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Ultra-smooth polishing of high-precision optical surface

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ABSTRACT

A new method of ultra-smooth uniform polishing was presented, which can avoid high-precision surface figure getting worse after ultra-smooth polishing. At first, the fundamental and process were introduced. Then the process was simulated with "Gauss" and "V" type removal function. It shows that there will be no significant influence on optical surface figure after ultra-smooth uniform polishing with any type removal function. To demonstrate the process, a high-precision Ø100 mm fused silica flat optical element was polished, which was prior figured by IBF. Its surface figure accuracy root-mean-square (rms) value is improved from initial 3.624 nm to final 3.393 nm, the mid-spatial frequency surface roughness rms value is improved from initial 0.477 nm to final 0.309 nm, and the high-spatial frequency surface roughness rms value is improved from initial 0.167 nm to final 0.0802 nm. At last, the surface quality of the lens was analyzed by power spectral density (PSD). The result indicates that the surface roughness of high-precision optical element could be improved by ultra-smooth uniform polishing method without the surface figure destroyed.

1. Introduction

The development of optical technology has increased the precisions in different frequency bands of optical elements, such as in semiconductor laser, soft X-ray and lithography system, high-precision surface figure and ultra-smoothing surface roughness are both required. The influence of errors in different frequency bands on the performance of optical system were investigated by Carl Zeiss in Germany. The surface figure error will cause image distortion and introduce various aberrations. The mid-spatial frequency error will cause small angle scattering and flares, which will affect the imaging contrast. The high-spatial frequency error will cause large angle scattering and reduce the refractivity of the lenses [1]. So the errors of every spatial frequency should be eliminated. Because of there was no processing method can remove them simultaneously, it is need some methods iteration. Many deterministic optical figure correction techniques were developed to improve the surface figure, such as computer-controlled optical surfacing (CCOS) [2], precession polishing [3], magnetorheological finishing (MRF) [4], abrasive jet polishing (AJP) [5] and ion beam figuring (IBF) [6]. And for the mid- and high-spatial frequencies surface roughness, some ultra-smooth polishing techniques were developed, such as bowl-feed polishing [7], float polishing [8], Elastic emission machining (EEM) [9] and canon super smooth polisher (CSSP) [10].

To ensure the wave aberration and imaging quality of 193 nm projection lithography system, the surface figures must be reached nanometer order, and the mid- and high-spatial frequencies roughness must be reached sub-nanometer order respectively. So the iterative of ultra-smooth polishing and ion beam figuring will be used in the finish polishing phase, it can entirely improve the surface figure, mid- and high-spatial frequencies roughness. The method of ultra-smooth uniform polishing was introduced, and the simulation and experiment were investigated in this paper.

2. Principle of ultra-smooth uniform polishing technology

2.1. Ultra-smooth polishing technology

In order to gain ultra-smooth surface roughness, a new non-contact ultra-smooth polishing technology called micro fluid jet polishing (MFJP) was developed, which is combined the principles of float polishing, computer-controlled optical surfacing (CCOS) and abrasive jet polishing (AJP). Fig. 1 shows the principle of micro fluid jet polishing (MFJP). The polishing slurry outflow from the spray holes of the polishing head, and the head was lifted a certain distance by the dynamic pressure caused by motion of the polishing slurry. Fine powder particles are brought to the workpiece surface in the flow of the polishing slurry, and the chemical reaction between the workpiece and the particles results in the removal of surface atoms from the workpiece. It can gain sub-nanometer order ultra-smooth surface without sub-surface damage.

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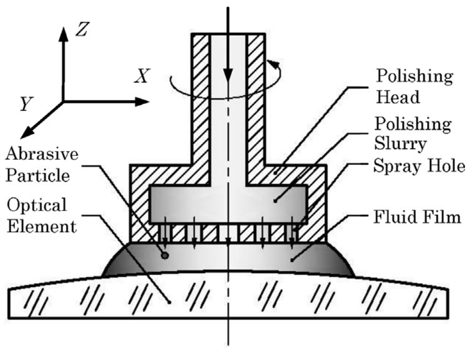

Fig. 1. Principle of micro fluid jet polishing (MFJP).

