Ultra-Precision Machining of X-Ray Telescope Mirrors

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Astronomers have developed their own astronomical telescopes for more than 400 years from visible light to X-ray. X-ray telescopes, which are used for the observation with the shortest wavelength among the astronomical telescopes, require reflectors with the highest shape accuracy and smooth surfaces because of the short wavelengths to be observed. The final mirror specifications are less than 100 nm shape accuracy and less than 0.3 nm rms surface roughness on aspheric reflectors coated on light aspheric substrates with metals or Pt/C multilayers. Ultra-precision machining is the most important key technology for development of X-ray telescopes. The X-ray telescopes launched in space and that in the planning stage will also be discussed from the ultra-precision machining point of view.

1. Introduction

The German X-ray astronomy satellite, Roentgen Satellite (ROSAT)[1], which was launched on 1 June 1990, reentered Earth's atmosphere above the Indian Ocean on 23 October 2011. This news attracted global attention because the zero-expansion glass-ceramic mirrors and the carbon-fiber-reinforced composite supporting the mirrors, weighing a total of 1,600 kg, would fall to Earth without burning up.

Although the light from stars flickers because of atmospheric turbulence, visible light (VL) is emitted from stars and reaches Earth as shown in Fig. 1. However, only VL, some infrared rays (IRs), and radio waves can be observed on Earth because of atmospheric absorption. It is extremely difficult to observe the remaining signals, such as IRs, ultraviolet rays (UVs), X-rays, and gamma rays, from Earth. Figure 1 shows the relationship between the appropriate altitude above ground level for astronomical observation (at atmospheric pressure) and the absorption of electromagnetic waves arriving from elsewhere in the universe. The solid line indicates the altitude at which the arriving electromagnetic waves are attenuated 100-fold by atmospheric absorption. Namely, astronomical observation is difficult owing to atmospheric absorption at altitudes lower than that indicated by the solid line. To avoid the absorption of electromagnetic waves and the effect of atmospheric turbulence, astronomical observation has started to be carried out in space. ROSAT was used for astronomical observation in space in the 1990s, which has provided many research achievements thus far.

Ever since the astronomers, Galileo Galilei and Isaac Newton, developed their own astronomical telescopes, astronomy has evolved along with the development of astronomical telescopes. X-ray telescopes, which are used for the observation with the shortest wavelength among the astronomical telescopes, require reflectors with the highest shape accuracy and

smooth surfaces because of the short wavelengths to be observed. Therefore, ultraprecision machining is required. In this report, examples of ultraprecision machining from the viewpoint of the fabrication of recent X-ray telescopes are overviewed.
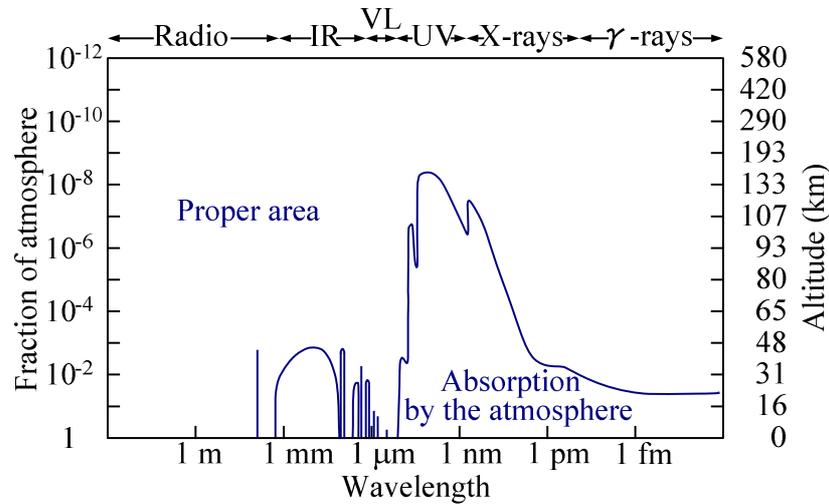

Fig. 1 Altitude appropriate for observation of electromagnetic waves arriving from space.

