Manufacture of aspherical molding dies for X-ray telescopes after ASTRO-H

Yoshiharu Namba*[a], Anthony Beaucamp[a], Hironori Matsumoto[b], Keisuke Tamura[b], Yuzuru Tawara[b], Hideyo Kunieda[b], Tadayuki Takahashi[c]
[a]Dept. of Mech. Engg., Chubu Univ., 1200 Matsumotocho, Kasugai, Aichi 487-8501, Japan; [b]Dept. of Physics, Nagoya Univ., Furocho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan; [c]Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5200, Japan.

ABSTRACT

Producing X-ray imaging space telescopes is a very expensive endeavor, due in great part to the difficulty of fabricating thin mirrors for Wolter type-I optical assemblies. To meet this challenge, replication from optical molding dies (also called mandrels) has become the preferred method, as it is reliable and economical. Several replication methods exist: in the case of the ASTRO-H mission, DC magnetron sputtering was used to deposit Pt/C multilayer coating on glass molding dies. The multilayer coating was then bonded with epoxy to aluminum shells and then separated from the die. Another mirror replication method consists of slumping thin glass sheets over a full (or a section of) revolution molding die under high temperature. This method was demonstrated in the case of the NuSTAR mission.

But the challenge of fabricating truly aspheric Wolter type molding dies, which are capable of highly accurate angular resolution (below 5 arcs), remains very expensive and time consuming. In this paper, three methods for producing X-ray optic molding dies are presented. Each method uses a different substrate material and process chain, as follows: electroless nickel plated aluminum (first diamond turned then correctively polished), fused silica (first precision ground then correctively polished), and CVD silicon carbide (which can be finished entirely with a newly developed Shape Adaptive Grinding process). The process chains employed for each method are explained in details, and their relative merits discussed. A way forward for the next generation of X-ray telescopes after ASTRO-H is then drawn out.

Keywords: X-ray optics, thin mirrors, replication, molding dies, ultra-precision, diamond turning, grinding, polishing.

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.

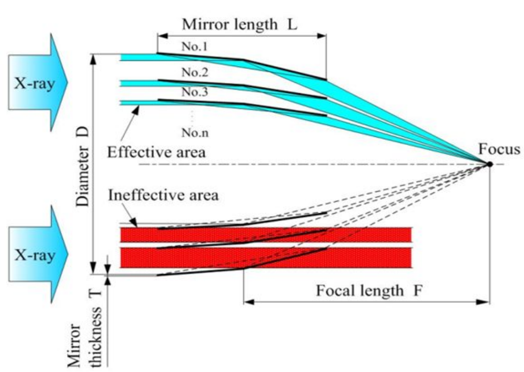


Figure 1. Wolter type-I configuration for grazing incidence X-ray imaging telescope.

Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray, edited by Tadayuki Takahashi, Jan-Willem A. den Herder, Mark Bautz, Proc. of SPIE Vol. 9144, 91444F · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2055290

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 [3], XMM-Newton [4], Suzaku [5] and ASTRO-H [6] 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.

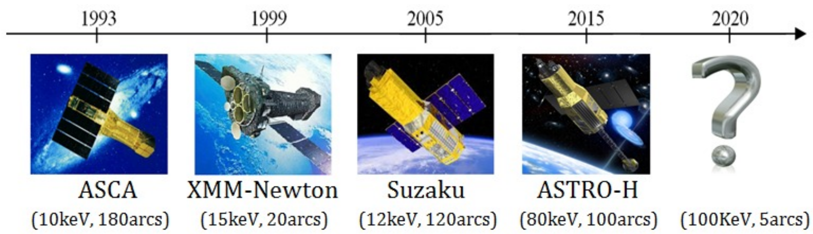


Figure 2. Past and future specifications of X-ray telescopes using replicated optics.

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 thermal forming and slumping of thin glass sheets over molding dies. These methods have been demonstrated in recent missions.

1.1 Replication from molding dies

One method to replicate thin mirrors consists of producing aluminum foils with the approximate shape of the molding die by thermal forming (see Fig. 3). After depositing a coating on the molding die, the aluminum foil and coating are bonded with epoxy, and then peeled off. This replication method was used in the case of the ASTRO-H mission [6].

