X-Ray Optics at MSFC

Brian Ramsey, Steve Bongiorno, Dave Broadway
Outline

1. Electroformed nickel replication (ENR) – Brian Ramsey
2. Computer-controlled polishing – Steve Bongiorno
3. Full shell optics by direct fabrication – Steve Bongiorno
4. Differential deposition – Brian Ramsey
5. Low-stress coatings – Dave Broadway
6. X-ray optics process flow / Conclusion – Steve Bongiorno
Electroformed Nickel Replication (ENR)

**Mandrel - machining Al bar, electroless nickel coating, diamond turning and polishing**

**Metrology on mandrel**

**Electroform Ni/Co shell onto mandrel**

**Separate optic from mandrel in cold water bath**

**Replicated X-ray shell**
ENR– Current and Recent Programs

ART-XC instrument on Spectrum Rontgen Gamma Mission

FOXSI (Rocket)

IXPE Small Explorer

Non-Astronomical Applications
  Neutron Imaging
  Plasma Diagnostics

FOXSI Small Explorer (Phase A study)

X-ray optics at MSFC
New Developments
Computer Controlled (CC) Polishing

**Challenge**
- The optical figure of mandrels used to produce replicated nickel cobalt grazing incidence optics directly impacts performance of the optic.

**Objective**
- Reach sub-arcsecond half-power diameter (HPD) mandrel figure error to enable future missions.

**Approach:**
- Test methods for aligning Zeeko CC polishing machine coordinates with mandrel coordinates with mandrel fiducials.
- Continue improving surface roughness and polishing wear function stability by adjusting abrasive slurry parameters.
- Polish mandrels with Zeeko machine for shape correction and super polish with large laps to achieve final surface roughness.
- Estimate finished mandrel performance with mandrel metrology on Zygo interferometer at MSFC.
**CC polishing process loop**

1. Characterize machine/bonnet wear function
2. Map optic/mandrel surface error
3. Deconvolve surface error map with wear function to generate toolpath
4. Polish optic
5. Iterate
## Computer Controlled (CC) Polishing ART M26H

Cylindrical Correction Complete, azimuthal average, Polishing time: 71.5 hours

<table>
<thead>
<tr>
<th></th>
<th>before</th>
<th>after</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure error (St. Dev.)</td>
<td>500 nm</td>
<td>10.7 nm</td>
</tr>
<tr>
<td>Slope error (&gt; 2 cm) (RMS)</td>
<td>6.32 arcsec</td>
<td>0.30 arcsec</td>
</tr>
<tr>
<td>Low frequency (&gt; 7 cm) slope error (RMS)</td>
<td>2.66 arcsec</td>
<td>0.09 arcsec</td>
</tr>
<tr>
<td>Mid frequency (2-7 cm) slope error (RMS)</td>
<td>5.73 arcsec</td>
<td>0.29 arcsec</td>
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Full width at half max ≈ 6.66 * RMS slope error = 2.00 arcsec
Computer Controlled (CC) Polishing

**TRL Level**
Currently at ~ 3

**Challenges and future work**
- Complete test mandrel polishing and quantify surface quality improvement.

**Applicable to Athena**
Yes, for direct polishing of full-shell optics.
**Challenge**
• Future X-ray missions require large effective area, lightweight, high angular resolution grazing incidence optics.

**Objective**
• Using high specific stiffness metal materials (Be, AlSi, AlBe), produce sub-arcsecond grazing incidence full-shell optics approximately 3 mm thick.

**Approach:**
• Diamond turn inner and outer surface of as-purchased metal/metal-composite shells.
• Implement in-situ metrology to measure the shape of the shell while mounted in the polishing machine.
• Directly polish shells in the Zeeko machine at MSFC.
• If needed, apply differential deposition in chamber at MSFC to improve mid-spatial frequency shape error.
Thin-shell direct fabrication

- Aluminum surrogate shell
- Shell support structure mounted to diamond turning machine
**TRL Level**
Currently at ~ 2

**Challenges and future work**
- Delivery of 3 mm thick figured and polished NiP plated aluminum shell
- Design of X-ray test support fixture, and cross-calibrated verification of in-situ metrology system. Delivery of X-ray test support fixture and verification of the 3 mm and 1.5 mm thick mirrors via X-ray testing.

