# Development of Ultrasonic Vibration Assisted Polishing Machine for Micro Aspheric Die and Mold

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**Abstract**
Demands are increasing for micro axis-symmetric aspherical lenses to be installed in various optical devices. The micro glass lenses are generally molded by glass press process with micro aspheric ceramic molding dies or molds made of tungsten carbide or silicon carbide. These dies and molds are mostly ground with micro diamond wheels, but require additional finishing process as the size of the dies and molds become smaller and the required accuracy becomes higher. In order to finish micro aspheric dies and molds with diameter less than 3mm, an ultrasonic vibration assisted polishing machine is developed. A small polishing tool is mounted on a 3-axis controlled table, and vibrated at an ultrasonic frequency with piezo-electric actuators. The polishing pressure can be controlled with a resolution of 2 mN. Some micro aspheric molding dies made of binder-less tungsten carbide were polished, and the form accuracy below 70 nmP-V and surface roughness of 7 nmRy were obtained with the developed machine.

**Keywords**:
Polishing, Ultrasonic, Mold/Die

## 1 INTRODUCTION

Demands are increasing for micro aspheric glass lenses to be installed in various optical devices, such as digital cameras, blue laser pick-up devices and optical transmission devices in order to improve the optical performance. The micro glass lenses are generally molded by glass press process with micro aspheric ceramic molding dies or molds made of tungsten carbides (WC) or silicon carbides (SiC). These dies and molds are mostly ground with micro diamond wheels [1-3], but generally require additional finishing process with loose super abrasives as the size of the dies and molds becomes smaller and the required accuracy becomes higher [1,2].

In the conventional aspherical polishing method, a rotating micro soft polishing tool, such as a rubber tool, is used to polish the aspherical surface of the rotating workpiece. The polishing tool applies a constant pressure against the workpiece surface, while loose super abrasives are supplied as shown in Figure 1 [4,5]. As the size of the aspherical shape, and hence the radius of curvature, become smaller, typically less than 3 mm in diameter, it becomes impossible to apply the conventional rotating polishing method. In order to overcome this problem, a new ultrasonic vibration assisted polishing machine has been developed to finish the micro aspherical ground dies.

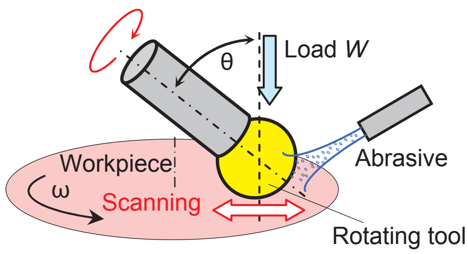



Figure 1: Conventional method with rotating polishing tool

In the conventional ultrasonic vibration assisted grinding/ polishing method, the bonded and fixed abrasive was usually used and longitudinal vibration was applied against the workpiece surface. Then optical mirror surface below 30 nmRy was difficult to be generated with the conventional ultrasonic vibration method [6].

In the proposed aspherical polishing method, as shown in Figure 2, loose abrasive and a micro spherical polyurethane tool is used, to which an ultrasonic vibration is applied laterally against the workpiece surface under a constant pressure. As the tool is not rotated, the polishing pressure can be kept constant and it can be applied to smaller aspherical shapes.

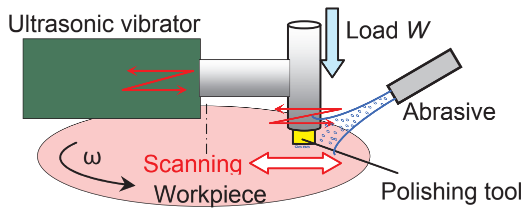



Figure 2: Proposed method with ultrasonic vibration assisted polishing tool.

