Lightweight, Scalable Manufacturing of Telescope Optics

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Telescope Optics: Motivation

Need for Lightweight Telescope Optics

- Decrease the weight of current Wolter Type I optics to allow for greater shell packing and thus increase effective X-ray collection area (i.e. increase the optical surface area per unit mass)
- Reduce the requirements and cost of telescope launch vehicle

Current State of the Art X-ray observatory (XMM Newton) utilizing 58 nested reflector shells; largest reflector 70cm diameter.

Note the increased number of shells compared to that of Chandra resulting in greater optical area and thus greater X-ray collection

Benefit of Electroformed Optic

- Individual mirror thickness reduced by greater than an order of magnitude (1mm vs. 20mm)
- Reduced mirror thickness allow for a greater number of shells to be nested

Disadvantage of Electroformed Optic

- Density of Ni compared to zerodur
- Figure accuracy not as good as zerodur
**Electroformed nickel replication (ENR)**

**Benefit of the Electroforming Process**
- Well suited for precision replication (widely used in optical manufacturing)
- Superpolished mandrel is reusable, can be “touched up” as necessary

**Disadvantage of Electroformed Optic**
- Density of Ni compared to zerodur (8.9 g/cm³ vs 2.5 g/cm³)
- Figure accuracy not as good as zerodur

**NiCo alone is too heavy for X-ray telescope missions**

There exists a need to replace much of the NiCo with a less dense material
Proposed Innovation

- Replace zerodur optic with NiCo shell and thermal spray ceramic support structure
- Utilize NiCo electroforming to replicate the surface micro-roughness of the mandrel
- Combine a graded-density lightweight ceramic support coating to hold figure accuracy and supply rigidity for handling

**Comparison: Mass of Wolter I Optic with a 70cm diameter, 60cm long**

- Current Standard: 20mm Zerodur - 68.7 kg
- Current State of the Art: 1mm NiCo - 11.8 kg
- Proposed Innovation: ≤100µm NiCo, 200µm Al₂O₃ - 1.9 kg

Thickness of NiCo remains constant as shell diameter increases.
What is Thermal Spray

Thermal Spray Processes

- Twin Wire Arc
- Flame / Combustion
- Atmospheric Plasma Spray
- High Velocity Oxy Fuel
- Cold Spray
- Detonation Spray

Spray Conditions:
- Torch Settings
- Powder
- Substrate Condition
- Spray Pattern

In Flight Particles:
- Temperature
- Velocity
- Trajectory

Coating Build-up:
- Splat Morphology
- Microstructure
- Porosity
- Interlamellar Contact

Properties:
- Mechanical
- Thermal
- Relibility

http://www.thermal spraying.org/site_plasmaarc.asp
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Associated with more than 100 variables

Photo Courtesy of Westaim Ambeon

Characteristics

- Flame Temperature: Approximately 12,000 - 20,000°F (6,000 - 11,100°C)
- Gases Used: Ar/H₂, N₂/H₂
- Particle Speed: 800 - 1,800 ft/s (240-550 m/s)

Tungsten Cathode Arc Gas

Electrical Connection & Water Outlet

Electrical Connection & Water Outlet

Insulated Housing

Powder and Carrier Gas

Substrate Coating

Spray Stream

Water Cooled Copper Anode

Electrical Connection & Water Inlet

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Photo Courtesy of Westaim Ambeon
# Wide Range of Thermal Spray Coated Components

## APPLICATIONS
- Energy - Gas Turbine Engine
- Industrial machinery
- Aviation Engine / Landing Gear
- Bio-implants
- Metal / Paper Manufacturing
- Electronics Manufacturing

## Thermal Spray Processes
- APS
- HVOF

## COATING MATERIAL & MICROSTRUCTURE
- GdZr
- Carbide-Metal
- Porous HA
- Carbide-Metal
- Dense YSZ

## PHYSICAL CHARACTERISTICS
- Thickness Weight Porosity
- Thickness Crack Porosity
- Thickness Crack Weight
- Thickness Defect Density Roughness
- Thickness Crack Roughness
- Thickness Defect Density