2. Soft X-ray telescopes currently in service

In 1962, Riccardo Giacconi and his colleagues discovered a cosmic X-ray source by observation using a rocket-borne X-ray detector[2]. In Japan, Satio Hayakawa of Nagoya University successfully observed cosmic X-rays using rockets in 1965. After that, Japan, the USA, and European countries launched many X-ray astronomy satellites. Currently, three soft X-ray satellites are orbiting Earth: the Chandra X-ray observatory[3] developed by the National Aeronautics and Space Administration (NASA), USA (launched in July 1999; effective area, 500 cm^2; weight of telescope, 1,500 kg; resolution, 0.5 arcsec), the X-ray multi-mirror (XMM)-Newton[4] developed by the European Space Agency (ESA) (launched in December 1999; effective area, 4,000 cm^2; weight of telescope, 1,320 kg; resolution, 15 arcsec), and the X-ray astronomy satellite Suzaku[5] developed by the Japanese Aerospace Exploration Agency (JAXA) (launched in July 2005; effective area, 1,400 cm^2; total weight of four telescopes, 80 kg; resolution, 2 arcmin). With these satellites, grazing incident X-rays are totally reflected on the inner wall of conical foil mirrors and focused to form images, as shown in Fig. 2. The satellites adopt a grazing incidence optical system, which includes two reflections, called a Wolter type I (Wolter-I) optical system, consisting of paraboloid (first reflection) and hyperboloid (second reflection) surfaces. A single-layer mirror of Ir or Au with 0.5 nm rms surface roughness is coated on the reflecting surfaces.

For the Chandra X-ray telescope, a zero-expansion glass-ceramic (Zerodur) substrate with a coefficient of thermal expansion of 10^{-8} and a thickness of 25.4 mm is used as the conical reflector substrate, enabling smooth aspherical polishing of the inner surface with high shape accuracy. A single Ir layer is formed on the thus obtained surface. Therefore, the reflector has high machined rigidity, thermal rigidity, and high shape accuracy of its surface, achieving

the highest imaging performance among the currently available telescopes. However, it has some disadvantages such as a small surface area where X-rays can be reflected relative to its weight and the necessity of a long polishing time.
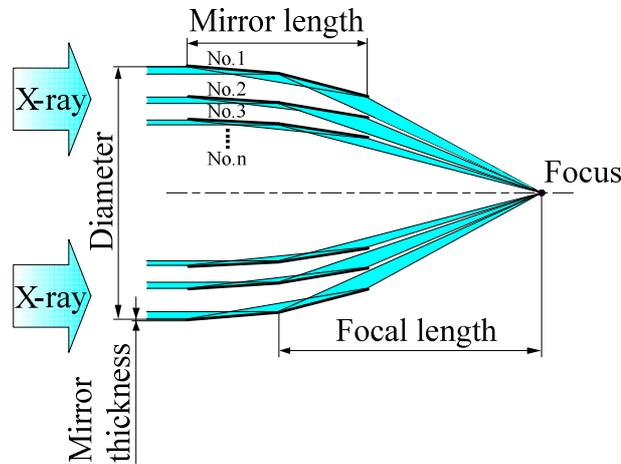
Fig. 2 Structure of Wolter-I grazing incidence X-ray telescope.

For the XMM-Newton X-ray telescope, a high-precision smooth-surface Wolter-I mandrel was fabricated by ultraprecision diamond turning followed by optical polishing of the aspherical aluminum mandrel coated with electroless Ni. The obtained surface was then coated with a Au layer and electroformed with a 1-mm-thick Ni layer. The material was separated at the boundary between the mandrel and the Au layer to form a thin Ni shell, the inner shell of which was coated with a Au layer as shown in Fig. 3. By this method, a high-precision X-ray mirror with an aspherical surface coated with a Au layer was obtained using the 1-mm-thick Ni shell as a substrate. However, the reflector obtained by this method was heavy because Ni was used as the material of the reflector substrate.

