Direct Fabrication of Full-Shell X-ray Optics

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X-ray Optics after Chandra

The challenge is to develop the optical fabrication technology capable of producing x-ray optics but with an order of magnitude lighter mirrors and at an affordable price.

The challenge can be approached from different directions:

- Very thin mirrors:
    - Replicated optics
    - Pore Optics
    - Figure Correction
- Not that thin full shells, direct fabrication, Chandra-like, Figure correction can be applied too

Mission-design studies have shown that full-shell optics of few-mm shell thickness can provide for scientifically compelling probe-class missions that satisfy the medium-term needs of x-ray astronomy.

Direct Fabrication

Technique is pioneered by the Astronomical Observatory of Brera, Italy

Material	Density (g/cm^3)	CTE (10^{-6} / K^{-1})	Elastic Modulus GPa	Yield Strength MPa
Fused Silica	2.2	0.5	72	48*
Beryllium	1.8	12	318	240
Al (6061)	2.7	24	69	276
AlSi	2.8	17	90	235
Duralcan F3S.30S AlSi+SiC(30% by vol)	2.8	14.6	120	210

Mechanical Properties of Potential Mirror Substrate Materials
*Maximal achievable value. The ‘working’ value is typically much less and depends on the surface/subsurface condition.

The 10 °C delta corresponds to a stress of ~ 2 ksi in the nickel coating. So, any inherent stress (in the electroformed NiP) should be much less than that OR such that it offsets the CTE mismatch stress, giving even lower stress in the room temperature article.

<u>Have to control the thickness of the NiP deposit on both sides of the mirror shell</u>

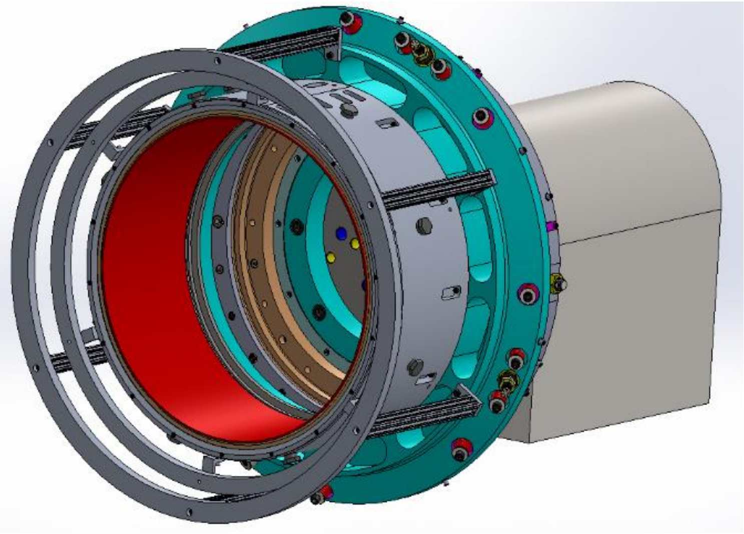
Ideally, the mirror shell has low density, low coefficient of expansion (CTE), high modulus of elasticity and high yield strength. It should also be a material that is not too difficult to figure and polish.