## PROPERTIES & PERFORMANCES
- Residual Stress Adhesion Sintering/Aging Conductivity Toughness
- Residual Stress Adhesion Strength Toughness Wear
- Residual Stress Adhesion Toughness Phase Stability
- Residual Stress Adhesion Strength Toughness Wear
- Residual Stress Adhesion Erosion Phase Stability Thermal Expansion
Design of Experiments

Spray parameter identification

InFlight Particle Analysis

Particle Temperature-Velocity Measurement

1st-order Process Map

Particle T-V to process parameters

Residual Stress Evolution Optimization

ICP Coating Deposition

Deposit low E process parameters on ICP sensor

Stress Evolution Analysis

Deposition-Thermal-Residual Stress Analysis

Stress-Modulus Analysis

Stress Evolution-Modulus relationship on process parameter
Why Thermal Spray for this Application?

**Materials Selection**
- Wide array of materials to select from
  - Metals, ceramics, polymers, composites
- Ability to tailor the material to not only match the expansion but also provide compliance via defects (thermal cycling compliance)

**Process Parameters**
- Ability to tailor the microstructure, density, and interface through use of graded layers
- Ability to control deposition temperature
  - Robot raster speed
  - Secondary cooling

**Component Manufacturing**
- Ability to deposit onto large cylindrical geometries
  - Easily scalable
  - Deposit directly onto electroformed shell
- Cost effective and efficient
- Established industry base, does not require large capital expense for application

NiAl deposited onto canvas
## Challenges and Mitigation Strategies

<table>
<thead>
<tr>
<th>Defined Challenges</th>
<th>Proposed Mitigation Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light weight, rigid &amp; high toughness carrier layer</td>
<td>Base structure of Al$_2$O$_3$ or other porous ceramic coating</td>
</tr>
<tr>
<td></td>
<td>Al$_2$O$_3$-Aluminum composite/functionally graded structure</td>
</tr>
<tr>
<td>Scale up production &amp; manufacturing</td>
<td>Demonstrate on 1/2m diameter mandrel surface</td>
</tr>
<tr>
<td>No damage to the electroplated NiCo layer</td>
<td>Minimal to no peening stress during TS coating deposition</td>
</tr>
<tr>
<td></td>
<td>Ductile metallic layer as a bond coat</td>
</tr>
<tr>
<td></td>
<td>Hard PVD interlayer (PVD TiN or BN)</td>
</tr>
<tr>
<td>TS Coating residual stress compatibility</td>
<td>Select similar CTE coating material as NiCo</td>
</tr>
<tr>
<td></td>
<td>TS coating deposition using in-situ coating sensor (ICP) to monitor residual stress evolution &amp; determine the optimal process parameters</td>
</tr>
<tr>
<td>Low substrate deposition temperature</td>
<td>Limit quenching stress</td>
</tr>
<tr>
<td></td>
<td>Low APS process condition. Explore Twin Wire Arc and Flame Spray</td>
</tr>
<tr>
<td></td>
<td>Cooling jet, faster raster speed, off-angle deposition</td>
</tr>
<tr>
<td>Strong adhesion to smooth NiCo layer</td>
<td>Apply a similar CTE bond coat</td>
</tr>
<tr>
<td></td>
<td>First coating pass analysis using ICP sensor for adhesion criteria</td>
</tr>
<tr>
<td></td>
<td>SEM cross-sectional metallography</td>
</tr>
<tr>
<td></td>
<td>ASTM C633 bond strength test for quantifying adhesion strength</td>
</tr>
</tbody>
</table>
## Proposed Coating Development

<table>
<thead>
<tr>
<th></th>
<th>Optic Shell</th>
<th>Barrier Layer</th>
<th>Bond Coat</th>
<th>Graded Ceramic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>NiCo</td>
<td>TiN, BN</td>
<td>No Bond Coat</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Al</td>
<td>5% wt Al / 95% wt Al₂O₃</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ni-5%Al</td>
<td>10% wt Al/90% wt Al₂O₃</td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>25µm</td>
<td>No Barrier</td>
<td>No Bond Coat</td>
<td>150µm</td>
</tr>
<tr>
<td></td>
<td>50µm</td>
<td>1-2µm</td>
<td>10µm</td>
<td>200µm</td>
</tr>
<tr>
<td></td>
<td>75µm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100µm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Process Variables</strong></td>
<td>Bath chemistry, pH, Stress</td>
<td>Deposition rate, Pressure, Gas flow, Target-sub distance</td>
<td>Nozzle, Torch Power, Total gas flow, Robot speed, Spray distance, Particle temperature, Particle velocity</td>
<td></td>
</tr>
</tbody>
</table>
**NASA SBIR Proposed Innovation**

