Shape Adaptive Grinding of CVD Silicon Carbide on Graphite for X-Ray Mirror Molding Dies

Yoshiharu Namba, Anthony Beaucamp
Richard Freeman (Zeeko Ltd.)

Producing X-ray imaging telescopes is a very expensive endeavor, due in large part to the complexity of fabricating thin mirrors for the Wolter type-1 assembly. An economical mirror replication method based on thin glass slumping was demonstrated in the case of NuSTAR, but the challenge of fabricating aspheric molding dies that are both ultra-precise and inexpensive remains. An economical method is proposed that consists of milling graphite, coating with Silicon Carbide by chemical vapor, and finishing by shape adaptive grinding using feedback from ultra-precise 3D profilometry. Aspheric mandrels with form accuracy below 100nm P-V and micro-roughness below 0.5 nm rms can be produced by this method.

１．Introductionに

The Nuclear Spectroscopic Telescope Array (NuSTAR) was the latest X-ray observatory sent into orbit, in June 2012. The on-board imaging telescope contained 133 concentric thin mirror shells arranged in the Wolter type-1 configuration, which is shown in Fig. 1. The X-ray radiations observed by this telescope are generated in space by extremely high energy celestial events. Such events include supernova explosions, destruction of positrons, creation of black holes, as well as the decay of radioactive matter in space. On-going observation of such phenomenon is crucial to continued advances in astrophysics, but depends on planning of future hard X-ray telescope missions.

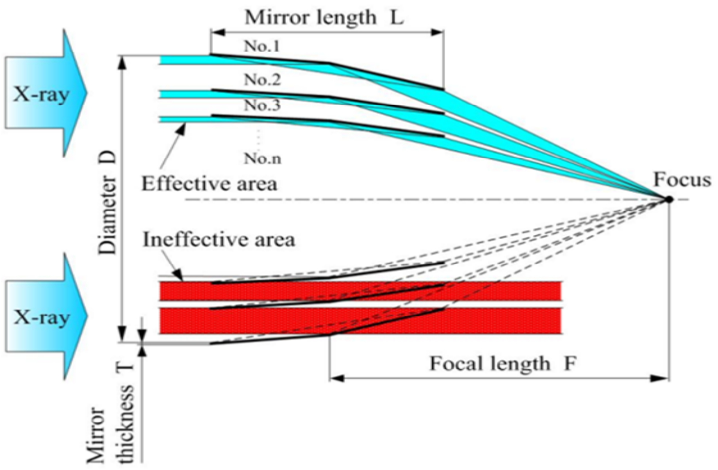


図１ Wolter type-1 configuration for grazing incidence X-ray mirrors

However, producing an X-ray imaging telescope is a very expensive endeavor. This is due in large part to the complexity of fabricating thin mirrors for the Wolter type-1 assembly. An economical mirror replication method was demonstrated in the case of NuSTAR. It consists of slumping super-smooth LCD thin glass over glass mandrels, as shown in Fig. 2. But while replication costs are alleviated, the challenge of fabricating aspheric molding dies that are both ultra-precise and inexpensive remains. The research carried out over the past year has consisted of demonstrating that this double challenge (accuracy and cost) can be overcome.

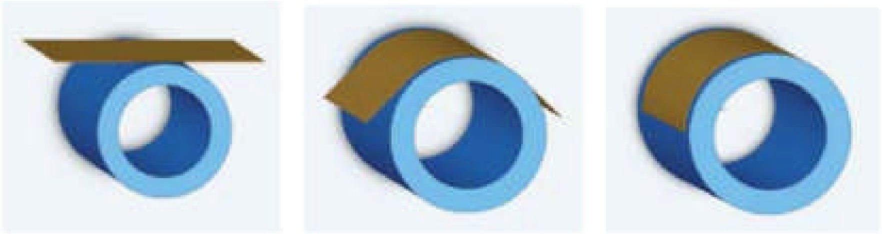


図２ Slumping thin glass over Wolter Type-1 mandrel

Firstly, the ability to produce aspheric mandrels with ultra-precise shape accuracy (Peak-to-Valley error below 100 nm) was demonstrated by grinding and correctively polishing a fused silica mandrel, using feedback from an ultra-precise Coordinate Measurement Machine (CMM) located at Panasonic production facilities in Osaka and corrective polishing equipment available inside our laboratory at Chubu University.

