Development of a Prototype Nickel Optic for the Constellation-X Hard X-Ray Telescope

S.Romaine[a], S.Basso[b], R.J.Bruni[a], W.Burkert[f], O.Citterio[b], V.Cotroneo[b], D.Engelhaupt[e],
M.J.Freyberg[f], P.Gorenstein[a], M.Gubarev[d], G. Hartner[f], F. Mazzoleni[b], S.O'Dell[c],
G.Pareschi[b], B.D.Ramsey[c], C.Speegle[g], D.Spiga[b]

[a]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138
[b]Istituto Nazionale di AstroFisica-Osservatorio Astronomico di Brera - 2380 8 Merate(Lc) - Italy
[c]Space Science Office,NASA/Marshall Space Flight Center
[d]Universities Space Research Association, Alabama
[e]Center for Applied Optics, University of Alabama in Huntsville
[f]Max-Planck-Institut für extraterrestrische Physik, Panter, Neuried, Germany
[g]Raytheon-ITSS, Alabama

ABSTRACT

The Constellation-X mission concept has been streamlined to a single Atlas V 551 configuration. This decision was reached by the project team after considering the increases in launch costs announced in 2006 coupled with the constrained budget environment apparent with the release of the NASA 2007 budget. Along with the Spectroscopy X-ray Telescopes, this new configuration continues to carry a Hard X-ray Telescope (HXT) component, with some modifications to the original requirements to adjust to the new configuration. The total effective area requirement in the 7 - 40 keV band has been reduced, but at the same time the angular resolution requirement has been increased from 1 arcmin to 30 arcsec.

The Smithsonian Astrophysical Observatory, Marshall Space Flight Center and Brera Observatory (Italy) have been collaborating to develop an HXT which meets the requirements of Constellation-X. The development work we have been engaged in to produce multilayer coated Electroformed-Nickel-Replicated (ENR) shells is well suited for this new configuration.

We report here on results of fabrication and testing of a prototype optic for the HXT. Full beam illumination X-ray tests, taken at MPE-Panter Test Facility, show that these optics meet the new requirement of 30 arcsec for the streamlined Constellation-X configuration.

This report also presents preliminary results from studies using titanium nitride as a release agent to simplify and improve the nickel electroforming replication process.

Keywords: X-ray Telescopes, X-ray optics, multilayers, electroformed optics

1. INTRODUCTION

The Constellation-X Mission,[1,2] scheduled to be launched in 2015-2020 timeframe, consists of 2 telescope systems: the spectroscopy X-ray telescope (SXT)[3] and the hard X-ray telescope (HXT).[4] The Constellation-X mission was streamlined in 2006 to launch on a single Atlas V 551 (see R. Petre et al., this conference).

The Smithsonian Astrophysical Observatory (SAO), the Marshall Space Flight Center (MSFC) and the Brera Observatory, Italy (INAF-OAB), are collaborating to design and build a prototype optic for the HXT of Constellation-X.[6,7] Our approach is to electroform nickel shells of full revolution which meet the requirements of the HXT. The use of full-shell optics which are inherently stable, offers the prospect of better angular resolution and therefore lower background and higher instrument sensitivity.[5] This technology was developed for

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Corresponding author: S. Romaine, email: sromaine@cfa.harvard.edu

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XMM/Newton which achieved a resolution of 15 arcseconds. The stringent mass allocations of X-ray astronomy missions such as Constellation-X place a tight mass constraint on the telescope optics. It was necessary to improve upon the electroforming process to fabricate much thinner, lighter weight shells while not degrading the figure. At the same time, the energy band of the HXT required multilayer coating on the inside surface of the shells, compared with the single layer metallic gold coatings of previous missions. Therefore many developments had to take place to move from the current status of the XMM telescope to meet the requirements of future NASA missions such as the HXT of Constellation-X.

2. REVIEW OF ACCOMPLISHMENTS TO DATE

Table I lists results of two of the shells tested at MPE-Panter Test Facility[8,9] and shows that the HEW achieved meets the present Constellation-X streamlined HXT resolution requirement of 30 arcsec.

