# MANUFACTURING OF REPLICATED Pt/C MULTILAYER MIRRORS FOR HARD X-RAY TELESCOPES


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## INTRODUCTION

Recent soft X-ray telescope satellites such as Chandra [1], XMM-Newton [2] and Suzaku [3] had launched in July, 2000, December, 2000 and July, 2005, respectively. All three telescopes are now working in order to observe new phenomena in the space. Figure 1 shows the structure of such X-ray telescope which is constructed by nested multiple reflecting mirrors. The grazing incidence reflecting mirrors need light weight and higher shape accuracy with very smooth surfaces. The telescope used a Wolter type I mirror which was consisted by a paraboloid and hyperboloid of revolution.

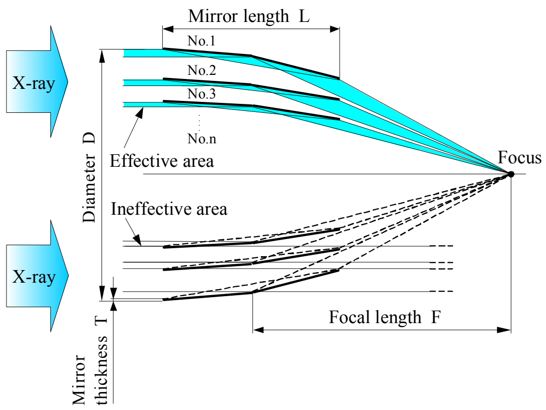



*FIGURE 1. Structure of a grazing incidence X-ray telescope.*

Chandra's aspheric X-ray mirrors were made of zero thermal expansion glass-ceramics, called ZERODUR and well polished and coated iridium inside mirror surfaces. The maximum diameter of the telescope is 1,200 mm and they have 4 aspheric mirrors as the first and second reflection, respectively. Chandra has the highest imaging resolution among three satellites, needed the longest manufacturing time and was the most expensive one. XMM-Newton was made by replication processes, that is, polishing aspherical electroless Ni mandrels, coating gold on the mandrels, electro-forming nickel of 1mm thickness on the mandrels, and separating the electro-formed nickel shell with gold film from the mandrel. Suzaku was made by different replication processes, that are, coating gold on glass tubes in the market, attaching an aluminum foil on gold-coated glass tube by a resin adhesive, curing them in the vacuum, and peeling off the foil with gold film from the glass tube. Each gold-coated foil mirror was a quarter arc of a circular cone and four mirrors were assembled in a circle.

Focusing optics in hard X-ray region above 10 keV will open a new window of the universe, where extremely hot astrophysical phenomena or non-thermal high energy phenomena like jet occur in unknown way [4]. This paper deals with a novel manufacturing process of replicated Pt/C multilayer mirrors which will be used for the next-generation hard X-ray telescope after 2012. The specifications of such mirrors are as follows; shape accuracy of aspherical mirrors is less than 100 nm and surface roughness is also less than 0.3 nm rms. The mirror tolerance is tighter than soft X-ray telescope, because of shorter wavelength application.

## MANUFACTURING PROCESS

In the case of a grazing incidence hard X-ray telescope, more than hundred of Pt/C multilayer mirrors of aspherical shape in high precision are needed for collecting X-ray from the galaxy. The weight of the telescope has to be light due to the space application, and the mirror surface area has to be larger for collecting power, so that the next-generation X-ray telescope consists of nested mirrors having Pt/C multilayer. For

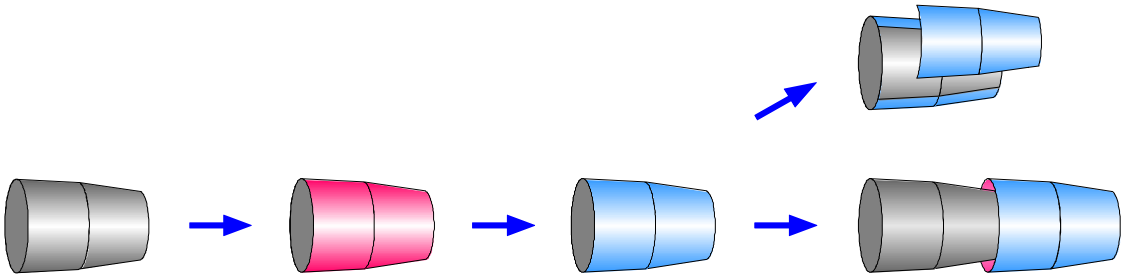



*FIGURE 2. Manufacturing process of replicated mirrors for hard X-ray telescopes.*

obtaining light-weight mirrors, replication technology is essential.

