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POWERPLANTS

Group Chair's Factual Report – Attachment #1

GE Aerospace - Metallurgical Investigation Report (DRB AvEng-558171.A)

July 25, 2025

Metallurgical Investigation Report
DRB AvEng-558171.A

METALLURGICAL EVALUATION OF A GENX-1B HPT STAGE 1 AFT BLADE RETAINER INVOLVED IN AN UNCONTAINED EVENT FROM ESN 956-102 OPERATED BY UNITED

Retainer

P/N: 2383M99P02
S/N: TMT4TK46
TSN/CSN: 10,681 / 1,750
Material: R65

SR Number None

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EMS- Metallurgical Investigations

Date: March 28, 2025

Export Classification: DoC, NLR, 9E991

Background

- A GEnx-1B HPT stage 1 aft blade retainer (P/N 2383M99P02, S/N TMT4TK46) from ESN **956-102** operated by United was submitted for metallurgical evaluation following an uncontained event on May 14, 2024, during a flight from Singapore (SIN) to San Francisco (SFO). Reportedly, at the end of climb, the engine experienced an uncommanded in-flight shutdown, followed by a fire warning and deployment of fire bottles. The aircraft then performed an air turn back to the original airport with a single engine uneventful landing. Upon engine inspection on the ground, two holes were found in the HPT case, along with damage to the cowls. During teardown at GE Aerospace in Evendale, under National Transportation Safety Board (NTSB) supervision, the blade retainer was found fractured and was submitted to the GE Engineering Materials Systems (EMS) lab for analysis. The engine reportedly accumulated 19,298 hours since new (TSN) / 3,320 cycles since new (CSN), while the retainer accumulated 10,681 hours / 1,750 cycles since new. ESN 956-102 was an early compliance engine, which was converted to a lease asset.
- The current investigation has been tied into 2 other retainers investigated by the NTSB in a similar timeframe with one being another uncontained event and the other a shop finding where the part was cracked, but not fractured (see Table 1 for part details). The overall GE TOPS8D investigation is documented in DRB **AvEng-558560.A.**

Summary

- The metallurgical evaluation of the retainer from ESN **956-102** confirmed an approximate **80-degree crack** consistent with **fatigue** extending from the collet radius from a single **surface-connected** origin/**inclusion** that was approximately **15 mils deep x 5 mils wide x 0.5 mils thick** (1 mil = 0.001 inch). The inclusion was rich **Ti, Al, Zr, Mg, O, Ca,** consistent with an inherent **OCNC***. The crack then grew in both directions circumferentially in a fully intergranular mode and had regular beach-marks, consistent with sustained-peak, low-cycle fatigue (**SPLCF**)/**hold-time fatigue growth**. The part dimensions, composition, microstructure, and hardness conformed to the requirements with no anomalies noted. Based on the alloy depletion zone (ADZ) thicknesses the part was estimated to have operated near **1200°F**, in the expected design temperature regime for the part, though on the hotter side of parts examined.
- At the time of issue of this report, **2 other** retainers were investigated from a shop find (ESN 958-071) and an uncontained event (ESN 956-397) showing that both also had similar single point, surface origins at roughly similar areas of the collet radius that grew circumferentially in an intergranular mode consistent with SPLCF/**hold-time fatigue**. On ESN **958-071** it was found to have an approximate **3 x 1.5 mil OCNC**, while on ESN **956-397** it had **smearing** at the surface 3-4 mils deep, so the actual origin source was **unknown**, but no OCNC was observed beyond.

Table 1: Pedigree/findings from the 3 retainers investigated in the lab

DRB	Operator	Consequence	ESN	P/N	S/N	CSN	Major Finding	Origin OCNC* (mils)
AvEng-552448.A	Redacted	Shop Find	958-071	2383M99P02	TMT11CNF	3,110	120-degree crack	3 x 1.5 x 0.5
AvEng-552805.A	Redacted	Uncontained	956-397	2383M99P02	TMT1JEP9	2,046	115-degree fracture	Unknown (max 3-4 mils deep, if present)
AvEng-558171.A	United	Uncontained	956-102	2383M99P02	TMT4TK46	1,750	80-degree fracture	15 x 5 x 0.5

The term **Oxide/Carbonitride/Nitride/Carbide (**OCNC**) is a JENQC (Jet Engine Nickel Quality Committee) defined standardized term to define specific melt-related anomalies (the group is formed by OEMs, the FAA, and melters). Similar terms are non-metallic inclusion (NMI) or to some degree stringer depending on size/shape and are a known nickel anomaly.*

Observations

- A schematic of the GEnx-1B cross-section showing the location/configuration of the fractured stage 1 aft blade retainer can be seen in Figure 1, with an overall view of the part in the as-received condition shown in Figure 2.
- Visual examination revealed that the entire outboard arm from the disk undercut rabbet radius was liberated. The inboard portion had an approximate **80-degree through-wall circumferential** crack between approximately 12-2:30 (relative to S/N) in the inboard **collet radius** consistent with fatigue (Figure 2). The crack then moved aft into the retainer disk rabbet radius and fractured 360 degrees around with features consistent with overstress (overlapping the fatigue region). At the fatigue/overstress transition region there was also a region with cyclic damage (Figures 2-3).
- Examination of the collet region showed that the fracture **initiated** from the collet rabbet radius **surface** from a **single origin.** The fracture grew in a planar manner with beach marks consistent with **fatigue.** The origin fracture plane was initially close to **20 degree angle from vertical** and initiated approximately **48 mils** forward of mid-seal OD rabbet, then moved further inboard toward mid-radius (Figures 3-6 and 30).
- Optical and scanning electron microscope (SEM) examination of the fracture **origin** revealed it was a **surface-connected inclusion** approximately **15* x 5 mil** (*there was post-fracture smearing damage on both fracture halves, so the length is estimated based on visible 12 mils on the inboard half, 13 mils on the outboard half, and adding approximately 2 mils of smearing to the largest measured)- Figures 7-10 and 31. The inclusion area using an ellipsoid shape was estimated to be approximately **60 square mils**.
- Energy dispersive spectroscopy (EDS) spectra and dot maps showed the inclusion was rich in **Ti, Al, Zr, Mg, Ca, O**, consistent with an **inherent melt-related OCNC**. In addition, the inclusion was not a single particle, but a “cluster” of mixed oxides (EDS 1 and 2 in Figures 10-13).
- Beyond the inclusion, the entire fracture surface was **intergranular** consistent with **hold-time fatigue growth**. No visible striations were observed, though beach marks were observed (Figures 4 and 15).
- **No surface anomalies** were observed such as machining/scoring marks, and the surface had dimpled depressions and a roughened surface, consistent with having been shot-peened and wet-blasted per the requirements (Figs. 7 and 14; comparison retainer views are shown in Appendix B).
- A series of axial/radial metallographic mounts were made showing the following (Figures 16-35):
    - In the undamaged remaining areas of the part the dimensions were generally conforming (aside from the deformation adjacent to the overstress fracture (Figure 16).
    - Mounts made at the origin (near 1:45) and the crack end (near 12 o’clock), confirmed that the initial fracture plane was at the upper portion of the collet radius, then moved inboard as the crack grew larger into the peak predicted stress location (Figures 17 and 19).
    - The surface adjacent to the origin was smeared on both fracture halves consistent with post-fracture damage, but the origin itself was a combination of oxide particles that was up to approximately 0.5 mils thick in the plane of polish with no adjacent alteration of microstructure consistent with an OCNC with similar elements as the fracture EDS (Figures 24-26 and 34-35).

Observations

- EDS analysis of the base material was consistent with the requirement of R65 per C50TF133 (EDS 3- Figure 27).
- The alloy depletion zone (**ADZ**) thickness near the cracked area was approximately **0.032 mils thick.** Based on limited ADZ growth data the part is consistent with **exposures in the 1150-1200°F** range using an assumed 583 hours of hot time (20 min/cycle), consistent with predicted part exposure regime, though on the hotter side of parts examined (Figures 20-21). In addition, no grain boundary phases were observed, consistent with similar temperature estimates (Figure 28).
- The **microstructure** was consistent with properly processed R65 material, with an average grain size of approximately **ASTM 10.5**, conforming to the requirements of C50TF133 CL-A (Figures 22 and 23).
- The average micro-**hardness** (Vickers, 500g load) was approximately **HRC 49,** conforming to the requirements of C50TF133 CL-A (not shown).

- At the crack transition from stable fatigue to overstress near 2:30, there was additional cracking further aft growing from the disk rabbet undercut radius inboard with progression marks consistent with cyclic damage. Optical and SEM examination showed that the larger cracks were intergranular and the smaller cracks near the edge had a mixture of intergranular and dimpled features. The overall findings are consistent with secondary, shorter-term hold time/cyclic tensile cracking (Figures 36-38). A laboratory study showed that static intergranular cracking could be produced in as little as 8 hours depending on the loading conditions used at 1100°F (Appendix A).
- A mechanical drag profilometer could not be inserted in the collet so comparative roughness readings were taken with a laser con-focal machine, which measured approximately **72 Ra** for ESN 956-102, 63 Ra for ESN 956-397 & 958-071, and 57 Ra for non-event ESN 959-374. There is no final part roughness requirement, but is close to the requirement of 63 Ra prior to peening/blasting; also a different analysis method was used (Appendix B).
- Fluorescent penetrant inspection (**FPI)** of remaining retainer revealed **no crack-like** linear indications (Figure 39).
- Due to the discrepancy between predicted part lifing and the event timing, part specific feature fatigue tests with the exact geometry/surface condition (peening/roughness) were performed by extracting ½ inch wide specimens from fielded parts with the intent to examine the following:

1) Shop finding vs. other parts (event parts couldn't be tested),
2) Variations in load,
3) Comparing effects of R-ratio (min stress divided by max stress),
4) R65 vs. R88DT (prior part number configuration of retainer)
5) LCF vs. SPLCF effects in R65 at high stress
6) Load vs. strain-controlled (the feature test is load-controlled). Typical LCF tests are strain-controlled and HCF tests are load-controlled.

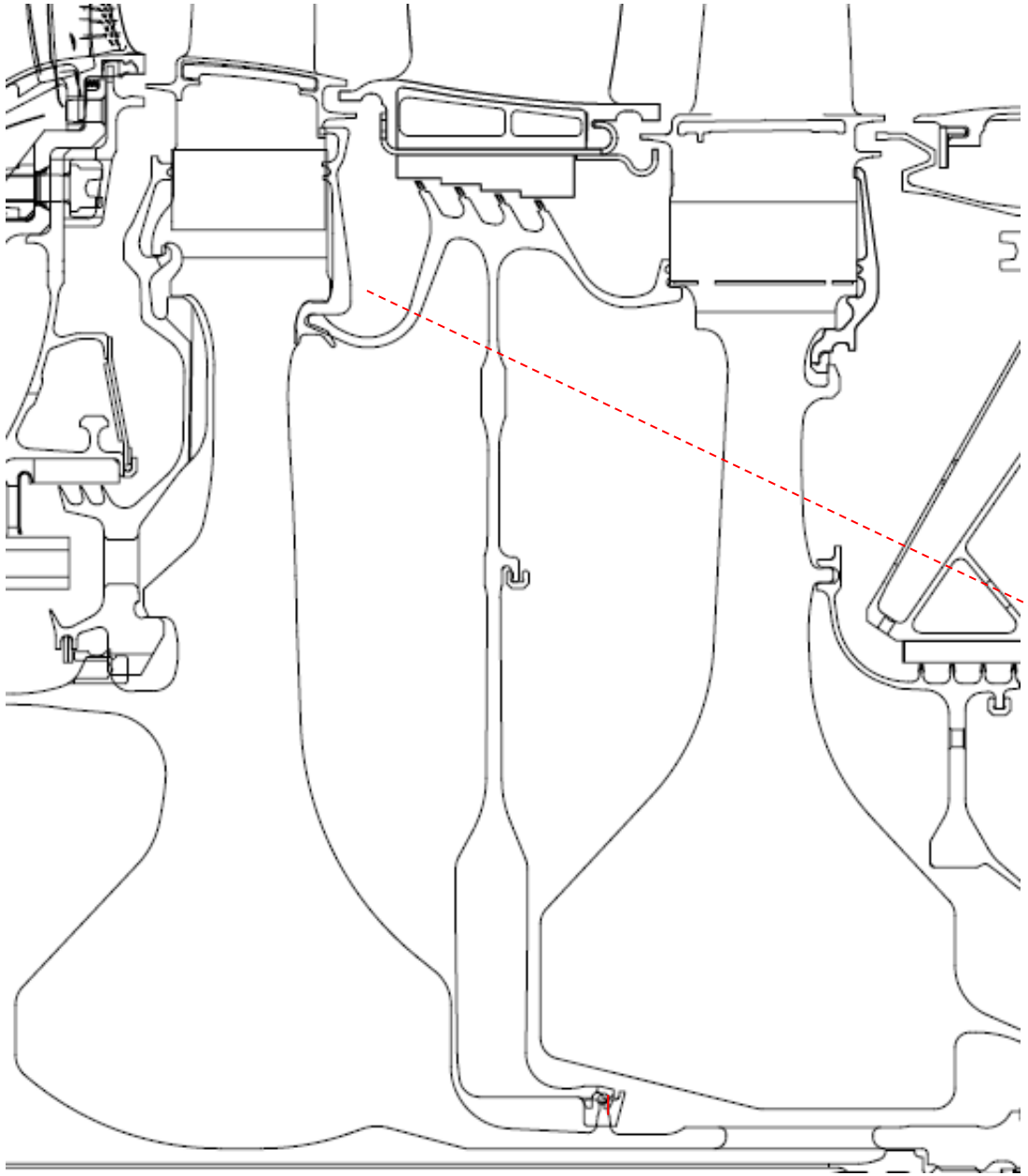
Observations

- The key results from the 1200°F LCF study (only part of the study is included and shown in Appendix C) are as follows:
    1) Loading
        - At very high stress: All had multiple origins at the surface initiating from the free surface, grit blast particles, or OCNCs. They did not look similar to the event/shop find parts.
        - At high stress : The lives had a **bimodal** distribution and either initiated with low lives at **surface OCNCs**, or subsurface at higher lives near average expectations.
        - At intermediate loads: **All** 5 specimens initiated **sub-surface** with average expected lives.
    2) The feature test specimens initiated at more **OCNCs** at surface compared to smooth uniaxial test bars.
    3) 2 out of 35 tests initiated at OCNC clusters at the surface (3 total). Both confirmed event/shop find parts had OCNC clusters.
    4) The largest tested surface OCNC was **6.3 square mils**, but most were closer to 1 square mil.
    5) The **load-controlled** testing showed a bimodal distribution of lives which was different than strain-controlled tests (not included).
    6) A **new** retainer also had a bimodal distribution, but initiated at surface grit blast media (vs oxidized OCNCs on the fielded specimens).
    7) At higher R-ratios the cycles to fracture were much higher than the R=0.1 tests (not included).
    8) Comparing **R88DT** showed that at very high loads the lives were similar to R65, but as the stress decreased the lives were improved without the very low data points (differences in OCNC/inclusion type/distribution/sizes).

Other hardware (Appendix D):

- *HPT case:* Two punctures were produced in the case: a smaller one approximately 1.4 inch long by 1 inch wide in the plane of the stage 1 blades, and a larger one up to approximately 11 inch long by 1.9 wide in the plane of the stage 1 shrouds/stage 2 nozzles with bulk deformation outward and rough features consistent with overstress. All nozzles were present, though some fell out during disassembly. All stage 2 nozzle leading edge tips were fractured, including the outer bands of 4 nozzles in the plane of the breach, consistent with event-related damage.

- *HPT Stage 1 disk and mid-seal:* No significant anomalies were observed. Uniform contact was observed at the mating disk/mid-seal interface, except for an angled area (consistent with where there retainer fracture moved aft), and axial scoring marks, consistent with disassembly damage.



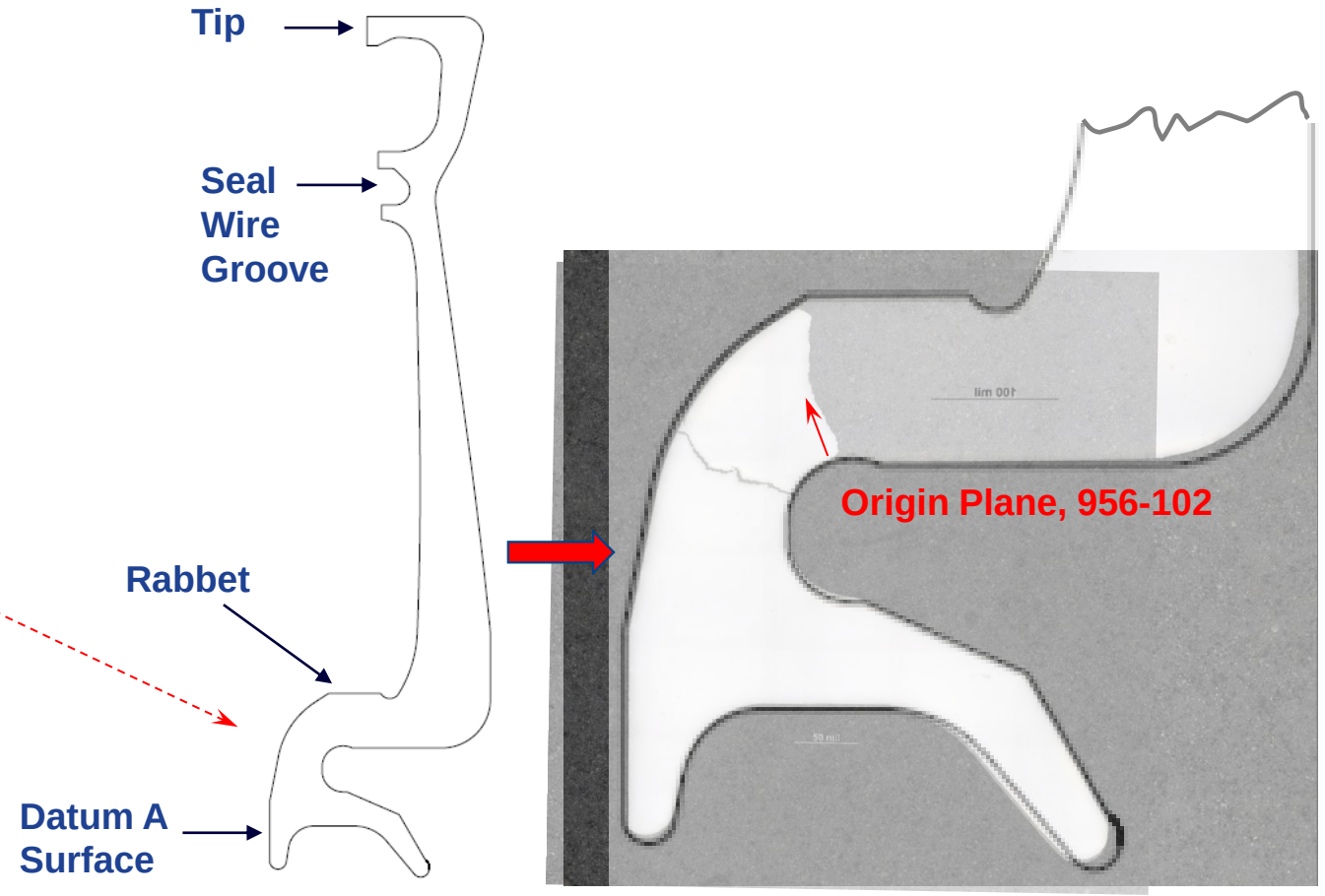


Figure 1: Schematic of the GEnx cross-section showing the location/configuration of the retainer and the fracture plane for 956-102 that grew from the outer area of the collet radius and grew outboard.

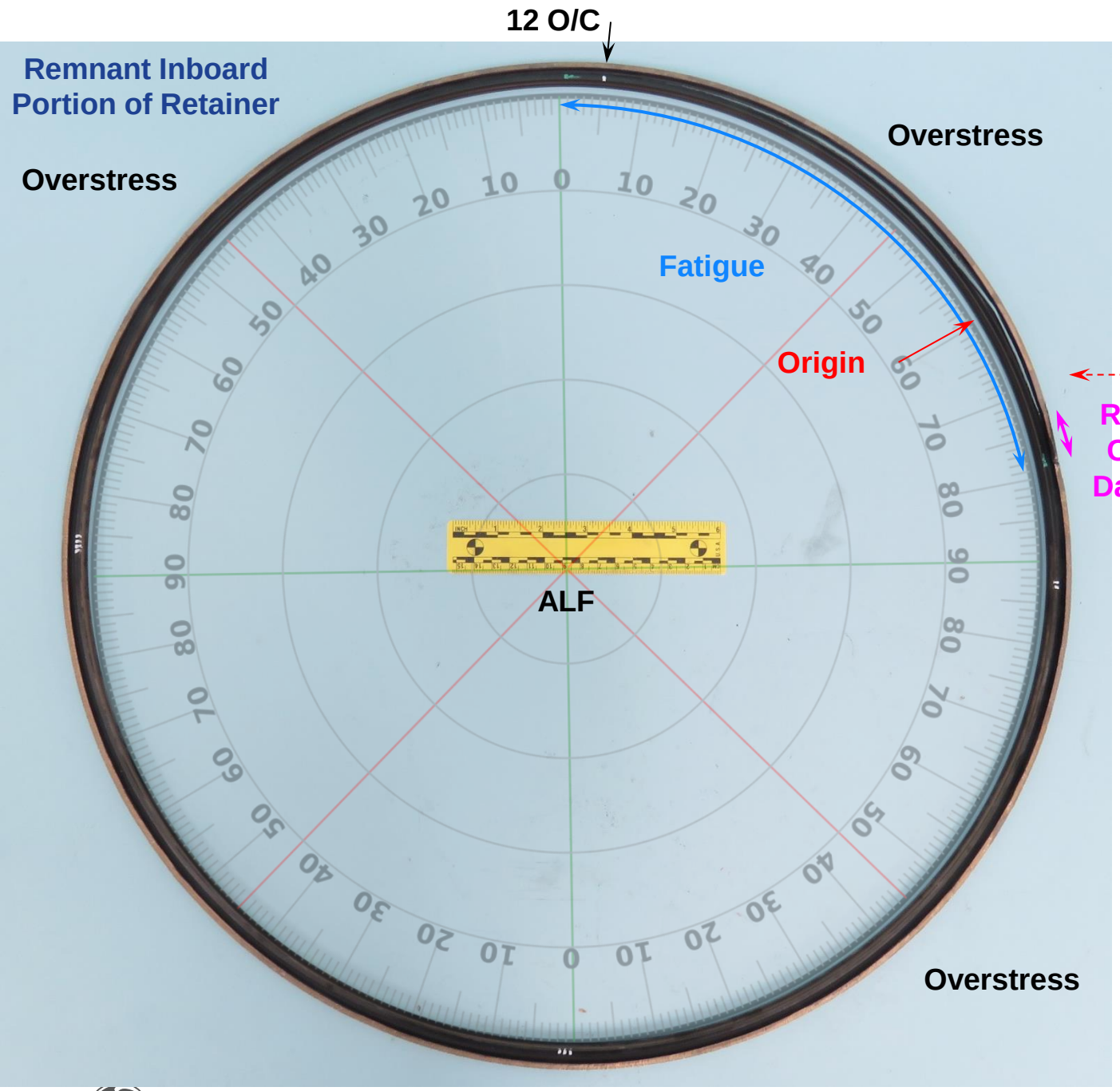


Figure 2: Optical views of the mated mid-seal and remnant portion of the retainer (right), with a view of only the retainer remnant on the left. The images show an approximate **80 degree** circumferential region consistent with fatigue that extended along the outboard part of the collet radius. The fracture then extended further aft in the disk rabbet radius in overstress and extended 360 degrees around and overlapped the fatigue region. In addition, there was a small region of cyclic damage near the end of the stable fatigue region.

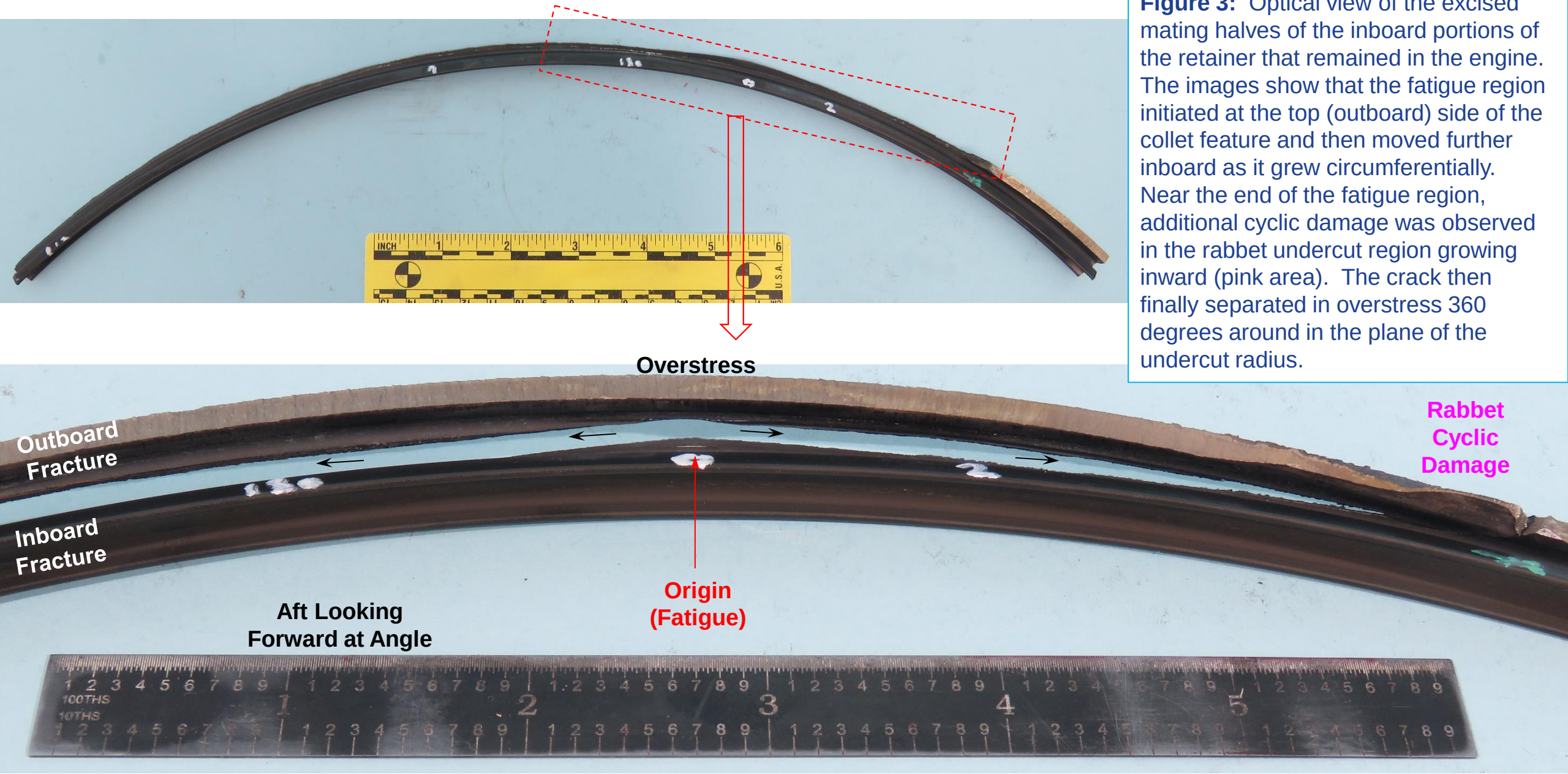
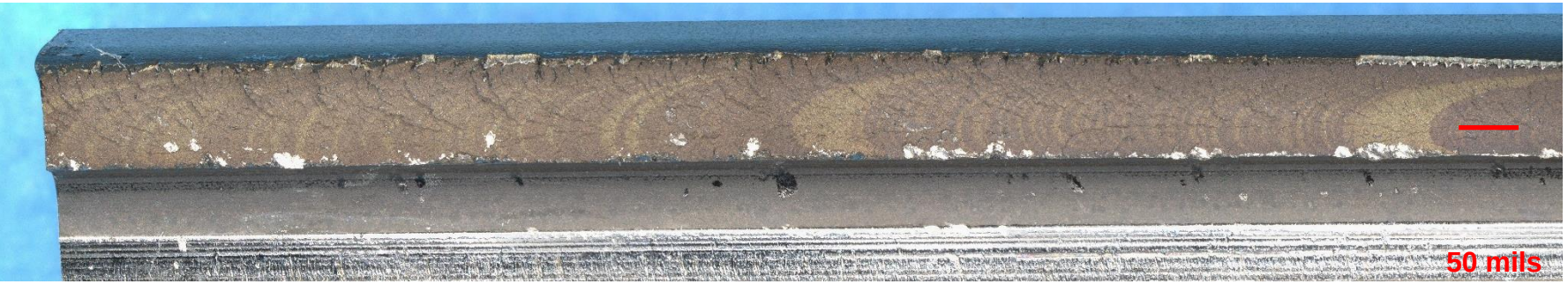
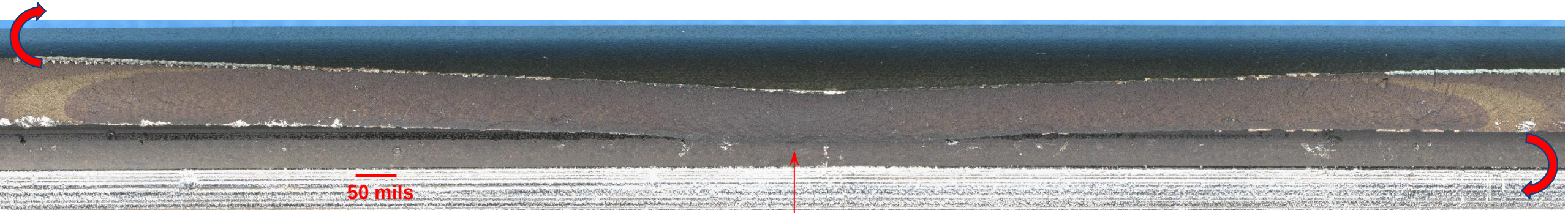


Figure 3: Optical view of the excised mating halves of the inboard portions of the retainer that remained in the engine. The images show that the fatigue region initiated at the top (outboard) side of the collet feature and then moved further inboard as it grew circumferentially. Near the end of the fatigue region, additional cyclic damage was observed in the rabbet undercut region growing inward (pink area). The crack then finally separated in overstress 360 degrees around in the plane of the undercut radius.

Inboard Fracture



Aft Looking
Forward at Angle



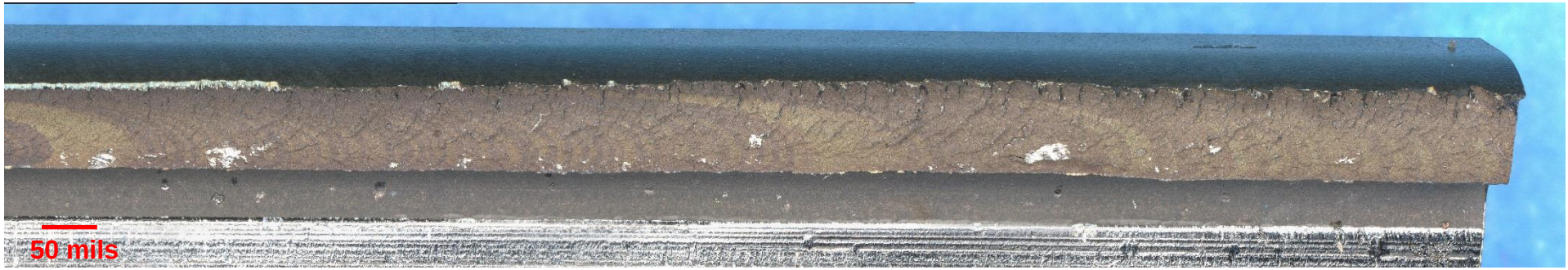


Figure 4: Optical views of the inboard fracture surface showing opposing beach marks consistent with cyclic growth/fatigue growing in both circumferential directions from the origin area in the collet radius.

