Development of Aspheric Surface Polishing for X-Ray Mirrors

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Fabricating super-smooth aspheric optics for future hard X-ray telescopes will require a new process chain. An innovative two-step freeform finishing method is presented, that combines fluid jet and precessed bonnet polishing on a common 7-axis CNC platform. The corrective capability of this finishing method is demonstrated in the case of two different process chains for manufacturing replication mandrels: Electroless Nickel mandrels used for DC magnetron sputtering and Fused Silica mandrels used for thin glass slumping. A novel bonnet tool-pathing method called "continuous precessing" is also presented, which can deliver super-smooth anisotropic surface texture of 0.28 nm rms.

1. Introduction

X-ray radiations are created in space by extremely high energy celestial events. Such events include supernova explosions, destruction of positrons, creation of black holes, as well as the decay of radioactive matter in space. However, such high energy rays cannot be reflected or refracted with conventional optics like other electro-magnetic radiations. Instead, the total reflection of X-rays over flat and smooth surfaces at very shallow angle of incidence was first reported by Compton in 1923. The discovery of this phenomenon called "grazing incidence" reflection led to the suggestion by Wolter in 1952 of a number of optical configurations using confocal paraboloid and hyperboloid sections to focus X-ray radiations. The most practical, for the purpose of building of an X-ray space telescope, is known as the Wolter type-1 configuration and shown in Fig. 1.

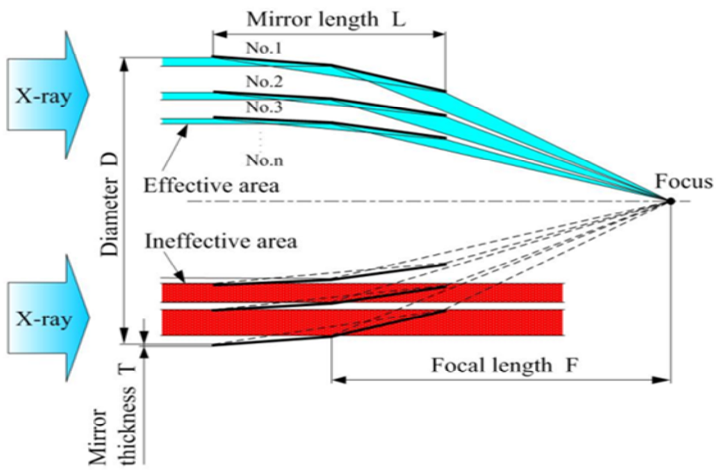


図1 Wolter type-1 configuration for grazing incidence X-ray mirrors

When dealing with high energy radiations, there exists a relationship between form accuracy and surface roughness of the optical surface on one hand, and the upper limit of radiation energy that it can reflect (keV) and resolution of the images it can produce (arcs) on the other hand. State-of-the-art finishing of molding dies has enabled the fabrication of X-ray imaging telescopes by replication, such as ASCA, XMM-Newton, Suzaku and ASTRO-H shown in Fig. 2. But in future years, the goal of building high resolution aspheric hard X-ray telescopes will require stringent specification: roughness less than 0.3 nm rms and deviation from aspheric shape less than 50 nm P-V.

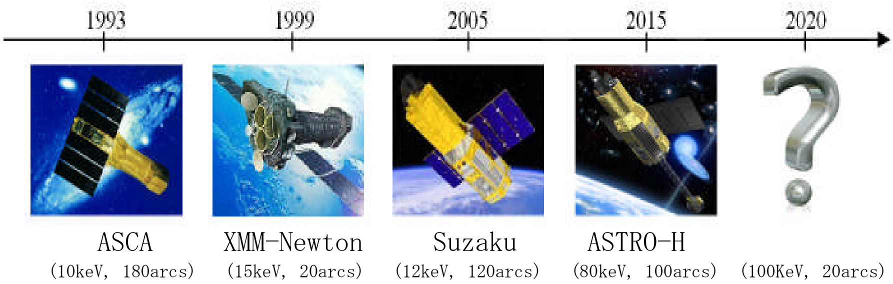


図 2　Past and future specifications of replicated X-ray telescopes.

