Lightweight, Scalable Manufacturing of Telescope Optics

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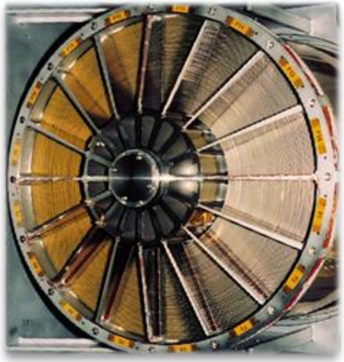
Need for Lightweight Telescope Optics

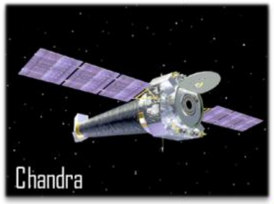
- Decrease the weight of current Wolter Type I optics to allow for greater shell packing and thus increase effective X-ray collection area
  (i.e. increase the optical surface area per unit mass)
- Reduce the requirements and cost of telescope launch vehicle

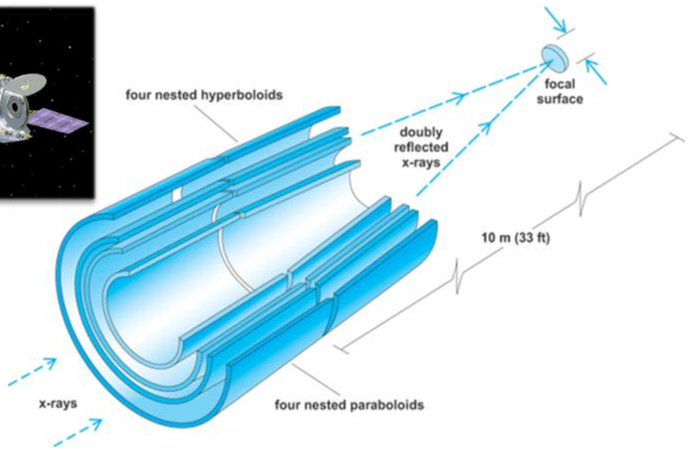
XMM Newton



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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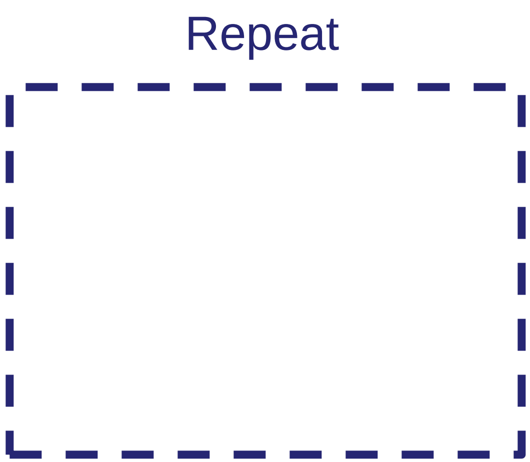
Electroformed nickel replication (ENR)



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

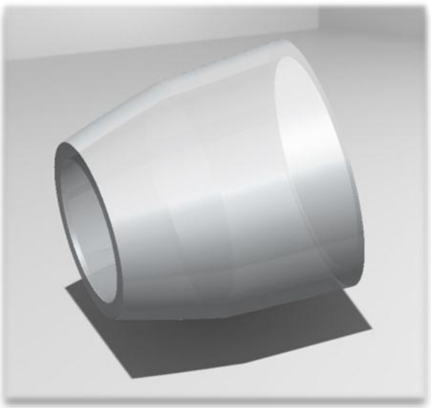
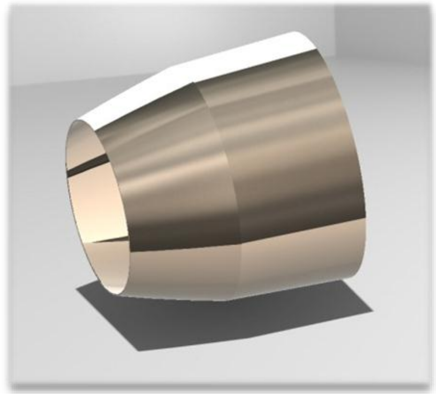
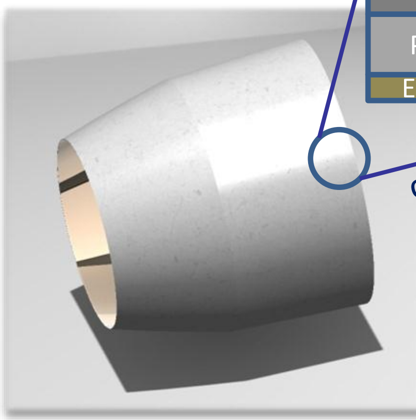
Disadvantage of Electroformed Optic