For the Suzaku X-ray telescope, a Au film was formed on a commercially available glass tube, to which aluminum foil bent into a cone was glued. The aluminum foil was then removed to form a reflector, resulting in conical approximation of the Wolter-I optical system. This method can be used to fabricate many lightweight reflectors by a simple process; however, the imaging

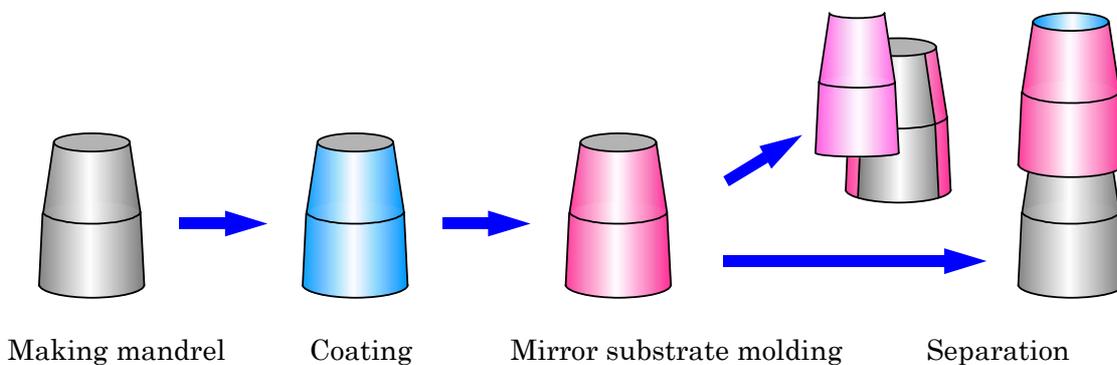Making mandrel   Coating   Mirror substrate molding   Separation

Fig. 3 Manufacturing process of replicated X-ray mirror.

performance is inferior to that of the previous two telescopes because of the low shape accuracy of the reflector.

3. Hard X-ray telescopes currently under planning phase X-ray astronomy satellite, ASTRO-H[6]

JAXA, in cooperation with NASA and ESA, carries out high-precision spectrometry, hard X-ray imaging observation, and observation over a broad energy range of 0.03-600 keV to explore the surroundings of black holes and the extremely distant universe, which is full of high-energy phenomena such as supernova explosions, as well as to observe galaxy clusters filled with high-temperature plasma.   To explore the structure of the universe and its evolution through such observations, in August 2014, JAXA plans to launch an X-ray astronomy satellite ASTRO-H[7] (Fig. 4) (length, 14 m; weight, 2,700 kg) to an altitude of 550 km using the JAXA H-IIA rocket.   The scientific instruments planned to be mounted include two hard X-ray telescopes (HXTs), two soft X-ray telescopes (SXT-S, SXT-I), two hard X-ray imagers (HXI), a soft X-ray spectrometer (SXS), an X-ray charge-coupled device (CCD) camera (SXI), and a soft gamma ray detector (SGD).

The design parameters of the SXTs are as follows: diameter, 450 mm; focal length, 5.6 m; number of reflectors, 203; effective area at 6 keV, 312 cm^2; resolution, 1.3 arcmin.   The reflectors consist of an aluminum substrate coated with a single Au layer.   The technology used for this telescope is essentially an extension of that used for Suzaku.   This time, however, the telescopes were developed by NASA.
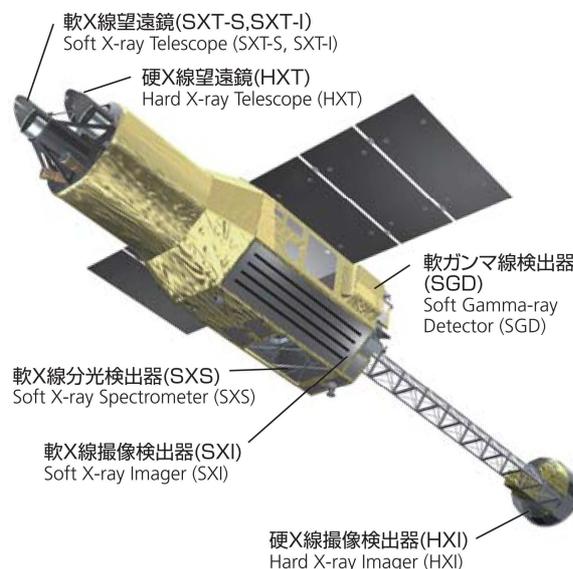