Two possible process chains have been proposed in the literature to produce future thin aspheric X-ray mirrors:

- The first process relies on diamond turning of electroless nickel plated molding dies, for thin aspheric mirror replication by DC magnetron sputtering (see Fig. 4).
- The second process relies on freeform grinding to produce aspheric fused silica mandrels, for replication of thin glass sheet by slumping process (see Fig. 5).

This paper focuses on the intermediate finishing steps that are necessary for realizing both process chains. In particular, a novel concept is presented of combining fluid jet and precessed bonnet polishing processes using a common 7-axis CNC platform, shown in Fig. 3.

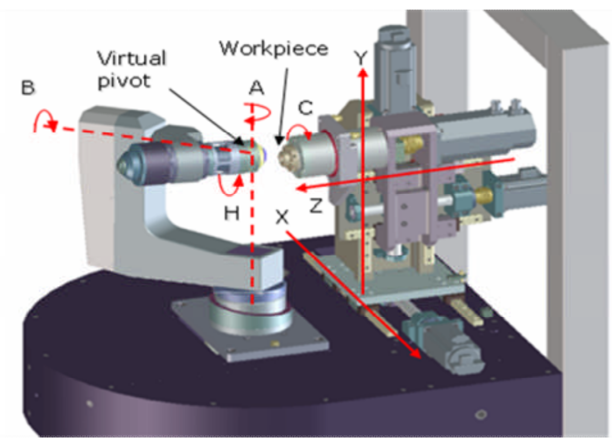
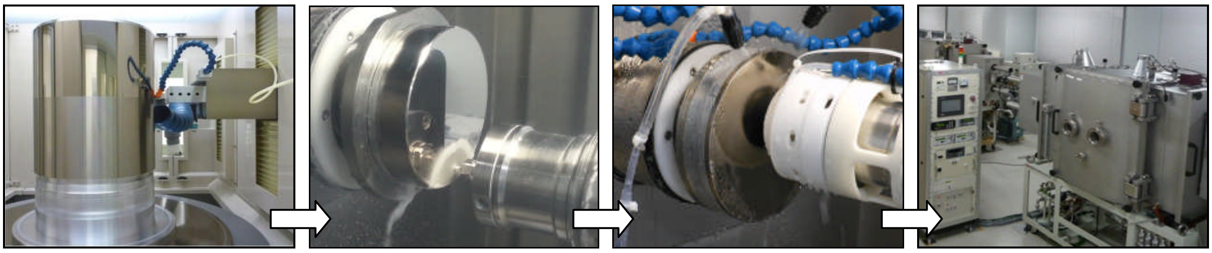


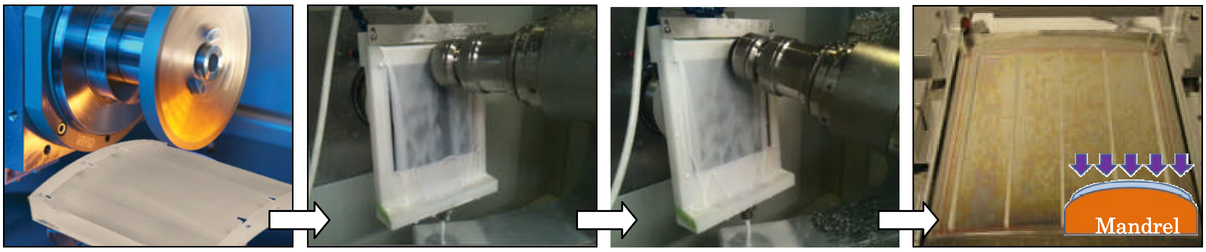
図 3　7-axis CNC platform used for fluid jet and bonnet polishing.