Table 1. `Measured half energy widths for assembled shells: 15 cm and 23 cm diameter; shells were fabricated at MSFC, coated at SAO and aligned at INAF-OAB.`

Energy (keV)	HEW (arcsec) 15 cm	HEW (arcsec) 23 cm
4.51	28.9	26.7
5.41	28.7	29.2
6.40	29.2	30.1
8.05	29.5	30.8

More recent tests indicate that this result can be inproved by a factor of 2, bringing the spatial resolution to 15 arcsec. Metrology on the individual shells before (and after) mounting into the telescope structure predicts a figure of 12 to 16 arcsec. The measured HEW of the shells mounted in the telescope structure is $\approx$ 30 arcsec. This decrease in resolution is due to a combination of gravity sag issues (the telescope testing is done in a horizontal geometry, as shown in figure 1) and stress at the epoxied mounting points of the spider arms used to hold the shells in place. Work to improve the mounting is now in progress.

3. NEW STUDIES

The electroform procedure used to replicate nickel shells from a mandrel involves many separate processes, including: fabricating and superpolishing the mandrel, adding a release layer to the mandrel, growing the nickel shell and finally separating the shell from the mandrel.

A typical release material for this process is e-beam evaporated gold, which separates easily from the electroless nickel coated mandrel via differential thermal expansion when the mandrel is cooled. The gold layer separates with the shell, leaving behind the uncoated mandrel surface. Therefore, before a 2nd shell can be grown using the same mandrel, another gold release layer must first be deposited. Although the gold releases well, it does not release perfectly, and there are some atomic layers of gold that remain on parts of the mandrel each time a replica is released. Therefore, the microroughness of each succeeding replicated shell increases slightly, and after a few replications it is necessary to touch up the mandrel by re-polishing.

Ideally, one would prefer to have a release layer material that adheres to the mandrel, allowing the shell to separate from the release layer, rather than the release layer separating from the mandrel, as happens with gold.

In these studies, titanium nitride was used as the release material in place of gold to test it's applicability in this process. The expectation was that the titanium nitride would stick well to the mandrel surface, and the release would occur at the titanium nitride surface. The vickers hardness of titanium nitride is slightly less than the hardness reported for silicon carbide, a material known for its high hardness. With such high hardness, the expectation is that this surface would withstand many replications, without the necessity to have to re-polish or re-coat the mandrel.

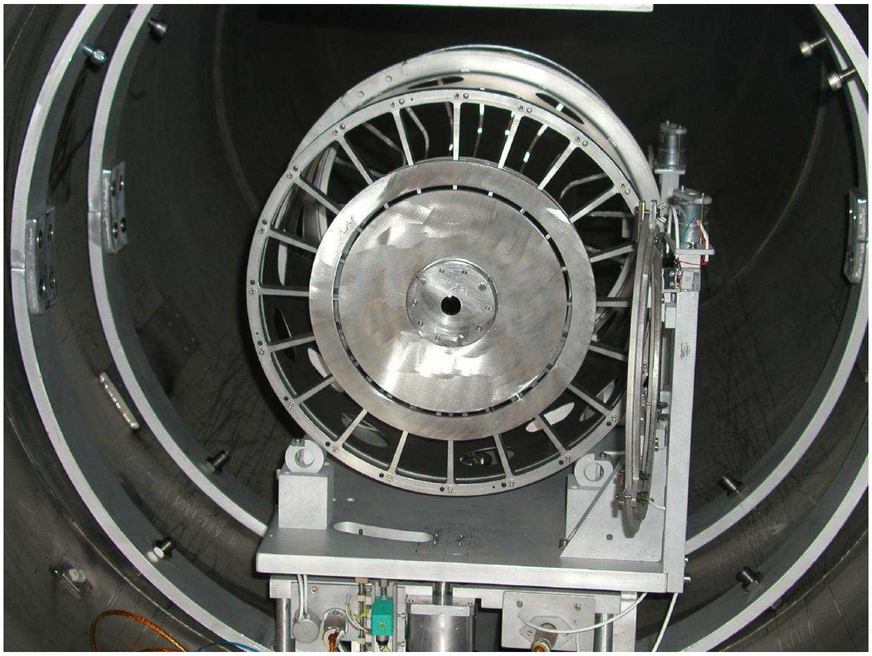

Figure 1. Photograph of HXT telescope module in X-ray pipe at Panter Facility. The testing is done with the telescope mounted in the horizontal position, as shown.