軟X線望遠鏡(SXT-S,SXT-I)
Soft X-ray Telescope (SXT-S, SXT-I)

硬X線望遠鏡(HXT)
Hard X-ray Telescope (HXT)

軟ガンマ線検出器
(SGD)
Soft Gamma-ray
Detector (SGD)

軟X線分光検出器(SXS)
Soft X-ray Spectrometer (SXS)

軟X線撮像検出器(SXI)
Soft X-ray Imager (SXI)

硬X線撮像検出器(HXI)
Hard X-ray Imager (HXI)

Fig. 4 Rendering image of ASTRO-H[7].

The HXTs of ASTRO-H employ a conically approximated Wolter-I multilayer grazing incidence optical system.   The design parameters of the HXTs are as follows: aperture, 450 mm; focal length, 12 m; mirror length of each stage, 200 mm; thickness of the aluminum substrate, 0.22 mm; effective area at 30 keV, 338 cm^2; resolution, 1.7 arcmin.   The 213 reflector shells with

different diameters are coaxially nested, and each shell is divided into three segments in the azimuthal direction. There are two stages used for two reflections; thus, 1278 reflectors are required to build each HXT.

In the soft X-ray region of 10 keV or less, X-rays can be reflected and focused by total reflection using reflector substrates coated with a heavy metal. However, in the hard X-ray region of 10 keV or higher, total reflection on a single-layer mirror cannot be used. In this region, an X-ray multilayer mirror with an artificial periodic structure in which a heavy element (Pt) and light element (C) layers with a nanometer-order thickness are alternately formed is used for Bragg reflection (Fig. 5(a)). The reflectivity of the mirror depends on the following factors: the elements selected for the layers, the periodic length, the precision of the layer thickness, the interfacial roughness, and the presence/absence of diffusion layers. As shown in Fig. 6, high reflectivity is obtained for a limited incident energy range because the periodic length of the multilayer mirror is constant. With the HXTs, hard X-rays with a broad energy range of up to 80 keV must be reflected to form images. Therefore, Pt/C multilayer supermirrors are adopted,[8-10] in which the periodic length is varied in the depth direction to induce Bragg reflection and broaden the range of reflection energy (Fig. 5(b)).

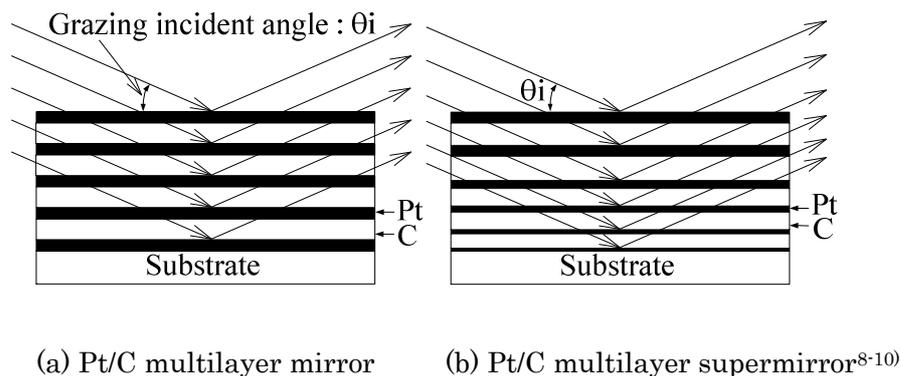(a) Pt/C multilayer mirror   (b) Pt/C multilayer supermirror[8-10]

Fig. 5 Structure of hard X-ray multilayer mirror.

Figure 6 shows the relationship between the reflectivity and incidence energy of X-rays in the case of a Pt single-layer mirror, a Pt/C multilayer mirror, and a Pt/C multilayer supermirror. As shown in the figure, the reflectivity of the Pt/C multilayer mirror is extremely high for a limited energy range, whereas the reflectivity of the Pt/C multilayer supermirror is sufficiently high over a broad energy range although the peak of the reflectivity is low.

