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Manufacturing advances in large grazing-incidence optics

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The fabrication of large grazing-incidence mirrors imposes needs for special fabrication and coating equipment, facilities, and raw materials. The economic realization of such optics has been readily accomplished through close interactions between the mirror users, the fabricator and the manufacturer of the raw material designated as mirror substrate. The manufacture and delivery of a 1.4 m flat and 1.0 m conical mirror are used to provide examples of recently demonstrated manufacturing technologies and effective interactions between participating organizations.

Keywords: conical mirrors; grazing-incidence optics; optical fabrication.

1. Introduction

The manufacture of mirrors for synchrotron applications requires special attention to characteristics of surface roughness and slope error, often while processing increasingly large rectangular substrates of optimistic thickness-to-length ratios. These mirrors are often needed with flat, cylindrical, or conical surfaces, requiring specialized machinery as a means of manufacture (Lunt *et al.*, 1992). Consequently, the realization of large optics for grazing-incidence applications can be as much a matter of facilitation and equipment as it is a matter of the skill and resourcefulness of an optical craftsman. The manufacture of a flat 1.4 m ULE mirror and a 1.0 m silicon conical mirror for advanced synchrotron applications are examples.

2. Defining the 1.4 m flat mirror

Discussions with the user of a 1.4 m flat synchrotron mirror began with an informal request for an engineering estimate of cost and schedule. Originally, this mirror was to be 1.5 m long, 75 mm wide and 50 mm thick, and was specified to be made from ultra-low-expansion titanium silicate (ULE), a product of Corning Glass Works. While assembling a manufacturing plan it developed that a 1.5 m rectangular mirror would carry a substantial cost penalty, due not to fabrication or coating considerations, but to issues concerning the convenient producability of the raw blank from existing ULE inventory. Corning Glass Works offered the alternate suggestion of using a mirror substrate 1470 mm long, or less, which could be provided for a cost substantially less than that of the 1.5 m size. With this information the mirror user was able to iterate the early conceptual design of the mirror, arriving at a mirror length of 1.4 m. Specifications for the final mirror are summarized below, in Table 1.

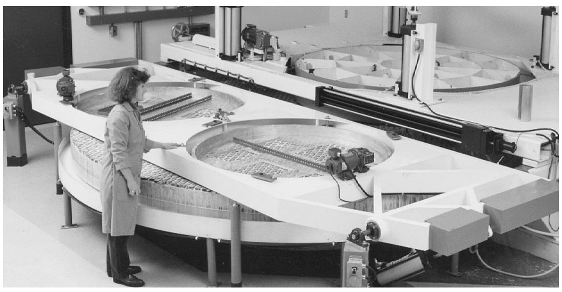

Figure 1
The 4.25 m (168″) planetary polishing machine.

Table 1
Mirror specifications.

Mirror length	1400 mm	Mirror width	100 mm
Mirror thickness	50 mm	Surface shape	Plano
Tangential slope error	10 µrad r.m.s.	Sagittal slope error	10 µrad r.m.s.
Surface roughness	10 Å r.m.s.	Coating	100 Å Cr/600 Å Au

3. Fabrication of the 1.4 m mirror blank

With the arrival of the ULE mirror blank, an incoming inspection verified the dimensions and absence of imperfections within the blank. The work that followed was permitted only because facilities and equipment suited to a mirror of this size existed in place. The blank proceeded through lapping operations where the front and rear surfaces and the sides were ground against a pre-flattened cast-iron lapping plate. Acid etch operations were performed with hydrofluoric acid in a specialized facility. This operation provided lapped surfaces believed to contain a minimum population of microfractures which might otherwise entrap manufacturing contaminants or release atmospheric species when the mirror is placed into UHV service. The front surface of the mirror was then lapped with a final abrasive to establish suitable flatness prior to transferring the mirror to the polishing facility.

4. Polishing, testing and coating the 1.4 m mirror

4.1. *Polishing and testing the 1.4 m flat mirror*

The ability to polish a mirror 1.4 m long was provided by a planetary polishing machine installed a few years earlier. This machine has a polishing table 4.25 m (168″) in diameter with work stations 1.5 m in diameter. The polishing table is supported at 70% of its diameter by an annular hydrostatic bearing. The machine is installed in a concrete-lined pit, about 1 m (39.4″) deep. The result of this arrangement is the efficient accommodation of the machine (Fig. 1). It can be seen that the low-profile installation provides ready access to the polishing table, allowing optics to be introduced or removed with relative ease. The work stations of the machine can be configured to hold a variety of workpieces for simultaneous processing.

