FABRICATION OF PARABOLIC WOLTER TYPE-I MOLDING DIE WITH 100 NM FORM ACCURACY

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1. INTRODUCTION

X-ray radiations are created in space by extremely high energy celestial events. Celestial objects such as supernova remnants, neutron stars, black holes, and clusters of galaxies can produce X-rays. 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 [1]. The discovery of this phenomenon called "grazing incidence" reflection led to the suggestion by Wolter in 1952 [2] of a number of optical configurations using confocal paraboloid and hyperboloid sections to focus X-ray radiations. The most practical is known as the Wolter type-I configuration and shown in Fig. 1.

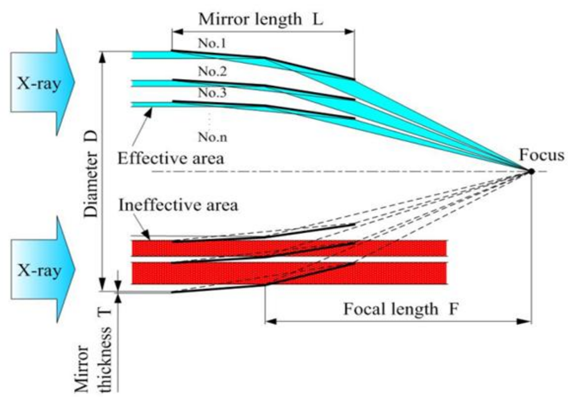

FIGURE 1. Wolter type-I configuration for grazing incidence X-ray imaging telescope.

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 [3] 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.

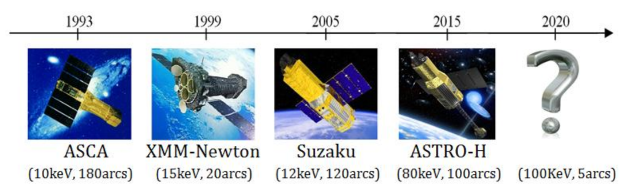

FIGURE 2. Past and future specifications of X-ray telescopes using replicated optics.

To meet this challenge, replication from optical molding dies has become the preferred method as it is economical and reliable. A few replication methods exist, amongst which replicating thin mirrors by slumping thin glass sheets (~0.2mm in thickness) across molding dies, under high temperature (see Fig. 3). This method was demonstrated in the case of the NuSTAR mission [4].

FIGURE 3. Slumping thin glass over Wolter Type-I molding die [4].

But the challenge of fabricating truly aspheric Wolter type molding dies, capable of highly accurate angular resolution (below 5 arcs), remains very expensive and time consuming. In this paper, the fabrication of a fused silica aspheric molding die using precision grinding and corrective polishing technology is reported in details.

2. METHODOLOGY

In order to produce a demonstration parabolic molding die with focal length 8.4m, a block of fused silica was precision ground in industry to the approximate freeform shape (see Fig. 4). The shape deviation after grinding was then measured with a UA3P Ultra-Precise Coordinate Measurement Machine.

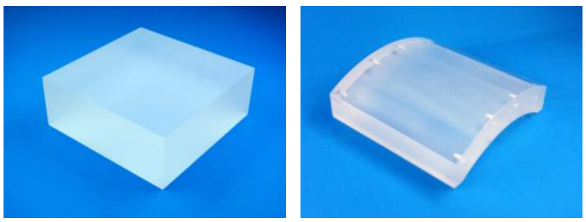

FIGURE 4. Block of fused silica, before and after grinding of the freeform shape.

A special measurement jig was made (see Fig. 5), to create a reference frame attached to the physical centre and orientation of the molding die (by intersecting lines passing through the centers of 4 silicon nitride balls).

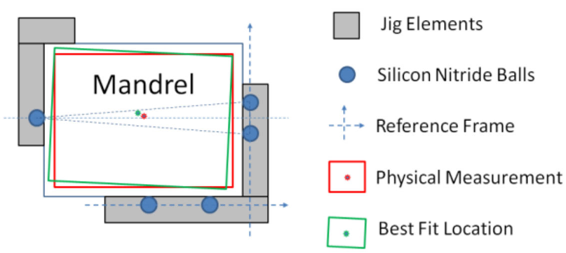

FIGURE 5. Jig referencing the best fitted error.

The centre point was then referenced against this frame using a 5th ball on the opposite side of the molding die (used to measure the exact width and length, which were then divided by 2). The jig and molding die were measured with a UA3P CMM at Panasonic in Osaka (see Fig. 6, left).

After determining the relative location of the best fitted error, this information was input into numerical optimization software that combined it with data about polishing removal rates to derive deterministic tool paths capable of reducing the form error. This tool path was run on a Zeeko 7-axis CNC machine (see Fig. 6, right).

FIGURE 6. Molding die being measured inside UA3P (left), and polished inside Zeeko CNC machine (right).

