The Development of Hard-X-Ray Optics at MSFC

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ABSTRACT

We have developed the electroformed-nickel replication process to enable us to fabricate light-weight, high-quality mirrors for the hard-x-ray region. Two projects currently utilizing this technology are the production of 240 mirror shells, of diameters ranging from 50 to 94 mm, for our HERO balloon payload, and 150- and 230-mm-diameter shells for a prototype Constellation-X hard-x-ray telescope module. The challenge for the former is to fabricate, mount, align and fly a large number of high-resolution mirrors within the constraints of a modest budget. For the latter, the challenge is to maintain high angular resolution despite weight-budget-driven mirror shell thicknesses (100 µm) which make the shells extremely sensitive to fabrication and handling stresses, and to ensure that the replication process does not degrade the ultra-smooth surface finish (~3 Å) required for eventual multilayer coatings. We present a progress report on these two programs.

Keywords: electroform-nickel replication, x-ray imaging, grazing-incidence optics, x-ray astronomy.

1. MOTIVATION

The motivation for the development of hard-x-ray optics is obvious. Grazing incidence telescopes have brought about spectacular advances at soft-x-ray wavelengths, yet the hard-x-ray region, where such instruments are yet to be routinely used, remains relatively unexplored at high sensitivity and fine angular scales. The power of focusing, though, is such that even modest collecting areas can give a large increase in sensitivity over non-focusing instruments. Consider Figure 1, which shows the equivalent mirror collecting area, as a function of integration time, necessary to equal the sensitivity of a 1000 cm^2 coded aperture system over the energy band 30-50 keV. The background for both detectors is taken to be 5×10^{-4} counts / cm^2 s keV, and the mirror has a focal length of 6 m. Two different mirror resolutions are considered. It is evident from this figure that a ~ 100-cm^2-class focusing hard-x-ray telescope would have an order of magnitude greater sensitivity than a typical (1000 cm^2) non-focusing system over typical observing times, and that the smaller the mirror's half power diameter (HPD), the larger this increase will be.

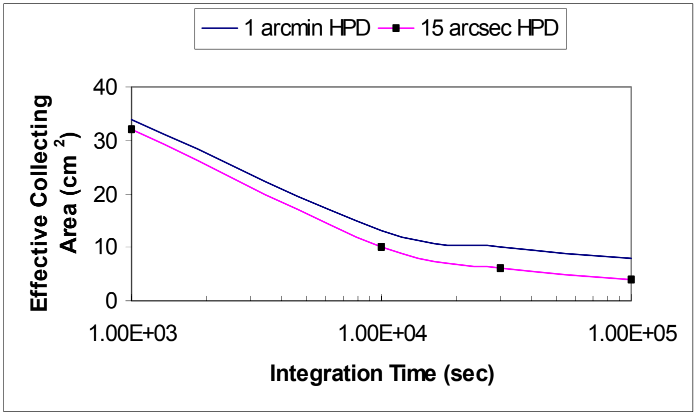

Figure 1: Equivalent mirror (6-m-focal-length) collecting area needed to equal the sensitivity of a 1000 cm^2 coded-aperture telescope for different integration times. The energy band is 30-50 keV, and the detector background is taken to be 5×10^{-4} counts / cm^2 s keV.

The combination of an energy region ripe for exploration together with the ability to perform groundbreaking science with modest and, as will be shown later, attainable collecting areas, has led us to a development program of x-ray optics for the hard-x-ray region. This program is discussed in detail below:

2. ELECTROFORMED NICKEL REPLICATION (ENR)

The mirror fabrication process that we have chosen to develop is that of electroformed nickel replication (ENR). In this, nickel mirror shells are electroformed onto a figured and superpolished aluminum mandrel from which they are later released by differential thermal contraction. This process was pioneered in Italy for x-ray mirror production and has been used for such missions as XMM-Newton[1], which features 3 mirror modules each with 68 electroformed nickel shells.

A distinct advantage of the electroforming process is that the resulting mirror shells are full circles of revolution which are inherently very stable. This typically results in better figure accuracy, and hence better angular resolution, than is possible with segmented optics. A drawback, however, is the high density of nickel, which necessitates very thin shells for lightweight optics. These shells must be made strong enough to withstand the stresses of fabrication and subsequent handling without being permanently deformed. They must also be electroformed in an ultra-low-stress environment to prevent stress-induced distortions in their free-standing state. To ensure high-quality optics, we have therefore made developments in the areas of : 1) material strength; 2) adhesion and release and; 3) plating bath stress control.

