

# 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 since it can produce optical surfaces with sub-micrometer form accuracy directly. However, the machining tool marks is a significant fact that leads to expected diffraction, which will seriously affect the optical performance. The inevitable 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 tests 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 the AFJ polishing method is demonstrated on an optical elements and optical system. The experimental results and the theoretical analysis prove that AFJ polishing technology can lead to the post-treatment of diamond-turned surfaces in a form-preserving manner.*

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## 1. Introduction (Times New Roman 10pt)

With the rapid development of ultra-precision CNC machining technology, single-point diamond turning (SPDT) has become a common method for producing optical components and optical systems [1, 2]. It enables the direct production of optical surfaces 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 applications in advanced optical instruments require smoother surfaces with high accuracy. Therefore, there is a strong need for an effective post-treatment method that can remove RTMs without compromising form accuracy.

Recently, an active fluid jet (AFJ) polishing technology has been developed and investigated for the removal of diamond turning marks. In this process, a small sub-aperture polishing pin is pressed against the workpiece surface using polishing fluid, while the pin is rotated eccentrically. Material removal occurs due to the relative velocity and pressure between the tool and workpiece, 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 materials. Many scholars have conducted theoretical analyses, experimental research, and proposed improved methods for AFJ polishing. Zhang et al. applied AFJ polishing to remove diamond turning marks, investigating the effect of polishing parameters on the material removal rate. They demonstrated the effectiveness and superior form-preserving capability of AFJ polishing on diamond-turned surfaces, showing that it enables deterministic post-treatment while preserving the surface form [4].

In this paper, the principle of the AFJ technology was applied and a comprehensive study was conducted to investigate the post-polishing process for side-wall surfaces through multi-scale analysis. Based on the analysis, a method was proposed to enhance the form-preserving capability during the polishing process. Based on the simulation model of AFJ polishing, the influence of processing parameters on the RTMs removal can be analyzed at the macroscopic scale so that the uniformity of RTMs removal in the polishing area can be evaluated. Finally, a series of experiments were conducted to validate the proposed theoretical analysis. In order to improve the uniformity of RTMs removal, an innovative AFJ tool was designed and optimized based on the simulation model. The experimental results demonstrated the effectiveness of the new AFJ polishing method in uniformly removing

## 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

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

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  $v^{\text{para}}$ ), the base and height of the triangle are represented as  $MN = 2a$ , and the penetration depth  $\delta$ , respectively. The triangle  $\Delta NJK$  in the height can be given as

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

As a result, the micro-cutting area ( $S_{\text{perp}}$ ) 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 ( $S_{\text{para}}$ ) is smaller as the abrasive primarily affects the material underneath it. This means that there will be no obvious ploughing or cutting phenomenon.

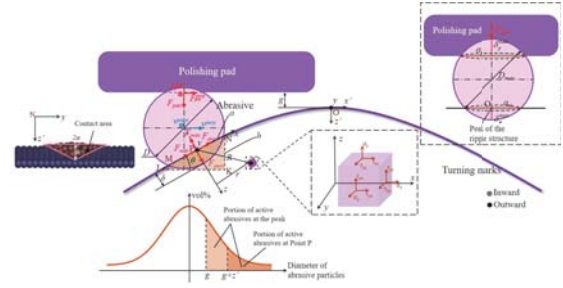


Fig. 1 Schematic diagram of material removal characteristics of AFJ.

### 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.

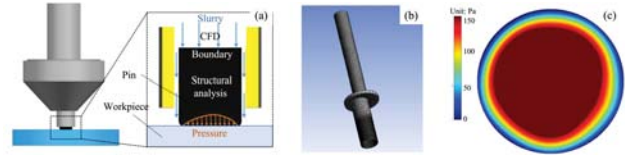


Fig. 2 Simulation of the AFJ polishing: (a) FSI model, (b) CFD model of the slurry flow, (c) the results of the pressure distribution on the workpiece.

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  $\mu\text{m}$  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, which

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  $1.397 \mu\text{m}^{-1}$  (logarithm of spatial frequency), which corresponds to the spatial period of the ripple structure. And the decrease of PSD amplitude at the spatial frequency indicates that the turning marks are alleviated with iterations. After the fourth polishing, there is no evident peak on the PSD curve.