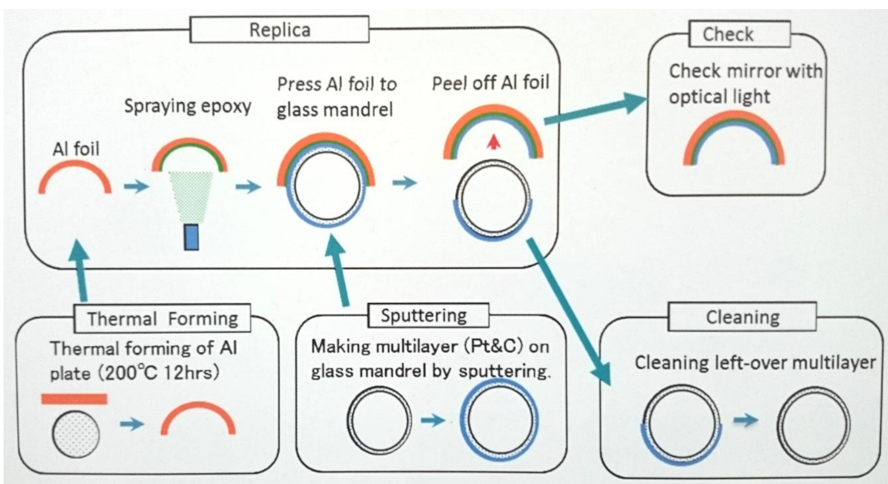


Figure 3. Principle of replication by thermal forming of aluminum foils, and bonding over a molding die [6].

Another method for replicating thin mirrors consists of slumping thin glass sheets (~0.2mm in thickness) across molding dies, under high temperature (see Fig. 4). This method was demonstrated in the case of the NuSTAR mission [7].

Figure 4. Principle of replication by slumping a thin glass sheet (~0.2 mm thick) over a molding die [7].

1.2 Deposition of Pt/C multilayer by DC magnetron sputtering

DC Magnetron Sputtering is a plasma vapor deposition method, capable of depositing sub-nanometer thick layers of pure material on a substrate (such as platinum or carbon). The process involves ejecting material from a "target" located inside a vacuum chamber, using ions accelerated along an electrical field. The ejected atoms are then re-deposited onto the optical surface. This technology can produce multilayered coatings of platinum and carbon, such that the reflectivity bandwidth of the final mirror is improved (see Fig. 5).

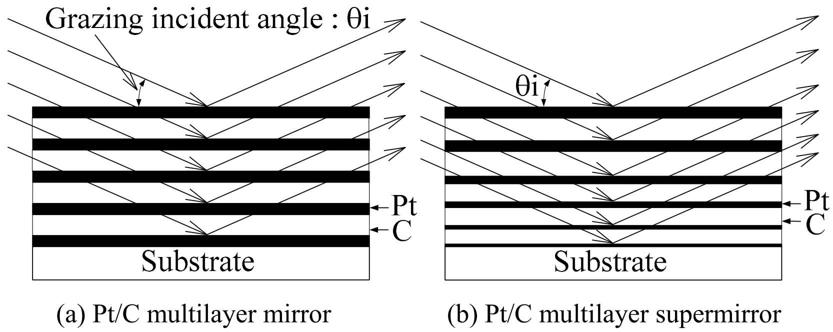


Figure 5. Principle of multilayer coating using Pt/C layers deposited by DC Magnetron Sputtering.

Depending on the replication method, the multilayer coating is deposited either on the molding die (thermal forming) or on the replicated thin mirror (glass slumping).

2. ASPHERICAL MOLDING DIES FABRICATION

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, three methods for producing X-ray aspheric molding dies are presented (see Table 1). Each method uses a different substrate material and process chain, as follows: electroless nickel plated aluminum (first diamond turned then correctively polished), fused silica (first precision ground then correctively polished), and CVD silicon carbide (which can be finished entirely with a newly developed Shape Adaptive Grinding process). The process chains employed for each method are explained in details in this section, and their relative merits discussed in the next section.

Table 1. Three different methods to fabricate molding dies for hard X-ray mirror replication.