3.1. Fabrication of the replicas

Two inch diameter half inch thick flat mandrels were used in all the the tests reported here, since working with 2 inch flats is easier and less expensive than using full cylindrical mandrels for testing. Two mandrels were fabricated, each one underwent the same processing. The mandrels were polished to 1.5 Åmicroroughness as measured on WYKO with 20x magnification. A 3000 Åthick coating of TiN was then deposited on the mandrels using a dc magnetron sputtering process, and the TiN was then polished to 1.5 Åas measured on WYKO. (the AFM was not operational at the time the polishing was done so WYKO measurements were used to check the surface microroughness during polishing.) Four replicas were then made from each mandrel. After the separation of each replica, the mandrel was cleaned before inserting it into the electroforming bath, but no other processing was used on the mandrel between replications. No difficulty was encountered in separating the replicas from the mandrels, and the separation occurred at the surface of the titanium nitride, leaving the titanium nitride release layer on the mandrel, as intended. Microroughness was measured using a Digital Instruments Nanoscope III AFM and the AFM data taken on each mandrel and on the replicas and is reported below.

4. MICROROUGHNESS MEASUREMENTS

4.1. AFM measurements of the mandrels

Figure 2 shows 3-dimensional AFM images (1 and 10 micron scans) of mandrel #1 after separating four replicas. The microroughness analysis is given in figure 3; both scans showing a surface roughness of 3 Å or better. Similar images are given in figures 4 and 5 for mandrel #2, showing a microroughness of 2 Å and 3.3 Å for the 1 and 10 micron scans, respectively. Although no AFM data exists for the mandrels before the electroforming, we reported above WYKO data of 1.5 Å on the just-polished mandrels. We know from past experience that measurements of our polished mandrels on AFM yield slightly higher microroughness than what we find with WYKO frequencies. Therefore we are confident in saying that the ≈ 3 Å microroughness we measure with AFM after four replications on each mandrel indicates little (if any) degradation of the surface.

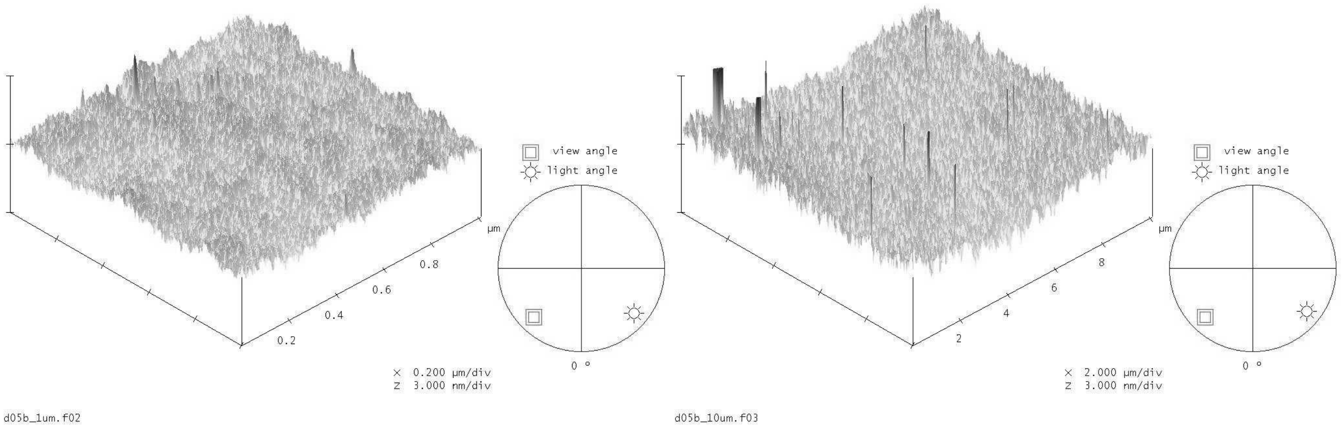

Figure 2. AFM 1 micron scan (left) and 10 micron scan (right) of mandrel #1. The z-axis is 30 Åper division. This 3d image gives an indication of the smoothness of the surface. The RMS microroughness is shown in the image Analysis below.

