



Solar Alpha Rotary Joint Anomaly: The Materials & Processes Perspective

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Aging Aircraft 2009

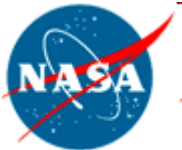
May 5th, 2009



Acknowledgements

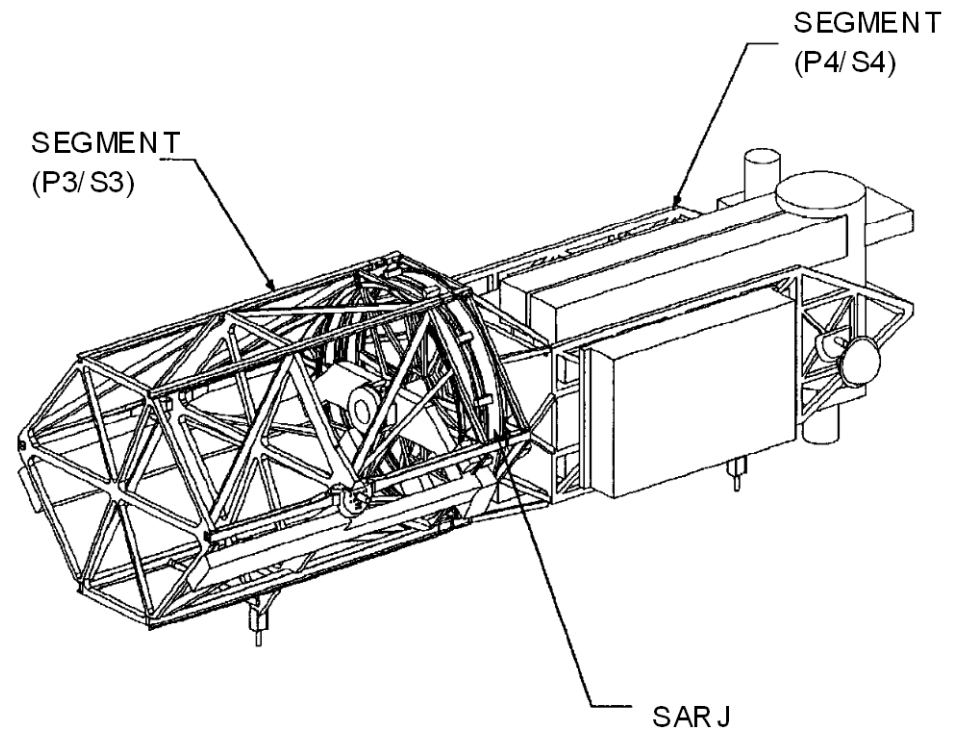
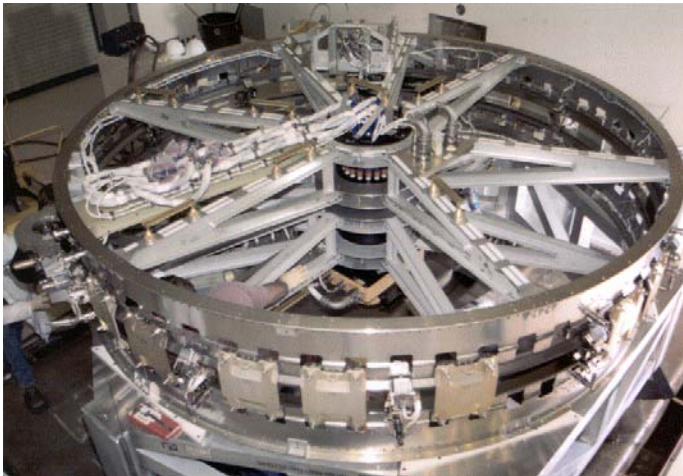


- **All work performed under NASA Contract NAS15-10000**
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- **NASA MSFC Lab: Greg German, Dr. Panda**
- **Boeing, Philadelphia; Dale Weires**
- **Lockheed Martin, Sunnyvale CA: Dennis Petrakis, Stu Lowenthal**



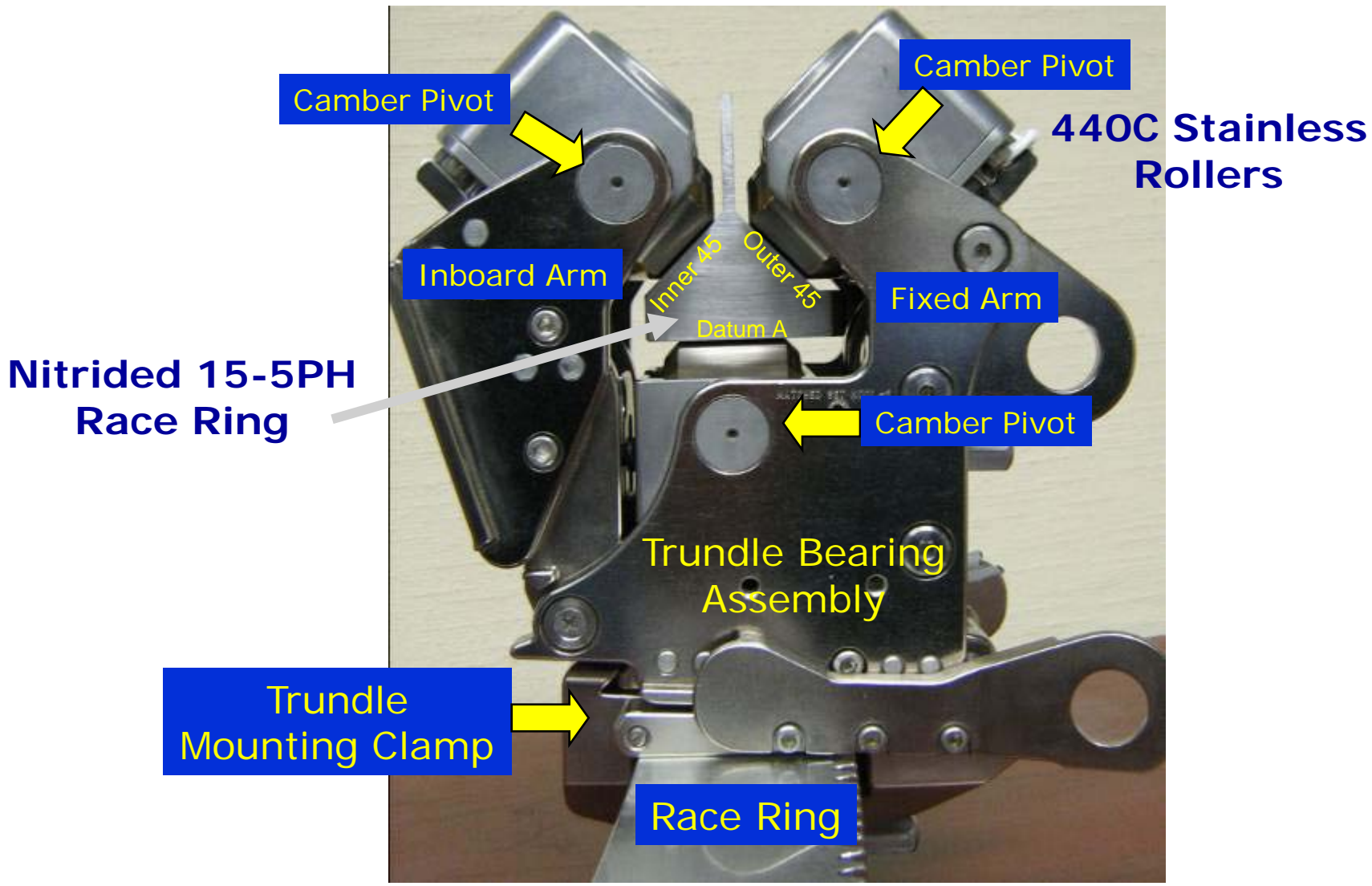
What is the SARJ?

The Solar Alpha Rotary Joint (SARJ) is used to rotate the outboard Solar Array Wings (SAW) and transfer generated power to the ISS