	Substrate Material	**Fabrication Process Chain**
#1	Electroless nickel (plating on aluminum)	1) Diamond turning 2) Form-correction by "Fluid Jet Polishing" 3) Super-smoothing by "Continuous Precess Smoothing"
#2	Fused silica	1) Precision grinding 2) Form-correction by "Precessed Bonnet Polishing" 3) Super-smoothing by "Continuous Precess Smoothing"
#3	CVD silicon carbide (coating on graphite)	1) High-speed milling of graphite (in industry) 2) CVD coating with silicon carbide (in industry) 3) Form-correction and smoothing by "Shape Adaptive Grinding"

2.1 Electroless nickel molding dies

A process chain for automated fabrication of X-ray molding dies using electroless nickel was reported in the literature [8]. The first step consists of diamond turning cylindrical molding dies on a large diamond turning machine (see Fig. 6a). Using calibration artifacts and compensation of the diamond tool wear, it is possible to produce large aspherical molding dies up-to 600mm in diameter with a form accuracy of few hundreds of nanometer [9,10]. After turning, the molding dies can then be finished using a combination of fluid jet polishing (FJP, see Fig. 6b) and continuous precess smoothing (CBS, see Fig. 6c) on a common 7-axis CNC platform.

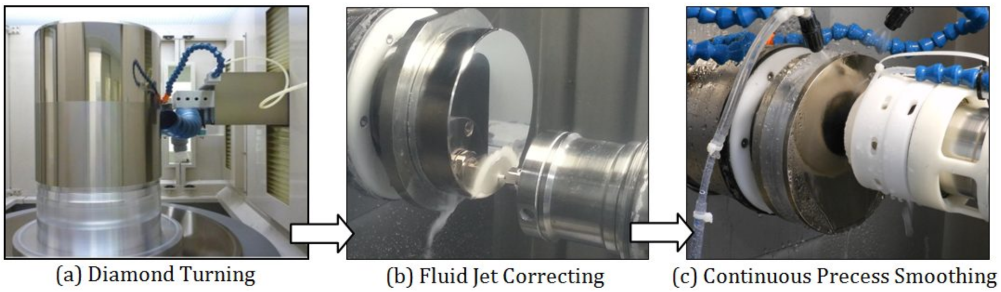


Figure 6. Process chain to fabricate X-ray molding die from electroless nickel plate aluminum drums [8].

In the FJP process, a mixture of water and abrasive particles is delivered by a pump to a converging nozzle of outlet diameter usually between 0.1 and 2.0 mm. The jet impinges the work-piece, thus generating an influence spot which is moved across the surface to follow a tool path programmed in to the 7-axis CNC machine. With this process, it is possible to remove cyclic diamond turning marks, and replace them with a random surface signature as shown in Figure 7. Using federate control, it is also possible to iteratively improve the form accuracy of the molding dies down to less than 50 nm P-V [11].

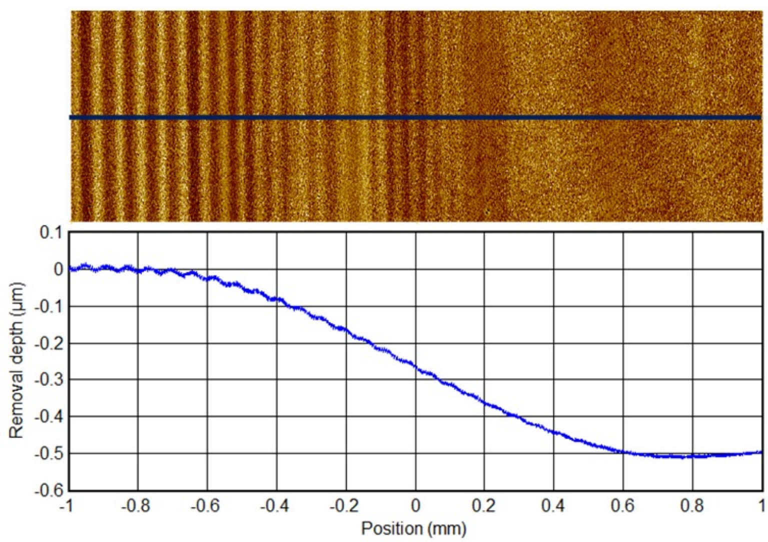


Figure 7. Measurement showing removal of diamond turning marks (top) as function of removal depth by FJP (bottom) [8].

After form correction has been completed, the molding dies are then finished using precessed bonnet polishing, a sub-aperture finishing process which has been described in the literature at various stages during its development [8,12]. The operation of the process in shown in Fig. 8 (left): 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.

