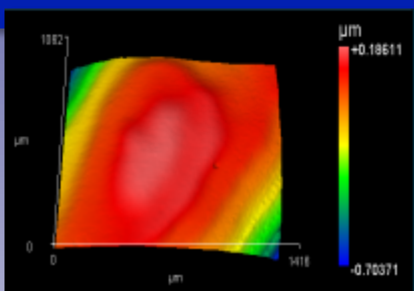
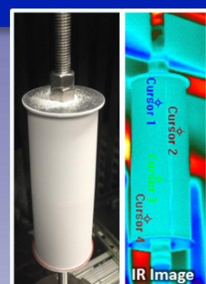
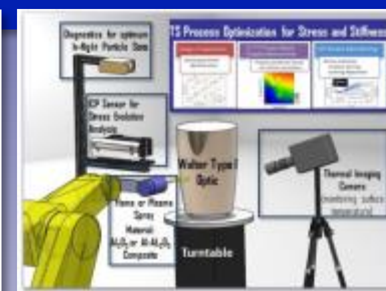
# *Lightweight, Scalable Manufacturing of X-ray Telescope Optics*





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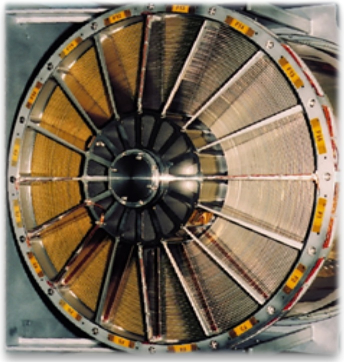
## Need for Lightweight Telescope Optics

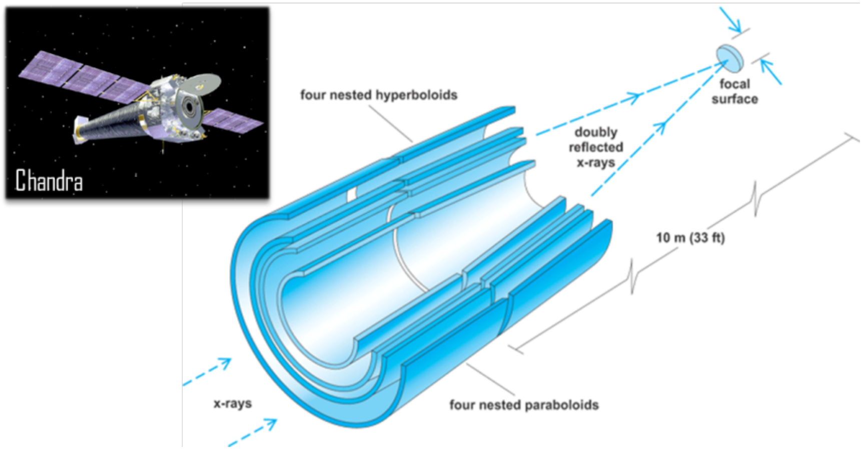
- Decrease the weight of current Wolter Type I optics to allow for greater shell packing and thus increase effective X-ray collection area
  (i.e. increase the optical surface area per unit mass)
- Reduce the requirements and cost of telescope launch vehicle



XMM Newton

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




Chandra X-ray observatory utilizing 4 nested zerodur optics with the outer shell measuring 1.2 meters in diameter.

Cross sectional view of Wolter I optic showing grazing angle reflection and nested reflector capability

## 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

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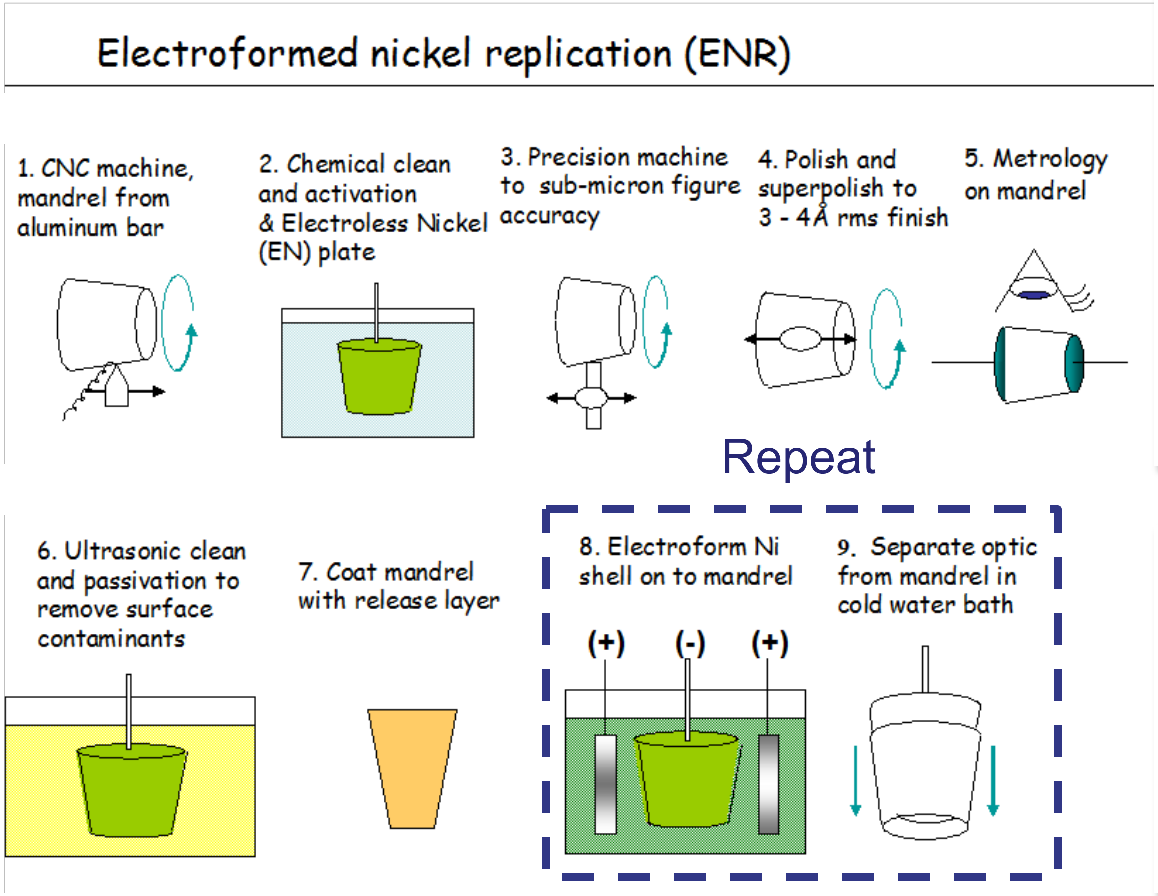
# Telescope Manufacturing






## Benefit of the Electroforming Process

- Well suited for precision replication (widely used in optical manufacturing)
- Superpolished mandrel is reuseable, can be "touched up" as necessary