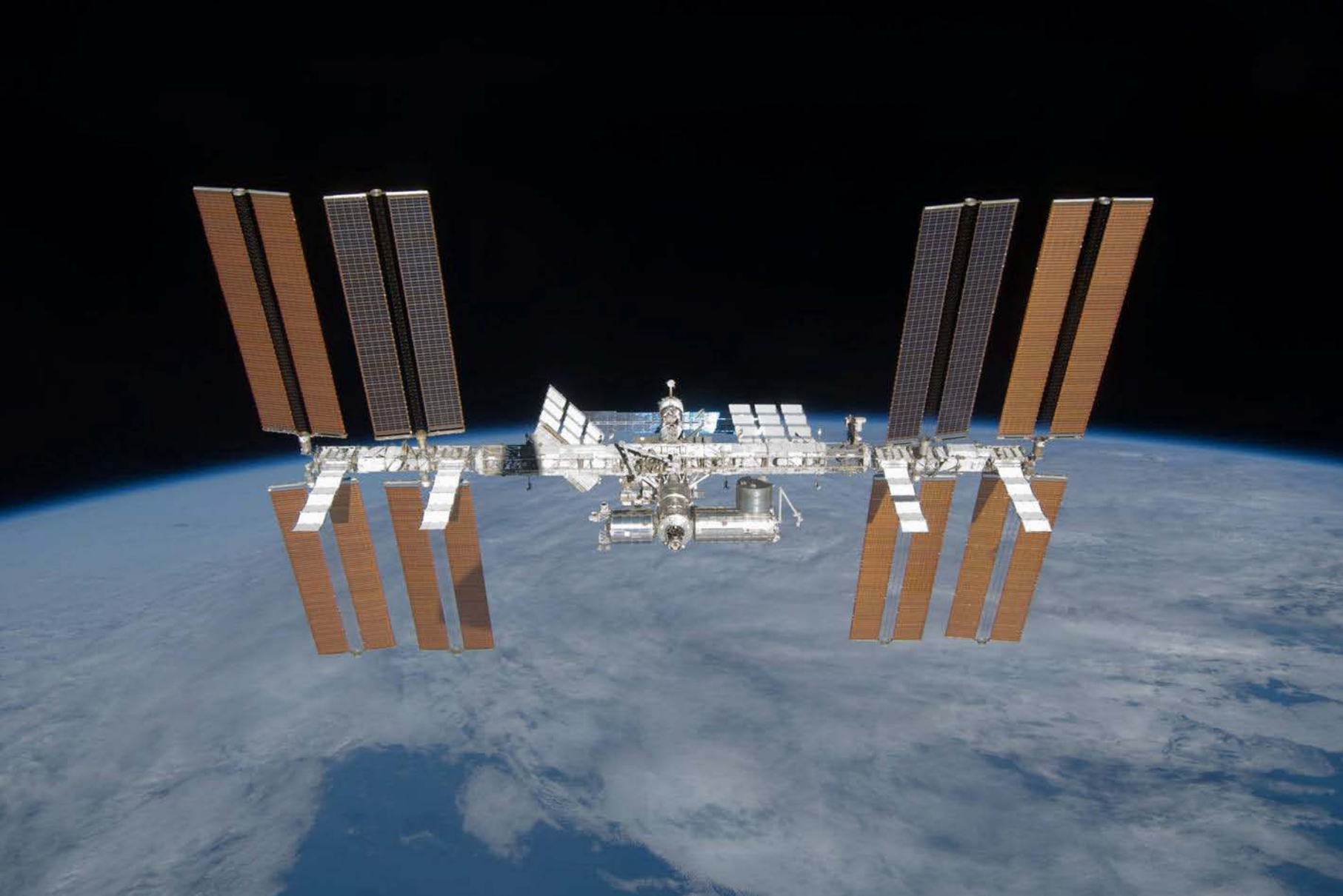


SARJ Race Ring Cross-Section View





ISS Overview



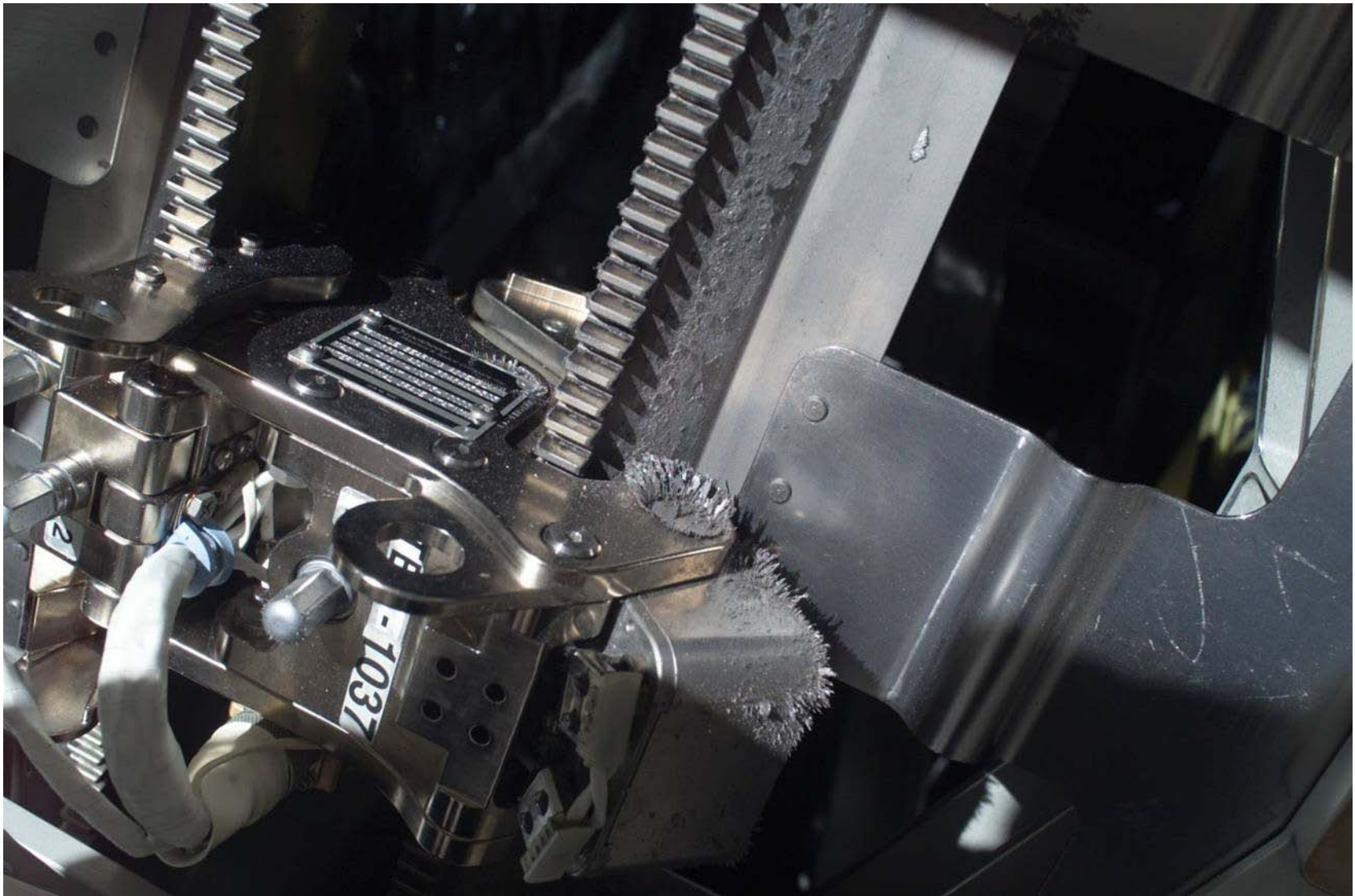


Metallic Debris Discovered



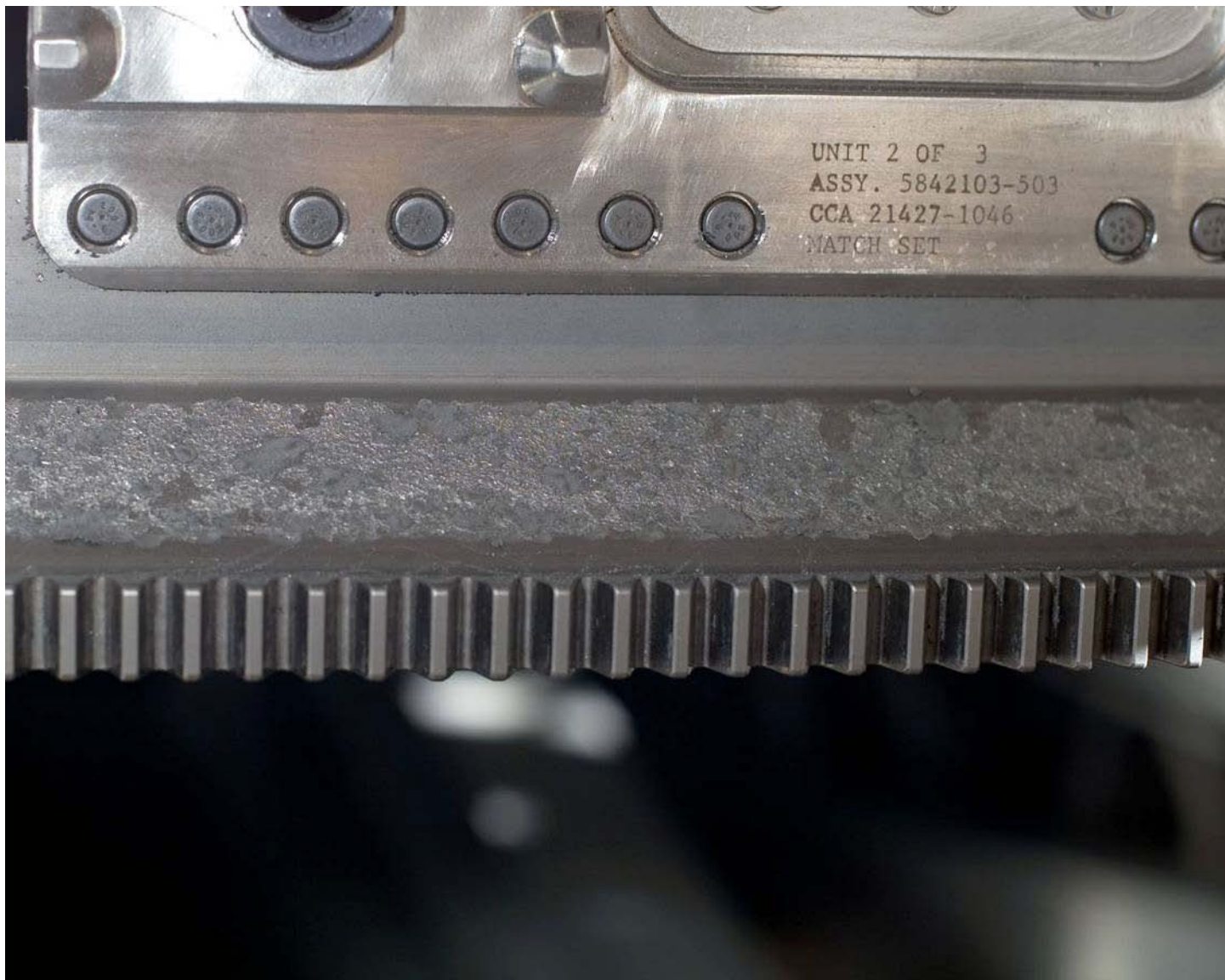
- **Anomalous telemetry and noticeable vibrations prompted a visual inspection of the SARJ mechanism.**
- **Metallic debris was observed throughout the vicinity of the mechanism, including on the surface of the race ring.**
 - **Debris exhibited slight magnetic effects, aligning with available magnetic fields.**
- **Samples were taken via tape-lift from starboard SARJ. Multiple accessible surfaces were sampled including the area of rolling contact.**
- **One of the Trundle Bearing Assemblies (TBAs) was returned to ground for examination.**
 - **Samples were taken from all rollers, the housing and packaging of the TBA.**
- **Nitride control coupons and maskant interface coupons from the original nitriding process were retrieved and used for metallographic analysis.**

Starboard SARJ – Metallic Debris



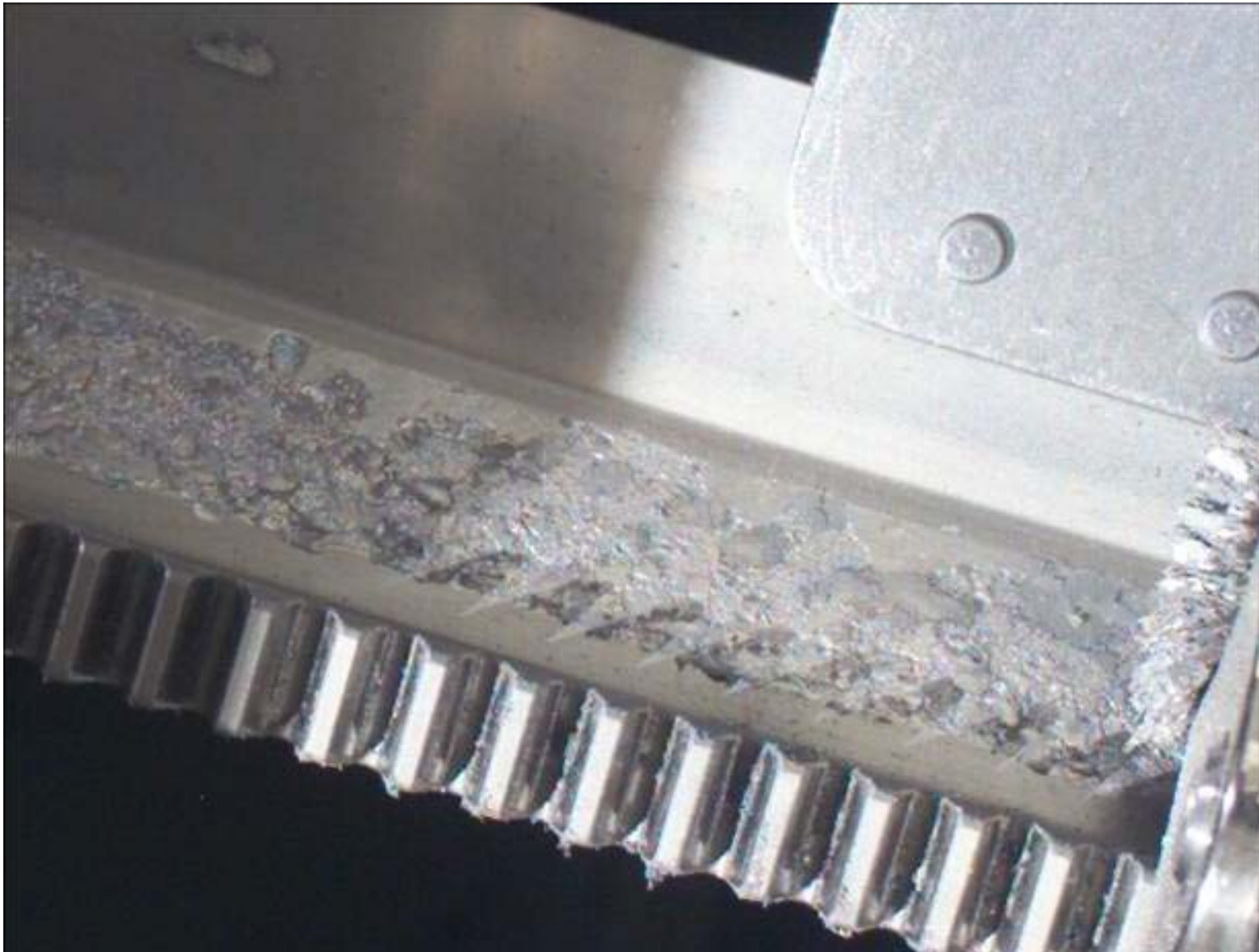


Starboard SARJ - Race Ring Surface





Starboard SARJ - Race Ring Surface



- Majority of debris is nitrided 15-5 PH Steel
 - Some gold, fluorinated grease, trace contaminants
- Only source of nitrided 15-5 PH steel is the race ring
- Particle size distribution skewed to fine particle size (less than 50 μm)

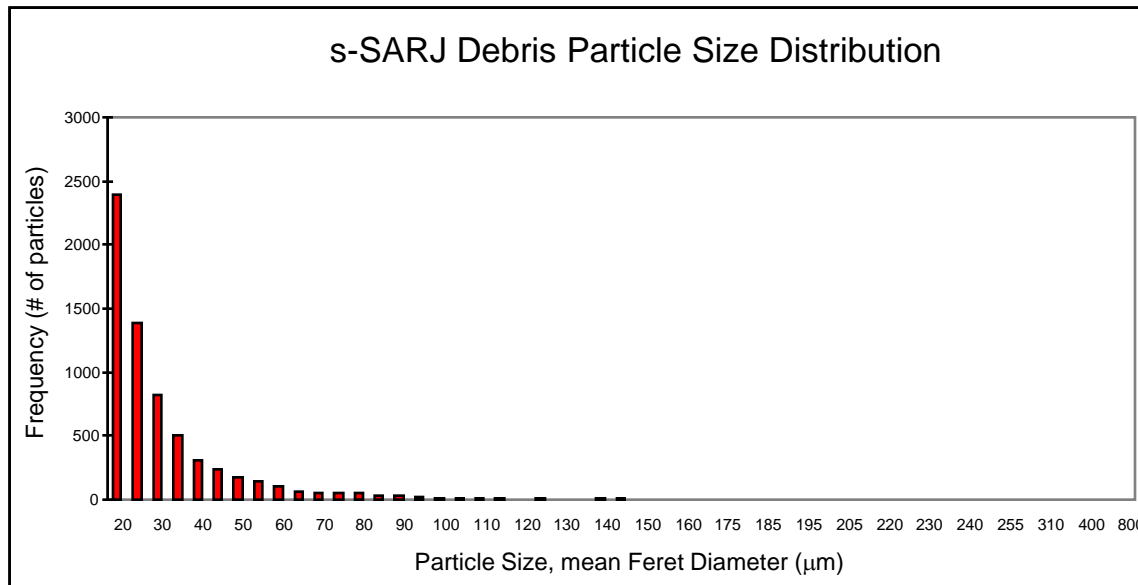
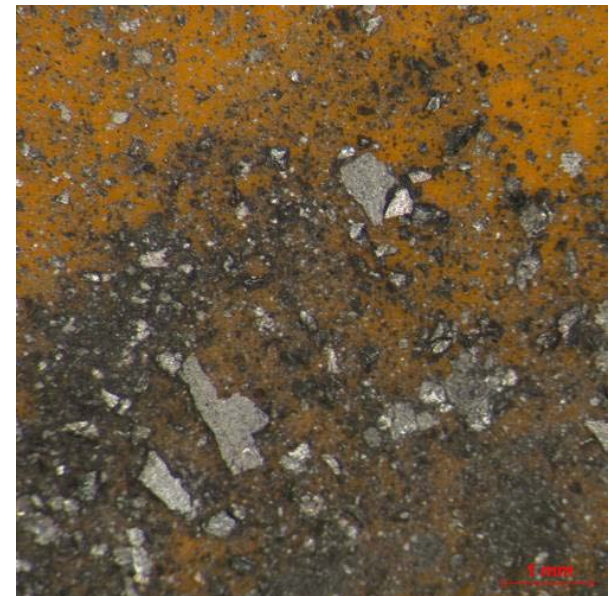