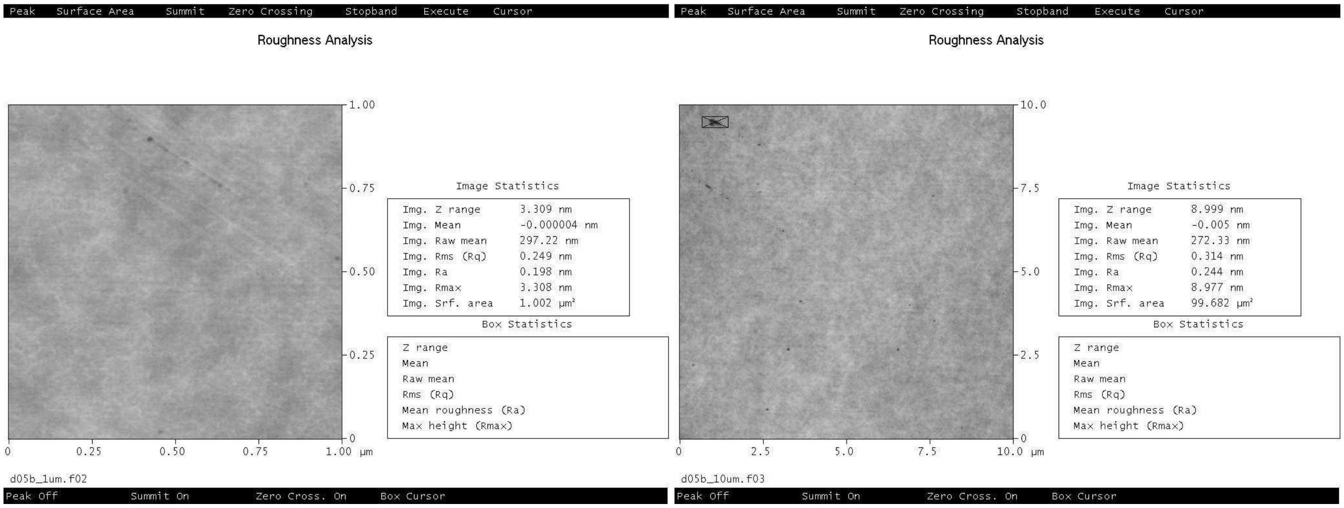

Image Statistics

Img. Z range	3.309 nm
Img. Mean	-0.000004 nm
Img. Raw mean	297.22 nm
Img. Rms (Rq)	0.249 nm
Img. Ra	0.198 nm
Img. Rmax	3.308 nm
Img. Srf. area	1.002 µm²

Box Statistics

Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Max height (Rmax)

Image Statistics

Img. Z range	8.999 nm
Img. Mean	-0.005 nm
Img. Raw mean	272.33 nm
Img. Rms (Rq)	0.314 nm
Img. Ra	0.244 nm
Img. Rmax	8.977 nm
Img. Srf. area	99.682 µm²

Box Statistics

Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Max height (Rmax)

Figure 3. AFM Roughness Analysis of mandrel #1. 1 micron scan (left) shows RMS microroughness is 2.5 Å; 10 micron scan (right) shows RMS microroughness of 3.1 Å.

4.2. AFM measurements of the replicated surfaces

Figure 6 shows AFM roughness analysis of one of the replicas. These scans are representative of all eight of the replicas. The 1 micron scan is 3.7 Å ; all eight 1 micron scans have microroughness below 4 Å , which is the limit we have set for an acceptable replicated surface for depositing graded-d multilayers for hard x-ray optics coatings. The 10 micron scan of figure 6 is also representative of all eight of the replicas. The high microroughness of ≈ 15 Å is due to voids in the nickel, which can easily be seen as white 'dots' in the AFM scan. These voids are not typical in the electroformed nickel process, and may be due to the cleaning process. The cause of these voids is under investigation.

5. SUMMARY AND FUTURE WORK

Results of full-illumination X-ray tests of 100 micron thick electroformed nickel shells coated with W/Si multilyers were presented. The results meet the present requirements for resolution for the hard X-ray telescope of the