- Be + NiP (CATS-ISS telescope)
- Al +NiP
- AlSi + NiP

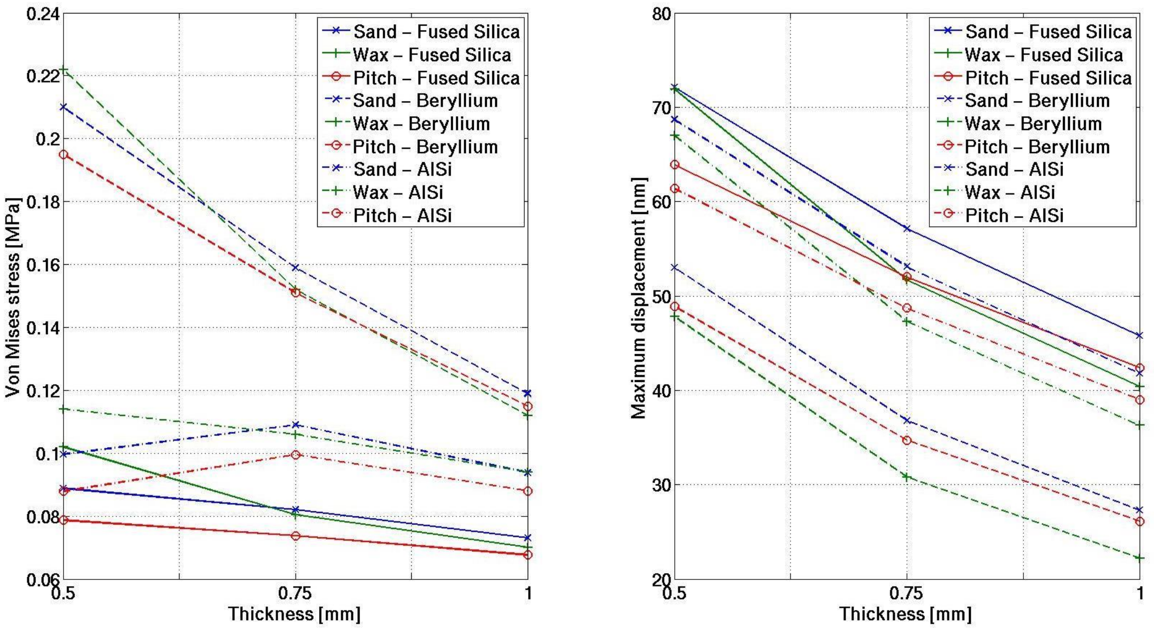
Challenges:

- CTE
- Electroless vs. electrolithic

Direct Fabrication

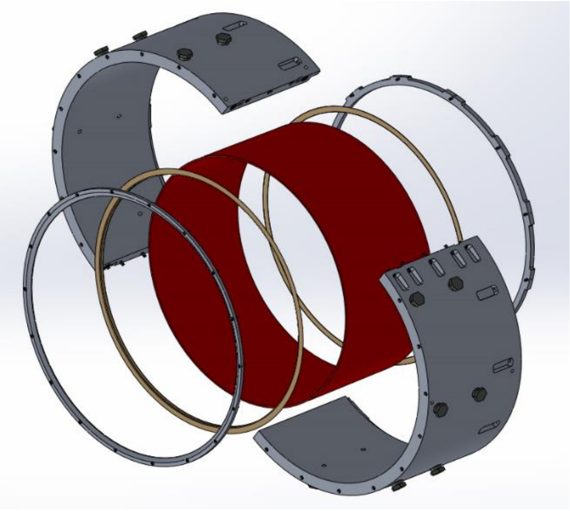


Backing support system installed on the precision lathe for diamond turning. The precision stage (blue) permit alignment of the mirror shell (red) with the lathe.



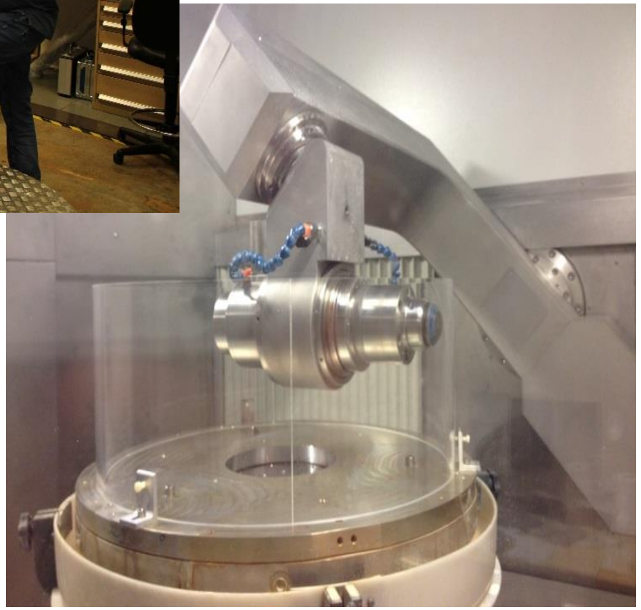
Maximum Von Mises stresses and displacements for different combinations of mirror shell and support backing materials, calculated for small (10 mm) bonnet footprint for the tool force value typical for the polishing machine as a function of mirror shell thickness. A 3-mm-thick backing material was assumed for the finite-element analysis.