Material Properties : Pure nickel is a ductile material with a very low yield point. Even modest applied stresses, such as those encountered when thin shells are separated from their mandrels, can cause the parts-per-million permanent strain of concern for high-resolution optics. To prevent such distortions, we have developed a nickel cobalt alloy[2] that is much stronger than pure nickel. Figure 2 shows permanent strain measurements, taken using a speckle interferometry technique, of this new alloy compared with pure nickel. It can be seen that for the nickel cobalt alloy the onset of plastic deformation is at a strain at least a factor of two higher. Modeling shows that this strain will never be exceeded in normal shell separation.

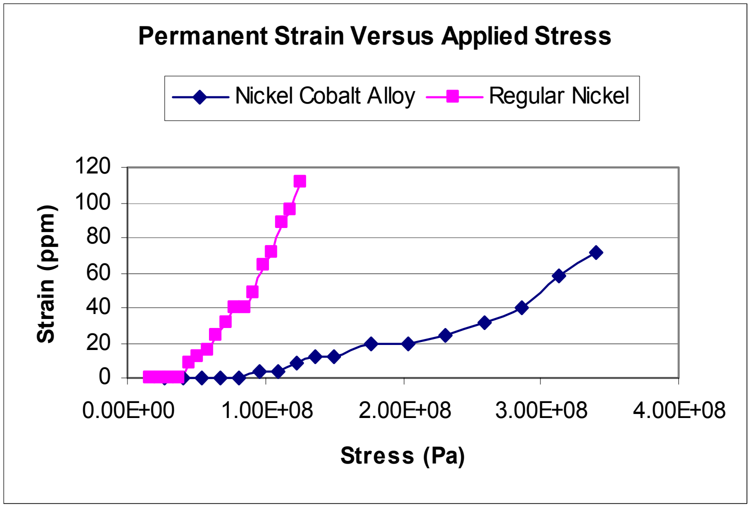

Figure 2: Permanent strain of pure nickel and nickel/cobalt alloy as a function of applied stress

Adhesion and release: The key here is to develop a surface preparation that provides adequate adhesion for mirror shell growth, while at the same time permitting an easy release after electroforming without figure-distorting stresses. In addition, the surface treatment should not significantly degrade the mandrel's few-angstrom-level finish after just a few replications. Our original process included a ‘ standard’ potassium dichromate treatment to form a release oxide on the mandrels surface. However, after repeated replications from the same mandrel a significant surface degradation was observed. While WYKO optical measurements confirmed a general worsening, the level was only measured to be 1-2 Å, despite the effect being highly visible under intense glancing-angle white light. Atomic force microscope analysis, a true topographical measure at finer spatial frequencies than is possible with the WYKO, confirmed, however, that the surface had degraded considerably, down to 10-20 A rms.

As very-high-quality mirror-shell surfaces are needed for multiplayer coatings (§3.2), we have departed from the potassium dichromate treatment and have developed a more controlled electrolytic process using a strongly alkaline solution. In this process, a scanning potentiostat is used to reduce the mandrel's existing oxide and grow a fresh layer prior to each electroforming run. Analysis of the mandrel and the replicate's surface after 18 replications shows the few-angstrom-level maintained, as desired.

Stress Control: Finally, to maintain figure in a free-standing mirror shell stresses imparted by the electroforming process must be minimized. To do this we have fine-tuned the electroforming bath to give near zero stress over a broad range of current densities, and have modeled and optimized the electric field configuration along the mandrel to ensure near uniform plating current density. It is estimated that the resulting stress variation along the full length of our shells is no greater than +/- $3x10^5$ Pa.

3. HARD-X-RAY MIRROR APPLICATIONS

3.1. HERO

HERO, for High Energy Replicated Optics, is an evolutionary balloon program. It utilizes in-house-fabricated hard-x-ray ENR mirrors plus supporting detectors, gondola and pointing system. The mirror design philosophy is to utilize a large number of shallow-graze-angle, iridium-coated shells, moderately nested in multiple mirror modules. The use of a large shell length to diameter ratio reduces the number of mandrels necessary. To keep costs appropriate to a balloon program, the mandrels are ground to figure and then polished on simple, in-house-designed machines. A multipart plater then permits several shells to be electroformed simultaneously. Figure 3 shows the electroforming tank (left), and a sample of the resulting mirror shells (right).

Figure 3: At left, the Ni/Co alloy electroforming bath with the multipart plater. At right, a selection of resulting mirror shells.

The full HERO payload, scheduled for flight in 2005, will consist of 16 mirror modules each housing 15 nested shells. Table 1 gives the optical configuration for this payload plus the sensitivity level that we expect to achieve with this payload on standard balloon flights, where a typical observation is 10^4 s, plus future long and ultra-long-duration flights where 10^5 and 10^6 s observations would be possible.