## 2 PRINCIPLE OF ULTRASONIC VIBRATION ASSISTED POLISHING

According to Preston's equation, the removal depth by polishing $\delta$ is expressed as follows:

$$\delta = k \cdot P \cdot V \cdot t \quad (1)$$

where, $P$, $V$ and $t$ are the polishing pressure, the relative velocity between the polisher and a workpiece and the polishing time, respectively. $k$ is the constant value, which is affected mostly by the abrasives and the workpiece materials.

In the case of ultrasonic vibration polishing, V is given by:

$$V = 2\lambda \cdot v \quad (2)$$

where $\lambda$ and $v$ are the amplitude and the frequency of ultrasonic vibration, respectively [7].

The dwell time, or the polishing time $t(x)$ at a radial position $x$ of the workpiece, see Figure 3, is given by:

$$t(x)=\frac{A}{2\pi \cdot x \cdot S(x)} \quad (3)$$

where $S(x)$ is the scanning speed of polishing tool and A is the area of the polishing removal function.
The polishing load $W$ is given by:

$$W=A \cdot P \quad (4)$$

From equations (1),(3) and (4), the desired scanning speed of the polishing tool at a radial position $x$ is given by:

$$S(x)=\frac{k \cdot W \cdot V}{2\pi \cdot x \cdot \delta(x)} \quad (5)$$

where $\delta(x)$ is the form deviation, or the amount to be polished. The actual scanning speed of the tool $S(x)$ is determined by referring to the form error of the ground workpiece measured prior to polishing.

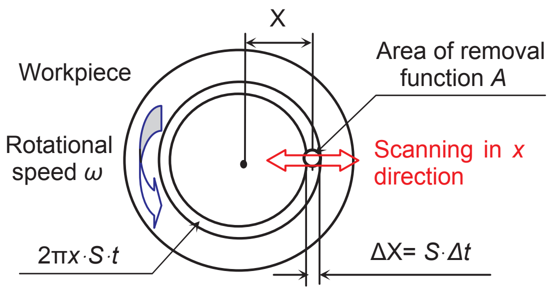



Figure 3: Polishing of axis-symmetric aspherical surface.

## 3 ULTRASONIC VIBRATION ASSISTED POLISHING MACHINE

Figure 4 shows a schematic illustration of the ultrasonic vibration assisted polishing machine developed. Figure 5 shows some photographs of the machine. The polishing head, attached to the polisher arm via the ultrasonic vibrator, is mounted on X-Y-Z table supported with linear guides. The resolution of motion of the X-Y-Z table is 0.1 μm in each direction. The workpiece is mounted on C-axis rotary table with a magnet chuck. The tool with micro polyurethane polisher is attached at the end of the polisher arm. The polishing load $W$ is applied by a spring and its value is adjusted by an adjusting screw with a resolution of 2 mN. The value of the tool scanning speed is calculated based on the aspherical form, the polishing load and the speed as given by equation (5), and the NC program is generated by the personal computer.