Secondly, the ability to reduce manufacturing costs was investigated and has directly led to the development of a novel freeform grinding method named "Shape Adaptive Grinding" (SAG). This new technology shows great potential for ultra-precise manufacturing of mandrels made from milled graphite coated with Chemical Vapor Deposited (CVD) silicon carbide (a much more inexpensive way of making mandrels, when compared to fused silica).

２．Manufacturing of Fused Silica Mandrel

2.1 Methodology

In order to produce a demonstration parabolic mandrel with focal length 8.4m, blocks of fused silica were precision ground in industry to the approximate freeform shape (see Fig. 3).

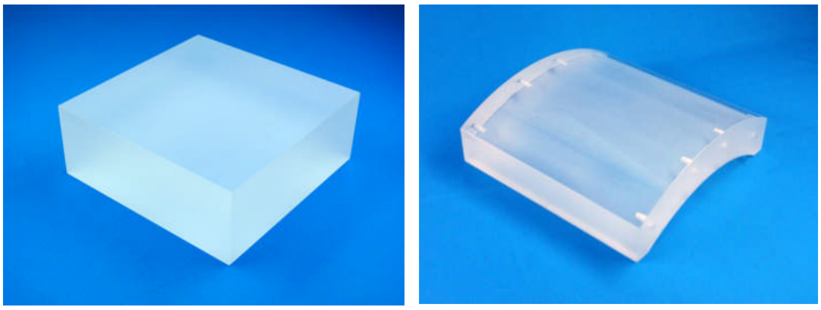


図３ Block of fused silica, before and after grinding of the freeform shape

A special measurement jig was made (see Fig. 4), to create a reference frame attached to the physical centre and orientation of the mandrel (by intersecting lines passing through the centers of 4 silicon nitride balls).

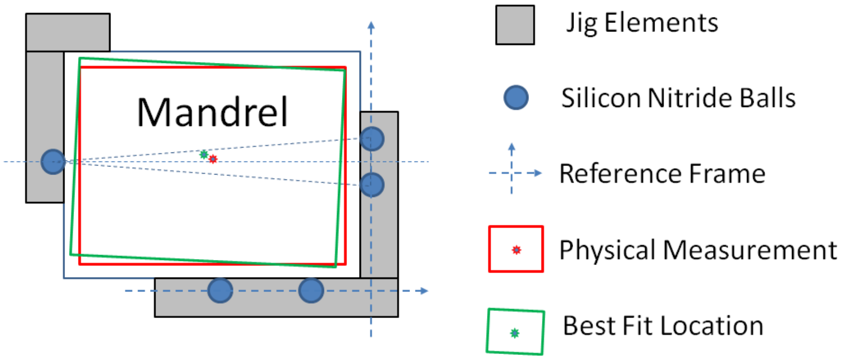


図 4　Jig referencing the best fitted error.

The centre point was then referenced against this frame using a 5th ball on the opposite side of the mandrel (used to measure the exact width and length, which were then divided by 2). The jig and mandrel were measured with a UA3P CMM at Panasonic in Osaka (see Fig. 5, left). After determining the relative location of the best fitted error, this information was input into numerical optimization software that combined it with data about polishing removal rates to derive deterministic tool paths capable of reducing the form error. This tool path was run on a Zeeko 7-axis CNC machine (see Fig. 5, right).

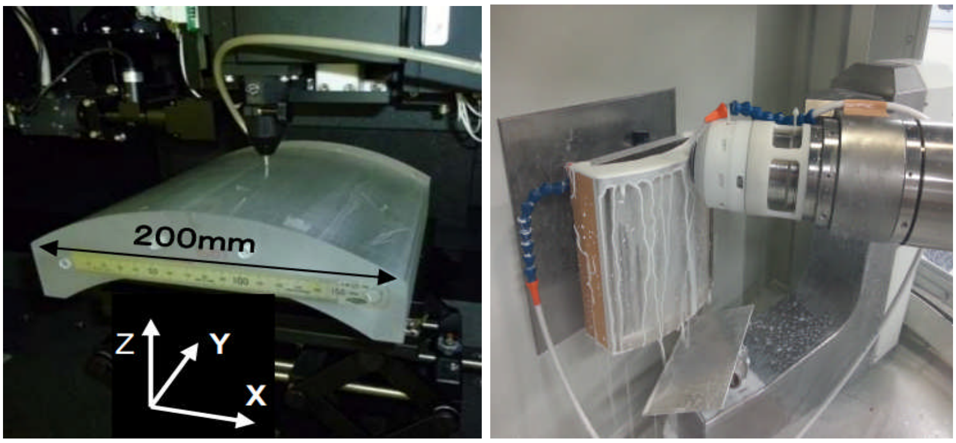


図 5　Mandrel being measured inside UA3P (left), and polished inside Zeeko CNC machine (right).

