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Precision cutting of Ni-P plated large mold for X-ray mirror - The effect of tool positioning error on the workpiece form deviation

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Abstract

Precision molds of electroless Ni-P plating are required to mold a Walter-type cosmic X-ray telescope to observe unknown astronomical phenomena such as supernova explosions and the formation of black holes. Conventional X-ray mirrors were made of resin, and they had low strength and low stiffness. In this study, therefore thin mirrors made of CFRP is proposed to overcome those problems. The target value of the maximum size is Φ400 mm, that of the form accuracy is less than 1 μm P-V and that of surface roughness is less than 10 nm Rz. In the cutting experiments, a mold of electroless Ni-P was turned with a single crystalline diamond tool using a vertical type ultraprecision lathe. After cutting, the mirror form accuracy was measured using a capacitive displacement sensor on the machine. In the measurement experiments, the effects of the sensor positioning deviation on the measured accuracy was simulated and the sensor position was compensated in axial and circumferential directions. In the experiment, an accurate mirror could be machined using the developed machining/measurement system.

Precision cutting, electroless Ni-P, X-ray mirror mold, on-machine measurement

1. Introductions

Large reflecting mirrors of high accuracy are used for X-ray telescopes in astronomical spaces to clarify the mechanisms of extremely high energy celestial events. X-ray radiations are is created in space by extremely high energy celestial events, including supernova explosions, the destruction of positrons, the creation of black holes, and the decay of radioactive matter. A number of large parabolic thin mirrors are installed in the Wolter type X-ray telescope where the mirrors are produced by a molding process with ultraprecision diamond-turned and polished molds made of electroless nickel (Ni-P) [1, 2]. To produce high accurate mirrors, it is necessary to measure accurate shape to cut the mold with compensations. In this study, an on-machine form measurement method was developed on the vertical lathe. Form measurement deviations due to sensor positioning deviations were simulated and corrected for position.

2. X-ray mirror for space telescope

High energy rays, such as X-rays, cannot be reflected or refracted with conventional mirrors and instead, X-rays can be reflected by super-smooth surfaces at very small incidence angles. Based on this phenomenon of "grazing incidence," the most practical X-ray telescope was proposed by Wolter, and it comprised a number of optical configurations with the use of confocal parabolic mirrors to focus X-ray radiations as shown in Fig. 1.

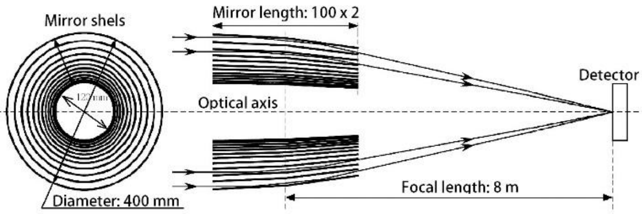
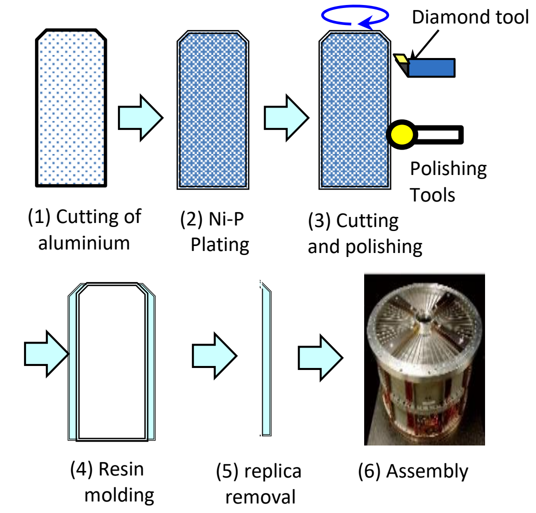