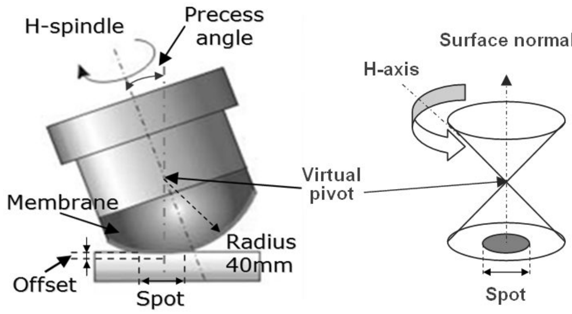


Figure 8. Principle of precessed bonnet (left) and "continuous precess" polishing (right) [8].

But rather than just rely on the usual "single precess" polishing regime described in previous literature, whereby the tool is precessed in a given direction for each polishing pass, a novel tool path control method called "continuous precess smoothing" was introduced (CBS). In this method, show in Fig. 8 (right), the direction of the surface tangent used to compute the plane of precession of the spherical tool is allowed to spin around the centre of the polishing spot. This method prevents directionality of the polishing marks, as shown in Fig. 9.

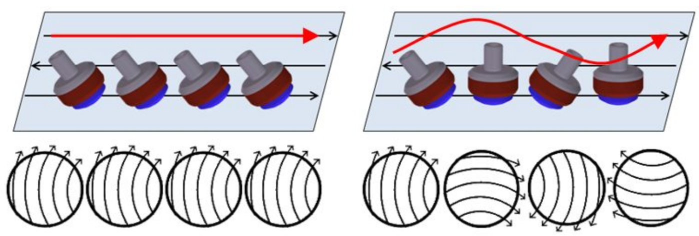
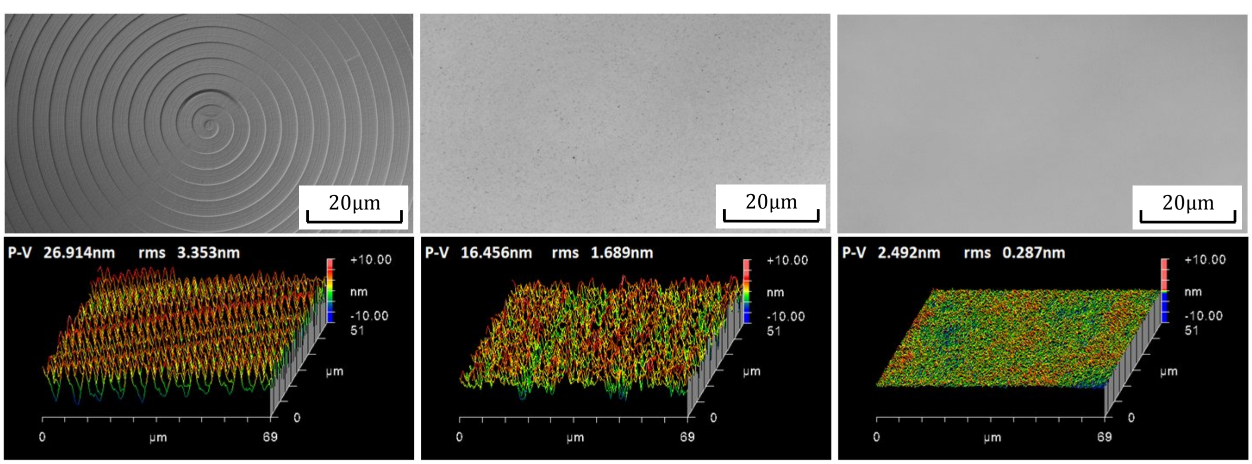


Figure 9. Single (left) and continuous precess (right) across raster tool path, with associated polishing direction (bottom) [8].

Post-smoothing of FJP polished surfaces by CBS can produce super-smooth and ultra-accurate optical surfaces on electroless nickel plated dies. Figure 10 shows Laser Confocal Micrographs (top) and Whitelight Interferometer Microscope (bottom) measurement of the electroless nickel plate surface of the various machining stages. Diamond turning marks (Fig. 10a) were removed by FJP polishing (Fig. 10b), after which the surface was super-smoothed by CBS (Fig. 10c). For this purpose, very fine slurry of 7 nm fumed silica particles mixed with pure water at a concentration of 20 g/L is fed above the bonnet with a disposable pipe connected to a peristaltic pump. It is thus possible to achieve super-smooth anisotropic micro-roughness below 0.3 nm rms.

