Numerical and experimental investigation of the form maintainability of structured array surfaces in maskless fluid jet polishing

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Structured array surfaces (SAS) can achieve special functions through technical design in different fields such as electronics, optics, and precision molds. To achieve high performance of SAS, it is essential to improve its surface quality by post-processing while retaining high form accuracy. Due to the small size of the structured surface features, it is hard for the machine tool to contact the surface uniformly and it may inevitably affect the form accuracy of the polishing surfaces. Maskless fluid jet polishing (MFJP) is a promising finishing method due to its superior shape-adaptive capacity even for small-size structures. In this paper, MFJP was utilized to obtain SAS with nanometric surface roughness and sub-micrometer form accuracy. The effect of jet impinging angle on the form maintainability of SAS was elucidated by computational fluid dynamics (CFD) simulation and validated by a series of polishing experiments. Finally, three strategies were proposed to improve the form maintainability in the MFJP of SAS. This study can provide some theoretical basis for the ultra-precision manufacturing of SAS regarding form accuracy control.

NOMENCLATURE

H = the material removal distribution in polishing
TIF= the tool influence function
(x, y)= the coordinates of dwell positions
$*$= the sign of convolution calculation

1. Introduction

Structured array surfaces (SAS) have been widely utilized in high-end fields such as electronics, optics, and precision molds due to their unique physical property. The component performance is closely related to the surface quality and form accuracy of SAS. Usually, the nanometer surface roughness and sub-micrometer form accuracy are needed, which poses a great challenge to the manufacturing of SAS. The SAS are mainly machined by milling [1], turning [2, 3], and Electric Discharge Machining (EDM) [4, 5], grinding [6, 7], et al. However, material debris and surface defects remain on the surface and deteriorate the performance of SAS even though some of them can obtain a high form accuracy. As a result, a post-processing process is necessary to improve the surface quality as well as maintain the form accuracy.

Abrasive polishing by copying tool polishing method can remove the regular tool marks effectively and achieve a nanometric surface quality [8, 9]. Brinksmeier [10] polished structured steel molds with V-grooves by abrasive flow machining. The surface quality of internal surfaces was improved to roughness Ra 60 nm and the burrs were removed completely while keeping an initial sharp edge. However, the specific polishing tool should be designed and fabricated for structured surfaces differently. Besides, the surface quality and form accuracy were limited by the severe tool wear and the positional accuracy of the machine tool. Magnetic field-assisted polishing was also developed to polish the structured array surfaces [11-14]. The surface roughness can be reduced to several nanometers, whereas it was hard to maintain the surface feature form, especially for structures with sharp edges [15].

Maskless fluid jet polishing (MFJP) is considered a promising method for the finishing of structured surfaces due to its unique advantages such as no tool wear, and super applicability to small-size structures [16, 17]. Wang et al. [18] polished various structured surfaces using MFJP and the effect of the key polishing parameters on the surface roughness and form maintainability was studied. A high-quality surface with a roughness of 14 nm and a form maintenance ratio of more than 95% was achieved. However, the detailed material removal process and the reason leading to the form error were not revealed. Even though MFJP has a great potential of being applied to the final finishing of SAS, the material removal in the polishing is nonuniform and the form error increases with the increase of polishing time [18]. In MFJP, the material removal is mainly affected by different parameters such as abrasive size, jet pressure, jet impinging angle, et al. In our previous study, the effect of abrasive size and jet pressure on the form accuracy of SAS was elucidated according to the analysis of the abrasive erosion [19]. However, the jet impinging angle was not considered. In this paper, the form maintainability of MFJP under different jet impinging angles was investigated by CFD simulation. Based on the results, some strategies for the form maintenance of SAS in MFJP were proposed, which can provide some scientific basis for the form accuracy improvement of SAS.