2.2　Experimental Results

The initial form error measured on the precision ground mandrel was 36.7 μm P-V. The corrective polishing runs were performed using the process parameters shown in Table 1, using cerium oxide (CeO_2) abrasives of nominal size 1.5 μm.

表 1　Process Parameters of Polishing Runs

Polishing tool	Precessed bonnet
Radius	40 mm
Cloth	Poromeric felt
Tool-path mode	Raster
Point spacing	1.0 mm
Tool offset	0.6 mm
Head speed	2000 rpm
Precess angle	20 deg
Surface feed	100~3000 mm/min
Abrasives	Cerium Oxide (Ce02)
Grain size	1.5 μm
Density	60 g/L

The surface feed was moderated between 100 and 3000 mm/min in order to improve form. The result after 6 iterative corrections is displayed in Fig. 6, showing improvement in the Y-axis direction (profile plots) down to 92 nm P-V over 150mm, and 49 nm P-V over 100mm.

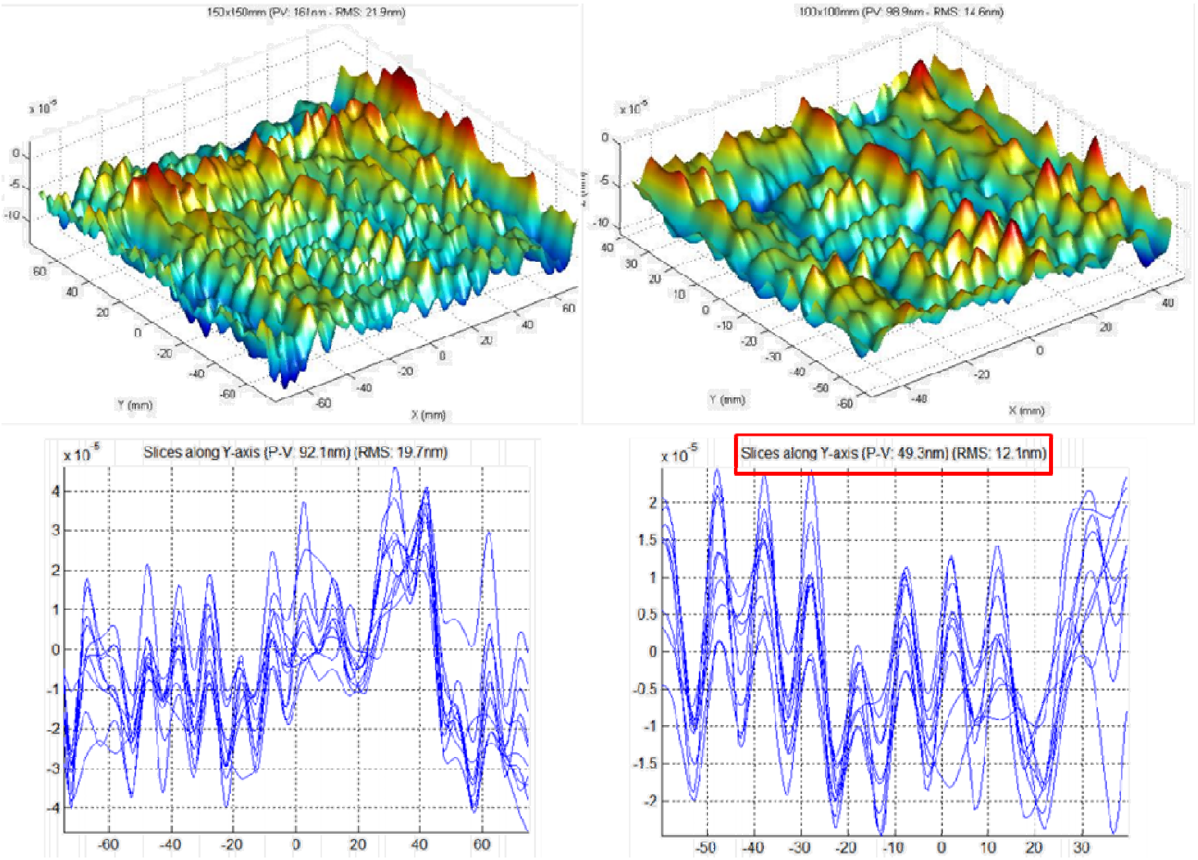
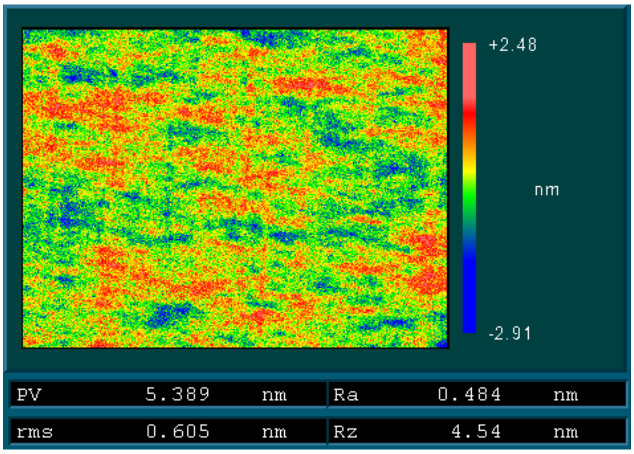


