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A new method for V-groove microstructured surface polishing using non-Newtonian fluids

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Normally, injection molding is employed to manufacture V-groove optical components, and ultra-precision turning is used to fabricate the mould. However, ultra-precision turning cannot meet the surface quality demands due to the tool marks. To solve this problem, a non-contact polishing method using non-Newtonian fluids has been proposed in this paper to achieve ultra-precision processing of V-groove microstructured surfaces. The effects of oxidant concentration, tool speed and vibration frequency on surface quality of microstructured surfaces were investigated. Meanwhile, profile of microstructured V-grooves before and after polishing was also analyzed. The optimum process parameters were obtained. The surface roughness of V-groove microstructured surface was reduced from the initial R_a 200 nm to 53 nm, less than 2 µm form accuracy were achieved, while the tool marks and burrs were effectively removed.

1. Introduction

V-groove microstructured surfaces are widely used in optical fiber communication, display film and optical lighting components, etc. Injection molding is generally employed to rapidly manufacture V-groove optical components, and the accuracy of the mold determines the accuracy of the optical components [1]. At present, single point diamond turning technology (SPDT) is usually used to fabricate high precision V-groove microstructured surfaces [2, 3]. Takashi et al. fabricated sinusoidal wave microstructures with wavelength and amplitude of 100 µm and 100 nm on aluminum alloy by turning, and the profile error after machining was micron [4, 5]. Rahman et al. obtained the microstructured surface on the nickel coated surface with a roughness value of R_a 0.05 µm by using fast tool servo [6]. Guo et al. used SPDT to fabricate V-groove microstructured surface, the peak and valley shape accuracy of the v-groove surface was less than 1 µm and the surface roughness was R_a 15 nm [7]. Wu et al. prepared a complex microstructure surface using a five-axis system with a surface roughness of R_a 50 nm and a shape accuracy of 0.65 µm [8]. Fang et al. machined complex eye structures, microlens arrays, and unidirectional sinusoidal surfaces, and the surface roughness could reach about R_a 6 nm [9]. The SPTD method is widely used for V-groove surface fabrication, but tool marks and burrs produced by this method are always unavoidable [10, 11]. At present, the main way to improve the surface quality after SPDT is polishing [12]. Guo et al. proposed a new vibration-assisted magnetic abrasive polishing (VAMAP) method, the quality of the V-groove surfaces after polishing is effectively improved, and the initial tool marks and burrs are removed, but this method is not suitable for magnetic workpiece [13, 14].

In this paper, in order to meet the high surface quality and shape accuracy requirements of V-groove microstructured surfaces, a non-contact polishing method using non-Newtonian fluids is proposed to achieve ultra-precision processing of V-groove microstructured surfaces. The effects of oxidant concentration, tool speed and frequency on surface quality and shape accuracy were studied. Finally, less than R_a 50 nm surface roughness and less than 2 µm shape accuracy were achieved on V-groove microstructured surface by using the proposed method.

2. Principle of the method

Non-Newtonian fluids with different rheological properties exhibit different rheological properties when the shear rate changes, and dilatant fluid with shear-thickening effects are often referred as shear-thickening fluids (STF). The main favorable feature of STF is that the process is reversible, so that the fluids turn to the initial liquid state after removing the loading from the medium [15]. Shear thickening polishing (STP) is a new polishing technology, which utilizes the shear thickening effect of non-Newtonian fluids to achieve flexible polishing successfully [15, 16]. Due to the high flexibility of the polishing fluid, the flexible contact area formed during polishing can be well adapted to the surface form of the V-groove microstructured surfaces and achieve effective material removal. In this work, an ultrafine non-Newtonian slurry for V-groove microstructured surfaces polishing was configured.

