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# Magnetic field assisted batch nano-polishing of optical glass

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**Abstract**
Optical glasses with different geometries have been widely used in imaging, illumination, and light control. Nanometric surface roughness is usually required for these kinds of components. Various kinds of polishing methods have been developed for the polishing of optical glass in recent decades, such as magnetorheological finishing, ion beam finishing, bonnet polishing, fluid jet polishing, etc. However, the optical glass components are usually polished one-by-one by these processes, leading to high polishing cost and low production efficiency. In this paper, a novel magnetic field assisted batch nano-polishing (MABNP) method is proposed for the polishing of optical glass, which can not only implement polishing of a batch of components simultaneously, but also can obtain nanometric surface roughness and micro-meter scale surface form accuracy. Shape adaptive algorithm we recently developed was used to determine the optimal impinging angle to implement the material removal as uniform as possible. Case studies were conducted on the optical glasses with different geometries to demonstrate the polishing performance of MABNP. The results indicate that MABNP can successfully polish six optical glasses simultaneously to obtain nanometric surface roughness and micro-meter scale surface form accuracy within 15 minutes. The number of the optical component polished for one time can be further increased through changing the design of the fixture. This method paves a new way for the high-efficiency and low-cost nano-polishing of optical glasses. Moreover, MABNP method is also suitable for the fast and cost-effective nano-polishing of other non-ferromagnetic materials.

Polishing; finishing; optical glass; magnetic field assisted; ultra-precision machining

## 1. Introduction

Optical glass including flat, spherical, aspherical, and even freeform surfaces have been widely used in various kinds of applications. [1-2] Ultra-precision accucacy including surface roughness and surface form is usually required for high-end products to implement superior functions. [3-4] Except for the molding process, the manufacturing of ultra-precision optical glass is usually a process chain containing pre-machining process and polishing. And the polishing process directly determines the final accuracy of the optical glass components.

In recent decades, different kinds of polishing processes have been developed for the precision polishing of optical glasses, such as computer controlled optical surfacing technology [5], magnetorheological finishing [6-7], ion beam finishing [8-9], bonnet polishing [10-11], fluid jet polishing [12-13], etc. These polishing processes can implement ultra-precision polishing of optical glass componnets, especially aspherical and freeform surface components. Nevertheless, these polishing processes normally polish the workpiece one-by-one, leading to the high polishing cost and low production efficiency. Current mass finishing process such as vibratory finishing [14-15], barrel finishing [16-17], etc. can hardly be used for the polishing of optical glasses. Moreover, the polishing accuracy of the current mass finishing processes are relatively low, cannot meet the requirements of most optical components. Hence, there is a need to develop a novel polishing process to meet the increasing demand of the optical glass components, which can not only implement precision polishing of optical glasses, but also possess high polishing efficiency.

Recently, the authors developed a novel magnetic field assisted mass polishing method (MAMP) [18], which can be used for high efficiency polishing of freeform surfaces. Polishing performance test have been conducted on different kinds of metallic materials, such as 304 stainless steel and Inconel 718. Nanometric surface roughness can be easily obtained after 20 minutes of polishing. [19-20] However, the polishing performance of the MAMP process has not been conducted on the optical glass. In this study, we investigated the polishing performance of the MAMP process on flat and concave optical glasses, aiming to test the feasibility of the MAMP process for the batch nano-polishing of optical glass components.

## 2. Principles of magnetic field assisted batch nano-polishing process

Figure 1 shows the schematic diagram of the magnetic field assisted batch nano-polishing (MABNP) process. In MABNP, at least two pairs of permanent magnets were installed on one rotating plate to generate the rotating magnetic field. The magnetic polishing media is poured into an annular chamber before polishing, and two or more brushes are generated under the effect of the magnetic field. The magnetic polishing media is a mixing of micrometer scale carbonyl iron podwer and polishing slurry with nanometer scale abrasives. Moreover, the rotating of the magnets can drive the magnetic brushes to rotate inside the chamber. A batch of optical componnets are installed on the fixtures inside the chamber as shown in Fig. 1, and the fixtures are connected to the lid. During polishing, the magnetic brush keeps impinging the optical components, leading to micro-nano metric material removal to implement the polishing purpose.