The Zeeko machine implements an innovative CNC polishing process based on tool precession which has been described in the literature [5-6] at various stages during its development. We summarize the operation of the process as follows: 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. While a classical polishing tool is pressurized against the surface of the part, with no attempt to control actively the Z position of the tool in a local or global coordinate frame, in the technique we describe the Z position and precession (but not directly the contact-force) are actively controlled with a CNC machine tool.

Fig. 7 shows the seven CNC-controlled axes available on the polishing machine: three axes of translation (X, Y, Z), two axes of rotation intersecting at a virtual pivot point (A, B), and two rotation spindles (H, C). It is possible to numerically control the precess angle, spindle speed, geometrical offset, and surface feed of the polishing spot to obtain variations in spot size and removal rate.

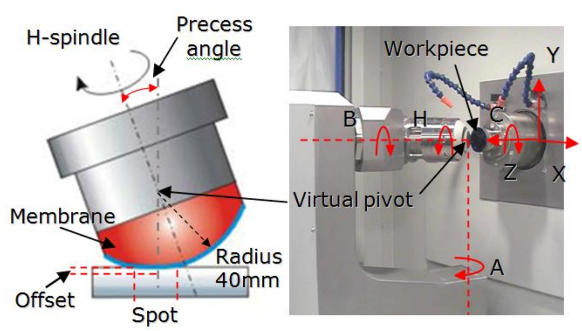

FIGURE 7. Principle of precessed polishing tool and 7-Axis CNC machine.

Additional experiments on flat fused silica substrate were also carried out using finer 0.5 µm cerium oxide abrasives, in order to estimate the best achievable finish condition on this material [6]. The results from these experiments will be used to further improve the surface finish of the actual molding die.

3. FABRICATION RESULTS

The molding die was correctively polished by iterations, using the process parameters shown in Table 1. The initial form error of the ground molding die was 36.7um P-V, as shown in Fig 8, left. The surface feed was moderated between 100 and 3000 mm/min in order to improve form. The result after 3 and 6 iterative corrections are also displayed in Fig. 8 (centre and right). The final improvement in 3D form error after the 6^{th} correction was down to 155 nm P-V.

Since the most critical direction for X-ray imaging optics is along the optical axis, a series of 10 slices were also taken along the Y-direction of the final 3D error map. The resulting profiles are shown in Fig. 9. Assessment over a 150 mm section shows an overall 2D form error of 92 nm P-V, and assessment over a 100 mm sub-section shows the 2D form error down to 49nm P-V.

Simulations for a pair of mirrors replicated from molding dies with such residual form error confirm that the overall angular resolution would be below the 5 arcs target.

TABLE 1. Process parameters of corrective polishing runs.

Workpiece	Fused Silica
Polishing tool Radius Cloth	Precessed bonnet 40 mm Poromeric felt
Tool-path mode Track spacing Tool offset Head speed Precess angle Surface feed	Raster 0.5~1.5 mm 0.6 mm 2000 rpm 20 deg 100~3000 mm/min
Abrasives Grain size Density	Cerium Oxide (CeO_2) 1.5 µm 60g/L

The micro-roughness after form correction was measured using a white light interferometer at 50x resolution. After removal of 4^{th} order terms, the 0.6 nm rms observed is adequate for slumping (see Fig. 10).