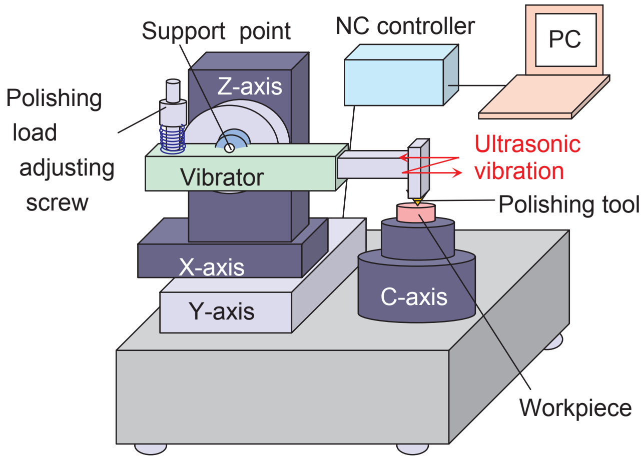
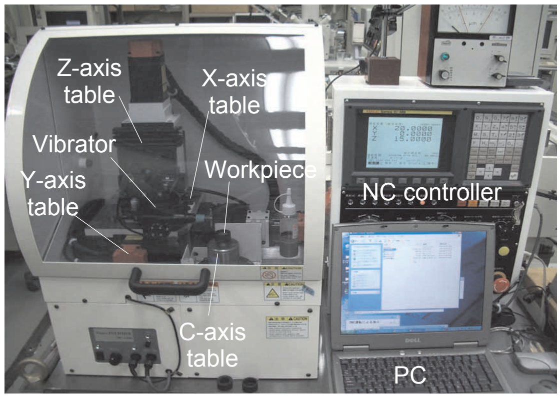
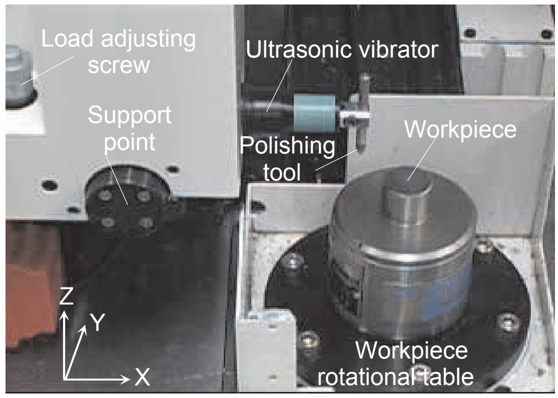



Figure 4: Schematic illustration of ultrasonic vibration assisted polishing machine.




(a) Whole view of the machine




(b) Polishing head
Figure 5: A view of ultrasonic assisted polishing system.

## 4 EXPERIMENTAL RESULTS

Preliminary polishing experiments and finish polishing experiments of the aspherical molding dies of binderless tungsten carbide were carried out to evaluate the polishing performances of the newly developed machine. The workpiece surface was ground prior to polishing, with a micro resinoid bonded diamond wheel on an ultra precision grinding machine with 1nm positioning resolution.

| | |
|---|---|
| Workpiece<br>Rotational speed | Binderless tungsten carbide<br>$\omega$=160 min$^{-1}$ |
| Polisher head<br>Radius<br>Hardness | Polyurethane<br>250 μm<br>90 |
| Polishing load | $W$=9.8 mN |
| Vibrating mode<br>Frequency<br>Amplitude | Traverse<br>$v$=25 kHz<br>$\lambda$=10 μm |
| Abrasive<br>Grain size<br>Density | Diamond slurry<br>0.5 μm<br>1 wt% |

Table 1: Major polishing conditions.

### 4.1 Polishing conditions and removal function

Major polishing conditions are summarized and shown in Table 1. As a polisher, a polyurethane tool with radius of curvature of 250 μm was adopted. Figure 6 shows the view of the polishing tool.
In order to study basic polishing performances, the tungsten carbide workpiece was polished at a fixed position without rotary motion for 5 minutes under a polishing load of 9.8 mN. Figure 7 shows the polished surface and the profiles of the polished part, or the removal function. The shapes of the

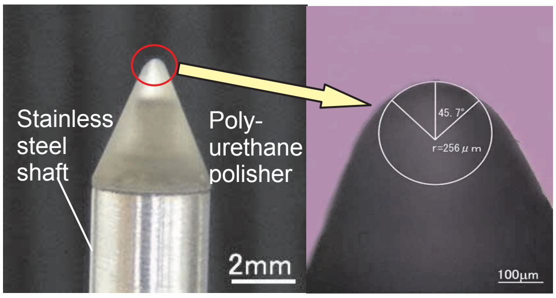



Figure 6: View of polishing tool.

