

CORRECTIVE FIGURING OF OPTICAL GLASS BY NANO-ABRASION MACHINING

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1. INTRODUCTION

Recently great advances have been accomplished in ultraprecision machining, but it is rather difficult to obtain a few nanometers form accuracy in ultraprecision grinding of ductile materials. To improve the form accuracy, some corrective figuring is performed by local material removal cooperated with feedback of the form error map. The methods used for the local removal are polishing with a small polisher, elastic emission machining (EEM), ion beam machining, plasma assisted chemical machining (PACM), magnetorheological finishing (MRF) and so on.

In previous paper [1], we proposed a new type of local removal method named "Nano-abrasion machining" and investigated its fundamental machining characteristics for different brittle work materials. There it was ascertained that the material removal rate and surface roughness were suitable for a local removal process in corrective figuring.

In this paper, the Nano-abrasion machining is applied to corrective figuring of optical glass and the feasibility is investigated.

2. NANO-ABRASION MACHINING

This method is similar with water jet abrasive machining or liquid honing. In water jet abrasive machining and liquid honing, generally, abrasive grits contained in water are ejected under a high pressure from a nozzle and collide on the surface of work materials at a high speed. Referring to the erosion tests done by Sheldon and Finnie, if the collision energy is low and the collision angle is shallow, the abrasion rate may decrease down to a few nanometers per minute and ductile mode abrasion with a few nanometers surface roughness may occur even for brittle work materials. Therefore this method is named "Nano-abrasion machining".

This method has a great advantage that the machining accuracy is almost independent of the machine accuracy because the working distance from the nozzle tip to the collision point is far enough. A warp of the workpiece induced by holding does not affect the machining accuracy therefore this method is suitable for repeating a post-process measurement and corrective figuring. Additionally, the machining characteristics are stable as there is no tool wear.

3. EXPERIMENTAL APPARATUS AND METHODS

In the machining chamber, the workpiece was mounted on a horizontal X-Y table controlled by a NC controller. The machining liquid was fed to a nozzle by a special screw pump under a high pressure. The work material was optical glass of BK-7. The machining liquid containing 1 wt% abrasive grains of white fused alumina (WA) was used. The grain mesh size and mean diameter were #10000 and $0.6 \mu\text{m}$. The diameter of nozzle was 1mm and the ejecting pressure was 4 MPa, then the velocity of jet flow was 91 m/s. The working distance was 20mm.

After the experiments, the machined surface was observed by an interferometer microscope

to measure the depth profile and surface roughness, then the form i.e. flatness was measured by a laser interferometer.

3.1 Circular motion machining

According to the results of fundamental experiments performed without scanning of the nozzle against the workpiece, when the nozzle was inclined, the removal spot always looked like a crescent moon and the contour map and profiles were not axis-symmetric. The machined area changed its form from oval to circular as the collision angle increased. When the nozzle was set upright, i.e. the collision angle was 90° , the removal spot was circular and the profile had an axis-symmetric W-shape, as shown in Fig. 1(a).

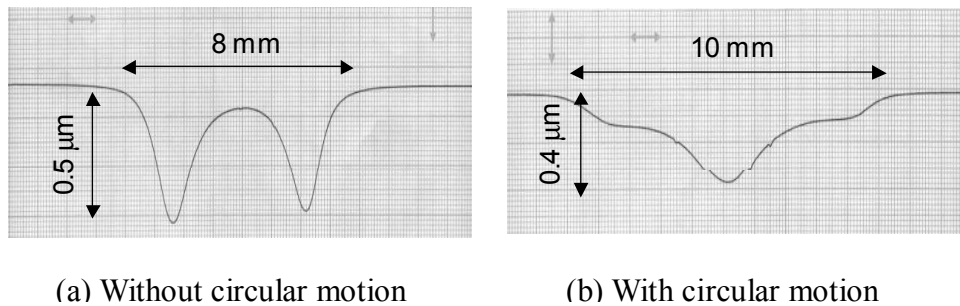


Fig. 1 Diametrical profiles of removal spot without/with circular motion machining
 Work: BK-7, abrasives: WA#10000, ejecting pressure: 2MPa, collision angle: 90° , radius of circular motion: 1mm, machining period: 30min.

