Investigation on form-preserving polishing of optical element/system via an active fluid jet

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A wide variety of optics are required to be manufactured efficiently in high form accuracy together with an ultra-smooth texture. Single point diamond turning (SPDT) shows an advantage of high efficiency in form generation sin ce it can produce optical surfaces with sub-micrometer form accuracy directly. However, the machining tool mark is a significant fact that leads to expected diffraction, which will seriously affect the optical performance. The inev itable residual turning marks affect the performance of the optical surface, which produces a diffraction effect and stray light. Motivated by this, an efficient post-treatment method of a diamond-turned surface with low cost, wide applicability, and superior form-preserving capability has been paid more attention. A series of spot polishing test s are carried out to study the effect of the AFJ polishing parameters on the material removal rate of the turning marks through orthogonal experiments and check the validity of the proposed model. Finally, the practicality of th e AFJ polishing method is demonstrated on an optical elements and optical system. The experimental results and t he theoretical analysis prove that AFJ polishing technology can lead to the post-treatment of diamond-turned surfa ces in a form-preserving manner.

1. Introduction (Times New Roman 10pt)

With the rapid development of ultra-precision CNC machinin g technology, single-point diamond turning (SPDT) has become a common method for producing optical compnents and optical systems [1, 2. It enables the direct production of optical surface s with sub-micrometer form accuracy and nanometric roughness, while ensuring precise position and orientation for each optical surface. However, the residual tool marks (RTMs) that remain after SPDT adversely affect the optical performance, leading to undesirable diffraction and stray light [3]. The expanding applica tions in advanced optical instruments require smoother surfaces with high accuracy. Therefore, there is a strong need for an effe ctive post-treatment method that can remove RTMs without com promising form accuracy.

Recently, an active fluid jet (AFJ) polishing technology has been developed and investigated for the removal of diamond tur ning marks. In this process, a small sub-aperture polishing pin i s pressed against the workpiece surface using polishing fluid, w hile the pin is rotated eccentrically. Material removal occurs due to the relative velocity and pressure between the tool and work piece, following Preston's law. Initially developed for correcting aspherical and freeform optics, AFJ polishing has gained interest due to its affordability and applicability to a wide range of ma terials. Many scholars have conducted theoretical analyses, exper imental research, and proposed improved methods for AFJ polis hing. Zhang et al. applied AFJ polishing to remove diamond tur ning marks, investigating the effect of polishing parameters on t he material removal rate. They demonstrated the effectiveness an d superior form-preserving capability of AFJ polishing on diamo nd-turned surfaces, showing that it enables deterministic post-trea tment while preserving the surface form [4].

In this paper, the principle of the AFJ technology was applie d and a comprehensive study was conducted to investigate the p ost-polishing process for side-wall surfaces through multi-scale a nalysis. Based on the analysis, a method was proposed to enhan ce the form-preserving capability during the polishing process. B ased on the simulation model of AFJ polishing, the influence of processing parameters on the RTMs removal can be analyzed a t the macroscopic scale so that the uniformity of RTMs removal in the polishing area can be evaluated. Finally, a series of exp eriments were conducted to validate the proposed theoretical ana lysis. In order to improve the uniformity of RTMs removal, an innovative AFJ tool was designed and optimized based on the si mulation model. The experimental results demonstrated the effect iveness of the new AFJ polishing method in uniformly removing

RTMs.

2. Material removal mechanism of turning marks in AFJ polishing process

2.1 Modelling of material removal characteristics of AFJ

The diamond-cut surface comprises a turning mark layer and a substrate, collectively defining the overall microtopography. At the microscopic level, the turning mark layer exhibits anisotropic properties due to its periodic structure in the high spatial frequency domain. Unlike isotropic surfaces, the presence of the ripple structure within the turning mark layer impacts the distribution of active abrasives and the micromachining state of a single abrasive. Consequently, the material removal process within the rippled layer varies significantly depending on the direction of abrasive movement and the position of contact. The primary objective of form-preserved post-polishing is to eliminate the ripple structure while preserving the integrity of the substrate. The distribution of abrasive particle sizes (diameters) in the polishing slurry affects the number of active abrasives. In most cases, this distribution follows a normal probability density function, as shown in Fig. 1. The number of active abrasive particles at point P can be given by

$$N = n\left\{1-\Phi\left[\frac{1}{s}\left(D_{\max}+z'-\bar{D}\right)-\frac{F_{pan}}{\pi s D_{\max}}\left(\frac{1}{H_w}+\frac{1}{H_p}\right)\right]\right\} \tag{1}$$

It can be found that the number of active abrasives N decreases as z' increases. This implies that the distribution of active abrasives exhibits periodic variations on the rippled surface due to the height deviation between the peaks and valleys. In particular, at the peak of the turning marks, a greater number of abrasive particles can participate in the material removal process compared to the valley regions.