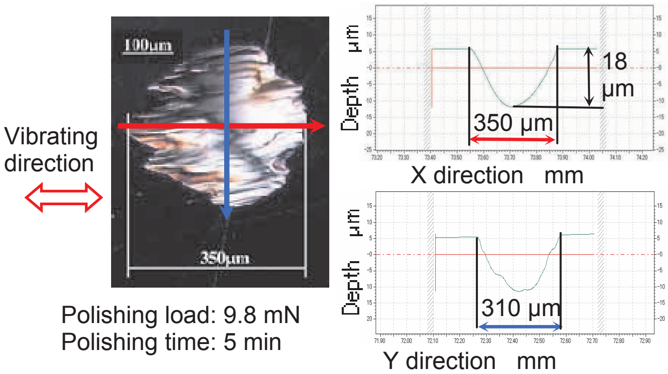



Figure 7: Shape of removal function.

removal function are convex in both the polishing direction, or X direction and the cross direction, or Y direction, which means that the present polishing method is suitable for aspheric generation polishing.

### 4.2 Basic polishing characteristics

The flat tungsten carbide workpiece was polished by varying the polishing pressure *P* from 115 kPa to 575 kPa. The polishing pressure was calculated from the polishing load and the area of removal function. Figure 8 shows the changes in the removal depth with the polishing time. The removal depth is almost proportional to the polishing time. The change in the removal rate with the polishing pressure was calculated and shown in Figure 9. As the area of polishing removal function is small, and the polishing pressure is high, the number of acting polishing abrasives decreases with an increase in the polishing pressure.

A tungsten carbide workpiece was ground with a resinoid bonded diamond wheel with grain size of #400, and polished under the same polishing conditions shown in Table 1. The polishing pressure was 345kPa. Figure 10 shows changes in the removal depth and the surface roughness with the polishing time. The ground surface with roughness of 17 nmRy was improved to that of 8 nmRy by removing the surface for 200 nm.

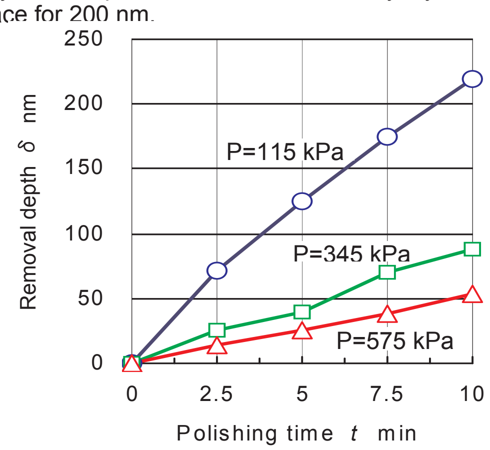



Figure 8: Change in removal depth with polishing time.

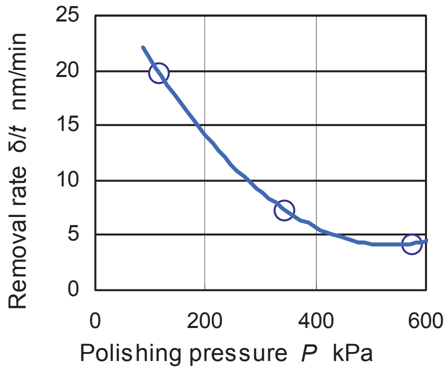



Figure 9: Relation between polishing pressure and removal rate.

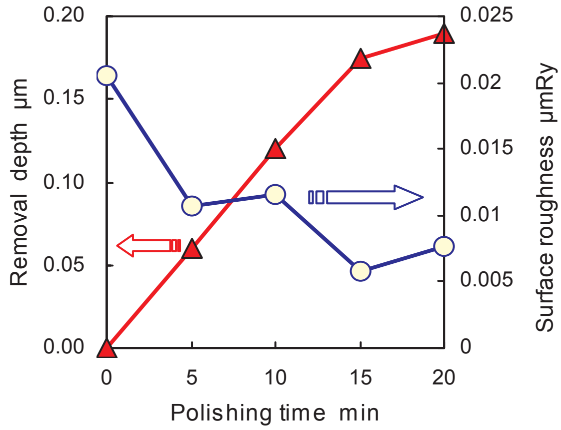



Figure 10: Changes in removal depth and surface roughness with polishing time.