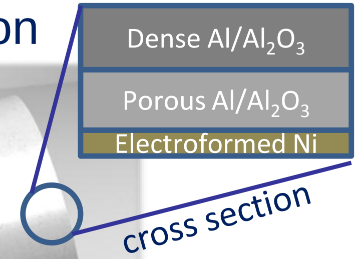
- Density of Ni compared to zerodur (8.9g/cm^3 vs 2.5 g/cm^3)
- Figure accuracy not as good as zerodur

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 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

Current Standard	Current State of the Art	Proposed Innovation
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

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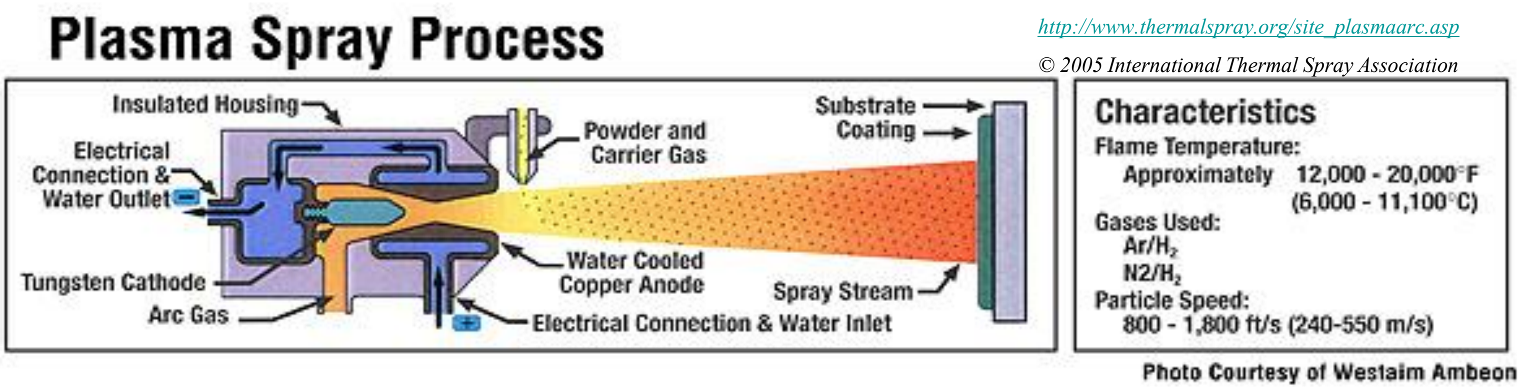
Thermal Spray Processes

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

Associated with more than 100 variables



Spray Conditions:

- Torch Settings
- Powder
- Substrate Condition
- Spray Pattern

In Flight Particles:

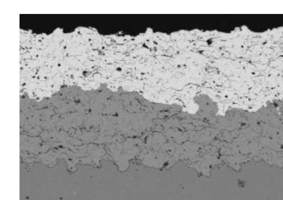
- Temperature
- Velocity
- Trajectory

Coating Build-up:

- Splat Morphology
- Microstructure
- Porosity
- Interlamellar Contact

Properties:

- Mechanical
- Thermal
- Relibility



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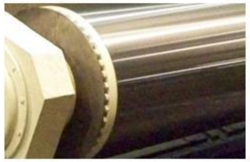
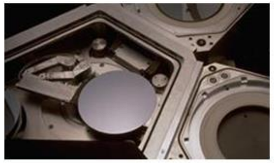
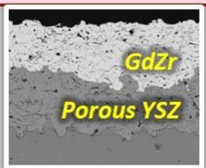
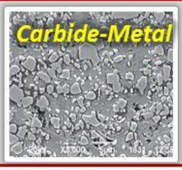
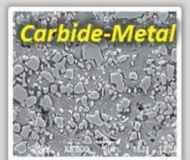
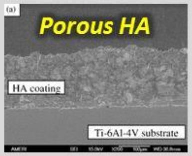
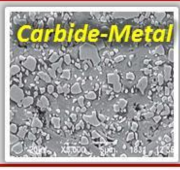
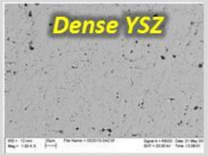
Wide Range of Thermal Spray Coated Components

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 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 Strength Toughness Wear	Residual Stress Adhesion Toughness Phase Stability	Residual Stress Adhesion Strength Toughness Wear	Residual Stress Adhesion Erosion Phase Stability Thermal Expansion

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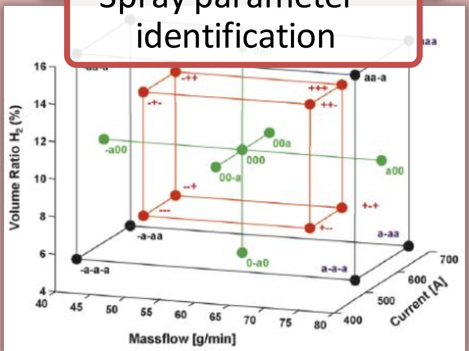
Process Optimization of Proposed Coating Structure