2. Materials and methods

The polishing experiments were conducted on the ZEEKO IRP200 ultra-precision polishing machine as shown in Fig. 1. The structured array surface used in the experiments was a cylindrical array surface, which can be utilized as the molds of optical components for light homogenization, such as the application of naked eye 3D displacement. The cylindrical array surface was machined by micro-milling. Fig. 1 shows the size of the cylindrical surface. The radius of the cylindrical surface was 1 mm, and the depth was 83.5 μm. The diameter of the orifice in the nozzle was 0.5 mm. The polishing slurry was obtained by mixing the abrasives and water with a weight ratio of 8:100. The feed rate direction is along the cylinder surface. The polishing parameters are listed in Tab. 1. In this paper, CFD simulations were conducted to investigate the effect of jet impinging angle on the material removal distribution and form maintenance ability in MFJP. The settings of the boundary condition and fluid field solution were the same as in our previous study [19].

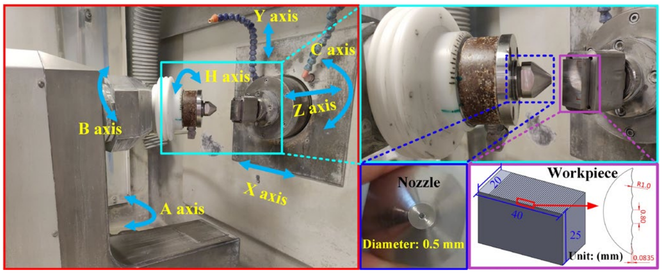

Fig. 1 The polishing machine and workpiece utilized in the experiments.

The surface roughness arithmetical mean height Sa was measured by a white light 3D interferometer (NewView 5022, Zygo, USA). The objective magnification of NewView is 50 times. The material removal depth was measured by a Form Talysurf PGI 1240 profilometer. The surface topography was observed by scanning electron microscope (SEM, Quanta 450 FEG, FEI Company, Hillsboro, USA).

Table 1 Experimental design

Parameters	Index
Abrasive size (μm)	3.5
Slurry	Al_2O_3 with a weight percentage of 8%
Feed rate (mm/min)	20
Pressure (bar)	8
Toolpath	Raster path
Polishing area	5 mm*5 mm
Stand-off distance (mm)	4 mm
Path spacing (mm)	0.1
Jet impinging angle (degrees)	90

3. Results and discussions

Fig. 2 shows the initial surface topography of the cylindrical surfaces machined by micro-milling. The tool marks and material debris can be found on the surfaces. After polishing, the surface becomes smooth and the material debris and tool marks are well eliminated. The small erosion pits appear on the surface instead, which result from the cutting action and indentation action of the abrasive impact in MFJP. Fig. 3 shows the surface roughness and morphologies before and after polishing. The surface roughness decreased from 110 nm to 12 nm after polishing. The results demonstrate that MFJP can remove surface defects and improve the surface quality of SAS well.

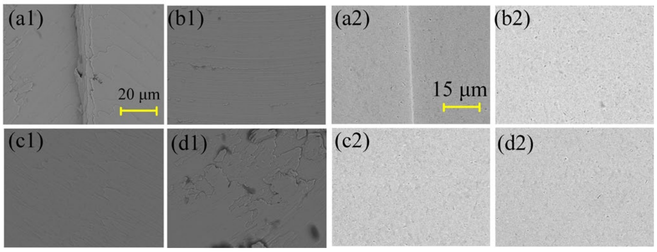

Fig. 2 The initial surface topographies observed by SEM before and after polishing at different positions. (a) top surface (b) bottom surface (c) right side surface (d) left side surface. The numbers 1 and 2 represent the surfaces before and after polishing, respectively.

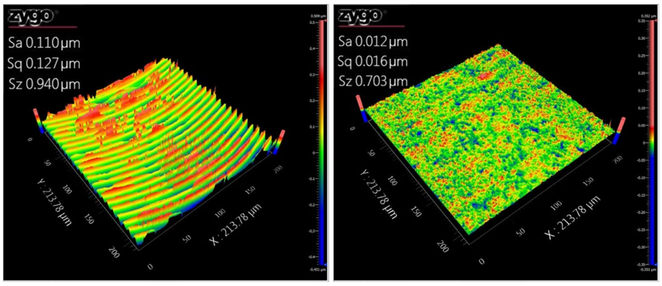

Fig. 3 The surface roughness and morphologies of the bottom surface before and after polishing

Fig. 4 shows the cross-section profile of cylindrical array surfaces after polishing. The material removal height on the top surfaces is 10.465 μm, which is far larger than that on the bottom surface of 4.854 μm. The result demonstrated that the abrasive erosion in the top surface is more drastic. As a result of the nonuniform material removal, the form accuracy deteriorates after MFJP. It is necessary to relieve the form errors in this process to improve the performance of SAS.