The hard X-ray reflectors used in the HXTs are fabricated by the replication method. The surface of a glass pipe is coated with a Pt/C multilayer to form the supermirror, onto which an aluminum substrate is glued, and then the aluminum substrate is released to fabricate a very lightweight replication reflector[9,10].
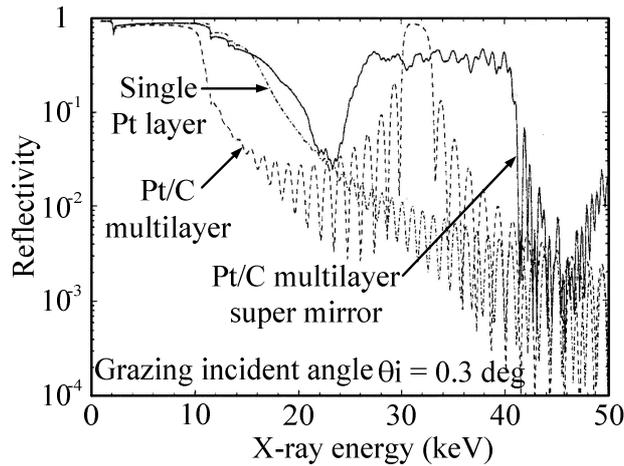
Fig. 6 Relationship between reflectivity and incidence energy of X-rays.

The periodic length of the Pt/C multilayer supermirror used in the HXTs varies between 2.4 and 13.64 nm. The number of Pt/C pair varies between 10 and 138, depending upon the position of the shell. The coating onto the surface of the glass-pipe mandrel is carried out using a DC sputtering system (Fig. 7); Pt and C, used as targets, are precisely and alternately coated. By this coating process, Pt/C multilayers with a periodic length of 4 nm are formed, for example. The parameters of the sputtering system are controlled to achieve a tolerance of ±1% relative to the designed value by measuring the periodic length using X-rays. Thus, a tolerance of ±3% relative to the periodic length (4 nm) is realized, which indicates that the multilayer thickness with a periodic length of 4 nm is controlled within 0.1 nm.

Fig. 7   DC sputtering system used for HXTs (Nagoya University).

Figure 8 shows photographs of the glass-pipe mandrel (right) and the Pt/C multilayer supermirror (left) released from the mandrel.

Figure 9 shows the surface roughness of the conical Pt/C multilayer supermirror measured optically with NewView. The surface roughness is 0.261 nm rms. Figure 10 shows the surface roughness of the Pt/C multilayer supermirror measured by scanning probe microscopy

(SPM).　The surface roughness is 0.171 nm rms.　Therefore, the required surface roughness of the HXTs, i.e., 0.3 nm rms or less, is satisfied.

Fig. 8 Photographs of glass-pipe mandrel (right) and HXT reflector (Pt/C multilayer supermirror) released from mandrel (left).
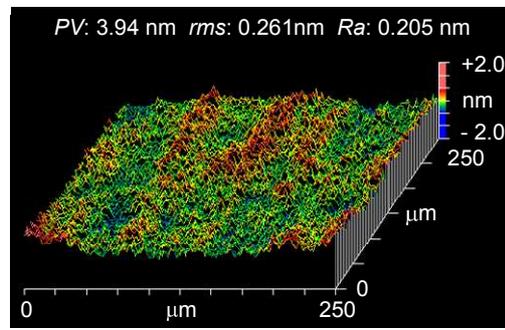

Fig. 9 Surface roughness of Pt/C multilayer supermirror measured with NewView.
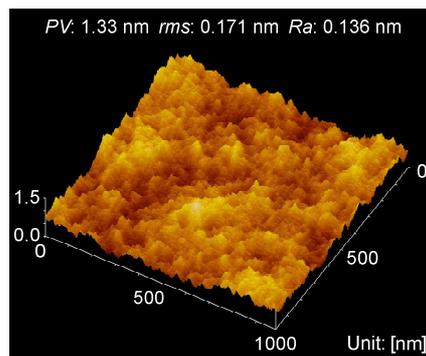

Fig. 10 Surface roughness of Pt/C multilayer supermirror measured by SPM.

Figure 11 shows the HXT housing, in which one-third of the circumference of each reflector with a length of 200 mm fabricated by the above process is housed.　The reflectors are aligned using the alignment bars.　The upper and lower stages form a conically approximated Wolter-I optical system.