## Disadvantage of Electroformed Optic

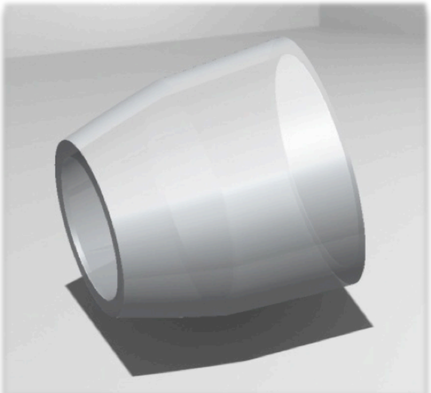
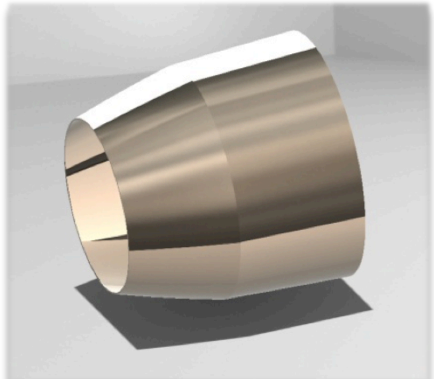
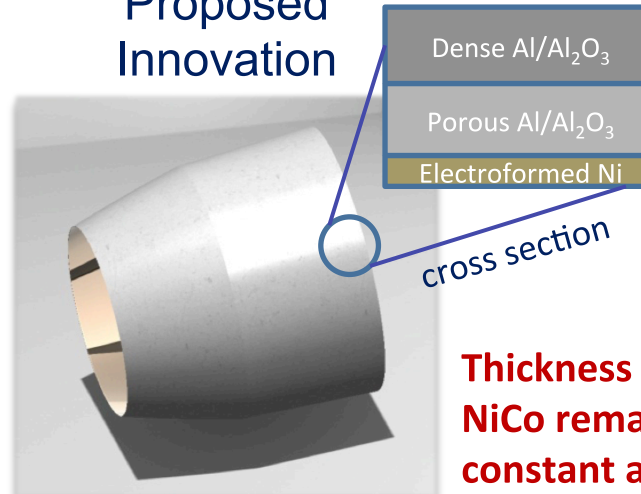
- Density of Ni compared to zerodur (8.9g/cm$^3$ vs 2.5 g/cm$^3$)
- Figure accuracy not as good as zerodur

**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**

# Telescope Optics: Proposed Innovation



| Current Standard | Current State of the Art | Proposed Innovation |
|---|---|---|
|  |  |  |
| **20mm Zerodur** | **1mm NiCo** | ≤100µm NiCo<br>200µm $Al_2O_3$ |

**Thickness of NiCo remains constant as shell diameter increases**

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

| 20mm Zerodur | 1mm NiCo | ≤100µm NiCo / 200µm $Al_2O_3$ |
|---|---|---|
| **68.7 kg** | **11.8 kg** | **1.9 kg** |

## 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

## Thermal Spray Processes

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

Associated with more than 100 variables

### Plasma Spray Process

http://www.thermalspray.org/site_plasmaarc.asp

*© 2005 International Thermal Spray Association*

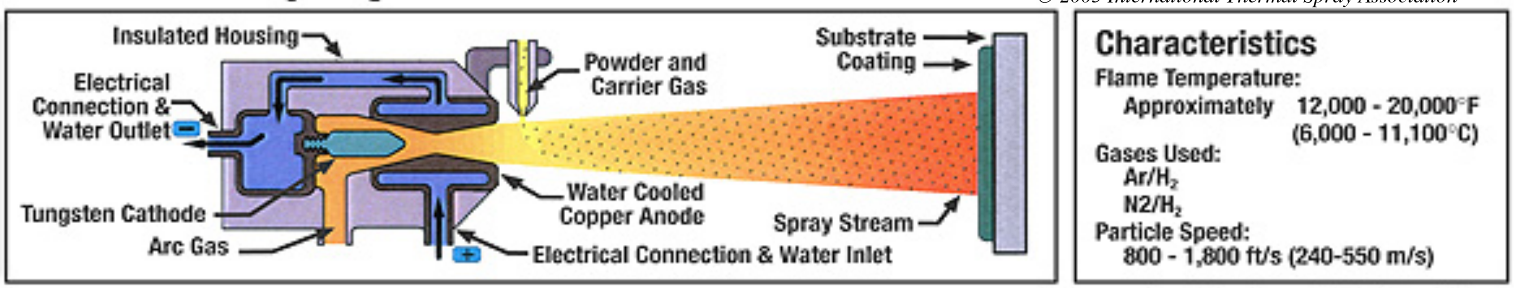



Photo Courtesy of Westaim Ambeon

**Spray Conditions:**

- Torch Settings
- Powder
- Substrate Condition
- Spray Pattern

**In Flight Particles:**

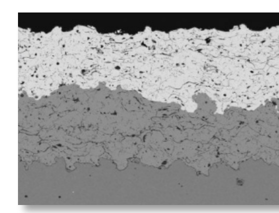
- Temperature
- Velocity
- Trajectory


**Coating Build-up:**

- Splat Morphology
- Microstructure
- Porosity
- Interlamellar Contact

**Properties:**

- Mechanical
- Thermal
- Relibility



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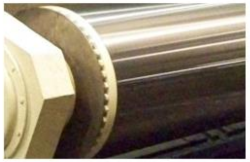
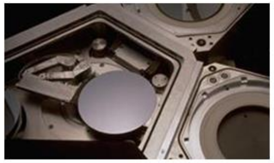
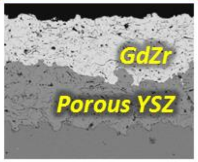
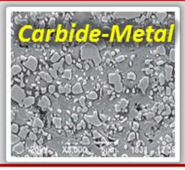
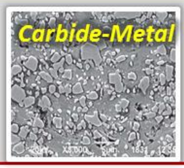
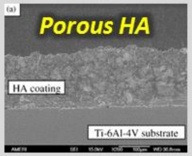
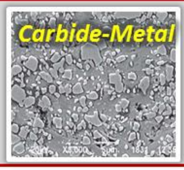
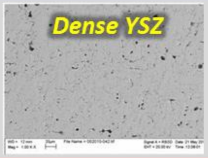
# Wide Range of Thermal Spray Coated Components

| APPLICATIONS | Energy - Gas Turbine Engine | Industrial machinery | Aviation Engine / Landing Gear | Bio-implants | Metal / Paper Manufacturing | Electronics Manufacturing |
|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |
| Thermal Spray Processes |  |  |  |  |  |  |
| COATING MATERIAL & MICROSTRUCTURE |  |  |  |  |  |  |
| PHYSICAL CHARACTERISTICS | Thickness<br>Weight<br>Porosity | Thickness<br>Crack<br>Porosity | Thickness<br>Crack<br>Weight | Thickness<br>Defect Density<br>Roughness | Thickness<br>Crack<br>Roughness | Thickness<br>Defect Density |
| PROPERTIES & PERFORMANCES | Residual Stress<br>Adhesion<br>Sintering/Aging<br>Conductivity<br>Toughness | Residual Stress<br>Adhesion<br>Strength<br>Toughness<br>Wear | Residual Stress<br>Adhesion<br>Strength<br>Toughness<br>Wear | Residual Stress<br>Adhesion<br>Toughness<br>Phase Stability | Residual Stress<br>Adhesion<br>Strength<br>Toughness<br>Wear | Residual Stress<br>Adhesion<br>Erosion<br>Phase Stability<br>Thermal Expansion |

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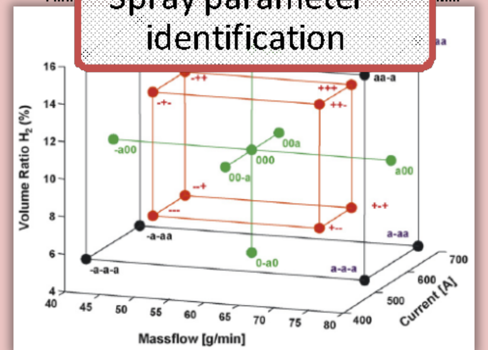
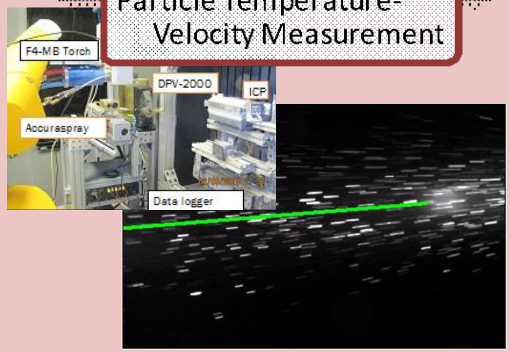
# Process Optimization of Proposed Coating Structure