**Mandrel Fabrication & Electroform NiCo**
- CNC Machine Mandrel
- Super Polish Mandrel
- Electroform NiCo Layer

**Coating Design Road Map**

**Multi-Layer TS Layer Deposition**

**Surrogate Mandrel Deposition for Layer physical/Thermal/Mechanical Optimization**

**Post Processing Measurements**
- Metallography
- Thermal Expansion
- 3D Surface Profilometry
- Adhesion Test
- Indentation Test

**Proposed Innovation**
- Replace zerodur optic with NiCo shell and thermal spray ceramic support structure
- Utilize NiCo electroforming to replicate the surface micro-roughness of the mandrel
- Combine a graded-density lightweight ceramic support coating to hold figure accuracy and supply rigidity for handling
Development and Optimization Approach

Initial Test Substrates
Evaluate potential particle damage using nickel and aluminum foil

Air Plasma Spray (APS) Deposition

NiCo Coated Si Wafer

Process development using NiCo plated silicon wafers (due to mandrel availability), continued testing on flat and conical mandrels to evaluate X-ray performance
Electroformed NiCo / Ni-5%Al Bond Coat & Al Coating

As-Deposited

TS Al Coating (~200um)
Strong Coating Adhesion to NiCo Layer

Si Wafer
Si wafer exhibited no surface deformation

NiCo – Si Wafer Side

No visible surface deformation on NiCo layer

Electroformed NiCo / Ni-5%Al Bond Coat / Al/Al₂O₃ Blend / Al₂O₃ Top Coat

As-Deposited

Ni-5%Al Bond Coat, Al/Al₂O₃ Blend Layer, and Al₂O₃ Top Coat

Uniform TS Coating Coverage with good adhesion

Si Wafer
Si wafer exhibited no surface deformation

NiCo – Si Wafer Side

• No visible surface deformation of NiCo layer
• Uniform NiCo Surface roughness

NiCo Center

NiCo Off-Center

Measurement Artifact

*Note: The images and text within the diagram provide details on the coating deposition summary, including images of the coating layers and their properties. The text highlights the adhesion, surface deformation, and roughness of the coatings.*
APS Multi-Layer Deposition on NiCo Coated Surrogated Mandrel

- As-received NiCo mandrel
- NiCo mandrel mounted on a turn table
- Post Ni-5%Al deposition
- Post Al-\(\text{Al}_2\text{O}_3\) deposition

Successfully released reflector coating from the mandrel

- Released Reflector Coating
- Conical Mandrel
- Post TS coating deposition state
- Post \(\text{Al}_2\text{O}_3\) deposition

IR Image
Phase I Accomplishment

NiCo coated Mandrel → Thermal spray coated mandrel → Separated NiCo/TS layer from the Mandrel

Past feasibility study between Stony Brook-SAO

Imperfections easily seen on optical surface

Current Accomplishment RCT-SAO Team

Optical surface considerably better as evident by the ability to image lines
Coating Physical Property Assessment

- Coating deposition on silicon wafers attached to surrogated mandrel on an instrumented turntable
- Assess optical surface deformation via 3D surface profilometry
- Coating microstructural analysis
- Mechanical properties: indentation, adhesion tests, stiffness
- Thermal properties: CTE analysis for stress evolution analysis

Metallography

SEM Microstructure
porosity/density analysis

Mechanical Property Analysis

Indentation Test
Elastic modulus, hardness

Adhesion Test
adhesion strength

Optic Surface Deformation Analysis

3D Surface Profilometry
Assess Optical Surface Deformation

Thermo-Mechanical Analysis

Thermal Expansion
Layer Thermal expansion coefficient
Phase II Deliverable: Two Nested Shell Telescope

**TS Deposition onto 2 Wolter mandrels**

- Assembly of 2 nested shell telescope
- Photographs of structure used to align multiple Wolter shells. Similar structure will be fabricated for X-ray testing in year 2.

**Full beam X-ray reflectivity measurements**
*Performed by SAO staff*