Image analysis particle size distribution



Stereomicroscope image.
Reference magnification: 20X



Two Types of Larger Particles Observed



- **Agglomerations**

- **Fine debris has been compacted into larger particles under nominal mechanical pressure of the SARJ**

- **Solid chips or flakes**

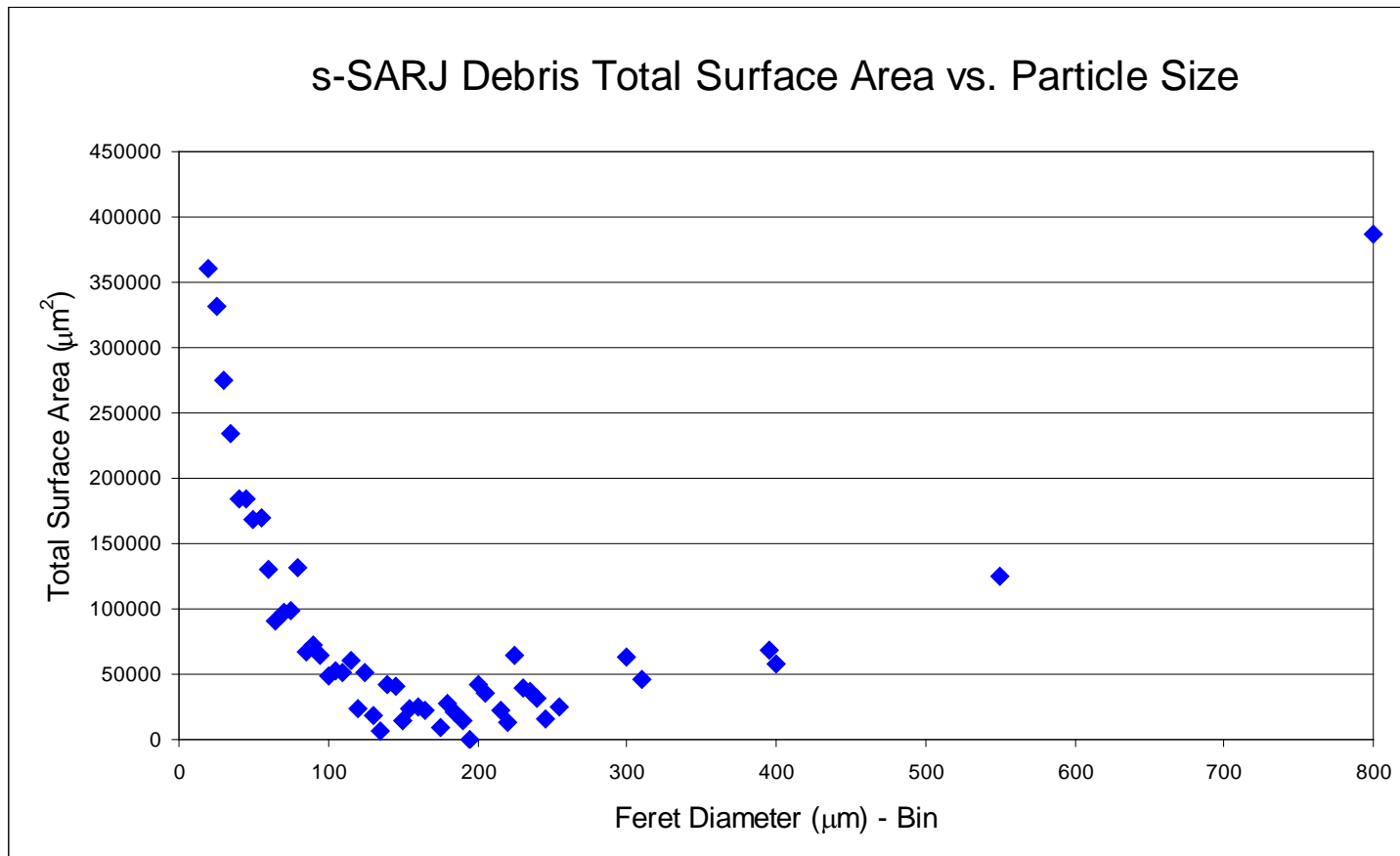
- **Some still exhibit original surface**
- **Brittle fracture features can be seen**
- **Maximum thickness of particles is at or less than the nitride case depth**



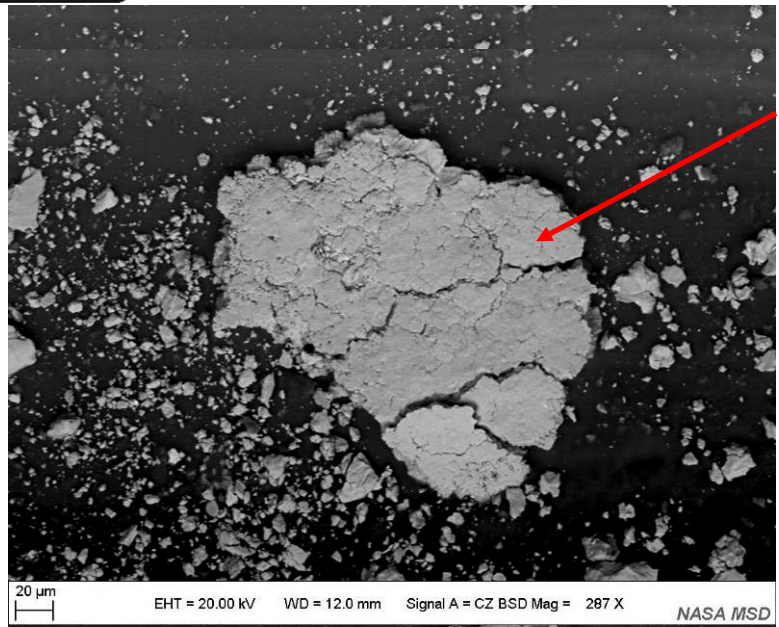
Two Types of Larger Particles Observed



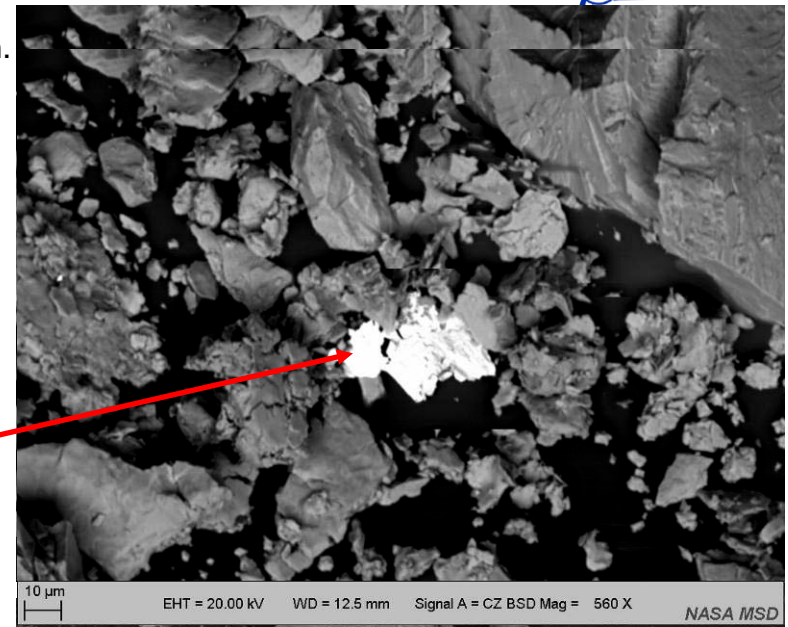
- **Larger particles, though few in number, contribute significantly to the total area of particles collected during sampling**
 - **Suggests that much of the surface damage occurred as these large particles**



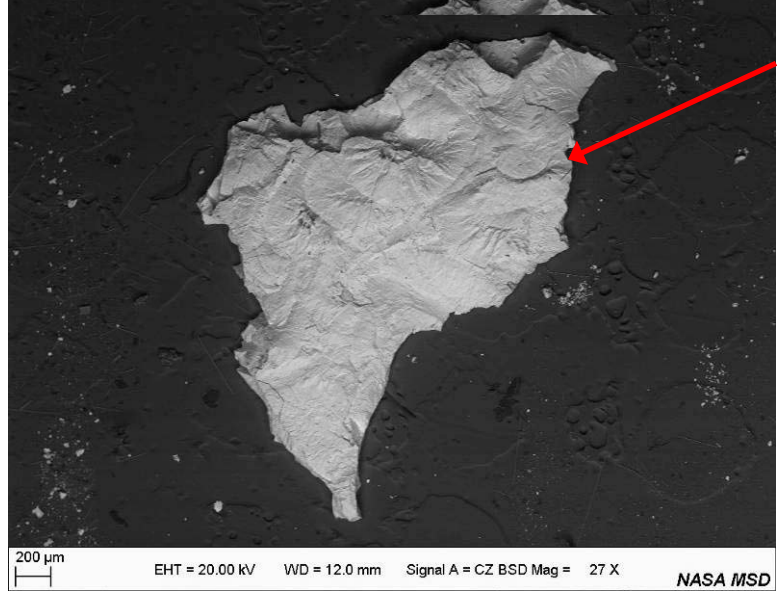
Typical Examples of Large Particles



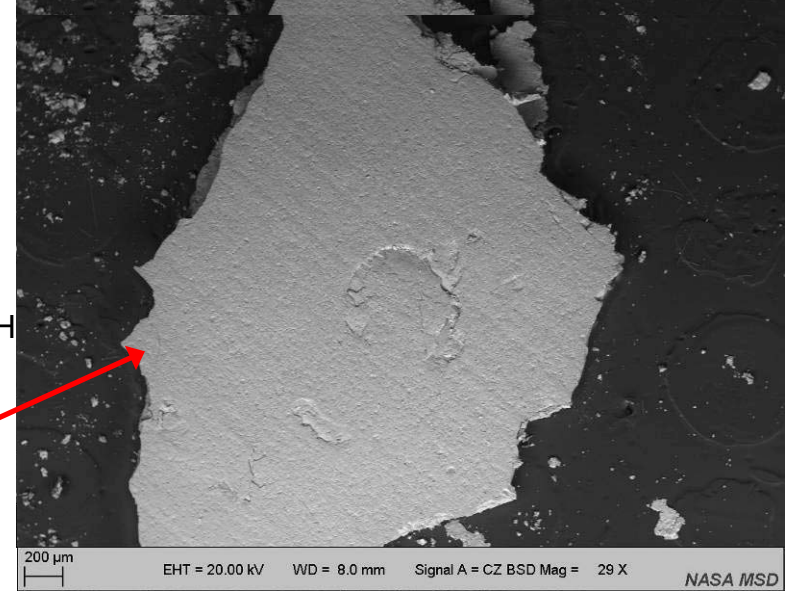
Agglomeration.



Gold particle showing atomic contrast.



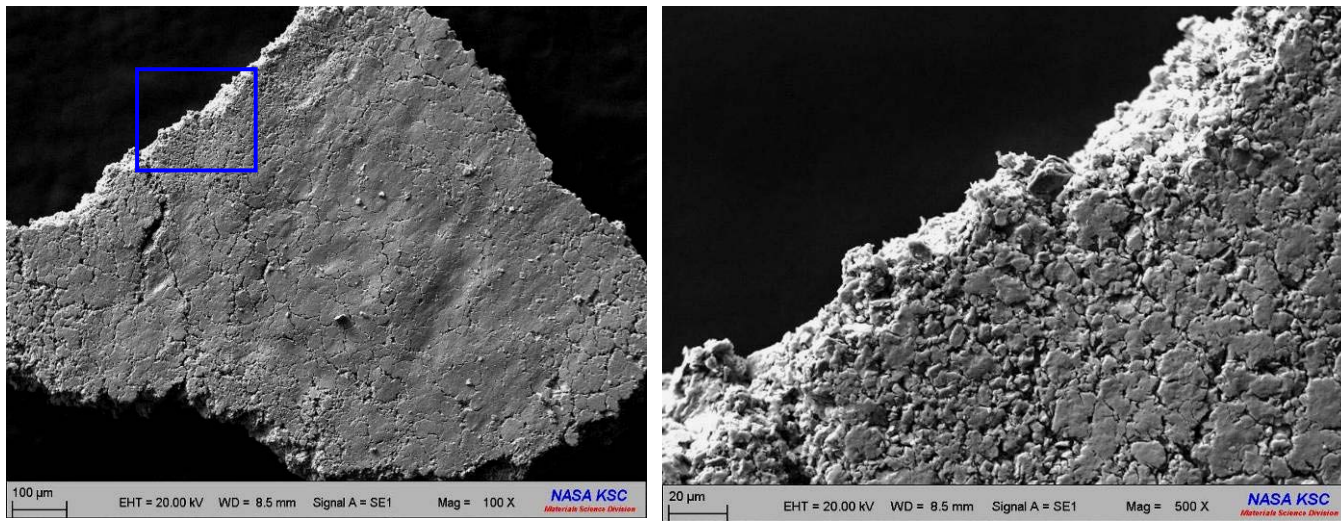
Evidence of crack arrest lines.