## Design of Experiments

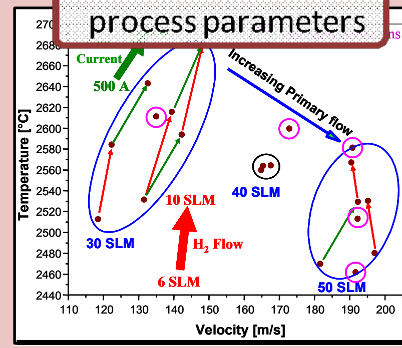
**Design of Experiments**
Spray parameter identification




**InFlight Particle Analysis**
Particle Temperature-Velocity Measurement



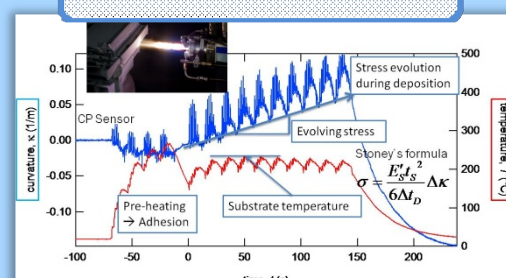

**1st-order Process Map**
Particle T-V to process parameters



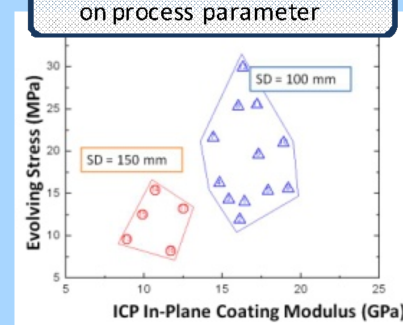

## Residual Stress Evolution Optimization

**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

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# Why Thermal Spray for this Application?

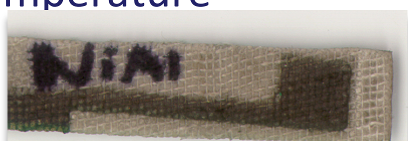


## Materials Selection

- 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

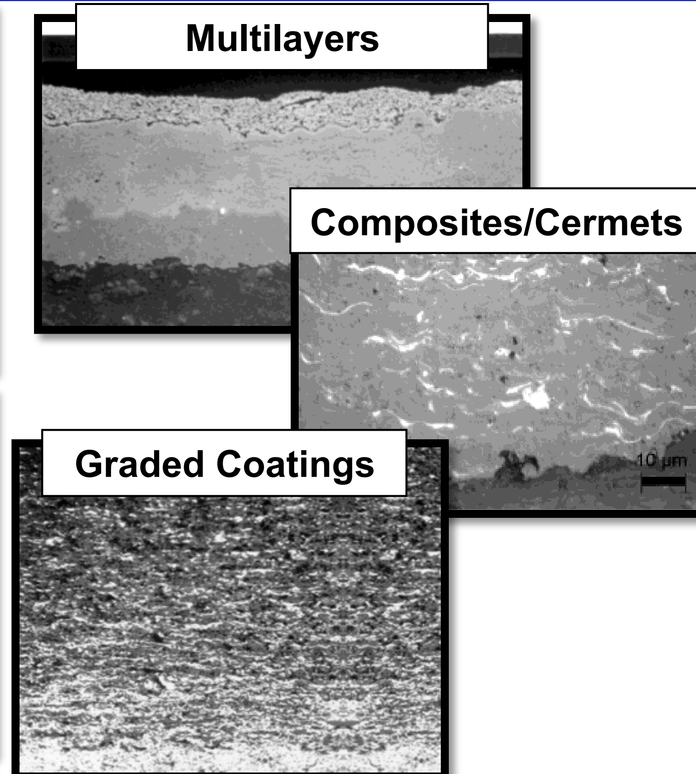
- Ability to tailor the microstructure, density, and interface through use of graded layers
- Ability to control deposition temperature
  - Robot raster speed
  - Secondary cooling

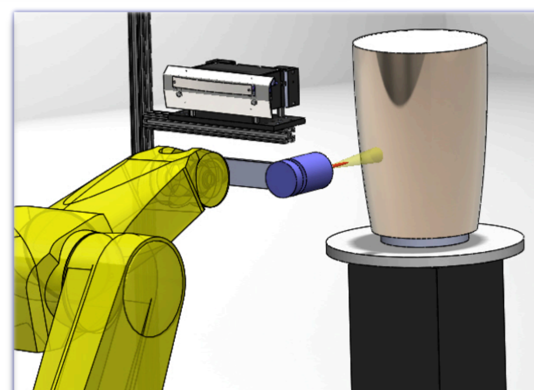



NiAl deposited onto canvas

## 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



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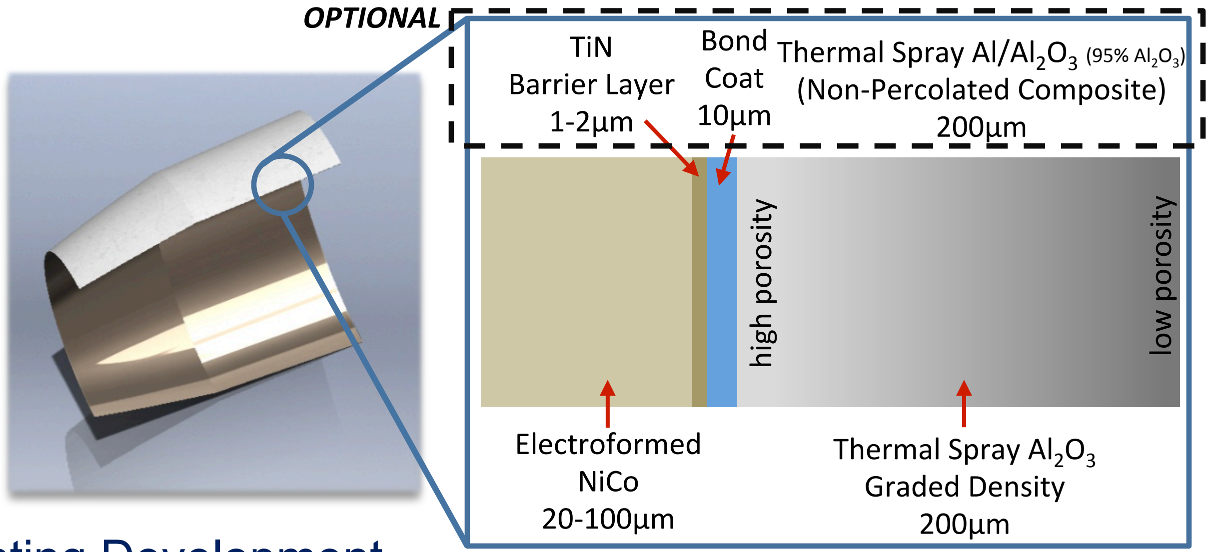
# Challenges and Mitigation Strategies