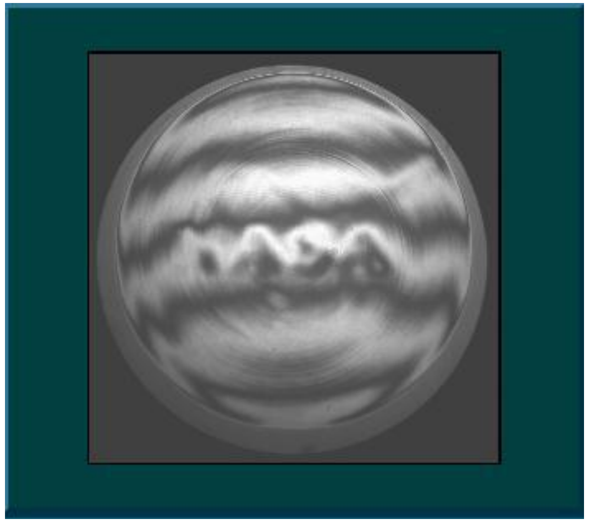
Thin-shell backing support system. A thin layer of backing material (not shown) acts as interface between the mirror shell (red) and the stiff outer support clam-shell (gray). The support rings and the gaskets shown contain the backing material.

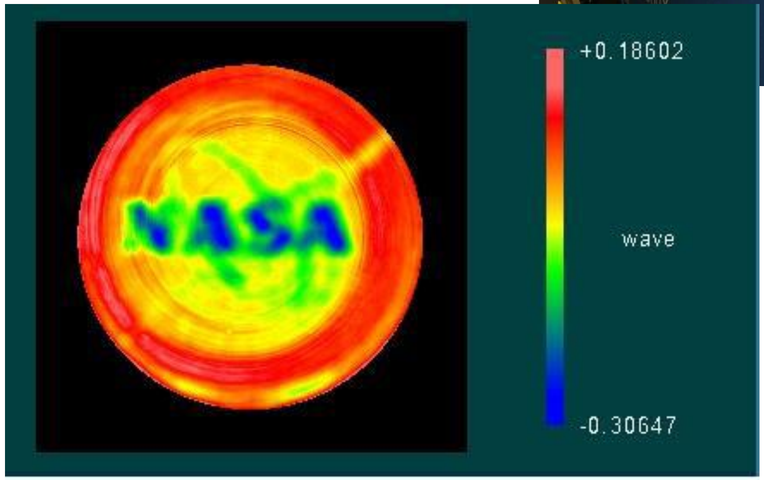


Zeeko machine

- The machine utilizes a “bonnet” technique in which an inflated rubber hemispherical diaphragm supports the polishing medium.
- there are different “bonnet” sizes (20 mm, 40 mm and 80 mm radii of curvature)
- This computer-controlled deterministic polishing processes leads to a high convergence rate.



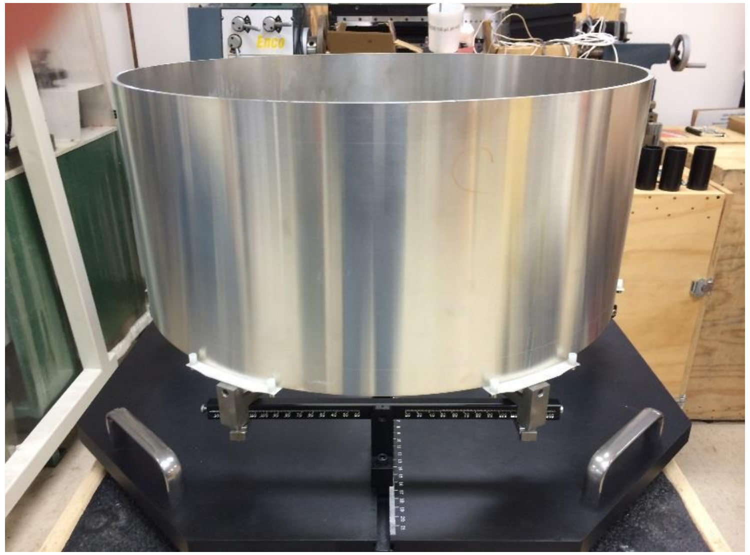




Metrology for Direct Fabrication

- Vertical Long trace profilometer;
- Skip test;
- Deflectometer for possible in situ measurements

Vertical Long Trace Profilometer



Whiffle tree station with an aluminum shell supported at 12 points.

A metrology fixture to support the mirror shell during the skip test.

CNC Polishing Wear Pattern Characterization

Currently, we are in the process of characterizing the Zeeko wear function for use in preparing for cylindrical shell polishing runs.

