Advanced fabrication technologies for ultraprecise replicated mirrors for x-ray telescopes

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Advanced fabrication technologies for ultraprecise replicated mirrors for X-ray telescopes

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ABSTRACT

For many years, Wolter mirrors have been used as imaging elements in X-ray telescopes. The shape error of Wolter mirrors fabricated by replicating the shape of a mandrel originates from the replication error in electroforming. We have been developing an X-ray focusing mirror for synchrotron radiation X-rays, as well as a high-precision electroforming process. In this paper, we report on the application of the advanced electroforming process to the fabrication of Wolter mirrors for the FOXSI Sun observation project. We also discuss the figuring accuracy of the mandrel.
Keywords: X-ray optics, X-ray mirrors, X-ray telescopes, electroforming

1. INTRODUCTION

The optical imaging elements used in X-ray telescopes, such as Chandra[1] and XMM-Newton[2], are Wolter mirrors[3]. A Wolter mirror consists of a parabolic mirror and a hyperbolic mirror that both reflect X-rays, satisfying the Abbe sine condition. The manufacturing processes for Wolter mirrors are divided into two types. The mirrors used in XMM-Newton were fabricated by electroforming of ultraprecise mandrels. The mirrors used in Chandra were fabricated not by replication but by ultraprecision machining with measured profiles. The Wolter mirror has also been used in X-ray microscopy. Aoki et al. constructed X-ray microscopes using small Wolter mirrors and conducted various pioneering studies over the years[4-6]. These microscopes are constructed by combining Wolter mirrors and several types of X-ray sources, such as synchrotron radiation X-rays and laser plasma X-rays. Another small Wolter mirror was made by the replica method, in which molten glass was imprinted on a metal mandrel[7].

As a different technology, Kirkpatrick-Baez (KB)[8] mirrors were developed to focus hard X-rays in the synchrotron radiation field. KB mirrors realize nano-focusing of hard X-rays below the diffraction limit[9-12]. Although KB mirrors consist of vertical and horizontal focusing mirrors, an ellipsoidal mirror can focus X-rays in two dimensions with a single reflection, but improvement of the figuring accuracy is necessary for use in X-ray microscopy. We established an ellipsoidal mirror fabrication process employing mandrel fabrication and electroforming[13,14], and successfully focused soft X-rays onto a spot several hundred nanometers wide[15-17]. A small Wolter-type mirror was also fabricated for imaging soft X-rays with a spatial resolution of 200 nm[18].

In this study, we applied the previously developed fabrication process to Wolter mirrors for X-ray telescopes. The first target is a Wolter mirror to be used for FOXSI[19], a project for X-ray observation of the Sun. The Wolter mirror has a diameter of 60 mm and a length of 200 mm. In this paper, we report on the replication accuracy of the electroforming system specially developed for this project and the accuracy of the latest mandrel fabricated by Natsume Optical Corporation.

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2. OVERVIEW OF ROTATIONALLY SYMMETRIC MIRRORS FOR X-RAY MICROSCOPY

We have been developing focusing and imaging systems for soft X-rays in the wavelength range of 1 to 10 nm for the last 10 years. Figure 1 shows an illustration of the optical system for focusing soft X-rays with an ellipsoidal mirror. The two focal points of the elliptic function are the source and the collecting point of X-rays. The soft X-rays from the light source are reflected by the inner surface of the ellipsoidal mirror and are focused at the focal point. The diameters of the ellipsoidal mirrors fabricated in our studies were from 5 to 10 mm.