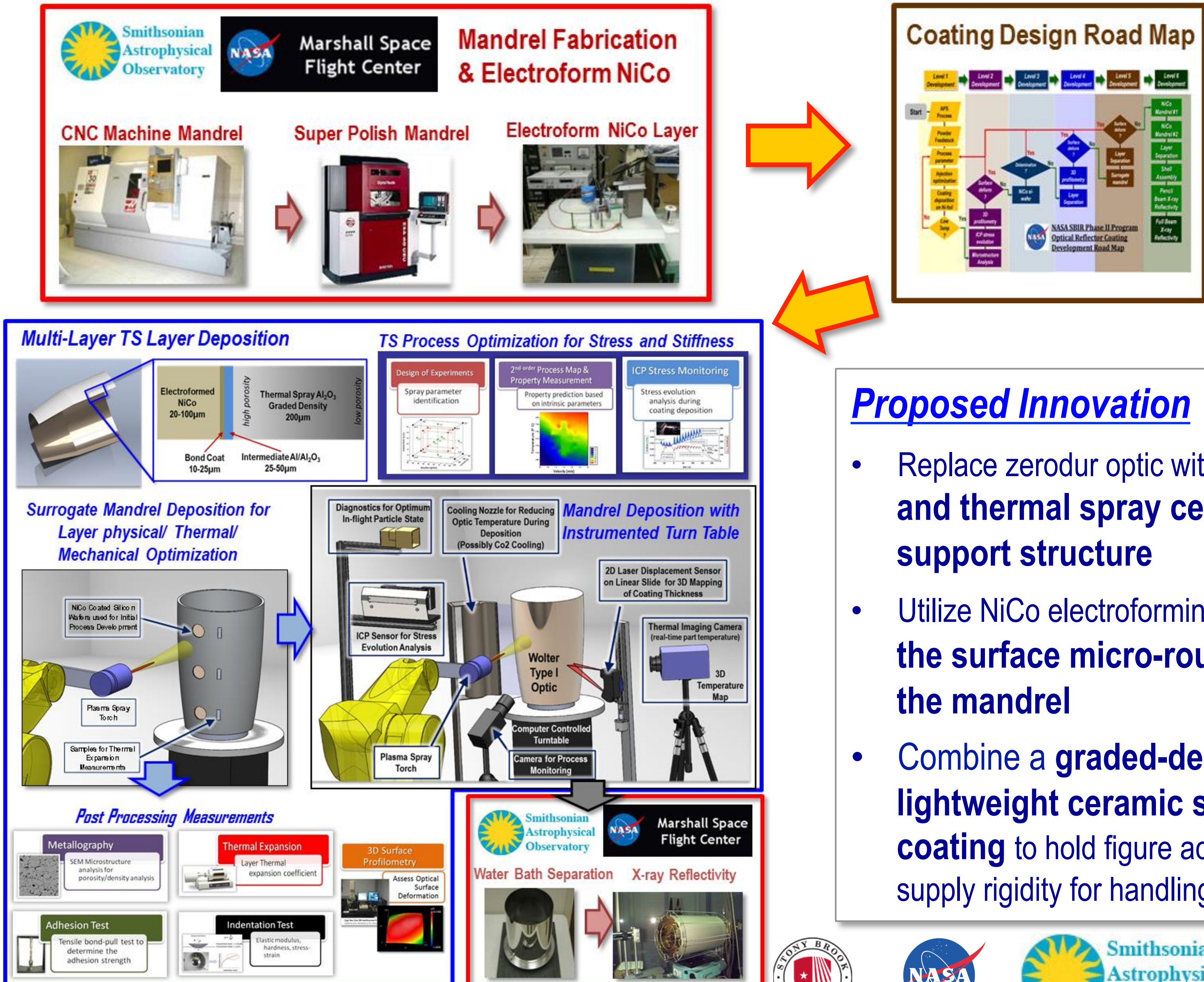


| Defined Challenges | Proposed Mitigation Strategies |
| --- | --- |
| Light weight, rigid & high toughness carrier layer | ▪ Base structure of $Al_2O_3$ or other porous ceramic coating<br>▪ $Al_2O_3$-Aluminum composite/functionally graded structure |
| Scale up production & manufacturing | ▪ Demonstrate on 1/2m diameter mandrel surface |
| No damage to the electroplated NiCo layer | ▪ Minimal to no peening stress during TS coating deposition<br>▪ Ductile metallic layer as a bond coat<br>▪ Hard PVD interlayer (PVD TiN or BN) |
| TS Coating residual stress compatibility | ▪ Select similar CTE coating material as NiCo<br>▪ TS coating deposition using in-situ coating sensor (ICP) to monitor residual stress evolution & determine the optimal process parameters |
| Low substrate deposition temperature | ▪ Limit quenching stress<br>▪ Low APS process condition. Explore Twin Wire Arc and Flame Spray<br>▪ Cooling jet, faster raster speed, off-angle deposition |
| Strong adhesion to smooth NiCo layer | ▪ Apply a similar CTE bond coat<br>▪ First coating pass analysis using ICP sensor for adhesion criteria<br>▪ SEM cross-sectional metallography<br>▪ ASTM C633 bond strength test for quantifying adhesion strength |




## Proposed Coating Development

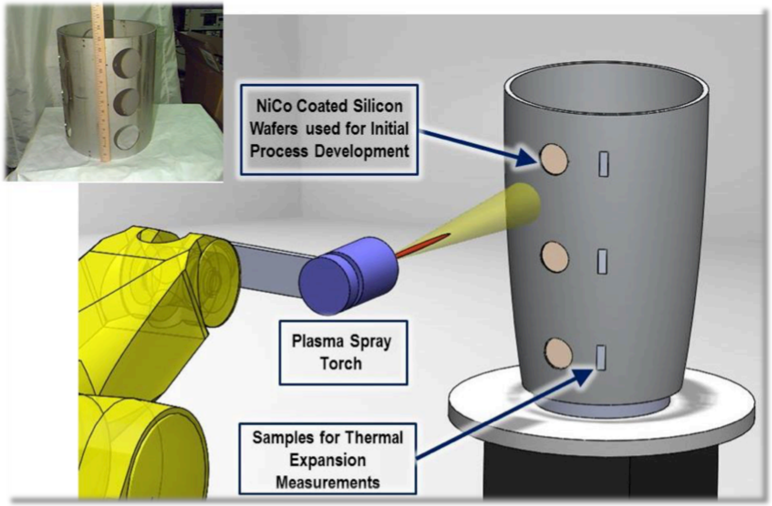
| | Optic Shell | Barrier Layer | Bond Coat | Graded Ceramic |
|---|---|---|---|---|
| **Composition** | NiCo | TiN<br>BN | No Bond Coat<br>Al<br>Ni-5%Al | $Al_2O_3$<br>5% wt Al / 95% wt $Al_2O_3$<br>10% wt Al/90% wt $Al_2O_3$ |
| **Thickness** | 25µm<br>50µm<br>75µm<br>100µm | No Barrier<br>1-2µm | No Bond Coat<br>10µm | 150µm<br>200µm |
| **Process Variables** | Bath chemistry, pH, Stress | Deposition rate, Pressure, Gas flow, Target-sub distance | Nozzle, Torch Power, Total gas flow, Robot speed, Spray distance, Particle temperature, Particle velocity | |




## 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

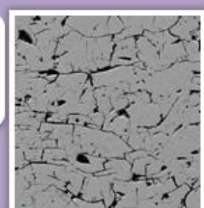
# Coating Physical Property Assessment – Overview




- Coating deposition on silicon wafers attached to surrogated mandrel on a 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

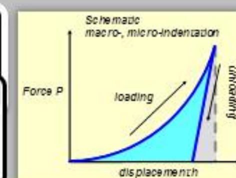
SEM Microstructure porosity/density analysis