Main Objectives:

- Determine dependence on machine setup parameters.
  - Depth and width vs. feed rate
  - Depth and width vs. bonnet pressure
  - Depth and width vs. spindle rotation rate
  - Depth and width vs. tool offset
  - Depth and width vs. precess and phi angles
- Determine dependence on bonnet/cover characteristics.
- Determine dependence on slurry characteristics.
- **Establish a baseline pressure, spindle rotation rate, tool offset based on simulations**
  - Then perform more finely sampled wear function vs. feed rate at baseline and +/- small variations to get the derivatives vs. pressure, spindle rotation rate, tool offset.
- Determine limiting factors for repeatability
  - Repeat a baseline test regularly and track changes to bound variability

CNC Polishing Wear Pattern Simulation

Parametric wear pattern simulation enables a more efficient method of exploring the polishing parameter space.

Based on Preston's law:

- Wear rate is proportional to
  - Bonnet pressure distribution
  - Velocity of bonnet surface

Velocity depends on

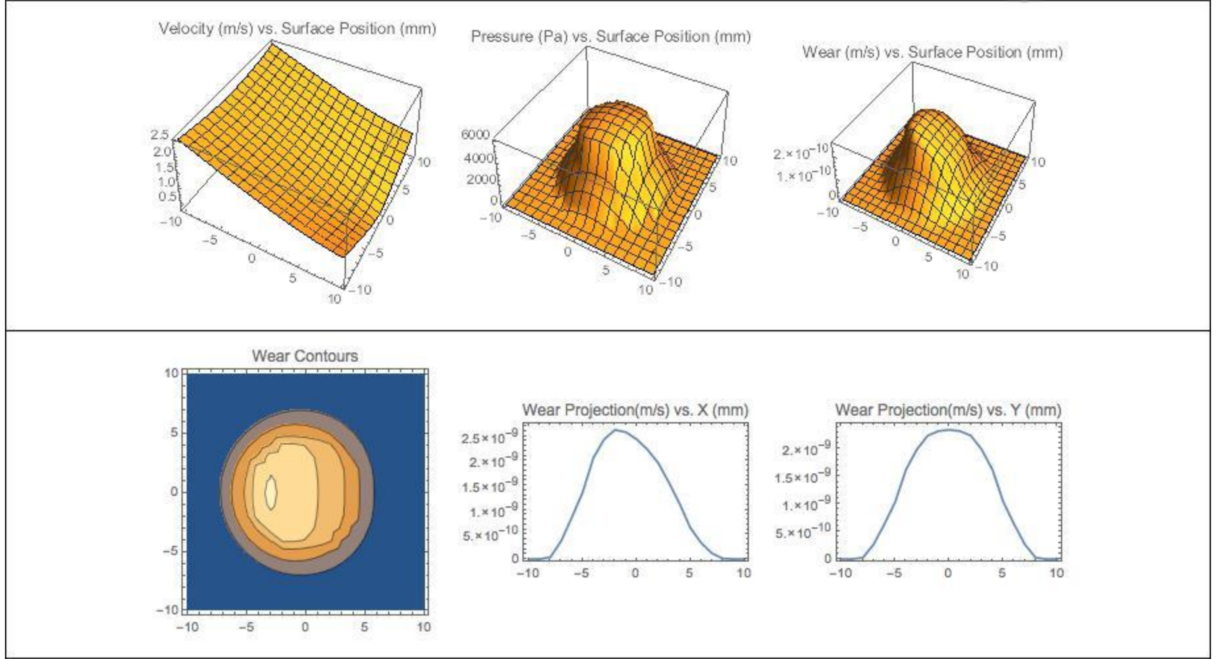
- Spindle rotation
- Head attack angles

Pressure depends on

- Internal pressure of bonnet
- Bonnet structural and mechanical properties
  - Static (current)
  - Dynamic (future)

Model will be validated and adjusted using measured data.