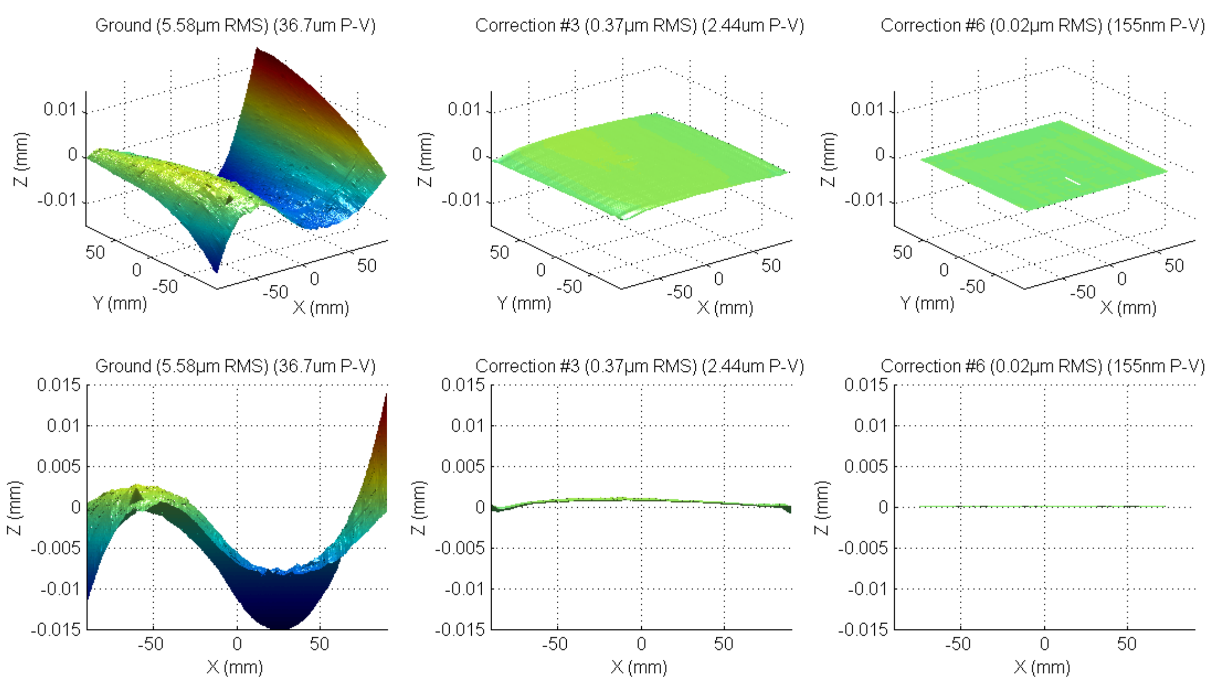

FIGURE 8. 3D form error from aspheric design, at various stages of fabrication.

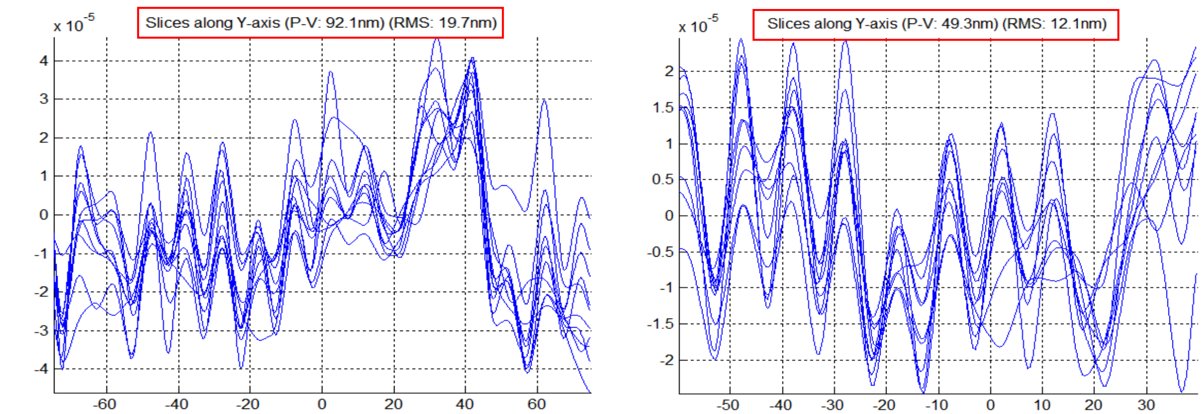

FIGURE 9. 2D form error along the optical axis, across 150 mm (left) and 100 mm (right) sections.

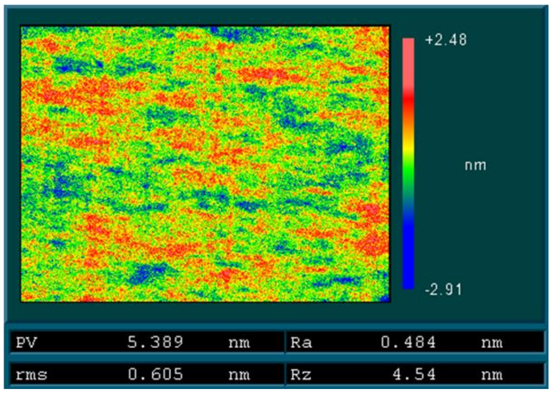

FIGURE.10. Micro-roughness (0.6nm rms).

For other replication methods such as thermal forming, which was demonstrated in the case of ASTRO-H [6], smoother micro-roughness down to 0.3 nm rms is required. A series of experiment was conducted on plano fused silica glass using finer 0.5 µm cerium oxide abrasives. The results were reported in the literature [6], and show that micro-roughness down to 0.3 nm rms (as measured by Atomic Force Microscope) is achievable on fused silica (see Fig. 11).

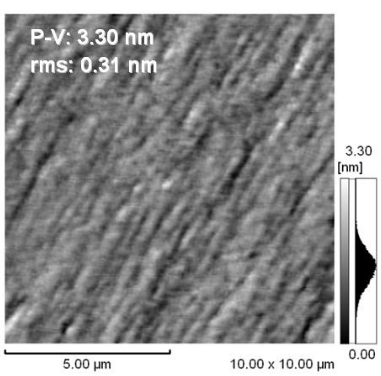

FIGURE.11. Achievable micro-roughness on fused silica using 0.5 µm CeO2 (0.3nm rms) [6].

4. CONCLUSION

In this paper, progress on the fabrication of molding dies for replication of thin hard X-ray mirrors with angular resolution less than 5 arcs was reported. An aspheric fused silica molding die was ground and correctively polished from ~36 µm down to less than 0.1 µm P-V of shape deviation along the optical axis. The intermediate surface roughness of 0.6 nm rms is adequate for replication by slumping method. The molding dies will be further smoothed down to 0.3 nm rms for application to other replication methods such as thermal forming.

ACKNOWLEDGEMENTS

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