2.2. Ultra-smooth uniform polishing

Ultra-smooth uniform polishing technology can remove a uniform layer (including scratches, sharp points and sub-surface damage) on the optical element surface to reduce the surface roughness. According to the CCOS principle, the removed material is a convolution of the removal function and the dwell time, given as follow [2]:

$$H(x, y) = R(x, y) * *D(x, y) \tag{1}$$

where $H(x,y)$ is the desired removal function, $R(x,y)$ is the removal function per unit time; $D(x,y)$ is the dwell time function.

To realize ultra-smooth uniform polishing, the dwell time on every dwell point should be equal, so the solution of the dwell time will be easier. A block diagram of ultra-smooth uniform polishing is given as Fig. 2. First, measure the initial surface figure and roughness of the optical element with interferometer and atom force microscope respectively, then determine the uniform removal quantity and calculate volume removal rate of the removal function through experiments. And then, calculate the dwell time and determine the scan path. At last, generate the NC file and begin NC polishing. The dwell time can be calculated with Eqs. (2) and (3). The process may be repeated as many times as desired.

$$t_{sum} = \frac{R_{sum}}{RF} \tag{2}$$

$$t = \frac{t_{sum}}{n} \tag{3}$$

where t_{sum} is total time, R_{sum} is total removal volume; RF is the removal volume of the removal function, t is the time of one dwell point, n is the numbers of dwell points.

3. Simulation analysis

To demonstrate the process, a simulation is conducted using “Gauss” type removal function. Fig. 3 shows the initial surface figure. Fig. 4(a) shows the ideal “Gauss” type removal function, whose peak and volume removal rate are 1 μm/min and 39.2572 μm mm^2/min respectively. The dwell time on every point is 0.5 min. The simulation result using “Gauss” type removal function is shown in Fig. 4(b), and we can observe that the surface was removed 4 μm but the surface figure was not changed. It preliminarily shows that there will be no influence of ultra-smooth polishing on high-precision optical surface figure.

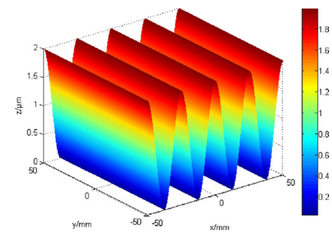

Fig. 3. Initial surface figure.

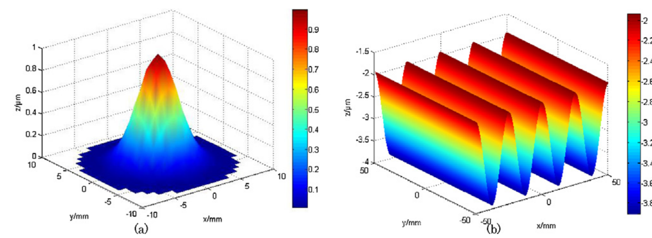

Fig. 4. (a) Idea “Gauss” type removal function; (b) surface figure after simulation.

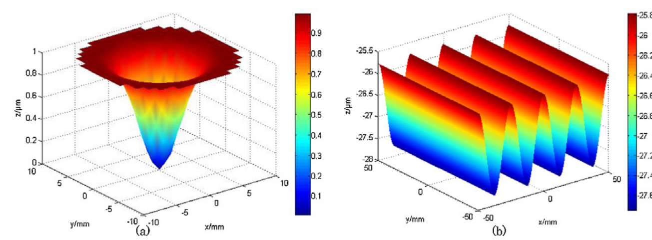

Fig. 5. (a) “V” type removal function; (b) surface figure after simulation.

It is difficult to gain idea “Gauss” type removal function, the influence of the removal function characteristics was analyzed with a “V” type removal function. Fig. 5(a) shows the “V” type removal function, whose peak and volume removal rate are 1 μm/min and 277.7428 μm mm^2/min respectively. The dwell time on every point is also 0.5 min. Fig. 5(b) shows the simulation result using “V” type removal function. The surface was removed more because of the more volume removal rate of the removal function, but the surface figure was still not changed. It shows that there will be no influence on high-precision optical surface after ultra-smooth polishing figure once more, and there will be no influence of the removal

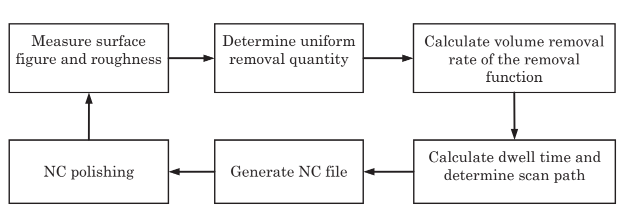

Fig. 2. Block diagram of ultra-smooth uniform polishing technology.