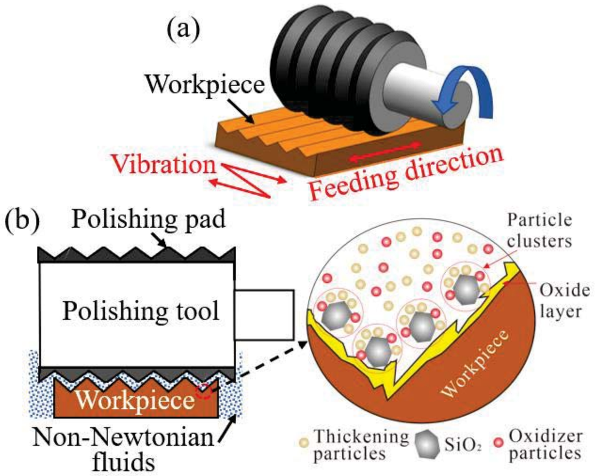

Fig. 1 Schematic diagram of polishing method (a) Schematic diagram of relative motion of workpiece and polishing tool (b) Microscopic principle diagram of material removal

3. Experimental setup and parameters

3.1 Experimental materials

The experimental workpiece was a 100 mm × 50 mm × 1 mm copper plate. As shown in Fig. 2(a), the V-groove microstructured surface was manufactured by SPDT method, and the height and width of the V-groove after cutting were 45 μm and 100 μm respectively. As shown in Fig. 2(b), the surface roughness of the prepared V-groove is about R_a 160 nm.

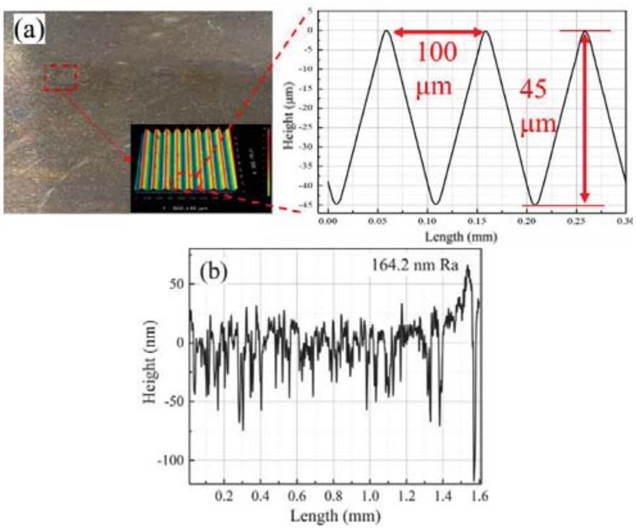

Fig. 2 Initial state of the experimental workpiece (a) Initial surface microstructure profile (b) Initial roughness

3.2 Experimental procedure and measurement

The experiment was carried out on a four-axis motion platform. The V-groove microstructured surface workpiece is mounted on the turntable through the fixture. The polishing tool is controlled by PLC to realize up and down movement along the Z axis, and the longitudinal movement distance of the Z axis is 1 cm. The working gap between polishing tool and workpiece is 0.2 mm. The speed of polishing tool can be adjusted from 100 to 12000 rpm.

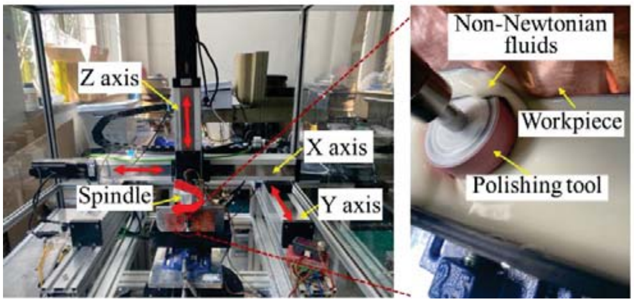

Fig. 3 Experimental setup

The polishing fluid in this study is composed of silica sol, polyhydroxyl polymer and deionized water. The polyhydroxyl polymer accounted for 54 wt% of the base solution (the base solution only contained polyhydroxyl polymer and deionized water), and particle size of silica abrasive and the concentration in the system are 50 nm and 10 wt%, respectively. Oxidant concentration, tool speed and vibration frequency are used as variables in this study. The effects of polishing parameters on the workpiece surface morphology and roughness were compared by single factor experiment. The experimental parameters are shown in Table 1. The surface morphology of the V-groove was observed using an ultra-field depth microscope (VHX-600E03041132). The surface roughness of the workpiece was measured and analyzed using a Stylus Surface Profilometers (TalySurf PGI 840).