When the abrasive moving direction is parallel to the turning mark (with a velocity denoted as v^{para}), the base and height of the triangle are represented as MN = 2a, and the penetration depth δ, respectively. The triangle ΔNJK in the height can be given as

$$S_{perp} = 2D\delta\sin\theta + \sqrt{D\delta}\frac{D}{2} - \sqrt{\left[\frac{1}{4}D^3\delta - D\delta\left[\sqrt{D\delta}-\left(\frac{D}{2}-\delta\right)\tan\theta\right]^2\cos^2\theta\right]} \tag{2}$$

As a result, the micro-cutting area (Sperp) is significantly larger since it encompasses both the front and underneath portions of the abrasive. On the other hand, when the abrasive's movement direction is parallel to the ripples, the micro-cutting area (Spara) is smaller as the abrasive primarily affects the material underneath it. This means that there will be no obvious ploughing or cutting phenomenon.

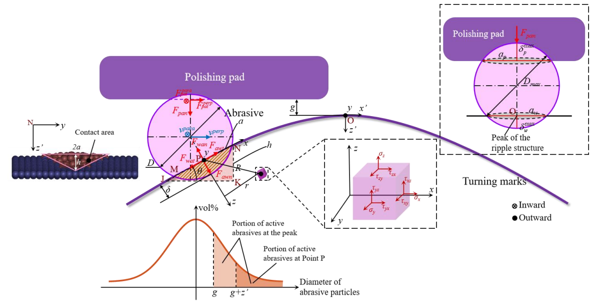

Fig. 1 Schematic diagram of material removal characteristics of AFJ.

2.2 Simulation

During the AFJ polishing process, the pin is pressed onto the surface through a constant flow of polishing slurry. The pressure is determined by the flow hydrodynamic characteristics in the nozzle and the elastic deformation of the pin. It means that the simulation is a multi-physics problem where the interaction between two different analyses is taken into account. As is known to all, the fluid-structure interaction (FSI) analysis is an effective method in solving the complicated nonlinear hydrodynamic-elastic problem. In the AFJ polishing, the deformation of the pin does not have a significant impact on the flow of the polishing slurry. So, the one-way FSI analysis is used in this model. The interaction between the two analyses takes place at the boundary (see Fig. 1), where the results of the CFD analysis are passed to the structural analysis as a load.

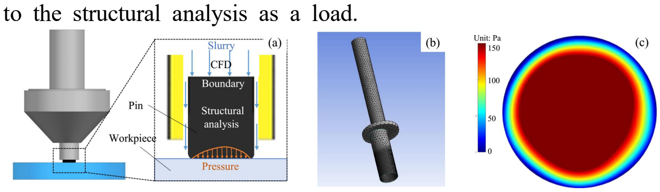

Fig. 2 Simulation of the AFJ polishing: (a) FSI model, (b) CFD model of the slurry flow, (c) the results of the pressure distribution on the workpiece.

The morphology evolution of the surface microtopography is simulated based on the flowchart proposed above. To evaluate the TMR, the polishing process is repeated four times and power spectrum density (PSD) analysis is introduced to visualize the spatial frequency. A contour line perpendicular to the turning marks is extracted and processed by a Fourier transform. The simulated results and the PSD analysis are shown in Fig. 9. It is worthy to note that the ripple structure is alleviated gradually with the increase of the polishing time and the periodicity of the turning marks can be eliminated before destroying the substrate. Initially, the SPDT surface microtopography appears to be of strong periodicity and the average height of the bottom is about 3.9 μm which can be regarded as the top of the substrate. At the first two iterations, plenty of micro-breaches are found in the peak. And the PV (peak-valley) value of the ripple structure decreases although the residual ripple structure is still evident. After the third polishing, turning marks are faint and can hardly be seen on the surface. After the fourth polishing, turning marks are removed completely and the height of the bottom decreases, whi ch indicates the substrate is destroyed slightly. Also, the turning marks evolution can be revealed through the PSD curves. There is a protruding peak on around 1.397 μm^{-1} (logarithm of spatia l frequency), which corresponds to the spatial period of the ripp le structure. And the decrease of PSD amplitude at the spatial fr equency indicates that the turning marks are alleviated with itera tions. After the fourth polishing, there is no evident peak on the PSD curve.