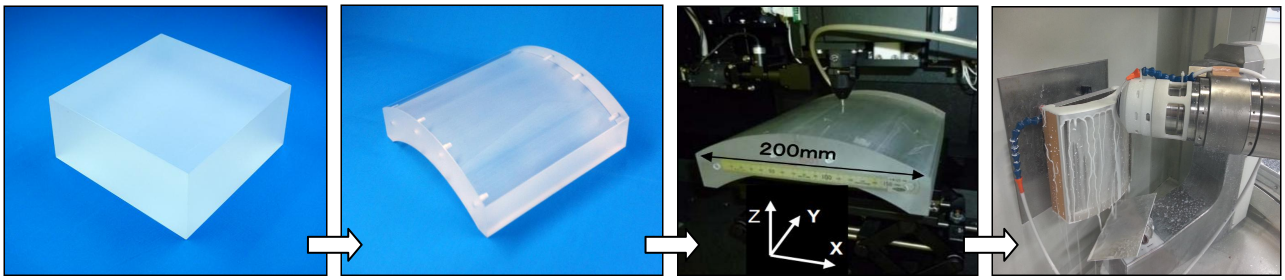


a) Diamond Turning b) Fluid Jet Correcting c) Continuous Precess Smoothing

Figure 10. Micrograph (top) and roughness (bottom) of nickel surface at various stages of the process chain [8].

2.2 Fused silica molding dies

A process chain for automated fabrication of X-ray molding dies using fused silica was also reported in the literature [13]. Blocks of fused silica (see Fig. 11a) are precision ground to the approximate freeform shape (see Fig. 11b) with an accuracy of few dozens of microns. The aspherical shape accuracy is then measured with an ultra-precise coordinate measurement machine (see Fig. 11c). By using adequate fiducialization between the measuring and polishing equipments, it is then possible to correctively polish the molding die using the bonnet polishing method described in the previous section (see Fig. 11d).



a) Block of fused silica b) Precision grinding c) Ultra-precise measuring d) Corrective polishing

Figure 11. Process chain to fabricate X-ray molding die from fused silica block.

Starting from an initial form error on the precision ground molding die of about 40 µm P-V, it is possible to bring down the form accuracy to below 100 nm P-V as shown in Fig. 12 (left). The corrective polishing runs are performed using cerium oxide (CeO_2) abrasives of nominal size 1.5 µm. Once corrective polishing has been completed, the molding die can be finished with a smoothing run that uses finer CeO_2 abrasives of nominal size 0.5 µm. Using such abrasives, it is possible to achieve a micro-roughness around 0.3 nm rms on fused silica (see Fig. 12, right) [14].

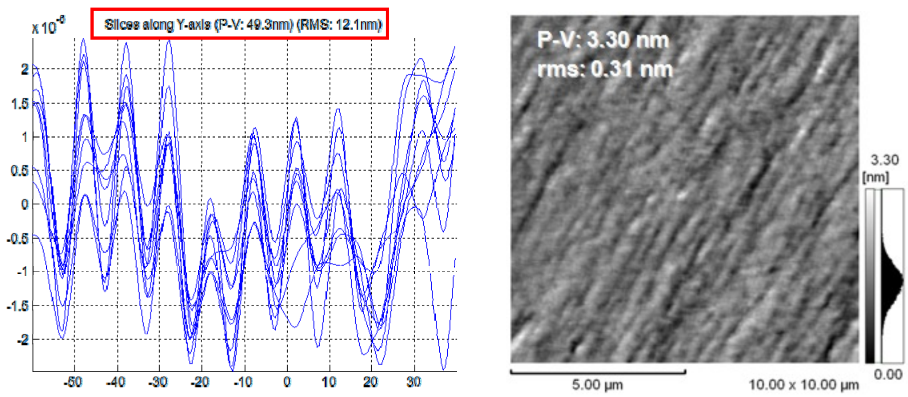
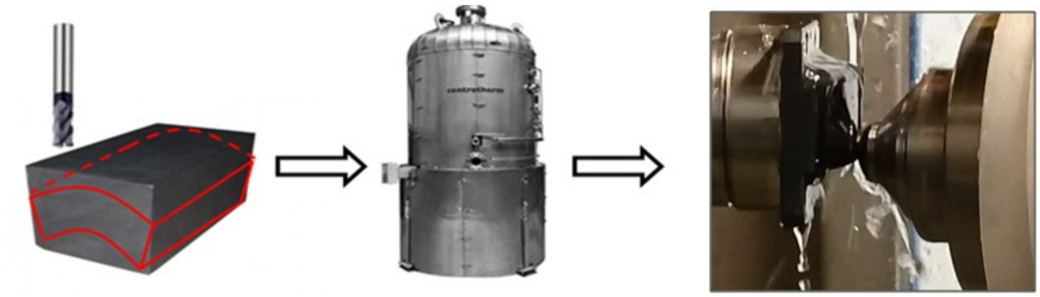


Figure 12. Residual form-error after final correction (left) [13]. Achievable micro-roughness on fused silica (right) [14].