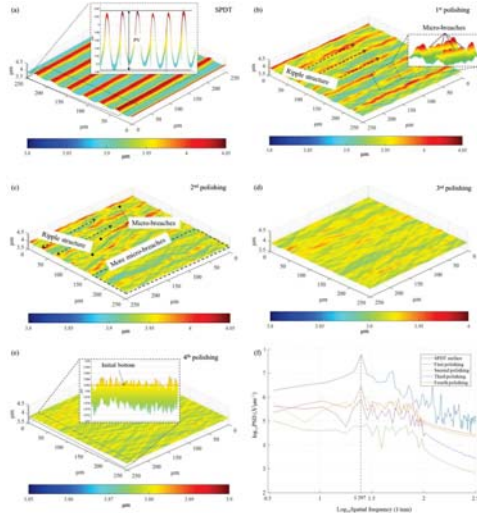


Fig. 2 Simulation results of the surface microtopography: (a) initial SPDT surface; (b) after 1st polishing; (c) after 2nd polishing; (d) after 3rd polishing; (e) after 4th polishing; (f) PSD analysis.

According to the simulation results, it can be inferred that the SPDT marks are removed gradually in the AFJ polishing process, which can reduce the chances of destroying the substrate. In other words, eliminating the tool marks without destroying the form accuracy can be realized by AFJ polishing technology. For this reason, two essential issues should be researched in the following study: one is the AFJ polishing parameters that can improve the efficiency of TMR; the other is the optimization of dwell time and tool-path to meet the demand of form-preserving capability in the 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 improved AFJ tool traveled 10 mm along straight lines. The AFJ polishing parameters are specified in . The polishing slurry comprised  $\text{SiO}_2$  abrasives with an average size of  $0.4 \mu\text{m}$  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 Newview) with a scan size of  $0.5 \text{ mm} \times 0.5 \text{ mm}$ . 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, while 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 the removal distribution of RTMs using traditional AFJ tools. The non-uniform RTMs removal could be attributed to several factors, including non-uniformity in the flow dynamics of the fluid jet, differences in the applied pressure, and the motion of the pin. Moreover, this phenomenon also raises concerns about potential damage to the substrate. It can be inferred that the substrate at point C3 may be damaged with increasing polishing time, while the RTMs are not removed at point C1 or point C2. Such non-uniform RTMs removal hampers the achievement of a form-preserved post-polishing process. Of course, to address this issue, the polishing parameters or the dwell-time can be adjusted to improve the material removal rate, ensuring that only RTMs at the bottom are removed. Meanwhile, complex adaptive tool paths are necessary to guarantee uniformity across the entire polished surface.

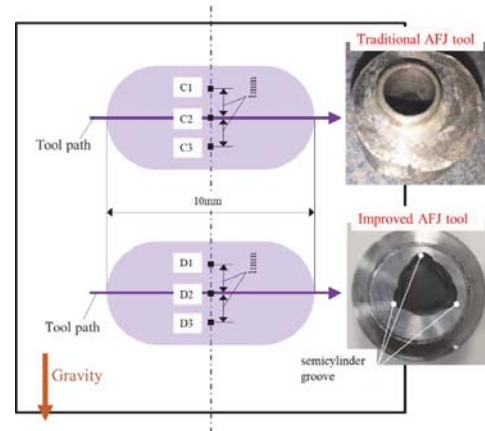


Fig. 5. Verification test of improved AFJ tool.

Nevertheless, these methods can lead to a decrease in efficiency and increased complexity in the form-preserving post-polishing process. Improvement can be observed in Fig. 6(b) and (c), respectively. The outlet of the flow field and the polishing pressure field rotate along with the AFJ tool during the process, overcoming the influence of gravity. It can be found that the use of the new AFJ tool results in identical RTMs removal at the three points (D1, D2, D3). The protruding peaks in the three PSD curves are similar, indicating uniform material removal within one polishing area. This suggests that the periodic marks can be 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-preserved 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   |

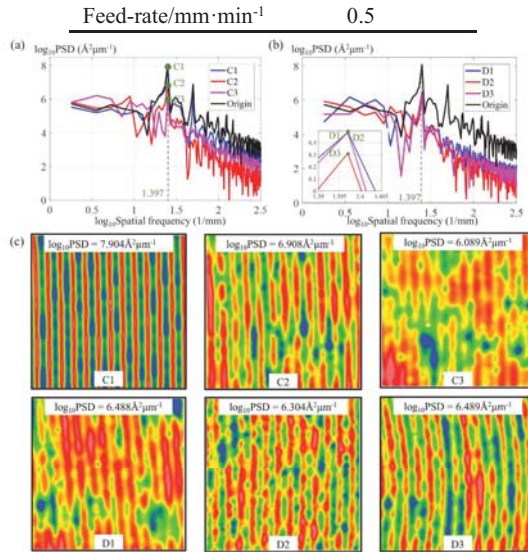


Fig. 6. Comparison of the uniformity of RTMs removal in AFJ polishing for side-wall surface: (a) PSD analysis of the surface polished by traditional AFJ tool; (b) PSD analysis of the surface polished by improved AFJ tool; (c) surface texture of the six measurement points.

#### 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 strong evidence 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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