

# Ultra-precision figuring using submerged jet polishing

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A new removal optimization method called submerged jet polishing (SJP) is reported. Experiments are conducted to obtain the removal shape. Results of SJP indicate that a Gaussian shape removal function can be obtained and that the removal rate is sensitive to variations in the standoff distance. SJP is applied to the corrective figuring of a BK7 optical glass. The flatness is improved from photovoltaic (PV)  $0.066 \lambda$  to  $0.024 \lambda$  ( $\lambda = 632.8 \text{ nm}$ ) after three iterations, and the root mean square (RMS) value is improved from  $0.013 \lambda$  to  $0.00395 \lambda$ . The experimental result indicates that SJP has a capability for ultra-precision figuring and can be applied in polishing complex-shaped surfaces.

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Aspheric optical components can effectively improve the image quality of optical systems; however, a method on how to shape and polish aspheric surfaces has always been a challenge in the optical fabrication industry. Fluid jet polishing (FJP), as a novel deterministic precision optical manufacturing technique, was first developed by Föhnle *et al.* in 1998<sup>[1–4]</sup>. Their research showed that it was feasible to utilize FJP for precision polishing. With FJP, they polished one flat BK7 optical glass, and the roughness of the surface (root mean square (RMS) value) decreased from 475 to 5 nm. The FJP system adopts a nozzle to guide premixed slurry to the workpiece at a high speed; the material is removed by the collision and shearing actions between the abrasive particles and the workpiece.

Compared with traditional polishing methods, the FJP process has many advantages<sup>[5]</sup>: there is no occurrence of tool wear; the precision of the shape of the surface can be controlled easily; the tool is cooling; the debris produced in the process can be removed by continuous slurry flow; and it is fit for polishing various complex surfaces. However, it has an important disadvantage: the removal function turning a ring-shaped profile is not an ideal one. According to the computer-controlled polishing theory<sup>[6]</sup>, an influence function with no or very little removal at the center can easily introduce high-frequency errors to the workpiece during polishing, thus it is unfit for use in finishing and polishing. Therefore, there is a need to obtain an influence function with a Gaussian shape for optics polishing.

Many ways have been studied to solve this problem. As described by Booij *et al.*, one way of getting an ideal removal shape is by inserting a coil into the nozzle, which will cause the water to follow the inside contours of the threaded nozzle<sup>[7]</sup>. The center of mass of the water in consecutive sections through the nozzle will show a circular motion. It can then obtain a profile in which the center has the maximum removal but is not symmetrical. Another way, as described by Li *et al.*, is by taking a cylindrical nozzle and rotating it around the indicated point<sup>[8]</sup>. Although it can yield a Gaussian shape, the system is complex and is not easy to operate.

In this letter, we report a new material removal optimization process for FJP, the submerged jet polishing

(SJP). An overview of the SJP setup is shown in Fig. 1. Water and abrasive particles are mixed by mechanical stirring in a recycle system, which contains a tank and a stirrer. The slurry, which is water with the homogeneously mixed particles, is then pumped from the tank by a low-pressure pump and guided through a nozzle. The nozzle is positioned above the surface that is being processed, where the standoff distance can be set. The respective orifice of the nozzle and workpiece are submerged in the slurry stored in the submerged device. The material is removed by the impact of the submerged jet. After being in contact with the surface, the slurry is collected and guided back to the tank for reuse. Submerged jet is a kind of jet impinging into the same medium, existing momentum, and mass exchanges between the submerged jet and the surrounding slurry.

With the method we proposed and the equipment we designed, experiments were carried out for validating the removal function. In our experiments, a cone-shaped and cylindrical nozzle with a diameter of 1.2 mm was chosen. Pressure of 0.4 MPa and a processing time of one minute were used. The standoff distance was set with different values for each experiment: 2, 5, 10, 15, and 20 mm. Figure 2 shows the profile of the material removal we achieved on a BK7 optical glass sample. It approximates an ideal Gaussian-shape profile with the deepest part at the center. The transverse profile shows that the influence function is a highly central symmetric profile, which is suitable for computer-controlled finishing and polishing. It shows that the removal rate is sensitive to variations in the standoff distance in Fig. 3, and the removal rate has a maximum when the standoff distance is

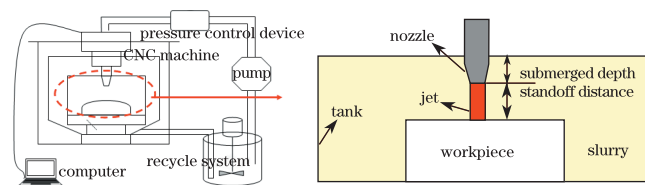


Fig. 1. SJP setup comprising a recycle device, a computerized numerical controlled (CNC) machine, a pump, a pressure control device, a nozzle, and a glass sample in submerged device.