Table 1 Experimental parameters

Category	Changing value	Fixed value
Oxidant concentration W (wt%)	0	S=3500 rpm F=10 Hz
	2	
	4	
Tool speed S (rpm)	2000	W=2 wt% F=10 Hz
	3500	
	5000	
Motion frequency F (Hz)	1	W=2 wt% S=3500 rpm
	5	
	10	

4. Results and Discussion

4.1 Effect of oxidant concentration

To investigate the effect of different oxidant concentrations on the surface quality of V-groove microstructured surfaces, experiments with different oxidant concentrations were carried out. As shown in Fig. 4, the addition of hydrogen peroxide can increase the material removal and improves the surface quality, but when the oxidant concentration reaches a certain value, the surface roughness increases. The surface roughness after polishing without the hydrogen peroxide addition was R_a 73.45 nm and the micro feature height was 44 µm. the surface roughness after polishing with the addition of 2 wt% and 4 wt% hydrogen peroxide was R_a 53.3 nm and 84.2 nm, and the microstructure height was 43 µm and 40 µm, respectively.

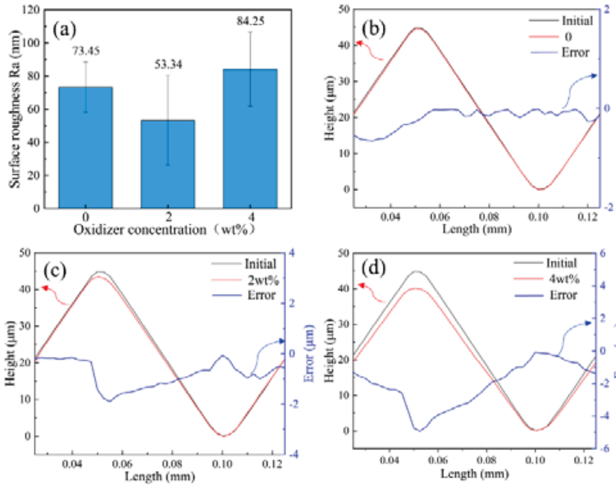

Fig. 4 Changes in surface roughness and form of workpiece after polishing with different oxidant concentrations (a) Changes in roughness after polishing (b) After polishing without adding oxidant (c) After polishing with 2 wt% oxidant (d) After polishing with 4 wt% oxidant

4.2 Effect of tool speed

The tool rotational speed determines the shear rate of the polishing fluid, and the shear rate affects the shear thickening effect of the polishing fluid. The speed parameters used in the experiments were 2000, 3500 and 5000 rpm. The variation of the V-groove surface quality at different tool speeds as shown in Fig. 5 The surface roughness decreases as the tool speed increases, and the surface roughness basically the same when the tool speed increases from 3500 rpm to 5000 rpm. The material removal efficiency was basically the same when the tool speed was 2000 and 3500 rpm, and the height of the polished microstructured surface was 43 µm. When the tool speed increased to 5000 rpm, the material removal increased and the structure height deteriorates to 38 µm.

4.3 Effect of vibration frequency

In order to investigate the effect of tool vibration frequency on surface quality of the V-groove microstructured surface, experiments with different vibration frequencies were carried out. The vibration frequencies used for the experiments were 1 Hz, 5 Hz and 10 Hz. The changes in the surface roughness of the V-groove microstructured surfaces at different vibration frequencies is shown in Fig. 6. The surface roughness decreases as the vibration frequency increases, and the material removal efficiency is basically the same when the vibration frequency is 5 Hz and 10 Hz, and the height of the V-groove after polishing is all about 43 µm.

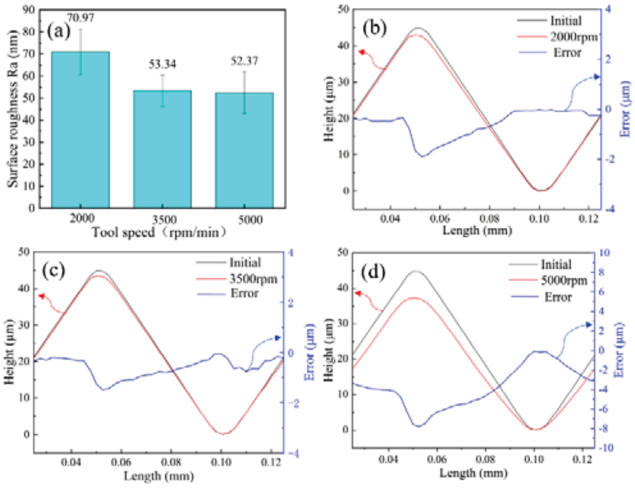

Fig. 5 Changes in surface roughness and form after polishing at different tool speed (a) Change of roughness after polishing (b) After polishing at 2000 rpm of tool speed (c) After polishing at 3500 rpm of tool speed (d) After polishing at 5000 rpm of tool speed