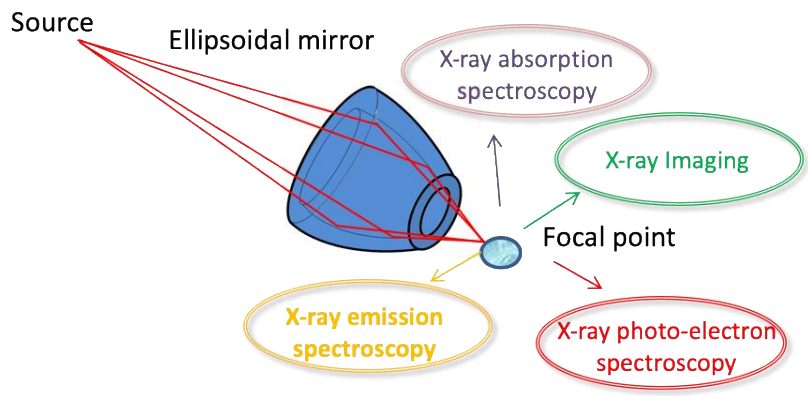


Figure 1. Optical system for focusing soft X-rays with an ellipsoidal mirror

To fabricate high-precision mandrels, we developed a figuring correction system using elastic emission machining[20], organic abrasive machining[21], magneto-rheological finishing[22,23], and shape measurement methods using laser probes with a resolution of 1 nm[13]. The mandrels have a root mean squared accuracy of several nanometers. In the figuring correction system based on the measured profile, the final figuring accuracy is determined by the figuring measurement method, because the employed processing methods have a depth controllability of about 1 nm. When the mandrel material is quartz glass, a root mean squared surface roughness on the order of 0.1 nm can be easily obtained.

Figure 2 shows the electroforming process. Nickel electrodeposition is performed in a nickel sulfamate solution bath. The electrode layer is formed on the mandrel surface by electron beam deposition. Nickel electrodeposition is carried out at room temperature to suppress the thermal deformation of the electrodeposited products after separation. The electrodeposition conditions are optimized to obtain a high replication accuracy. Because the thermal expansion coefficients of quartz glass and nickel are significantly different, these materials can be easily separated simply by dipping them in warm water.

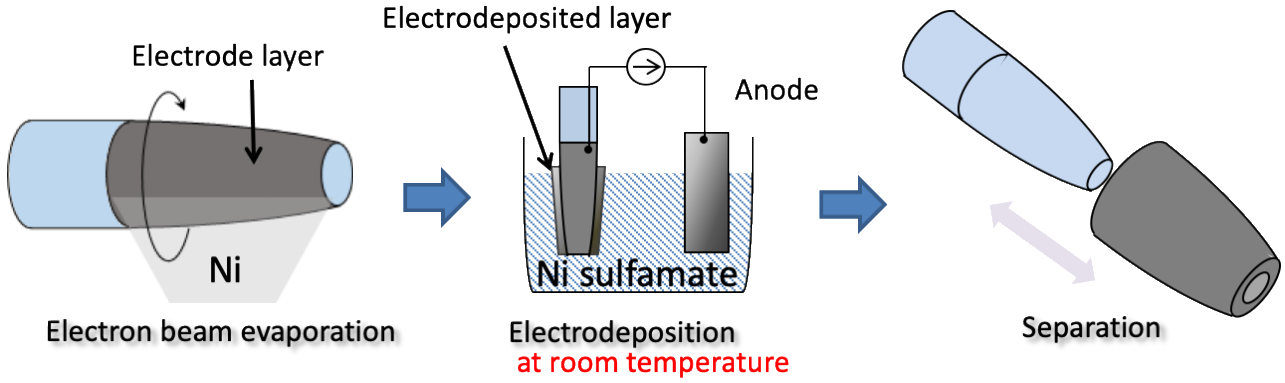


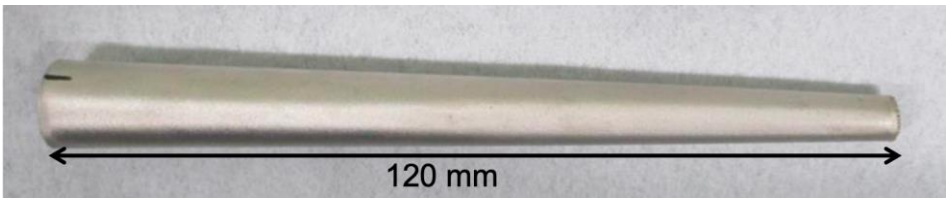
Figure 2. Electroforming process

Figure 3 shows photographs of the mandrel and the fabricated elliptical mirror. The roundness of the inner surface of the ellipsoidal mirror can be easily evaluated by a commercial roundness measurement device. The replication accuracy was demonstrated to be about 30 nm from profiles in the circular direction[14].