Table 1: HERO final mirror configuration

Parameter	Value
Mirror shells per module	15
Inner shell diameter (mm)	50
Outer shell diameter (mm)	94
Total shell length (mm)	610
Focal Length (m)	6
Shell thickness (mm)	0.25
Interior coating	50 nm Iridium
Number of mirror modules	16
Effective area (cm^2)	200 @ 50 keV, 120 @ 60 keV
Angular resolution (half power diameter)	15" (goal)
Field of view	9' at 40 keV, 5' at 60 keV
Payload sensitivity (5σ) @ 40 keV, 10 keV band, 40 km altitude, for an integration time of :	
10^4 s	1 mCrab (6.10^{-6} photons/cm^2 s keV)
10^5 s	140 μCrab (10^{-6} photons/cm^2 s keV)
10^6 s	30 μCrab (2.10^{-7} photons/cm^2 s keV)

It is evident from these numbers that the HERO payload will give very high sensitivities; even a three-hour observation will give milli-Crab-levels which will make over 100 galactic sources available for study. For the longer integration times, possible on future long- and ultra-long-duration flights, this numbers will increase to many thousands.

3.1.1. Current Status

A HERO partial payload flight is currently scheduled for the Spring of 2004 from Fort Sumner, New Mexico. The payload will consist of 8 mirror modules each with 8-10 mirror shells, giving a total effective area of 60-75 cm^2 at 50 keV. To date, 8 mandrels have been completed and another two are in fabrication. The shells from the completed mandrels have yet to be coated with iridium, but some have been tested to check their figure quality. These tests were performed at the 102-m stray-light facility at MSFC, with the optics and test detector located in air at the end of the beam tube. Figure 6 (left) shows a mirror module mounted on a tip/tilt stage immediately in front of the beam tube's beryllium exit window, and Figure 6 (right) shows a close up of the module with 4 test shells mounted in it.

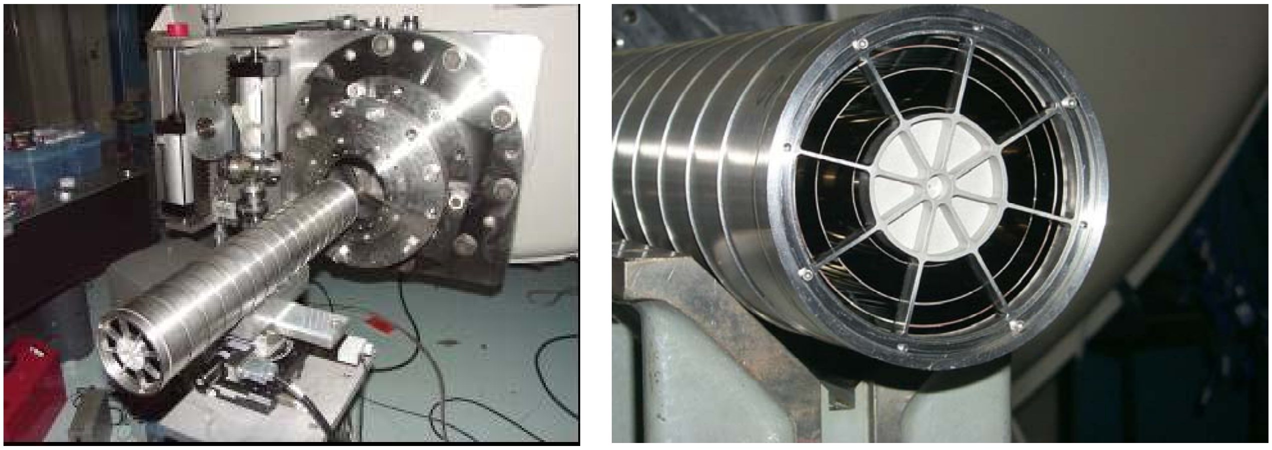

Figure 6: A HERO mirror module at exit of the 102-m beam line (left). A close up of the module showing 4 mirror shells under test.

Figure 7 below shows representative data from these tests. On the left is the encircled flux measured for one of the larger HERO shells (88mm diameter) and on the right is the same data from the 4-shell mirror module pictured above which includes the same shell. Typical mandrel metrology gives a performance prediction for the shells of around 8-10 arcsec Half Power Diameter (HPD). Individual mounted shell measurements show 13-15 arcsec HPD, as in the case of the 88-mm shell below, which has a HPD of just under 14 arcsec. When multiple shells are mounted, this degrades to ~ 17 arcsec, as for the module below right. As indications are that the mirror mount is distorting the shell figure, we are investigating different methods of attaching the shell to the support spiders in an effort to achieve our 15 arcsec mirror module performance goal. Note that because the shells are uncoated, and because of the finite source distance, the upper energy cut-off of the shells is quite low. All the tests above were performed over an energy range from 15-30 keV.