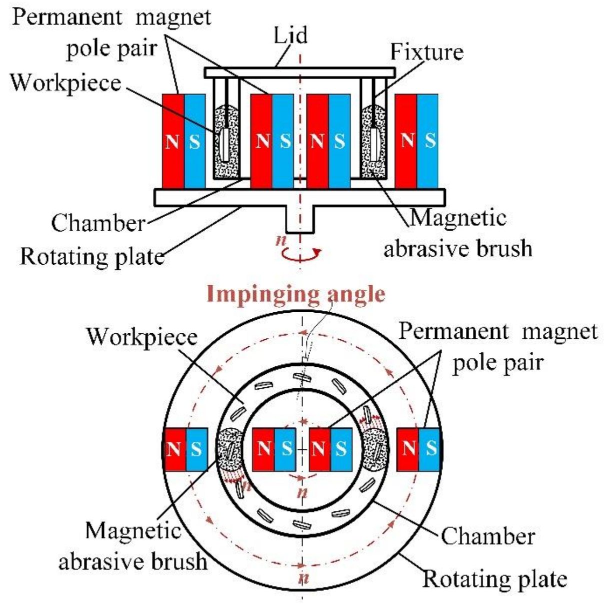


**Figure 1.** Schematic diagram of magnetic field assisted batch nano-polishing process

### 3. Experiments

#### *3.1. Experimental design*

In order to test the polishing performance of MABNP on the optical glasses, we have built up an experimental prototype of the MABNP machine showed in Fig. 2. In this design, 6 optical coponents can be polished simultaneously for one time as shown in the right top part of Fig. 2. The number of the workpieces polished for one time can be increased through changing the design of the lid, and can even be much larger through scaling up the prototype. The diameter of the workpiece is 12.7 mm in this study. Both flat surface and concave surface optical glass made of BK7 were tested here by three groups of experiments as shown in Table 1. The workpiece was placed in the middle of the magnet along the height direction to ensure covering of the brush as uniform as possible.The initial surface roughness of the workpiece were different of these three groups of experiments through using different pre-processing methods, including grinding and lapping using different grades of silicon caride sand paper. The impinging angle is one of the key parameter for MABNP, especially for the surface form accuracy. In this study, the impginging angle was determined using the method presented in our previous study [19], which is not discussed in detail here. The rotation speed used in this study is 500 rpm. Carbonnyl iron powder with the average size of 3 μm (Provided by BASF Co. Ltd., Germany) was used and the diamond polishing slurry with the average size of 125 nm (Provided by Universal Photonics Inc., USA) was used as the polishing slurry. Other conditions are listed in Table 1.

#### *3.2. Measurement method*

In this study, both the surface roughness and surface form accuracy were evaluated before and after polishing. The surface roughness by a ZYGO NEXVIEW white light interferometer. 40 × objective lens was used, and the measurement size is 213.78 μm ×213.78 μm for each point. The lateral and vertical resolutions of the measurement were 208.8 nm and 0.1 nm, respectively. The arithmetic average surface roughness (Sa) was defined according to ISO25178 standard. The surface roughness was analyzed using the software MX. A nine-order polynomial filter was used, and other settings were the default settings of the software.Three randomly distributed points were selected for the measurement of each surface. The surface roughness in terms of arithmetic meanheight (Sa) and maximum height (Sz) were used for the evaluation of the surface roughness in this study. The surface form accuracy was evaluated through analyzing the surface profiles in two orthogonal directions before and after polishing, using the Talysurf PGI1240.