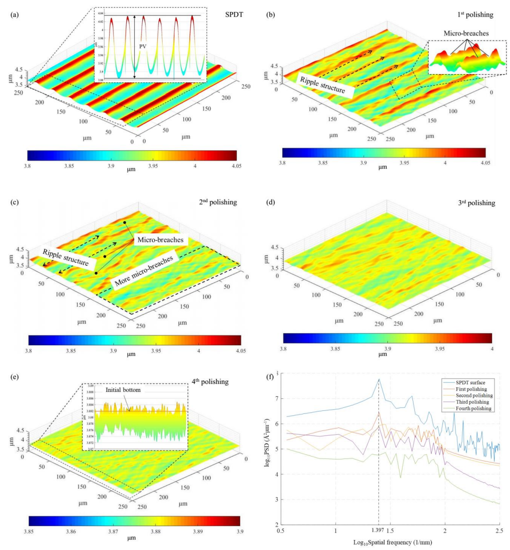

Fig. 2 Simulation results of the surface microtopography: (a) init ial SPDT surface; (b) after 1st polishing; (c) after 2nd polishing; (d) after 3rd polishing; (e) after 4th polishing; (f) PSD analysis.

According to the simulation results, it can be inferred that th e SPDT marks are removed gradually in the AFJ polishing proc ess, which can reduce the chances of destroying the substrate. I n other words, eliminating the tool marks without destroying the form accuracy can be realized by AFJ polishing technology. Fo r this reason, two essential issues should be researched in the fo llowing study: one is the AFJ polishing parameters that can imp rove the efficiency of TMR; the other is the optimization of dw ell time and tool-path to meet the demand of form-preserving c apability inthe post-polishing process.

3. Experimental setup and results

A comparative experiment was conducted to demonstrate the form-preserving capability of the improved AFJ tool. A planar Al6061 aluminum mirror was vertically mounted after diamond cutting. In this test, both the traditional AFJ tool and the impro ved AFJ tool traveled 10 mm along straight lines. The AFJ poli shing parameters are specified in . The polishing slurry compris ed SiO_2 abrasives with an average size of 0.4 μm in deionized water, with a concentration of 20 vol%.

The surface roughness of six points (C1, C2, C3, D1, D2, D3) was measured using a white light interferometer (Zygo Ne wview) with a scan size of 0.5 mm × 0.5 mm. Fig. 6(a) and (c) illustrate the non-uniform RTMs removal achieved using the traditional AFJ tool. The ripple structure is faint at point C3, w hile it remains evident at point C1. PSD analysis was performed to visualize the spatial frequency, revealing that the protruding peak in the PSD curve of point C3 is smaller than the others. This implies a higher RTMs removal rate at the bottom of the polishing area. This observation has profound implications for th e removal distribution of RTMs using traditional AFJ tools. The non-uniform RTMs removal could be attributed to several facto rs, including non-uniformity in the flow dynamics of the fluid j et, differences in the applied pressure, and the motion of the pi n. Moreover, this phenomenon also raises concerns about potenti al damage to the substrate. It can be inferred that the substrate at point C3 may be damaged with increasing polishing time, wh ile the RTMs are not removed at point C1 or point C2. Such n on-uniform RTMs removal hampers the achievement of a form-p reserved post-polishing process. Of course, to address this issue, the polishing parameters or the dwell-time can be adjusted to l ower the material removal rate, ensuring that only RTMs at the bottom are removed. Meanwhile, complex adaptive tool paths a re necessary to guarantee uniformity across the entire polished s urface.

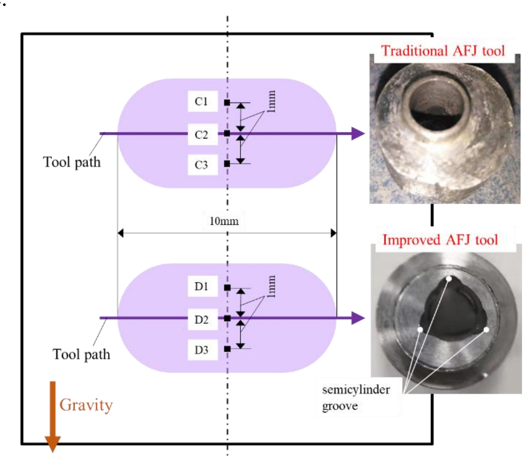

Fig. 5. Verification test of improved AFJ tool.

Nevertheless, these methods can lead to a decrease in efficie ncy and increased complexity in the form-preserving post-polishi ng process. Improvement can be observed in Fig. 6(b) and (c), respectively. The outlet of the flow field and the polishing pres sure field rotate along with the AFJ tool during the process, ov ercoming the influence of gravity. It can be found that the use of the new AFJ tool results in identical RTMs removal at the t hree points (D1, D2, D3). The protruding peaks in the three PS D curves are similar, indicating uniform material removal within one polishing area. This suggests that the periodic marks can b e eliminated without compromising the surface form by simply adjusting the dwell time in practical applications, eliminating the need for complex tool paths. These results demonstrate that the improved AFJ tool enables the achievement of a form-preserve d AFJ post-polishing process for side-wall surfaces.