Inboard Fracture

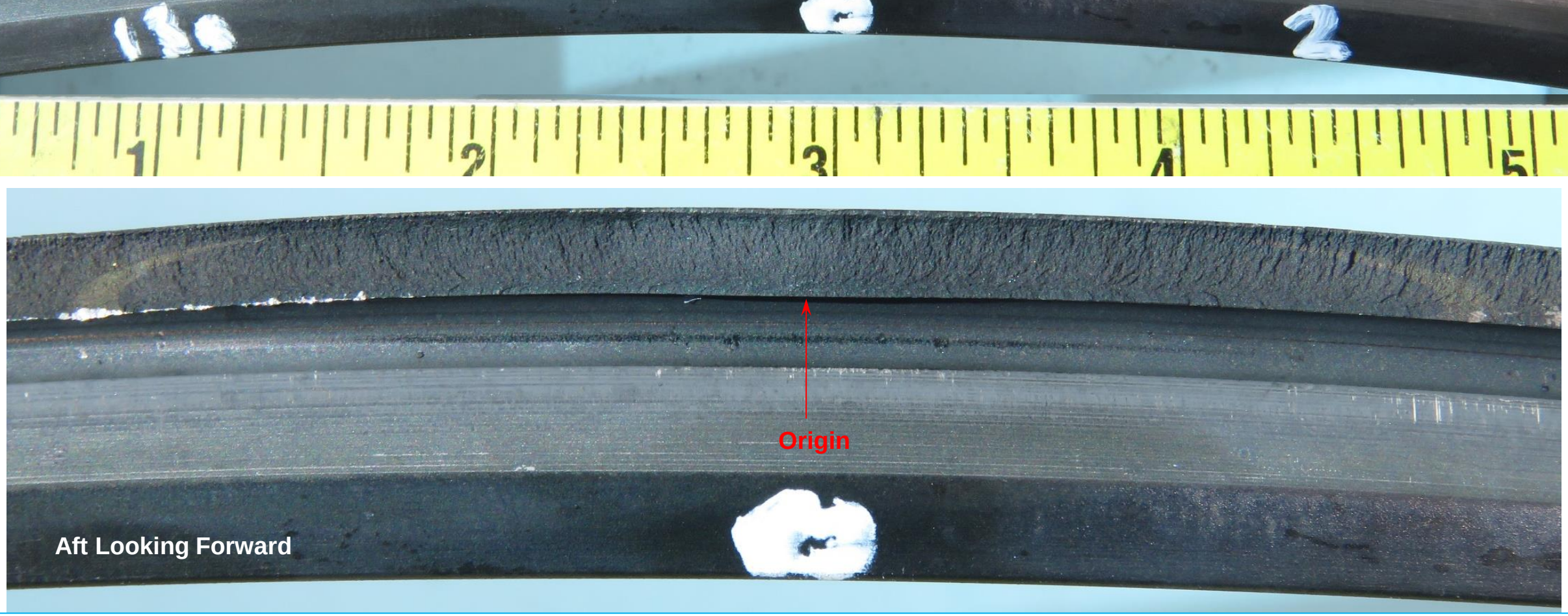
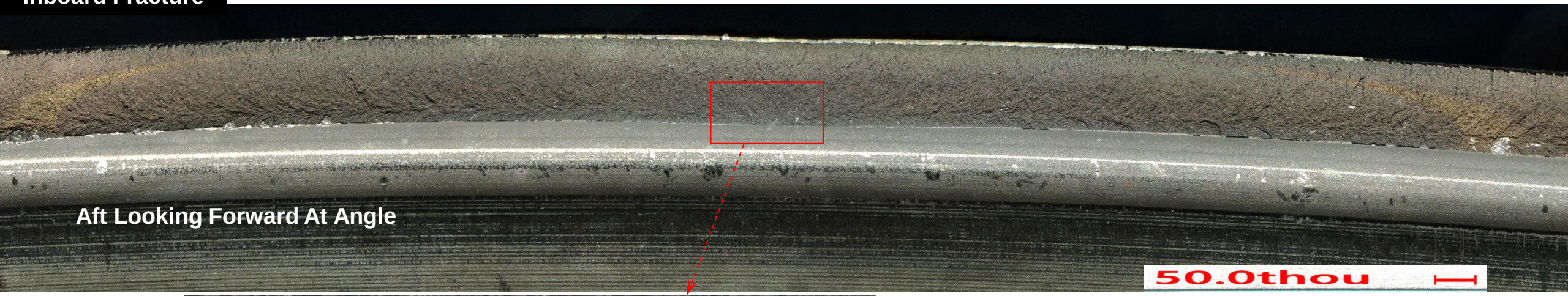


Figure 5: Close-up low-angle optical lighting view of the inboard fracture showing it was planar consistent with fatigue extending from a single origin at the collet surface growing through-thickness and circumferentially in both directions.



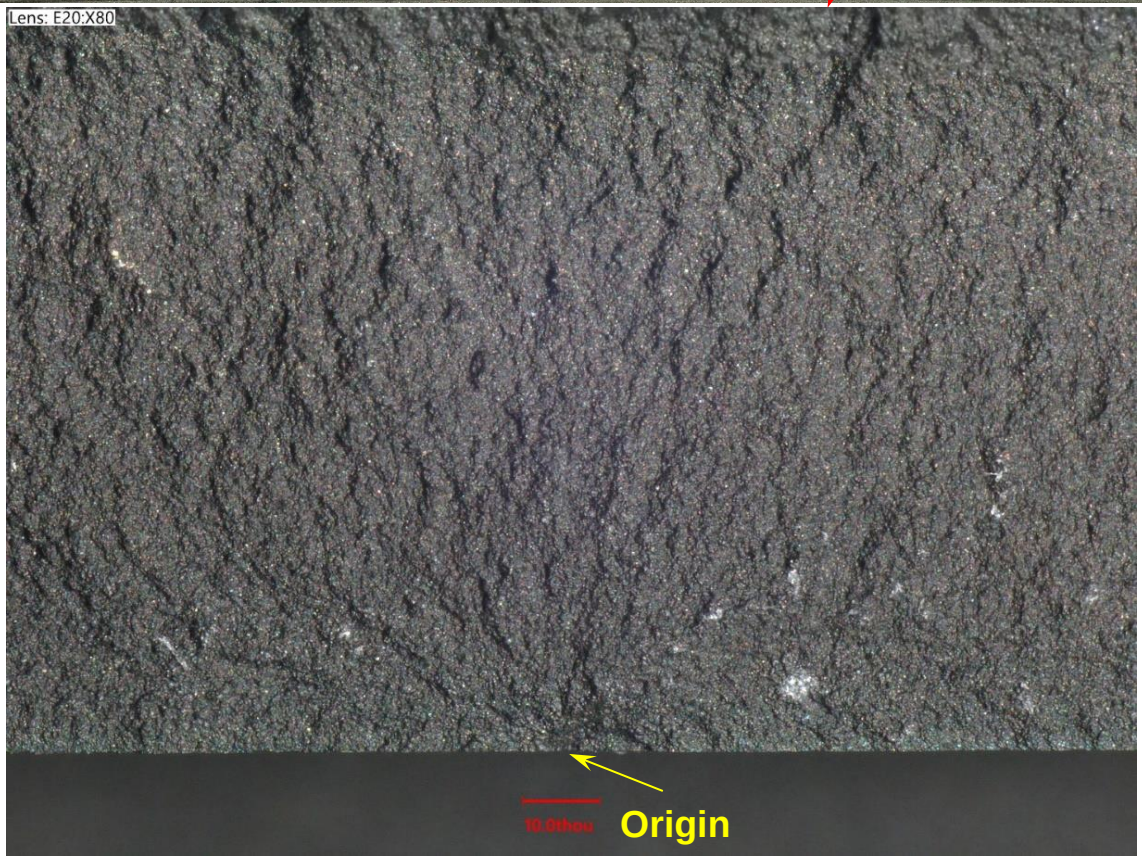


Figure 6: Close-up optical view of the fracture surface in the region of the origin showing that it initiated from a single origin at the surface (see SEM).

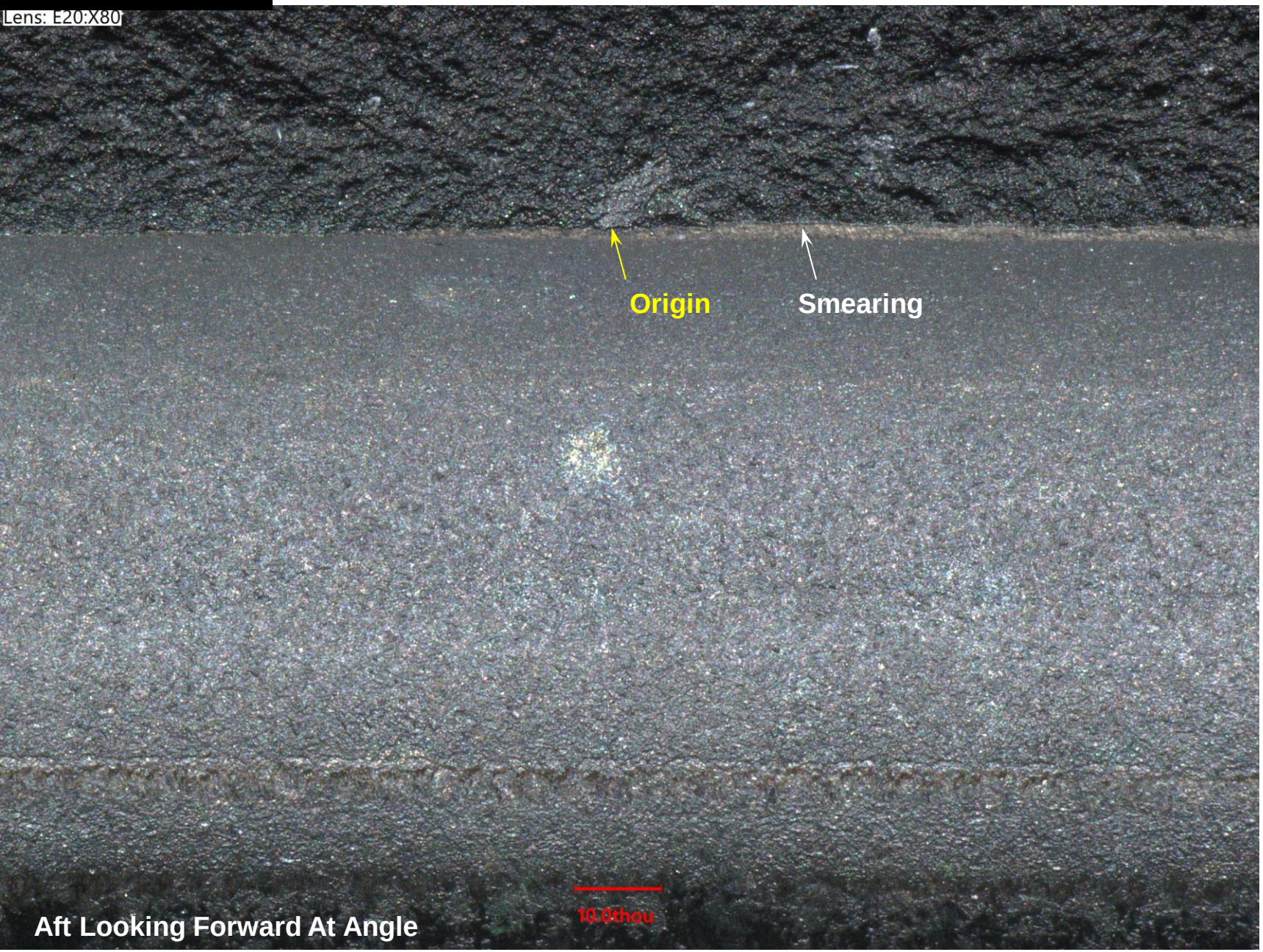
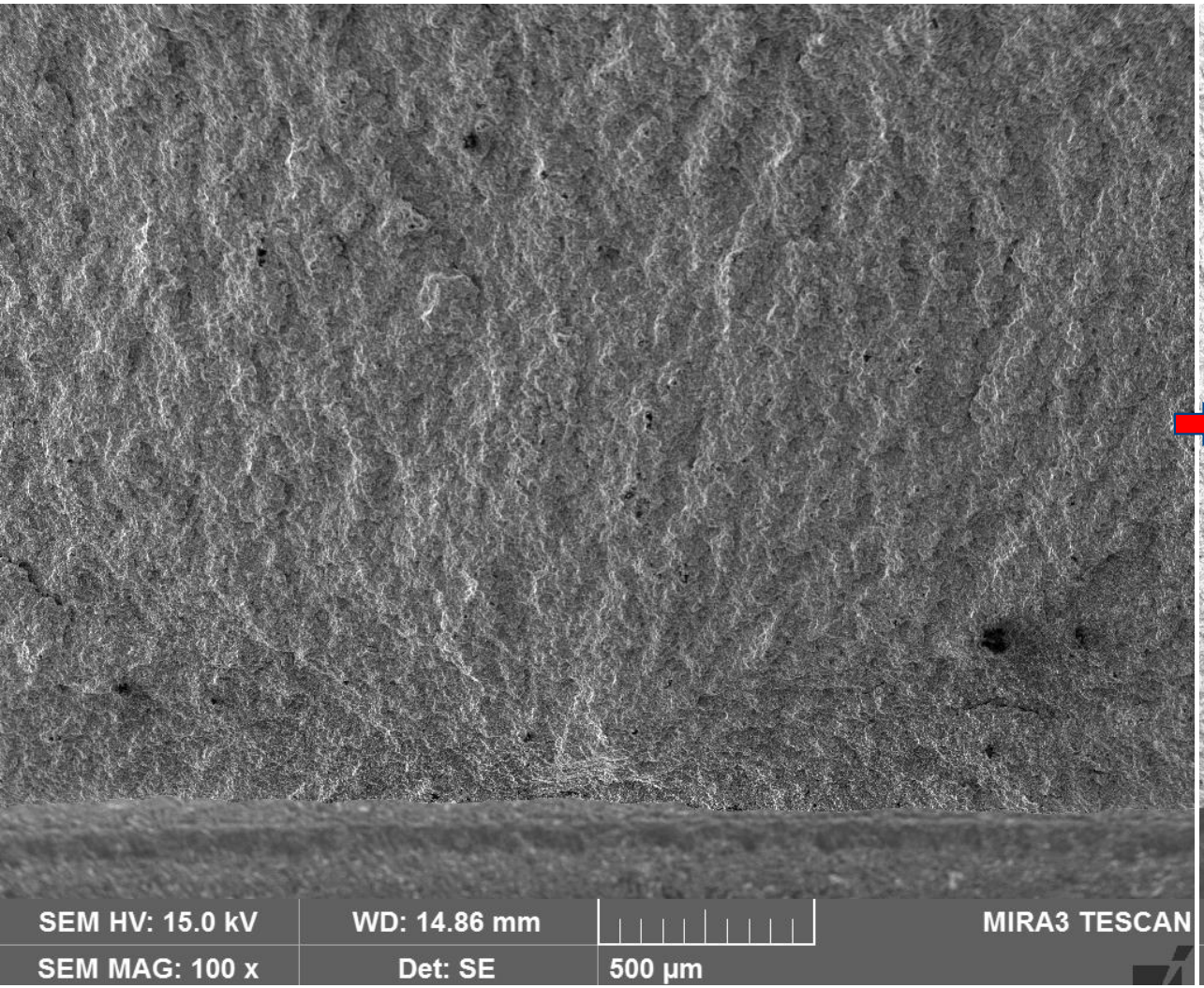


Figure 7: Close-up optical view of the collet surface in the area of the origin showing that the surface had a dimpled pattern with roughened features, consistent with having been shot-peened and wet-blasted per the requirement.



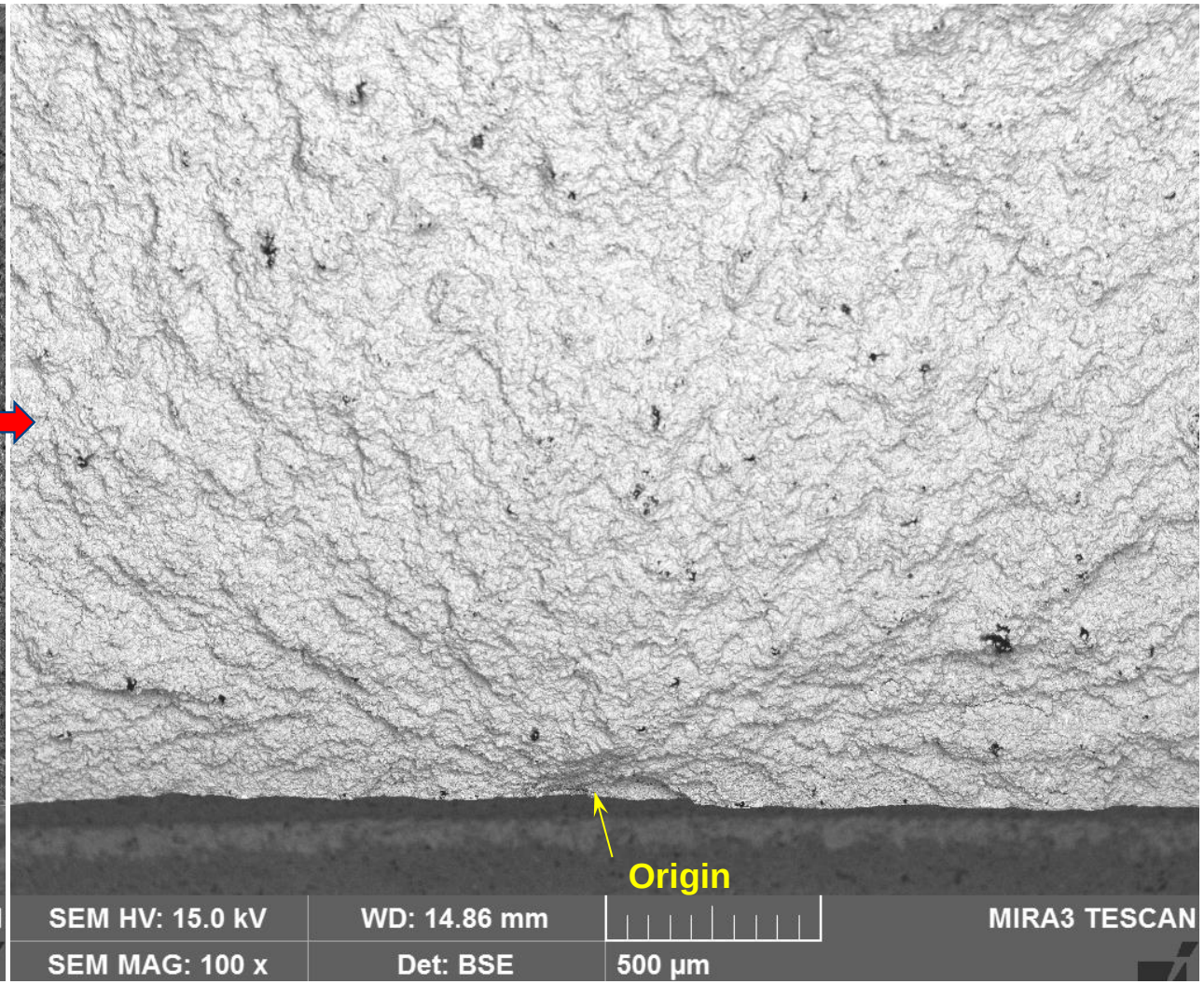


Figure 8: SEM examination in SEI and BEI modes confirmed initiation at the surface from a single origin where an OCNC inherent inclusion was observed (see following pages).

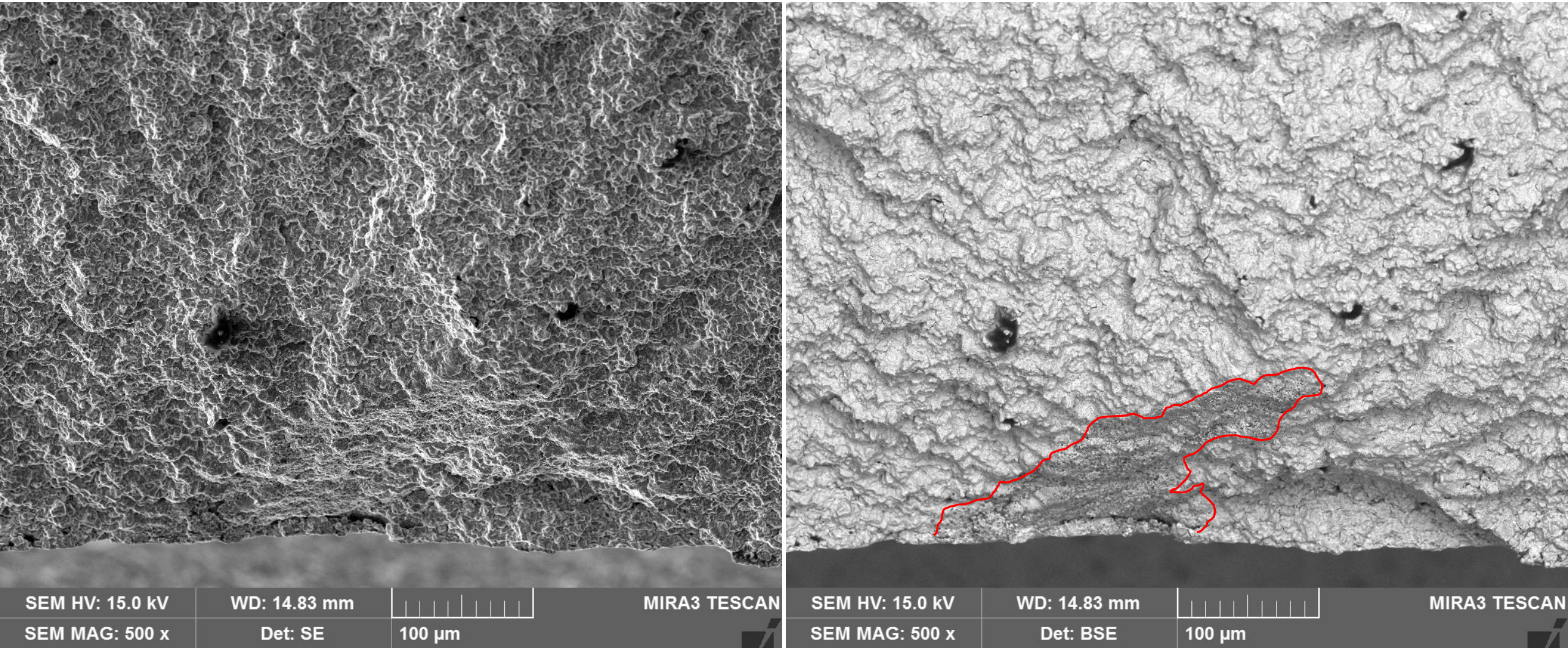
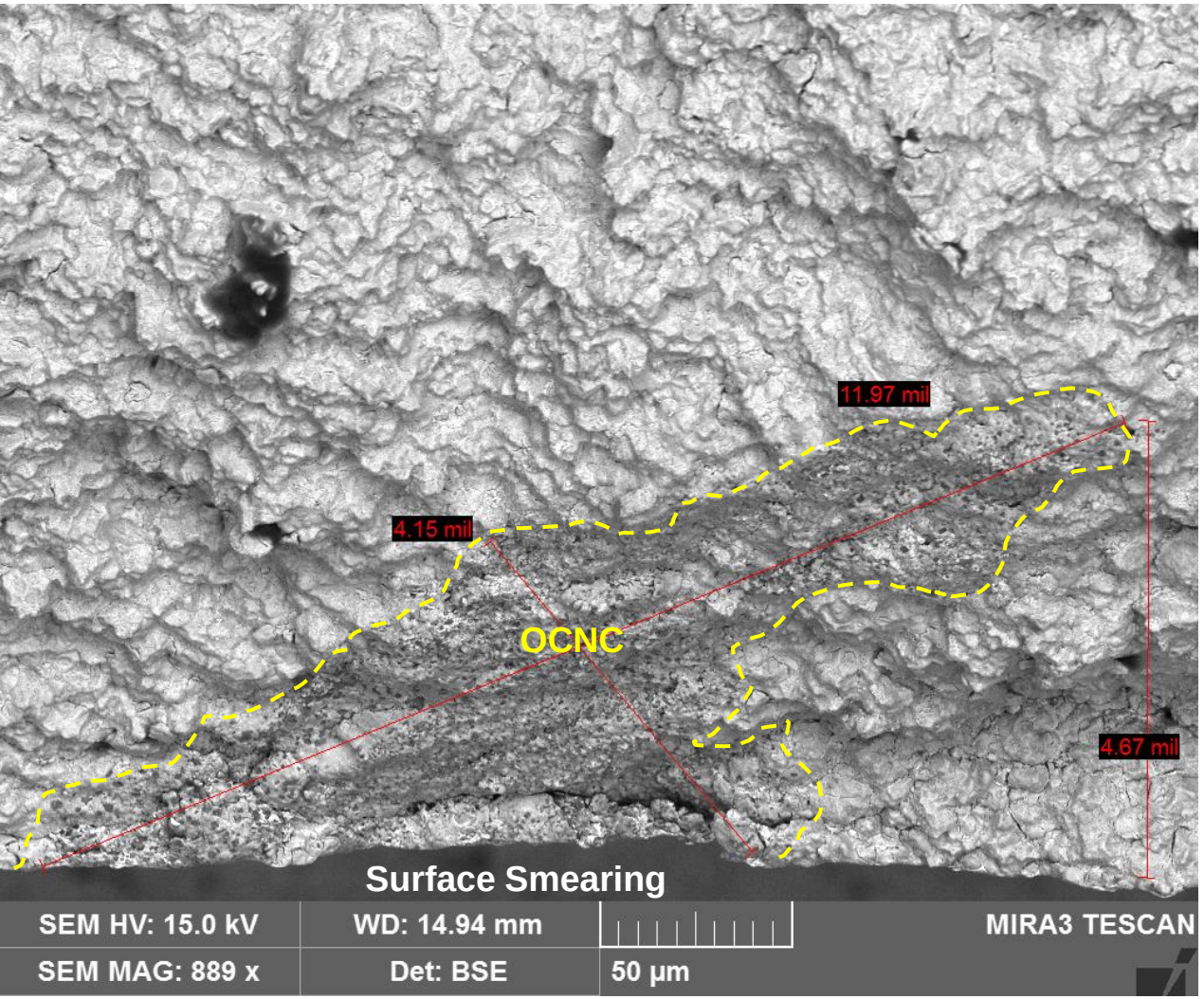


Figure 9: Higher magnification SEM images showing initiation from a surface-connected OCNC.

Tilted



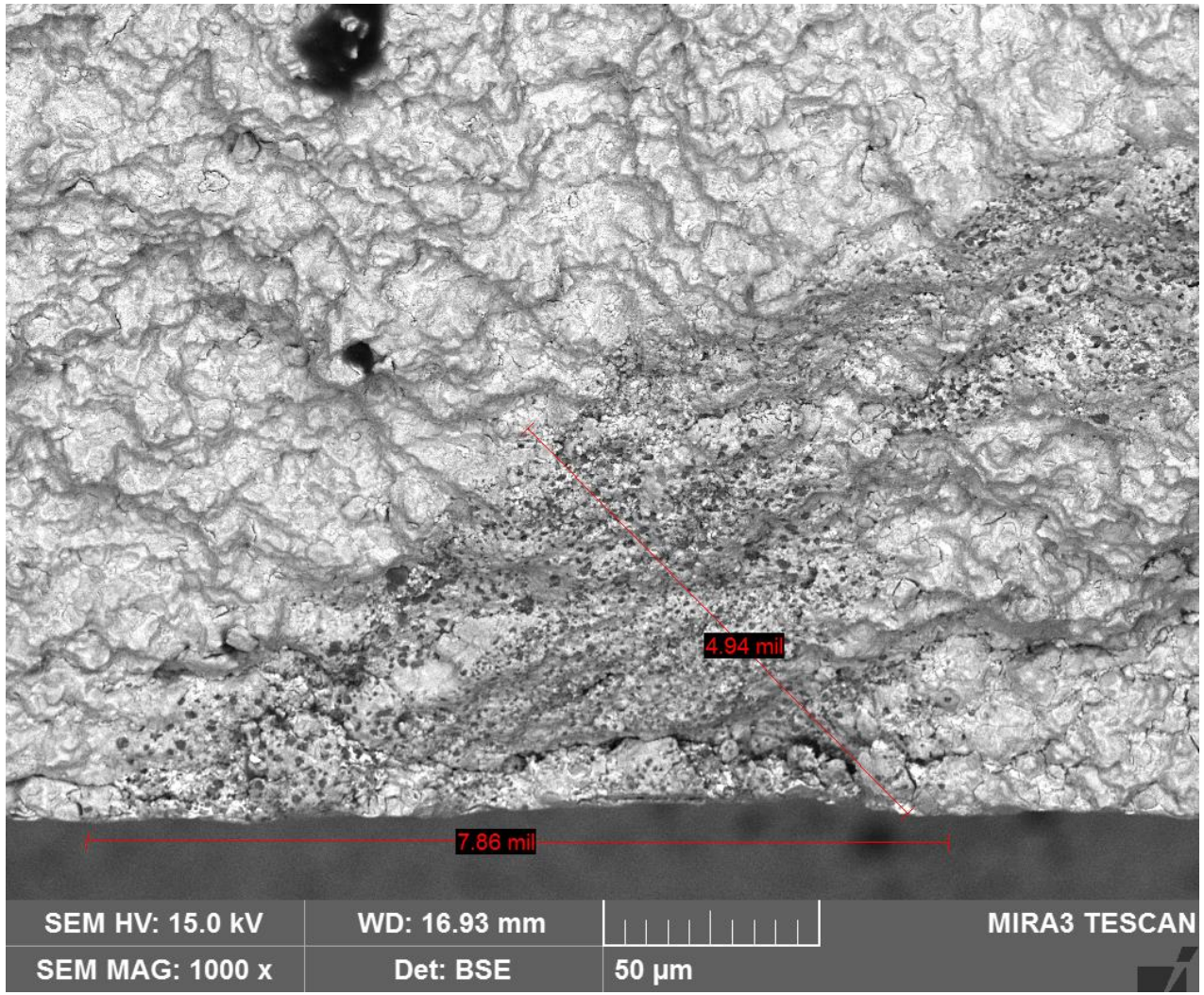
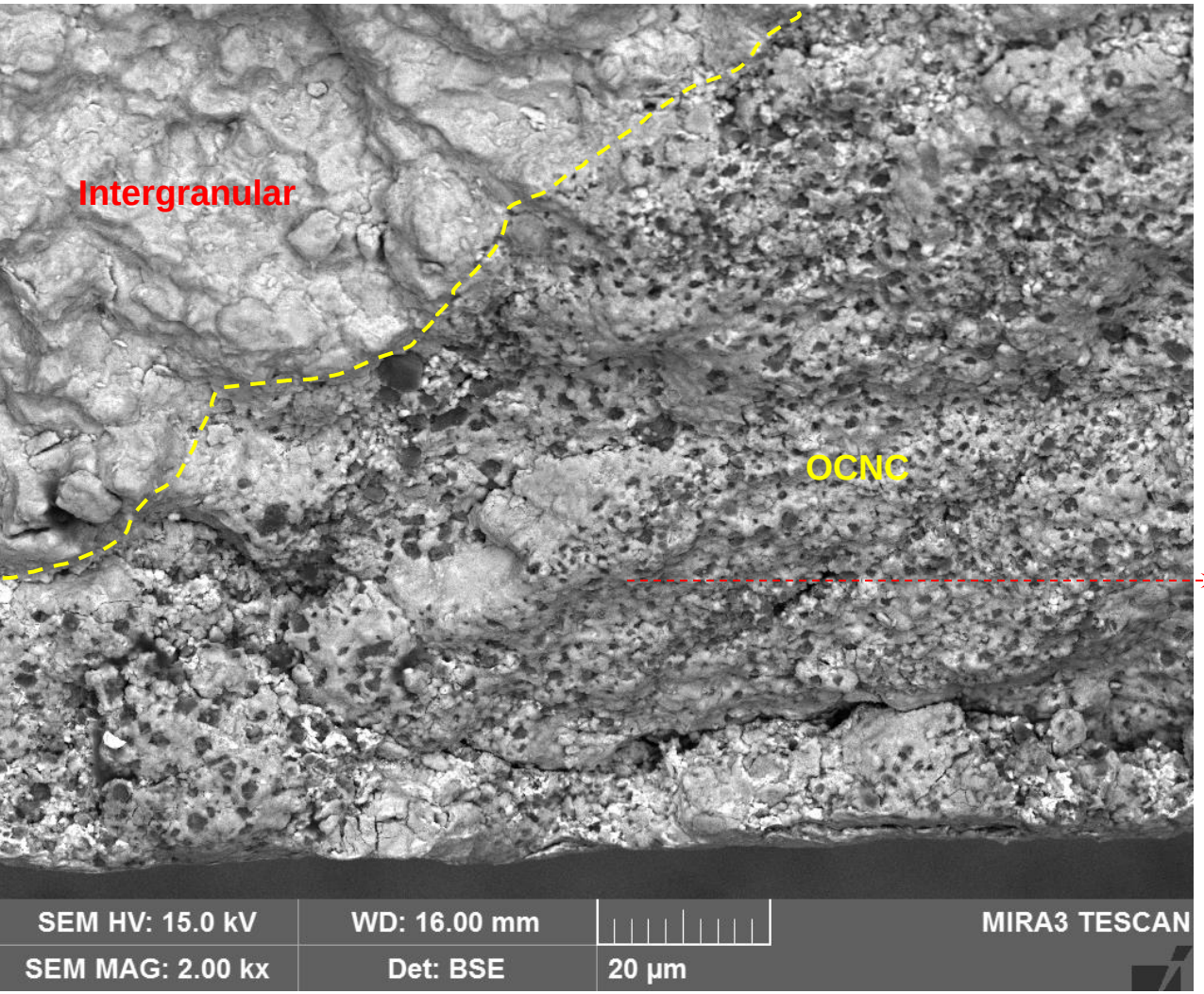


Figure 10: Higher magnification SEM images of the OCNC at different angles showing that it was approximately **5 mils wide** by **12 mils long** (not including smeared area; **13 mils** visible on the smeared outboard fracture). The surface-connected portion of the OCNC was approximately 8 mils long.