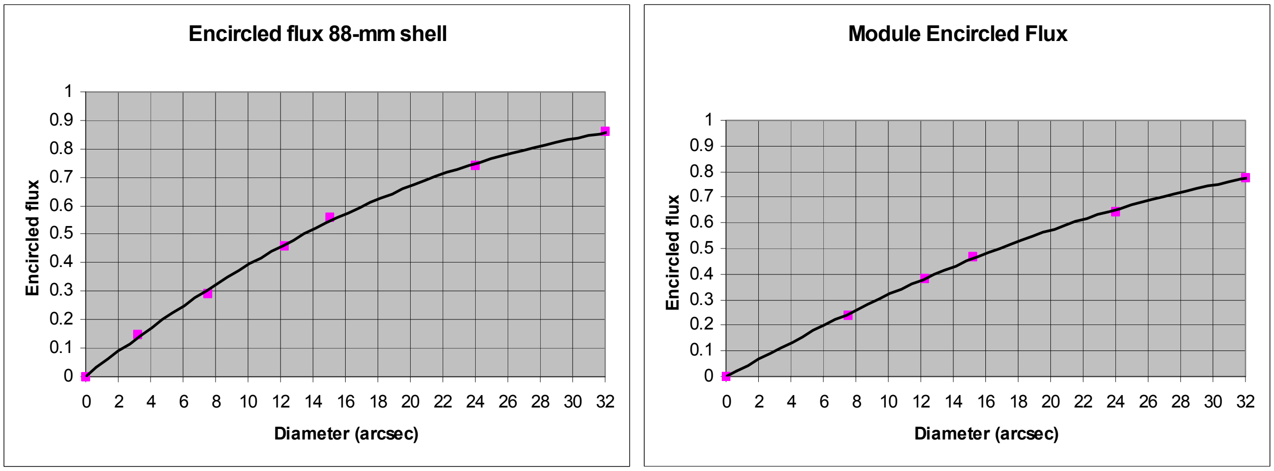

Figure 7: Encircled flux measurements (15-30 keV) on an individual shell (left) and a 4-shell module (right)

To register the focal plane images in flight, a set of 8 gas-scintillation proportional counters is being constructed. Further details on these can be found in [3]. The detectors and the mirror will be mounted at opposite ends of a 6-m-long carbon-composite optical bench, designed to provide stability over the large range of temperatures seen during a typical balloon flight. The optical bench in turn is mounted inside a gondola which houses the avionics and provides protection for the payload. A drawing of the gondola with the optical bench tube deployed is shown below in Figure 8. The gondola is currently nearing completion in a local machine shop.

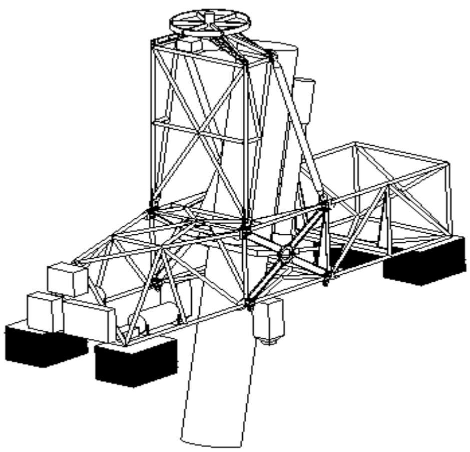

Figure 8: Design of the HERO gondola.

3.2. Constellation-X

Together with the Smithsonian Astrophysical Observatory and the Astronomical Observatory of Brera, Italy, we are working towards building and testing (2004) a prototype Constellation-X hard-x-ray telescope based on the ENR process[4]. MSFC's role in this is the production of an inner and an intermediate-size shell, the former 150 mm in diameter and coated with sputtered iridium, and the latter 230 mm diameter and coated with multilayers by SAO. Assembly of these into a mirror module, together with additional intermediate and outer shells provided by Brera, will be done in Italy.

The challenging aspects of this work are the very thin mirror shell walls dictated by the tight Constellation-X weight budget, and the high-surface-quality finish on the interior of the shells designated for multiplayer coating. The former necessitates production of shells of only 100 µm thickness and the latter dictates a surface finish of better than 3 Å rms.