The 1.4 m mirror was installed in a septum to register its position within its assigned work station ring. Polishing operations proceeded while controlling the temperature of the room, of the polishing slurry and of the hydraulic oil pumped to the table bearing. This establishes a steady-state condition and limits changes of tables flatness to be those imposed by varying the radial position of the conditioner disc on the annular pitch lap.

Table 2
Post-coating surface roughness.

Spatial period	Measured roughness
20–2000 μm	5.22–5.56 Å r.m.s.
5–250 μm	5.02–5.26 Å r.m.s.

Once the mirror surface was brought to full polish, ongoing operations were periodically interrupted to measure surface figure and roughness by means of a phase-modulated interferometer. The errors detected on the mirror surface were used to infer the shape of the pitch lap and to prescribe a corrective placement of the conditioner disk on the lap. Work continued until in-process measurements indicated a surface had been achieved which was within the specifications assigned to the mirror. Upon completion of polishing operations characteristics of surface figure and surface roughness were rigorously measured. Surface figure data for tangential slope errors are shown in Fig. 2. Surface roughness measurements included overlapping spatial periods to provide coverage from 5 to 2000 μm. Typical measurements for surface roughness at 5× are shown in Fig. 3. Sagittal slope errors were limited to 8.41 μrad r.m.s.

Residual surface errors left by the planetary polishing system are dominated by low-frequency aberrations such as power, third-order spherical aberration, coma and astigmatism. The process, by its very nature, normally discriminates against errors in the mid-frequency regime. These effects can be seen by comparing the tangential slope errors of Fig. 2 with those of Fig. 4. Here, the low-frequency aberrations of power, astigmatism, coma and third-order spherical aberration have been subtracted to reveal the extent of mid-frequency errors. The residual slope errors are 1.69 μrad r.m.s. These are dominated by turned edges at the extremities of the mirror surface.

4.2. *Coating the polished surface*

A coating of gold, 600 Å thick, was specified to optimize the performance of the mirror. This layer was preceded by a binder layer of chrome, 100 Å thick. The equipment used to deposit these films consists of a linear sputtering system equipped with two sputtering guns installed at the center of a horizontal vacuum cylinder 3 m in length.

The linear coating system allows the deposition of thin films on mirror substrates up to 1.5 m long and 250 mm wide. The 1.4 m flat mirror substrate was cleaned and loaded into a transport carrier suspended from an elevated rail. In this assembly the substrate was transferred into the vacuum chamber and the port was closed. After pump down to sufficiently low pressure a lead screw advanced the mirror carrier through the chamber, passing it above an energized sputtering gun having a chromium target. The mirror was returned to its starting position within the chamber and a second coating cycle was performed using the second sputtering gun equipped with a gold target. The film thickness resulting from these operations is a function of dwell time of the mirror substrate as it passes over the gun. Roughness measurements were repeated at seven sites on the coated surface; the results are summarized in Table 2. In Fig. 5 the 1.4 m mirror is shown prior to coating and is compared to a 1.0 m ULE mirror having two coating strips.

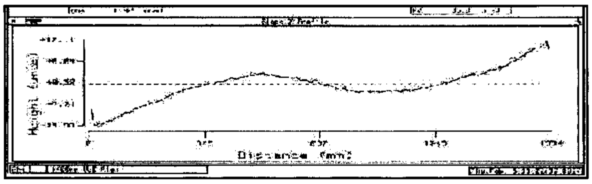

Figure 2
Tangential slope errors of the 1.4 m flat mirror – 6.42 μrad r.m.s.

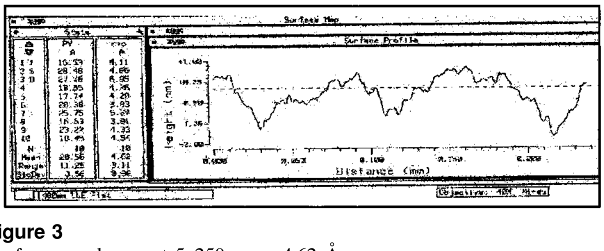

Figure 3
Surface roughness at 5–250 μm – 4.62 Å r.m.s.