**Applicable to Athena**
Yes, for direct polishing of full-shell optics.
Objective
Develop a process to provide post-fabrication improvement to x-ray optics

Approach
Use physical vapor deposition to selectively deposit material on mirror surface to reduce figure errors.
Differential Deposition - Process

Differential deposition process flow

1. Surface profile metrology
2. Develop correction profile "Hitmap"
3. Simulations – translation velocity of shell
4. Differential deposition
5. Surface profile metrology
6. X-ray testing

Simulation of successive corrections with finer slits

1. Desired profile vs Pre correction - 7.8 arc-sec
2. Desired profile vs Post correction 1 - 5.2 arc-sec
3. Desired profile vs Post correction 2 - 2.7 arc-sec
4. Desired profile vs Post correction 3 - 0.9 arc-sec
Differential Deposition - Results

Axial figure profiles: Initial (blue), after 1 correction pass (red), after 2 correction passes (black)

Intra-focus x-ray image showing uncorrected and corrected mirror quadrants

• Using ART-XC mirror shells, have obtained a factor of > 2 improvement in angular resolution for a single stage of correction from 17 arcsec to 7.2 arcsec HPD.

• Metrology on mirror shell with 2 stages of correction shows factor of 3 improvement from 17 arcsec to 5 arcsec HPD.
**TRL Level**
Currently at ~ 3

**Challenges and future work**
- Assess coating-stress effects.
- Implement active slits to compensate for change of internal diameter of shell with length (less of a challenge for large-diameter optics)
- Develop in-situ metrology
- Develop custom masks for rapid correction

**Applicable to Athena**
Yes, for figure control of full shell (or segmented) optics.
**Challenge**

- Small amounts of coating stress can significantly distort a large thin-shell optic.
  - Preservation of substrate figure after deposition of x-ray reflective coatings is a leading technological challenge.

**Objective**

- Develop advanced low stress x-ray optical coatings (single-layer and multi-layer) that will enable future missions.

**Approach:**

- The use of a proven novel highly-sensitive method of in-situ stress measurement that will be adapted to curved substrates.
  - Investigate stress growth in films and methods for its reduction.
- The design and implementation of a novel single and multilayer coating scheme for achieving inherently uniform coatings on flat and curved segments.
Thin Film Coatings- In-Situ Stress Measurement Method

- Film stress deforms figured substrates and degrades imaging resolution.
- We measure stress in-situ using a high resolution (i.e. 5 nm) fiber optic displacement sensor.
- The sensor measures the cantilever tip deflection caused by the film stress which is calculated using the Stoney Eqn:

$$\sigma_{hf} = \frac{E_s h_s^2 \delta_x}{3(1 - \nu_s) x^2}$$

25 MPa*nm sensitivity
Thick Film Coatings- Zero Stress Iridium

- The requirements for missions are typically satisfied with 10-20 nm of Ir
- Through Ar pressure optimization we can reduce the stress to near zero (measured 3 orders of magnitude decrease)
- Surface roughness increases from 3 to 4.5Å
Thin Film Coatings - Capability at MSFC

- Procured with MSFC innovation funding (CIF) award
- For development of depth graded ML’s
- Designed for flexibility in deposition geometry
- Currently utilizes up to four 2 in. dia. circular cathode positions
- Ion milling capability
- Spinning substrate holder
  - Holds up to 4 inch dia. substrates
  - Bias can be applied
- Future work includes system upgrade to expand capability to coat segmented substrates
Thin Film Coatings - Measurement

Periodic ML for high resolution wavelength selective applications

Depth graded ML for broadband response

MSFC X-Ray Reflectometer used to measure thin film properties
**TRL Level**
Currently at ~ 3

**Accomplishments**
- Reduced iridium coating stress by three orders of magnitude by exploiting the film’s growth mechanism that was revealed by in-situ stress measurement capability.
- Demonstrated approach for achieving targeted reflectivity response of the depth graded multilayer coatings.

**Challenges and future work**
- Completion of new deposition system design to enable the coating and in-situ stress measurement of curved optical segments
- Development of in-situ stress measurement during thermal annealing processes

**Applicable to Athena:**
Yes, to maintain figure of full shell (or segmented) optics.
Full-shell Optic Fabrication Process Applicable to Athena

- Machined mirror blanks
- Diamond turning TRL~2
- Computer controlled polishing TRL~3
- Differential deposition TRL~3
- Low-stress reflective coatings TRL~3
- Alignment and module integration TRL~3

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