Design of Experiments

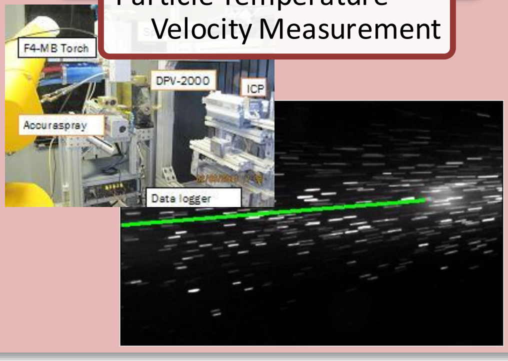
Design of Experiments

Spray parameter identification



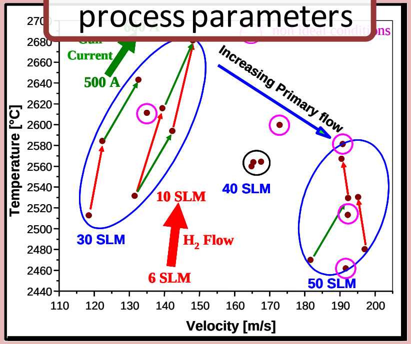
InFlight Particle Analysis

Particle Temperature-Velocity Measurement



1st-order Process Map

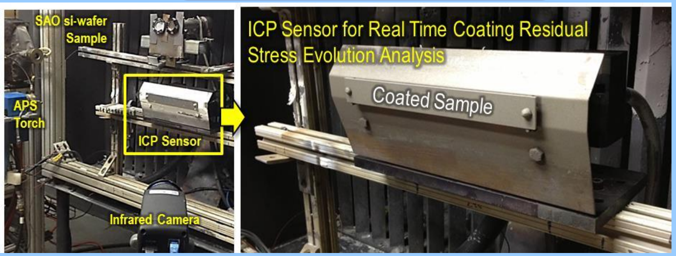
Particle T-V to process parameters



Residual Stress Evolution Optimization

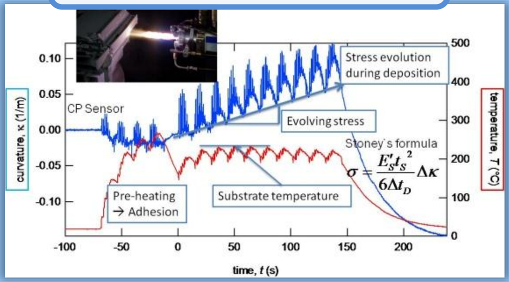
ICP Coating Deposition

Deposit low E process parameters on ICP sensor



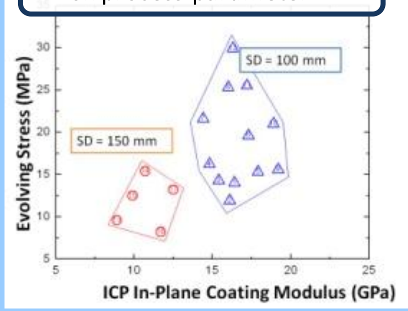
Stress Evolution Analysis

Deposition-Thermal-Residual Stress Analysis



Stress-Modulus Analysis

Stress Evolution-Modulus relationship on process parameter



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)

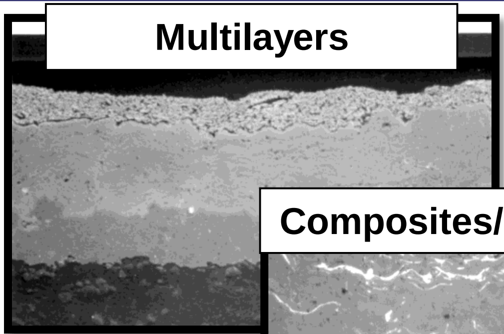
Process Parameters

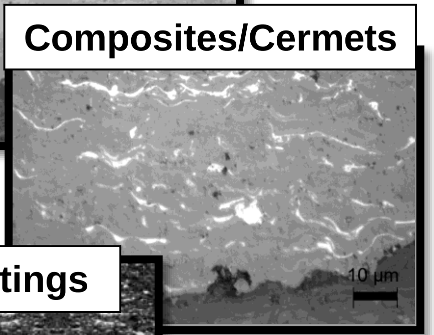
- Ability to tailor the microstructure, density, and interface through use of graded layers
- Ability to control deposition temperature
  - Robot raster speed
  - Secondary cooling