Fig. 11   Schematic of assembled HXT reflector.

4. Nuclear Spectroscopic Telescope Array (NuSTAR)

For the Nuclear Spectroscopic Telescope Array (NuSTAR) [11, 12], which is planned to be launched by NASA in June 2012, commercially available 0.2-mm-thick liquid-crystal glass plates (surface roughness, 0.2 nm rms) are used as reflector substrates.   These thin glass plates are placed on optically polished cylindrical quartz mandrels with different diameters, which are then heated and softened in a furnace to shape the plates into mandrels.   The obtained system is referred to as segmented glass optics (SGO) [13]   (Fig. 12). On the surface of the 133 concentrically nested shells with different diameters, Pt/SiC and W/C multilayers are formed. This method is advantageous in the sense that the mandrel does not required a smooth surface because the surface roughness of the mandrel is not transcribed onto the shell, although the macroshape of the mandrel is transcribed.   The surface roughness of the liquid-crystal glass plates does not change even after thermal forming.   By this method, X-ray reflectors with high rigidity can be fabricated in a simple process without changing the multilayer forming conditions depending on the position of the reflector, although the imaging performance is reduced owing to the adoption of a conically approximated Wolter-I optical system.
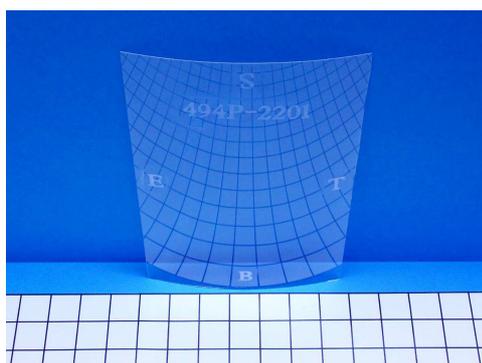

Fig. 12   A segmented glass substrate for NuSTAR.

5. International X-ray Observatory (IXO)/ATHENA

The International X-ray Observatory (IXO) [14] had been planned so that it would realize pioneering contributions to astrophysics in the 2020s.   This project combines the mission

concepts of both NASA's Constellation-X and the X-ray Evolving Universe Spectrometer (XEUS) planned by ESA and JAXA. The planned parameters of the X-ray telescope were as follows: aperture, 3.2 m; focal length, 20 m; effective area at 1.25 keV, 2.5 m^2; effective area at 6 keV, 1 m^2; effective area at 30 keV, 350 cm^2; resolution, 5 arcsec. The satellite with a total weight of 6,400 kg (weight of the reflector, 1,700 kg) was planned to be launched in 2022 to an altitude of 750,000 km using a rocket. However, ESA abandoned this cooperative development with NASA in March 2011 and decided to plan a new project, the Advanced Telescope for High Energy Astrophysics (ATHENA) [15].

The target energy of the new telescope is in the range of 0.1-40 keV and the focal length is 11.5 m. Grooves are made on the back side of a commercially available silicon wafer with a mirror finish (diameter, 300 mm; thickness, 1 mm) (Fig. 13). A conically approximated Wolter-I optical system called silicon pore optics (SPO) [16] will be fabricated by lamination while applying an external force to bend the wafer. Passing through the grooves, soft X-ra will be totally refected on the top surface of the coating, and hard X-rays will be Bragg reflected at the multilayers formed on the silicon surface. The structure of this reflector will have various advantages: not only will it have high rigidity but it will also have a high effective area per unit weight of the reflector. Therefore, ultraprecision polishing of the curved surface will not be necessary. The accuracy of the assembled laminated reflector will enable a resolution of 1 arcsec, and a resolution of 5 arcsec is assumed for the entire reflector.
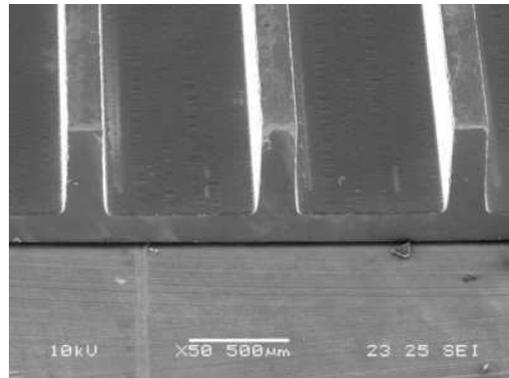

Fig. 13 Structure of back side of laminated silicon reflector[16] .