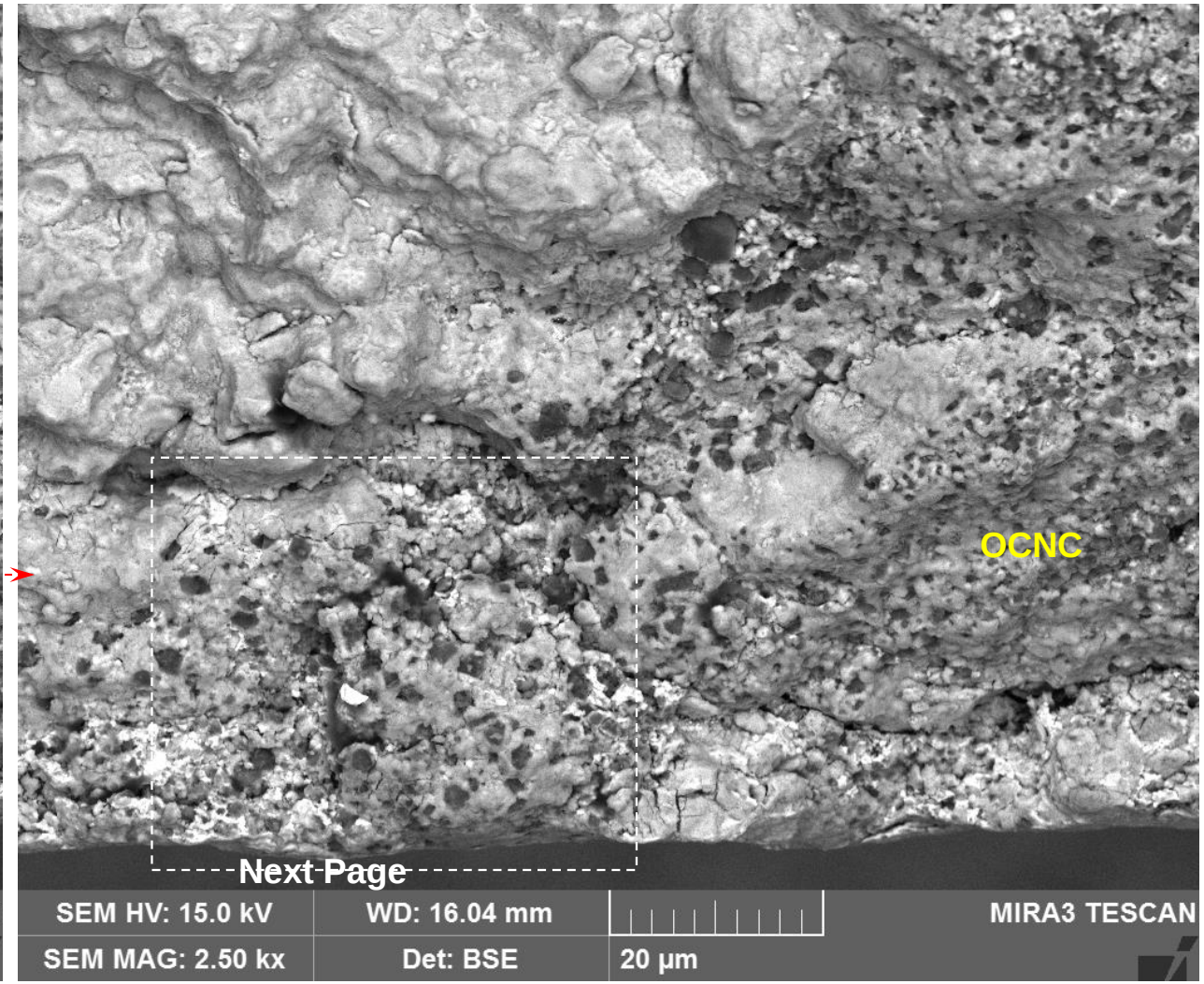
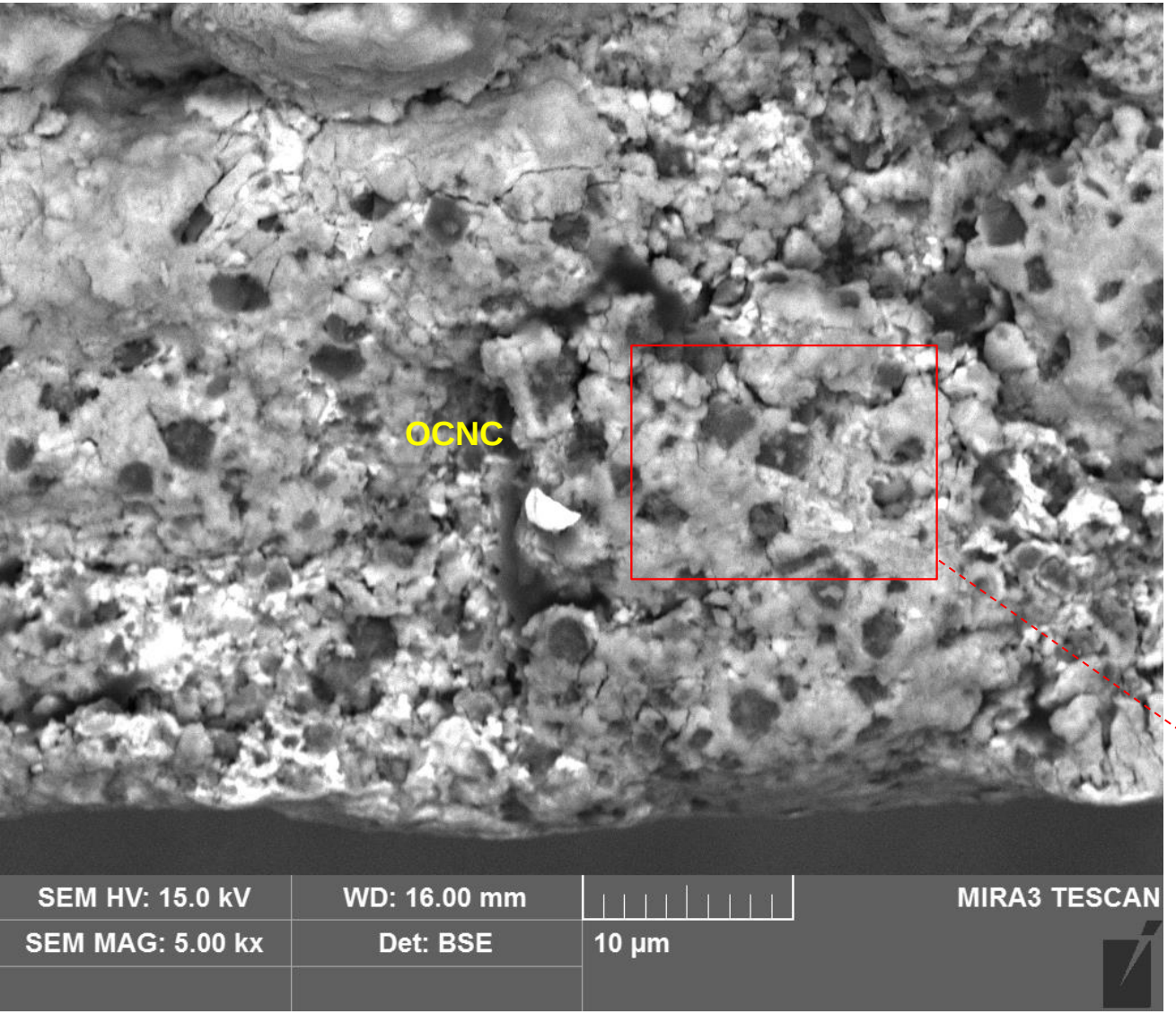
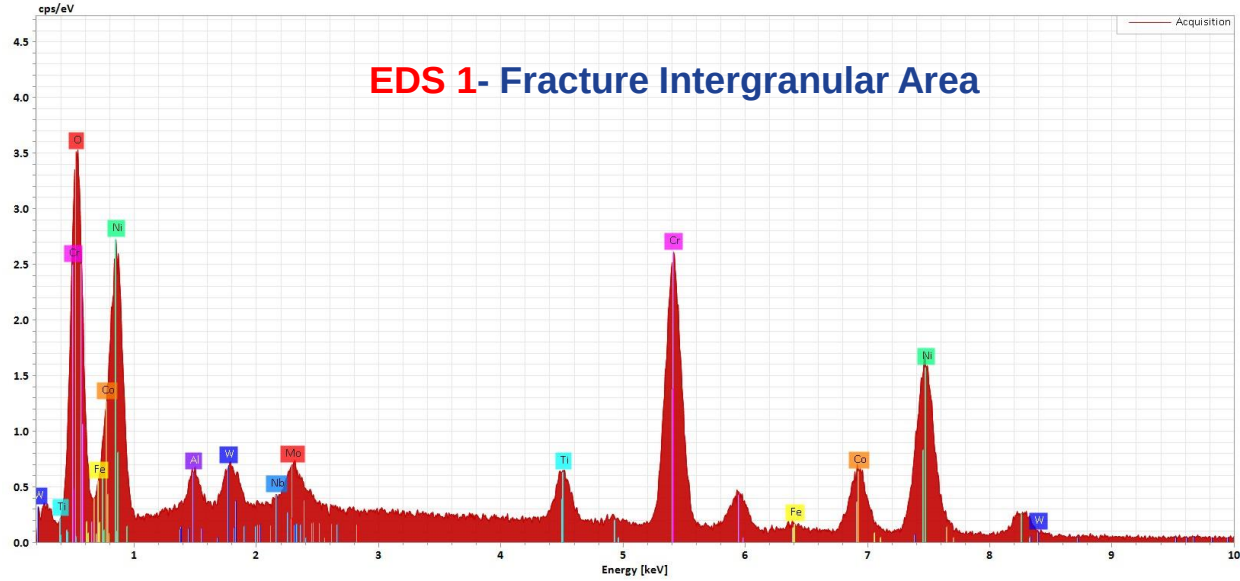


Figure 11: Higher magnification views of the OCNC that showed a “cluster” morphology with mixed oxides present (see following slides). The fracture then propagated in an intergranular manner from the OCNC.





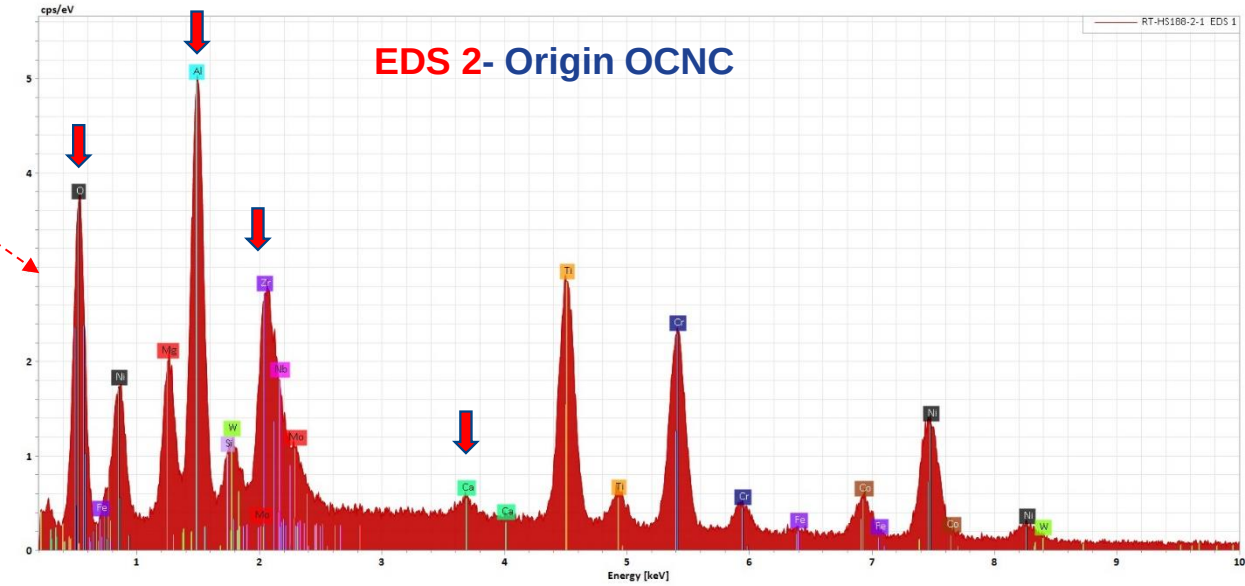
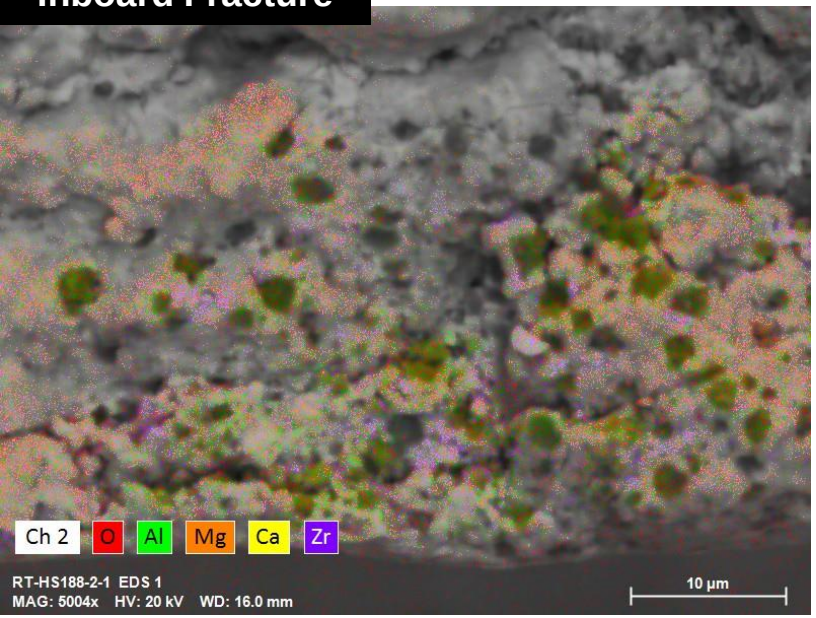
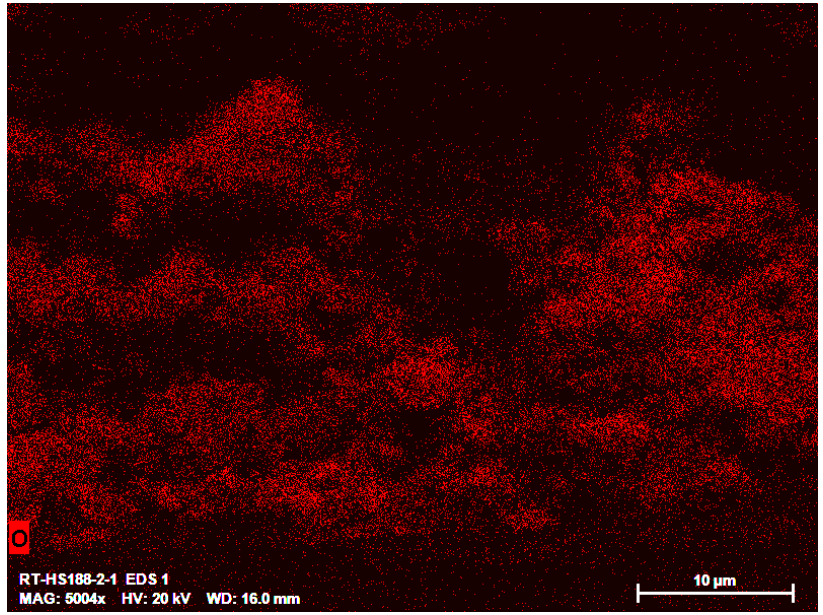
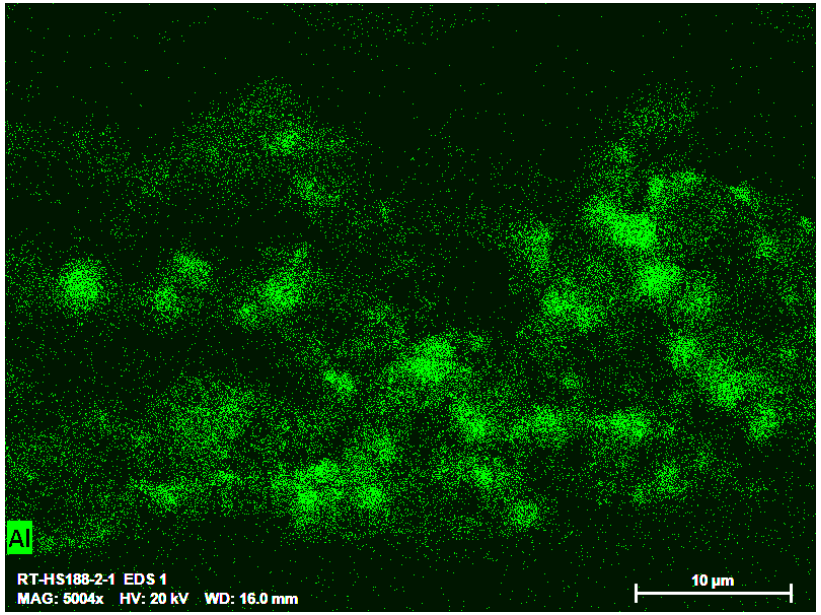


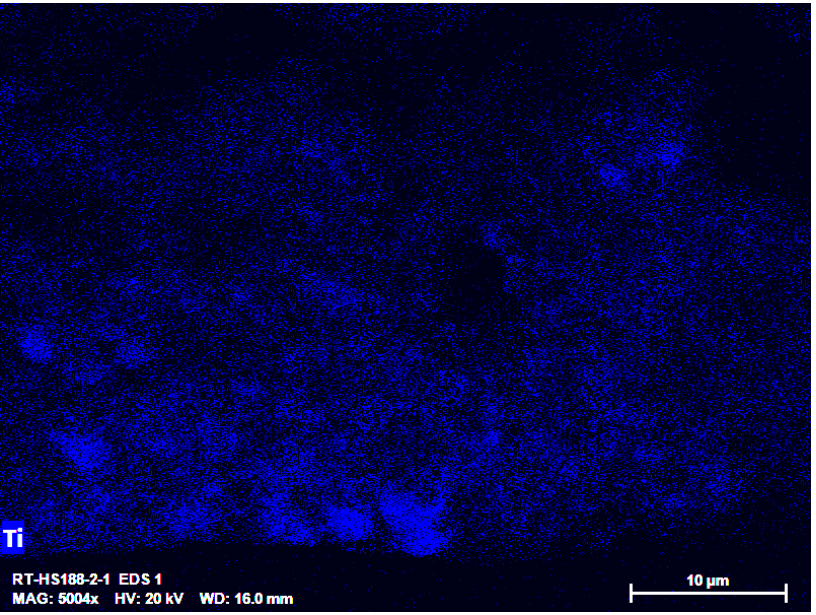
Figure 12: EDS analysis of the origin showed the presence of mixed oxides rich in **Ti, Al, Zr, Mg, Ca, O,** consistent with an inherent Oxide/Carbonitride/Nitride/Carbide (OCNC) inclusion.

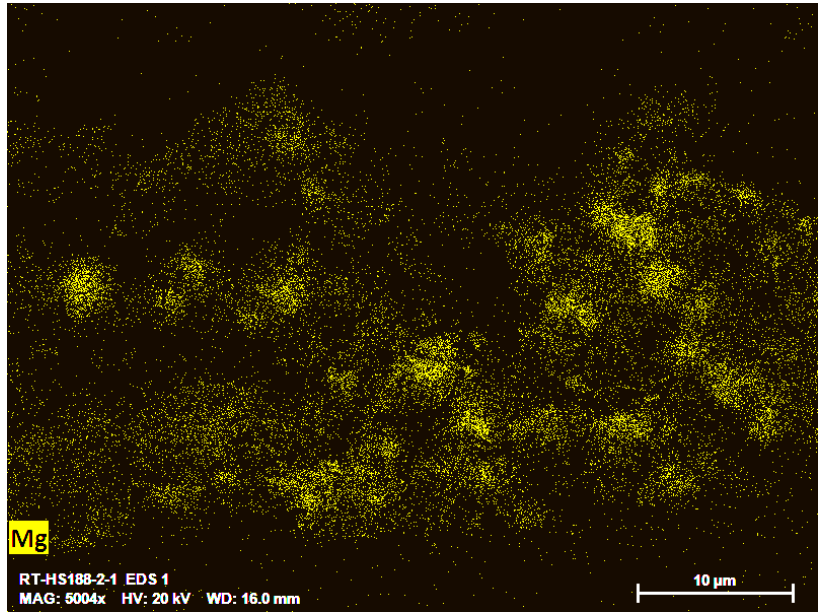
Inboard Fracture











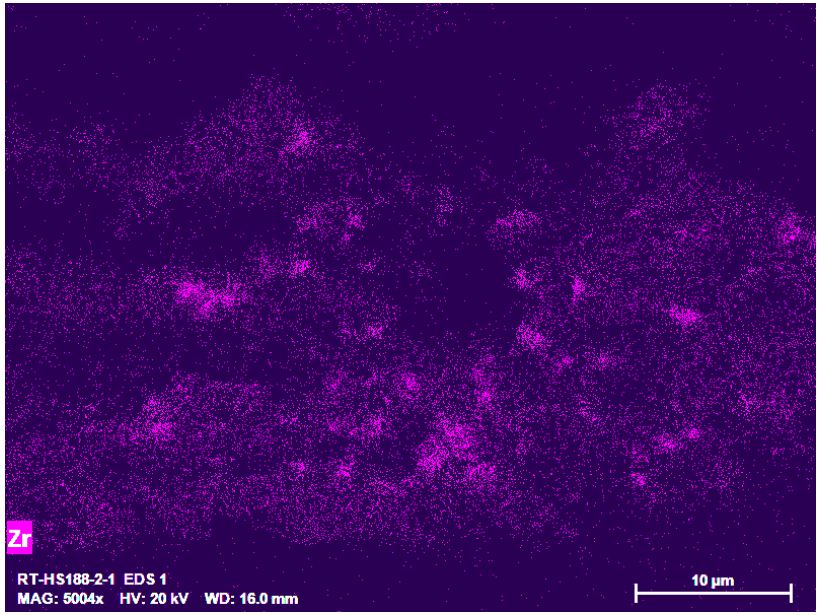


Figure 13: EDS dot maps showed similar results with mixed oxides rich in **Ti, Al, Zr, Mg, Ca, O,** consistent with an inherent OCNC inclusion.

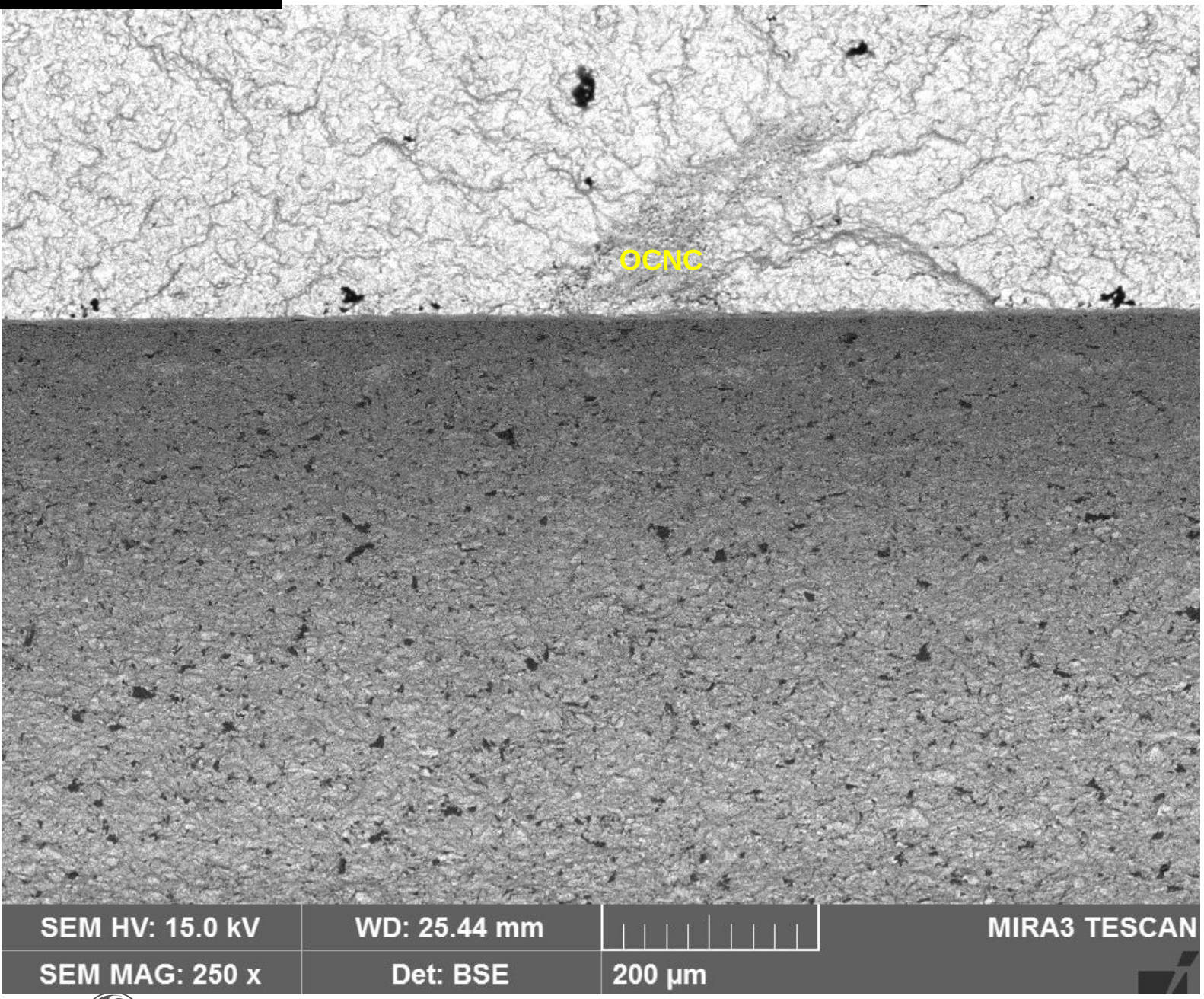


Figure 14: An angled SEM view of the origin area did not reveal any surface anomalies such as scoring marks, nor secondary cracking. The surface was roughened and had angular particulates, consistent with having been grit-blasted per the requirements.

At Origin

Far from Origin

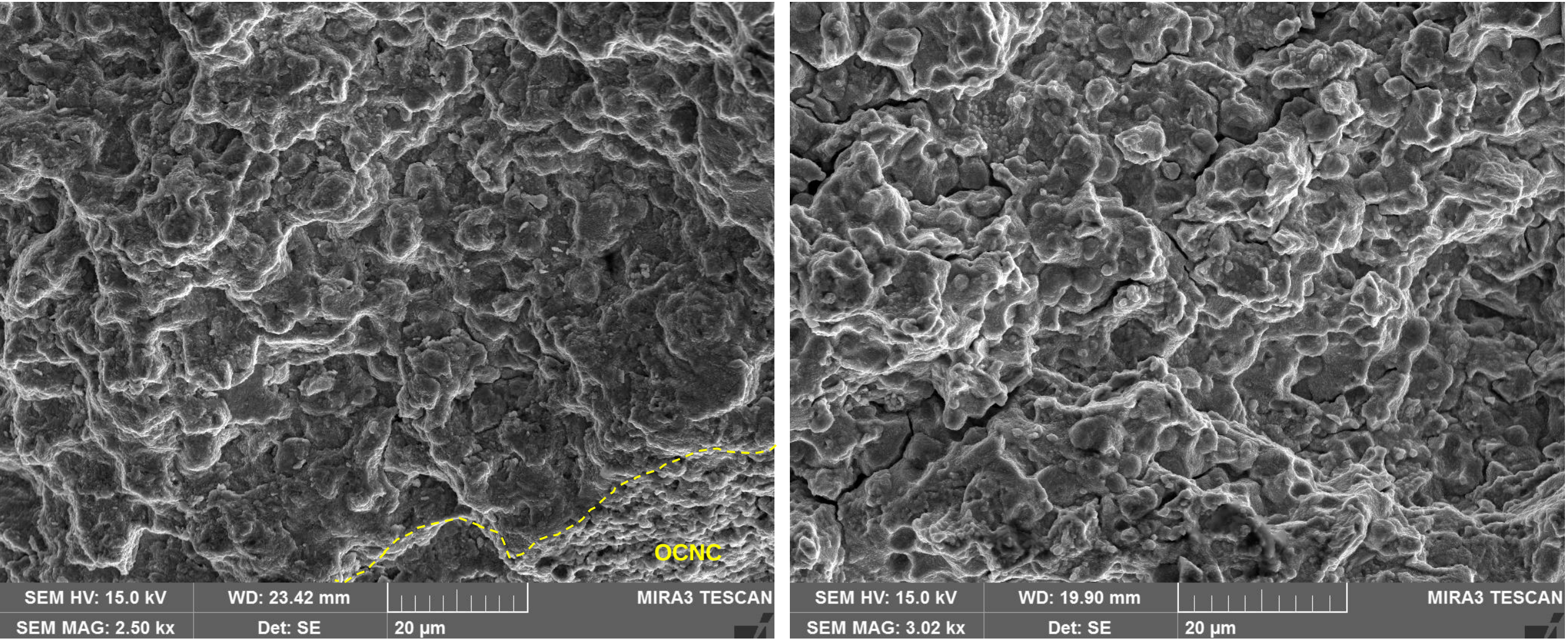


Figure 15: The fracture grew in a fully intergranular manner throughout the collet region with more secondary cracking observed far from the origin area, consistent with SPLCF/hold-time fatigue crack growth.

Geometry

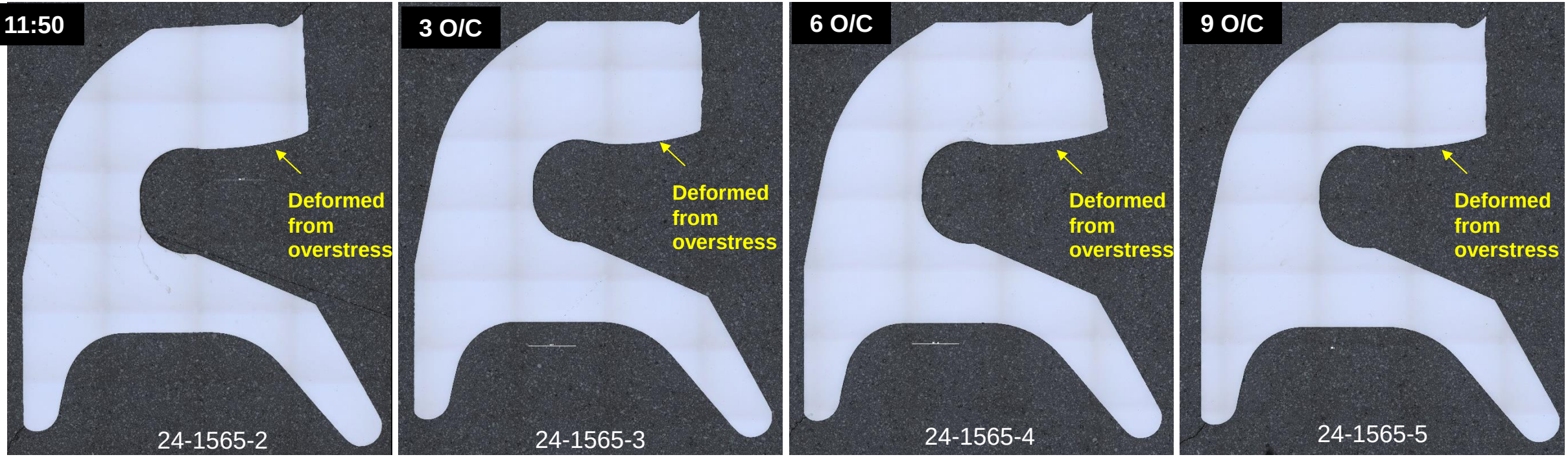


Figure 16: Four cross-sectional mounts made at the intact regions of the collet (beyond the fatigue crack) generally showed a conforming geometry, except in the outboard region adjacent to the disk rabbet, consistent with deformation from final overstress.