Figure 2 shows a manufacturing process of replicated Pt/C multilayer mirrors. The only material which can be ultra-smoothly polished is an amorphous material such as glass and electroless nickel. In this paper we used the latter one as molding die or mandrel material, because it is easy to be diamond-turned into aspherical shapes. Diamond turned aluminum mandrels are covered with electroless nickel plating and diamond turned again, then polished in to smooth surfaces less than 0.3 nm rms. After that, the polished surface has to be cleaned up. Pt/C multilayers are deposited on the electroless nickel mandrel after the deposition of a thin film for separation and glued a metal shell over the mandrel. All parts are put into a vacuum chamber for curing and then put into cold water in order to separate the Pt/C multilayer mirror from the mandrel.

The Upgraded hard x-ray telescope with Pt/C multilayer supermirrors for the InFOCμS balloon experiments were performed [4-6] by our group, in this case cylindrical glass tubes were used as the mandrel material like the Suzaku's mirrors. It is easy to separate the Pt/C multilayer from the glass mandrel by a quarter arc of an aluminum foil. However, no one has succeeded in separate the Pt/C multilayer from electroless nickel mandrels, though machining of electroless nickel is much easier than that of glass.

## EXPERIMENTAL PROCEDURE

Electroless nickel deposited aluminum samples were turned in to plane, conical or aspherical shapes by a single-point diamond turning machine as shown in Fig. 3. The machine was installed on a vibration proof foundation in a temperature controlled clean room.

*FIGURE 3. Single-point diamond turning machine in a temperature controlled clean room.*

The diamond-turned samples were optically polished or float polished or hand-polished.

The Pt/C multilayer was deposited on polished plane dies, conical and aspherical mandrels by DC magnetron sputtering. The number of layer pair was 30 and the periodic distance was 4 nm. Various materials were used as an intermediate layer between the electroless nickel and platinum for separation.

Substrates for mirrors were separately prepared by inner-turning of steel. In the case of plane mirrors, we used thick glass plates as a substrate. The Pt/C coated mandrel and substrate were fixed with epoxy resin, and cured in a vacuum camber, then dipped in cold water for separation.

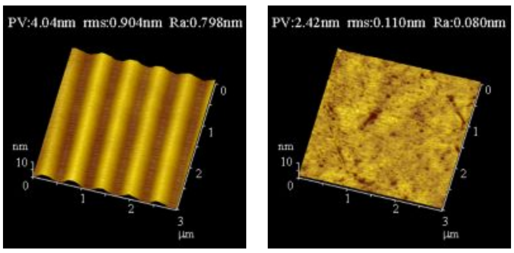
## EXPERIMENTAL RESULTS

There are so many problems for establish the manufacturing process of replicated Pt/C multilayer mirrors for hard X-ray telescope. In this paper we will explain some of the experimental results.

### Polishing of plane electroless mandrel

Electroless nickel samples of 30 mm in diameter and 10mm in thickness were diamond turned and optically polished as well as float polished. Figure 4 shows the surface roughness of machined plane samples, measured with a scanning probe microscope (SPM). Diamond turned and float-polished samples show the surface roughness of 0.90 nm rms and 0.11 nm rms, respectively. The latter surface satisfies the specification for hard X-ray telescope mirrors. The smoothest diamond-turned surface of 0.344 nm rms was obtained on an electroless nickel plane surface at the cutting conditions of 1 μm depth of cut, 0.5 μm/rev feed rate, 15m/s cutting speed with a sharp single point diamond tool having 10 mm nose radius. This number does not satisfy the specification of hard X-ray telescopes even on a plane surface, so the ultra-precision polishing is essential after the diamond turning.

0.904 nm rms 0.110 nm rms




(a) Diamond turned (b) Float polished

*FIGURE 4. Surface roughness of machined electroless nickel sample, measured with an SPM.*

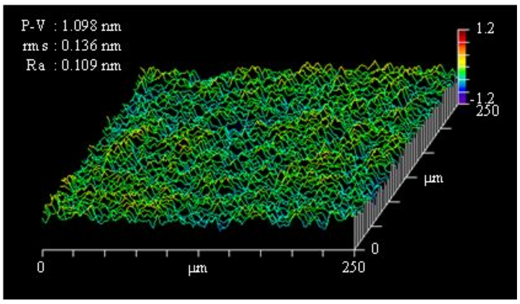
**Replication of plane mirrors**

In the case of separation of the Pt/C multilayer from the glass mandrel, the intermediate layer is not necessary [6]. However, we need the intermediate layer between an electroless nickel mandrel and Pt/C multilayer for separation.

Various materials were tested as an intermediate layer such as carbon, titanium, gallium, gold, vapor of silicon oil as well as Langmuir-Blodgett film. The coated intermediate layer has to be smooth on the surface less than 0.3 nm rms and very thin. Separation and transference of the die surface were good in the case of using carbon, titanium and Langmuir-Blodgett film as an intermediate layer. The gold is the perfect separation material, however the coated gold film is not smooth enough for this purpose.

