Advances in ultra-precision grinding and polishing of silicon carbide for application to imaging X-ray optics

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1. Introduction

When dealing with high energy X-ray radiation, 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. To meet this challenge, replication from super-polished optical molding dies has become the preferred method. Fig. 1 shows a chronology of past X-ray telescope missions based on replicated imaging optics: from ASCA to XMM-Newton, Suzaku, and ASTRO-H, incremental progress in finishing and replication technologies have enabled ever improved angular resolution and/or energy bandwidth.

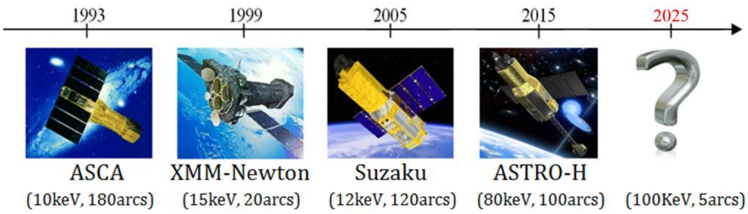

Fig. 1. Past and Future Specifications of X-ray Imaging Telescope Missions.

Over the past 3 years, we have been researching new methods for fabricating optical molding dies for the next generation telescope, with ever more stringent shape accuracy (below 100 nm P-V) and surface roughness (below 0.3 nm rms). A full size demonstrator aspheric mold meeting this specification was successfully produced using fused silica as the substrate material [1]. Our next aim has been to reduce the costs associated with the fabrication process. For this purpose, we have sought to replace the expensive fused silica substrate with more economical graphite coated with CVD silicon carbide. The proposed process chain involved in such case is shown in Fig. 2, which includes a newly developed super-fine grinding method called Shape Adaptive Grinding (SAG) [2,3]. This paper report on the production of an aspheric optics using the shape adaptive grinding process.

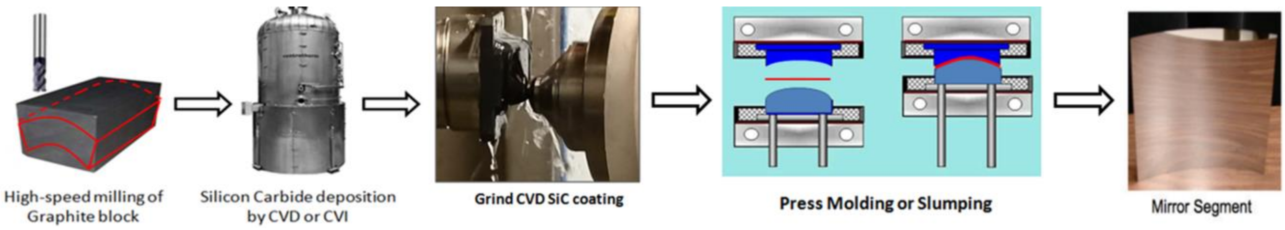

Fig. 2. X-ray optics replication process, using graphite molds coated with CVD silicon carbide.

2. Fabrication of aspheric silicon carbide optic

2.1 Workpiece preparation

A 100mm diameter aspheric convex optic was coated in industry with a 100µm CVD silicon carbide layer, as shown in Fig. 3 (top). Form deviation after coating was 40µm P-V, and micro-roughness was 4µm Ra.

2.2 Rough grinding

The workpiece was rough ground with our shape adaptive grinding technology using 40µm and 9µm diamond tools. Form deviation was reduced to less than 2µm P-V, and micro-roughness down to 20nm Ra.

2.3 Pitch smoothing

A shape adaptive grinding tool was coated with optical pitch, in order to smooth out mid-spatial frequencies on the surface (in the range of 0.5 to 5mm wavelength), without compromising the overall form accuracy.

2.4 Fine grinding

Finally, the workpiece was fine ground with our shape adaptive grinding technology using 3µm diamond tools, down to the final condition shown in Fig. 3 (bottom). Form deviation was reduced to ~200nm P-V (15nm rms), as shown in Fig. 4, and micro-roughness down to less than 1nm Ra.

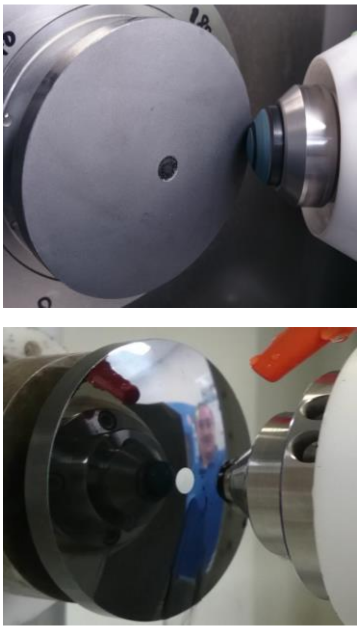

Fig. 3. Aspheric optic before and after SAG grinding

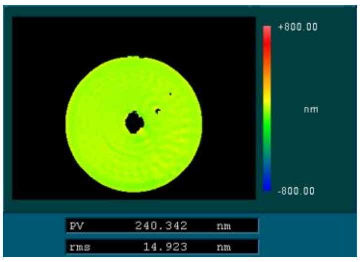

Fig. 4. Form error of finished silicon carbide aspheric optic

3. Conclusion

The summary presented in Fig. 5 shows that our newly proposed fabrication method based on SAG machining of CVD SiC coated graphite compares very favorably against the established methods on electroless nickel and fused silica. Some aspects require further research, especially 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, but it can be envisaged that the CVD SiC coating on graphite fabrication method may become the preferred method to manufacture optical molding dies in a future X-ray telescope mission.

	Electroless nickel (plating on aluminum)	**Fused silica**	**CVD silicon carbide (coating on graphite)**
Cost of raw materials	++	+	+++
Portability of molding dies (weight/size)	+	++	+++
Cost of machining equipment	+	++	+++
Overall machining time	+	++	+++
Ease of attaining the final roughness	+	+++	++
Ease of replication	+	+++	?

Fig. 5. Comparison of various X-ray optical dies fabrication methods.

References

[1] A. Beaucamp, et al.: Ultra-precision machining of aspheric molding dies, Proc. 12th XIO (2013).

[2] A. Beaucamp, et al.: Shape adaptive grinding of CVD silicon carbide, Annals of the CIRP, 63, 1 (2014).

[3] A. Beaucamp, et al.: Process mechanism in shape adaptive grinding (SAG), Annals of the CIRP, 64, 1 (2015).