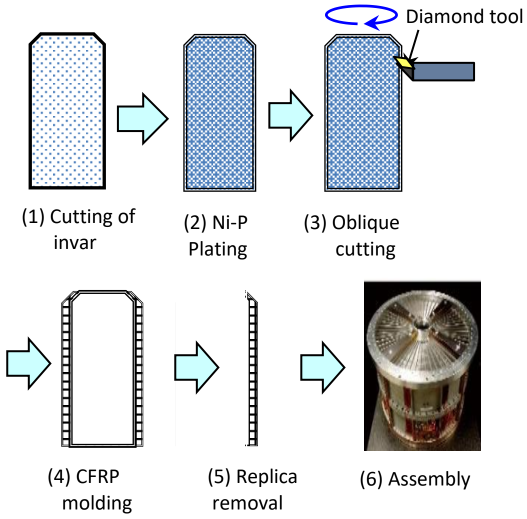
Figure 1. Optical system of an X-ray telescope

The mirrors require a surface roughness of 0.5 nm Ra and a form accuracy of 0.1 μm P-V. In the conventional fabrication process, X-ray mirrors are fabricated using the molding process of the replication method as shown in Fig. 2 (a). The Ni-P layer plated on the base material of harden stainless steel or aluminium was turned ultra-precisely and polished with fine abrasives. Finally, the mirrors of rein were molded with the electroless Ni-P mold, and the replica mirrors were separated and assembled. However, this conventional mirrors had a form deviation based on the high thermal expansion of the mold, and the strength and stiffness of the molded replica mirrors were low.

The proposed process is shown in Fig. 2 (b). Invar having a low thermal expansion was used as the base mold to reduce the form deviation based on the thermal expansion. In addition, CFRP will be molded to increase a specific strength, and to reduce the total mirrors weight.



(a) Conventional molding process



(b) Proposed molding process

Figure 2. Fabrication process of X-ray mirrors

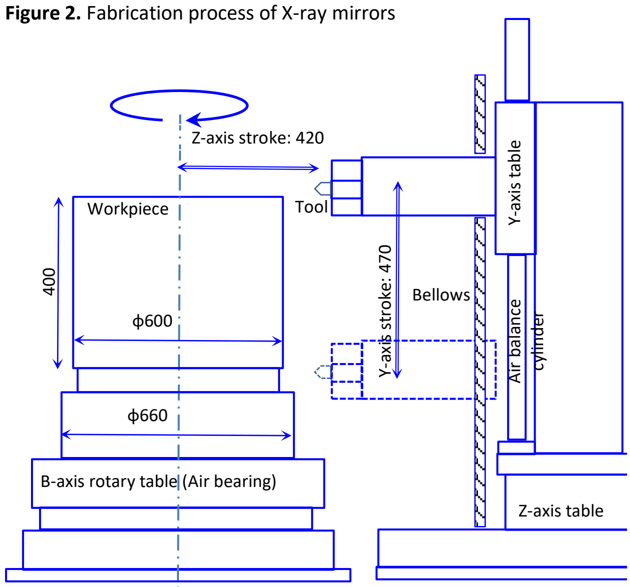


Figure 3. Schematic of ultra-precision machine

3. Experimental set-up and method

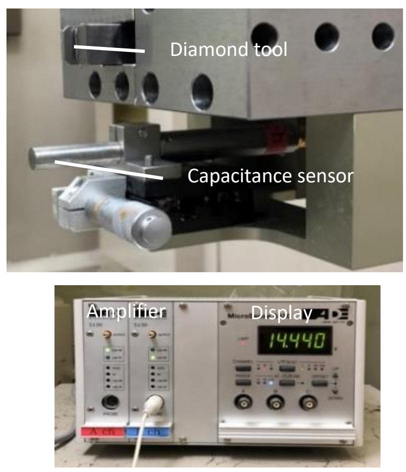
A large ultraprecision lathe, UTD-600A (Shibaura machine Co.Ltd.) was used for the X-ray mirror cutting experiments in this study. A schematic illustration of the turning machine is shown in Fig. 3 and, its specifications are shown in Table 1. The diamond tool was mounted on the ultraprecision machine, and the capacitance sensor was mounted 30 mm below the tool as shown in Fig. 4(a). The cutting conditions for the X-ray mirrors are shown in Table 2. The mold surface was plated with 100 µm of Ni-P on the base mold metal of invar. The invar base was used to decrease the thermal expansion of the mirror. The depth of cut was 2 µm and the feed rate was varied from 1 - 2 mm/min.