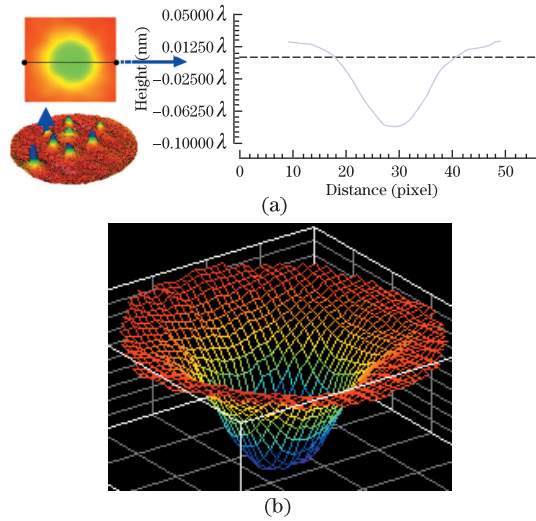


Fig. 2. Removal profile: (a) two-dimensional view and (b) three-dimensional figure.

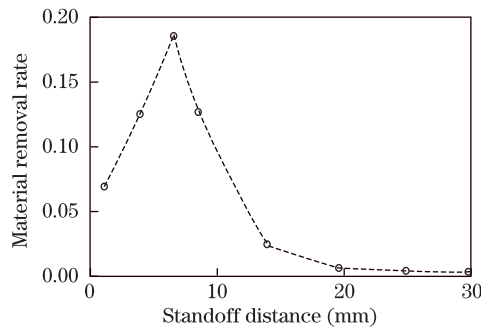


Fig. 3. Highest amount of removed material.

8 mm in our experiment conditions. According to the submerged jet theory, the relation between the velocity and the standoff distance can be defined as<sup>[9]</sup>

$$\frac{u}{u_0} = C_u \left( \frac{h}{d} \right)^{-1/2}, \quad (1)$$

where  $u_0$  is the initial jet velocity,  $h$  is the standoff distance,  $d$  is the diameter of the nozzle, and  $C_u$  is a coefficient. As described by Yu *et al.*,  $C_u$  approximates a value of 2.7, and the equation is credible when  $h/d$  is larger than or equal to  $C_u^2$ .

Equation (1) shows that the jet velocity will decrease when the standoff distance increases. The larger the velocity, the stronger the impact action, and the higher the removal rate. Hence, the removal rate is smaller when the standoff distance is larger (see Fig. 3). However, the removal rate is lower when  $h/d$  is smaller than  $C_u^2$  (see Fig. 3) because the rebound action of impinging behaves actively when the standoff distance is small and the action, in turn, can counteract the impact action and weaken the removal action of the submerged jet.

Experimental results with SJP indicate that a Gaussian-shape influence function with the maximum removal amount at the center can always be obtained and that the Gaussian shape is related to the impact pressure, the standoff distance, and the diameter of the nozzle. Our analysis of the SJP removal shape suggests

that it is caused by the SJP material removal principle. Material is removed by particles' impinging action and wall movement erosion in FJP. Owing to the fact that the amount of material removed by the impinging action is less than the one by erosion, the W-shaped removal profile is formed. However, in the SJP process, impinging action becomes the dominating removal action because of the movement erosion weakened by the resistance of the surrounding slurry. Therefore, the removal function has the maximum removal at the center and eventually yields a Gaussian shape.

The SJP system not only has similar advantages as the FJP system, but also has some additional advantages. Firstly, the SJP system can easily obtain an ideal removal function without the need for any complex devices and operations. Secondly, the SJP process is safer because there is no spattering out of fluid after submerged impinging. Finally, the nozzle need not be oblique and rotating during the figuring process, thus it is easy to control and operate.

The SJP system shown in Fig. 4 was applied to the corrective figuring of a BK7 optical glass. The sample—which was flat and has a diameter of 32 mm—was pre-machined by traditional technique, and its initial surface is shown in Fig. 5. For our experiments, the following parameters were chosen: a premixed slurry containing 6.3 wt.-% abrasive grains of cerium oxide ( $\text{CeO}_2$ ); grain mesh size of W 2.5 ( $2 \mu\text{m}$ ); nozzle diameter of 1.2 mm; ejecting pressure of 0.6 MPa; and standoff distance of 8 mm.

The removal function experiment was done first under the above-mentioned parameters, and the material removal function extracted from the interferogram data was used to calculate the dwell time. Corrective figuring was then processed controlled by the computerized numerical controlled (CNC) machine. The slurry was guided onto the submerged workpiece through the nozzle. As the initial surface was almost symmetrical, the spiral tool path was employed in the process. After two polishing periods, the flatness was improved from photovoltaic (PV)  $0.066 \lambda$  to  $0.02412 \lambda$  ( $\lambda = 632.8 \text{ nm}$ ) and the RMS value was enhanced from  $0.013 \lambda$  to  $0.00428 \lambda$ . The experimental results obtained with the Zygo Veri Fire Asphere interferometer are shown in Figs. 6 and 7.