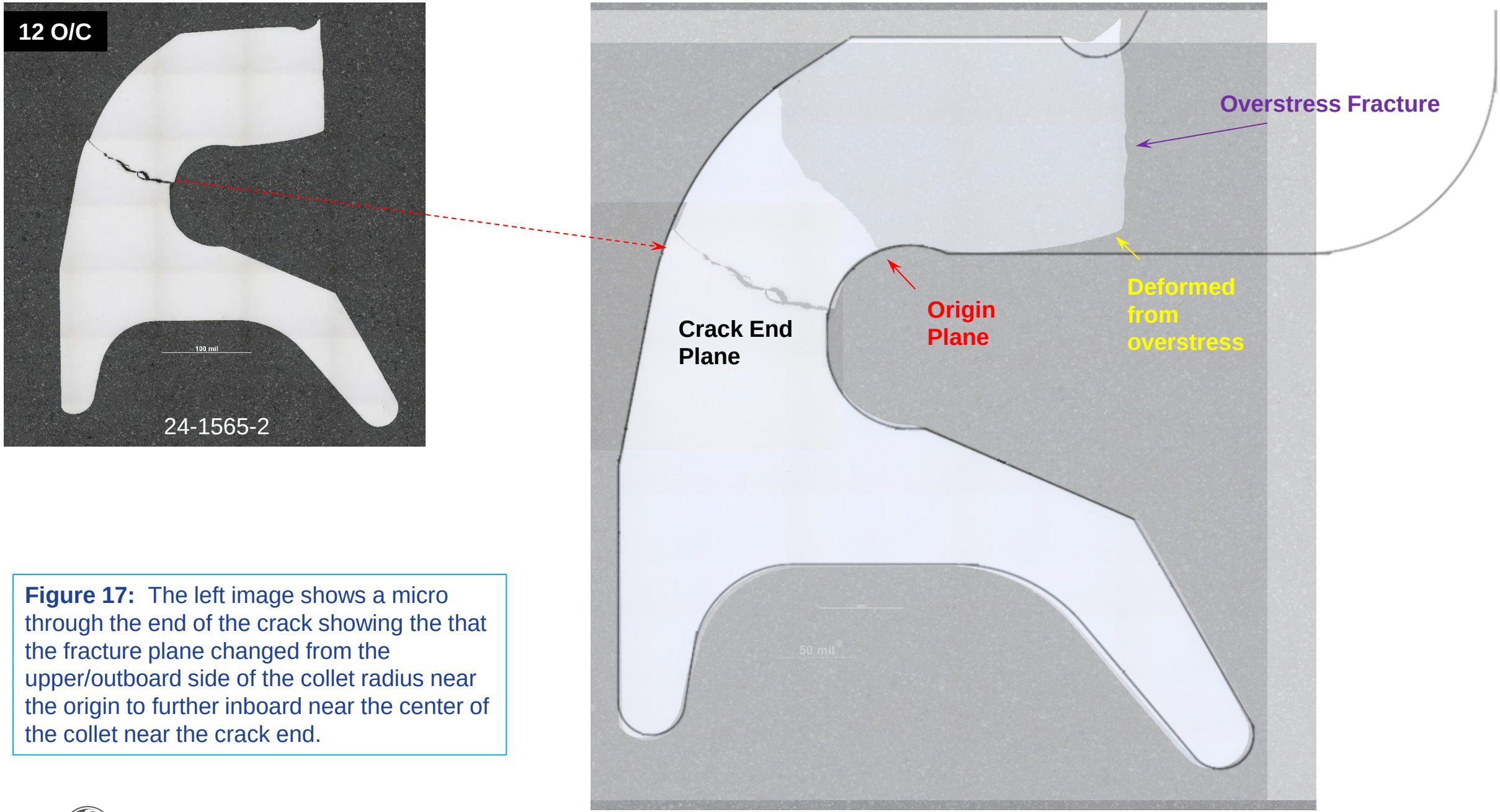
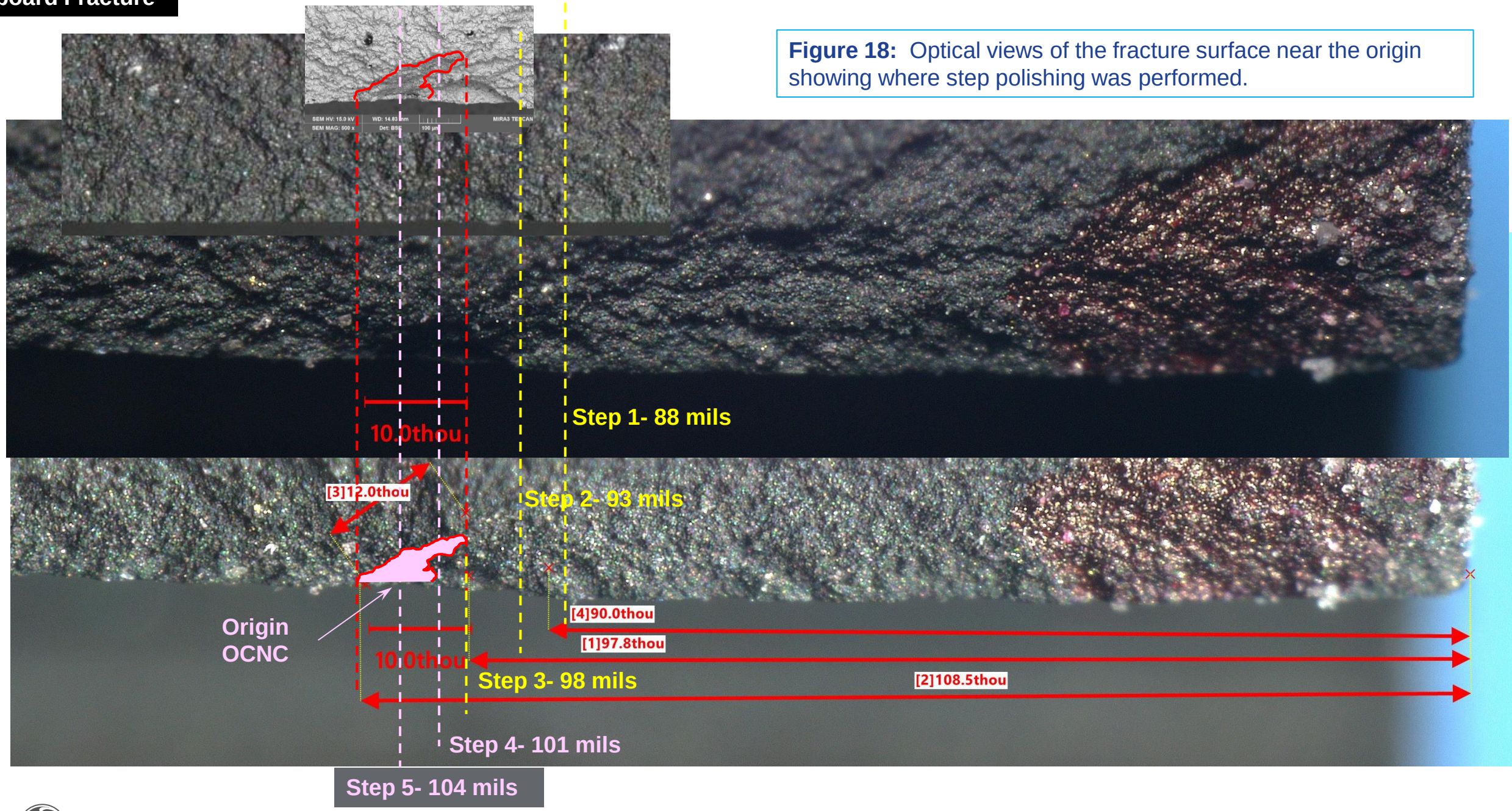
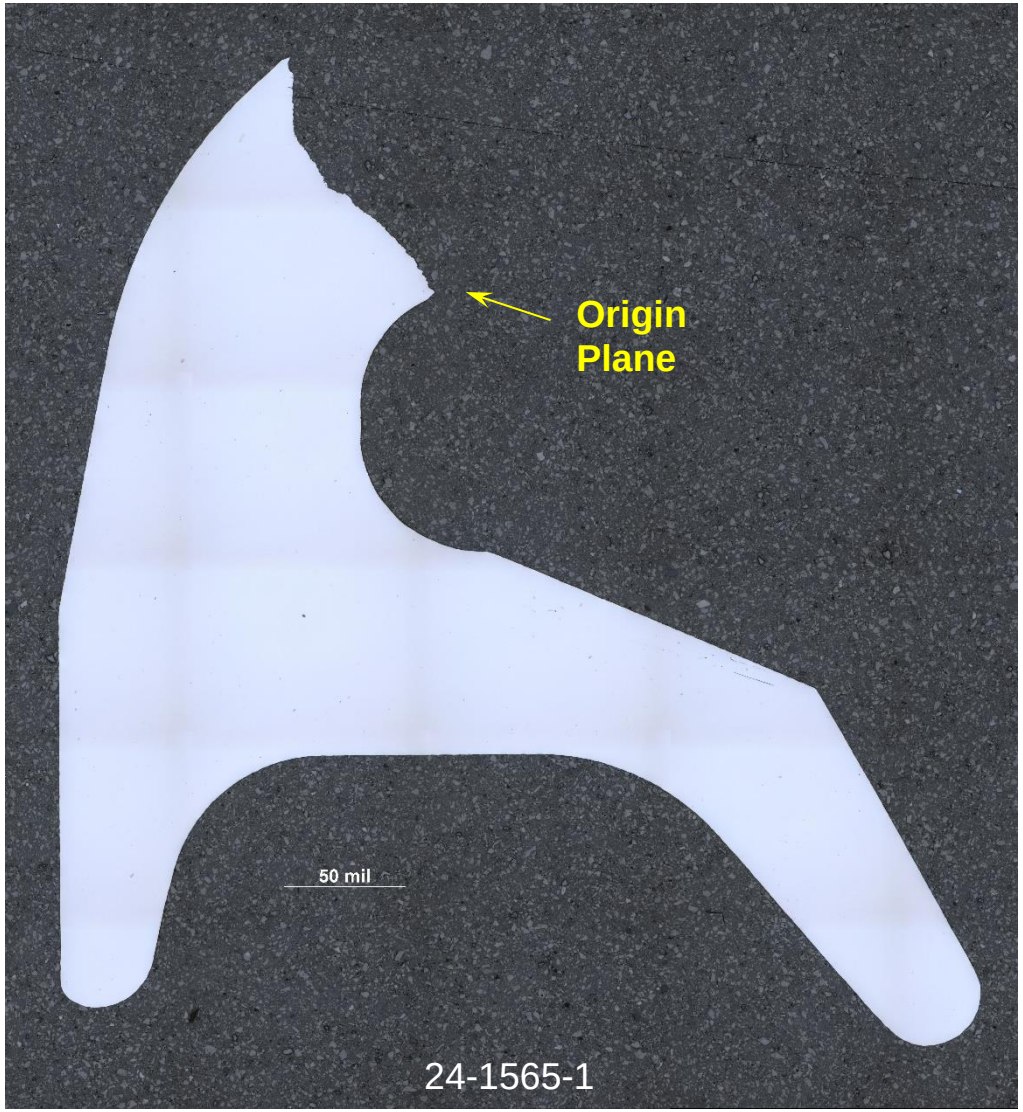


Figure 17: The left image shows a micro through the end of the crack showing the that the fracture plane changed from the upper/outboard side of the collet radius near the origin to further inboard near the center of the collet near the crack end.

Figure 18: Optical views of the fracture surface near the origin showing where step polishing was performed.



Inboard Fracture- Step 1 (88 mils- start plane)



1st Principle

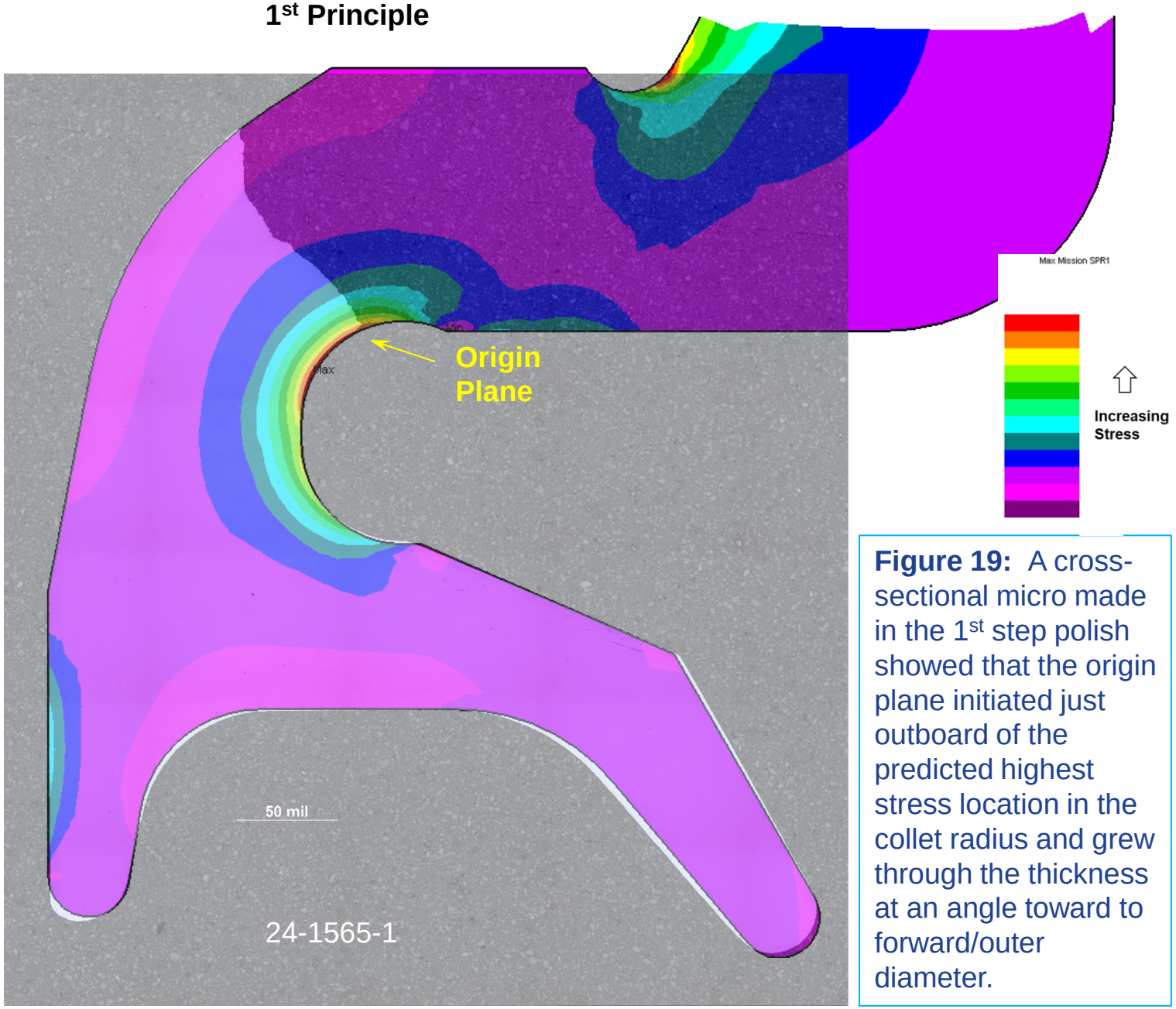
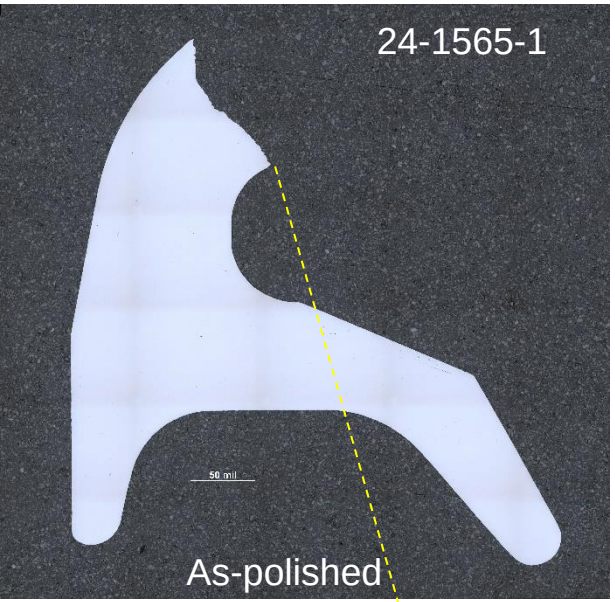
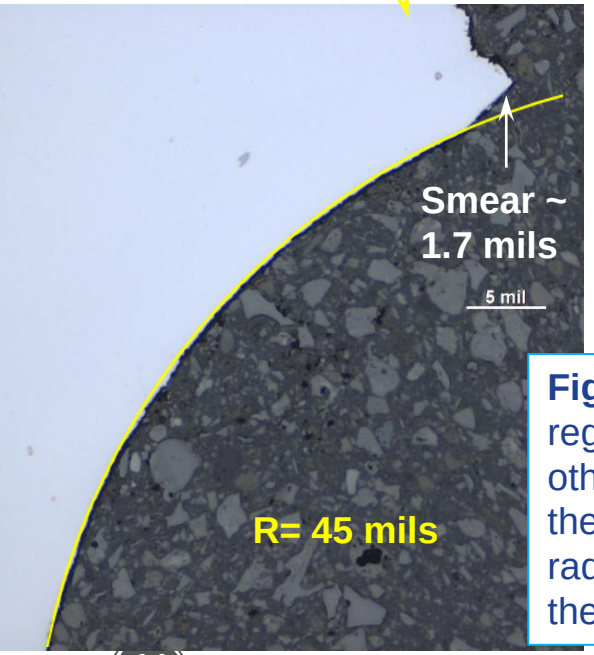
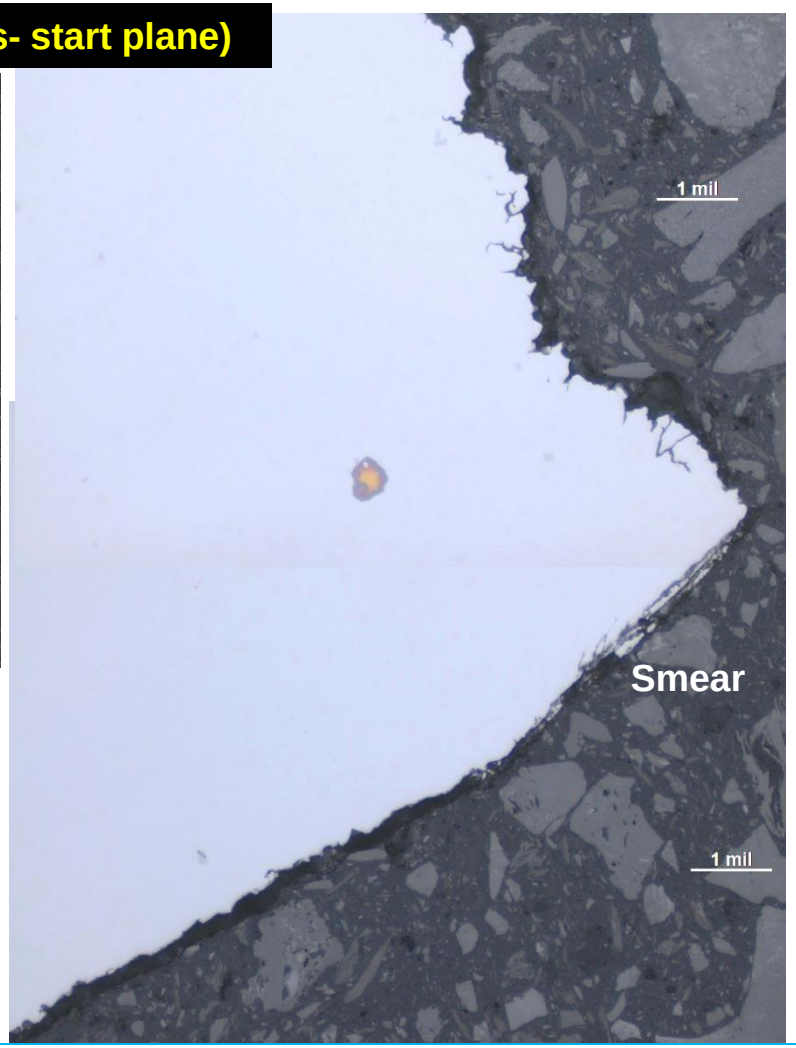


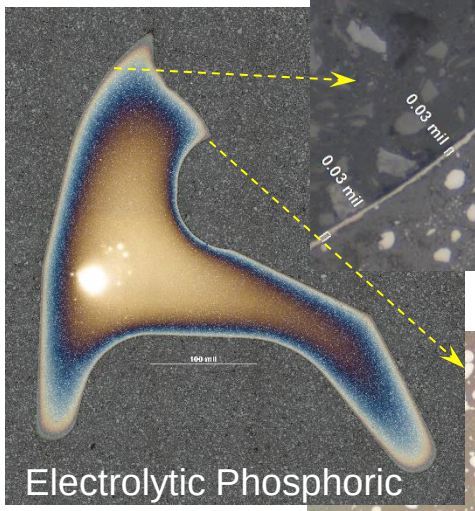
Figure 19: A cross-sectional micro made in the 1st step polish showed that the origin plane initiated just outboard of the predicted highest stress location in the collet radius and grew through the thickness at an angle toward to forward/outer diameter.

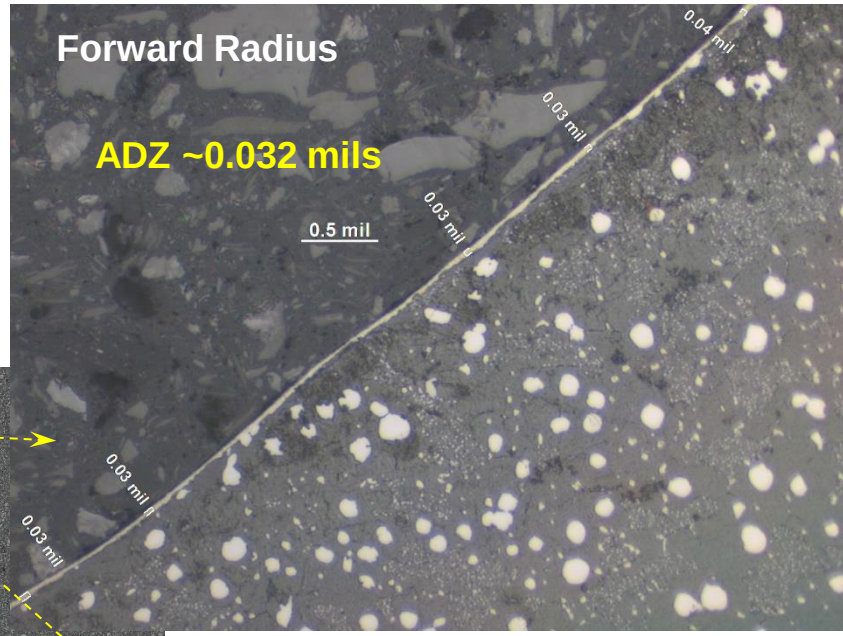
Inboard Fracture- Step 1 (88 mils- start plane)











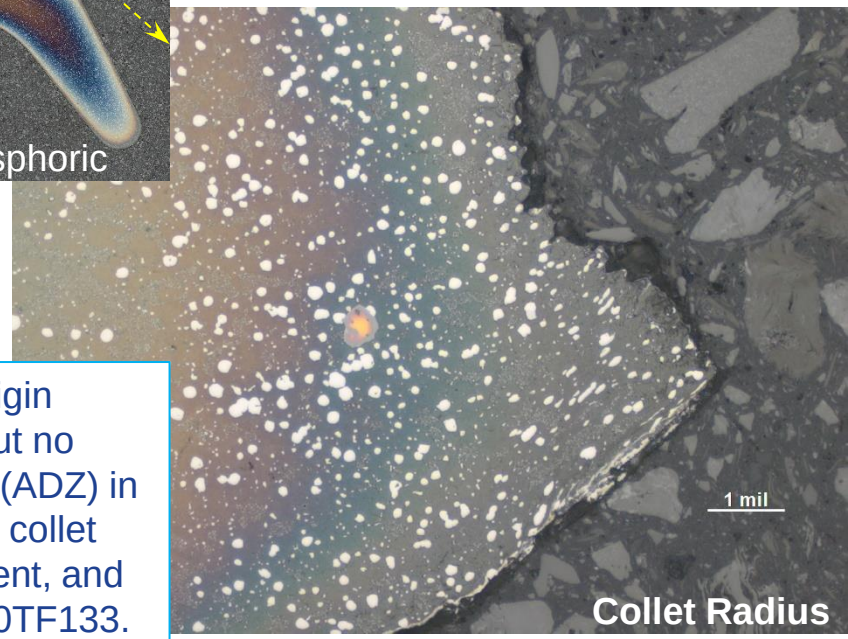
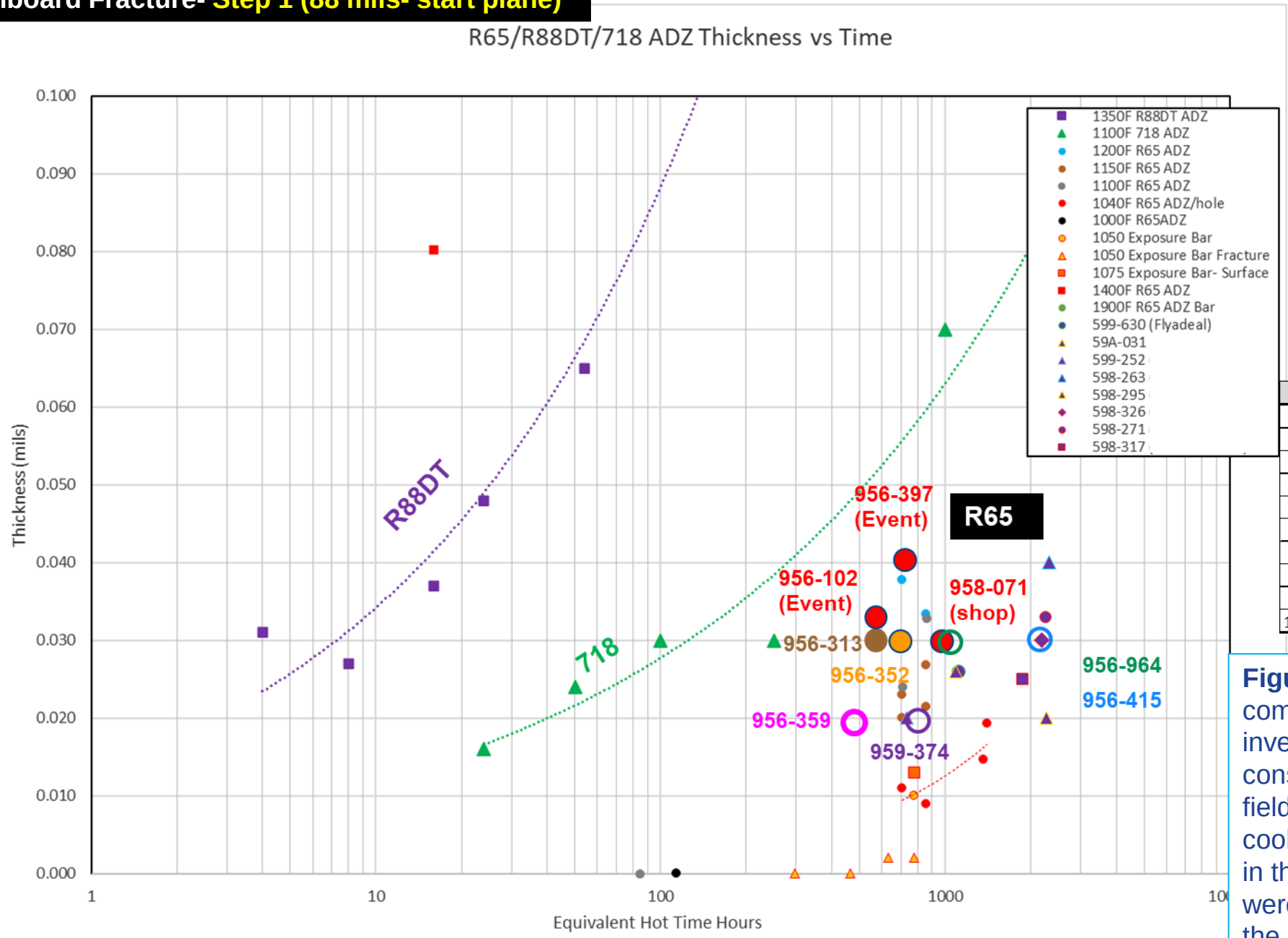


Figure 20: 1st step as-polished and etched micros showing that the origin region had approximately 1.7 mils of post-fracture smeared material, but no other material anomalies were observed and the alloy depletions zone (ADZ) in the undamaged forward radius was approximately 0.03 mils thick. The collet radius was approximately 45 mils, conforming to the drawing requirement, and the microstructure was consistent with properly processed R65 per C50TF133.