### 4.3 Micro aspherical polishing

In order to evaluate the aspherical polishing performances, a tungsten carbide workpiece was ground with a resinoid bonded diamond wheel to the shape shown in Figure 11, and polished according to the process shown in Figure 12. The polishing conditions are the same with those shown in Table 1. The scanning speed of the polishing tool in *x* direction was computed to compensate the geometrical error of the previously finished surface. The aspherical shape was evaluated with use of an aspheric analysis software by using the raw data obtained by Form Talysurf (Taylor Hobson Co. Ltd.), and the distribution profile of the form deviation is calculated. Figure 13 shows changes in the form deviation profiles before and after the aspherical polishing. The form deviation of 0.12 μmP-V was reduced to 0.07 μmP-V by polishing. Figure 14 shows Nomarski micrographs of the workpiece surface before and after polishing. A center mark can be observed at the workpiece center and grinding scratches can be observed in the outside area after grinding. They cannot be observed after polishing. Figure 15 shows surface roughness profiles measured with a non-contact type measuring instrument. The surface roughness was improved from 15 nmRy to 7 nmRy.

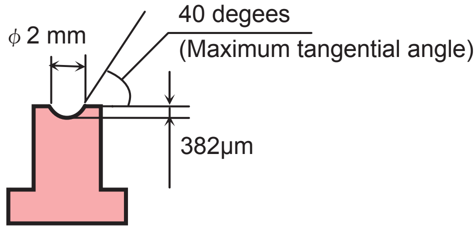



Figure 11: Geometry of workpiece for aspherical polishing.

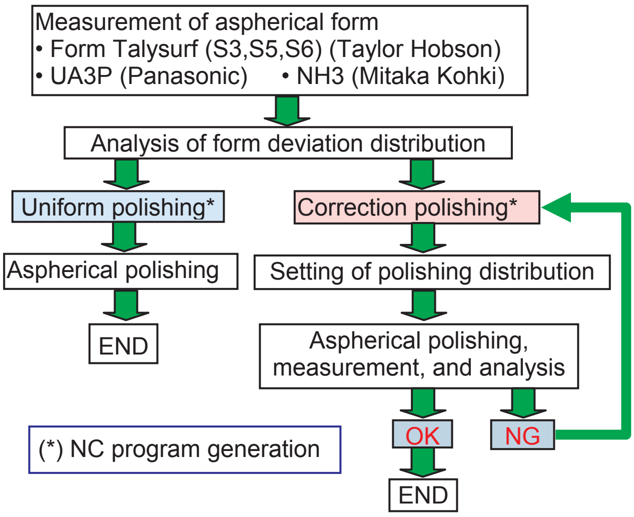



Figure 12: Flow chart of aspherical polishing process.

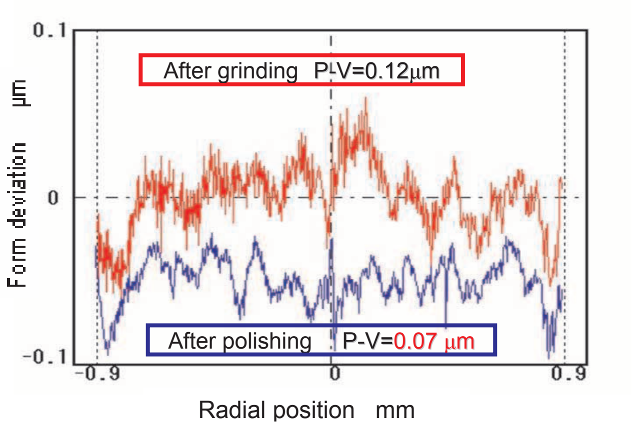



Figure 13: Form deviation profiles measured before and after polishing.