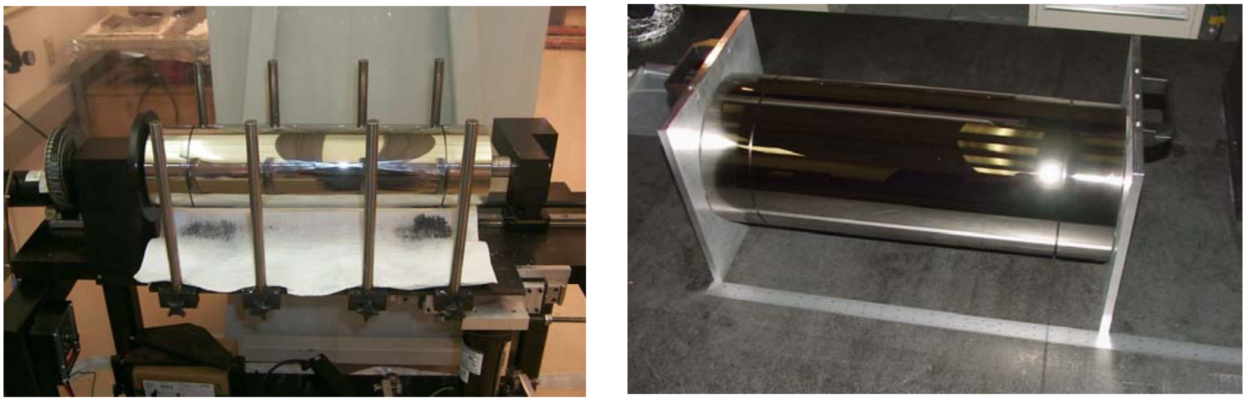

Figure 9: The 150-mm-diameter mandrel on the polishing machine (left) and the completed 230-mm mandrel ((right).

To date, the 230-mm mandrel has been completed and is ready for electroforming. Wyko data indicate a 'P' and 'H' surface roughness of 2.8 and 2.6 Å respectively and a figure error of less than 0.1 micron. The performance prediction for shells from this mandrel, which is a conical approximation to a Wolter-1 geometry, is 10 arcsec HPD. The 150-mm mandrel has been ground to figure and is currently being polished. Figure 9, above, shows this unit on the polishing machine (at left with polishing arms removed) and, at right, the completed 230-mm unit in a holding fixture.

One area of concern with multilayer-coated thin shells is that small amounts of stress in the coatings, either inherent or because of a mismatch in thermal expansion coefficients between the coatings and the shell, may distort the shell figure. Modeling was performed at MSFC and indicated that temperatures would need to be controlled tightly during deposition to ensure uniformity. To confirm this could be done, a series of 100-µm-thick test shells were fabricated at MSFC and shipped to SAO for test coatings. Metrology was performed before and after coating to look for stress-induced distortions. This work is still in progress, but to date no significant stress effects have been seen. Figure 10 shows one of the test shells in a support ring designed to facilitate handling.

Figure 10: 100-µm-thick shell for multilayer stress tests

4. CONCLUSION

We have developed the electroformed-nickel-replication process to produce light-weight, moderate-resolution optics for the hard-x-ray region. Two current applications of this technology are for the HERO balloon program and for a Constellation-X prototype hard-x-ray telescope. In the former, 240 shallow-graze-angle, iridium-coated mirror shells are being produced ranging in diameter from 50 to 94mm. Recent tests show that these have resolutions of 13-15 arcsec HPD. A flight of a partial payload with ~ 80 mirror shells is scheduled for Spring 2004, with a flight of the full payload planned for the Fall of 2005. For Constellation-X, we are fabricating 100-µm-thick shells of diameters 150 and 230mm, the former to be coated with sputtered Iridium at MSFC, and the latter with multilayers by our collaborators at SAO. The larger (completed) mandrel has metrology-derived performance prediction of 10 arcsec HPD. The smaller mandrel is still in fabrication.

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REFERENCES

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[1] http://www.sci.esa.int/science-e/www/object/index.cfm?fobjectid=31318

[2] D.Engelhaupt, B.D.Ramsey, S.L.O'Dell, W.Jones and K.Russell, " New Alloys for Electroformed Replicated X-Ray Optics,", **SPIE** 4138, pp. 154-163, 2000.

[3] M.V.Gubarev, B.D.Ramsey and J.A.Apple, "Gas scintillation proportional counters for high-energy x-ray astronomy," conference 5165, X-Ray and Gamma-Ray Instrumentation for Astronomy, this symposium.

[4] S. Romaine et. al., ' Development of a prototype nickel optic for the Constellation-X hard-x-ray telescope,' these proceedings.