This combination can correctively polish ultra-precise aspheric shapes on both electroless nickel plated and fused silica mandrels. For final smoothing, the surfaces are then polished with a novel precessed bonnet tool pathing method named "continuous precessing". This new method can deliver super-smooth anisotropic surface texture when used with nano-particles slurry.



(a) Diamond Turning　(b) Fluid Jet　(c) Continuous Precess　(d) DC Magnetron Sputtering

図 4　Process chain #1 for fabricating aspheric hard X-ray shells



(a) Freeform Grinding　(b) Single Precess　(c) Continuous Precess　(d) Thin Glass Slumping

図 5　Process chain #2 for fabricating aspheric hard X-ray shells

2. Corrective Polishing

2.1　Fluid Jet Polishing of Electroless Nickel

Fluid Jet Polishing (FJP) has been studied in recent years as a potential finishing method for optical lenses and molds with a number of materials, such a glass and nickel. In the FJP process, a mixture of water and abrasive particles is delivered by a pump to a converging nozzle of outlet diameter usually between 0.1 and 2.0 mm. The jet impinges the work-piece, thus generating an influence spot which is moved across the surface to follow a tool path programmed in to the 7-axis CNC machine.

Corrective polishing by fluid jet was demonstrated on a 100 mm diameter sample, by iteratively measuring form on a Fizeau interferometer and feeding the error to a feed moderation algorithm. Initial form error on the sample was 120 nm P-V (see Fig. 6). It was improved down to 27 nm P-V with the following polishing sequence:

(1)　4.0 μm Al203, 16 bar fluid pressure (45 nm P-V).

(2)　4.0 μm Al203, 8 bar fluid pressure (27 nm P-V).