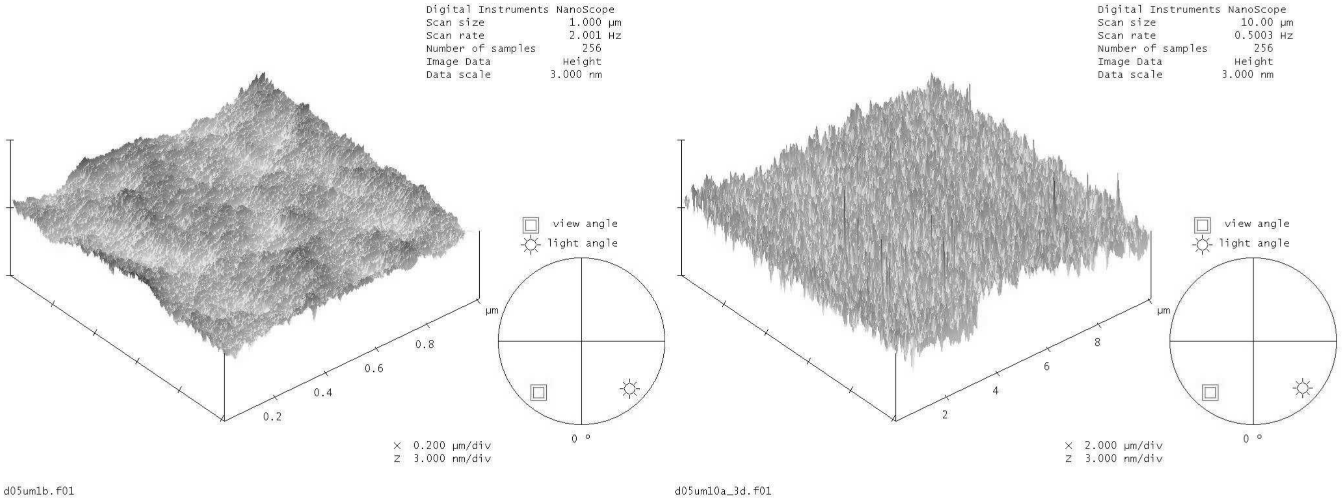

Figure 4. AFM 1 micron scan (left) and 10 micron scan (right) of mandrel #2. The z-axis is 30 Åper division. This 3d image gives an indication of the smoothness of the surface. The RMS microroughness is shown in the image Analysis below.

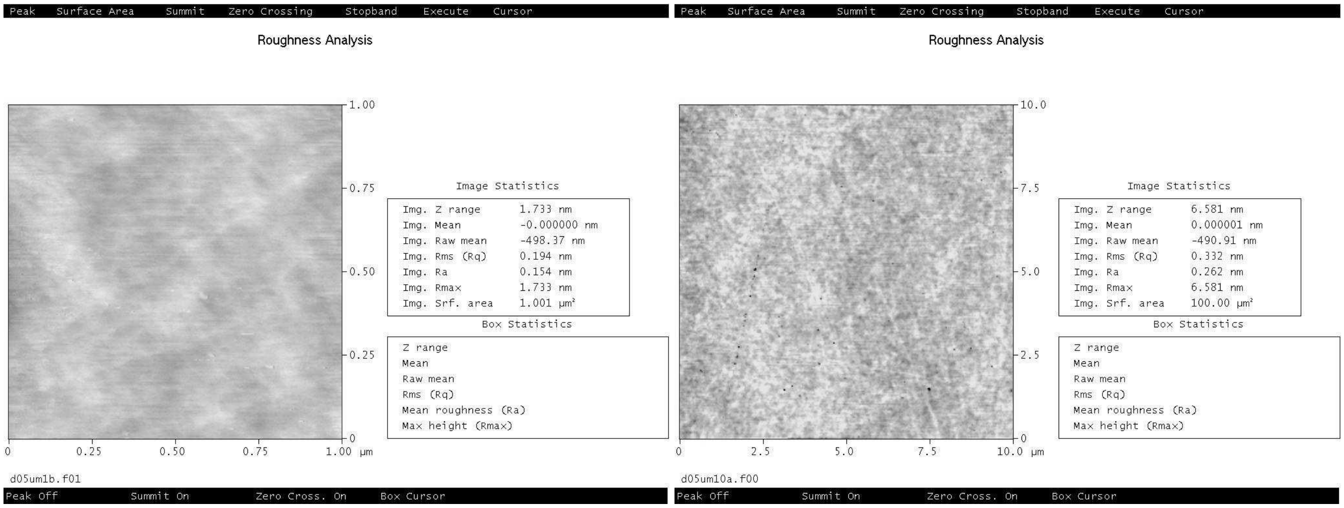

Image Statistics

Img. Z range	1.733 nm
Img. Mean	-0.000000 nm
Img. Raw mean	-498.37 nm
Img. Rms (Rq)	0.194 nm
Img. Ra	0.154 nm
Img. Rmax	1.733 nm
Img. Srf. area	1.001 µm²

Image Statistics

Img. Z range	6.581 nm
Img. Mean	0.000001 nm
Img. Raw mean	-490.91 nm
Img. Rms (Rq)	0.332 nm
Img. Ra	0.262 nm
Img. Rmax	6.581 nm
Img. Srf. area	100.00 µm²

Figure 5. AFM Roughness Analysis of mandrel #2. 1 micron scan (left) shows RMS microroughness is 1.9 Å; 10 micron scan (right) shows RMS microroughness of 3.3 Å.