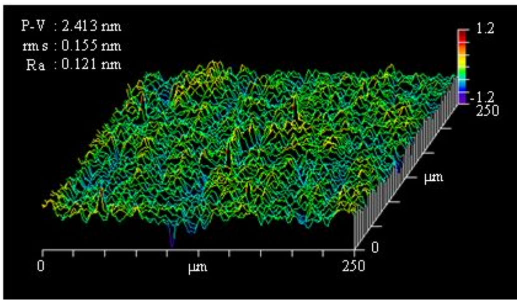
Figure 5 shows the surface roughness of the float-polished electroless nickel plane die and the replicated Pt/C multilayer plane mirror after separation, measured with ZYGO NEWVIEW 200. The surface roughness are 0.136 nm rms and 0.155 nm rms on the electroless nickel plane die and replicated Pt/C multilayer mirror, respectively. In this case, we used the carbon intermediate layer.

0.136 nm rms




(a) Float-polished electroless nickel plane die

0.155 nm rms




(b) Replicated Pt/C multilayer plane mirror

*FIGURE 5. Surface roughness of electroless nickel plane die and replicated Pt/C multilayer plane mirror after separation.*

The shape accuracy is also important in the replication process as well as the surface roughness. The flatness of replicated Pt/C multilayer on a glass plate of 8 mm thick was about the same flatness on the electroless nickel die plate.

**Replication of conical mirrors**

Figure 6 shows a conical mandrel made of aluminum alloy coated with electroless nickel on the left, and a replicated Pt/C multilayer inner mirror on the right. The maximum diameter and mirror length were 38 mm and 35 mm, respectively on the mandrel, and the vertical angle of the cone was 20 degrees. This angle is much steeper compared with the hard X-ray telescope mirrors of less than 0.3 degrees. The thickness of carbon steel substrate was 5 mm. We could separate the Pt/C multilayer from the electroless nickel mandrel only when we used titanium as an intermediate layer. The picture shows the status of mandrel and replicated mirror just after the separation in cold water.

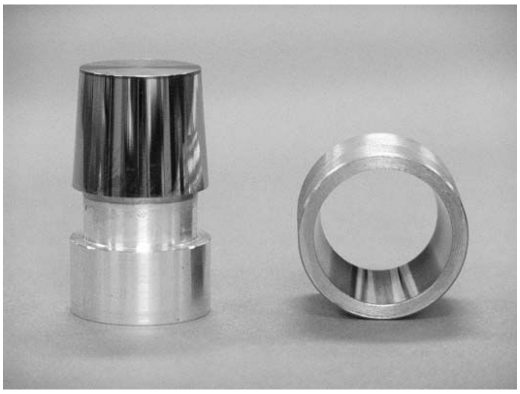


*FIGURE 6. Diamond turned and polished conical electroless nickel mandrel (left) and replicated Pt/C multilayer conical mirror (Right).*

**Replication of aspherical mirrors**
Electroless nickel mandrels of 102 mm maximum diameter and 75 mm in mirror length were machined for making a Wolter type I mirror of 8 m in focal length. The outer shape of mandrel was composed by a paraboloid and hyperboloid of revolution. The mandrel was coated by titanium in 10 nm thickness and deposited with Pt/C multilayers.

Carbon steel mirror substrates of 5 mm thick were mounted on the Pt/C multilayer coated mandrel with epoxy resin. However, Pt/C multilayer mirrors were not separated from the mandrel by the above-mentioned way up to now.

A glass fiber cloth was dipped in epoxy resin and a Pt/C multilayer-coated mandrel was partially covered with the fiber cloth. After curing, we can peel off the Pt/C multilayer-coated cloth of 0.5 mm thick from the mandrel. Titanium was used as an intermediate layer of 10 nm thick. This is another way of making replicated Pt/C multilayer mirrors.

The manufacturing method of whole circumference of replicated Pt/C mirrors will be still remained as the next step research.

**SUMMARY**
In order to obtain replicated Pt/C multilayer mirrors for a next-generation hard X-ray telescope, some basic experimental works have been done using electroless nickel mandrels which were single-point diamond turned and polished.

The surface roughness less than 0.2 nm rms was obtained on electroless nickel plane dies by the float polishing, and also we could get Pt/C multilayer plane mirrors less than 0.2 nm rms in surface roughness by replication technology using an intermediate layer. We succeeded in the separation of Pt/C multilayer from a cone mandrel. Titanium is one candidate as an intermediate layer between an electroless nickel mandrel and Pt/C multilayer from the view point of separation and transferability. The perfect replicated Pt/C mirrors for next-generation hard X-ray telescopes could not obtained yet.

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