Table 1 Polishing parameters for verification

Parameters	Value
Rotation speed/RPM	200
Inlet pressure/MPa	0.05
Eccentric distance/mm	0.5

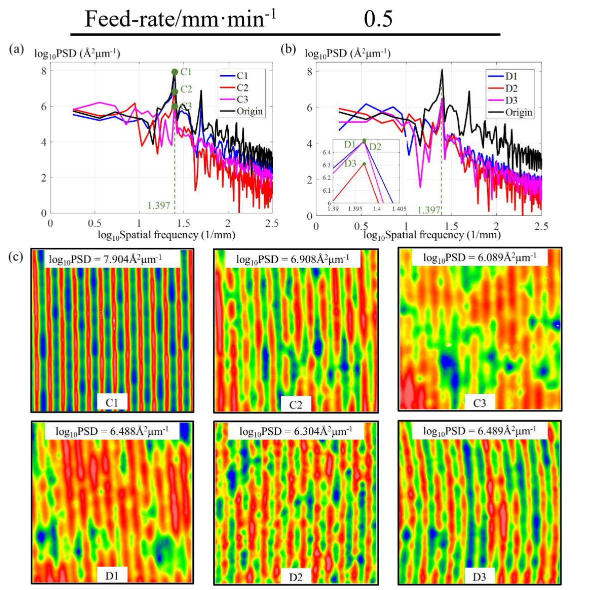

Fig. 6. Comparison of the uniformity of RTMs removal in AFJ polishing for side-wall surface: (a) PSD analysis of the surface polished by traditional AFJ tool; (b) PSD analysis of the surface polished by improved AFJ tool; (c) surface texture of the six measurement points.

4. Application

The practicality of the the optimal parameters is demonstrated in the AFJ polishing process which is performed on a CNC machine provided by OptoTech GmbH. A convex aluminum spherical surface with a radius of 100 mm and a diameter of 70 mm is taken as a sample.The PSD curves reveal that after AFJ polishing, the surface quality has been improved dramatically. The pictures of the initial surface and the polished surface are demonstrated in Fig. 30. These results show strongevidence of the form-preserving capability and efficiency of the AFJ polishing method to remove the turning marks.

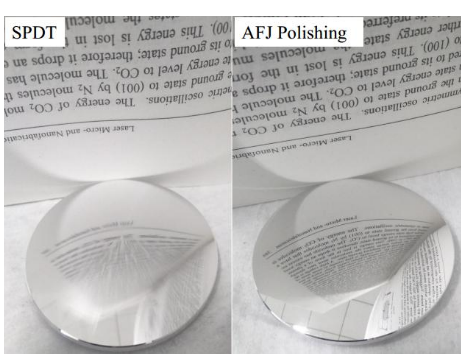

Fig. 7. Photos of the initial surface and the polished surface.

The uniformity of AFJ post-polishing for side-wall surfaces is analyzed and optimized, and the newly designed tool expands the application of AFJ polishing technology to various integrated optomechanical systems with special spatial distributions of optical components, such as MMSWs. The research presented in this paper holds significant research value and potential in the fields of freeform optics and advanced optical systems, as shown in Fig. 8.

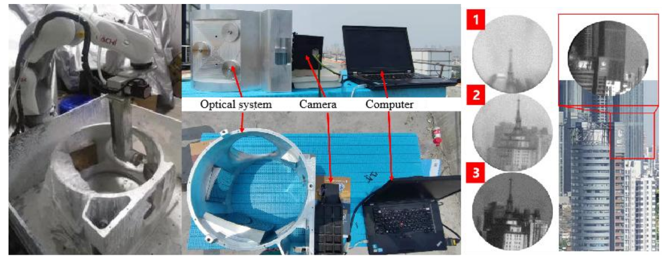

Fig. 8. Application of AFJ on optical system.

3. Conclusions

The paper investigates the form-preserving capability of AFJ post-polishing for side-wall surfaces through theoretical and experimental approaches. The contributions of the study can be summarized as follows.

(1) Micromachining characteristics of anisotropic diamond-cut surfaces are discussed. The effects of the periodic structure on active abrasives and micromachining state are analyzed theoretically, providing insights into the removal characteristics at the microscopic scale.

(2) Theoretical and experimental results demonstrate that the v-m stress is larger and RTMs removal is more pronounced when the motion direction of the polishing abrasive is perpendicular to the ripples. This is attributed to the anisotropy in the horizontal dimension of the rippled surface.

Based on the simulation method, a new AFJ tool is designed and optimized to improve the uniformity of RTMs removal. Experimental results demonstrate the effectiveness of the new tool in achieving a more uniform material removal.

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