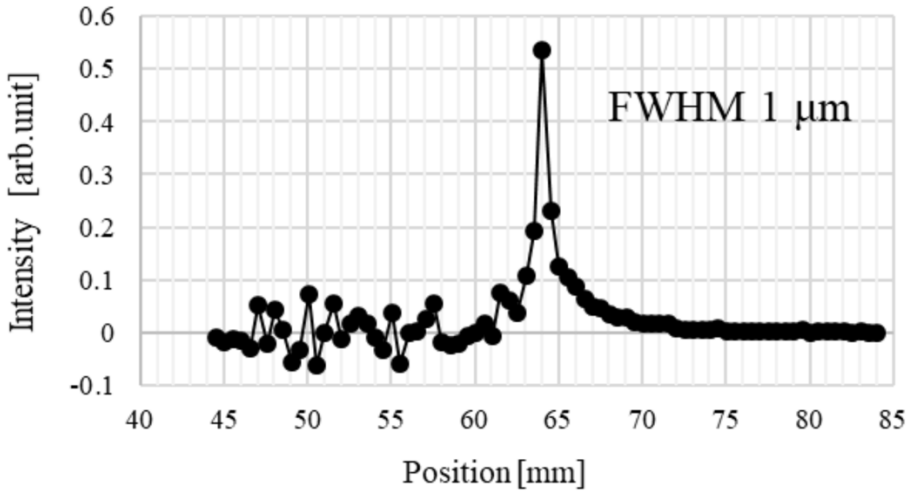
(a) (b)

Figure 3. Photographs of (a) the mandrel and (b) the fabricated elliptical mirror

The mirrors we fabricated have been used for focusing soft X-rays in a beamline with high-order harmonics[15], a synchrotron radiation facility[13,17], and an X-ray free-electron laser facility[16]. Here we show an example of soft X-ray focusing at the SPring-8 synchrotron facility. The optics and the focusing profile are for focusing 300-eV soft X-rays using an ellipsoidal mirror 120 mm long[24]. The soft X-rays are focused onto a spot less than 1 μm wide. This result indicates high accuracy in both mandrel fabrication and electroforming replication. Recently, we have also succeeded in focusing 500-eV soft X-rays down to 100 nm using a two-stage focusing system[25]. Currently, small replicated nickel focusing mirrors are commercially available.



(a)



(b)

Figure 4. (a) Photograph of 120-mm-long ellipsoidal mirror. (b) Beam profile at the focal point obtained by the knife-edge scanning method.

3. WOLTER MIRRORS FOR X-RAY TELESCOPES

During the development of mirrors for focusing X-rays, high replication accuracy was achieved. By using electrodeposition at room temperature, we expect to improve the figuring accuracy for a Wolter mirror large enough for an X-ray telescope. We conducted an electroforming test using a cylindrical glass rod with a diameter of approximately 60 mm, as shown in Fig. 5, and confirmed a roundness replication accuracy of approximately 2 μm. From this result, the development of a large Wolter mirror was started for X-ray telescopes. The first target is a Wolter mirror with a diameter of 60 mm, a length of 200 mm, and a focal length of 2 m for FOXSI. The optical system is shown in Fig. 6. Because all the processing systems were designed for mirrors with a diameter of about 10 mm, it was necessary to develop processing, measurement, and electrodeposition equipment for a larger Wolter mirror. In this project, Nagoya University designed and evaluated the Wolter mirror, Natsume Optical Corporation in Japan developed the mandrel fabrication technology, and the University of Tokyo developed the electrodeposition process.