After cutting, the capacitance sensor was equipped onto the tool holder near the cutting tool, and the form deviations from the designed form were measured by the Capacitance sensor on the machine, and the form deviation profiles were calculated and plotted.

Table 1. Specifications of ultra-precision machine

Y- axis	Stroke Driving system Positioning resolution	420 mm Linear motor drive 1 nm
Z-axis	Stroke Driving system Positioning resolution	420 mm Linear motor drive 1 nm
B- axis	Maximum rotation Stroke Bearing system Positioning resolution	500 min^{-1} 360 deg. Air bearing 1/10000 deg.

(a) View of cutting



(b) On-the-machine measurement sensor

Figure 4. Views of cutting machine and on-machine measurement set-up

Table 2. Cutting conditions for X-ray mirror

Tool material	Natural monocrystalline diamond
Cutting edge radius	5.0 mm
Mold metal	Invar
Plating material	Electroless Ni-P
Plating thickness	100 µm
Maximum diameter	200 mm
Rotation	500 min^{-1}
Depth of cut	2.0 µm
Cutting times	4 times
Feed rate	1.0, 2.0 mm/min
Coolant	White kerosene mist

4. Effects of sensor positioning deviation on the measurement form accuracy

A calculated form deviation of the mold radial direction on the thrust position, ΔZ, is expressed as follows;

$$\Delta Z = Z(Y) - Z'(Y) \quad (1)$$
$$Z'(Y) = (Z(Y)^2 - \Delta X^2)^{0.5} \quad (2)$$

Where, Y is the thrust (vertical) coordinate of the mold, Z(Y) is the radial coordinate on the position of Y, ΔX is a deviation on the sensor position of the X-direction, and Z'(Y) is a radial value with the deviation of ΔX in the X-direction.

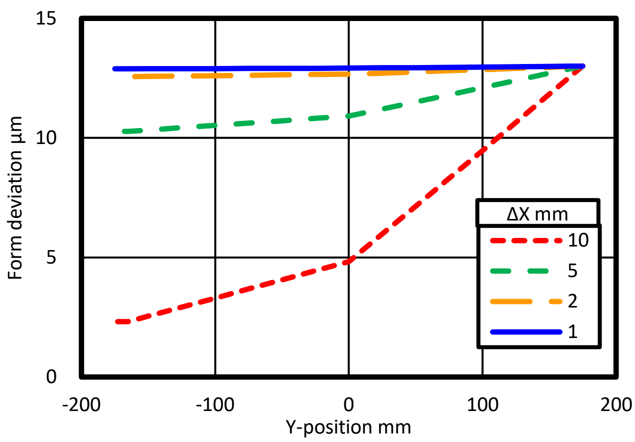


Figure 5. Form deviation curve with the positioning deviation in the X-direction

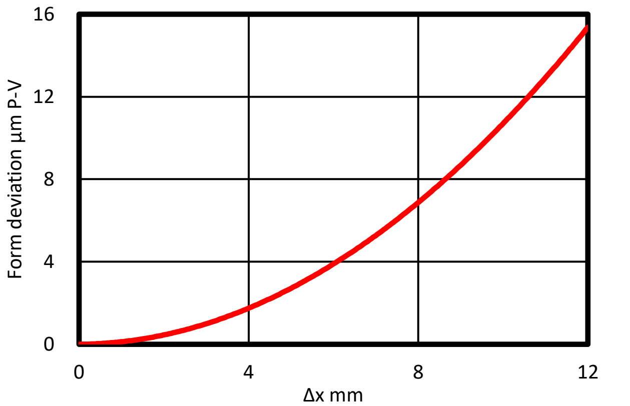


Figure 6. The effect of positioning deviation in X-direction on measured form accuracy

The mold height was 350 mm in the Y-direction and the diameter is was approximately Φ200 mm at the top, and Φ195 mm at the bottom. When there was a tool positioning deviation in the X-direction, the simulated workpiece form deviation curve was calculated using eq. (1) as shown in Fig. 5. The deviation curve increased with the mold radius. Based on these results, the effect of the tool positioning deviation ΔX in the X-direction on the machining accuracy is shown in Fig. 6.