Example of Output from Model Run



bonnet

	value	unit
pressure	0.05	bar
thickness	0.5	mm
radius	41.	mm
density	1.3	g/cm^3
elasticModulus	20.	MPa
eModChangewFreq	0.01	MPa/Hz
poissonRatio	0.45	
damping	0.05	
dampChangewFreq	0.01	1/Hz
maxDamping	0.35	

2 levels | 10 rows

bonnetCover

	value	unit
thickness	0.5	mm
friction	0.04	
fracContact	0.5	

2 levels | 3 rows

slurry

	value	unit
viscosity	0.05	Pa s
fracSolids	0.1	
gritSize	0.03	micron
prestonCoef	2.9	10^{-14}/Pa
smoothScale	1.	mm

2 levels | 5 rows

machineAxes

	value	unit
springK	100000.	N/m
rotationRateSpindle	1000.	RPM
toolOffset	0.3	mm
precessAngle	17.	deg
phiAngle	0.	deg

2 levels | 5 rows

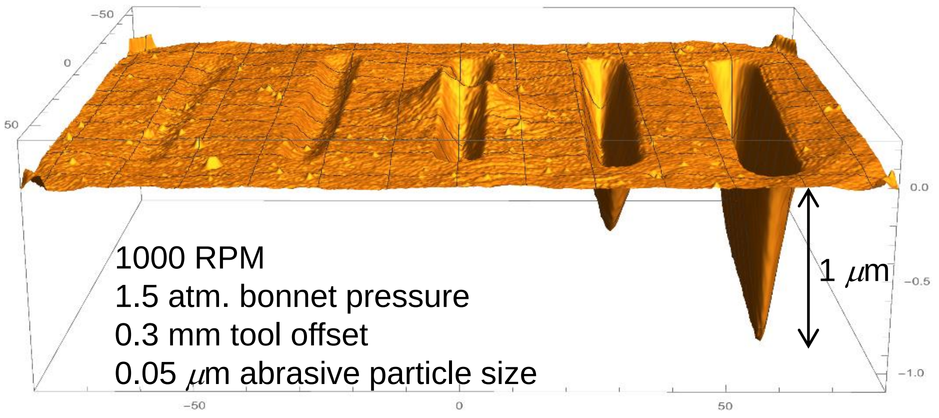
surface

	value	unit
radiusofCurvature	20.	cm
wearGridHalfWidth	10.	mm
wearGridStep	1.	mm

2 levels | 3 rows

CNC Polishing Wear Pattern Measurement

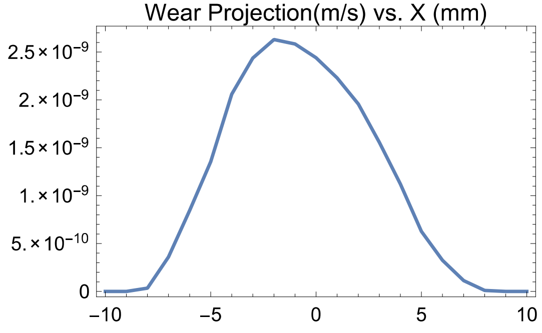
Measured wear data from wave front sensor

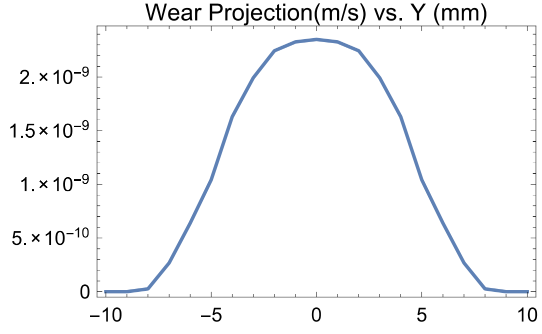


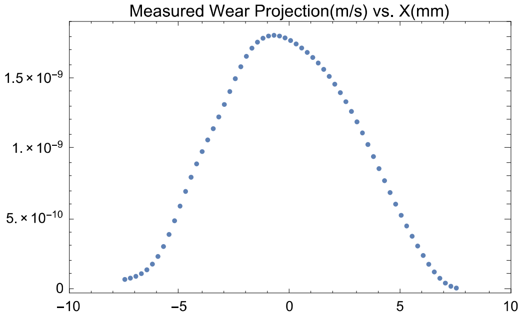
- 100 mm diameter, Ni-P-plated, diamond-turned polishing samples have trenches polished with varying parameters.
  - In this case feed rate was varied from 2 to 32 mm/min
- Wear is measured using Zygo wave front sensor.
- Wear rate function is derived from data.