図 6　Final form error over 150x150mm (left) and 100x100mm (right).

As for micro-roughness, it was measured with a white light interferometric microscope with 50x objective. The final set of measurements showed an average of 0.6 nm rms (see Fig. 7), which is adequate for X-ray mirror replication by slumping.



PV 5.389 nm Ra 0.484 nm
rms 0.605 nm Rz 4.54 nm

図7 Final micro-roughness of mandrel measured by white light interferometer (0.6 nm rms).

３．Cost Reduction using Graphite/SiC

2.1 Proposed Process Chain

Having demonstrated the ability to fabricate a mandrel for replication of hard X-ray mirrors by thin glass slumping, the next challenge consists of reducing the costs of manufacture. Indeed, fused silica is an expensive material to acquire and requires top of the range, high stiffness equipment for grinding to a shape close enough before undertaking ultra-precision corrective polishing.

For this reason, an alternative method consisting of manufacturing CVD SiC coated graphite mandrels was investigated. The manufacturing principle is shown in Fig. 8: A high-speed milling machine is used to cut the aspheric mandrel shape into a block of graphite, a material that is inexpensive to acquire and machine (at least one order of magnitude cheaper than fused silica). The cut mandrel is then placed inside a reactor, where a coating of silicon carbide is deposited by CVD process.

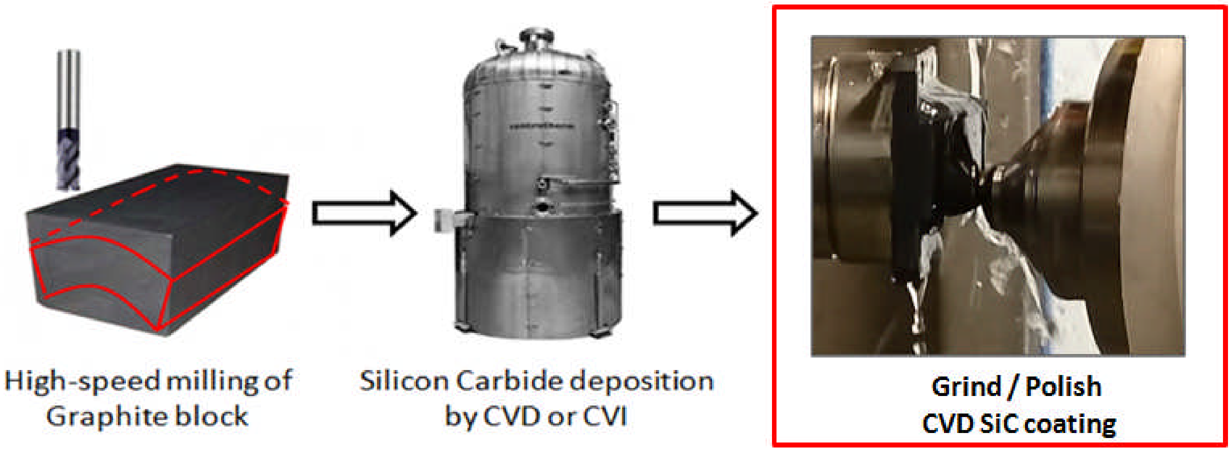


図8 Proposed fabrication chain to produce hard X-ray mandrels from graphite coated with SiC.