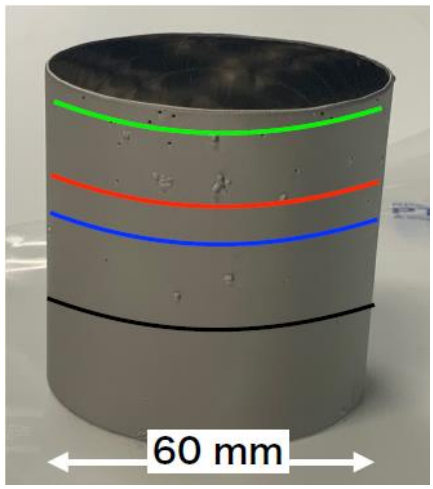


Figure 5. Cylindrical replica with a diameter of approximately 60 mm

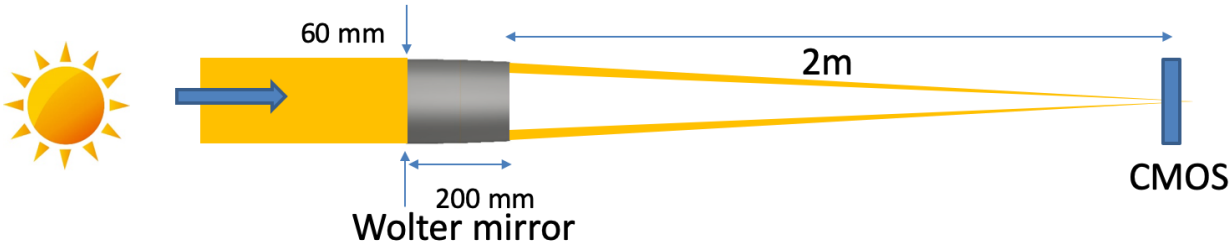


Figure 6. Optical system on-board FOXSI 4

4. FABRICATION OF WOLTER MIRROR FOR FOXSI 4

4.1 NEW ELECTRODEPOSITION SYSTEM

Figure 7 is a photograph of the newly developed electrodeposition apparatus. Nickel electrodeposition at room temperature is accompanied by hydrogen generation. When the electrolyte is depressurized, the bubbles become large and are removed by buoyancy. Therefore, nickel electrodeposition is performed in a vacuum chamber. To obtain a uniform thickness of the deposited product, the current distribution must be uniform. Therefore, the electrode structure was optimized. The electric field distribution in the electrolyte is calculated by the commercial software COMSOL. Figure 8 indicates good agreement between the calculated current density distribution on the mandrel and the measured thickness of the electrodeposited product.

Figure 7. Electrodeposition apparatus, in which the nickel electrodeposition bath is placed in a vacuum chamber

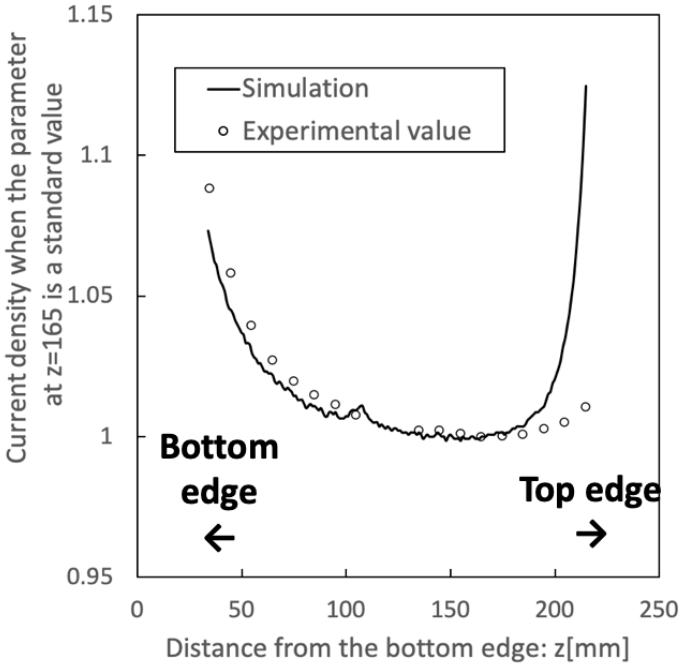
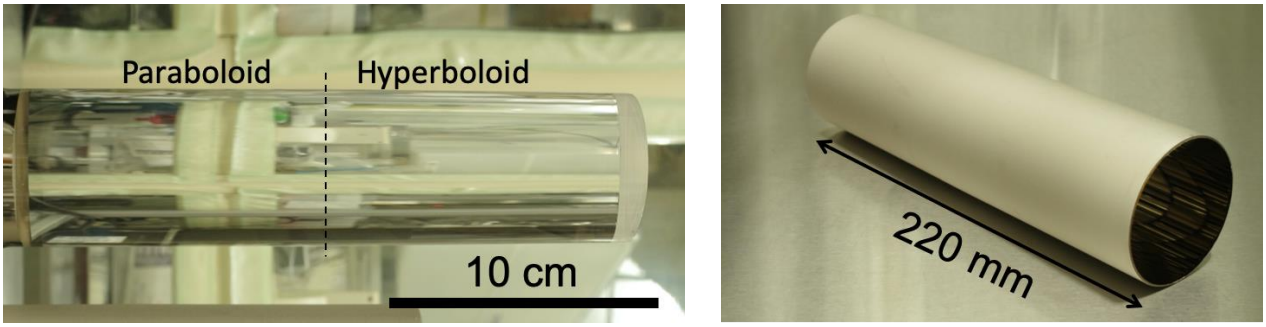