For a local material removal in corrective figuring, a removal spot with a circular plane figure and axis-symmetric V-shape profiles may be preferable because it is easy to make a simulation program and generate the NC program. To obtain such a removal spot, it is necessary to modify the form of removal spot for collision angle 90° by moving the nozzle or workpiece

In this study, a circular motion of workpiece was employed to realize such a removal spot. To predict the profiles of removal spot, computer simulations were performed for different radii of circular motion, based on the diametrical profile of removal spot obtained for collision angle 90° , as shown in Fig. 1(a).

Then machining was performed with circular motion. Fig. 1(b) shows the experimental result for the best radius, $r = 1$ mm. The obtained profile seems suitable for corrective figuring.

3.2 Simulations of corrective figuring

A computer program has been developed to generate the NC program for corrective figuring and predict the machining accuracy to be obtained.

Fig. 2 illustrates the circular motions and scanning paths in corrective figuring. The circular motion is performed around every machining point distributed with a constant step on the scanning path. To generate the NC program for corrective figuring, it is necessary to determine the velocities of circular motions around every machining point. In this study, the X-direction step and the Y-direction step were 0.54mm equal to the pixel size of flatness measurement by the laser interferometer. The step size a is much smaller than the diameter of removal spot $d = 10$ mm and resultant material removal at a point is a sum of the material removals obtained by machining at the point and a number of neighboring points. As it is very difficult to predict the material removals, the velocities of circular motion at neighboring points were assumed to be

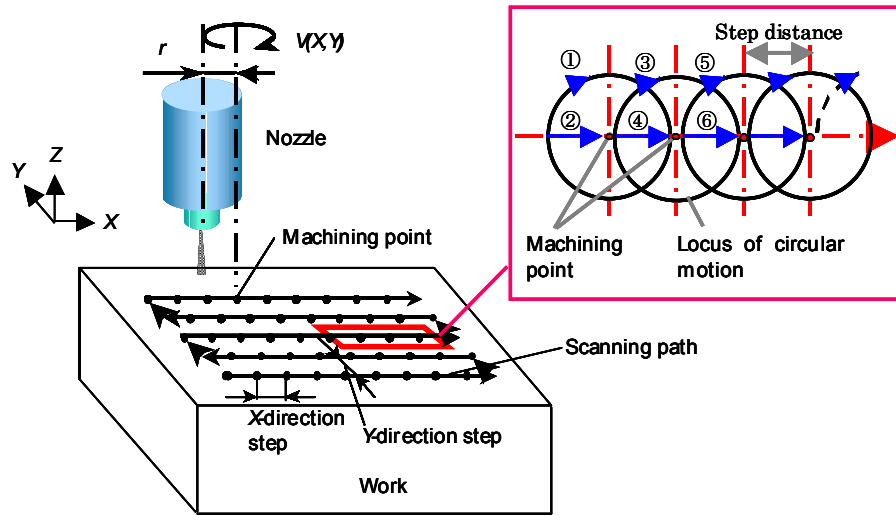


Fig. 2 Circular motions and scanning paths

equal to that at the point. Moreover, the material removal was assumed to be inversely proportional to the velocity of circular motion, following the Preston's law.

In the above calculation, the diametrical profile of removal spot shown in Fig. 1(b) was expressed by two different ways. One was "Cone approximation" where the profile was assumed to be triangular and another was "High order function" where the profile was expressed by a high-order function.

After the generation of NC program, the machining accuracy was predicted and evaluated by computer simulation. Fig. 3 shows an example of predicted machining accuracy. The pre-machined surface had an axis-symmetric sinusoidal convex with a height δ_{max} and wavelength λ . The machining intended to make a flat surface. The curve noted "Velocity correction" is the result obtained after correcting the velocities of "High order function" at several points where the residual errors were larger. The larger errors were considered due to the above-mentioned assumption that the velocities of circular motion at neighboring points were equal to that at the point.