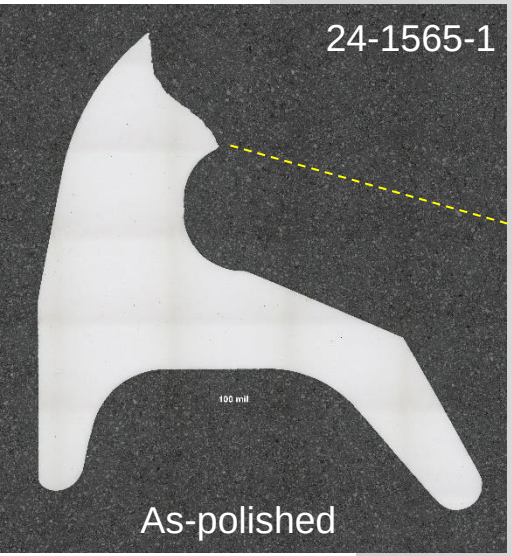


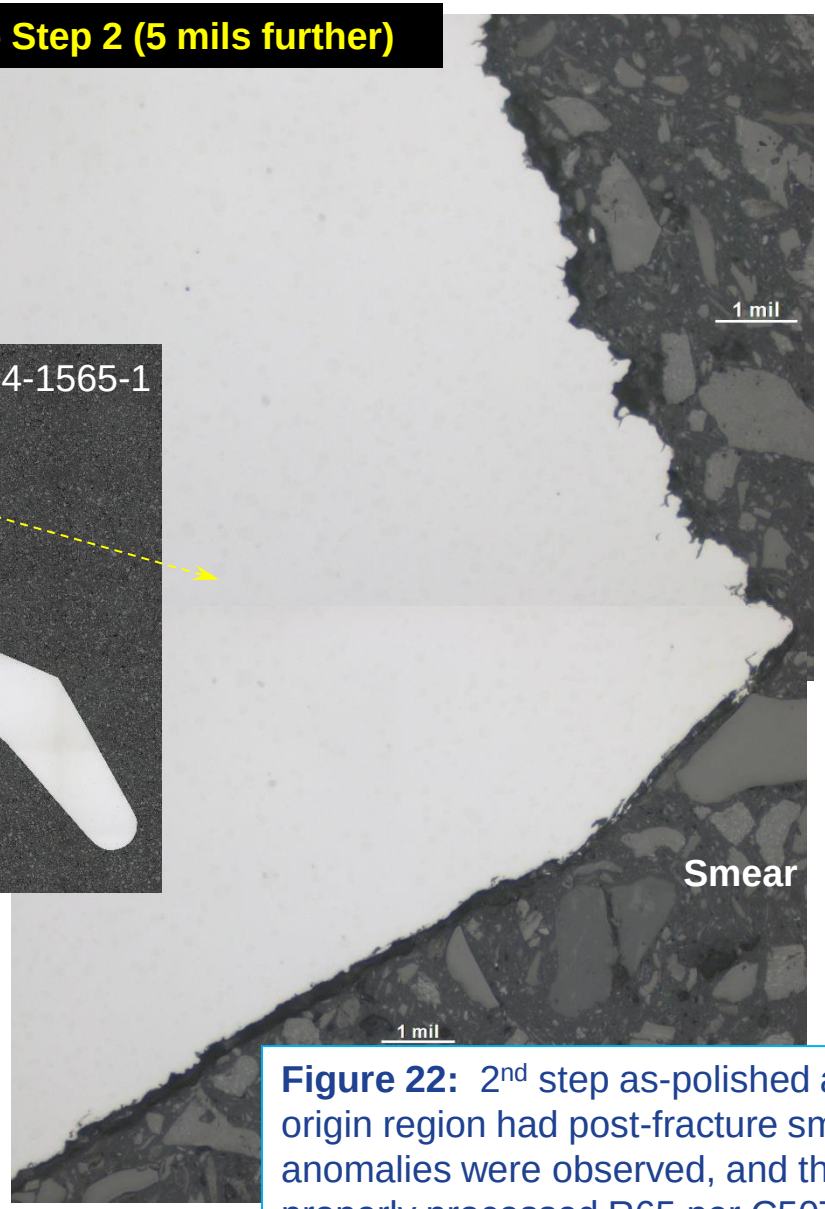
956-102 Retainer
P/N: 2383M99P02
S/N: TMT4TK46
CSN: 1,750→ ~583 Hot hours (20 min/cycle)
ADZ ~0.032

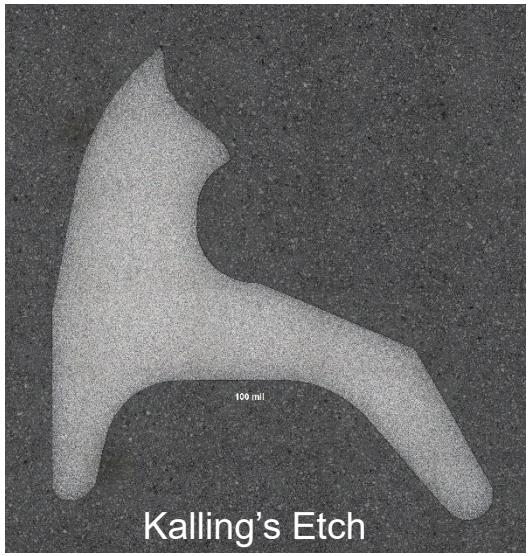
	S/N	Cycles	Time	ESN	Operator	Condition
1	TMT1JEP9	2046	8612	956-397		Dirty
2	TMT11CNF	3110	13826	958-071		Dirty
3	TMT1JM59	1441	11390	956-313		Dirty
4	TMT1JM56	2091	10579	956-352		Dirty
5	TMT4SY27	6464	24456	956-415		cleaned
6	TMT10NFL	2336	15287	959-374		cleaned
7	TMT5AN63	3506	29867	956-964		cleaned
8	TMT5AN49	3461	29664	956-963		cleaned
9	TMT4TE83	3738	15497	956-632		Dirty
10	TMT1JR26	1512	7324	956-359		cleaned

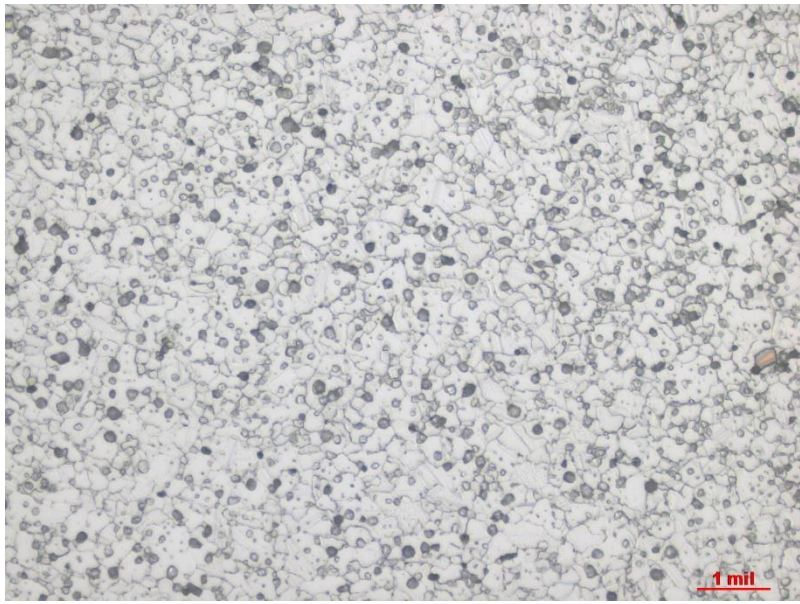
Figure 21: Based on limited R65 ADZ comparison data, the current part and 2 investigation retainers (large red circles) were consistent with operation near 1200°F. Other field retainers were in a similar range or slightly cooler. The solid circles show parts examined in the dirty condition, while the empty circles were cleaned at the shop (slight alteration of the surface).

Inboard Fracture- Step 2 (5 mils further)









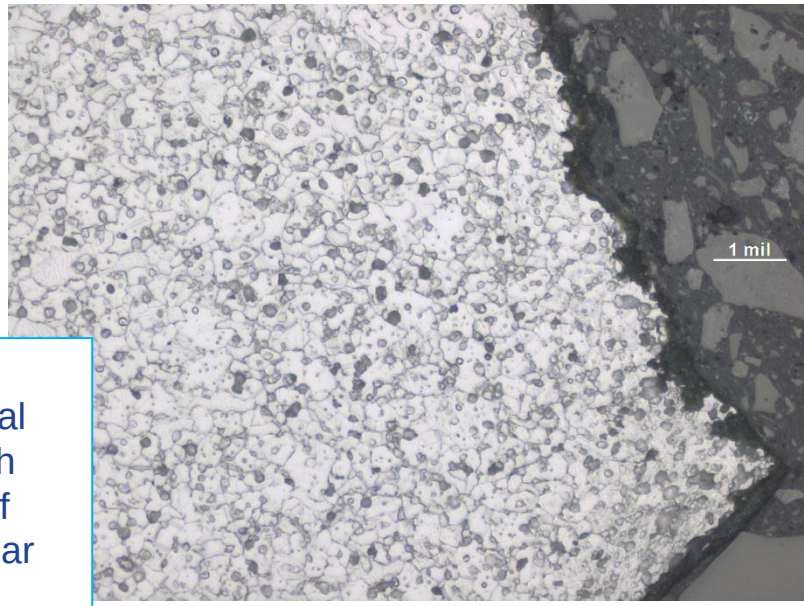
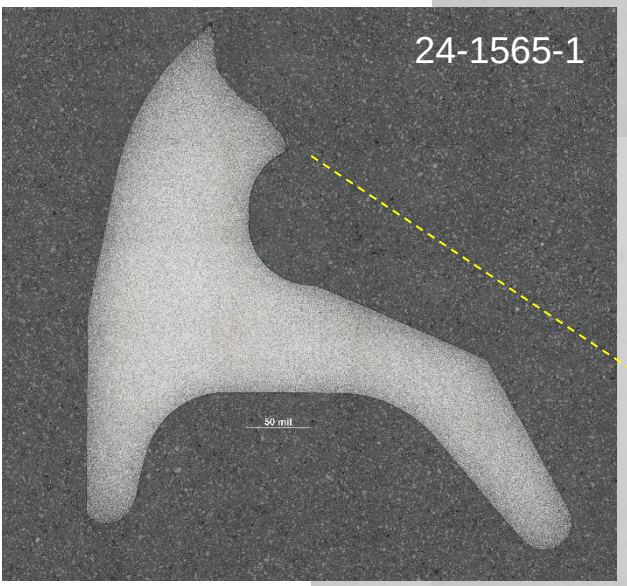
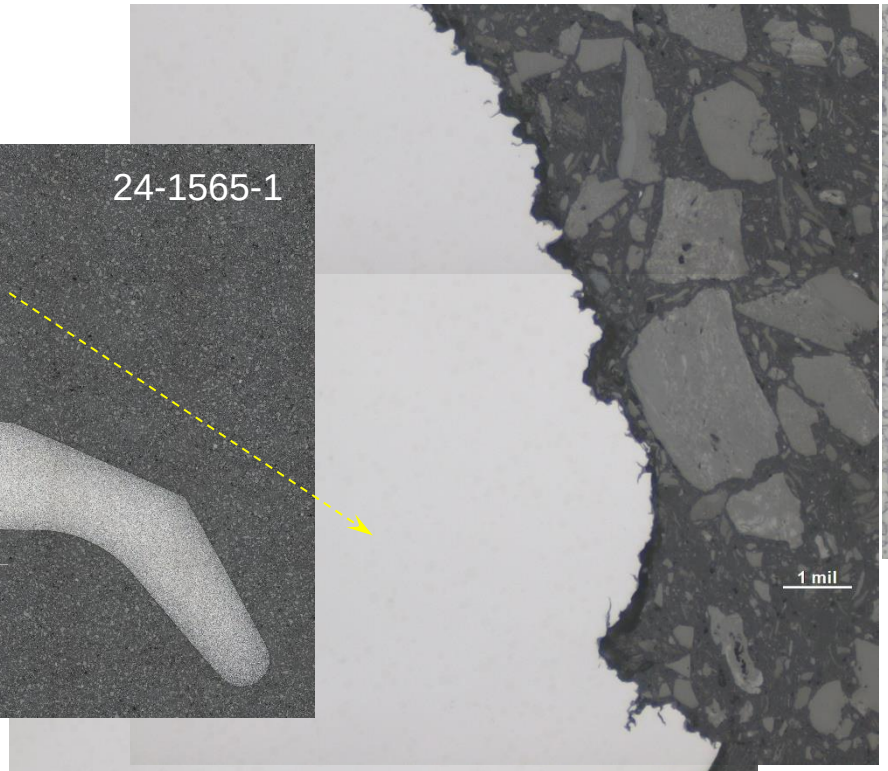
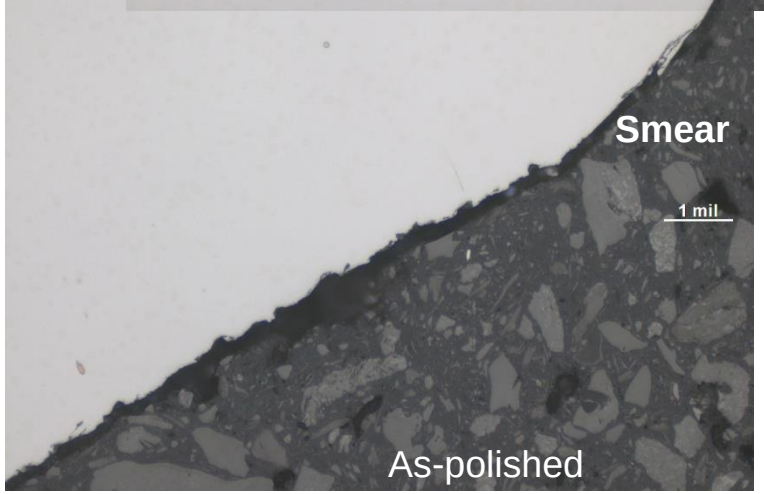


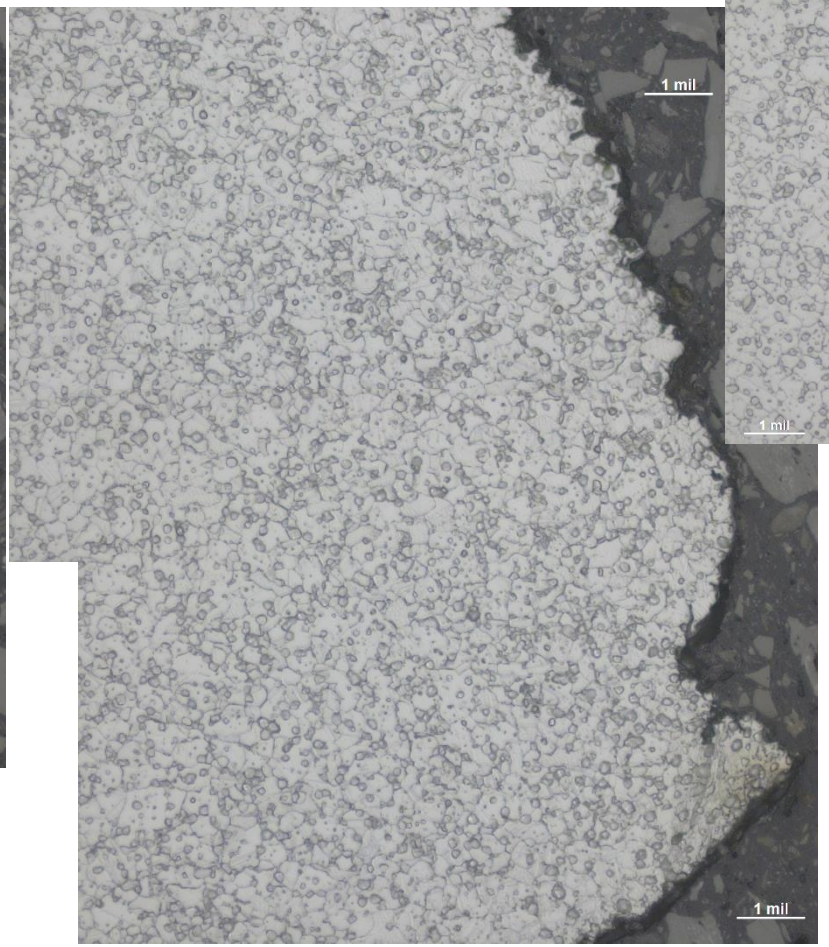
Figure 22: 2nd step as-polished and etched micros showing that the origin region had post-fracture smeared material, but no other material anomalies were observed, and the microstructure was consistent with properly processed R65 per C50TF133, with an average grain size of approximately ASTM 10.5. The fracture progressed in an intergranular manner, consistent with fatigue hold time crack growth.

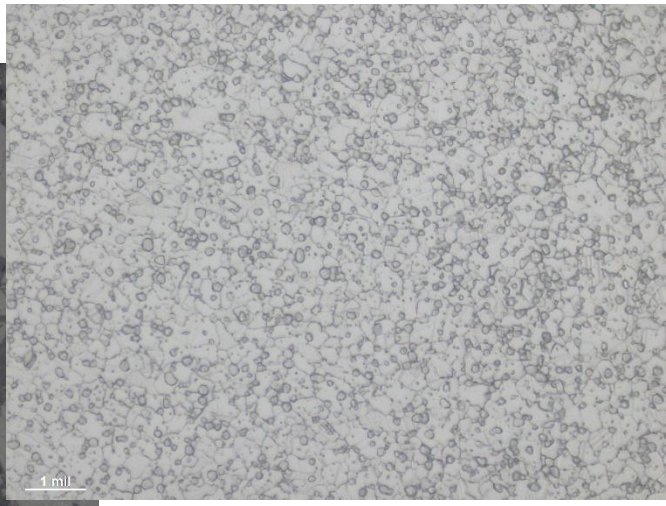
Inboard Fracture- Step 3 (5 mils further) at anomaly edge







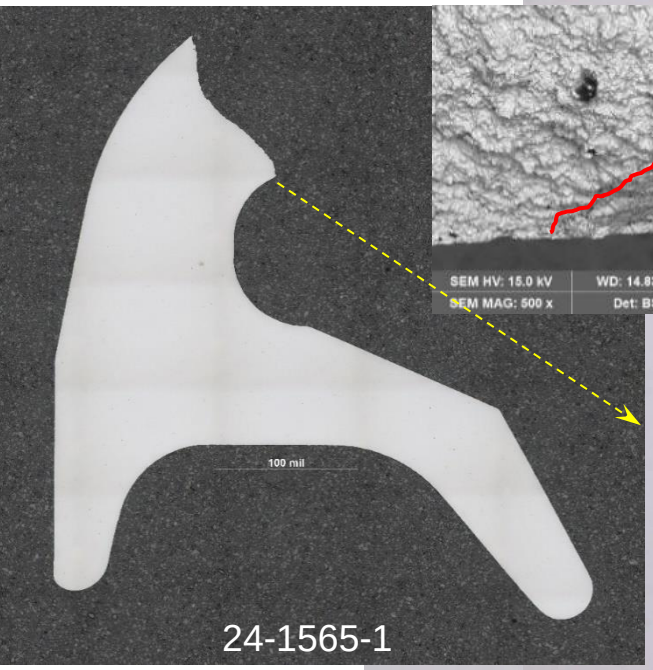


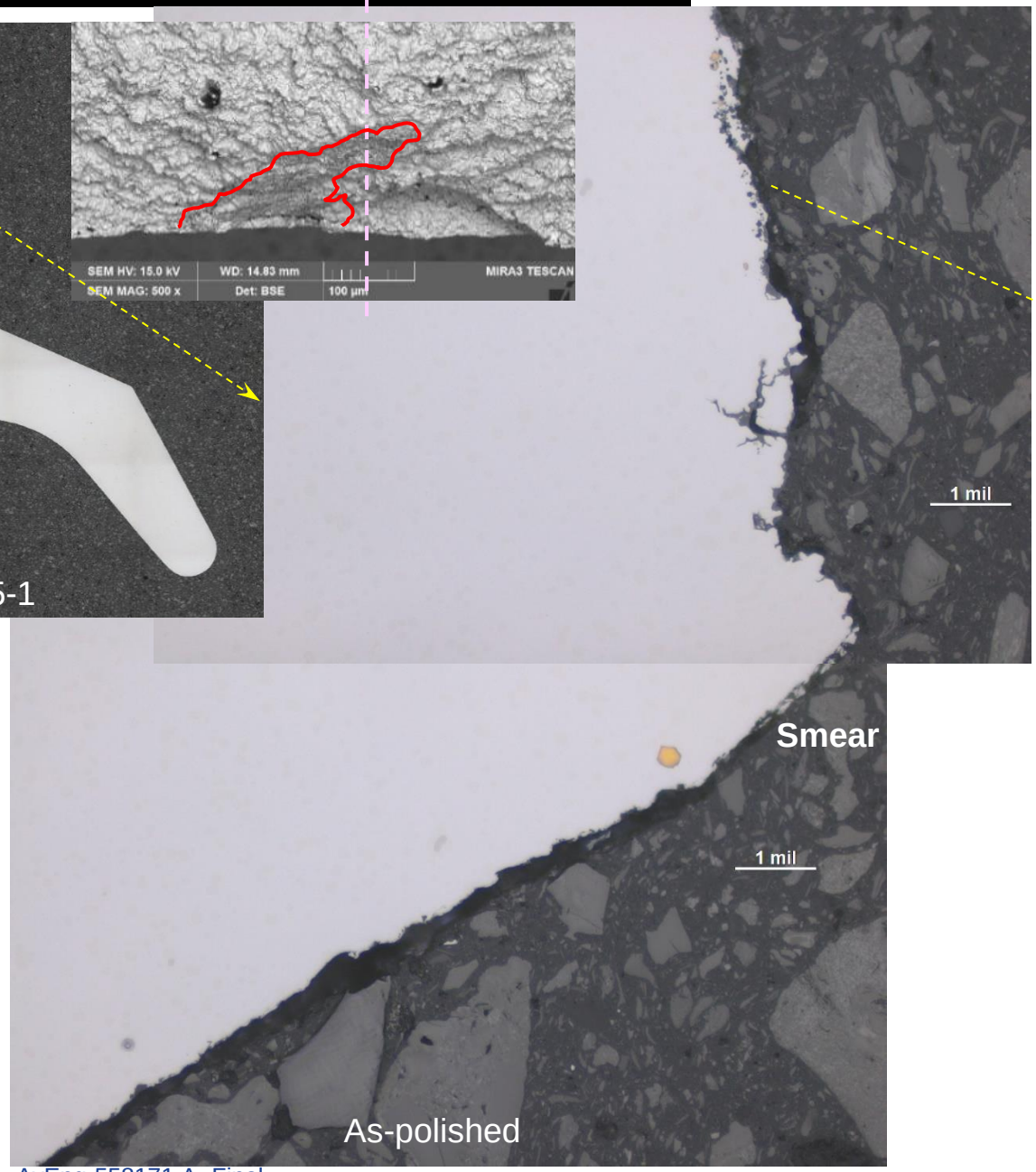


Kalling's Etch

Figure 23: 3rd step as-polished and etched micros at the edge of the origin showing it had post-fracture smeared material, but no other material anomalies were observed, and the microstructure was consistent with properly processed R65 per C50TF133, with an average grain size of approximately ASTM 10.5.

Inboard Fracture- Step 4 (3 mils further) INTO ANOMALY





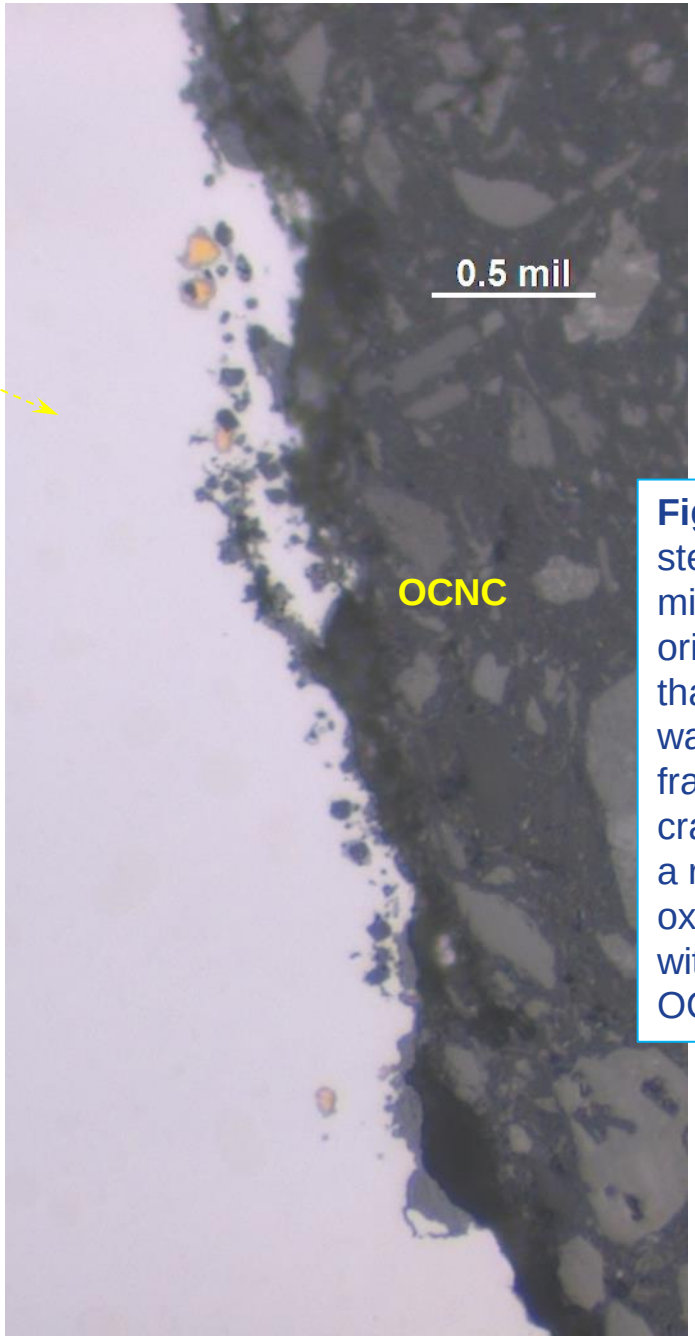
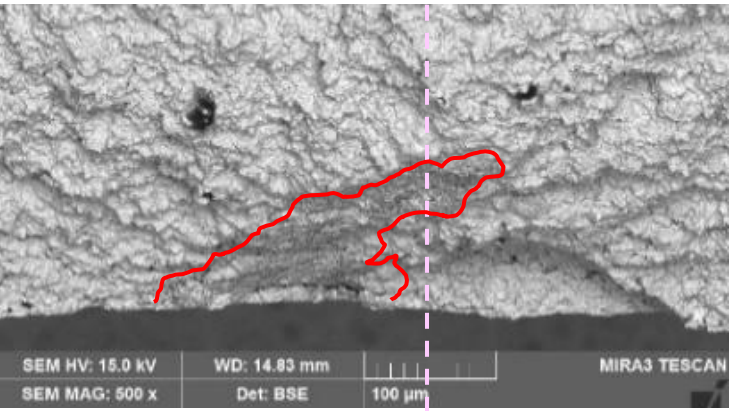
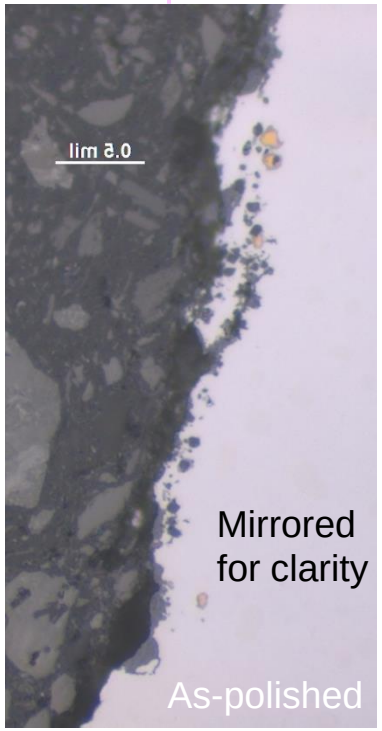
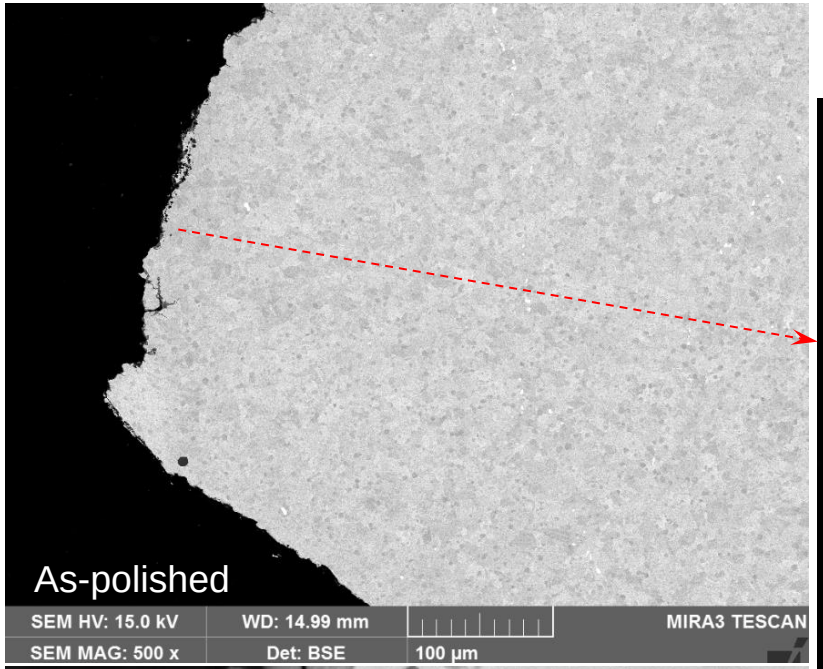


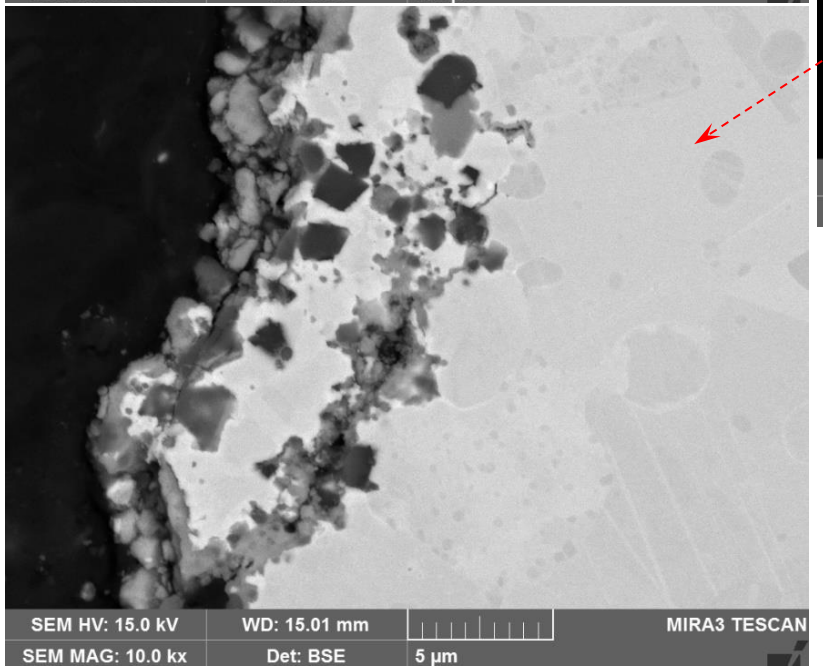
Figure 24: 4th[rd] step as-polished micros through the origin area showing that the surface itself was smeared (post-fracture), but the crack extended from a region of mixed oxides consistent with an inherent OCNC inclusion.

Inboard Fracture- Step 4 (3 mils further) INTO ANOMALY









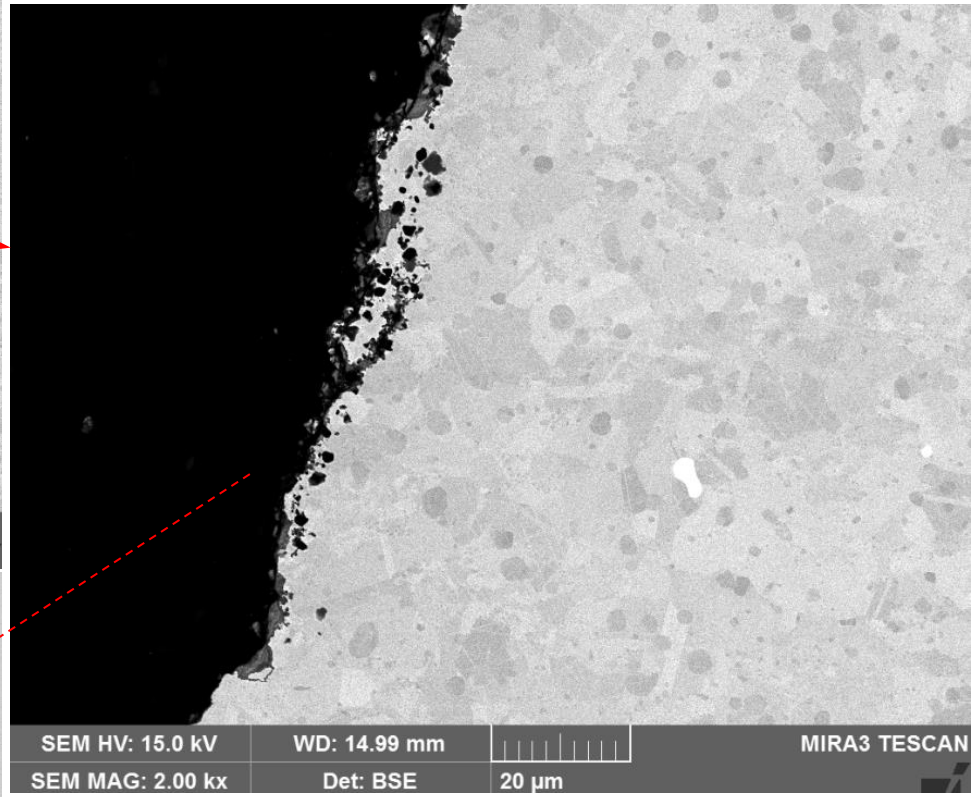


Figure 25: Views of the same micro in the as-polished condition in the SEM showing a conforming microstructure, but the origin area had mixed-oxides, consistent with an inherent OCNC (see next page).