Original 15-5 PH nitrided surface with machine markings.

Agglomerated Particles

- Friable large particles are actually agglomerations of small particles

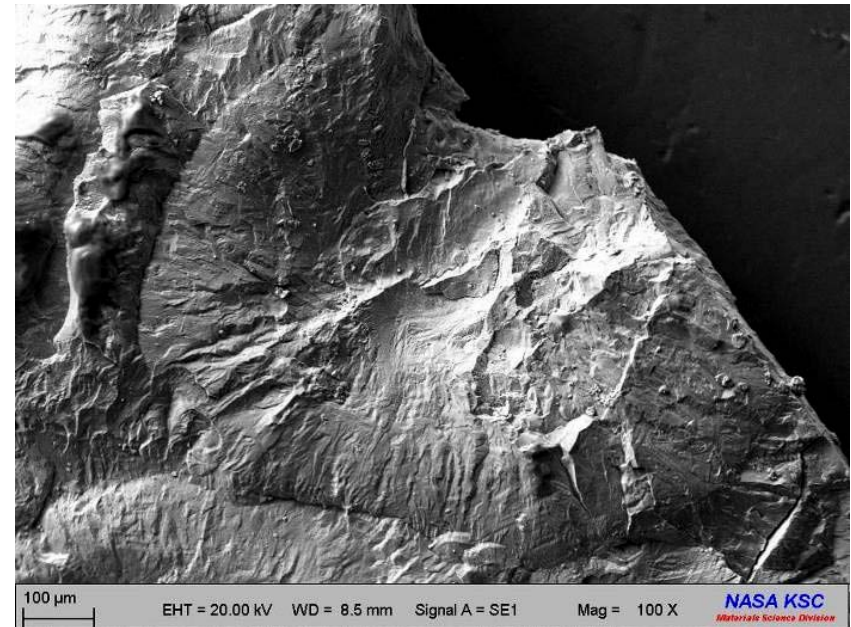
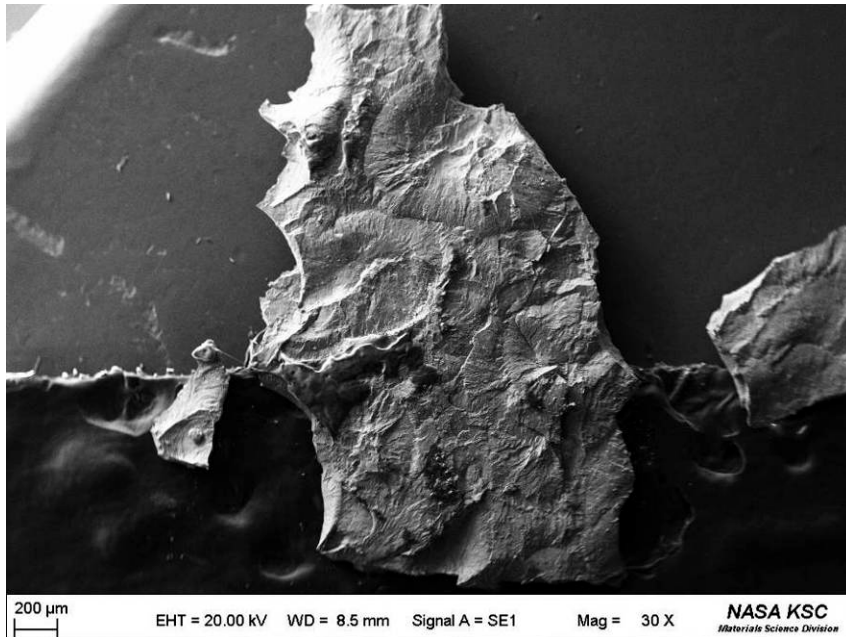


Nitrided 15-5 PH agglomerated fragment from Tape Sample 31
imaged under high vacuum.

Reference magnifications: 100X (left), 500X (right)

Fracture Features

- Chip-Type fragments often exhibit crack initiation and arrest features
- Multiple initiation sites indicate a system-wide condition



Nitrided 15-5 PH Chip-Type fragment from Tape Sample 31 imaged under high vacuum showing fracture surface and crack initiation/arrest features. Reference magnifications: 30X (left), 100X (right)

Crack Propagation in Larger Flakes



Nitrided 15-5 PH Chip-Type fragment from Tape Sample 31 imaged in cross section, showing original surface (with residual white layer) and transgranular fracture surface after 2% Nital etch

- **When viewed in cross-section, the propagation path does not appear to preferentially follow areas of intergranular networking**
- **Cracking is transgranular**

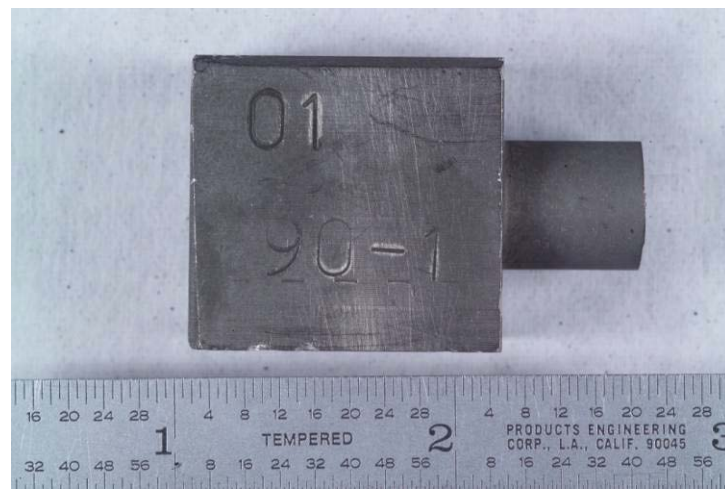


Artifacts from Nitride Process



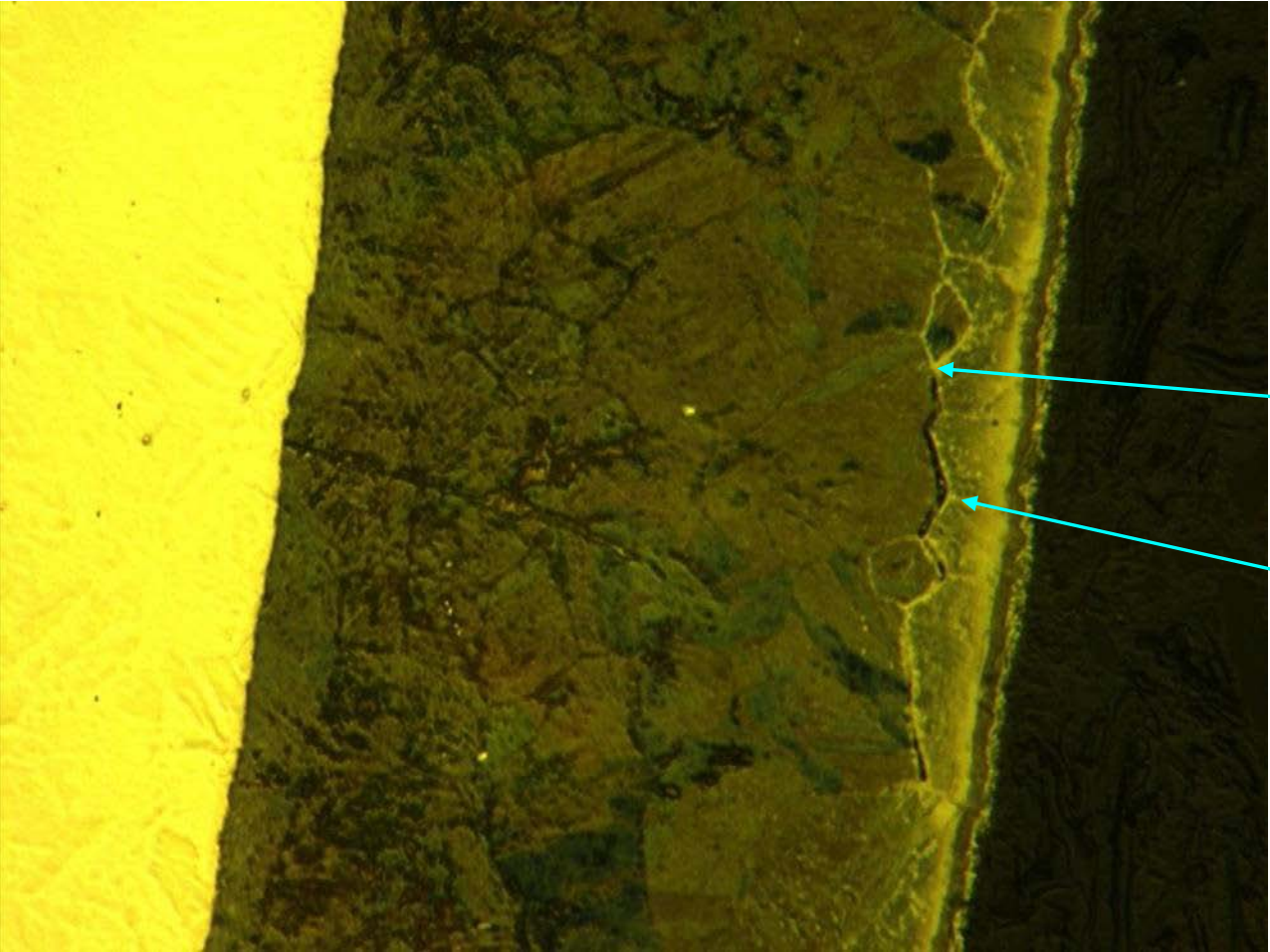
- **Metallographic examination determined white structure in excess of engineering requirements (0.0003in) is still present on the nitride control coupons (NCCs), maskant interface coupons (MICs), and on chip-type particles from the s-SARJ.**
- **While original certifications indicated that the white layer requirement was met, it appears that the specimen preparation technique was not sufficient to observe the true depth of inter-granular networking**
- **The inter-granular network (0.001 to 0.002in observed) appears as a higher concentration of iron and chromium nitrides along the grain boundaries**
- **Inter-granular separations or voids were also noted along some grain boundaries.**

Nitride Control Coupon (NCC) – Nitrided in same furnace at fixed locations as the flight SARJ race ring.





Nitride Control Coupon

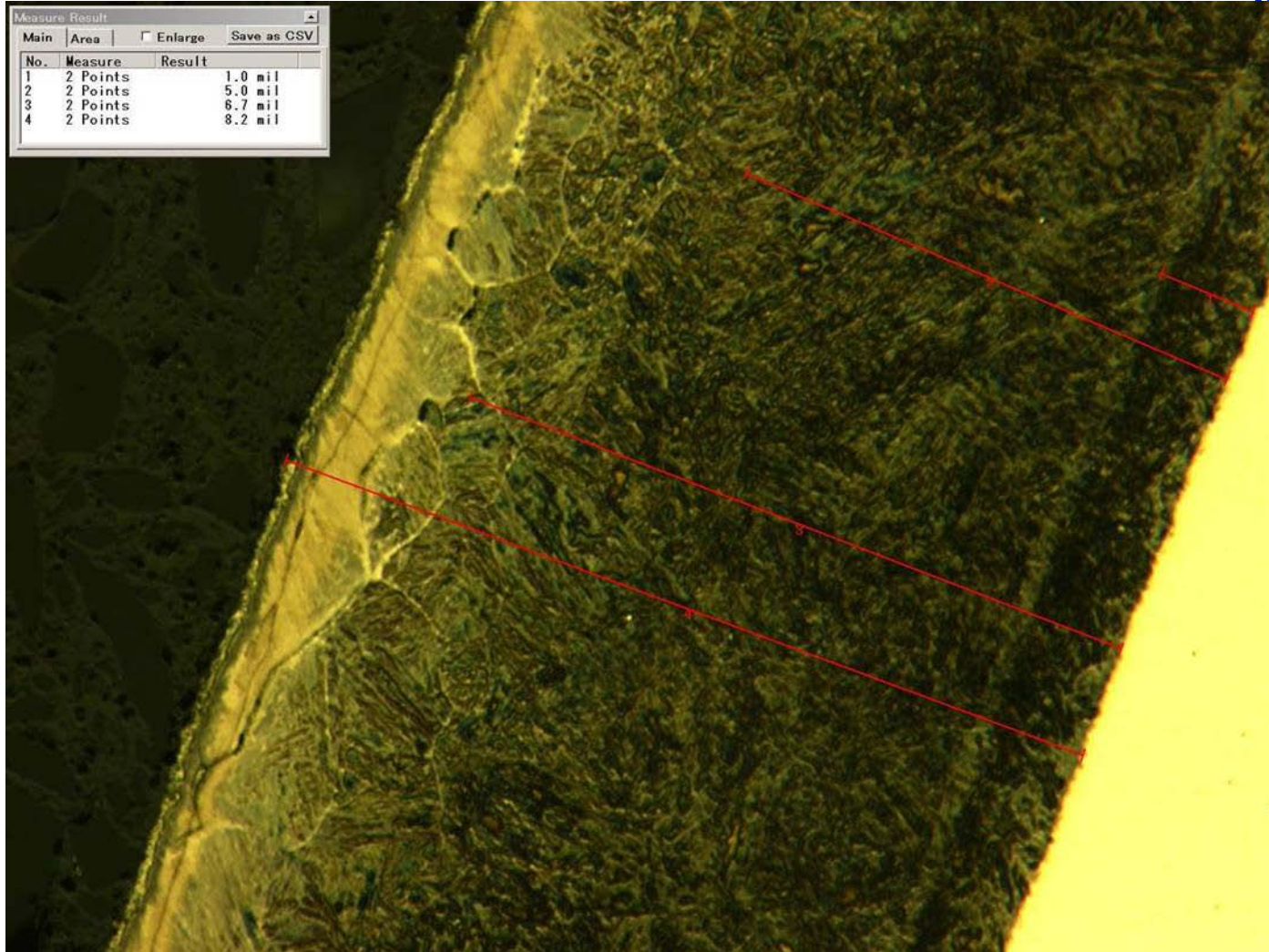


Networking

Intergranular voids
(appear like cracks)