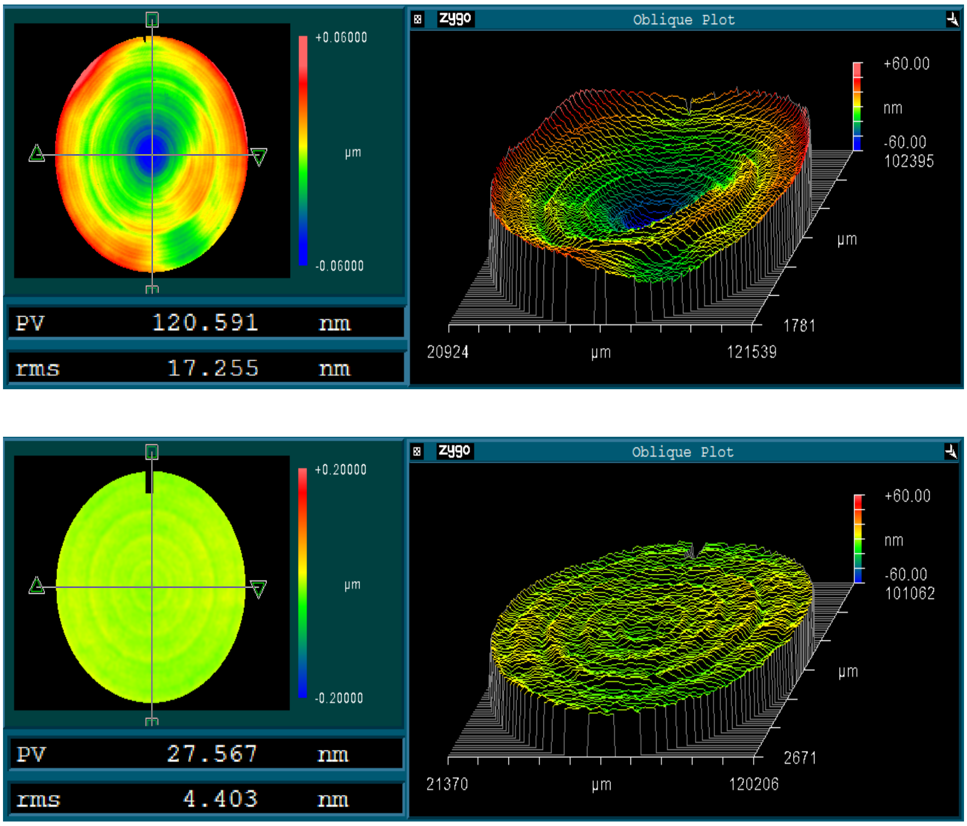


図 6　Form Correction on Electroless Nickel by Fluid Jet Polishing

2.2　Bonnet Polishing of Fused Silica

Precessed bonnet polishing is a sub-aperture finishing process which has been described in the literature at various stages during its development. The operation of the process in shown in Fig. 9 (left): The position and orientation (precession angle) of a spinning, inflated, membrane-tool are actively controlled as it traverses the surface of a workpiece. The workpiece may have any general shape, including concave, flat, or convex, aspheric or free-form.

Corrective polishing by precessed bonnet was demonstrated on a 150x150 mm fused silica sample, by iteratively measuring form on a Fizeau interferometer and feeding the error to a feed moderation algorithm. Initial form error on the sample was 610 nm P-V (see Fig. 7). It was improved down to 41 nm P-V with the following polishing sequence:

(1) 1.5 μm Ce02, 1 bar air pressure (126 nm P-V).

(2) 1.5 μm Ce02, 0.5 bar air pressure (41 nm P-V).

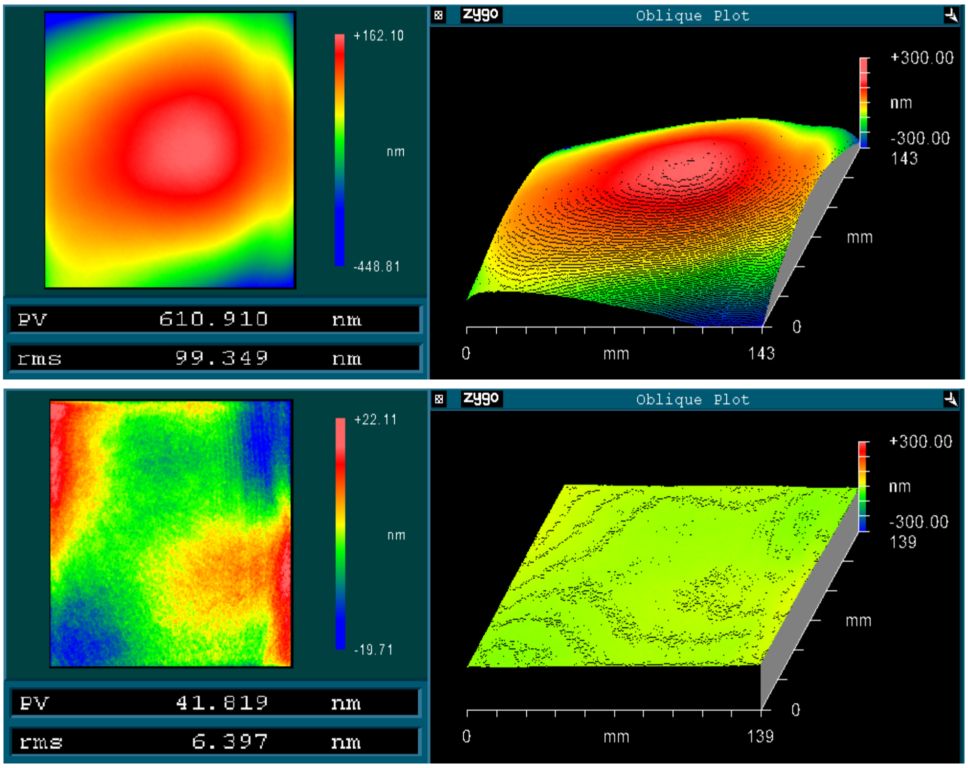


図 7　Form Correction on Fused Silica by Precessed Bonnet Polishing

2.3　Manufacturing of Parabolic Mandrel (on-going)

A 200x200 mm parabolic section of nominal radius 200mm was precision ground in industry from a fused silica block (see Fig 8). The ground mandrel was measured with an ultra-accurate UA3P CMM (at Panasonic in Osaka). The error after grinding was 36 µm. The mandrel is currently being polished correctively, with the following status having been achieved:

(1) 1.5 µm CeO2, 1 bar, 33% removal target (25 µm P-V).