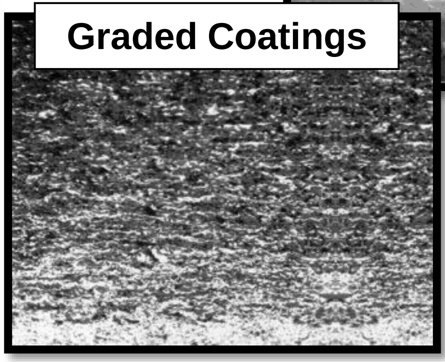
NiAl deposited onto canvas

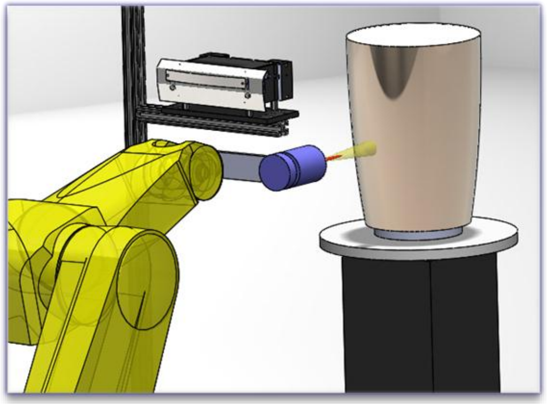
Component Manufacturing

- 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 ▪ 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 ▪ Ductile metallic layer as a bond coat ▪ Hard PVD interlayer (PVD TiN or BN)
TS Coating residual stress compatibility	▪ Select similar CTE coating material as NiCo ▪ 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 ▪ Low APS process condition. Explore Twin Wire Arc and Flame Spray ▪ Cooling jet, faster raster speed, off-angle deposition
Strong adhesion to smooth NiCo layer	▪ Apply a similar CTE bond coat ▪ First coating pass analysis using ICP sensor for adhesion criteria ▪ SEM cross-sectional metallography ▪ ASTM C633 bond strength test for quantifying adhesion strength

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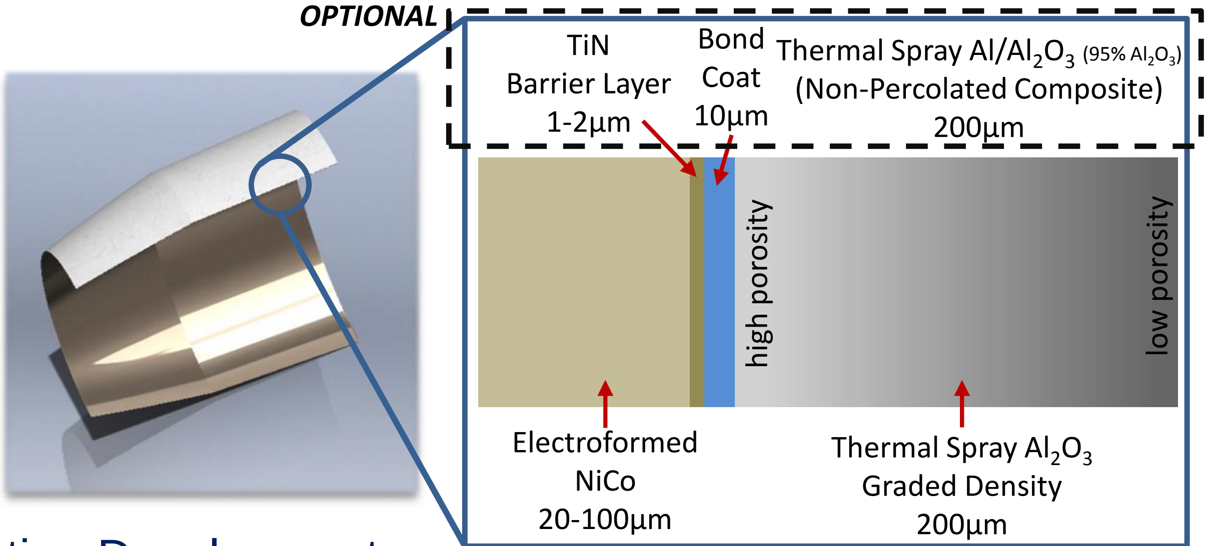
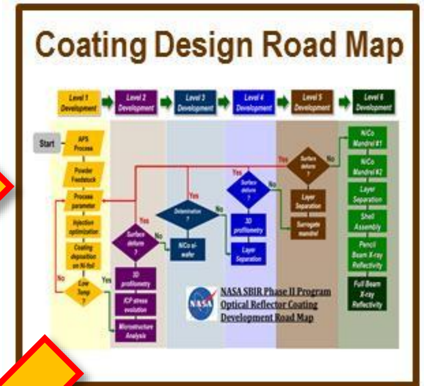
Detailed Design Plan of Proposed Innovation