**Metallurgical Evaluation of SARJ Race Ring S/N 4
Sample Coupon (Polished, Etched and View @1000X)**

Nitride Control Coupon



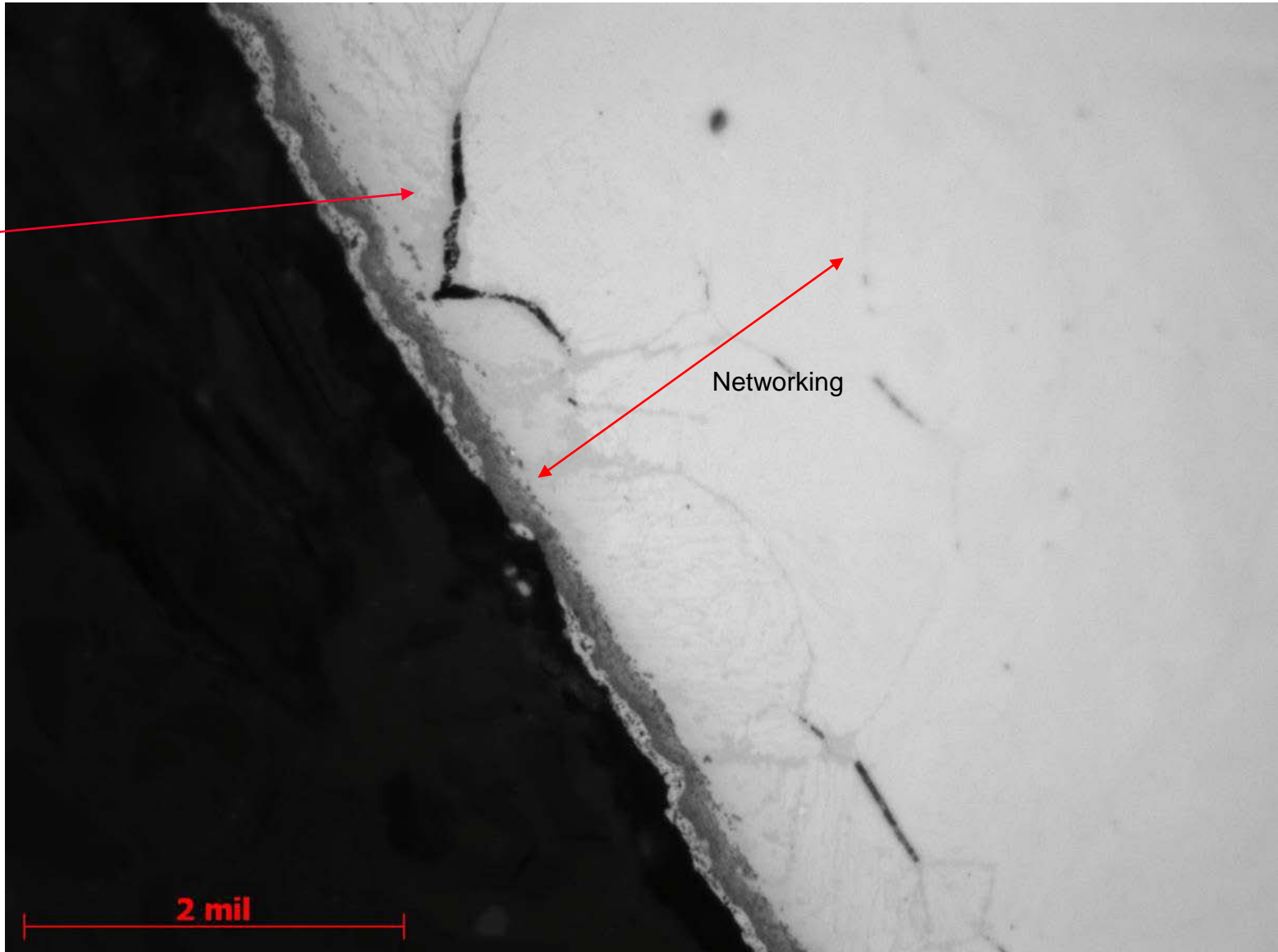
Metallurgical Evaluation of SARJ Race Ring S/N 7
Sample Coupon (Polished, Etched and View @1000X)



Nitride Control Coupon



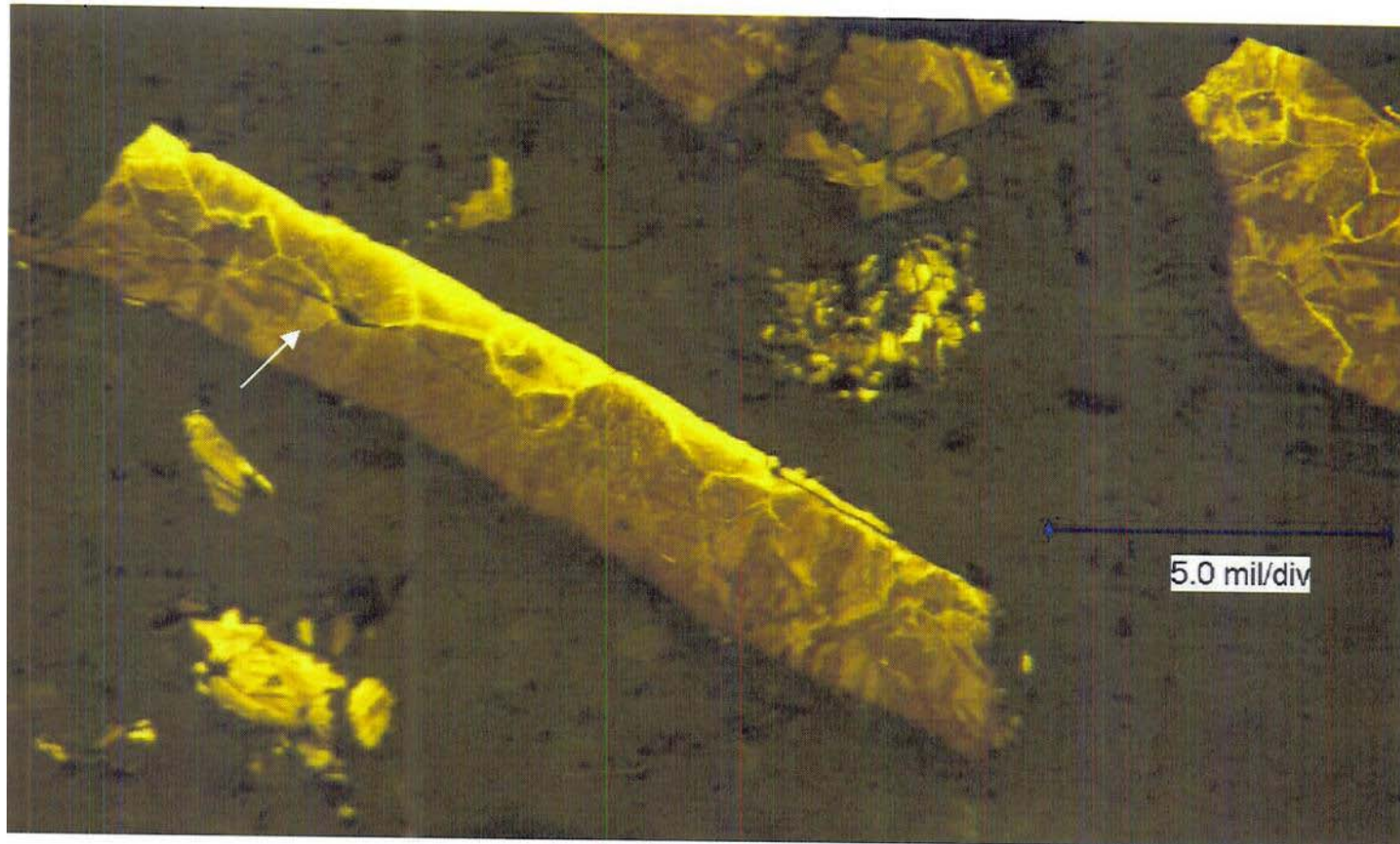
Separation /
void



Networking

2 mil

Chip-Type Debris



White layer is present in many locations, it was not removed by the 320 grit garnet blasting operation (post-nitriding) in many locations. The visual cue for post-nitride grit blast was a bright surface; this blasting process removed the dark oxide scale (from the gas nitride activation process) but not all of the white layer.