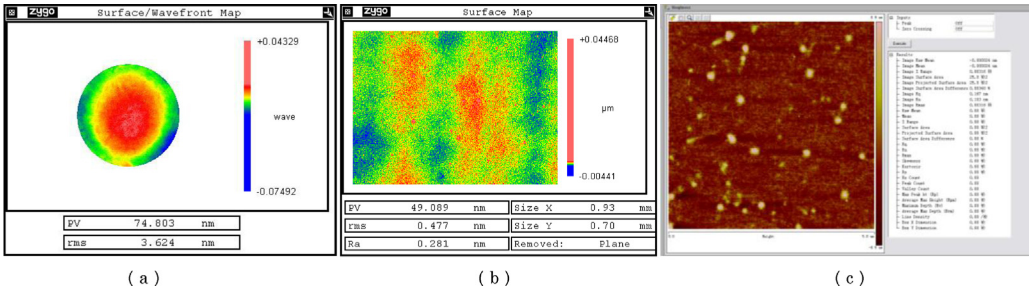

Fig. 6. (a) Initial surface figure (rms 3.624 nm); (b) mid-spatial frequency roughness (rms 0.477 nm); (c) high-spatial frequency roughness (Rq 0.167 nm).

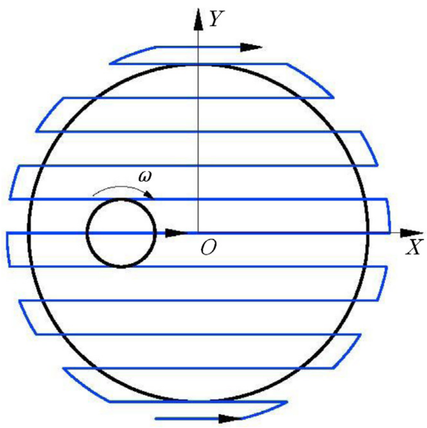

Fig. 7. Motion and scan path of the polishing head.

function characteristics either. So in the actual experiment, we will not consider the removal function characteristics.

4. Experimental analysis

4.1. Experimental conditions

A high-precision Ø100 mm (95% effective aperture) fused silica flat optical element was polished using the MFJP ultra-smooth polishing machine. The polishing head is made by asphalt, and its diameter is 20 mm. The rotation speed of the head is 120 r/min, and the pressure is 25.4 kPa. The processing time is 2 h, and the processing path is raster. The surface figure was measured using Zygo GPI interferometer, and the figure of the reference lens is 1/50λ (λ = 632.8 nm). The mid-spatial frequency surface roughness was measured using Zygo NewView 700 white-light interferometer with a measurement window 930 μm × 700 μm, and the high-spatial frequency surface roughness was measured using DIMENSION EDGE atom force microscope with the scan range 5 μm × 5 μm.

The initial testing results of the optical element are shown in Fig. 6. The results show that the surface figure is 3.624 nm (rms), the mid-spatial and high-spatial frequency surface roughness are 0.477 nm (rms) and 0.167 nm (Rq) respectively. The motion and scan path of the polishing head are shown in Fig. 7, and the scan pitch is 1 mm. The head extended 1/3 diameter out of the optical element edge to reduce the edge effect.

4.2. Experiment results

The testing results after ultra-smoothing uniform polishing is shown in Fig. 8. Its surface figure accuracy (rms) is improved from initial 3.624 nm to final 3.393 nm. The mid-spatial frequency surface roughness (rms) is improved from initial 0.477 nm to final 0.309 nm, and the high-spatial frequency surface roughness (Rq) is improved from initial 0.167 nm to final 0.0802 nm.