6. New proposals for HXTs

Efficient aspherical polishing is indispensable for the development of HXTs with a high imaging performance. For the HXTs explained above, the process of optical polishing, which was adopted for Chandra and XMM-Newton, will be avoided. Therefore, the shape of the reflectors will not be precisely those in a Wolter-I optical system but a conically approximated Wolter-I optical system. Conically approximated optical systems have a merit of ease of multilayer formation; however, the ultimate goal of the above-mentioned HXTs is the realization of a precise Wolter-I X-ray telescope with a precise aspherical shape. Therefore, the

next-generation HXTs should be fabricated using advances in aspherical surface-forming techniques and replication technologies used for soft X-ray telescopes. For example, an electroless Ni ultraprecise aspherical mandrel with a shape accuracy of ±50 nm or less and a surface roughness of 0.3 nm rms or less is formed by diamond turning and aspherical polishing. The Pt/C multilayer supermirror described above is formed on the obtained mandrel.   After the substrate is glued and cured, the Pt/C multilayer supermirror is released from the mandrel. Figure 14 shows aspherical mandrels with diameters of 300 and 500 mm consisting of paraboloid and hyperboloid surfaces fabricated using an ultraprecise aspherical polishing machine[17] that enables the machining of surfaces of up to 600 mm diameter.
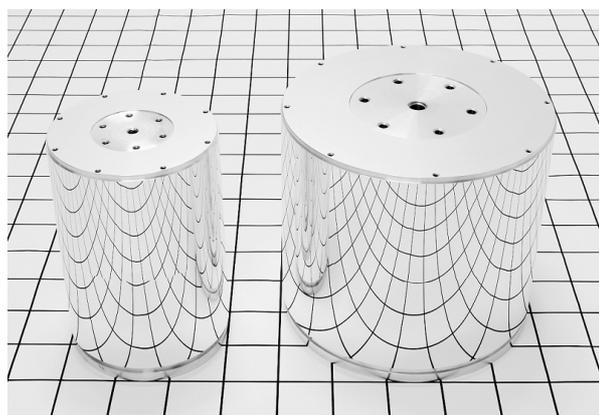

Fig. 14 Machined aspherical mandrels (diameters, 300 and 500 nm; mirror length, 400 mm) consisting of paraboloid and hyperboloid surfaces

High-precision lightweight aspherical reflectors can be fabricated by this method.   However, the shape accuracy of the mandrel is currently over ±50 nm.   An efficient polishing technique to suppress the surface roughness of the aspherical surface to 0.3 nm rms or less is currently under development[18,19].   Furthermore, techniques for fabricating a Pt/C multilayer supermirror with a nonuniform thickness along the generatrix of the mandrel, fabricating high-precision reflector substrates, and releasing the multilayer mirror from the mandrel have not been established. These problems should be resolved by the researchers involved in the manufacture of the reflectors.

7. Conclusions

To further advance Japanese X-ray astronomy, which is highly acclaimed worldwide, plans to launch an X-ray astronomy satellite ASTRO-H are underway as mentioned earlier.   ASTRO-H is a giant space structure with a total length of 14 m, meaning that obtaining a suitable balance between reducing the weight and increasing the performance (precision) is important.   An X-ray reflector that consists of 21-217 layers of Pt and C with a nanometer-order thickness alternately and nonperiodically stacked will be mounted on ASTRO-H.   A tolerance of ±3% in

the periodic length (4 nm), which is equivalent to a thickness accuracy of 0.1 nm (1×10^{-10} m), is expected to be realized.   Owing to this ultraprecise microstructure, we will be able to observe objects at a distance of 8×10^{25} m from Earth.   To enhance the international presence of Japan in this field with the background of cooperation and competition with European countries and the USA, we need to propose new HXTs based on our original ultraprecision machining technology.

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