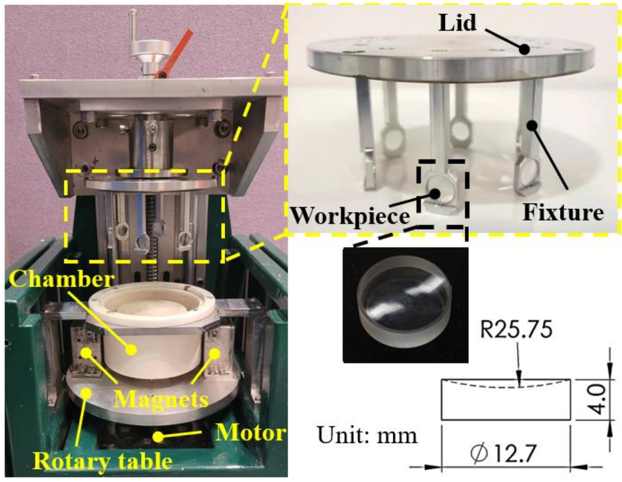


**Figure 2.** Experimental set up

**Table 1** Design of the experiments

| Conditions | Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| **Pre-processing method** | Rough grinding | Lapped by 800# SiC sand paper | Lapped by 2500# SiC sand paper |
| **Initial surface roughness Sa (nm)** | 110~120 | 50~60 | 30~40 |
| **Rotational speed (rpm)** | 500 | 500 | 500 |
| **Impinging angle (deg)** | 15 | 15 | 15 |
| **Polishing time (min)** | 10, 20, 30, 40, 50, 60 | 15, 30 | 10 |

### 4. Results and discussions

#### *4.1. Analysis on the surface roughness*

In the experiment of group 1, the roughly grinded optical glass was used as the initial surface, whose surface roughness was around Sa 110 nm ~120 nm. The total polishing time was 60 minutes and the surface roughness was measured after each 10 minutes. Figure 3 shows the surface roughness varies with the polishing time. After 10 minutes polishing, the surface roughness was sharply reduced to less than Sa 30 nm from Sa 120 nm. After 20 minutes polishing, the surface roughness can obtain less than Sa 3 nm. The ultra-smooth surface with the surface roughness Sa around 1 nm can be obtained after 60 minutes of polishing. And the surface roughness in Sz was also improved from 2231.7 nm to 195.2 nm.

As for the optical glass lapped by the 800# silicon carbide sandpaper, with the surface roughness Sa 50 nm ~60 nm, the surface roughness in Sa around 1 nm was obtained much easier after 30 minutes of polishing as shown in Fig. 4. The surface roughness in Sa was reduced from 48.7 nm to 0.9 nm, and the surface roughness in Sz was smoothened from 1305 nm to 26.2 nm.