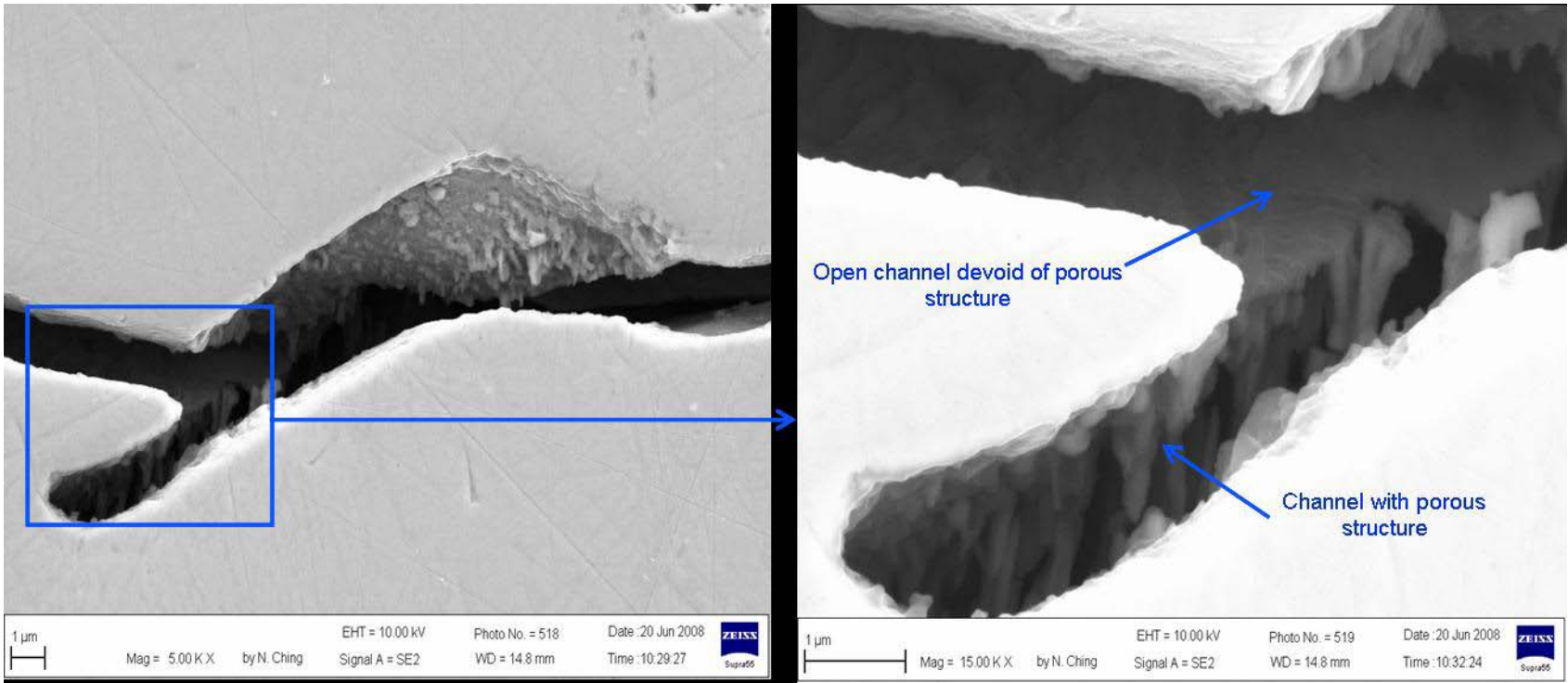


Discontinuous Intergranular Separations - DIGS



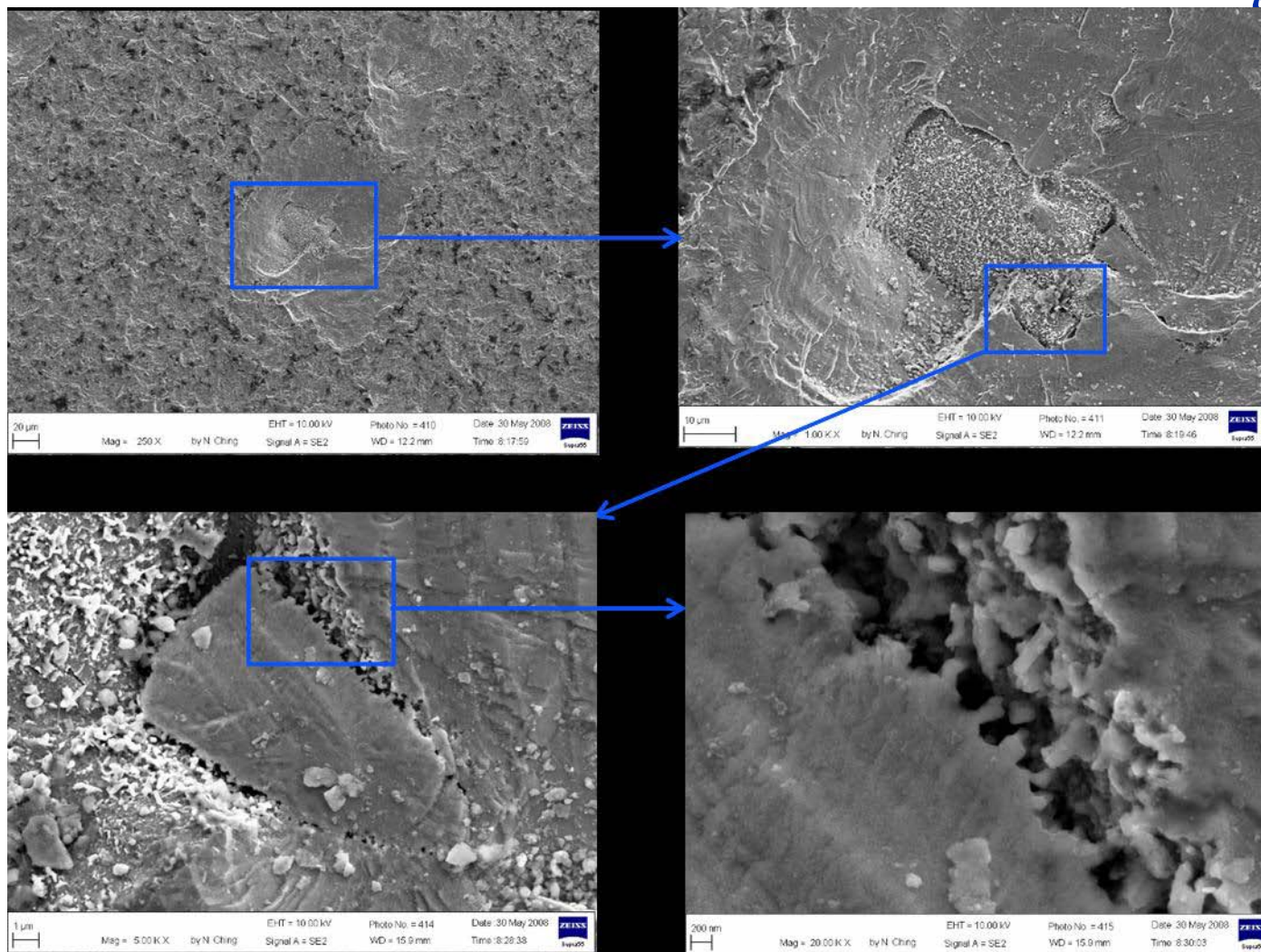
- **Analysis by Lockheed-Martin Sunnyvale and later by MSFC, found that what originally appeared to be cracks in the nitride layer were actually Discontinuous Intergranular Separations (DIGS)**
- **Our theory is that supersaturation of nitrogen occurs in the surface layer (.002in) of the nitride coating during the nitride process. As the hardware cools post-nitriding, nitrogen comes out of solution and forms gas pockets along the grain boundaries**
- **The presence of DIGS was noted in both NCC specimens from original manufacture, and recently fabricated test coupons**
- **While the effect of DIGS is not fully understood, their presence is undesirable and does not meet the original engineering requirements**

DIGS in Nitrided Rolling Test Coupon



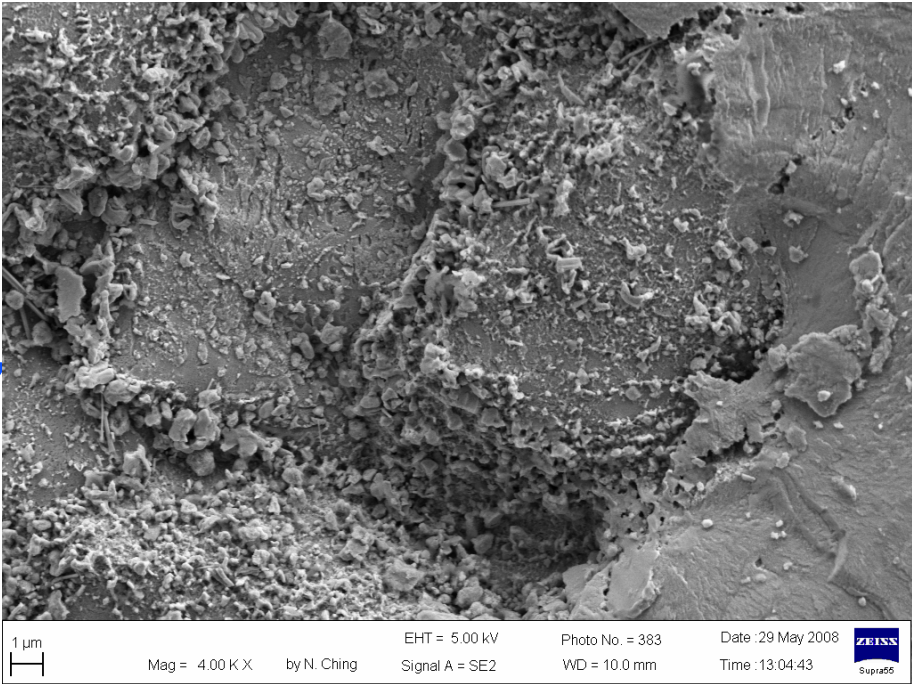
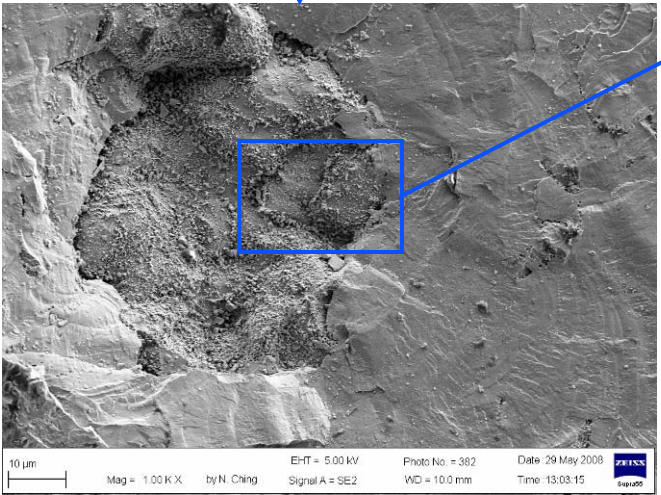
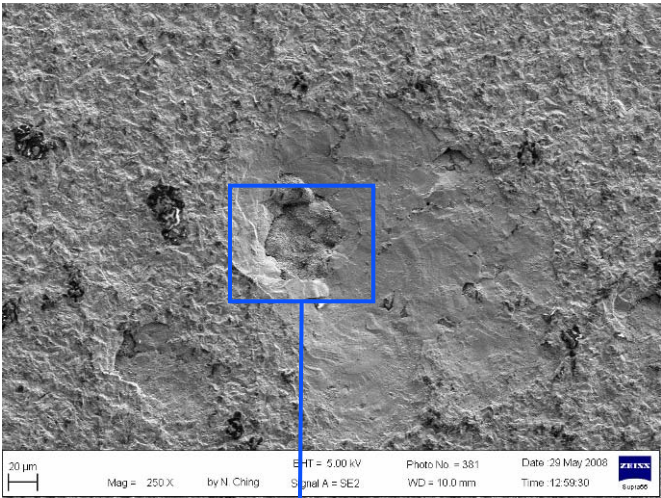
Sectioned and polished nitrided rolling test coupon. Branching of DIGS with different degree of porosity in each branch. Upper branch has a smooth surface and forms a single void while lower branch has a rough surface suggesting the existence of an earlier porous structure.

DIGS in Nitrided Rolling Test Coupon



Progressively increased magnification illustrating the porous nature of DIGS in nitride test coupon.

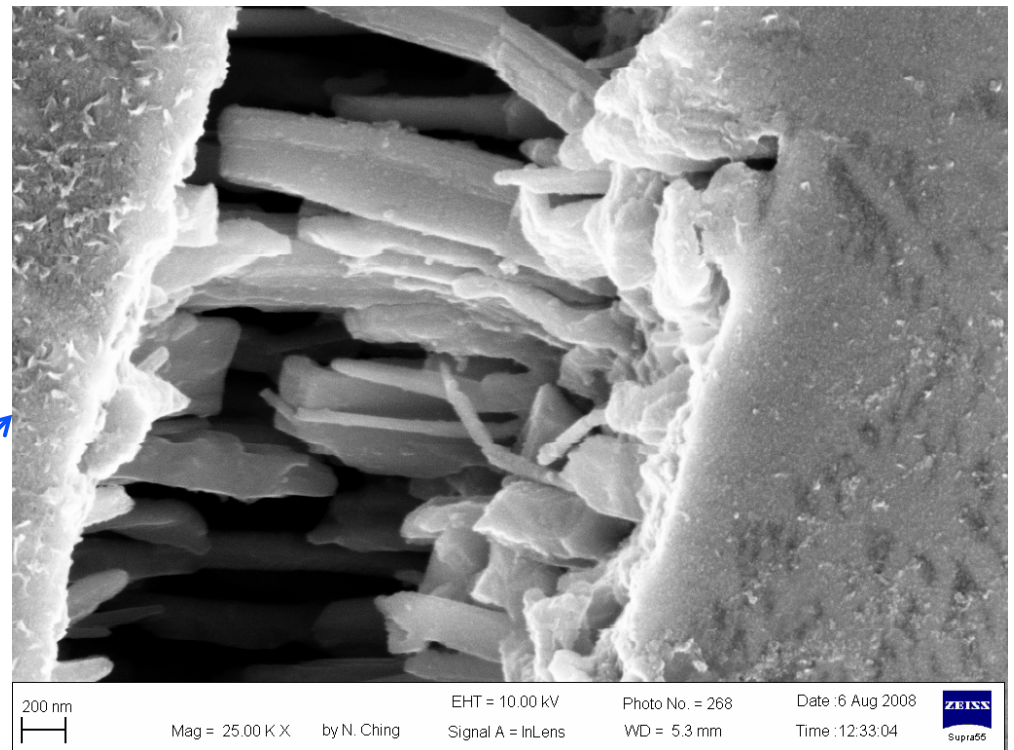
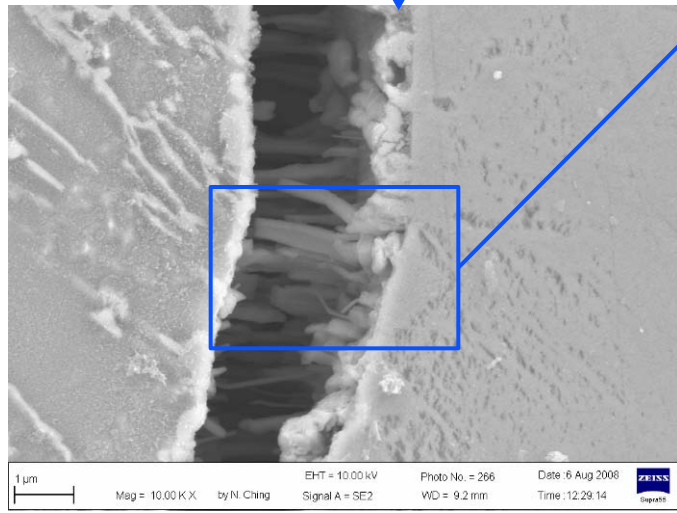
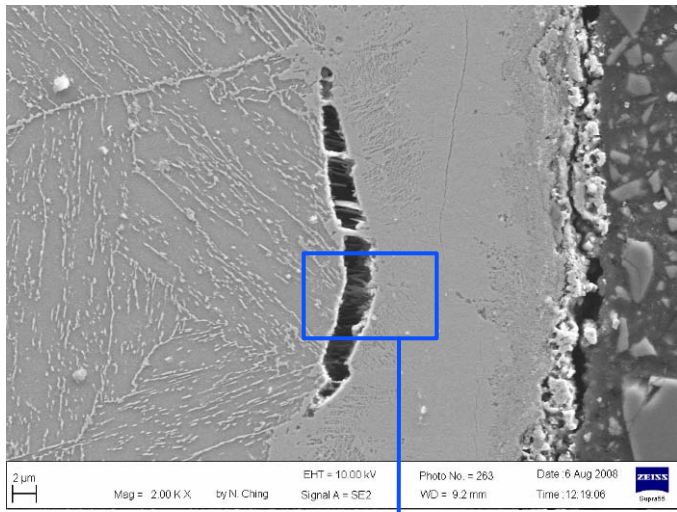
DIGS in Nitrided Rolling Test Coupon



Spalls created during the rolling test are associated with DIGS. Cracks originate in DIGS and propagate radially to form spalls.