4.3. Power spectral density analysis

The information of an optic surface is a very complicated mixture signal, which not only contains some cycle components but also some random. The traditional evaluation parameters of the surface roughness are limited, such as peak-to-valley (PV) and root-mean-square (rms) etc., which cannot give the user complete information about the surface microstructure. For example, the topographies of some surfaces are different but their roughness may be equal.

Power spectral density function (PSD) is another way to characterize an optical surface, which is defined as the surface height squared per spatial frequency. The benefit of using PSD to characterize a surface is that one can determine which features (i.e. what spatial frequencies) have the largest influence on the surface topography [11].

The PSD curve before and after ultra-smoothing uniform polishing was shown in Fig. 9. The PSD value of the surface figure

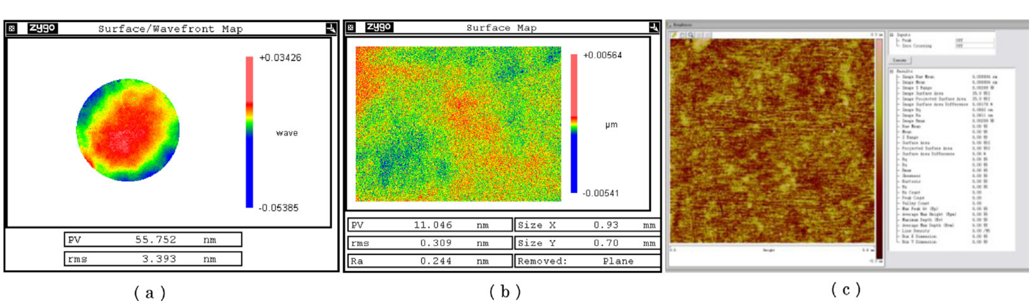

Fig. 8. (a) Surface figure (rms 3.393 nm); (b) mid-spatial frequency roughness (rms 0.309 nm); (c) high-spatial frequency roughness (Rq 0.0802 nm) after ultra-smoothing uniform polishing.

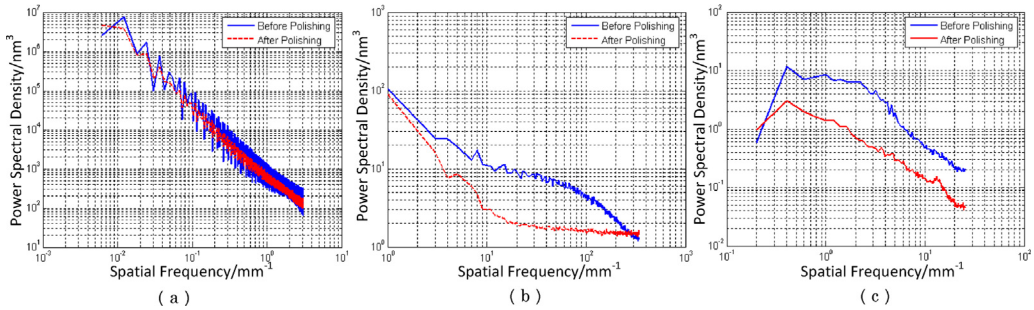

Fig. 9. (a) PSD curve of low frequency; (b) mid-spatial frequency; (c) high-spatial frequency before and after ultra-smoothing uniform polishing.

was unclear change, while the value of the mid- and high-spatial frequencies decreased significantly. It shows that the influence on high-precision optical surface figure after ultra-smooth uniform polishing is not obvious, but the mid- and high-spatial frequencies roughness of the optical element improved significantly.

5. Conclusions

This paper presented a method of ultra-smooth uniform polishing, and introduced it's fundamental and process. According to the simulation and experiment, the influence on the high-precision surface figure after ultra-smooth polishing was investigated, and the detailed conclusions are summarized as follows:

(1) The simulation results show that there will be no significant effect on the surface figure of the optical element after of ultra-smooth uniform polishing, and so as the removal function characteristics either.
(2) The experimental results show that the ultra-smooth uniform polishing technology can significantly improve the mid- and high-spatial frequencies roughness without destroying the surface figure of high-precision optical components.

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