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Fabrication of replicated aspheric Pt/C multilayer mirrors for hard X-ray microscopes

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Abstract
For making precision hard X-ray inner mirrors, aluminum alloy rods of A7075 were cut into ellipsoid-hyperboloid of revolution mirror mold surfaces of by single-point diamond turning (SPDT). Then, the aspheric molds were plated with an electroless nickel film of 0.11 mm thickness. The electroless nickel surfaces were cut by SPDT and polished manually to super smooth finish of less than 0.3 nm rms. In order to get the adequate release agent, various materials were tested. The aspheric molds were coated with very thin uniform titanium film as a release agent and coated with Pt/C multilayer super mirrors, where this technology was used for making hard X-ray telescopes launched in 2016 as ASTRO-H (Hitomi). The inner surface of a hollow cylindrical substrate was turned, and the coated mold was inserted into the a hole together with epoxy resin. The glued parts were immersed in icy water and released by utilizing the difference in thermal expansion. Whole circumference Pt/C multilayer aspheric inner mirrors of small diameter were successfully fabricated by this epoxy replication method.

Keywords: Single-point diamond turning, electroless nickel plating, polishing, release agent, Pt/C multilayer deposition, separation, epoxy resin

1. Introduction

Soft X-ray microscopes using Fresnel zone plates, normal incidence multilayer mirrors [1] or grazing incidence mirrors [2-5] have been used to observe biological cells in near natural environments.

The grazing incidence optic in an X-ray microscope is based on the total reflection of X-rays from a smooth surface. One well-known grazing incidence optic is the Wolter type I mirror which is composed of two coaxial, confocal ellipsoidal and hyperboloidal surfaces of revolution as shown in Figure 1. An X-ray source is at F_{e1} and the X-rays passing through the mirror are focused at F_{h1}. In the hard X-ray region, the Bragg reflection is more effective than the total reflection used in the soft X-ray region [6]

Unlike X-ray telescopes, X-ray microscope mirrors have the following problems on production due to their size; (1) high precision machining of an elongated inner diameter, (2) precise figure measurement on inner surface, (3) precise polishing on aspheric inner surface, (4) precise deposition of Pt/C multilayer on the inner surface.

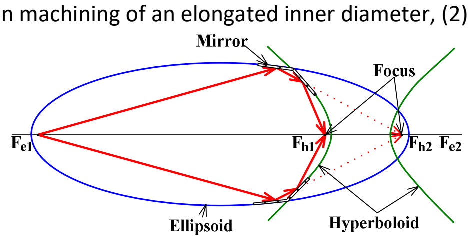

Figure 1. Geometry of the Wolter type I X-ray mirrors.

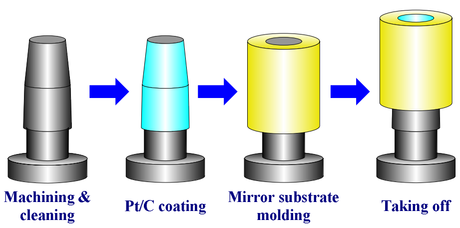

Figure 2. Replication process for making Pt/C multilayer inner mirror.

To confront such difficulties, the epoxy replication process may be proposed for making Pt/C multilayer inner mirror, as shown in Figure 2. Production of the mold at the left end of the figure is most important.

In hard X-ray reflecting mirrors, figure accuracy of ±50 nm P-V and surface roughness of 0.3 nm rms are required [7].

This paper deals with a method of manufacturing mirrors for grazing incidence hard X-ray microscopes by applying the Pt/C multilayer deposition technology developed in the process of manufacturing the hard X-ray telescopes equipped in the ASTRO-H (Hitomi) satellite.

2. Experimental Procedures

2.1. Single-point diamond turning of mold rod

A7075 aluminum alloy mold rods were machined to a thickness below 75 μm from the ideal surface contour by a single-point diamond turning machine AHN30 [8], manufactured by TOYODA Machine Works, Ltd.

2.2. Electroless Nickel coating on mold rod

It is difficult to machine the aluminum alloy down to 0.3 nm rms surface roughness, so we plated an electroless Ni film of 110 μm in thickness on the above mentioned diamond turned mold rods. The plated electroless Ni contained about 10 % weight phosphorous and showed amorphous structure.

2.3. Single-point diamond turning of electroless Ni film

The electroless Ni film on the aluminum alloy rod was diamond turned into both ellipsoid-hyperboloid of revolution by the AHN30 at a cutting speed of 0.2 m/s, feed rate of 5 μm/rev, depth of cut 1 μm with a sharp single crystal diamond tool of 1 mm nose radius, whilst spraying misty white kerosene.

2.4. Precision polishing of diamond turned electroless Ni film

The diamond turned aspheric surfaces were too rough for hard X-ray application, so the surfaces were polished manually with 15 nm SiO_2 powder and polyuethane pads.