These first two steps in our proposed fabrication chain are readily available in industry, both in Japan and internationally, at very competitive prices. A shortcoming was however identified in the final step, shown as a red box in Fig. 8, which consists of grinding/polishing the coated mandrels down to ultra-precision level of accuracy (P-V less than 100 nm, rms less than 1 nm) as required for replication. The absence of such technology in industry has led to the development inside our laboratory of a novel freeform grinding technology named "Shape Adaptive Grinding" (SAG).

2.2 Principle of Shape Adaptive Grinding

The basic principle of the shape adaptive grinding 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. 9. But at the same time, hard contact is achieved at relatively smaller scale by rigid pellets covering the surface of the elastic tool, such that effective grinding can take place (rather than a soft contact resulting in polishing).

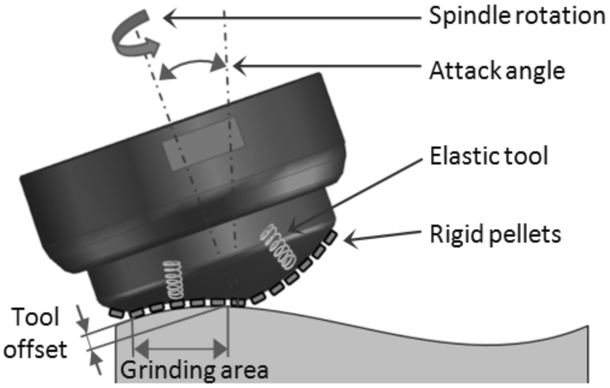


図9 Principle of Shape Adaptive Grinding tool.

We summarize the operation of the SAG process as follows: The position and orientation 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. While a classical grinding tool is moving against the surface of the part and cutting as it moves, in the technique we describe the Z position and tool inclination (but not directly the contact-force) are actively controlled with a CNC machine tool. It is possible to numerically control the inclination angle, spindle speed, geometrical offset, and surface feed of the grinding spot to obtain variations in spot size and removal rate.

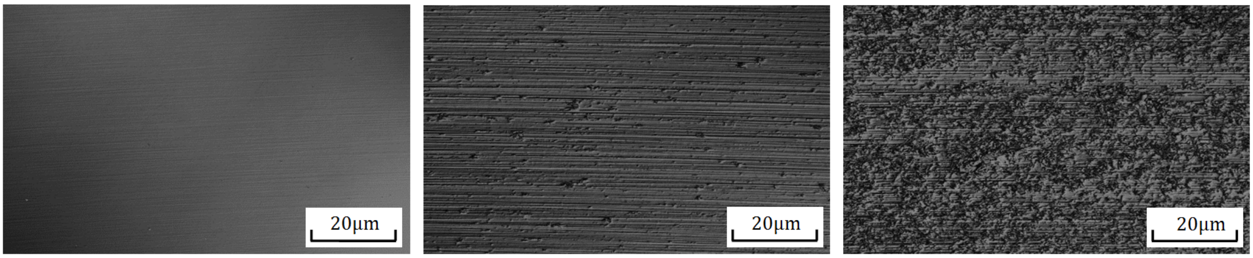
2.3 Experimental Results

A series of process characterization experiments were carried out on CVD silicon carbide, using the process parameters shown in Table 2. The samples were 100 mm diameter graphite pucks coated with 100um thick CVD silicon carbide, prepared in industry. The range of parameters included usage of resin and nickel for the pellet material, diamond grit sizes ranging from 3 to 40 μm diameter, SAG tool radius ranging from 10 to 40 mm, and machine feed rates ranging from 10 to 1000 mm/min.

表 2　Process Parameters of SAG Experiments

Tool Type	Rubber reinforced with Kevlar
Grinding Cloth	Intertwined textile/metal fabrics
Tool Diameter	10 to 40 mm
Pressure Range	0.5 to 2.0 bar
Tool Path Mode	Raster
Track Spacing	0.15 mm
Attack Angle	10 to 20 deg
Feed Range	10 to 1000 mm/min
Spindle Speed	100 to 3000 rpm
Abrasives	Diamond
Grain Size	3, 9, 40 μm
Pellet Binder	Nickel and resin