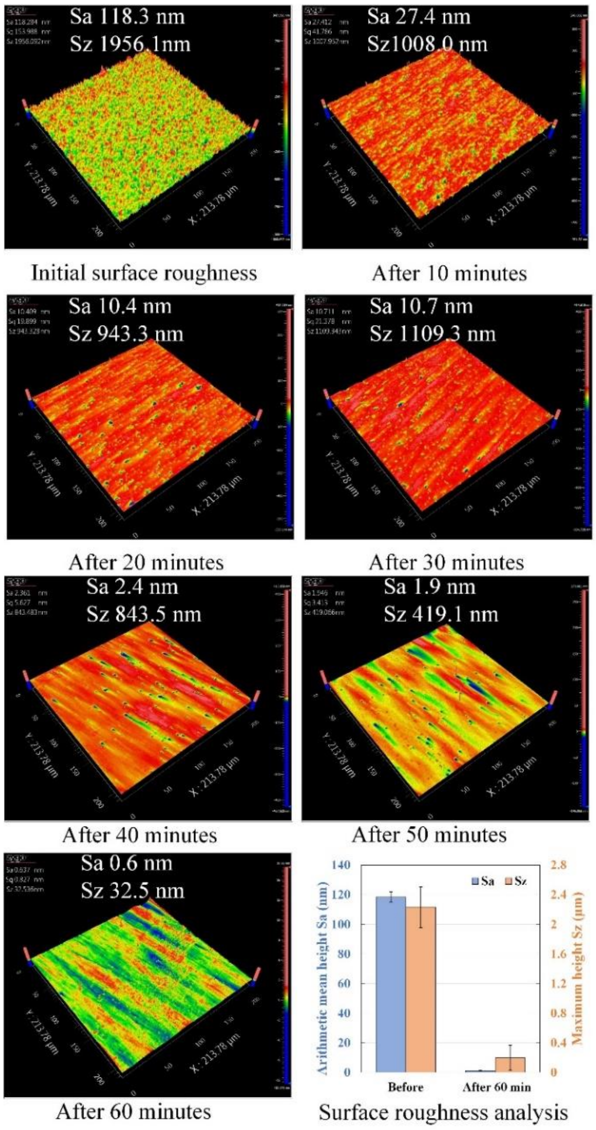


**Figure 3.** Surface roughness improvement of the ground optical glass with the increase of the polishing time

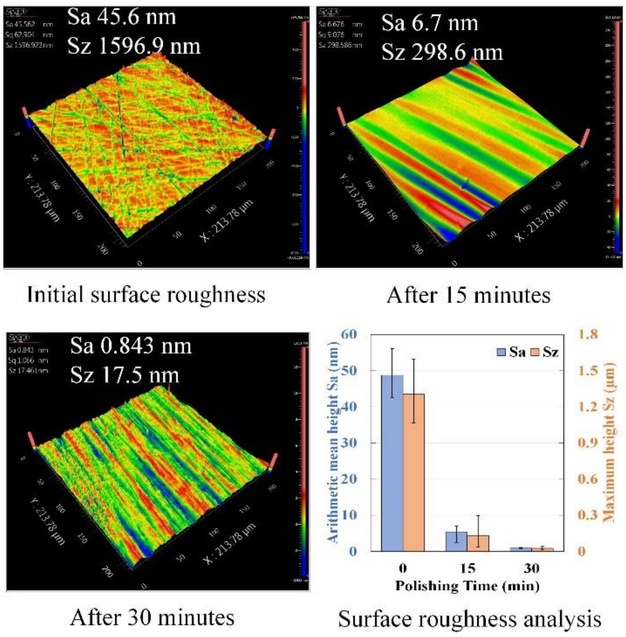


**Figure 4.** Surface roughness improvement of the optical glass lapped by 800# silicon carbide sand paper

As for the polishing of the concave optical glass lapped by the 2500# silicon carbide sandpaper, with the surface roughness Sa 30 nm ~40 nm, the surface roughness in Sa around 1 nm was obtained much faster, which was within 10 minutes. As shown in Fig. 5, the surface roughness in Sa was reduced from 35 nm to 0.9 nm, and the surface roughness in Sz was improved from 0.92 µm to 0.37 µm. The improvement of the surfac equality can also be reflected from their photographs showed in Fig. 5.

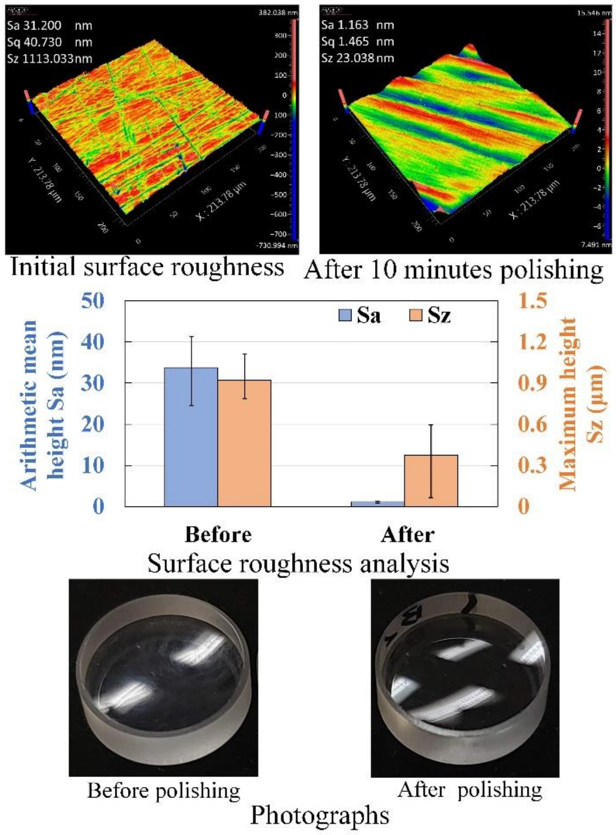


**Figure 5.** Surface roughness improvement of the concave optical glass lapped by 2500# silicon carbide sand paper

### *4.2. Analysis on the surface form maintainability*

Unlike corrective polishing [21], uniform polishing is usually needed in wide range of components. And in uniform polishing, the polishing process is required to maintain the surface initial form, rather than to change the form. Hence, the surface form of the concave optical glass was compared to reveal the surface form maintainability of the MABNP process on optical glass. Figure 6 shows the surface form comparison before and after 10 minutes polishing of concave surfaces in group 3. The surface form profiles in two directions before and after polishing were highly coincidence with each other. For better comparison, the deviation of the profiles before and after polishing were extracted, showed in the bottom part of Fig. 6. The surface form deviation in x-direction is 0.75 µm, while the surface form deviation in y-direction is 0.41 µm. Hence, the surface form of the optical glass can be maintained within 1µm, meanwhile obtaining ultra-smooth surface with the surface roughness Sa around or less than 1 nm.