Constellation-X Mission. There is a plan in place to try to improve this resolution by a factor of two, to 15 arcsec. Preliminary results were presented from new studies to develop a hard-coat release layer for the mandrel in the electroforming process. This would simplify the replication process and increase the replica yield. Indications are that the polished titanium nitride surface is a better release agent than gold for nickel electroforming process. AFM scans of the mandrels after four replications show an Rms microroughness of 3 Åor better; AFM scans of the replicas show that the surface is consistently better than 4 Åmicroroughness for 1 micron scans. However, at scan lengths of 10 microns, voids can be seen in the growth of the nickel on the replica which leads to surface microroughness of 15 ÅRms. Work is now proceeding to understand the cause of the voids. Once this is fully understood and corrected, it will be possible to fabricate several replicas from the mandrel with only one application of a release layer and with no polishing of the mandrel between replicas, making the process more robust and less costly.

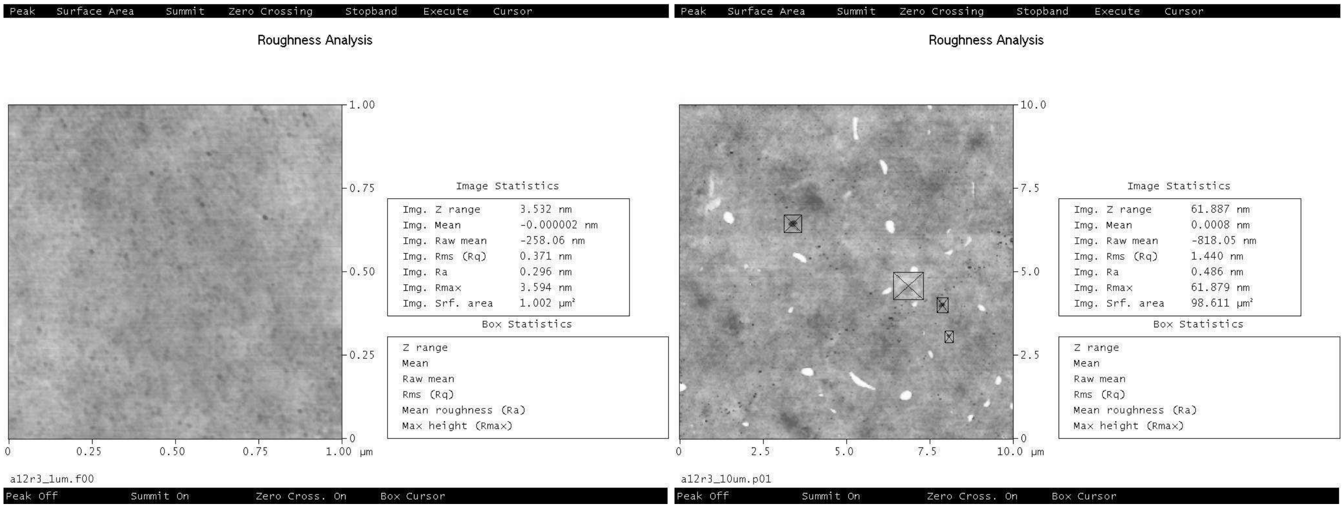

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Image Statistics
Img. Z range      3.532 nm
Img. Mean         -0.000002 nm
Img. Raw mean     -258.06 nm
Img. Rms (Rq)     0.371 nm
Img. Ra           0.296 nm
Img. Rmax         3.594 nm
Img. Srf. area    1.002 µm²
Box Statistics
Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Max height (Rmax)
```

```
Image Statistics
Img. Z range      61.887 nm
Img. Mean         0.0008 nm
Img. Raw mean     -818.05 nm
Img. Rms (Rq)     1.440 nm
Img. Ra           0.486 nm
Img. Rmax         61.879 nm
Img. Srf. area    98.611 µm²
Box Statistics
Z range
Mean
Raw mean
Rms (Rq)
Mean roughness (Ra)
Max height (Rmax)
```

Figure 6. AFM Roughness Analysis of one of the replicas. The RMS microroughness is shown for the 1 micron scan (left) and 10 micron scan (right). The microroughness of 3.7 Åfor the 1 micron scan is below the 4 Ålimit we set for an acceptable surface. However, the 10 micron scan has a microroughness of 14.4 Ådue to voids which can be seen in this image as white 'dots'. This set of images is typical of all of the replicas (see text for details).

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