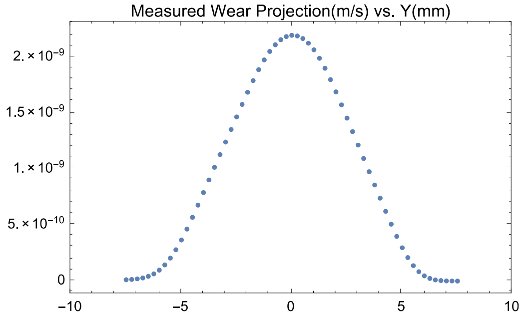
- A priori, simulated profiles are based on a Preston coefficient = 2.9×10^{-14} Pa^{-1} found in literature.*
- Peak projected wear rate ~2.5 nm/sec.

- Measured wear rate function shows peak ~2.2 nm/sec
- **Agrees well with prior estimate.**







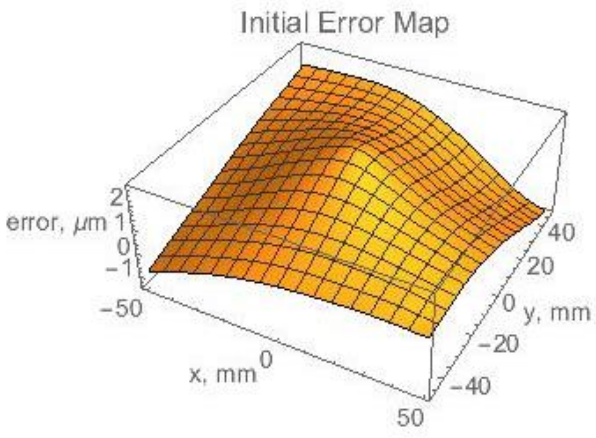


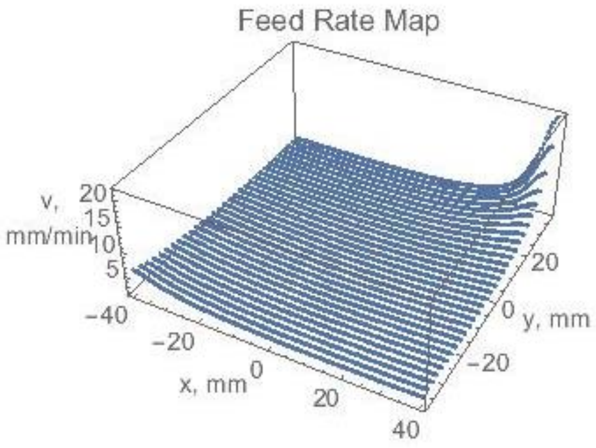
* Maury, A. et al. *Adv. Metalization Conference*, 1997

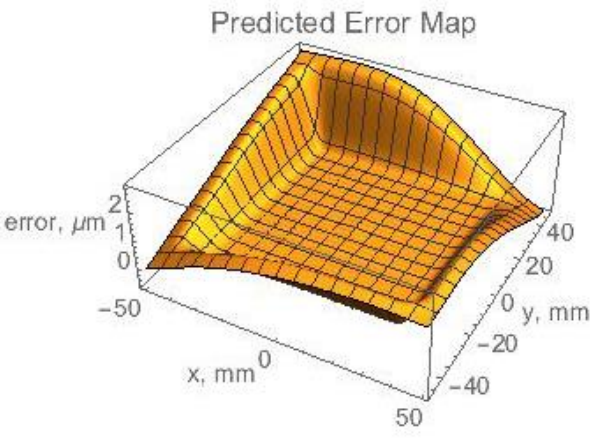
CNC Polishing Wear Pattern Application

- Several options for determining the feed rate map from error map have been explored
  - Initially using a Richardson-Lucy deconvolution algorithm + small nonlinear correction
    - Tends to generate smoother edge transitions

- Simulated Example for a single iteration.







- Initial error map derived from Wyco data.
- RMS slope errors along x-axis are **8 arcsec.**

- Derived feed rate map.
- Feed rates range from 1.35-20 mm/min.

- Predicted result of 1st polishing iteration.
- RMS slope errors along x-axis are predicted to be **1.4 arcsec.**
- Measured results await machine repair.

Conclusions

- MSFC develops the direct fabrication technology for full shell x-ray optics made from metal substrates;
- Support fixtures for diamond-turning, polishing and metrology are designed and currently in production;
- Wear functions were determined using NiP plated flat samples;
- Tool path generation software is developed;
- Electrolithic NiP plated samples are fabricated for the Tool path generation software verification;
- Technology, if developed, will increase competition;
- The technique can be married with the Differential Deposition
- The experiments are pending the machine repair