2.5. Release agent

In the case of gold film for soft X-ray telescopes or microscopes, it is ease to separate the film from glass or electroless Ni molds because of its releasability. Pt/C multilayer film can be separated in part from a glass mold without release agent, however, it is very difficult to separate the whole circumference of Pt/C multilayer aspheric inner mirrors with small diameter from the molds without a release agent. The release agent has to be very thin, smooth and uniform, as well as feature good releasability. We coated carbon, Ti, Au, and silicon oil on polished electroless Ni plano samples and measured surface roughness. Releasability was also measured.

2.6. Pt/C multilayer coating

Soft X-ray microscopes or telescopes have used grazing incidence mirrors with gold mono layers. On the other hand, gold mono layer mirrors may not be used in hard X-ray region. In the hard X-ray region an X-ray multilayer mirror with an artificial periodic structure, in which layers of a heavy element (Pt or W) and light element (C) with a nanometer-order thickness are alternately formed, is used for Bragg reflection.

Pt/C multilayer super mirrors [6] were coated on the Ti precoated molds using DC magnetron sputter apparatus which had been also used for making hard X-ray telescopes, for the satellite named ASTRO-H (Hitomi).

2.7. Fabrication of mirror substrate

Mirror substrates made of steel were bored at the center, and the inside of the hole was machined with an NC turning lathe.

2.8. Mirror substrate molding with epoxy

The Pt/C coated mold was inserted inside the hole of the mirror substrate together with epoxy resin. The protruding resin was removed completely by hand. The whole parts were cured in an oven for a day.

2.9. Separation of Pt/C multilayer mirrors from aspheric molds

After curing process, whole parts were immersed in icy water and released by utilizing the difference in thermal expansion. This technology is the same as used for soft X-ray telescope gold coated mirrors.

3. Results and Discussion

Figure 3 shows the difference between required shape and machined part, measured with a Form Talysurf Plus from Taylor Hobson. There was ±93.5 nm in figure error after first cut. After compensating the cutter path, the second cut shows a more precise result of ±47.5 nm in figure error.

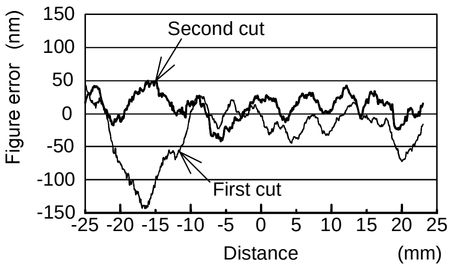

Figure 3. Figure errors of machined aspheric mold for a condenser mirror.

Figure 4 shows the surface roughness of polished hyperboloid part of aspheric mold, measured with NewView 200 from ZYGO Corp. The obtained surface roughness of 0.267 nm rms is smooth enough for hard X-ray application [6]. Incidentally, the surface roughness of diamond turned hyperboloid part showed 6 nm rms.

Gold is a good release agent, however gold deposition formed island shapes when the film thickness was thin. Coated thin film of Ti was smooth and uniform, and had no influence on the Pt/C multilayer. Therefore, it was decided that Ti was the best release agent for Pt/C multilayer mirrors.

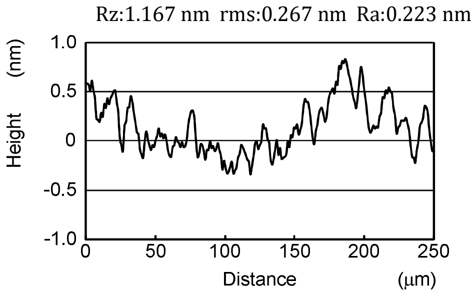

Figure 4. Surface roughness of aspheric mold.

Figure 5 shows the ultra-precision aspheric molds of electroless Ni covered on aluminum alloy rods (left), and the whole circumference replicated Pt/C multilayer grazing incidence X-ray inner mirrors (right) by the epoxy replication method. The size of the squares in the photograph is 20 mm.

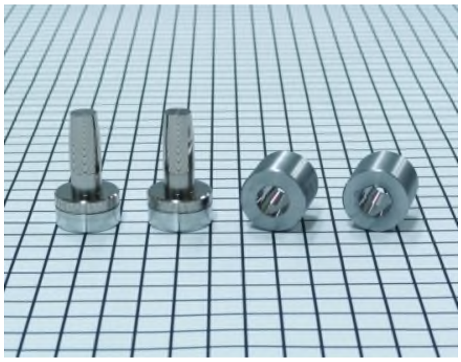

Figure 5. Master ultra-precision aspheric molds (left) and replicated Pt/C multilayer X-ray inner mirrors (right) by the epoxy replication method.

4. Conclusions

It was the first time in the world that Pt/C multilayer reflectors for hard X-ray microscope were fabricated by replication from electroless nickel aspheric mold of ellipsoid and hyperboloid of revolution. The figure accuracy and the surface roughness of the molds were better than ±50 nm P-V and also better than 0.3 nm rms.

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