Figure 8. Comparison between the calculated current density distribution on the mandrel and the measured thickness of the electrodeposited product

4.2 REPLICATION ACCURACY

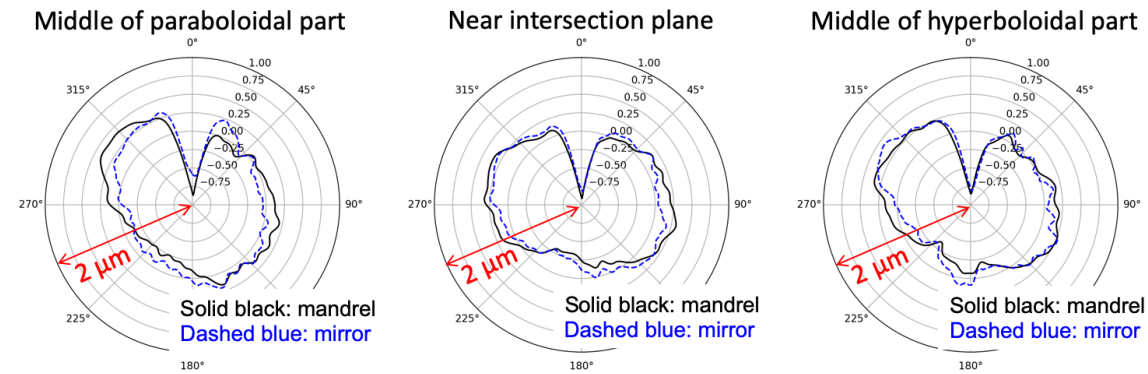
A mirror with a diameter of 60 mm and a length of 200 mm was fabricated by the process shown in Fig. 2. Photographs of the fabricated mandrel and replicated mirror are shown in Fig. 9. The mandrel used in the evaluation of the replication accuracy had a shape error of several micrometers.

The surface profile for the mandrel and mirror were compared. Figure 10(a) shows a comparison of the circumferential profiles of the mandrel and mirror. Figure 10(b) compares the two longitudinal profiles. They were measured using the high-precision roundness measuring device developed for small mirrors. The two profiles in the circular and longitudinal directions agree well at the 100-nm level. The measurement method must be improved for more detailed evaluation. However, this result indicates that the electroforming process also has sufficiently high replication accuracy for a large mirror.