## Mechanical Property Analysis

### Indentation Test

Elastic modulus, hardness



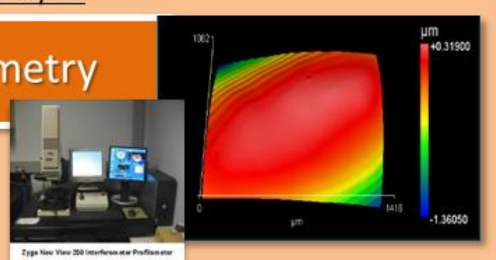

### Adhesion Test

adhesion strength

## Optic Surface Deformation Analysis

### 3D Surface Profilometry

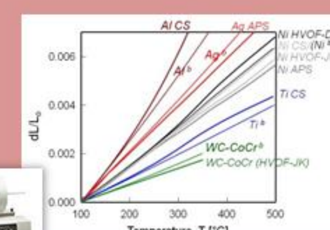
Assess Optical Surface Deformation




## Thermo-Mechanical Analysis

### Thermal Expansion

Layer Thermal expansion coefficient

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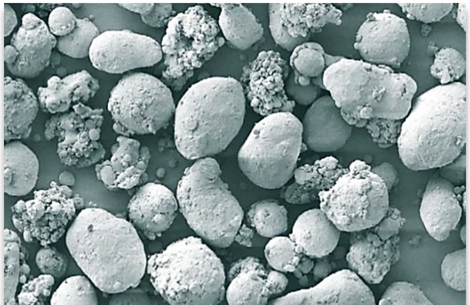
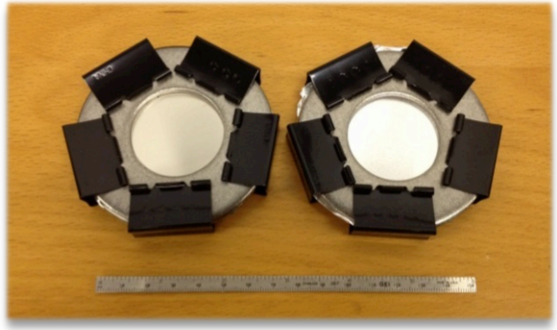
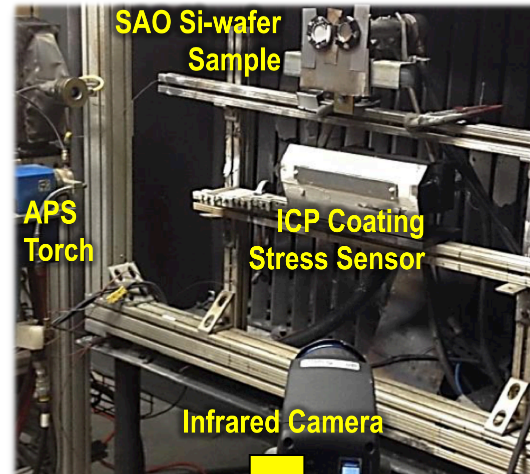

Aluminum Powder

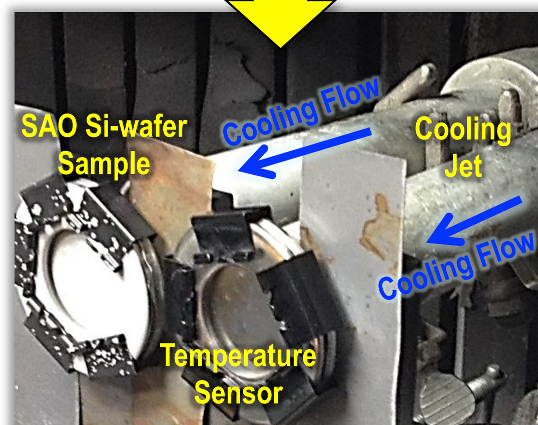
Fine powder size to minimize particle energy

## Initial Test Substrates

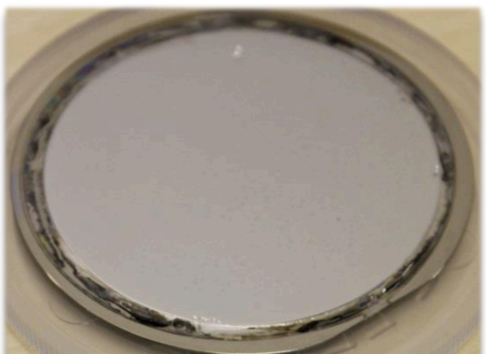

Evaluate potential particle damage using nickel and aluminum foil

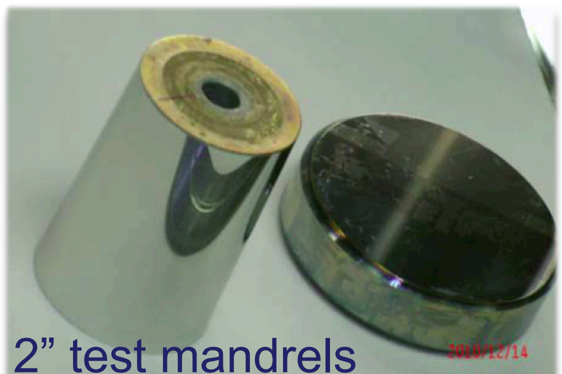
## Air Plasma Spray (APS) Deposition




## NiCo Coated Si Wafer With NiAl TS Layer





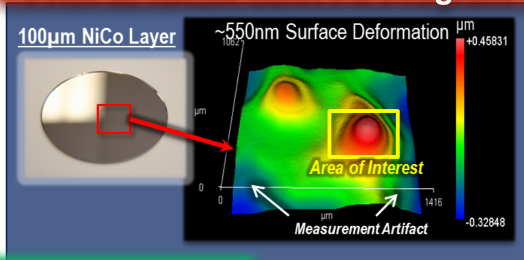

Process development using NiCo plated silicon wafers (due to mandrel availability), continued testing on conical mandrels to evaluate X-ray performance

# Coating Deposition Summary – NiCo-Plated Si-Wafers

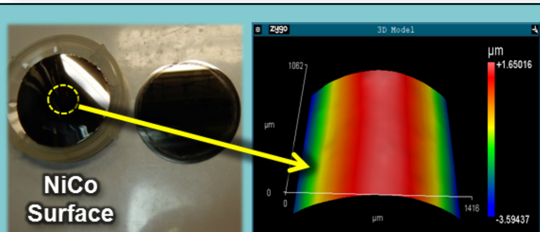
- NiCo coated Si wafers to simulate polished mandrel surface roughness
- Assessed NiCo optical surface deformation after Thermal Spray coating deposition and release
- Evaluate coating adhesion & integrity of TS coating on smooth deposition surface

## Coating Integrity/Deformation Evaluation

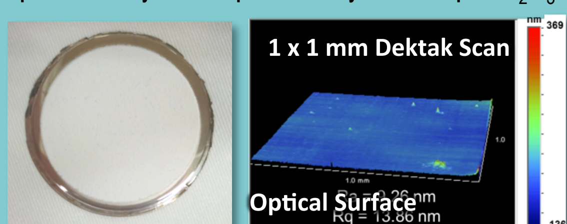
**Prior to NASA SBIR PII Program**




**Current Achievement**




100 µm NiCo layer – 50 µm NiAl layer – 200 µm $Al_2O_3$ layer

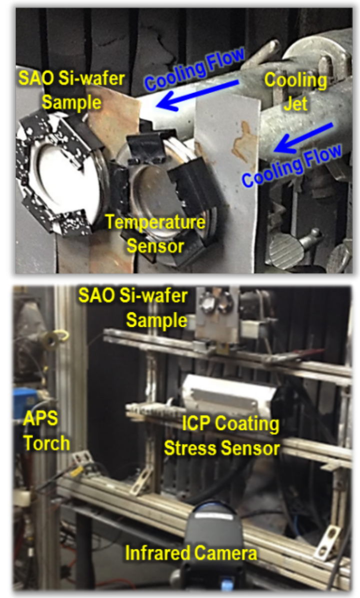



100 µm NiCo layer – APS NiAl & $Al_2O_3$ layers

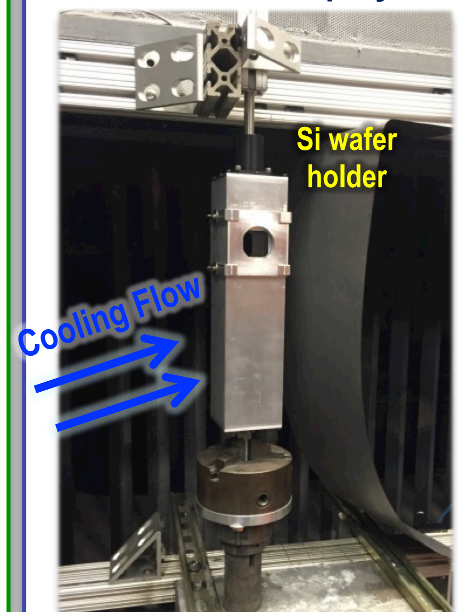
✓ ***No optical surface deformation on NiCo surface***
✓ ***Coatings deposited uniformly with good adhesion***