Fragmented DIGS porous structure is shown as debris

DIGS in Nitride Control Witness Coupon



Polished metallographic sample exhibiting DIGS.
The degree of porosity and the type scaffolding structure remaining inside each DIGS varies and at times appears as a nanostructure.



System Lubricant – Gold Plating

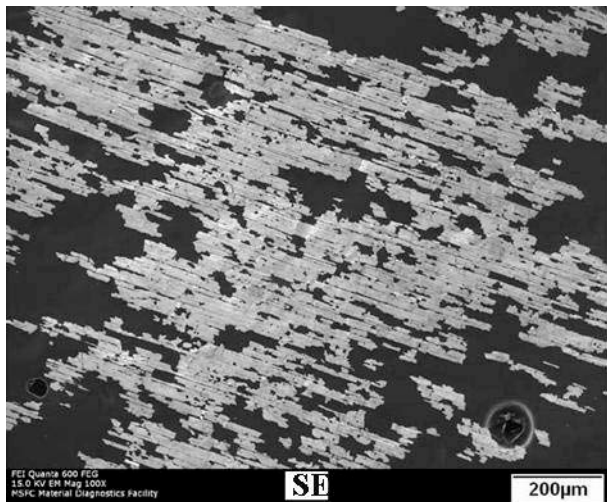
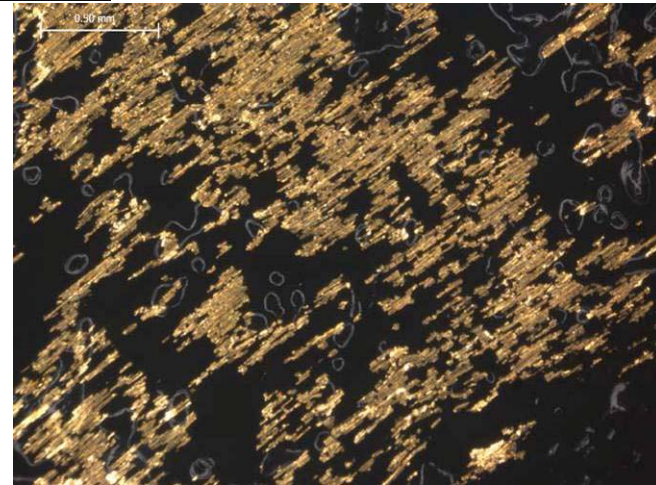


- **Gold was the intended lubricant for contact surface between the nitrided 15-5PH steel race ring and the 440C TBA rollers**
- **Adhesion of the gold was investigated to determine if the lubrication was functioning as expected**
- **The tape test method was used as a preliminary indicator of adhesion. Gold plating should be metallurgically bonded to substrate, with much greater strength than the tape test method can evaluate**
- **Six flight spares and one structural test article TBA were evaluated**
- **Loss of coating occurred on the majority of rollers. On the flight spare TBAs, gold was typically only lost from the roller contact surface. Gold was removed from the structural test article rollers on the chamfered edges of the roller (none remained on the contact area)**
- **The coating appears to detach in ribbons. The fine strips are typically 20-40 μm wide and 500 μm long**

Gold Adhesion Tape Test

NASA MSFC EM30 Material Diagnostics Team

TBA 1045, Datum A, Test #2, Carbon Tape



- Gold removed from TBA 1045 was segmented into strips, typical for all TBA roller tape tests with gold adhesion failures.

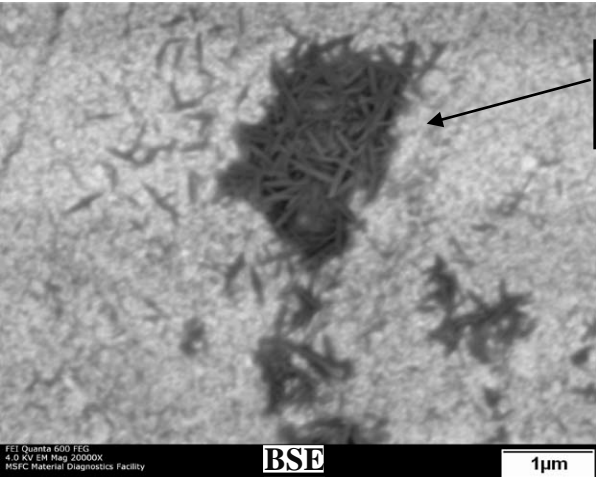
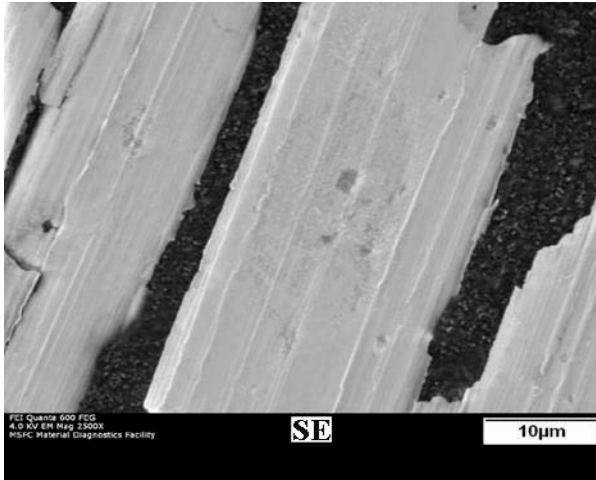
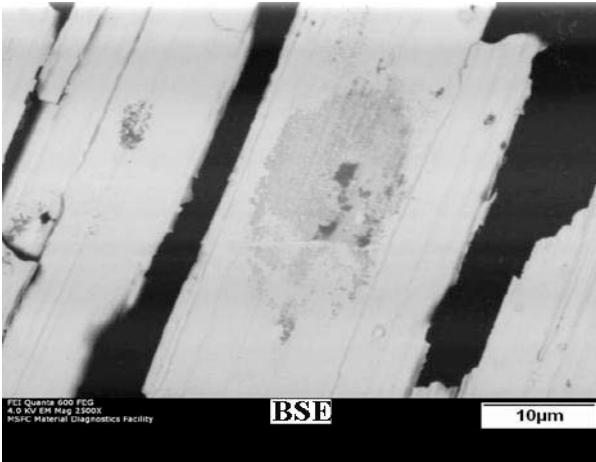


Failed Surface Analysis – Presence of Iron Oxide

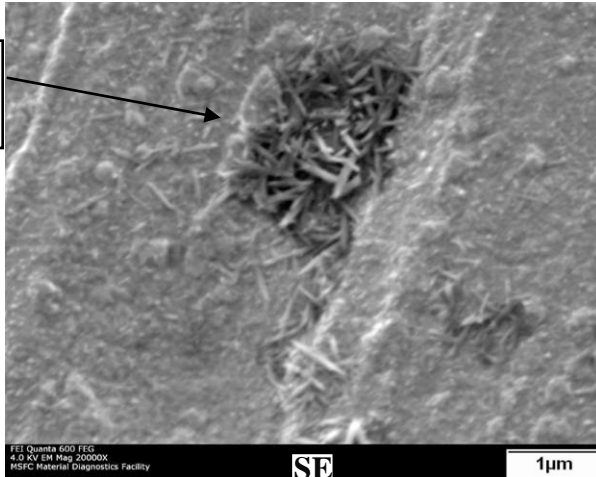


NASA MSFC EM30 Material Diagnostics Team

TBA 1005, Outer 45, Test #1, SEM



Iron Oxide (by elemental analysis)



Prelim SARJ TBA Tape Pull Specimen Analysis



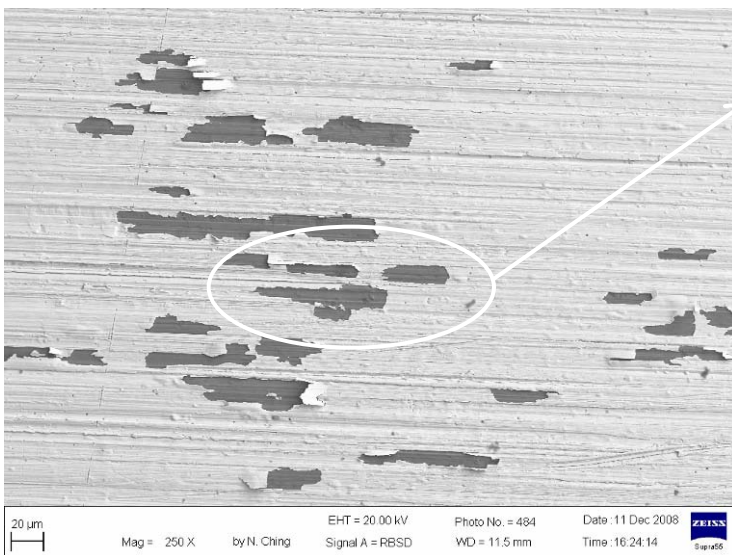
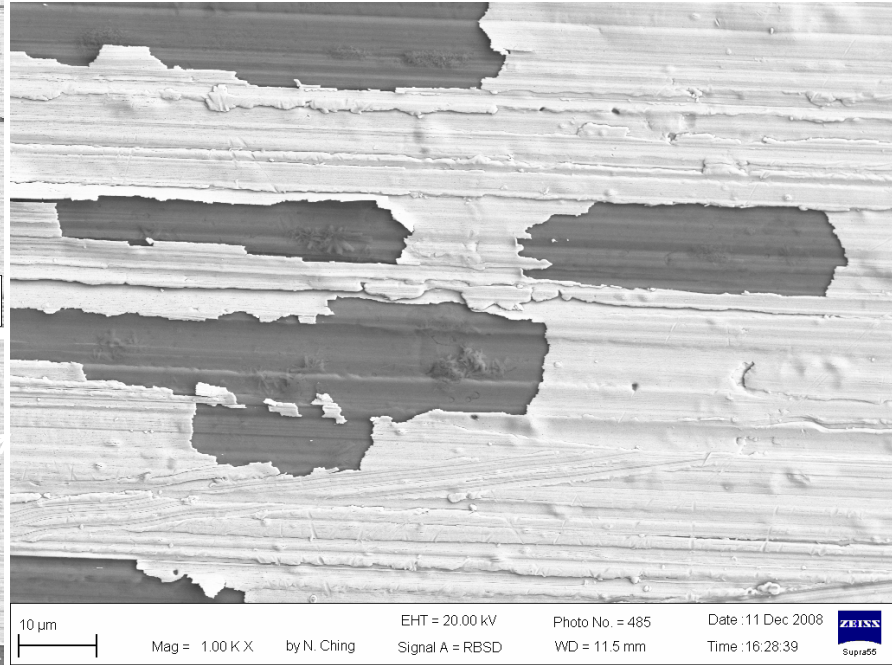
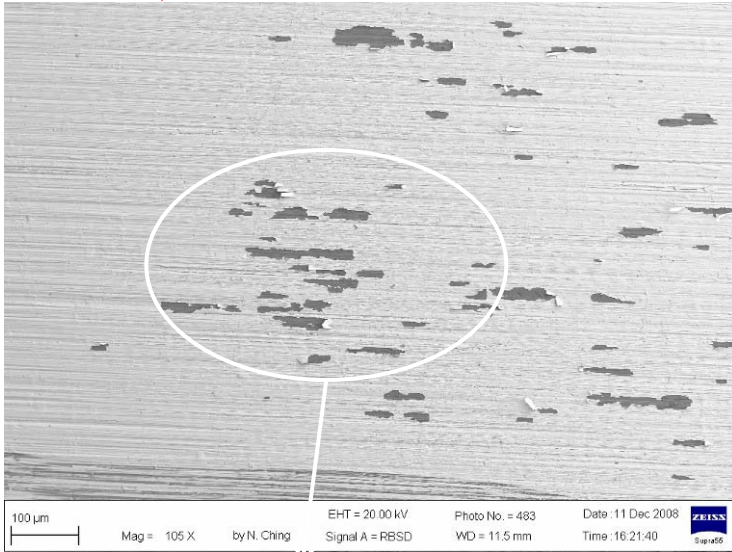
Accelerated Aging Test