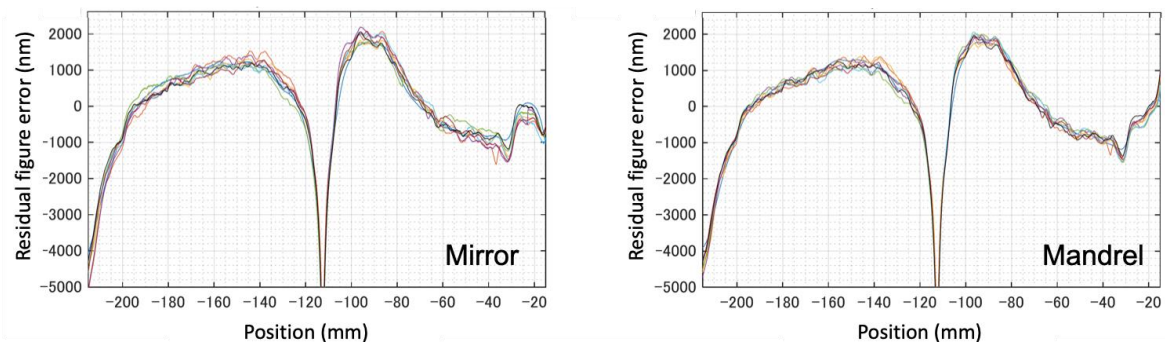


(a) (b)

Figure 9. Photographs of the (a) mandrel and (b) fabricated Wolter mirror



(a)

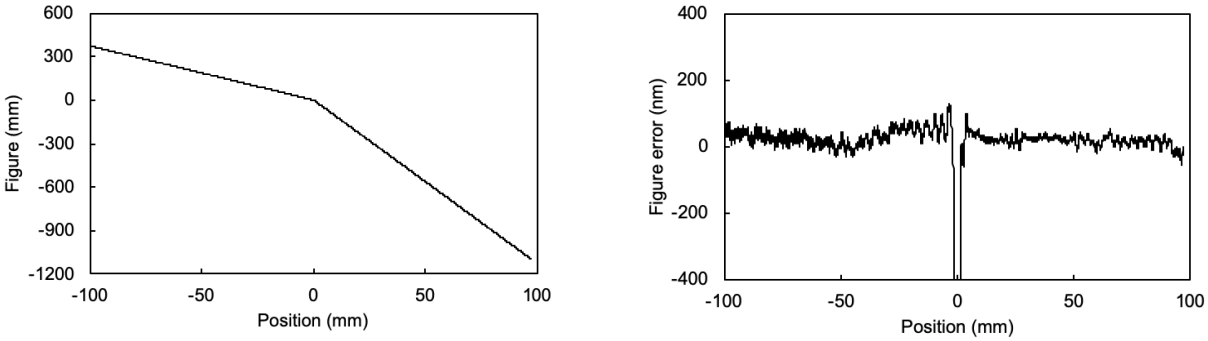


(b)

Figure 10. (a) Circumferential profiles of the mandrel and mirror. (b) Longitudinal profiles of the mandrel and mirror.

4.3 MANDREL FABRICATION

Currently, the figuring accuracy of the mandrel is being improved. Figure 11 shows the figuring error profile and the surface roughness for a recently fabricated mandrel. The longitudinal profile has an error of only about 100 nm from peak to valley over the whole surface. Mandrel fabrication involves a combination of conventional polishing techniques and an advanced figuring correction method. Because the removal depth in figuring correction can be controlled at the level of 1 nm, the accuracy of the mandrel is determined by the accuracy of the measurement system.



(a) (b)

Figure 11. Mandrel longitudinal profiles:
(a) cross-sectional surface figure profile and (b) residual figuring error profile.

5. DISCUSSION AND FUTURE PLANS

After a few mirrors were fabricated, we recognized problems to be solved in the developed process for fabricating large mirrors. We plan to fabricate a Wolter mirror using a high-quality mandrel by the spring of 2021. The mirrors will be evaluated with X-rays at SPring-8. To improve the electrodeposition process, we will fabricate several mirrors while changing the electrodeposition conditions. The relationship between the electrodeposition conditions and the replication accuracy will be investigated. Evaluation of the mandrel shape is still now difficult. We will collaborate with several institutions in Japan to conduct multifaceted evaluations. Then, we will also start the development of our metal deposition method for Wolter mirrors.

With these improvements, we plan to be able to supply a high-performance Wolter mirror for FOXSI by the end of 2021.

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