5. Experimental results

Cutting experiments were performed and the effects of the positioning deviation, deviation in the X-direction on the measured form accuracy were tested. In the cutting of the mirror, ΔX was adjusted to 0, and the mirror of electroless Ni-P was turned at a feed rate of 2.0 mm/min. Fig. 7 shows the change of the experimental form accuracy with the X-axis deviation of the capacitance sensor. The form accuracy became minimum at the range of ΔX =0 - 1 mm, and however, the experimental deviations were too large compared to the calculated ones shown in Fig. 6.

Finally, the tool position and the sensor position were adjusted based on the simulated results in Figs. 5 and 6, and the mold of the electroless Ni-P was machined and measured. The machined and measured form deviation profiles of the X-ray mirror mold were shown in Fig.8. The form deviation of the diamond-turned mold was 2 µm P-V and was not enough for the X-ray mirror mold. This seems to be based on the tool wear because the workpiece size was too large and cutting distance was so long. The deviation will be decreased by using much higher diamond tool such as nanopolycrystalline diamond (NPD) tool and the tool wear prediction.

The surface roughness of the large mirror could not be measured using the white light surface roughness interferometer. However, from the cutting experiment of a small dummy workpiece of electroless Ni-P, the surface roughness of less than 10 nm Rz was obtained.

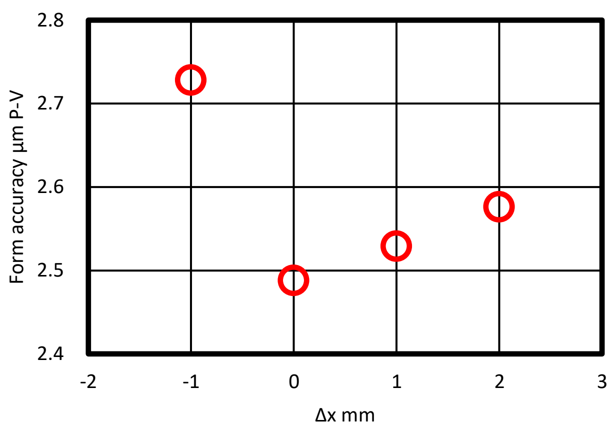


Figure 7. Changes of machined form accuracy with X-axis deviation of the capacitance sensor

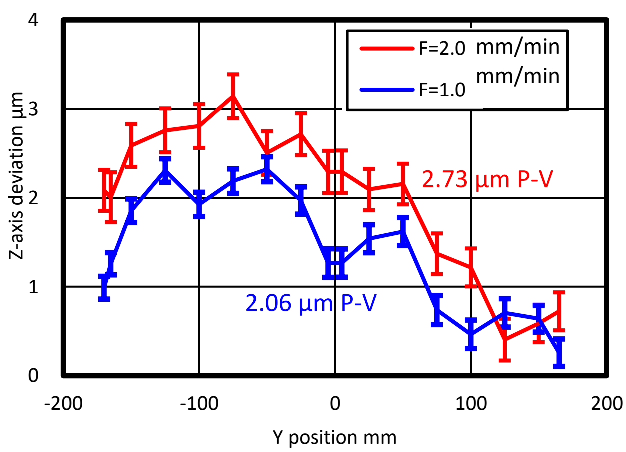


Figure 8. Machined and measured form deviation profile of X-ray mirror mold

6. Conclusions

In this study, a vertical turning system for a large mold and an on-machine form measurement system using a capacitance sensor were developed, and form measurement deviations due to sensor positioning deviations were simulated and corrected for the position in the experiments. In the experiments, the form deviation of the diamond-turned mold was about 2 µm P-V and was not enough for the X-ray mirror mold. The deviation will be decreased by using much higher diamond tool and the tool wear prediction.

References

[1] Wolter H, Mirror systems with grazing incidence as image-forming optics for X-rays, *Annals of Physics*, **6**, 10 1952 94–114.

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