2.3 Graphite/CVD SiC molding dies

A new process chain to fabricate X-ray molding dies is now proposed, using graphite coated with CVD silicon carbide**.** The cost of CVD technology has steadily decreased over the past few years, making it increasingly ubiquitous. High speed 5-axis milling is commonly used in industry to machine approximate molding die shapes from blocks of graphite (see Fig. 13a) [15]. CVD SiC coating is then deposited to produce a highly resistant surface (see Fig. 13b) [16].



a) Milling block of graphite b) Coating with CVD SiC c) Shape Adaptive Grinding

Figure 13. Process chain to fabricate X-ray molding die from CVD silicon carbide coated graphite.

The CVD deposition process tends to produce grain like structured surfaces that become rougher as the deposition depth increases (usually around 1.0 µm Ra), so it is necessary to machine the CVD surface by grinding or polishing [17]. But in the case of freeform surfaces, it is difficult to obtain a smooth surface while retaining the 5-axis milled shape accuracy. To address this issue, an innovative Shape Adaptive Grinding (SAG) tool has been developed that can finish CVD silicon carbide surfaces down to optical mirror quality (see Fig 14) [18].

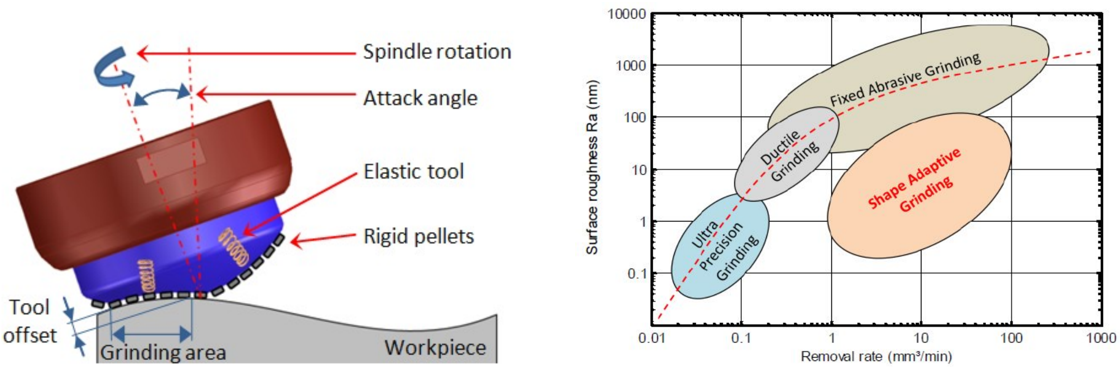
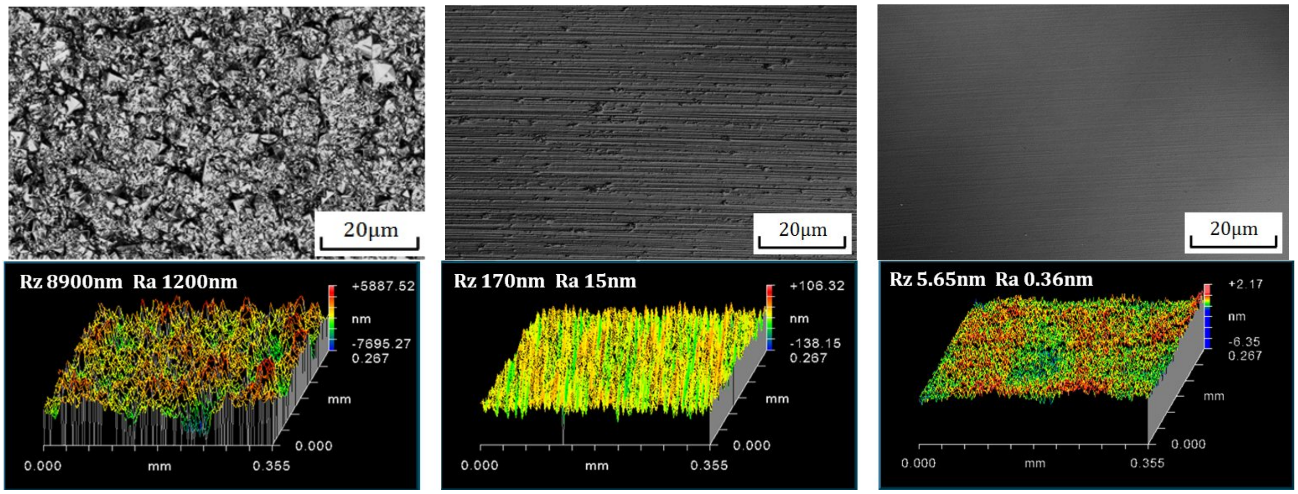