5. Defining the 1.0 m conical mirror

The need for a conical X-ray mirror developed from design work performed by the Consortium for Advanced X-ray Sources (CARS) at the University of Chicago (Meron *et al.*, 1995). In this work it was found that a grazing-incidence mirror of conical prescription, when bent to appropriate tangential curvature, would allow 2:1 focusing of the X-ray light source. An image could be thus provided 40 m from the source where a monochromator would transfer the light to an experimental station 5 m away. This arrangement satisfied the need to illuminate effectively virus samples of large size and the practical need of working within the physical constraints of the experimental hall. At the intended location of the mirror in the beamline, the incident flux on it was determined to be such that heat would need to be removed from the optic by incorporating a heat exchanger into the body of the mirror. Though the conical shape of the surface seems a straightforward extension of technology producing common sagittal cylinder mirrors, the feasibility of readily fabricating such a surface to a specified cone angle, slope error and surface roughness had not been demonstrated. This led to a developmental effort which resulted in the fabrication of a 1/3 scale prototype mirror, with encouraging results (Meron *et al.*, 1995). With this experience it was then possible to proceed with

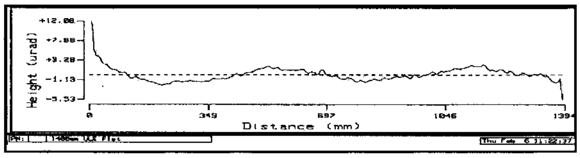

Figure 4
Mid-frequency contributions to tangential slope error profile – 1.69 μrad r.m.s.

Figure 5
The uncoated 1.4 m flat mirror is compared to a coated 1.0 m mirror.

Table 3
Conical mirror parameters.

Mirror length	1000 mm	Mirror width	75 mm
Design angle of incidence	4.1 mrad	Cone angle	0.97 (5) mrad
Sagittal radius (mean)	80.5 (5) mm	Sagittal slope error	15 μrad r.m.s.
Tangential slope error	5 μrad r.m.s.	Surface roughness	6–7 Å r.m.s.

Table 4
Achieved conical mirror characteristics.

Cone angle	0.957 mrad
Sagittal radius (mean)	80.95 mm
Sagittal slope error	10.7 μrad r.m.s.
Tangential slope error	3.4 μrad r.m.s.
Surface roughness	3.0 Å r.m.s.

the design and manufacture of a 1 m-long mirror blank incorporating an integral heat exchanger. The parameters assigned to the conical mirror are presented below, in Table 3.

The specification for sagittal slope errors applied to an optically clear aperture comprising the central 32 mm of the mirror width; the tangential slope error tolerance applied to an optically clear aperture equal to 80% of the mirror length.

6. Manufacture of the water-cooled silicon mirror blank

The heat exchanger of the water-cooled silicon mirror consisted of a simple channel flow design. For this device a two-layer silicon assembly was produced where one of the common interface surfaces contained the details of the coolant channels and distribution manifold, while passages extending through the rear component of the assembly provided inlet and outlet for coolant flow. The manufacturing process began with a boule of single-crystal silicon from which two rectangular planks were carefully cut by means of a band saw equipped with a diamond blade. The resulting planks were surface ground to desired size and the surfaces were lapped. Coolant channels were ground into one interface surface using an ultrasonic impact grinding process (Moore, 1988). Inlet and outlet passages were ground through the rear component by rotary-assisted impact grinding. The surface stresses inflicted by the various grinding operations were removed by acid etch, thereby stabilizing the mirror components in a low-stress state (Bender & Wahl, 1991). The separate components were permanently joined and metal fittings were attached to the assembly. At this point the integrity of the mirror blank was verified by a proof pressure test and a helium leak test.

7. Optical fabrication and coating the conical mirror

7.1. *Grinding and polishing the conical prescription*

The task of producing the conical surface began when a sagittal radius of 81 mm was ground into the front surface using a vertical milling machine equipped with a right-angle head and diamond abrasive wheel. This operation produced a cylindrical surface. To convert the cylindrical curvature to the conical prescription the mirror was transferred to a cylinder lapping/polishing machine, where it was free-abrasive ground against a conical mandrill of revolution.