- **Tape test results and their examination at NASA MSFC suggested that prior use (in a rolling contact) and time affected gold adhesion, necessary to function as a solid transfer-film lubricant**
- **New gold rollers were manufactured using as close as possible to the original flight hardware processing conditions and testing demonstrated proper gold adhesion**
- **Samples were then artificially aged, using high temperature and humidity**
 - **95F & 95%humidity for seven days – no changes were observed**
 - **Samples were returned to aging environment at a higher temperature (125F) for seven additional days – highly localized gold adhesion loss was observed**
 - **After seven more days of accelerated testing (21 days total), gold adhesion loss was widespread and very similar to tape test results from the flight spares**
 - **Comparable area of iron oxide corrosion observed, undercutting adhesion between gold coating and substrate**

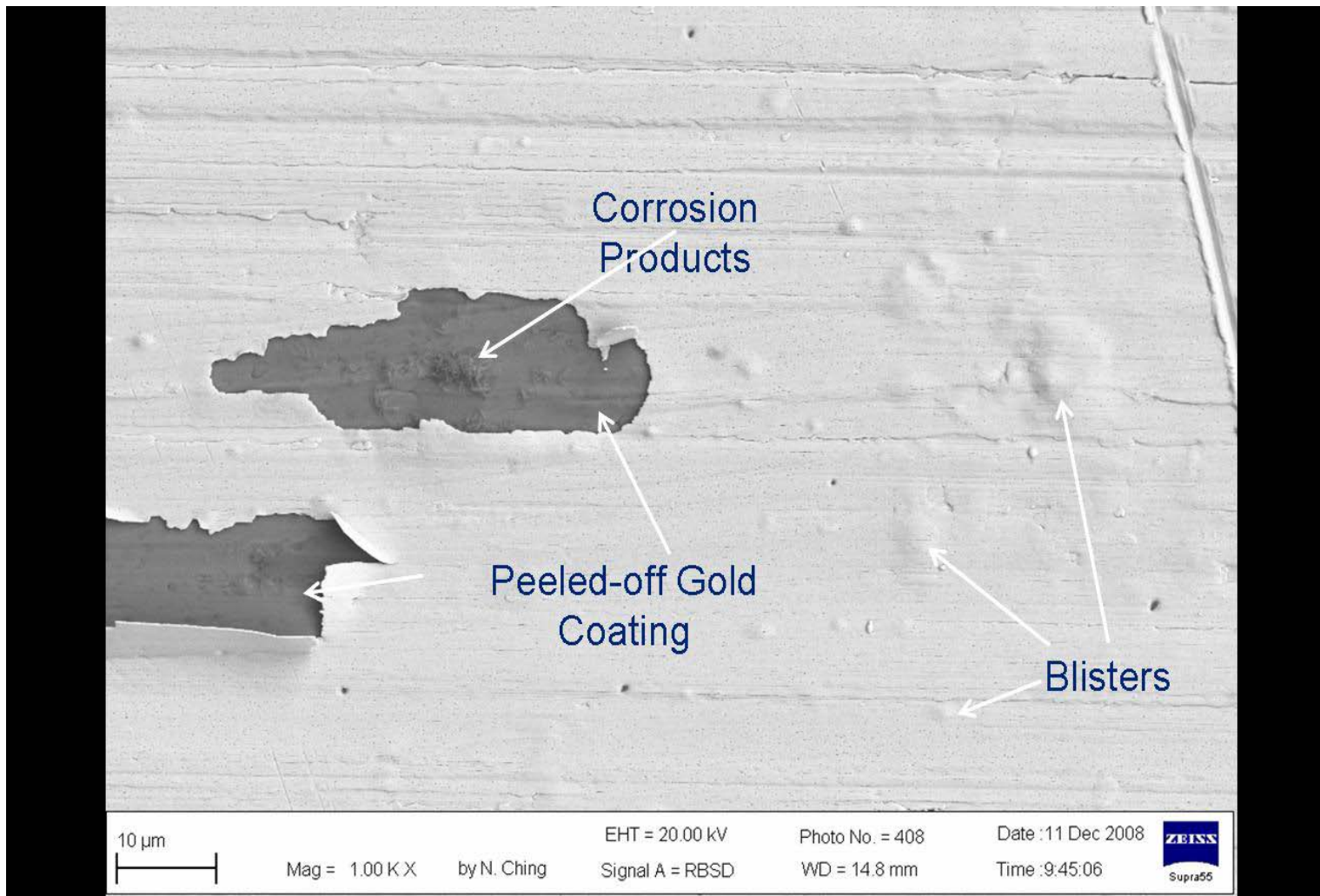


Accelerated Aging Test



Accelerated Aging Test

B-1 After 4th Aging Stage, 1st Intersection





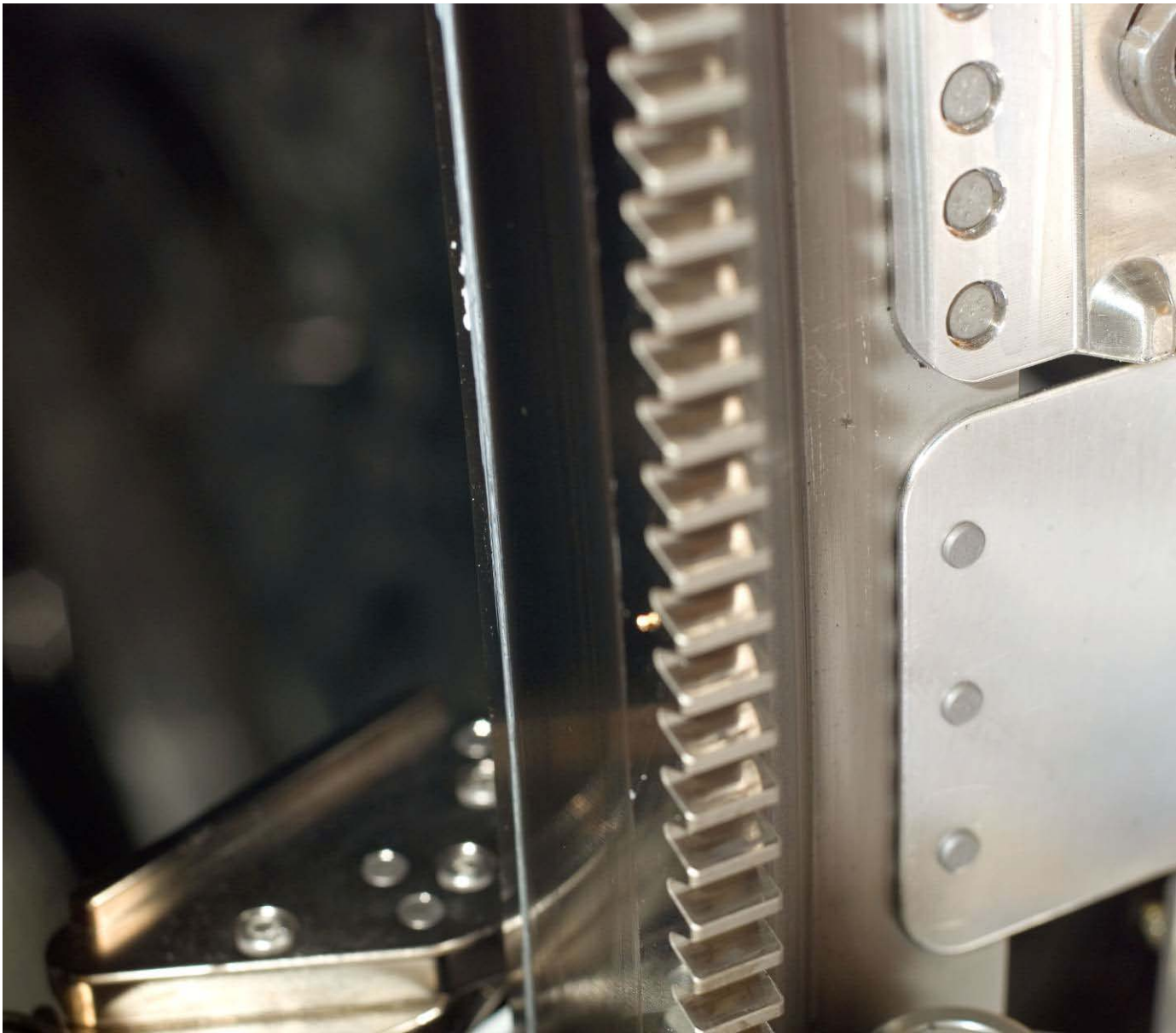
Port SARJ Inspection



- **Port SARJ has not displayed anomalous behavior to date, an inspection was conducted to assess the status of the race ring surface**
 - **Did not observe any obvious visible damage**
- **Inspection indicated the presence of a continuous streak of white substance along one edge – determined to be Braycote 601, which is used elsewhere in the mechanism**
- **A small number of tape-lift samples were taken from the non-rolling contact surface**
 - **Debris collected consisted of ~30% 15-5PH, ~70% 440C, and a small amount of gold particulate.**
 - **Composition of debris is consistent with expected wear of the SARJ mechanism, based on comparison with residual debris from hardware qualification tests**



Port SARJ - Evidence of Unintentional Grease





Port SARJ - No Visible Damage to Rolling Surface





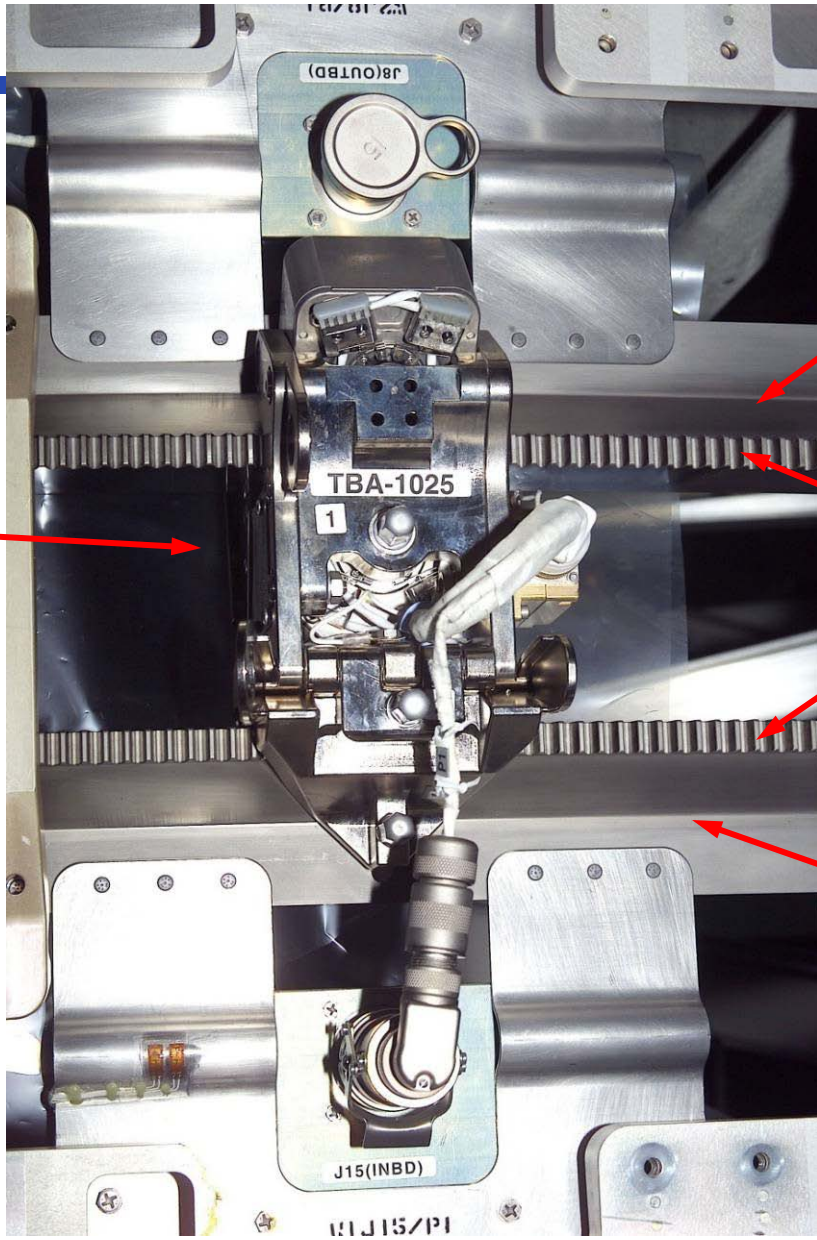
Conclusions



- **Metallography indicates the presence of several types of defects in the nitride layer that did not meet original engineering requirements**
 - **Intergranular networking**
 - **Discontinuous Intergranular Separations (DIGS)**
- **These nitride defects, though contributors to the mode of failure, were not the root cause of the race ring surface failure**
 - **Cracking due to mechanical stresses could be initiated at DIGS**
- **Gold plating as the sole lubrication for the TBA roller / race ring interface, could not function as intended because of deteriorating adhesion over time (aging)**
- **Inadequate lubrication led to high levels of friction and roller contact conditions, which ultimately led to the destruction of the race ring nitride surface**



Questions?



Trundle Bearing

Outboard Race

Gear Teeth

Inboard Race



RESIDUAL STRESS PROFILE X-RAY DIFFRACTION



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