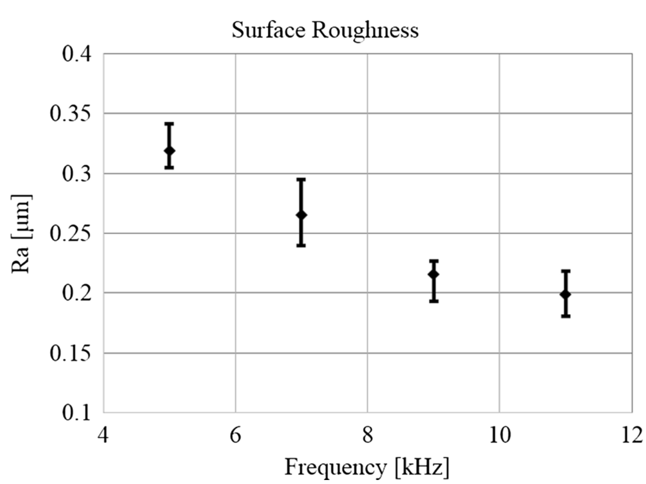

Fig. 6 Surface roughness with vibration frequency (amplitude 1.2 μm, feed rate 0.4 μm/tooth, radial depth of cut 25 μm)

Table 3 Standard deviation of surface roughness results with vibration frequency (μm)

Vibration assistance condition	Vibration frequency (kHz)			
Normal vibration	5	7	9	11
	0.014	0.020	0.014	0.017

where s is the travel distance of the tool tip, v is the cutting velocity, and f is the frequency of the vibration assistance. When the frequency of the vibration assistance increases, the travel distance of the tool tip at each cycle of the applied vibration decreases and therefore generates lower waves on the machined surface, which in turn decreases the Ra value.

3.3 Effect of vibration on surface damage

In order to determine the effect of vibration assistance on the brittle-ductile transition of glass material, an optical surface profilometer is used to investigate the surface damage after the milling process. A micro-milling tool with a small diameter (0.889 mm) is used to have a brittle-dominated milling process due to low structural stiffness. Different values of radial depth of cut, feed rate, vibration frequency and amplitude are used. Table 4 shows the conditions of two cutting tests, with the pictures of side surface profile given in Fig. 7a, b. Each figure shows the surface corresponds to one tooth passing, with the left-hand side representing the vibration-assisted milling in normal direction and the right-hand side portion representing the milling without vibration. The dark regions in the pictures show the voids left on the machined surface, which means the occurrence of brittle deformation in the milling process. It is found that when the vibration assistance is applied, the surface damage reduces extensively. Therefore, it is concluded that the vibration assistance in normal direction enhances the brittle-ductile transition of the material in the micro-milling of glass.

Table 4 Surface profile measured by optical profilometer

Axial depth of cut (mm)		0.5	
Spindle speed (rpm)		10,000	
Feed rate (μm/tooth)		1.0	
		Test (a)	Test (b)
Vibration assistance	Frequency (kHz)	4	11
	Amplitude (μm)	0.8	0.5
Radial depth of cut (μm)		15	3

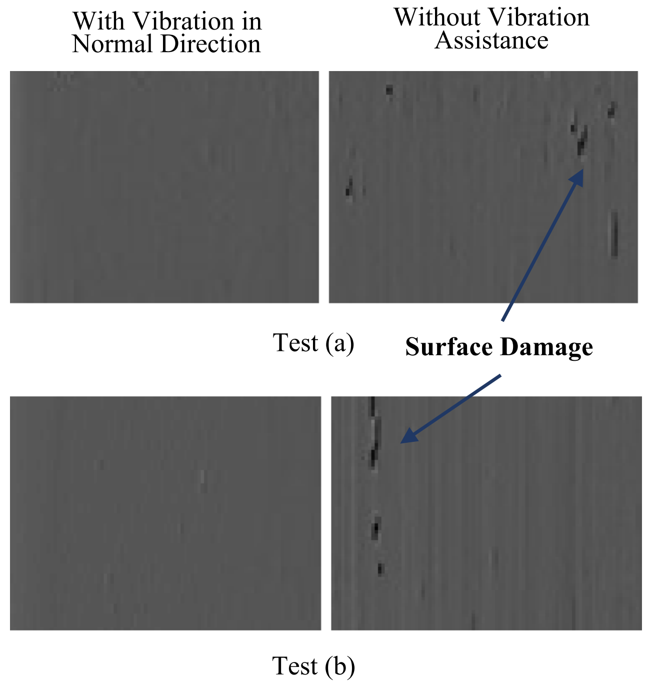

Fig. 7 Comparison of surface profile with and without vibration assistance

4 Conclusion

This paper presents the experimental study on the micro-milling of glass material when vibration assistance is provided in normal and feed directions. It is proposed that the vibration assistance in normal direction causes the tool's indentation into the workpiece, while the vibration in feed direction results in the burnishing effect on the surface. A 2D vibration stage is developed based on flexure design with a piezoelectric actuator. The frequency response function of the vibration stage is experimentally calibrated. The system is able to provide vibration assistance in the frequency range of 5–11 kHz. Vibration-assisted micro-milling tests are conducted, and the following conclusions are drawn based on the experimental results:

(1) The average surface roughness value decreases by 45 % when the amplitude of the vibration assistance in normal direction increases from 1 to 4 μm, while the vibration assistance in feed direction does not have a significant influence on the surface roughness. The improvement of the surface quality is due to the increase of hydrostatic pressure in the tertiary deformation zone at a higher vibration amplitude.

(2) When the frequency of the vibration assistance applied in normal direction increases from 5 to 11 kHz, the surface roughness decreases asymptotically by 38 %. A higher frequency of the applied vibration reduces the waviness of the surface and therefore improves the surface quality.

(3) The observation of surface damage by optical profilometer shows that surface damage reduces significantly when the vibration assistance is applied in normal direction, which demonstrates that the brittle-ductile transition of glass material is enhanced during the micro-milling process with vibration assistance.

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