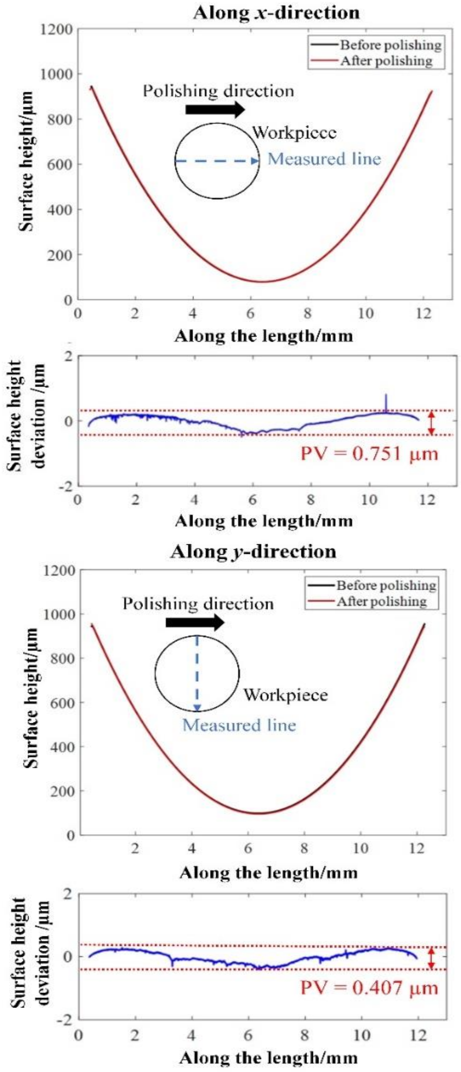


**Figure 6.** Surface form profile comparison of the concave optical glass

### *4.3. Discussions*

Based on the above results, we can see that it is feasible to use the MABNP process for the batch nano-polishing of optical glass. Longer time is needed for the surface with larger surface roughness. Even though the surface roughness around 1 nm can also be obtained after a long time of poishing, the surface form accuracy would be degraded seriously. Because it is impossible to implement uniform material removal over the whole surface in MABNP process since the whole surface was covered by the brush, and longer polishing time corresponds to the larger form degradation. According to the results in the previous research [18], longer poliging time can lead to larger material removal, leading to larger form deviation. Hence, it is highly recommended to obtain smaller surface roughness before the MABNP process to shorten the polishing time and ensure good surface form maintainability, especially for the applications with stringent requirement of the form accuracy.

BK7 is a typical optical glass, the successful polishing of BK7 glass also can reveal the feasibility of the MABNP for the polishing of other optical glasses. The main difference should be the material removal rate induced by different hardness. Further research on polishing of other glasses will be conducted in the future, such as fused silica, etc.

The diamond polishing slurry with the size of the 125 nm in average was used in this study, which is a typical fine polishing slurry. As for MABNP for rough optical glass, other polishing slurry will be tested in the future for the rough polishing to enhance the polishing efficiency, such as cerium oxide slurry.

## 5. Conclusions

This paper proposed a novel magnetic field assisted batch nano-polishing (MABNP) process for the batch nano-polishing optical glass components. The effectiveness of the MABNP process was verified through a series of experiments on flat and concave optical glasses. The following conclusions can be drawn based on the experimental results:

(1) The MABNP process can implement polishing of 6 optical components simultaneously in the current prototype. And the number of the components polished for one time can be further increased through changing the design of the fixture and scale-up the size of the prototype.
(2) The surface roughness of the optical glass after grinding or lapping can be easily improved by MABNP to obtain nanometric surface roughness, and even sub-nano surface roughness.
(3) Except for the nano-metric surface roughness, the MABNP can also implement sub-micrometer scale form maintainability of the optical glass components through using optimized impinging angle.

In the future, investigation on the deeper material removal mechanism will be conducted to provide the theoretical basis for the further optimization of this process. Other different types of the polishing slurry will be tried and compared. Moreover, , since the magnetic field also has significant effect on the material removal rate and surface integrity according to our previous studies, its effect on the polishing of optical glasses will also be conducted in our future work.

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