## *Sample Spray Transition*

**Stationary Spray**




**Rotational Spray**




- ✓ **Allows for greater options in cooling**
- ✓ **Thermal imaging camera for temperature monitoring**
- ✓ **More closely represents deposition on mandrel**

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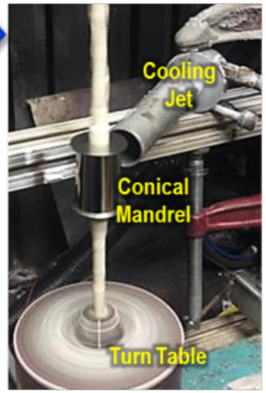
## APS Multi-Layer Deposition on NiCo Coated Surrogated Mandrel

As-received NiCo mandrel

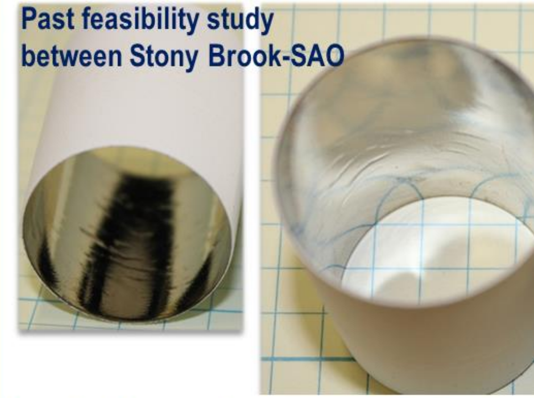
NiCo mandrel mounted on a turn table




Post Ni-5%Al deposition

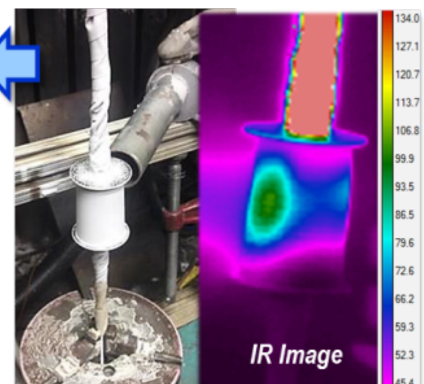
Post Al-$Al_2O_3$ deposition

Past feasibility study between Stony Brook-SAO



Imperfections easily seen on optical surface

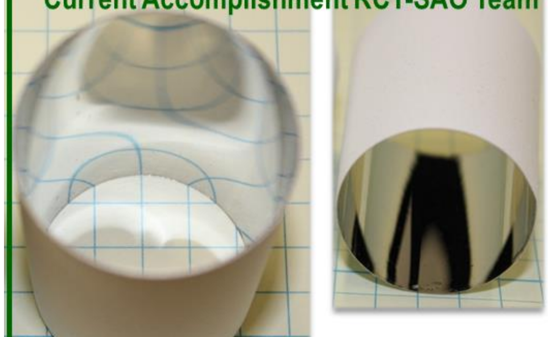
Post $Al_2O_3$ deposition




Post TS coating deposition state

Successfully released reflector coating from the mandrel


Current Accomplishment RCT-SAO Team



Optical surface considerably better as evident by the ability to image lines

- NiAl-$Al_2O_3$ onto 2" mandrel
- IR temperature monitoring
- Coating shell separated for pencil-beam X-Ray reflectivity testing

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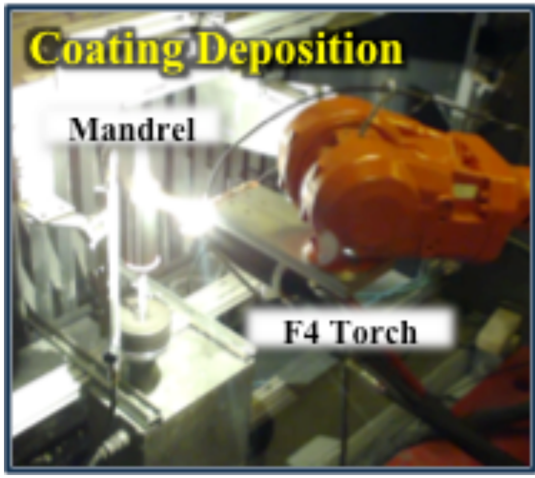
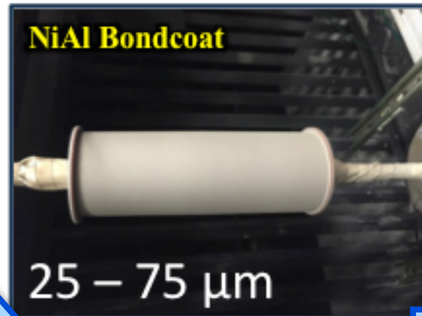
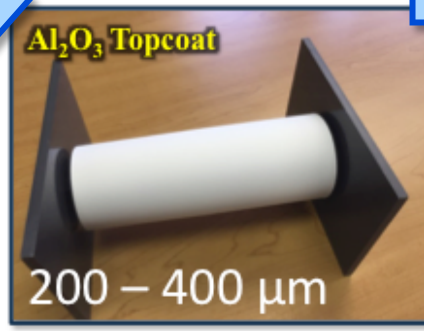
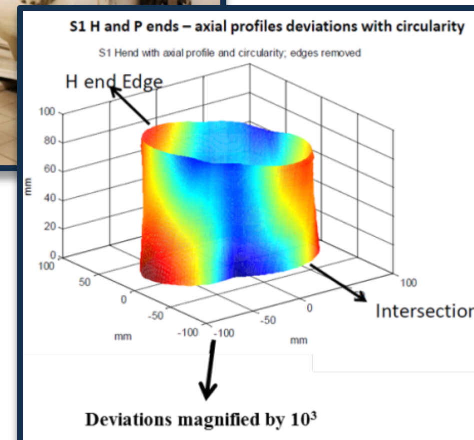
# Thermal Spray Deposition on 62mm Wolter I Mandrels



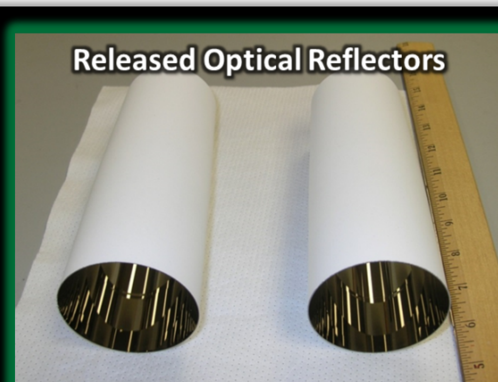








- Three 62mm Wolter mandrels have been manufactured and sprayed using an innovative APS process parameters
- Coating shells separated for X-Ray reflectivity and structural integrity evaluation
- X-Ray data obtained successfully from thermally sprayed shells (established current project baseline)




**Current Achievement**

- ✓ *Established baseline performance metrics*
- ✓ *Product fabrication & characterization*