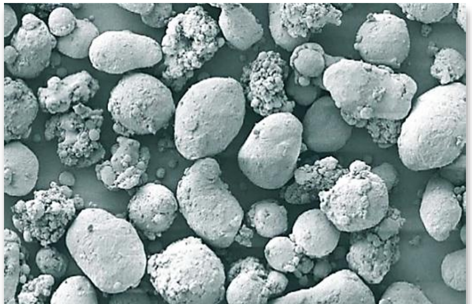
Proposed Coating Development

	Optic Shell	Barrier Layer	Bond Coat	Graded Ceramic
Composition	NiCo	TiN BN	No Bond Coat Al Ni-5%Al	Al_2O_3 5% wt Al / 95% wt Al_2O_3 10% wt Al/90% wt Al_2O_3
Thickness	25µm 50µm 75µm 100µm	No Barrier 1-2µm	No Bond Coat 10µm	150µm 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

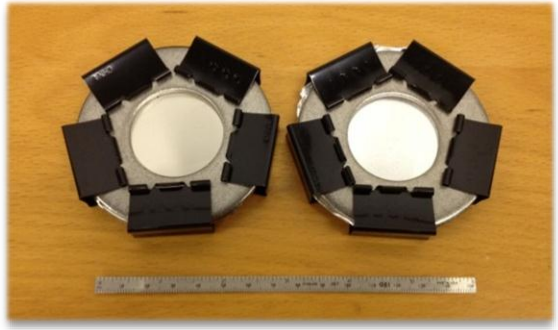
- Replace zerodur optic with **NiCo shell and thermal spray ceramic support structure**
- Utilize NiCo electroforming to **replicate the surface micro-roughness of the mandrel**
- Combine a **graded-density lightweight ceramic support coating** to hold figure accuracy and supply rigidity for handling



Aluminum Powder

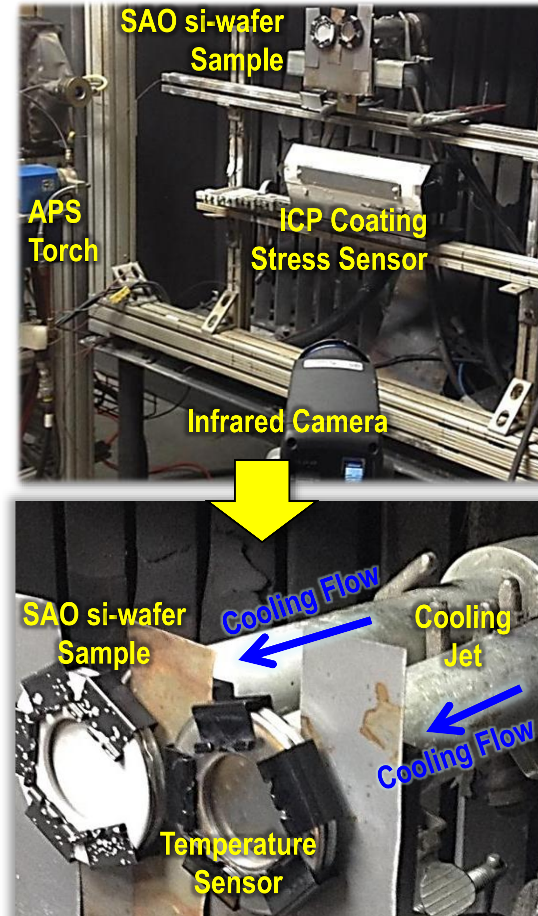
Fine powder size to minimize particle energy

Initial Test Substrates

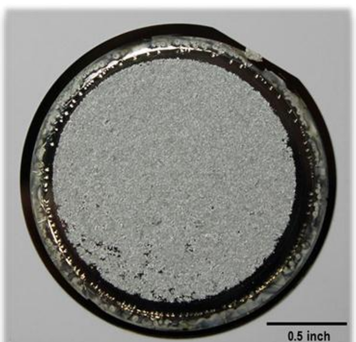


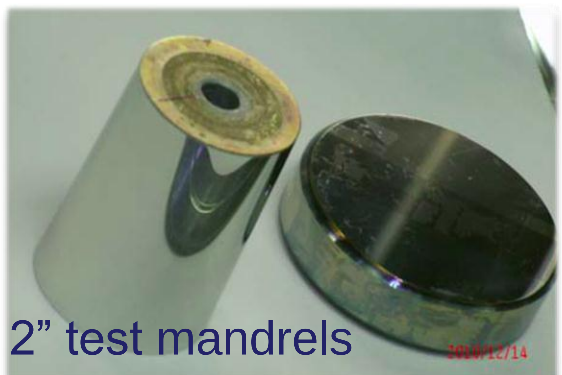
Evaluate potential particle damage using nickel and aluminum foil