Figure 14. Principle of Shape Adaptive Grinding (SAG) and comparison with conventional grinding methods [18].

The basic principle of the SAG tool consists of maintaining general compliance between the tool and freeform surface over a sub-aperture contact area of the workpiece, as shown in Fig. 14 (left). But at the same time, hard contact is achieved at relatively smaller scale by rigid pellets loaded with diamonds that cover the surface of the elastic tool, such that effective grinding can take place (rather than a soft contact resulting in polishing).

In conventional grinding, there exists a direct relationship between removal rate and the achievable surface roughness. The red line in Figure 14 (right) shows the typical path followed when going from brittle to ductile grinding regime, and then going on to ultra-precision grinding. Namba et al [17] demonstrated that ultra-precision grinding of CVD SiC can deliver roughness less than 0.1 nm Ra, although at very low removal rates. The SAG tool offers an alternative to this traditional path by achieving low surface roughness down to less than 0.4 nm Ra while maintaining very high removal rates (2 orders of magnitude higher). Figure 15 shows Laser Confocal Micrographs (top) and Whitelight Interferometer Microscope (bottom) measurement of the silicon carbide coating at various machining stages, including the initial CVD condition (left), rough grinding with 9 µm diamond abrasives (centre) and final grinding with 3 µm diamond abrasives (right) down to 0.36 nm Ra.



a) Initial CVD SiC coating b) Rough ground with 9 μm diamonds b) Fine ground with 3 μm diamonds

Figure 15. Micrographs (top) and micro-roughness (bottom) of CVD SiC surface at various stages of the process chain [18].

3. SUMMARY AND DISCUSSION

Looking ahead to the next generation of X-ray telescopes after ASTRO-H, there is a requirement for improved performance (in terms of energy bandwidth and angular resolution) together with reduced costs compared with previous missions. The ability to produce aspheric molding dies with shape accuracy below 100 nm P-V was demonstrated on fused silica. An analysis of the residual aspheric shape error on this molding die suggests that replicated mirrors would have an angular resolution below the target of 5 arcs per pair (parabolic + hyperbolic sections). Achieving this target is also possible on electroless nickel and CVD silicon carbide (all the polishing and grinding experimental work shown in this paper was carried out using the same 7-axis CNC machine and software). Therefore, a comparison of the other relative advantages/disadvantages of the various molding die fabrication method proposed in this paper is shown in Table 2.

Table 2. Comparison of the different fabrication methods (+++ means cheapest, lightest, fastest, easiest).

	Electroless Nickel (plating on aluminum)	**Fused Silica**	**CVD Silicon Carbide (coating on graphite)**
Cost of Raw Materials	++	+	+++
Weight of Molding Die (portability)	+	++	+++
Cost of Machining Equipment	+	++	+++
Overall Machining Time	+	++	+++
Ease for Attaining Final Roughness	+	+++	++
Ease of Use for Replication	+	+++	?

The cost of raw materials is cheapest in the case of graphite coated with CVD SiC, because the rough molding dies can be produced in industry. By comparison, fused silica is an expensive raw material that is difficult to machine, so only specialist companies can grind the rough shape. The weight of molding dies is another important criterion for portability between machining, measuring and replication equipment. In this respect, electroless nickel plated dies are very heavy compared to CVD SiC coated graphite which is very light. The cost of machining equipment is highest for electroless nickel because of the need for a large ultra-precise diamond turning machine, located inside a temperature controlled environment. By comparison, the CVD SiC molding dies can be processed on a single machine that performs both the rough and fine grinding down to final finish. The material which has both the easiest machinability (in terms of reaching final surface roughness) and use for replication of thin mirrors (particularly multilayer Pt/C) is fused silica. By comparison, electroless nickel presents challenging difficulties when separating the DC magnetron sputtered multilayer Pt/C coating (there is presently no data available on the ease of replication for CVD silicon carbide).