Inboard Fracture- Step 4 (3 mils further) INTO ANOMALY

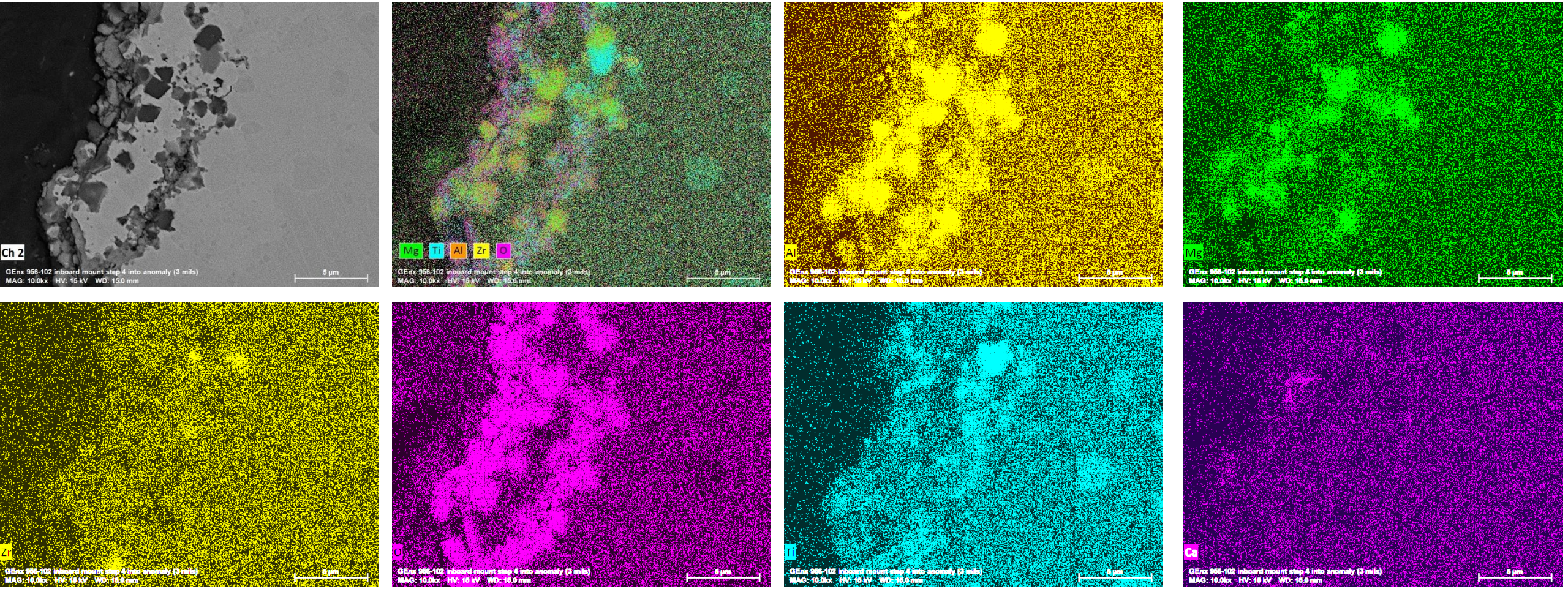
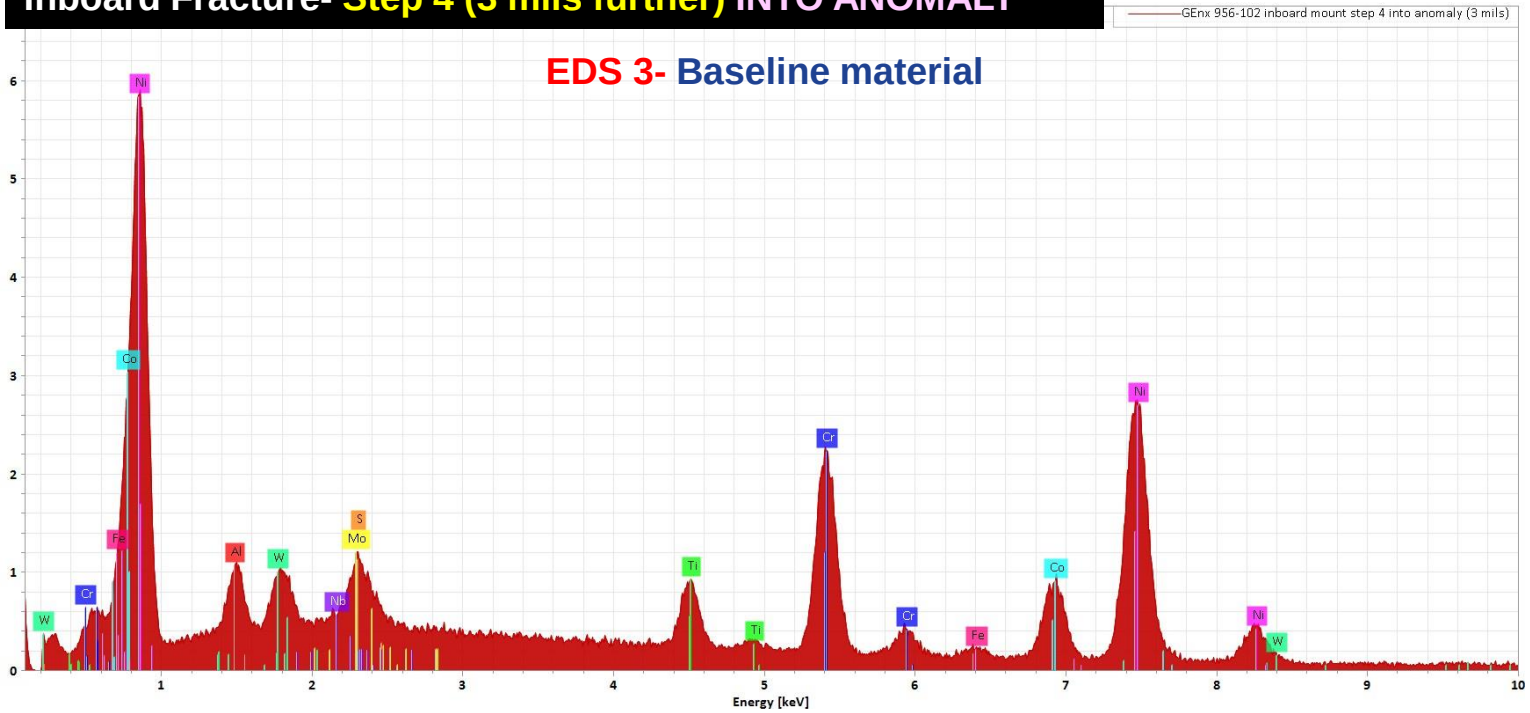


Figure 26: EDS dot maps taken across the origin area showed a region of mixed oxides rich in Al, Mg, Zr, Ti, O, consistent with an inherent OCNC inclusion.

Inboard Fracture- Step 4 (3 mils further) INTO ANOMALY

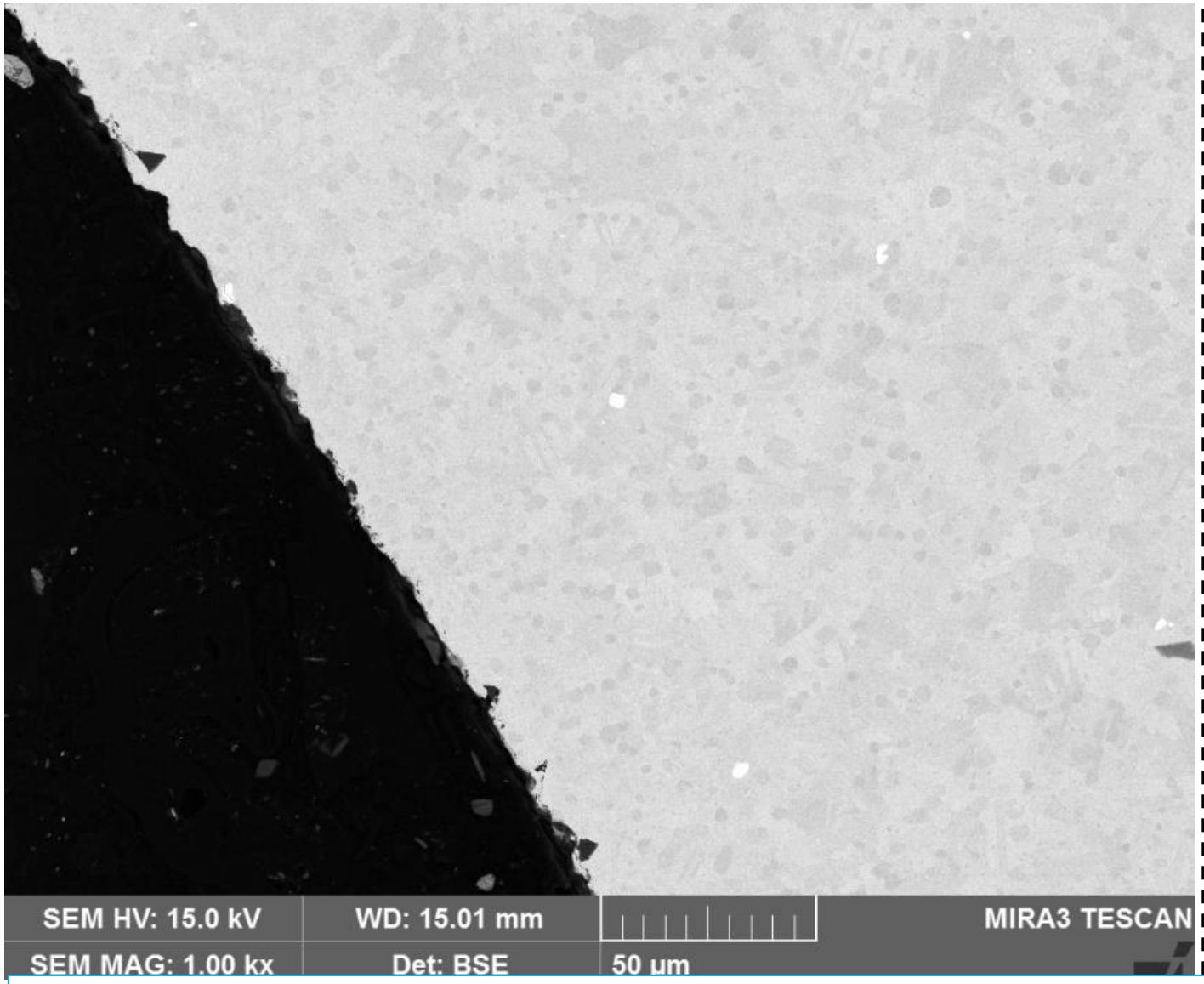


GEnx 956-102 inboard mount step 4 into anoma

Element	At. No.	Net	Mass [%]	Mass Norm. [%]		wt% req
Aluminium	13	4484	1.82	1.90	Al	2.1
Titanium	22	6651	3.86	4.03	Ti	3.7
Chromium	24	21957	15.84	16.52	Cr	16.0
Iron	26	947	0.97	1.01	Fe	1.2
Cobalt	27	9065	12.84	13.39	Co	13.0
Nickel	28	31507	53.05	55.34	Ni	56.4
Niobium	41	942	0.47	0.49	Nb	0.7
Molybdenum	42	7350	3.65	3.81	Mo	4.0
Tungsten	74	5308	3.36	3.50	W	4.0
		Sum	**95.86**	**100.00**		

Figure 27: An EDS spectrum and semi-quantitative readings were consistent with the requirement of R65 per C50TF133.

Inboard Fracture- Step 4 (3 mils further) INTO ANOMALY



GEAR work: R65 GEnx-2B HPT Stage 2 disk Study

T Vishwanath, Sachin Nalawade, Kaustubh Venkatraman, Mallikarjun Karadge, Ram Oruganti

956-102 Retainer
P/N: 2383M99P02
S/N: TMT4TK46
CSN: 1,750→ ~583 Hot hours

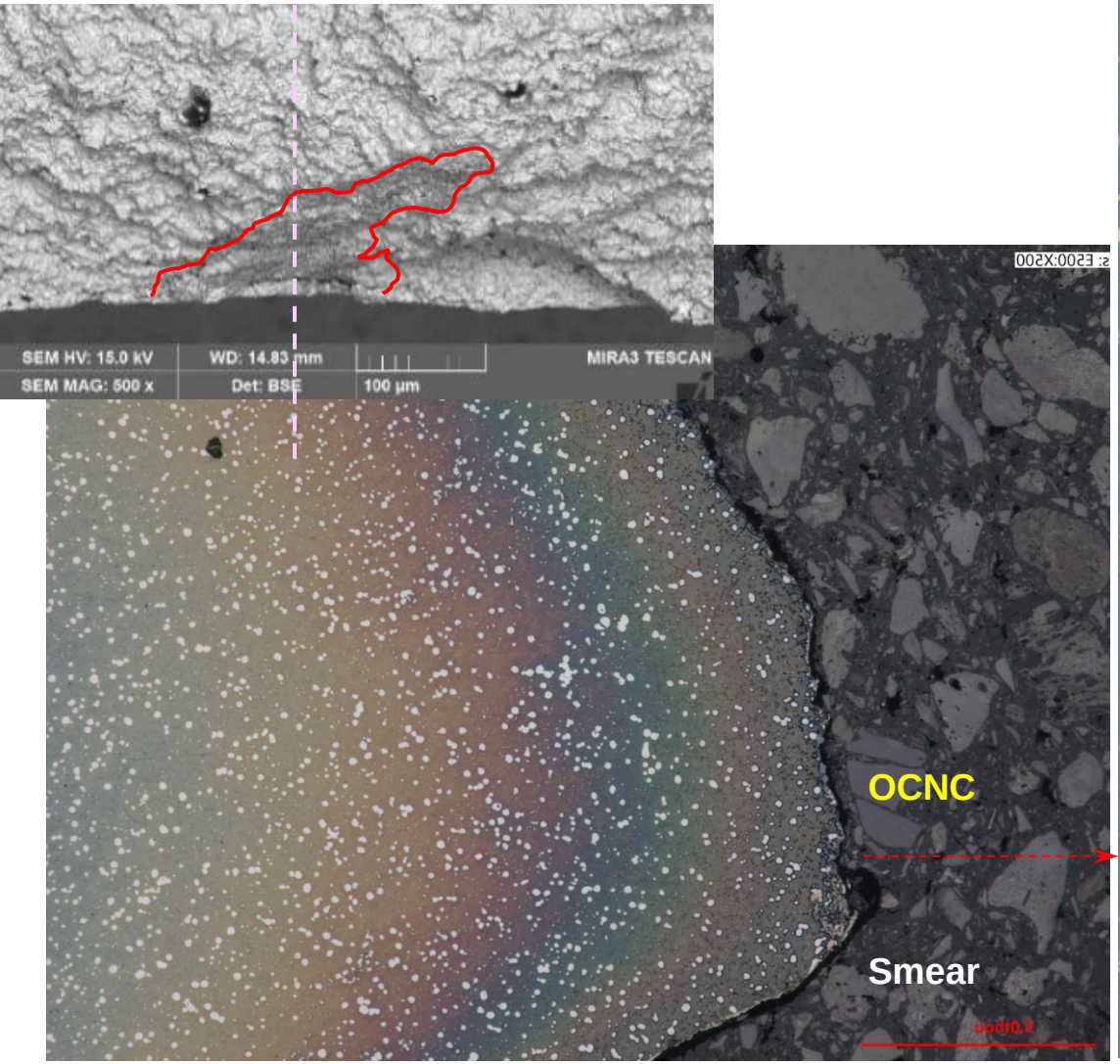
GB phases in R65 and R88 during isothermal exposure

Not observed | Observed | No data available yet

Temp	Time (Hr)						
	10	50	100	250	500	1000	2000
1100F	R88	R88	R88	R88	R88	R88	R88
	R65	R65	R65	R65	R65	R65	R65
1200F	R88	R88	R88	R88	R88	R88	R88
	R65	R65	R65	R65	R6	R65	R65
1300F	R88	R88	R88	R88	R88	R88	R88
	R65	R65	R65	R65	R65	R65	R65
1400F	R88	R88	R88	R88	R88	R88	R88
	R65	R65	R65	R65	R65	R65	R65

Figure 28: Work performed by GE Aerospace Research showed that there were no grain boundary precipitated phases observed, consistent with the part operating near/below 1200°F assuming 583 hot hours of hot time (20 min/cycle).

Inboard Fracture- Step 5 (6 mils further) INTO ANOMALY



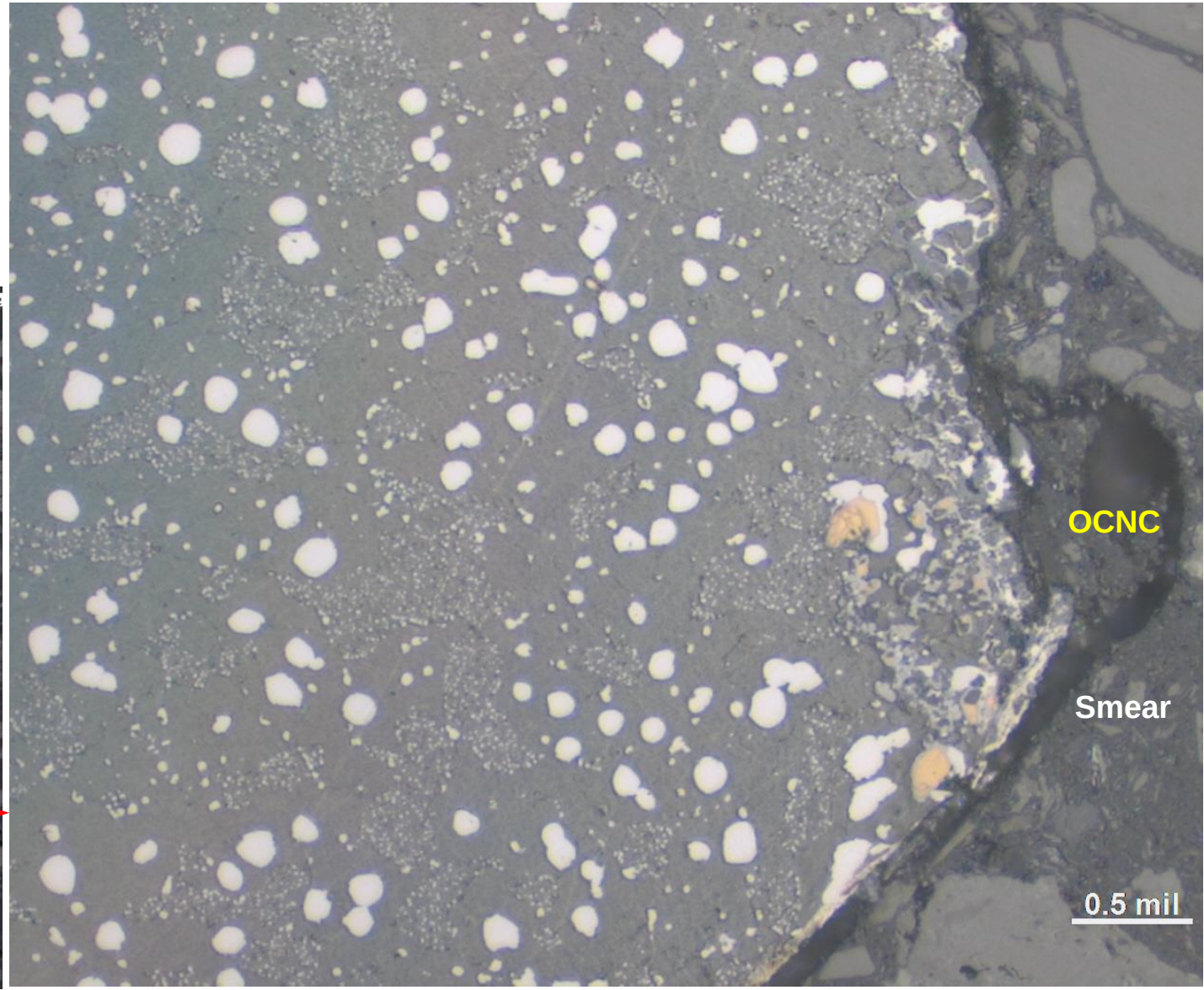


Figure 29: 5th step etched micro through the origin area showing that the surface itself was smeared, but the crack extended from a region of mixed oxides consistent with an inherent OCNC inclusion that was approximately 0.5 mils thick in the plane of polish.

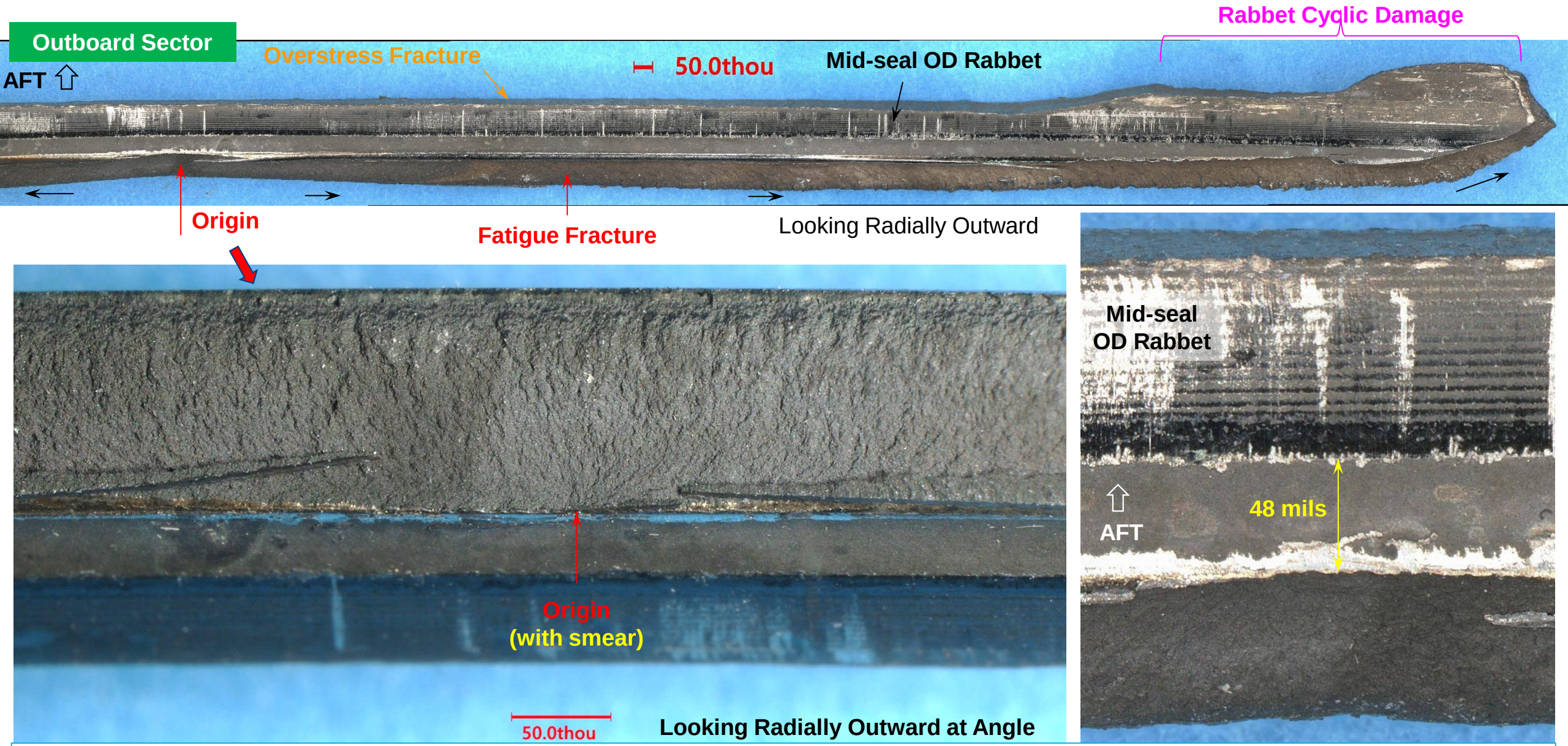
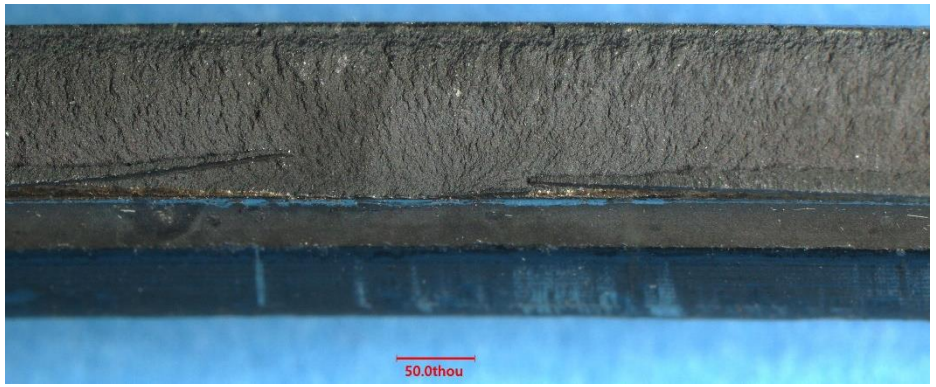
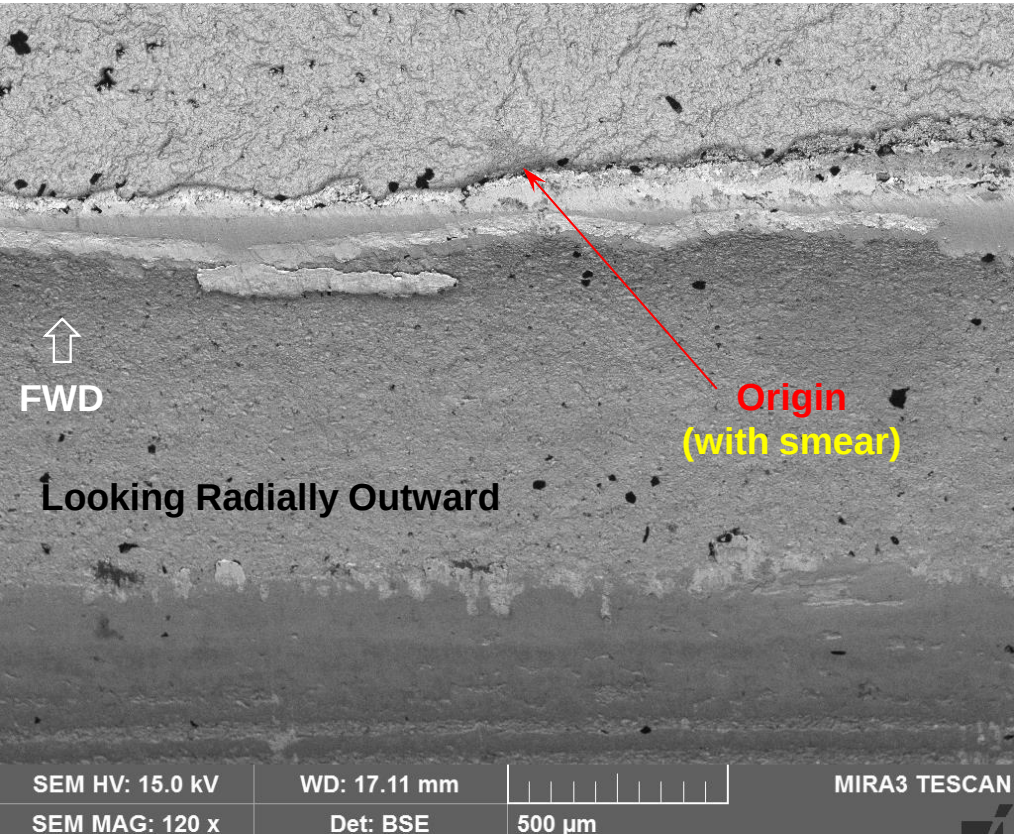


Figure 30: Optical views of the outboard fracture half showing a similar single point origin at the surface, but the surface itself had more pronounced post-fracture smearing (shiny). The origin area was approximately 48 mils forward of the mid-seal OD rabbet. Also visible are the secondary fracture plane in the region of the disk rabbet undercut radius with features consistent with overstress (orange) and cyclic tensile/hold time (pink).

Outboard Sector- Origin Area





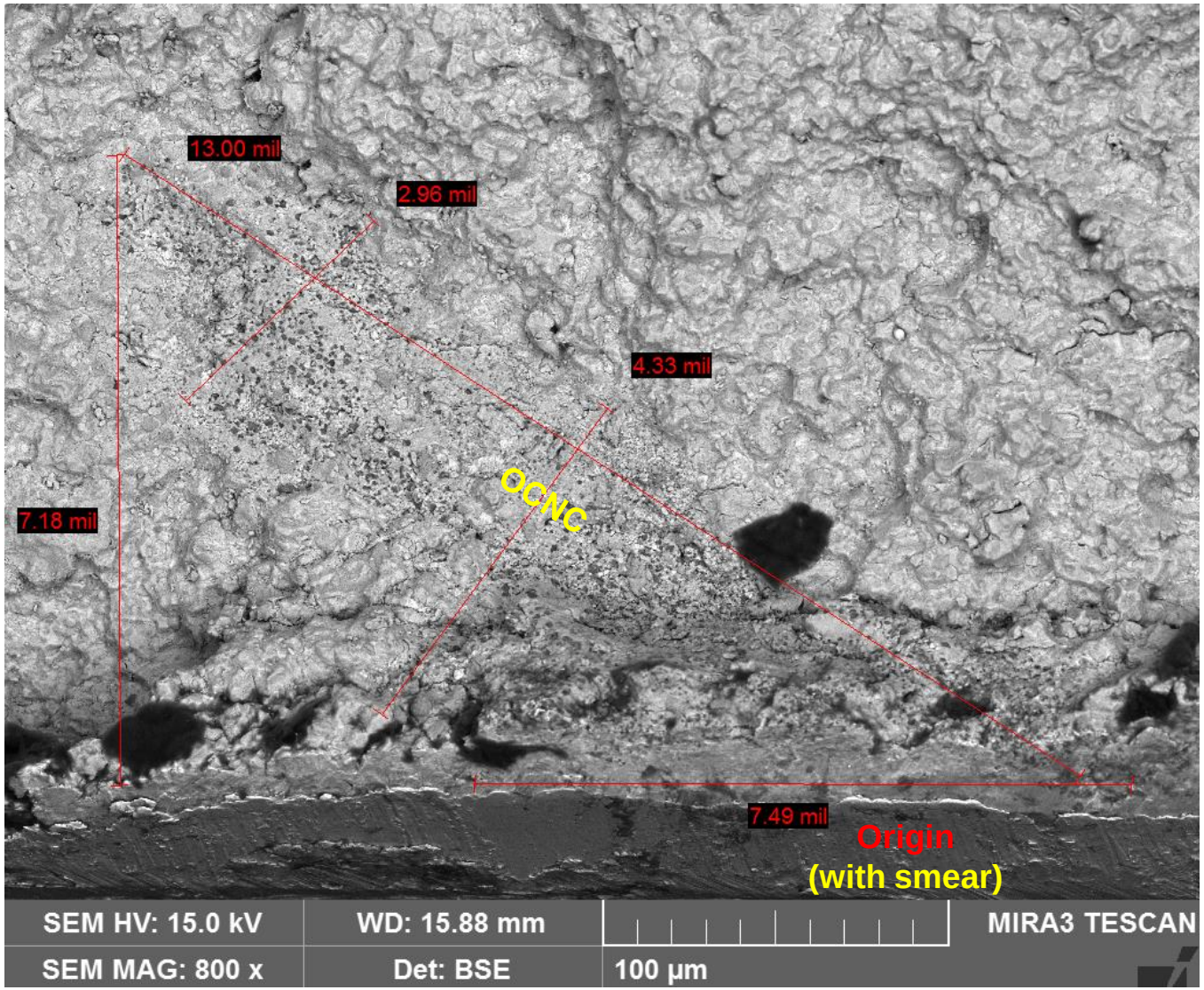
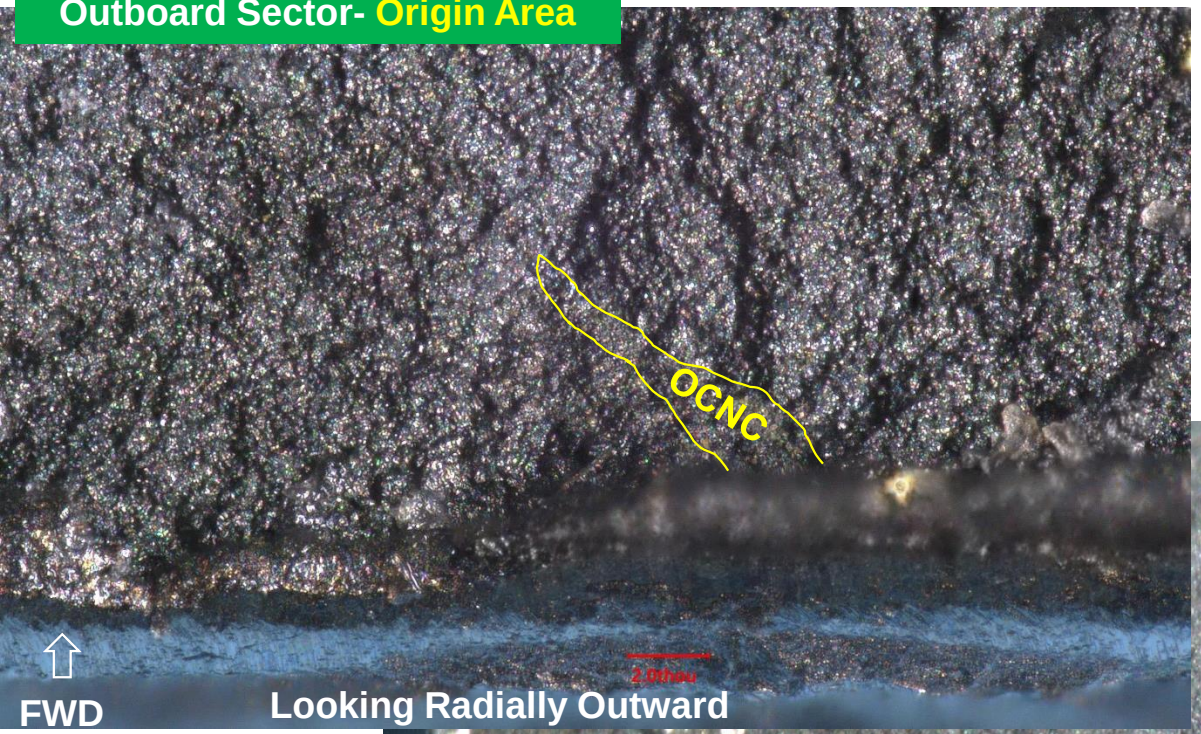


Figure 31: SEM views of the mating outboard origin area showing that it had the similar region of mixed oxides and was estimated to be approximately **13 mils** long with post-fracture smearing observed at the surface.