## 5 SUMMARY

A new ultrasonic vibration assisted polishing methods is proposed and a new polishing machine is developed to finish micro aspherical molding dies that are ground with micro diamond wheels. A small polishing tool is mounted on a 3-axis controlled table, and vibrated laterally at an ultrasonic frequency with piezo-electric actuators. The polishing load can be controlled with a resolution of 2 mN. Series of polishing experiments were carried out to evaluate the performances of the machine developed. An aspheric molding die of tungsten carbide is polished to the form accuracy below 70 nmP-V and the surface roughness of 7 nmRy.

## 6 REFERENCES

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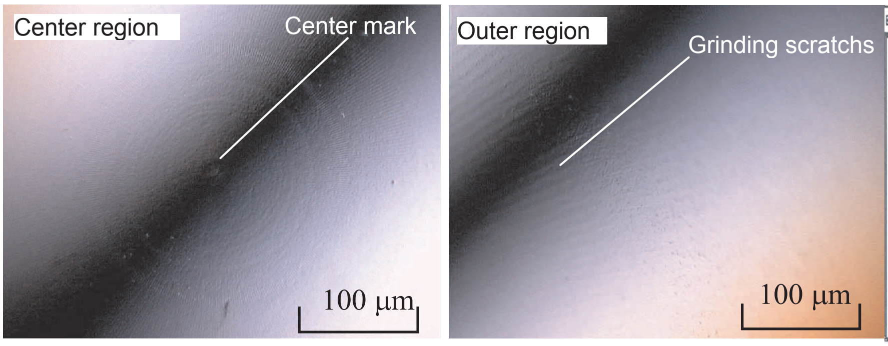
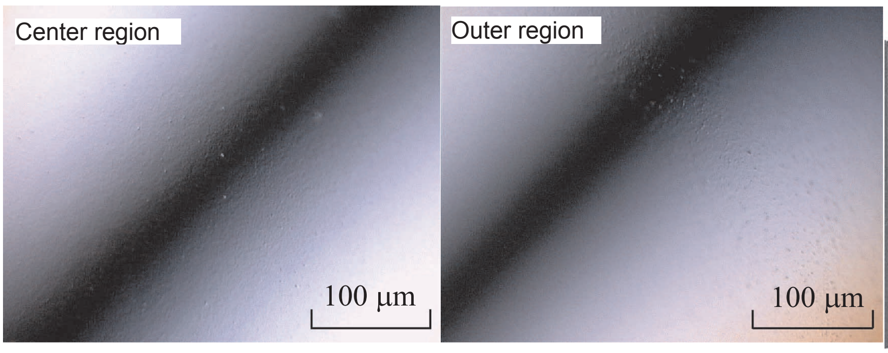
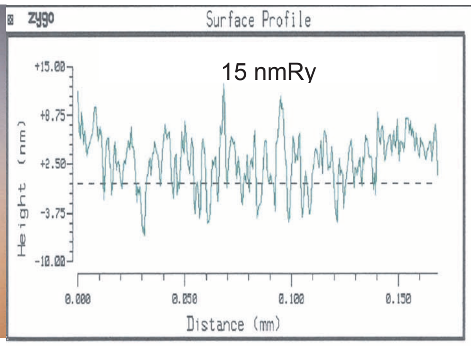



(a) Before polishing (After grinding)

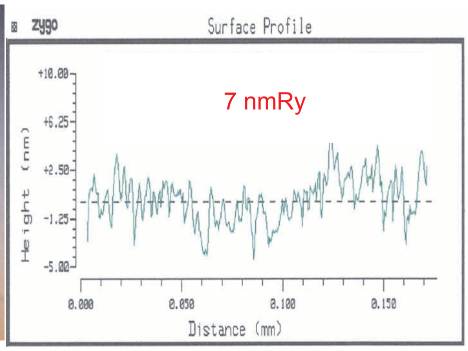



(b) After polishing

Figure 14: Nomarski micrographs of tungsten carbide workpiece before and after polishing.




(a) Before polishing (After grinding)




(b) After polishing

Figure 15: Changes in surface roughness of tungsten carbide workpiece.