Air Plasma Spray (APS) Deposition



NiCo Coated Si Wafer





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

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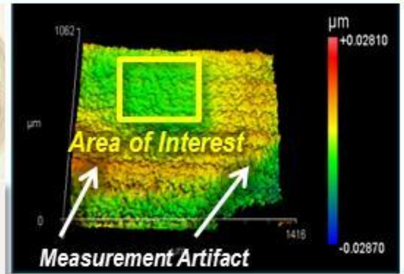
Coating Deposition Summary: APS Coating

Electroformed NiCo / Ni-5%Al Bond Coat & Al Coating

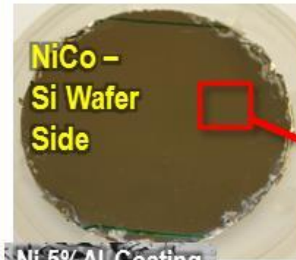
As-Deposited

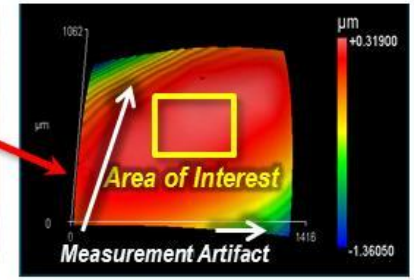
TS Al Coating (~200um)

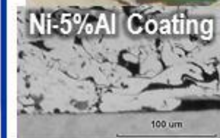
Strong Coating Adhesion to NiCo Layer



Si wafer exhibited no surface deformation







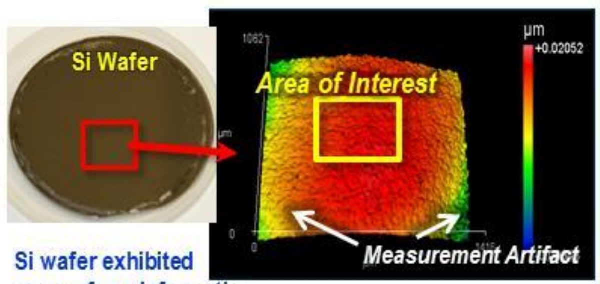
No visible surface deformation on NiCo layer

Electroformed NiCo / Ni-5%Al Bond Coat / Al/Al_2O_3 Blend / Al_2O_3 Top Coat)

As-Deposited

Ni-5%Al Bond Coat, Al/Al_2O_3 Blend Layer, and Al_2O_3 Top Coat

Uniform TS Coating Coverage with good adhesion



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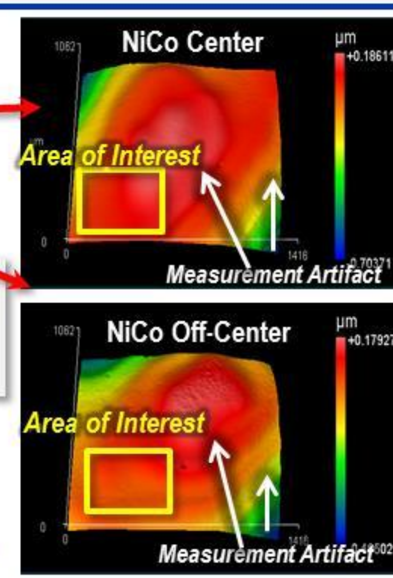
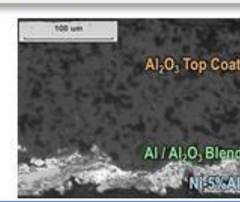


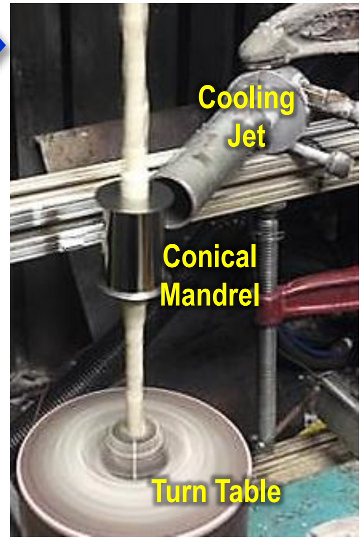
- No visible surface deformation of NiCo layer
- Uniform NiCo Surface roughness