Outboard Sector- Origin Area



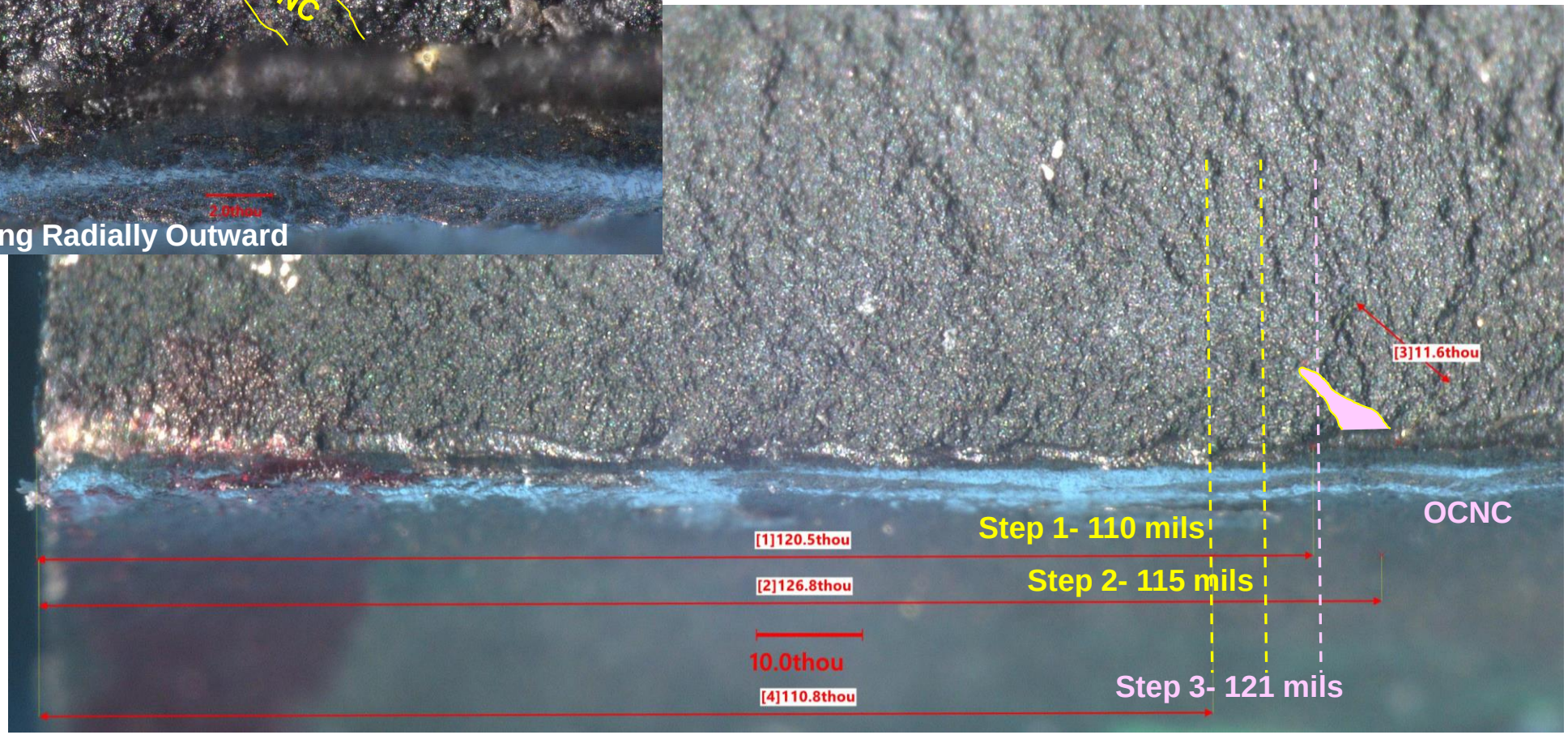


Figure 32: Optical views of the outboard fracture surface at/near the origin showing where step polishing was performed.

Outboard Sector- STEP 1- 10 mils from anomaly

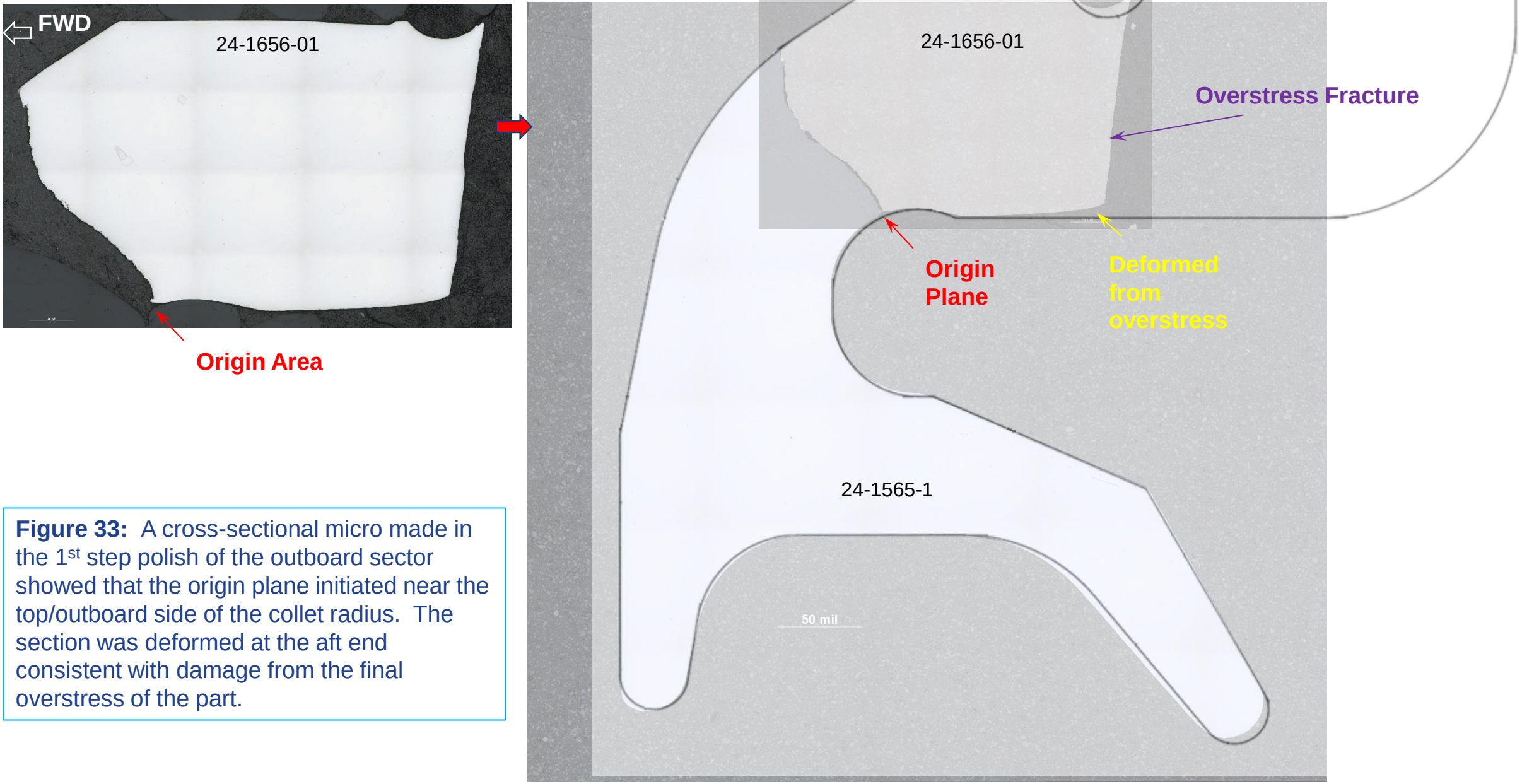
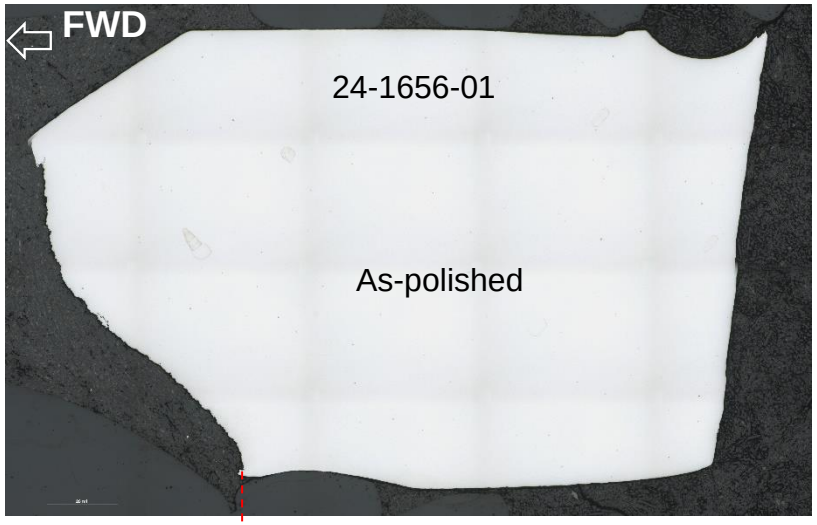
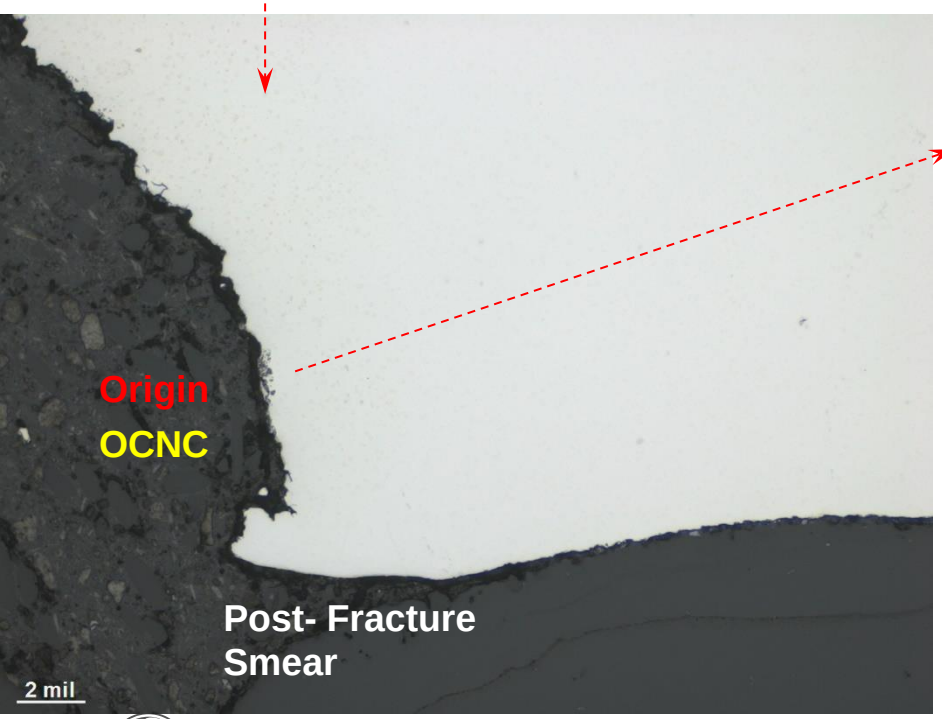
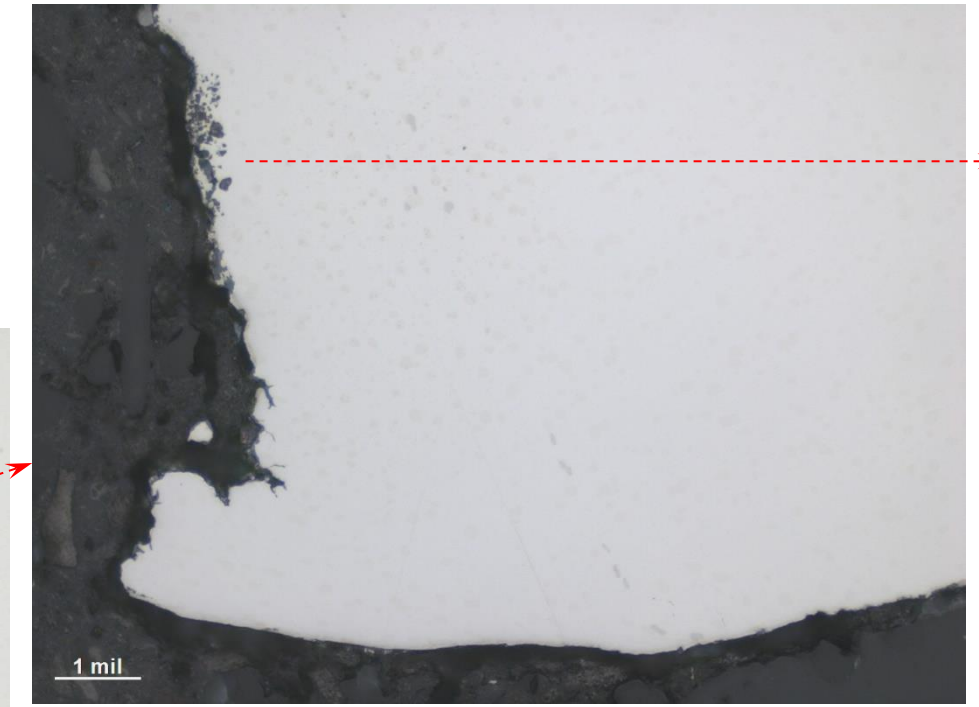


Figure 33: A cross-sectional micro made in the 1st step polish of the outboard sector showed that the origin plane initiated near the top/outboard side of the collet radius. The section was deformed at the aft end consistent with damage from the final overstress of the part.

Outboard Sector- STEP 3 ~2 mils into anomaly







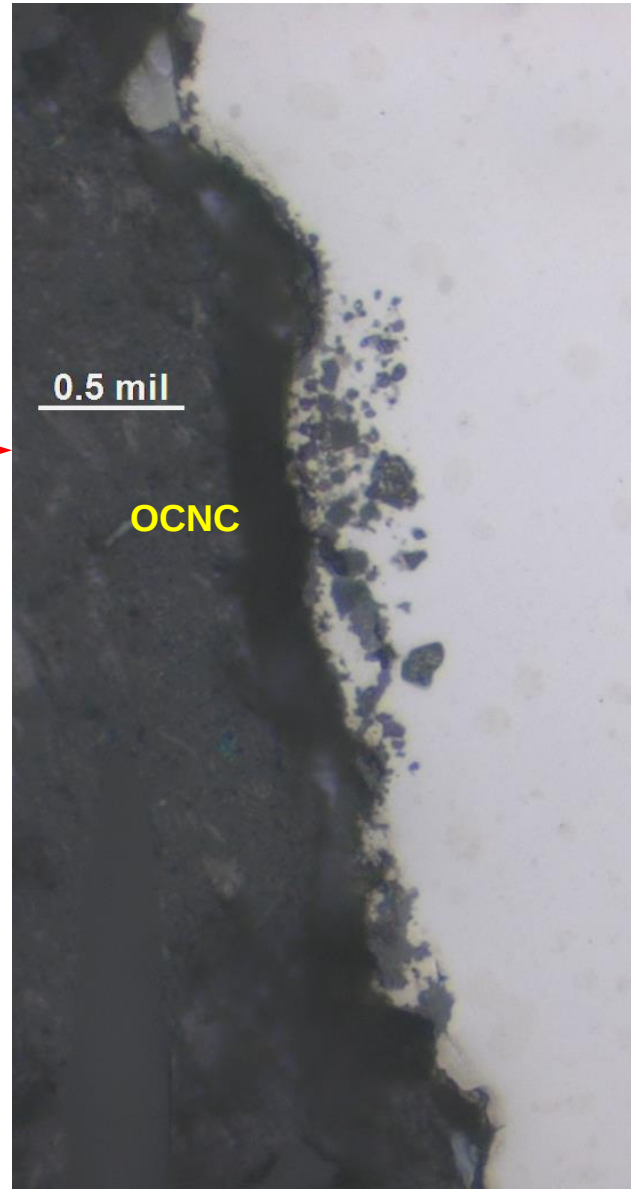
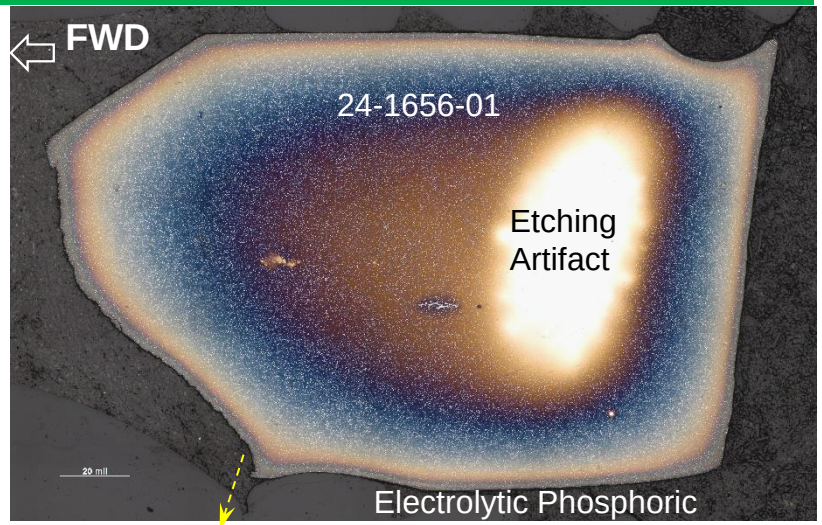
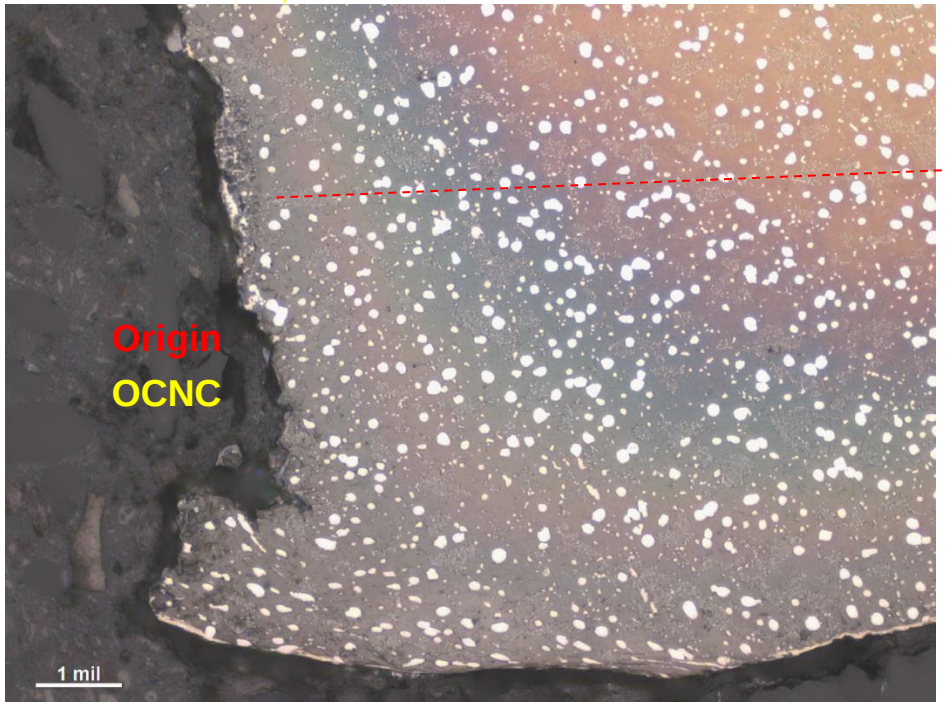


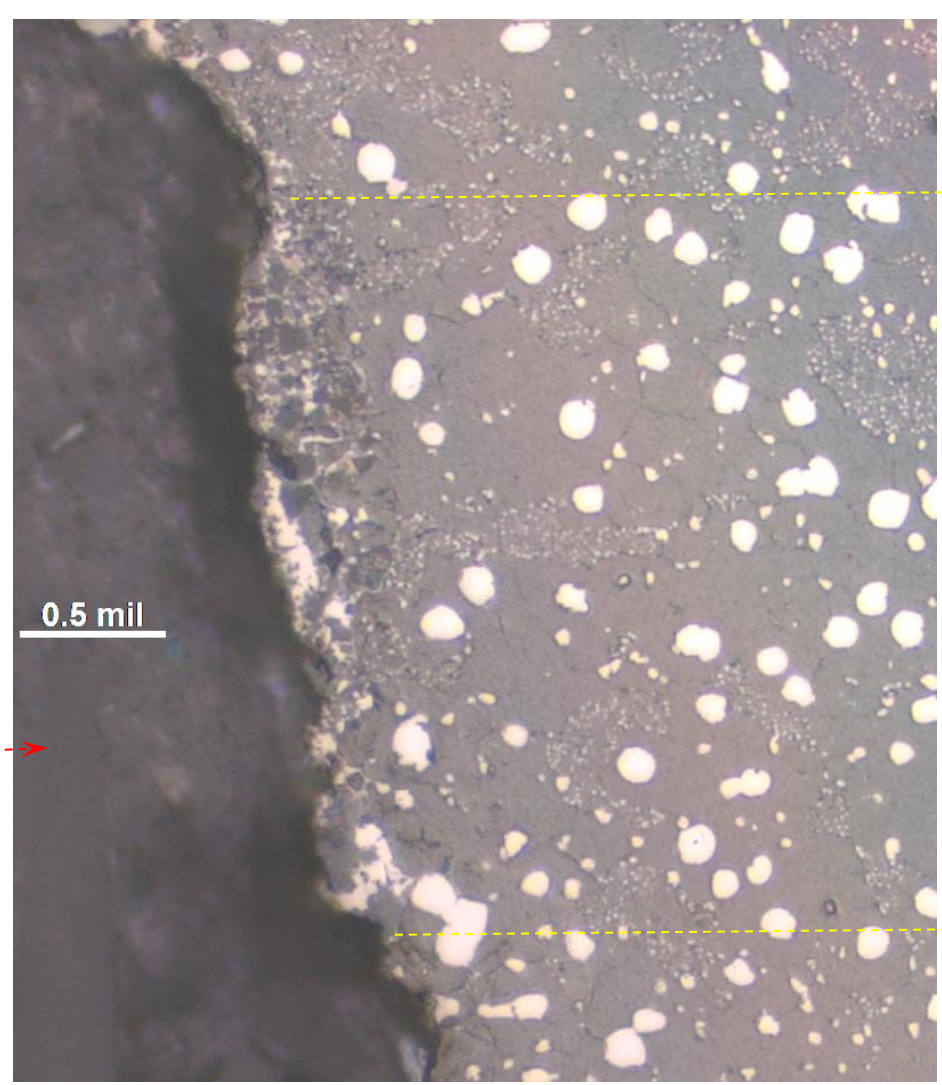
Figure 34: A cross-sectional micro made across the outboard mating origin half showed that that the surface itself was smeared, but the crack extended from a region of mixed oxides consistent with an inherent OCNC inclusion that was approximately 0.5 mils thick in the plane of polish.

Outboard Sector- STEP 3 ~2 mils into anomaly

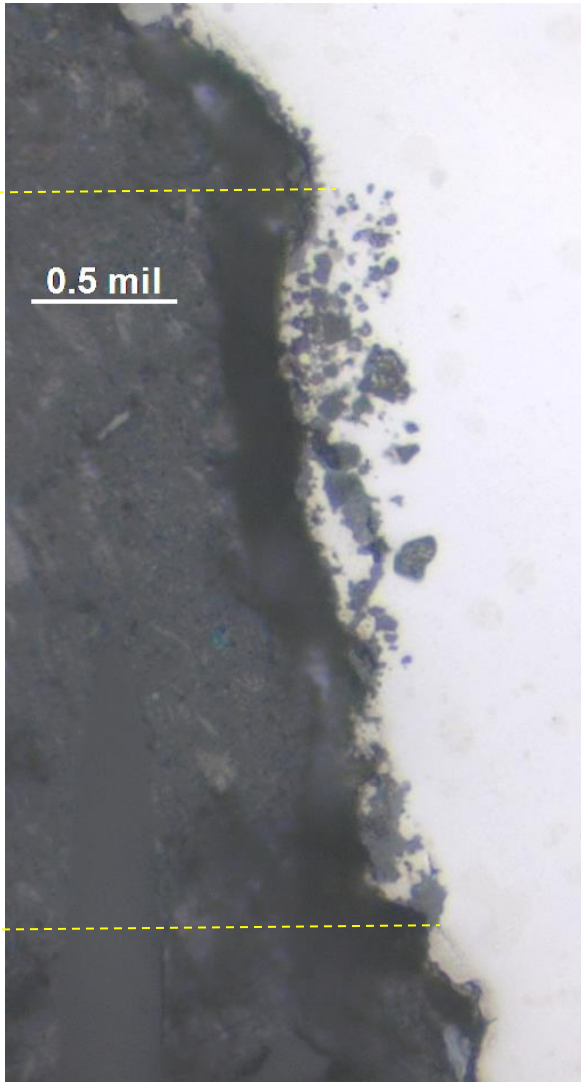




Post- Fracture Smear



Electrolytic Phosphoric



As-polished

Figure 35: Etched views of the origin area showing mixed oxides consistent with an inherent OCNC inclusion.

Outboard Sector- Rabbet

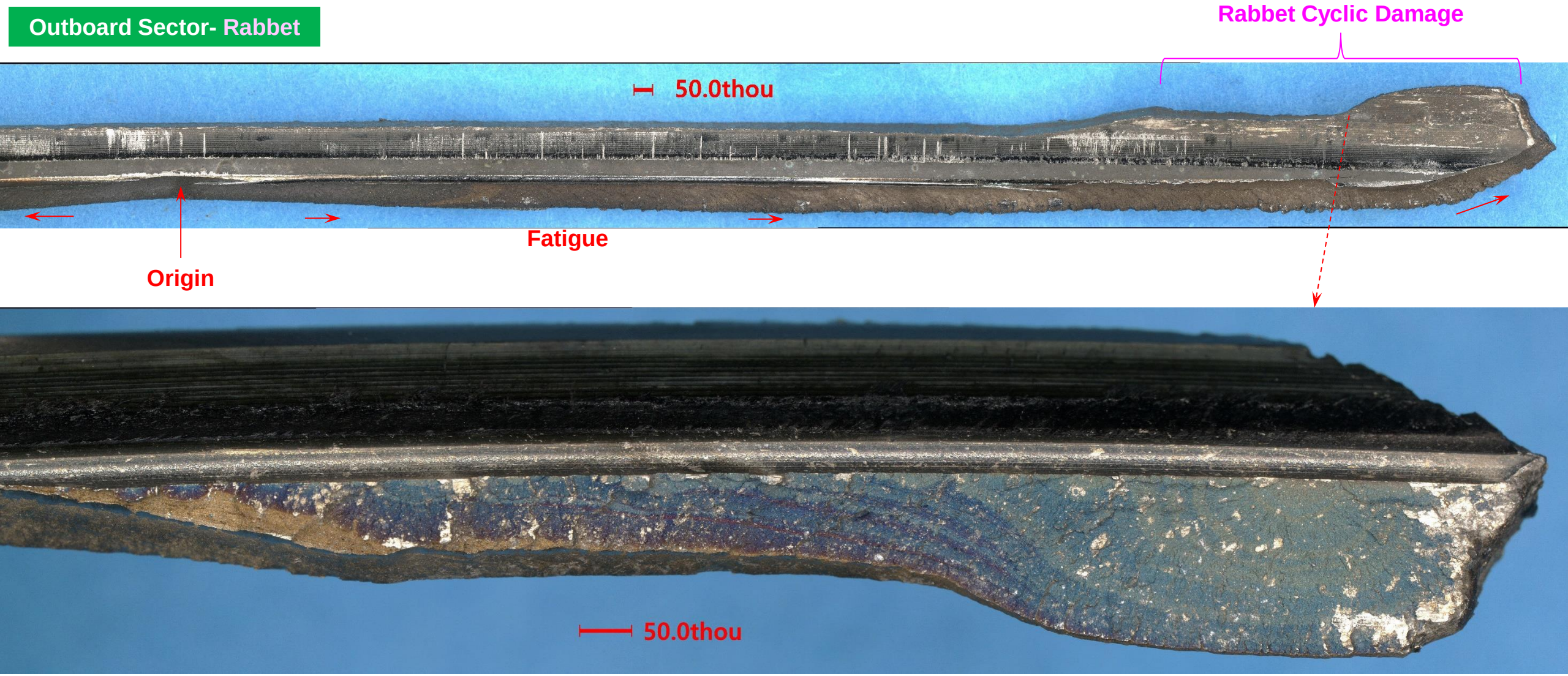
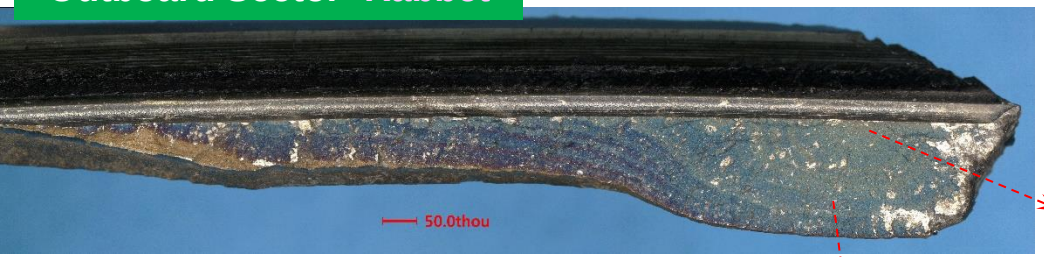
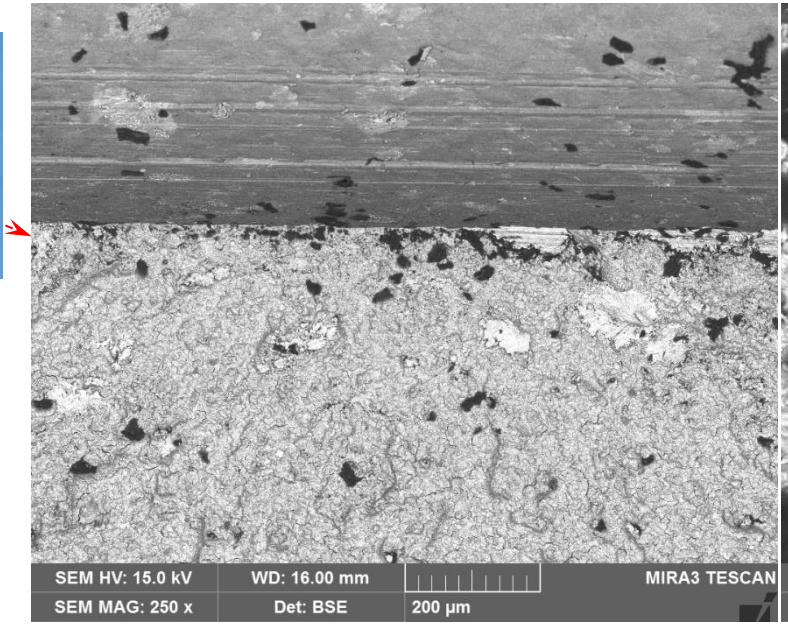
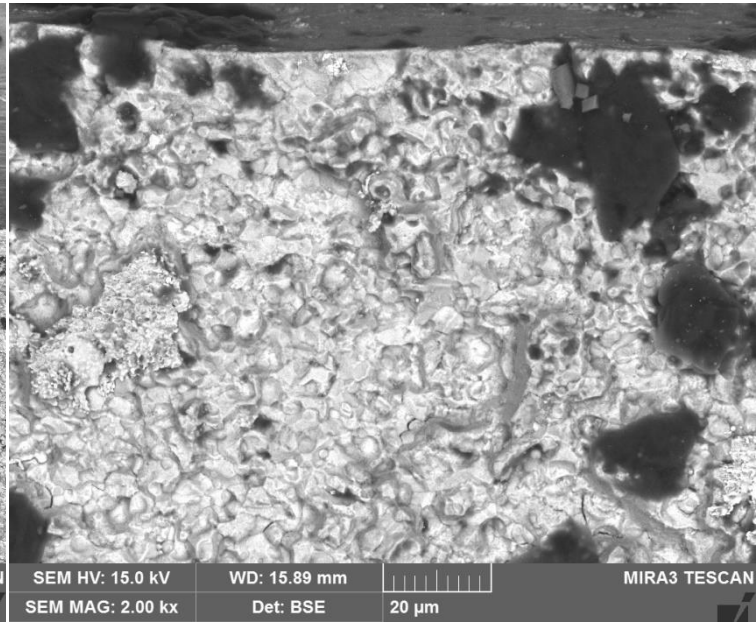


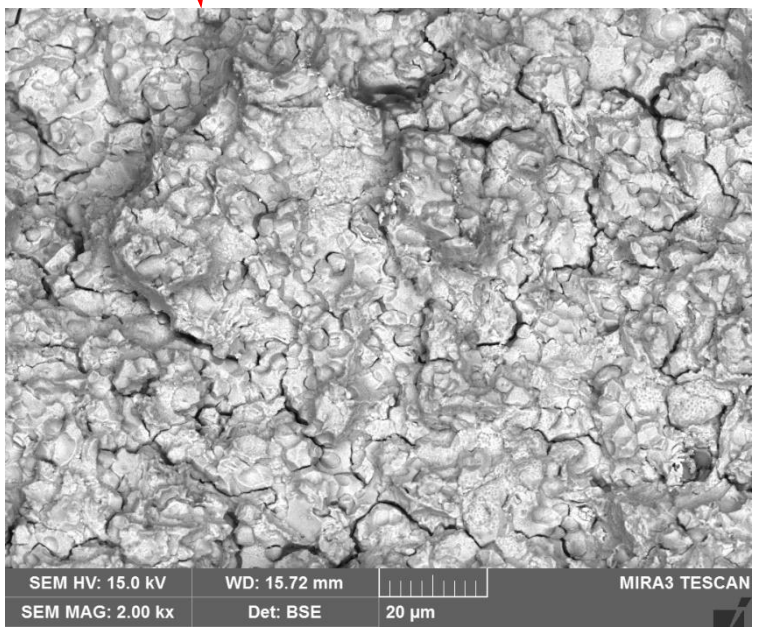
Figure 36: Optical image showing that near the end of the stable fatigue region (red), there was additional cracking extending from the disk rabbet undercut radius and growing toward the ID. The region had multiple origins and had progression/beach marks, consistent with secondary cyclic hold-time/tensile cracking (see following slides).