(2) 1.5 µm CeO2, 1 bar, 85% removal target (3.1 µm P-V).

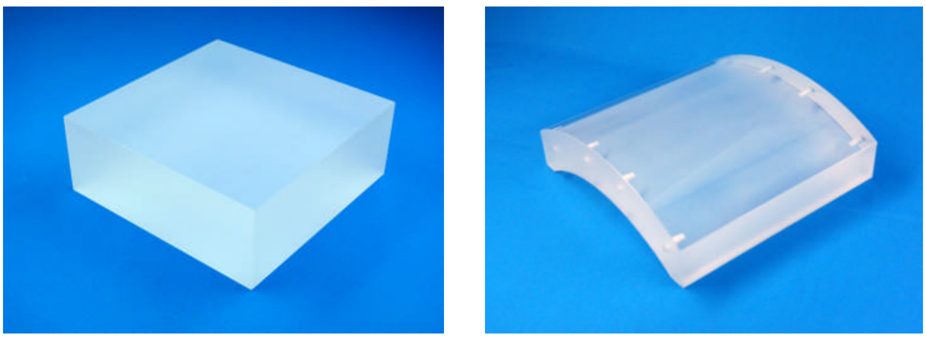


図 8　Fused Silica block before and after Precision Grinding.

Corrective polishing of this mandrel will carry on until achieving form error below 100 nm P-V, at which point it will be used for glass slumping trials.

3. Final Super-Smoothing

3.1 Principle of "Continuously Precessed" Bonnet

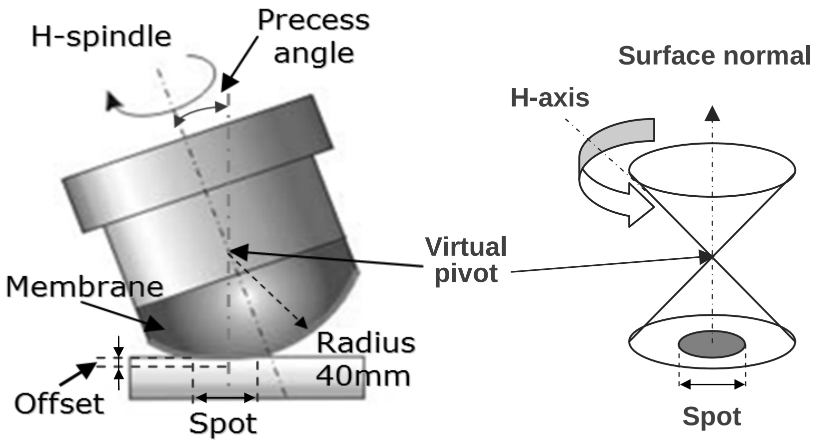


図9 Precessed Bonnet (left) and "Continuous Precessing" (right).

Rather than just rely on the usual "single precess" polishing regime described in previous literature, whereby the tool is precessed in a given direction for each polishing pass, a novel tool path control method called "continuous precessing" is introduced. In this method, show in Fig. 9 (right), the direction of the surface tangent used to compute the plane of precession of the spherical tool is allowed to spin around the centre of the polishing spot. This method prevents directionality of the polishing marks, as shown in Fig. 10.

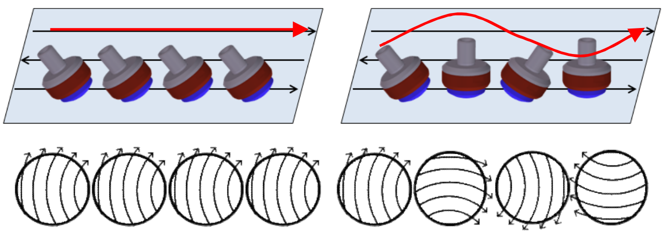


図10 Single (left) and Continuous Precessing (right) across Raster Tool Path.