APS Multi-Layer Deposition on NiCo Coated Surrogated Mandrel

As-received NiCo mandrel

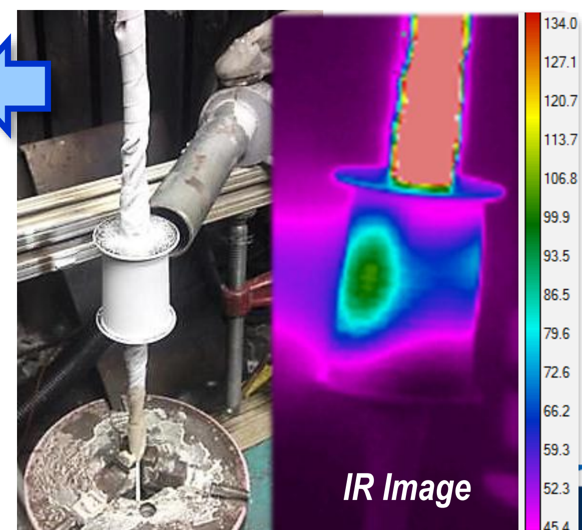
NiCo mandrel mounted on a turn table



Post Ni-5%Al deposition

Post Al-Al_2O_3 deposition

Post Al_2O_3 deposition

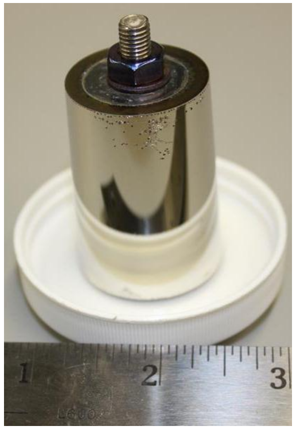


Post TS coating deposition state

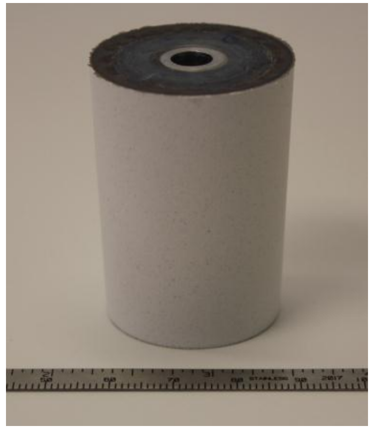
Successfully released reflector coating from the mandrel

Phase I Accomplishment

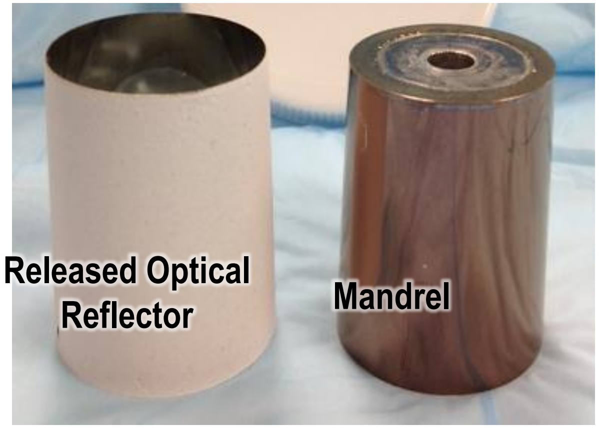
NiCo coated Mandrel



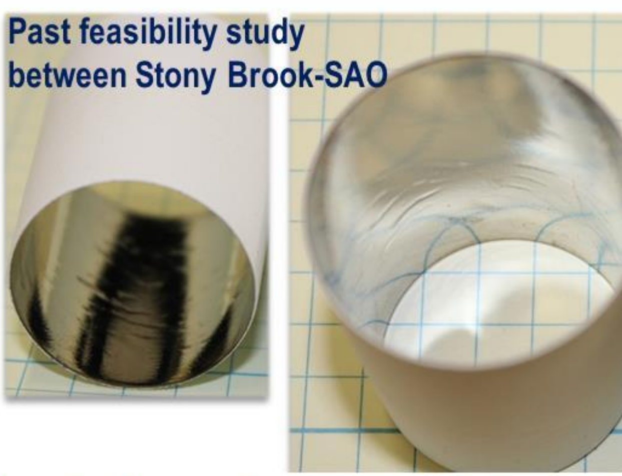
Thermal spray coated mandrel



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

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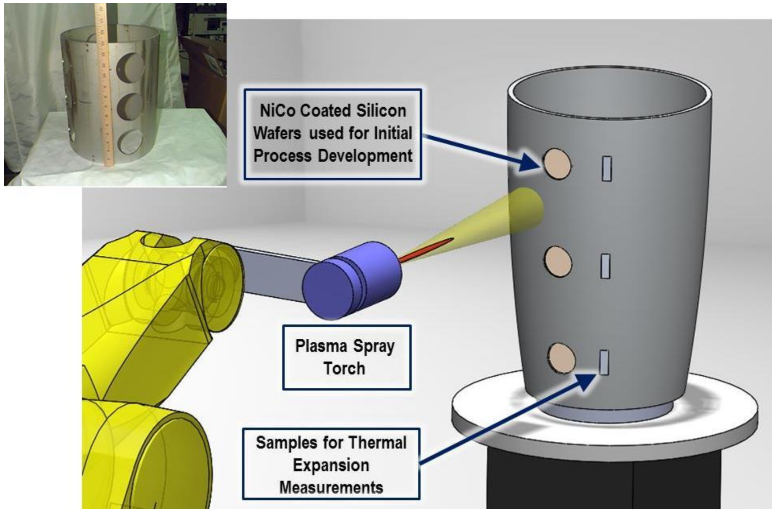
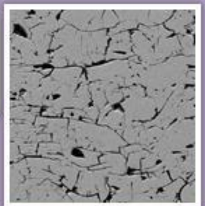
Coating Physical Property Assessment