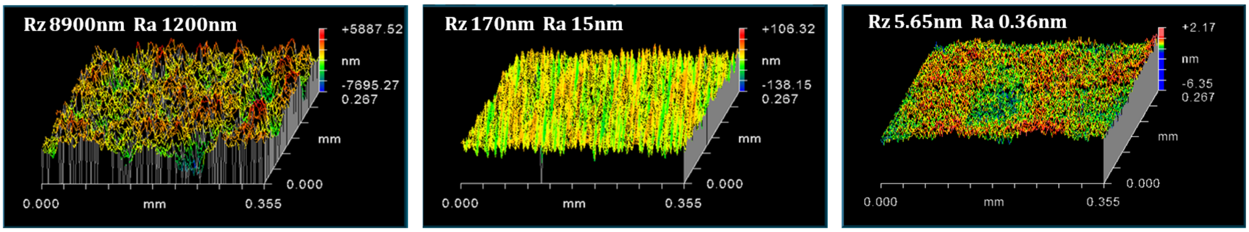
Grinding modes were characterized with a laser confocal microscope at 100x magnification. The microphotographs showed grinding modes from purely ductile to fracture, as shown in Fig. 10. Microphotographs for the 9 μm diamond abrasives bound in either nickel or resin were identical, suggesting that pellet material does not influence much the grinding mode. Likewise, air pressure did not have much influence on the number of fracture pits observed in the micrographs.



(a) Ductile mode　(b) Ductile and fracture mode　(c) Fracture mode

図 10　Micrographs of the various grinding modes observed (100x objective).

Optimum surface conditions are shown for selected pellets in Fig. 11. In the case of 9 μm diamond bonded in nickel it was possible to achieve roughness 15 nm Ra, and in the case of 3 μm diamond bonded in resin roughness less than 0.4 nm Ra at both 10x and 50x magnification.



(a) CVD SiC coating (b) Ground with 9 μm diamond (nickel pellets) (c) Ground with 3 μm diamond (resin pellets)

図 11 White light interferometer measurements of surface conditions (10x objective).

4. Conclusions

Plans for future hard X-ray space telescope missions will rely on the ability to produce highly accurate aspheric mandrels for thin mirror replications, with significantly reduced costs when compared to previous missions. In the first instance, this research has demonstrated a capability to produce fused silica aspheric Wolter type-1 mandrels with form accuracy below 100 nm P-V, through the use of Ultra-precise measuring and corrective polishing equipment. In the second instance, cost reduction through the use of graphite/SiC instead of fused silica has been investigated, leading to the development of a novel grinding technology capable of finishing SiC coatings with micro-roughness below 0.5 nm rms. It is expected that this new technology can be applied in the same manner as the polishing technology used to correctively polish fused silica mandrels.

References

1) A. Beaucamp, Y. Namba, H. Combrinck, P. Charlton, R. Freeman, Shape adaptive grinding of CVD silicon carbide, Annals of the CIRP, **63**, 1 (to be published in Aug. 2014).

2) A. Beaucamp, Y. Namba, W. Messelink, D. Walker, P. Charlton, R. Freeman, Surface integrity of fluid jet polished tungsten carbide, Procedia CIRP, **13** (to be published in May 2014).

3) A. Beaucamp, Y. Namba, Novel Grinding Method for CVD Silicon Carbide, Proc. JSPE Spring Meeting, pp.1245-1246, 2014.

4) A. Beaucamp, Y. Namba, P. Charlton, R. Freeman, Ultra-Precision Machining of Aspheric Molding Dies for Future Hard X-ray Telescope Missions, Proc. 12th International Conference on X-ray Imaging Optics, pp.3-4, 2013.

5) A. Beaucamp, Y. Namba, P. Charlton, R. Freeman, Advances in Corrective Finishing of Optical Moulds for Future Aspheric Hard X-ray Telescopes, Proc. Frontiers in Optics 2013/Laser Science XXIX, pp.FTh4E-1-2, 2013.

6) Y. Namba, A. Beaucamp, Ultra-Precision Machining of Aspheric Molding Dies for Next Generation X-Ray Telescopes, Proc. JSPE Autumn Meeting, pp.239-240, 2013.

7) A. Beaucamp, Y. Namba, P. Charlton, R. Freeman, Finishing of EUV Photomask Substrates by CNC Precessed Bonnet Polisher, Proc. SPIE, **8880**, pp.888018-45-1-8, 2013.

8) A. Beaucamp, Y. Namba, R. Freeman, Development of hybrid fluid jet/float polishing process, Proc. SPIE, **8838**, pp.88380-27-1-8, 2013.