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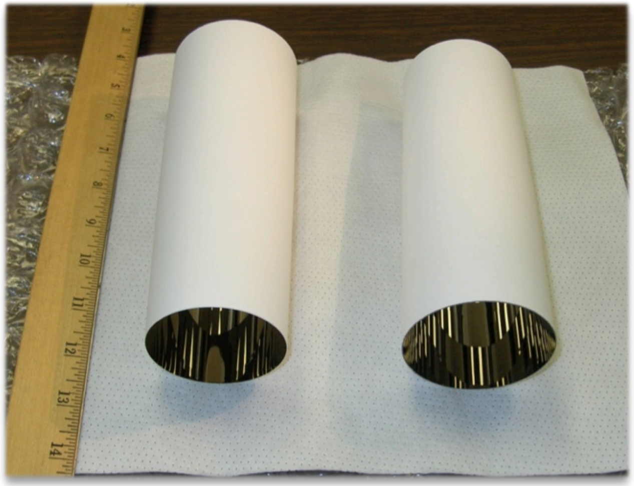
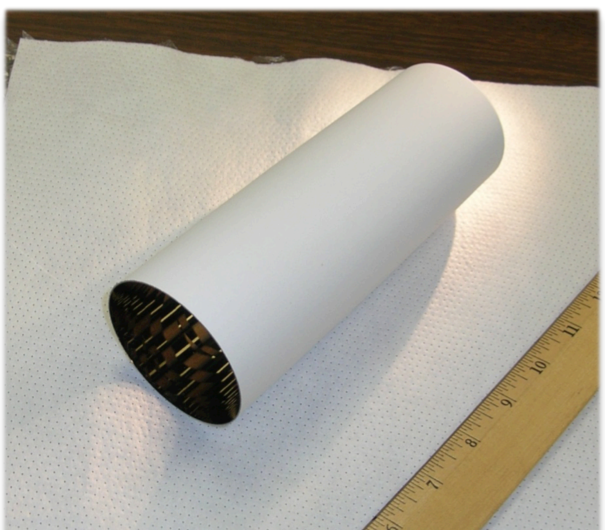
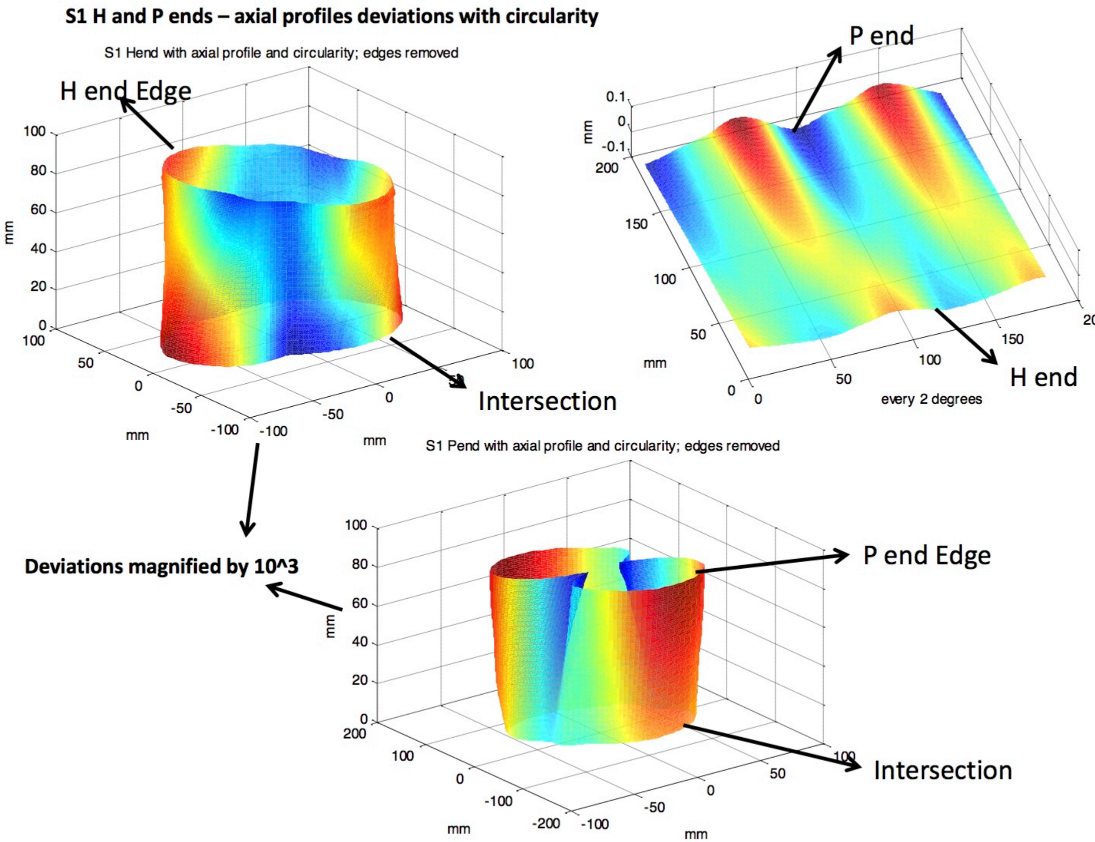
# Analysis of Shells Manufactured with 62mm Mandrel



## ***Deposition on 62mm Mandrel Resulting in 3 Shells***








***Primary Obstacle***: **Obtaining shell figure necessary for X-Ray reflectivity (based on *Talysurf surface profilometry measurement*)**

**RCT & collaborators have determined that shell figure distortion likely derives from relatively high internal stresses during thermal spray coating deposition**

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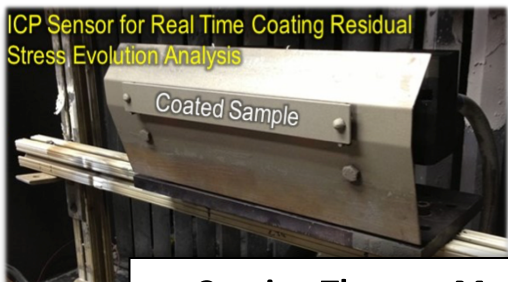
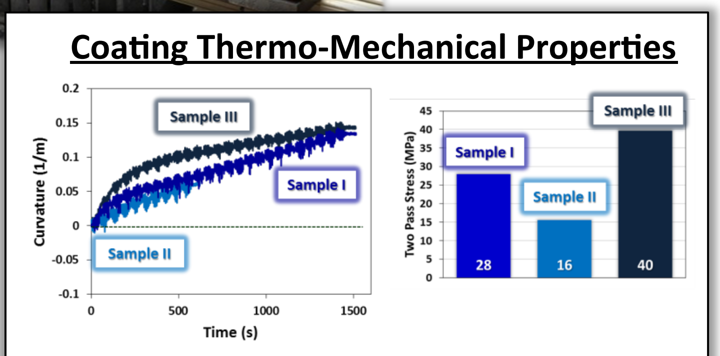
## Process Optimization

Tune process parameters to minimize coating residual stress

- Improve rotational setup
- Residual stress evaluation using ICP Sensor
- Bond coat layer modification
  - Layer thickness, Composition
- Introduce coating morphology gradation
  - Functionally graded layers

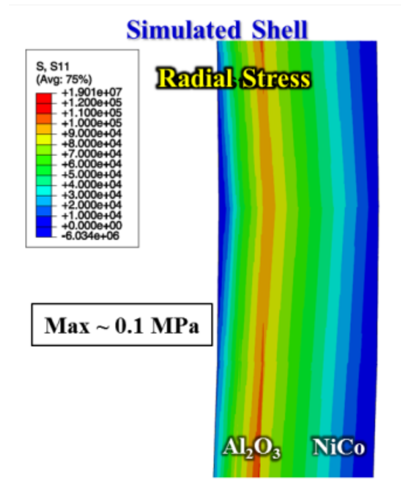


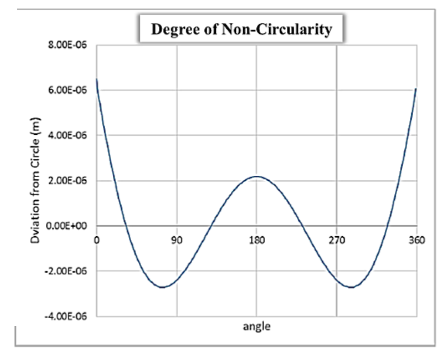




## Solid Mechanics Stress Modeling

*Modeling based optimization* for stress reduction

- Adjust model to fit experimental data
  - Determine cause of figure distortion
- Iterate model to determine acceptable residual stress levels
  - Determine tensile/compressive stress balance