- 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

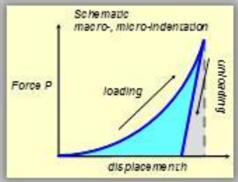
SEM Microstructure porosity/density analysis



Mechanical Property Analysis

Indentation Test

Elastic modulus, hardness



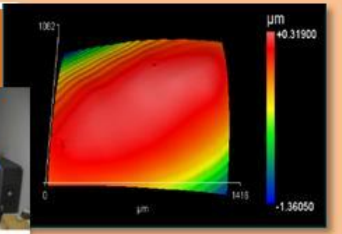
Adhesion Test

adhesion strength

Optic Surface Deformation Analysis

3D Surface Profilometry

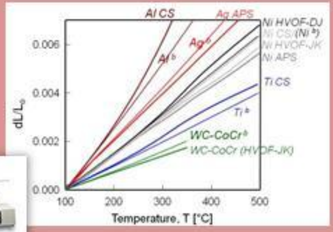
Assess Optical Surface Deformation



Thermo-Mechanical Analysis

Thermal Expansion

Layer Thermal expansion coefficient



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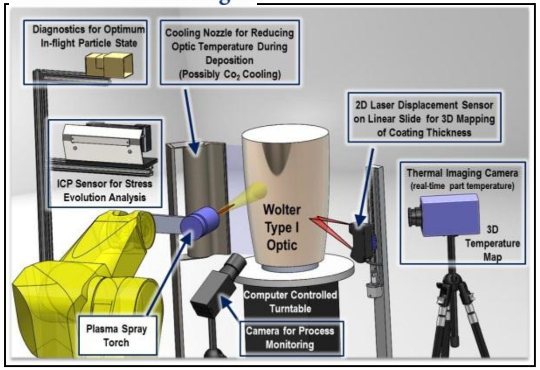
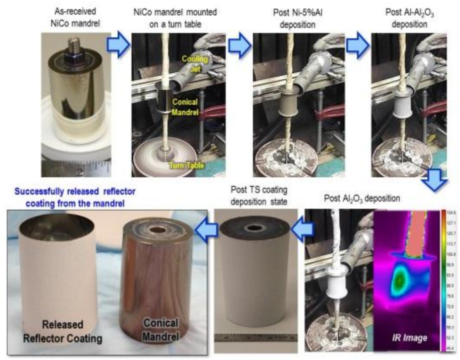
Phase II Deliverable : Two Nested Shell Telescope

ReliaCoat Technologies

TS Deposition onto 2 Wolter mandrels





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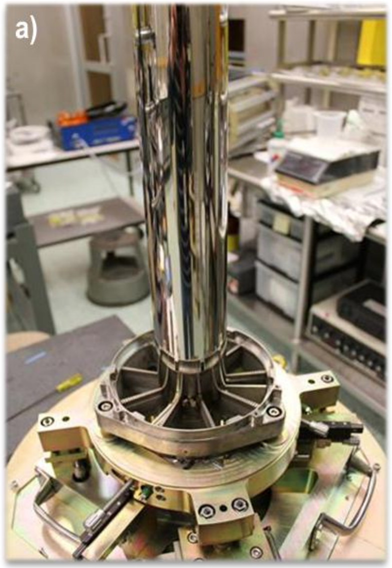
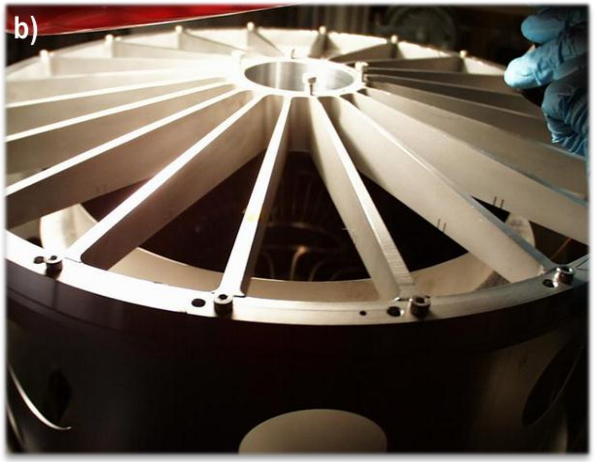
Assembly of 2 nested shell telescope





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

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

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