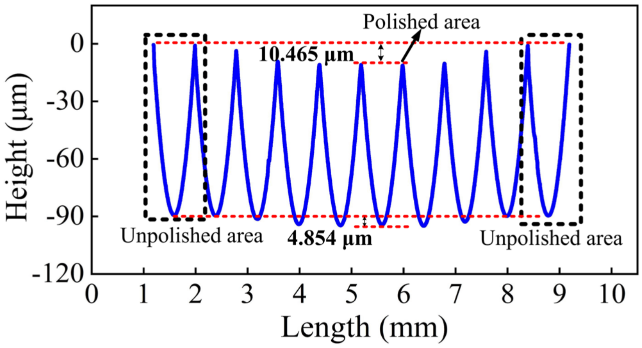

Fig. 4 The cross-section profile of cylindrical array surfaces after polishing

To investigate the effect of jet impinging angle on the material removal, the flow field distribution in MFJP under different jet impinging angles including velocity distribution and static pressure distribution were simulated as shown in Fig. 5. The stagnation zones exist in the polishing interface. In the stagnation zone, the fluid resists the movement of high-velocity abrasives due to its small velocity. It can be seen that the jet impinging angle greatly influences the flow field in MFJP. When the jet impacts the workpiece surface at a normal angle, the fluid field and stagnation zone are symmetrical, which is different from the polishing under the jet impinging angle of 60 degrees. The variation in the fluid field affects the movement of abrasives, resulting in different material removal characteristics.

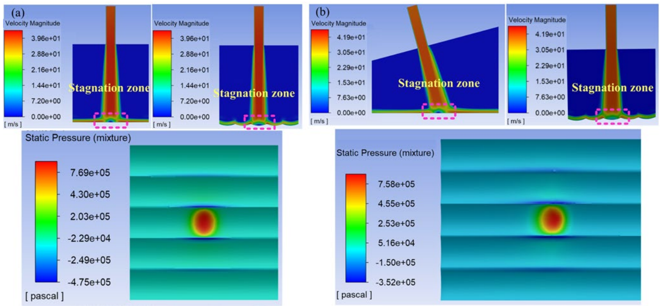

Fig. 5 The flow field distribution when polishing under different jet impinging angles: velocity distribution in different cross-sections and pressure distribution at bottom surface (a) 90 degrees (b) 60 degrees

Fig. 6 shows the tool influence function of MFJP when polishing under different jet impinging angles. A symmetrical material removal was obtained for the jet impinging angle of 90 degrees. However, when the inclination angle of the nozzle was 60 degrees, the shape of the tool influence function changed and there was no material removal on the side away from the nozzle. In the polishing of SAS, uniform material removal is preferred to maintain the form accuracy of the components.

The material removal can be determined by the convolution of tool influence function and tool path as expressed in Eq. (1),

$$H(x,y) = TIF(x,y) * T(x,y) \tag{1}$$

where $H(x,y)$ is the material removal distribution; TIF is the processed tool influence function; $T(x,y)$ is the dwell time distribution at different positions; $*$ represents the convolution calculation. As a result, the shape of the tool influence function is closely related to the form accuracy after polishing, which should be paid more attention to. As shown in Fig. 6(c) and Fig. 6(d), when polishing with the abrasives with a diameter of 12 μm, a uniform erosion zone can be obtained by inclining the nozzle. However, the material removal mainly focuses on the bottom of the cylindrical surface.