3.2 Demonstration on Electroless Nickel

The 150 mm diameter sample previously polished by fluid jet was post-finished with the "continuous precess" method. Very fine slurry of 7 nm fumed silica particles mixed with pure water at a concentration of 20 g/L was fed above the bonnet with a disposable pipe connected to a peristaltic pump. To prevent drying and crystallization of the slurry on the work-piece surface, a series of pure water atomizers were arrayed around the bonnet to keep a high humidity level inside the polishing enclosure. It was possible to achieve a super-smooth anisotropic surface below 0.3 nm rms, as shown in Fig. 11 (right).

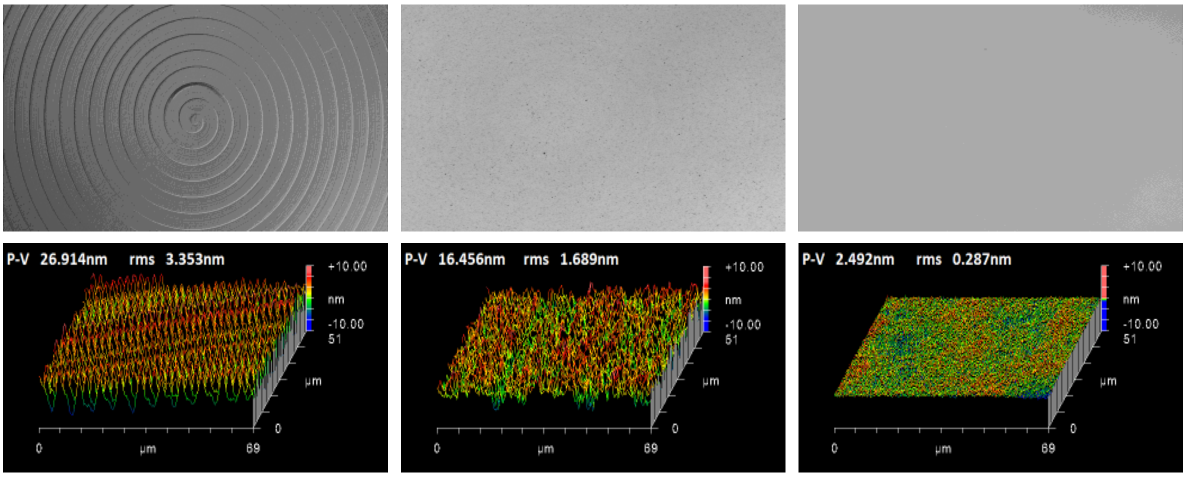


図 11　Surface texture after diamond turning (left), fluid jet polishing (centre), and continuous precess polishing with 7 nm abrasives (right).

4. Summary or Conclusions

Two process chains have been proposed for replication of thin aspheric mirrors in X-ray telescopes. But the applicability of these process chains to high energy, high angular resolution hard X-ray has been held back by lack of an automated method that can correctively finish aspheric molding dies down to a form error less than 50 nm P-V and super-smooth surface texture less than 0.3 nm rms. In this paper, a fully automated two-step finishing method deployed on a common 7-axis CNC platform was demonstrated, that can replace manual finishing.

In the case of the first process chain, fluid jet polishing was used to correctively polish Electroless Nickel down to 27 nm P-V. In the case of the second process chain, bonnet polishing was used to correctively polish Fused Silica down to 41nm P-V.

To bring molding dies to final super-smooth finish, a novel polishing method called "continuous precessing" was introduced, which produces surface texture free from any directionality. By applying this method with very fine 7 nm slurry, fluid jet polished surfaces can be improved down to less than 0.3 nm rms.

References

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