These operations resulted in a fine-ground near-conical surface having low to mid-frequency errors as influenced by the limited length of the stroke and those errors either existing or developing in the mandrill surface. Optical interferometry, however, revealed the error of greatest magnitude to be a mild toroidal shape due to the existence of a convex curvature amounting to 13.9 μm (0.00054″) along the tangential axis of the mirror surface. The magnitude of this error and the finish of the surface, however, were small enough to proceed to the next stage of work. Polishing operations were performed on the same piece of machinery after replacing the conical mandrill with a special pitch polishing tool. This tool was designed to accommodate the conical prescription and ensure that the mirror would not be preferentially returned toward a cylindrical shape. It was possible to correct and control the optical figure by varying polishing parameters of stroke length and speed, and by induced preferential wear. In-process measurements were made by a combination of long-trace-profiler (LTP) and a variety of automated phase-modulated interferometric techniques. These allowed separate assessment of the tangential surface figure, sagittal surface figure, surface roughness and the local sagittal radii present at intervals along the tangential surface. At the conclusion of polishing operations the tangential curvature had been reduced to about 1 μm with slope errors limited to 3.4 μrad r.m.s. Measured characteristics for the completed mirror surface are summarized in Table 4, while the actual measurement data are presented in Figs. 6 and 7. Discrete radius data illustrating the linearity of the cone and its relationship within specified tolerances are summarized in the plot of Fig. 8. The conical mirror is shown in Fig. 9. Upon conclusion of polishing operations proof pressure and helium leak tests were repeated to verify again the integrity of the heat exchanger.

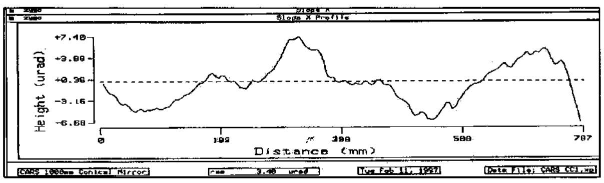

Figure 6
Tangential slope errors – 3.4 μrad r.m.s.

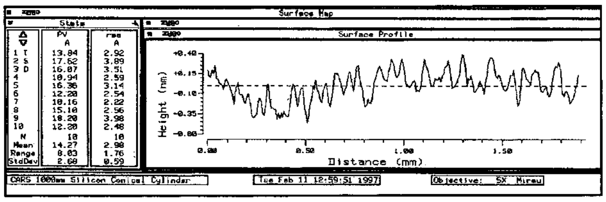

Figure 7
Typical surface roughness – 3 Å r.m.s.

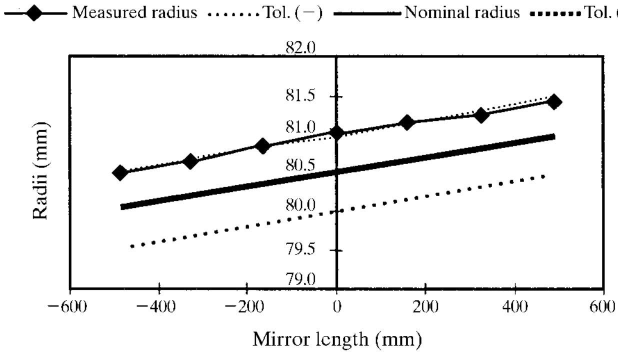

Figure 8
The achieved conical shape.

Figure 9
The polished water-cooled silicon conical mirror.

7.2. *Coating the polished surface*

A single layer of rhodium, 500 Å thick, was specified to optimize the performance of the conical mirror. Coating uniformity was validated for the curved mirror surface by first processing sample coupons arranged within the chamber to simulate the geometry of the mirror. Step-height measurements were made to confirm a ±15Å tolerance for coating uniformity.

8. Conclusions

An ultra-low-expansion 1.4 m flat synchrotron mirror was manufactured to customer specifications for X-ray use. The availability of a mirror of this size and shape suited to grazing-incidence application was due in part to timely commitments in terms of polishing and coating equipment and support facilities. Early interactions between the mirror user and the manufacturer identified available economies in the cost of a designated substrate material. A water-cooled silicon conical mirror of 1 m-length was successfully manufactured and coated for use at the Advanced Photon Source. This work was preceded by optical analysis verifying the performance of such a mirror and by developmental work performed on a sub-size mirror which validated initial concepts for producing a conical prescription within desired tolerances. The success of the preliminary effort then justified the design and manufacture of a sizable water-cooled mirror blank and allowed the use of second-generation refinements to the optical fabrication procedure.

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