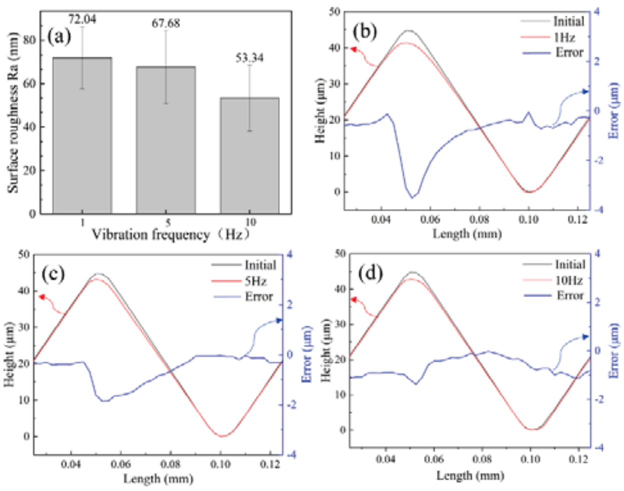

Fig. 6 Changes in surface roughness and form after polishing with different vibration frequency (a) Changes in roughness after polishing (b) After polishing with vibration frequency 1Hz (c) After polishing with vibration frequency 5 Hz (d) After polishing with vibration frequency 10 Hz

4.4 Surface morphology comparison

As shown in Fig. 7(a), obvious defects such as tool marks and burrs can be observed. The optimal parameters are used for V-groove polishing, which are 2 wt% oxidizer concentration, 3500 rpm tool speed and 10 Hz vibration frequency. As shown in Fig. 7(b), the V-groove microstructured surface after polishing is smoother, and the tool marks and burrs on the surface are effectively removed.

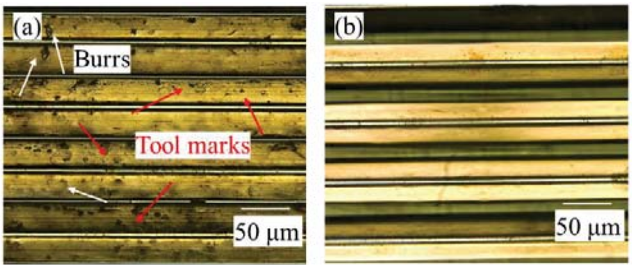

Fig. 7 Surface microscopic morphology before and after polishing(a) Before polishing (b) After polishing

5. Conclusions

In this paper, a non-contact polishing method using non-Newtonian fluids is proposed to achieve ultra-precision processing of V-groove microstructured surfaces. The effects of oxidant concentration, tool rotation speed, and vibration frequency on the polishing performance of V-groove microstructured were investigated, and the following conclusions were obtained.

1. Non-Newtonian fluid and conformal tool is used for V-groove microstructured surface polishing. The surface roughness of V-groove microstructure reaches R_a 53 nm after polishing, and the variation of V-groove height caused by polishing is less than 2 μm.

2. The surface quality is significantly affected by oxidant concentration. When the oxidant concentration is less than 2%, the addition of hydrogen peroxide has no obvious effect on surface quality. When the oxidant concentration exceeds 2 wt%, the surface of the workpiece will appear pit defects and the roughness deteriorate.

3. The shape accuracy is greatly affected by both oxidant concentration and tool speed. With the increase of oxidant concentration and tool speed, V-groove height gradually decreases. The vibration frequency has little effect on V-groove height.

4. The optimum polishing parameters obtained by experiments are 2 wt% oxidant concentration, 3500 rpm tool speed and 10 Hz vibration frequency.

Therefore, this method achieved low roughness while maintaining the profile of microstructured V-grooves. Future work will investigate the performance of this method on rectangular and sinusoidal microstructured surfaces.

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