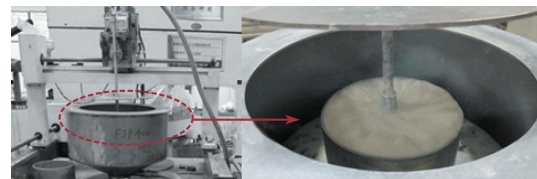


Fig. 4. SJP system during processing.

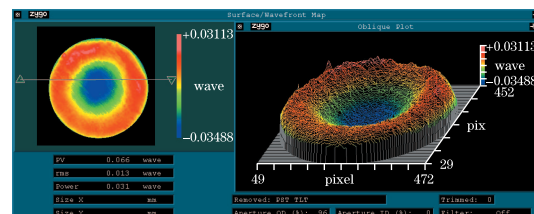


Fig. 5. Initial surface of BK7 flat glass.

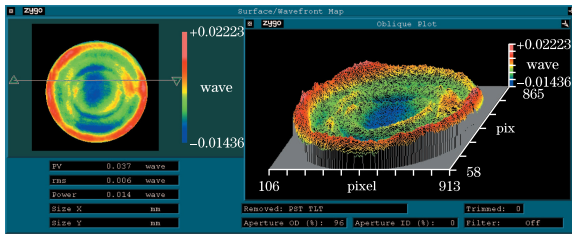


Fig. 6. Surface after one polishing period.

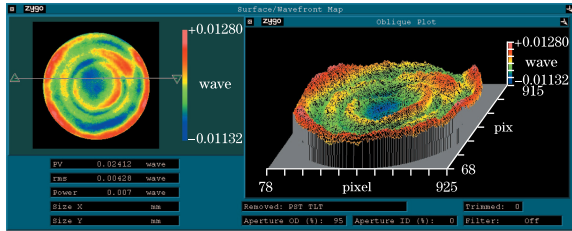


Fig. 7. Surface after two polishing periods.

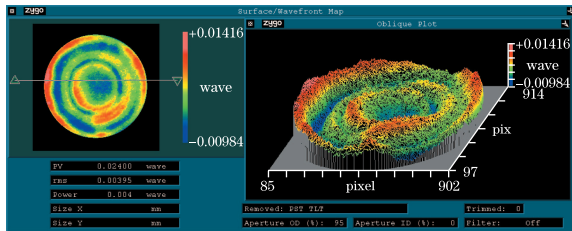


Fig. 8. Surface after three polishing periods.

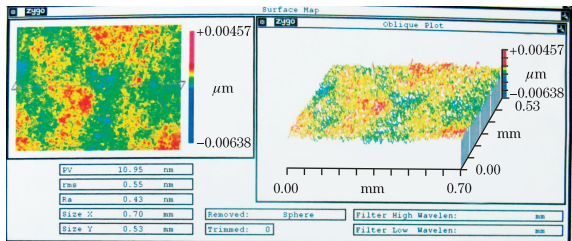


Fig. 9. Roughness of the polished surface.

The repeated stability precision of the interferometer is 0.1 nm. The first polishing period costs 37.3 min, whereas the second period costs 5.8 min. Furthermore, in order to validate the ultra-precision figuring capability of SJP, the third period, which costs 3.4 min, was carried out to improve the surface, and the result is shown in Fig. 8. Compared with the surface during the second period, it was not significantly improved because of the

limitation of the CNC machine. Eventually, the PV value reached  $0.02400 \lambda$ , and the RMS value was  $0.00395 \lambda$ . However, this can be improved further by a better CNC machine. From the results, it can be seen that the edge surface is not very good, which may be due to the edge effect. The edge effect can be corrected by algorithm optimization, and further work will be taken to study these problems. The mean surface roughness after polishing is  $R_a = 0.57 \text{ nm}$  (see Fig. 9), which is slightly worse than the original value of  $R_a = 0.45 \text{ nm}$ .

In conclusion, we present a material removal optimization process and a new polishing method for FJP and SJP. In the SJP process, material removal is mainly caused by the abrasive impact action, and the removal function is a Gaussian shape, which is fit for ultra-precision figuring. The process is sensitive to variations in the standoff distance. Since SJP employs a submerged jet for machining, there is no tool wear and spattering out of fluid; the tool also cools and removes debris in the process. SJP is applied to the corrective figuring of a BK7 optical glass. Results show that the flatness is improved from PV  $0.066 \lambda$  to  $0.02400 \lambda$  after three iterations and that the RMS value is improved from  $0.013 \lambda$  to  $0.00395 \lambda$ . The experiments demonstrate the feasibility of the optimized process for corrective figuring of precision optics, indicating that it is practicable to apply the SJP process in polishing and shaping complex-shaped surfaces as well as in ultra-precision optical manufacturing.

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