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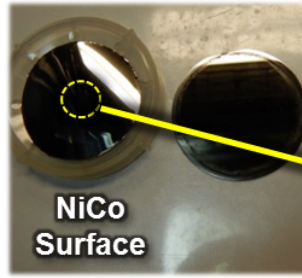
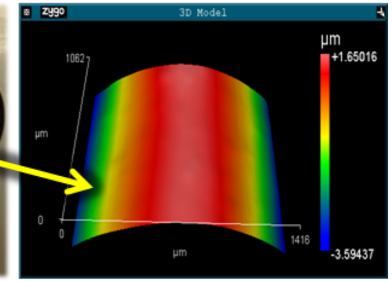
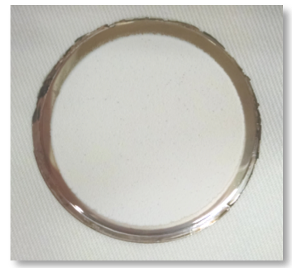
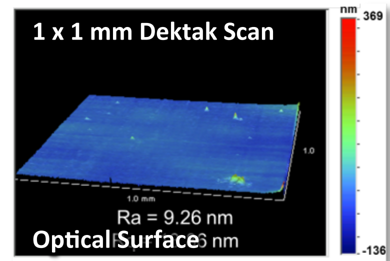
## Thermal Spray Coating Process

- ✓ Developed process parameters to eliminate optical surface deformations and maintain surface finish of electroformed NiCo
- ✓ Achieved good adhesion to smooth NiCo layer



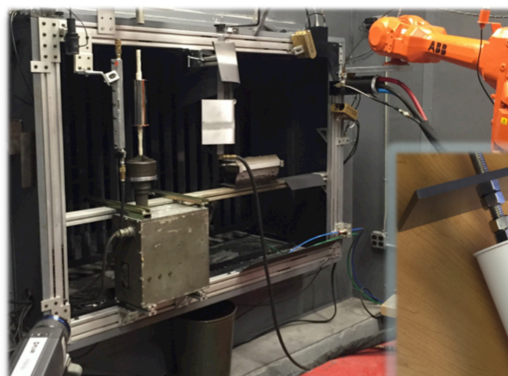






## Deposition on Wolter I Mandrel

- ✓ Demonstrated ability to release structure from mandrel
- ✓ Established that TS coating process does not adversely effect mandrel
  - ✓ No observable damage to mandrel
- ✓ Prepared to spray two mandrels this quarter



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## TS Deposition onto 2 Wolter mandrels

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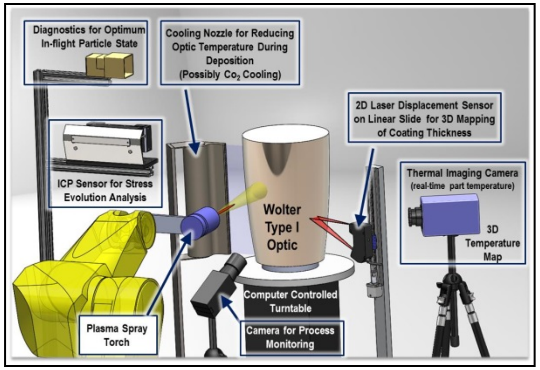


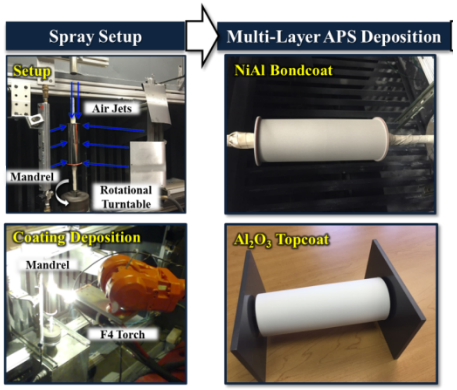


## Assembly of 2 nested shell telescope

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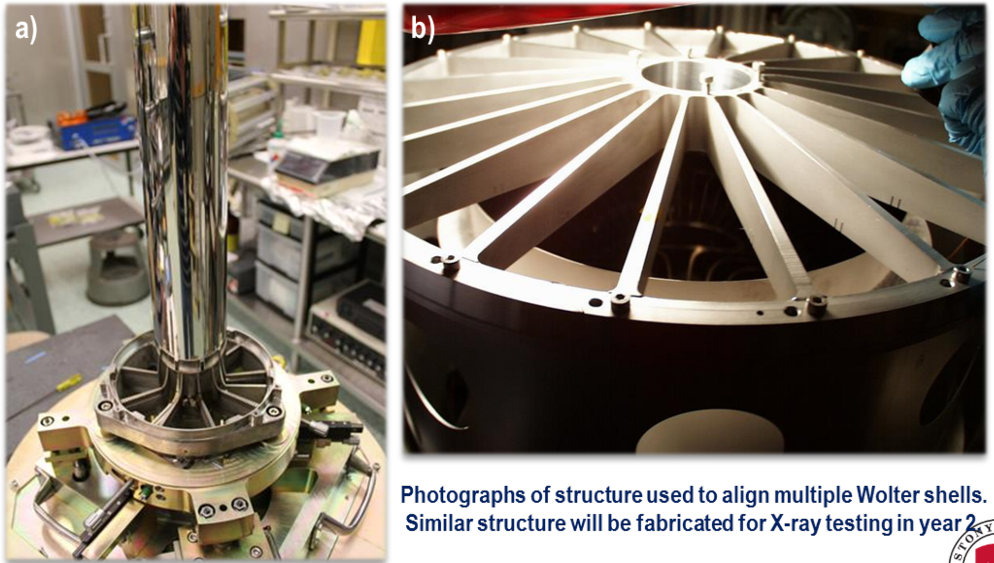
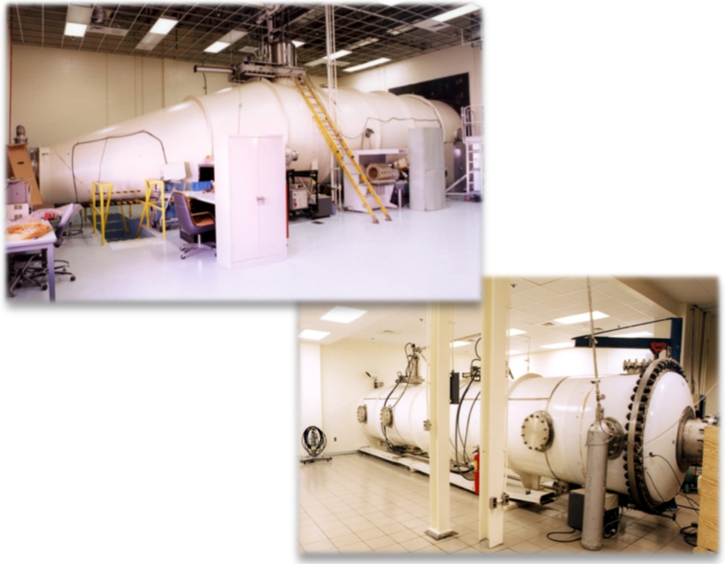



Photographs of structure used to align multiple Wolter shells.
Similar structure will be fabricated for X-ray testing in year 2.

## 15cm and 23cm Diameter Mandrels

NASA Marshall Space Flight Center



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

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