From this figure, it is clear that the machining accuracy depends on the ratio of wavelength

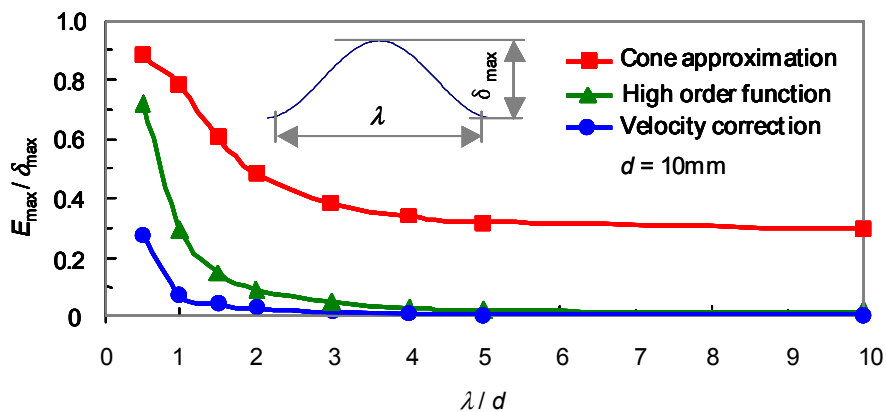


Fig. 3 Machining accuracy predicted by computer simulation

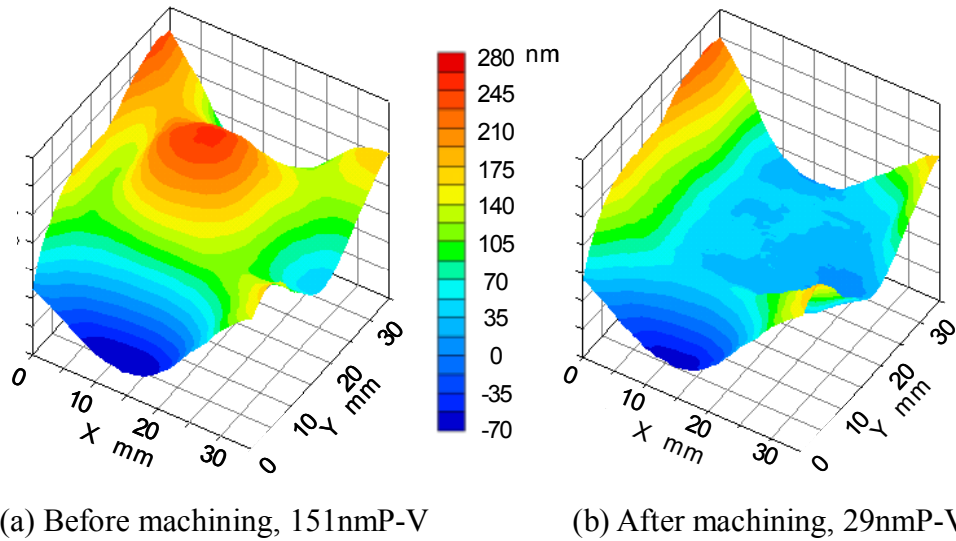


Fig. 4 Experimental result of corrective figuring

of form error λ to the diameter of removal spot d . For example, a sinusoidal form error with 200nm height can be reduced to several nanometers, if $\lambda/d > 1$.

4. EXPERIMENTAL RESULTS

Finally, a series of experiment was performed for corrective figuring. Work material was optical glass BK-7 and the work surface was pre-machined so that it had axis-symmetric sinusoidal concaves with 200nm height and 20mm wavelength. The corrective figuring was performed to make a flat surface of 15x15mm square.

Fig. 4 shows an example of experimental result obtained by corrective figuring of one scanning. The flatness was improved from 151nmP-V to 29nmP-V. The surface roughness was 1.1nmRa slightly better than that of pre-machined surface.

5. CONCLUSIONS

Nano-abrasion machining was applied to corrective figuring of optical glass surface. By modifying the scanning motion, it became easier to generate the NC program for figuring and predict the machining accuracy. It has been ascertained by experiments that the Nano-abrasion machining is applicable to corrective figuring of brittle materials.

ACKNOWLEDGEMENT

The authors would like to express their sincere thanks to Mr. Y. Yoshidomi of Nikon Corporation for preparation of workpieces and to Dr. S. Itoh of Aichi Industrial Technology Institute for flatness measurements.

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