The data presented in Table 2 shows that the newly proposed X-ray molding die fabrication method based on SAG machining of CVD SiC coated graphite compares very favorably against the more established fabrication methods on electroless nickel and fused silica. Some areas need further improvement and research, specially in relation to attaining the final roughness required for hard X-ray (less than 0.3 nm rms), and assessing the ease of use when replicating both multilayer Pt/C coatings and slumped glass on CVD SiC surfaces. Future research will concentrate on producing demonstration dies using this new methodology, for subsequent testing on X-ray beam-lines. It is envisaged that the CVD SiC coating on graphite fabrication method may lead to cheaper and faster fabrication of molding dies for future X-ray telescope missions beyond 2020.

ACKNOWLEDGMENTS

This work is supported by a Grant-in-Aid for Scientific Research (B) No. 22360063 and also by the Postdoctoral Fellowship Program for Foreign Researchers, from the Japan Society for the Promotion of Science.

REFERENCES

[1] Compton, A. H., Philos. Magazine 45, 1121 (1923).
[2] Wolter, H., “Glancing Incidence Mirror Systems as Imaging Optics for X-rays”, Annals of Physik 10, 94 (1952).
[3] http://heasarc.gsfc.nasa.gov/docs/asca/
[4] http://xmm.vilspa.esa.es/
[5] http://www.astro.isas.ac.jp/suzaku/index.html.en
[6] Kunieda, H., Awaki, H., Furuzawa, A., Haba, Y., Iizuka, R., Ishibashi, K., Ishida, M. et al. "Hard X-ray Telescope to be onboard ASTRO-H", In SPIE Astronomical Telescopes+Instrumentation, 773214-773214 (2010).
[7] Zhang, W. et al, “Development of mirror segments for the Constellation-X observatory”, Astronomical Telescopes and Instrumentation, 503-518 (2003).
[8] Beaucamp, A., Namba, Y., “Super-smooth finishing of diamond turned hard X-ray molding dies by combined fluid jet and bonnet polishing”, Annals of the CIRP 62(1), 315-318 (2013).
[9] Namba, Y., Shimomura, T., Shimizu, T., Kunieda, H., Ogasaka, Y., Yamashita, K., “Development of Large Ultra-precision Diamond Turning Machine for Making Next Generation Hard X-ray Telescopes”, Proceedings of ASPE, 65-68 (2007).
[10] Shinozaki, A., Namba, Y., “Diamond Tool Wear in the Ultra-Precision Cutting of Large Electroless Nickel Coated Molding Dies”, International Journal of Automation Technology 5(3), 283-288 (2011).
[11] Beaucamp, A., Namba, Y., Freeman, R., “Dynamic Multiphase Modeling and Optimization of Fluid Jet Polishing Process”, Annals of the CIRP 61(1), 315-318 (2012).
[12] Beaucamp, A., Namba, Y., Inasaki, I., Freeman, R., “Finishing of optical moulds to λ/20 by automated corrective polishing”, Annals of the CIRP, 60(1) 375-378 (2011).
[13] Beaucamp, A., Namba, Y., Charlton, P., Freeman, R., “Ultra-Precision Machining of Aspheric Molding Dies for Future Hard X-ray Telescope Missions”, Proc. 12th International Conference on X-ray Imaging Optics, 3-4 (2013).
[14] Beaucamp, A., Namba, Y., Charlton, P., “Corrective finishing of EUV photomask blanks by precessed bonnet polisher”, Applied Optics, 53(14) 3075-3080 (2014).
[15] Schulz, H., Moriwaki, T., “High-speed machining”, Annals of the CIRP, 41(2) 637 (1992).
[16] Knowle, W., Withers, J., Ronsone, P., “CVD and CVR silicon based functionally gradient coating on carbon/carbon composite”, Carbon, 33(4) 415 (1995).
[17] Namba, Y., Kobayashi, H., Suzuki, H., Yamashita, K., Taniguchi, N., “Ultraprecision surface grinding of chemical vapor deposited silicon carbide for X-ray mirrors using resinoid-bonded diamond wheels”, Annals of the CIRP, 48(1) 277 (1999).
[18] Beaucamp, A., Namba, Y., Combrinck, H., Charlton, P., Freeman, R., “Shape adaptive grinding of CVD silicon carbide”, Annals of the CIRP, 63(1) (2014).