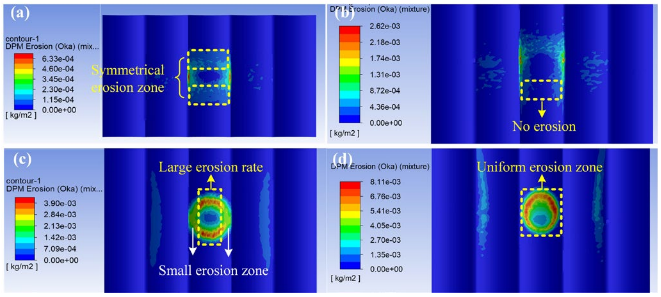

Fig. 6 The tool influence function of MFJP when polishing under different jet impinging angles (a) 90 degrees, 3.5 μm abrasives (b) 60 degrees, 3.5 μm abrasives (c) 90 degrees, 12 μm abrasives (d) 60 degrees, 12 μm abrasives

4. Proposed methods for improving the form accuracy maintenance

As demonstrated in the above sections, MFJP is an effective method to finish the SAS and achieve a high surface quality. However, the form accuracy of SAS deteriorates after polishing due to the nonuniform material removal resulting from the effect of the structure unit on the flow field. As a result, it is essential to reduce the form error by optimizing the polishing strategy. In this paper, three main strategies for restraining the deterioration of form accuracy were proposed as shown in Fig. 7. First, long-time polishing leads to a large material removal. Consequently, the form error is proportional to the polishing time. To meet the requirement for the form accuracy of SAS, the polishing time of MFJP should be optimized to avoid unnecessary material removal. On the one hand, the good initial surface quality of SAS contributes to achieving a high surface quality within a short time, which reduces the polishing time and enhances the form accuracy. Hence, a critical polishing time (corresponds to the maximum feedrate of nozzle) under different polishing conditions can be predicted to meet the form accuracy requirements. Second, the polishing conditions can be optimized to enhance the form maintenance ability. As investigated in our previous study and this paper, the abrasive size, jet pressure and jet impinging angle utilized in MFJP affect the form maintenance ability. Hence, the polishing parameters can be optimized for different requirements for SAS. Third, composite polishing processes including rough polishing and fine polishing can be utilized to achieve high surface quality as well as high form accuracy. Rough polishing with large-size abrasives can remove material debris and surface defects efficiently while keeping a high form accuracy due to its good form maintenance ability [19]. After rough polishing, fine polishing with small-size abrasives can be conducted to improve the surface quality and achieve a nanometer surface roughness while keeping a high form accuracy due to the small material removal amount in this process.

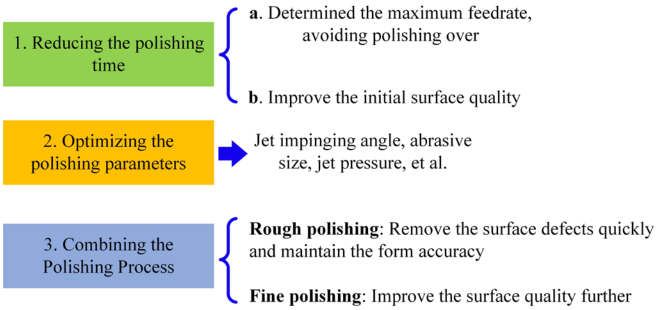

Fig. 7 Three main strategies for restraining the form accuracy deterioration of SAS.

5. Conclusions

Structured array surfaces (SAS) play an important part in the field of optical components, and precision molds. The small structure unit and complex shape of these surfaces pose a great challenge to the ultra-precision finishing process. In this paper, to achieve a high surface form accuracy, the effect of jet impinging angle on the material removal characteristics was elucidated by experiments and CFD simulation. The main conclusions can be summarized as follows:

(1) Three strategies for restraining the form error resulting from maskless fluid jet polishing (MFJP) were proposed to improve the form accuracy of SAS after polishing.

(2) The computational fluid dynamics (CFD) simulation indicated that the jet impinging angle affected the distribution of the flow field, leading to different material removal characteristics in MFJP.

(3) The tool influence functions under different jet impinging angles were obtained and compared by simulation.

(4) The surface defects including material debris, and tool marks can be removed by MFJP to achieve a high surface quality.

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