Outboard Sector- Rabbet









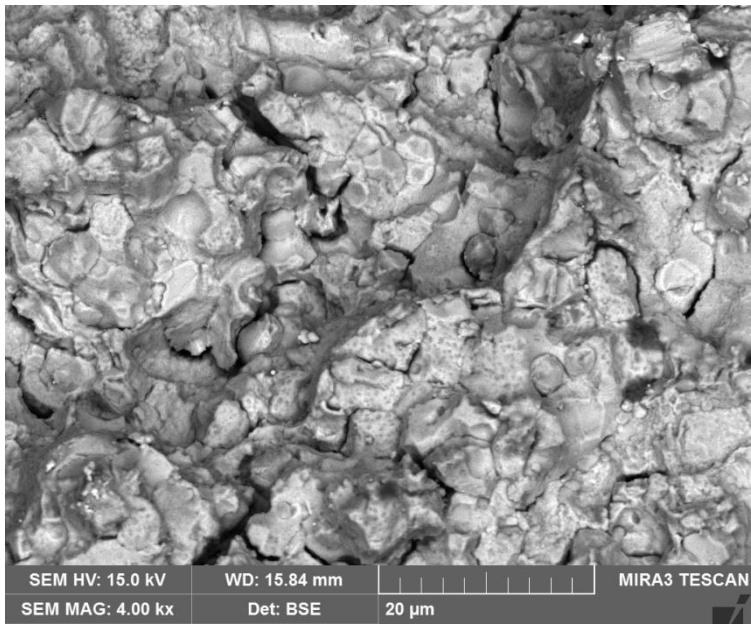
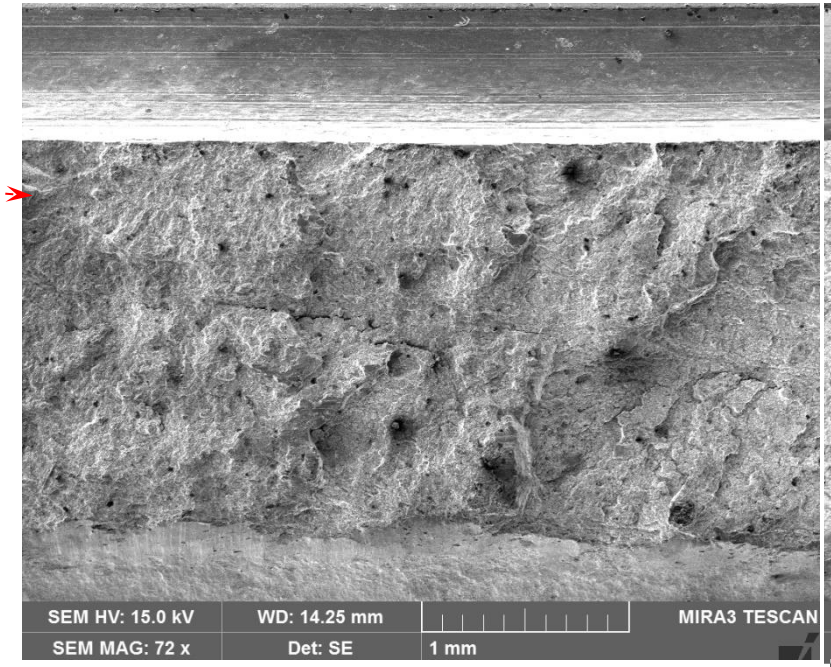
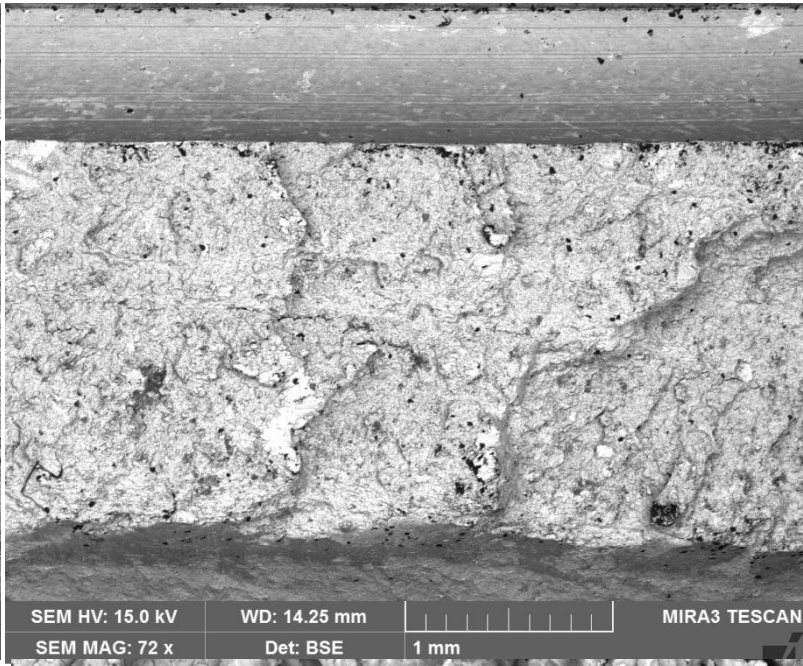


Figure 37: The OD rabbet undercut region with beach marks was examined in the SEM and shown to be fully intergranular in the larger thumbnail-shaped region, consistent with secondary cyclic hold-time damage.

Outboard Sector- Rabbet





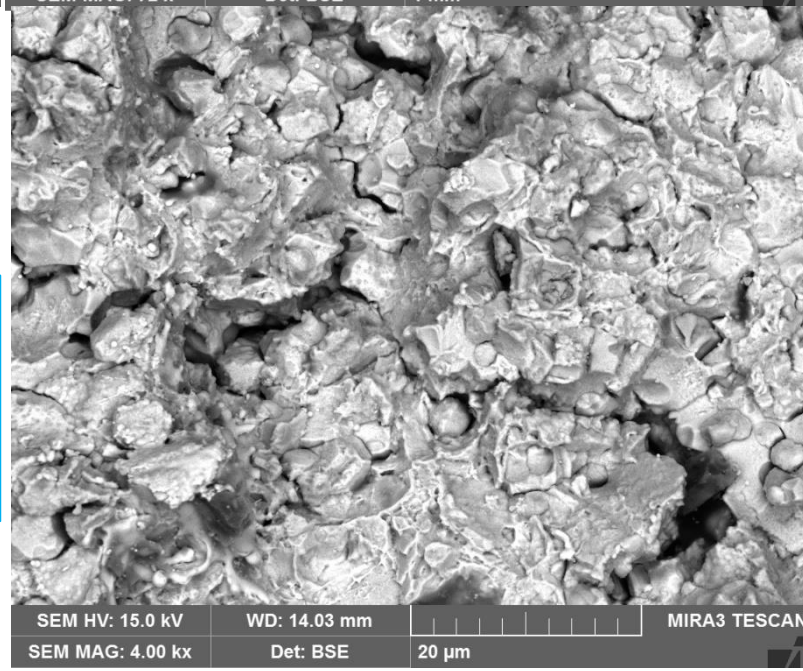


Figure 38: Moving toward one of the smaller thumbnails in the OD rabbet radius beach mark region revealed a combination of intergranular and ductile dimple regions, consistent with secondary cyclic tensile/hold time fatigue region.

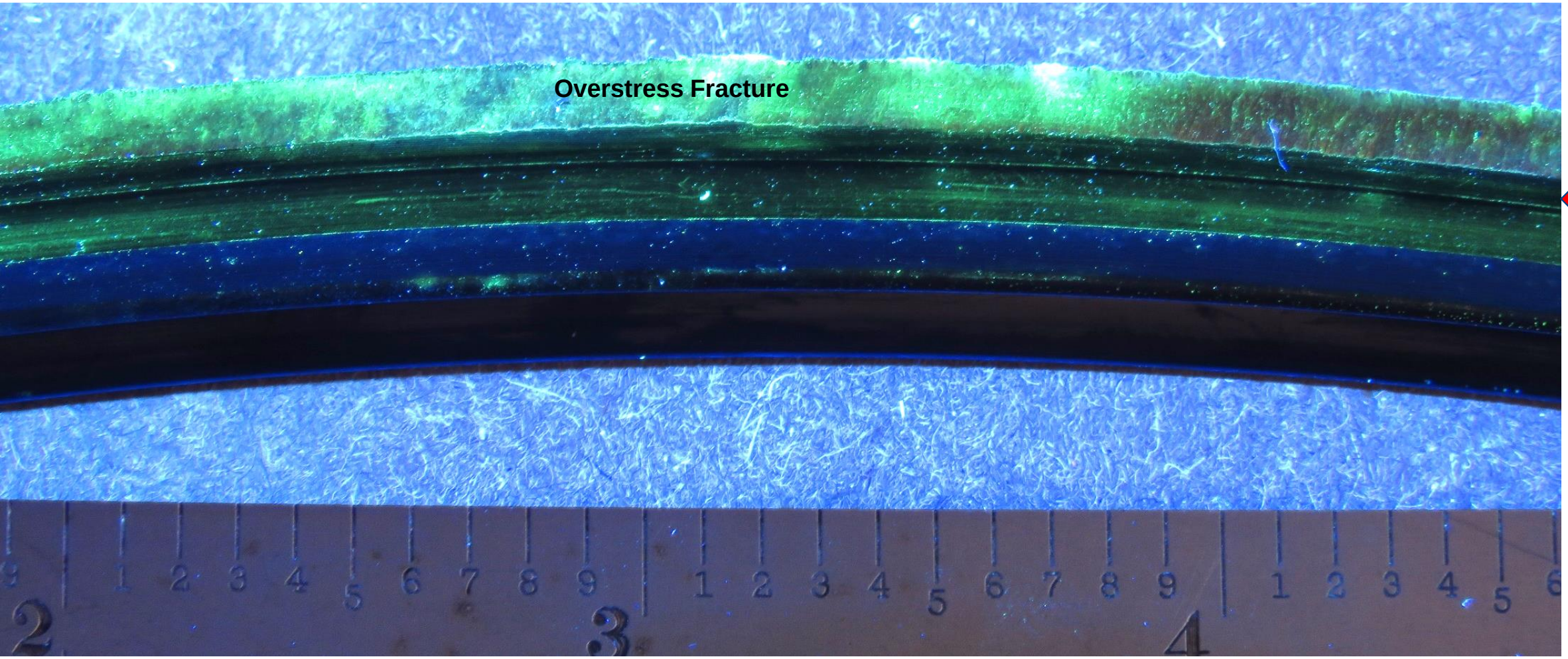


Figure 39: The remainder of the retainer was FPI'ed and no additional crack-like indications were observed.

Appendix A

Feature Testing- Intergranular Static Hold Time

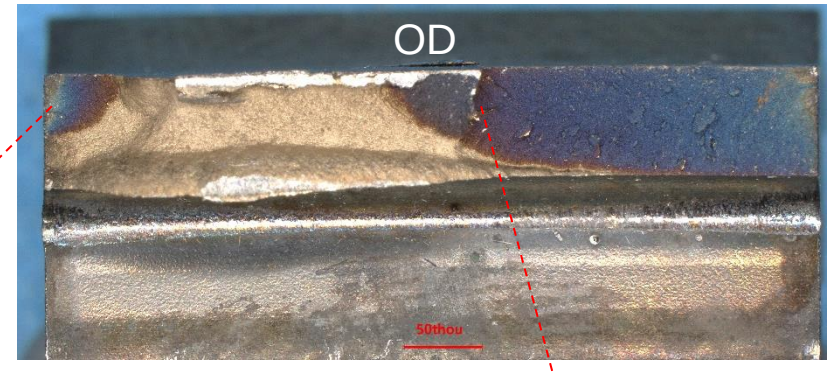
DRB AvEng-549950.A

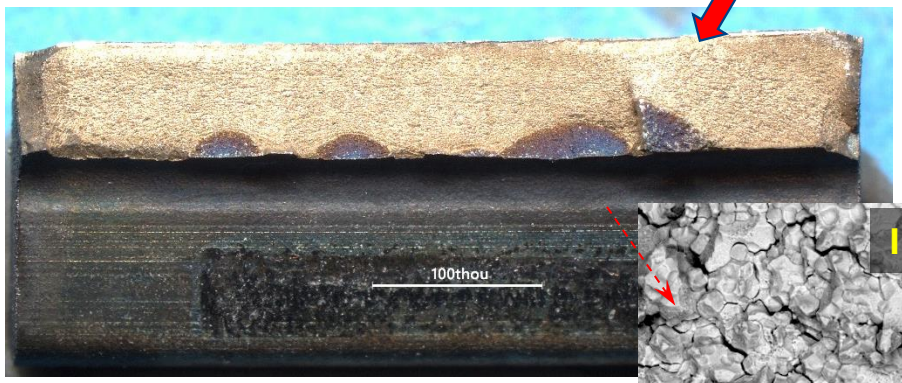
Feature Testing- Strain Effects (AvEng-549950.A)

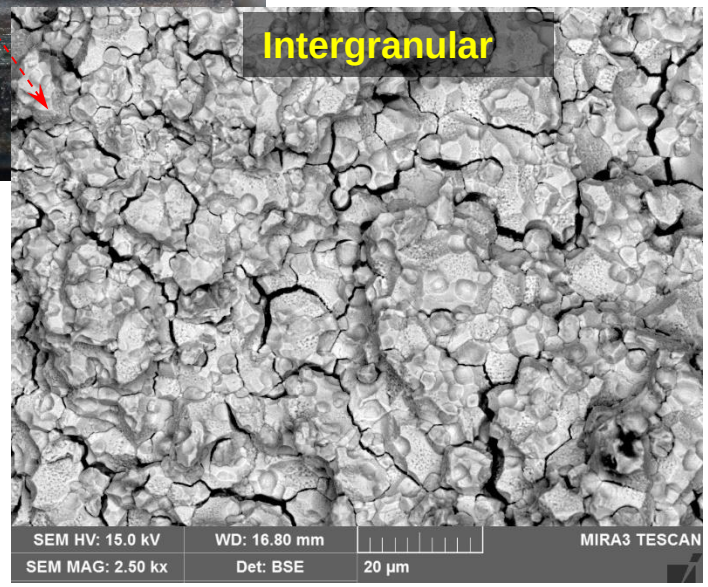
- **Tensile test**:
  - 1100°F → fractured at **1,539 lbf→ ductile dimples** (undercut radius)

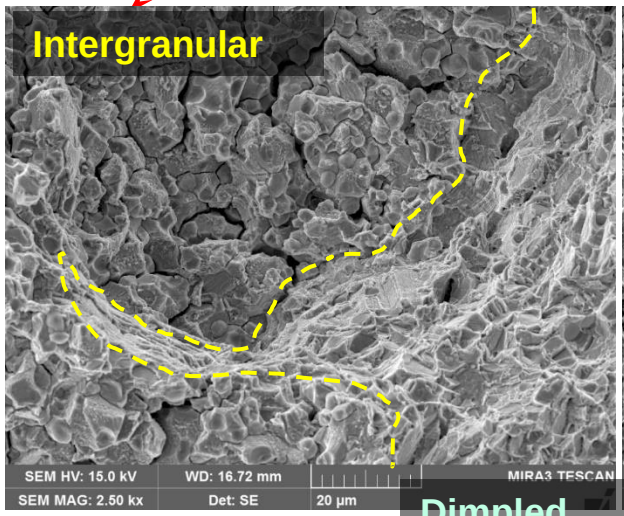
- **Static Hold test**
  1) 1100°F, **1000 lbf** → Fracture in **46 hours** → Fracture **intergranular**.
  2) 1100°F, **1200 lbf** → Fracture in **8.5 hours** → features are **intergranular (undercut radius)**

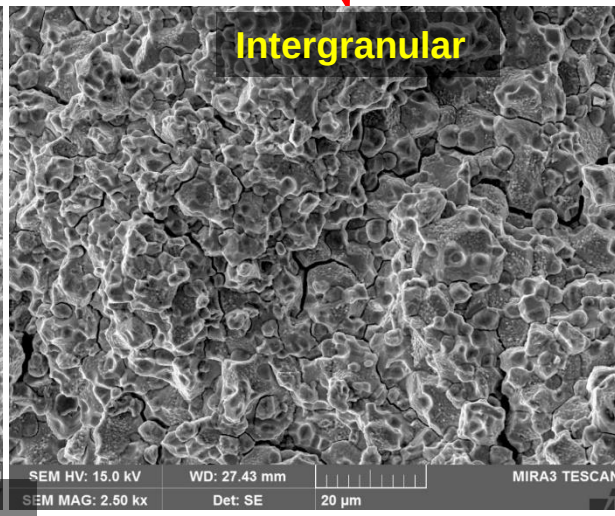
1100°F; 1000 lbs (arm fracture)









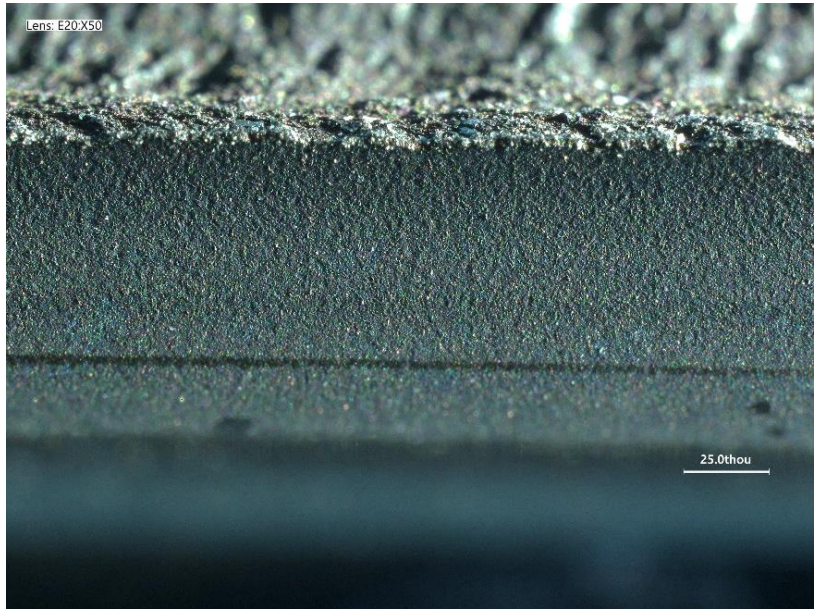


Dimpled Overstress

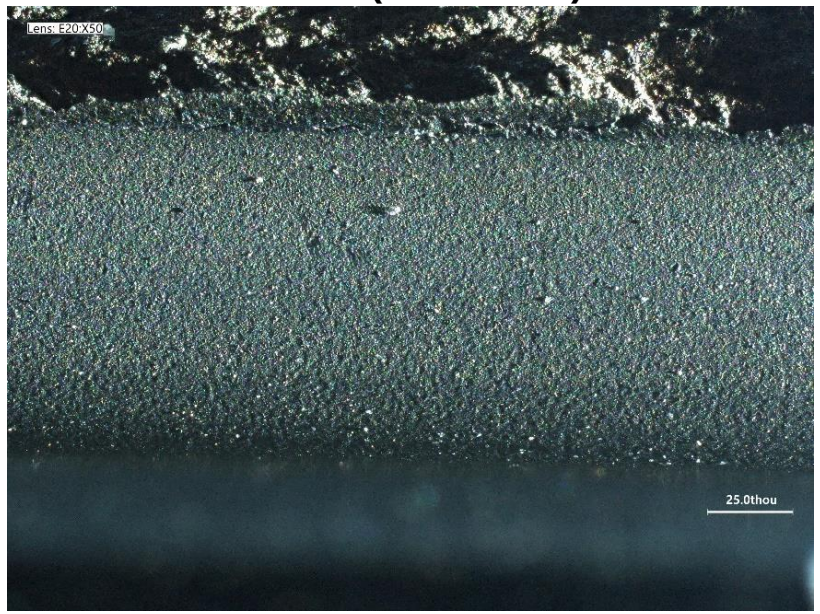
Appendix B

Retainer Peening and Roughness

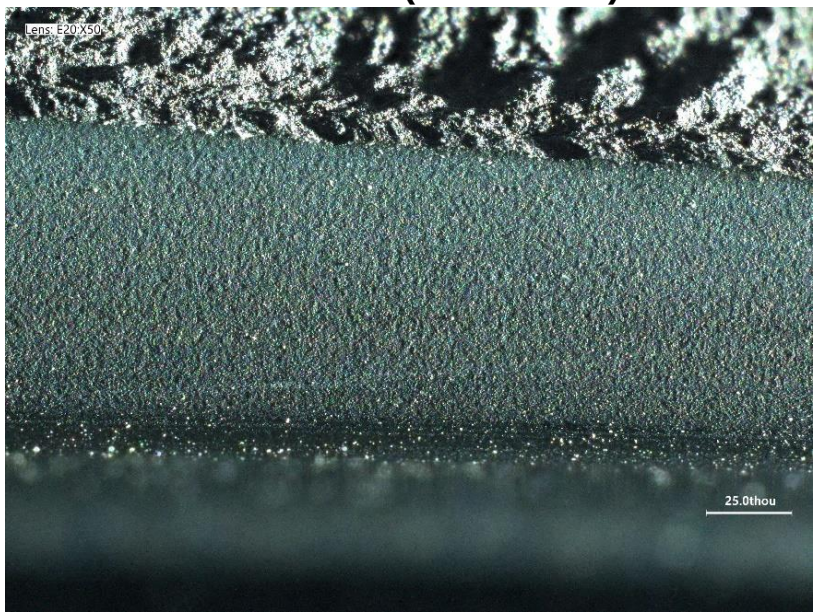
UAL 956-102 (TMT4TK46)



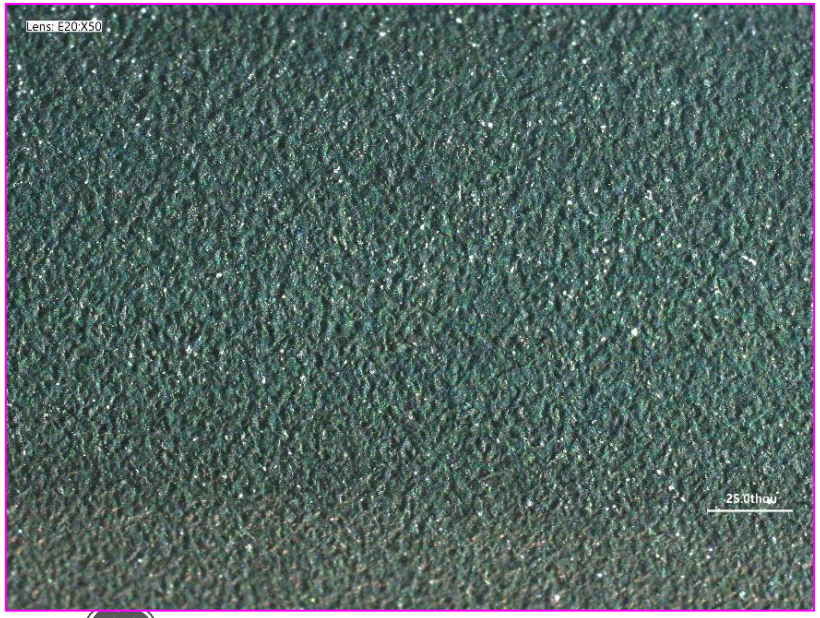
956-397 (TMT1JEP9)



958-071 (TMT11CNF)

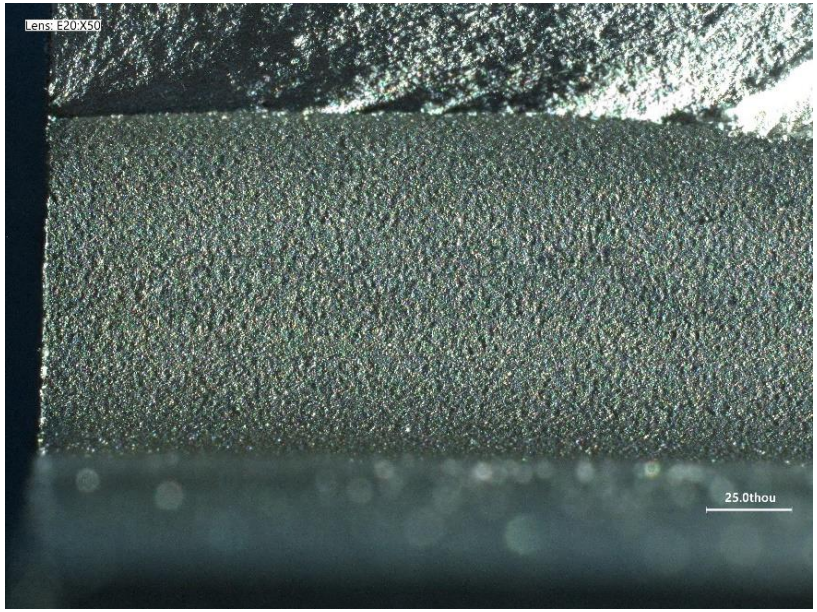


UAL 956-102 Fwd Radius (for comparison- peened only)

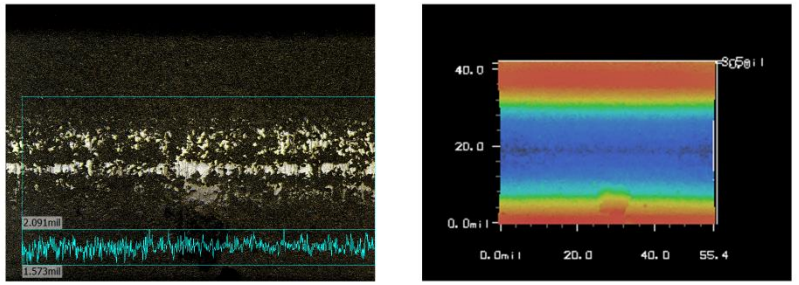


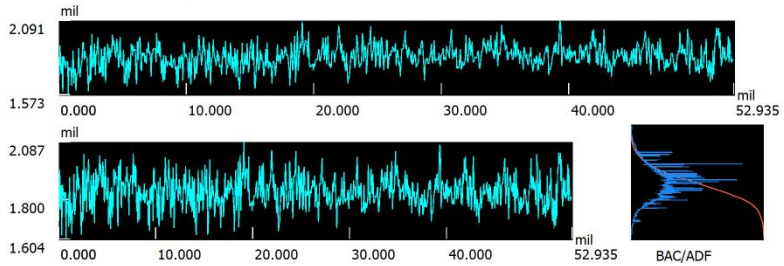
Collet Radius

959-374 (TMT10NFL)



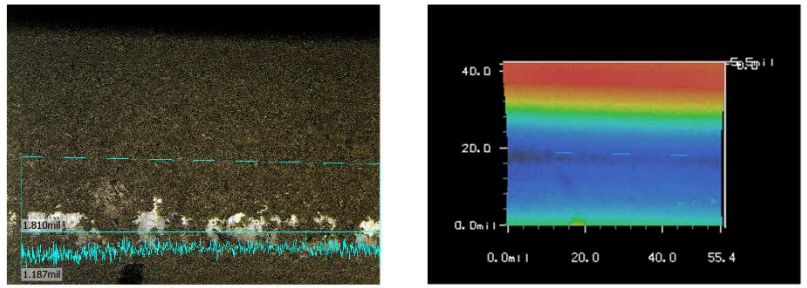
958-071

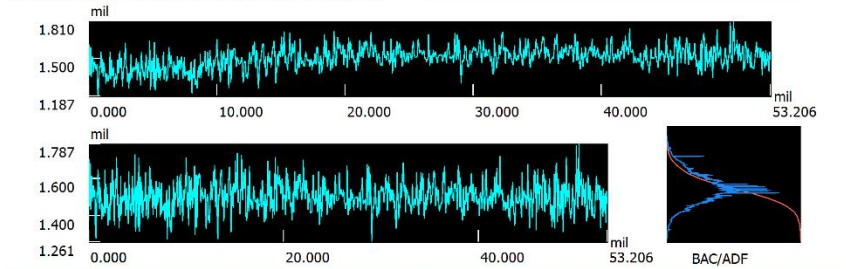




63 Ra uin

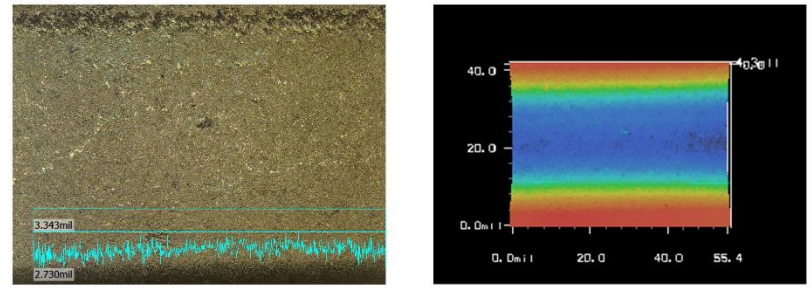
956-397

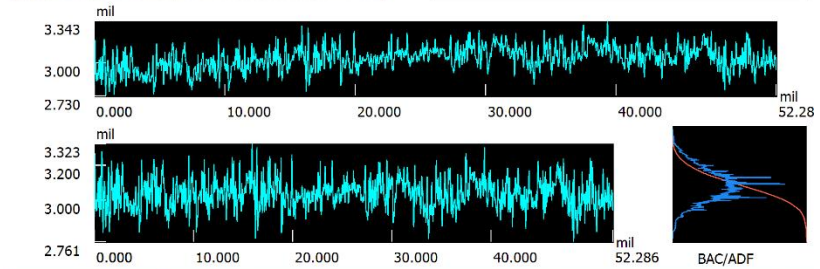




63 Ra uin

956-102

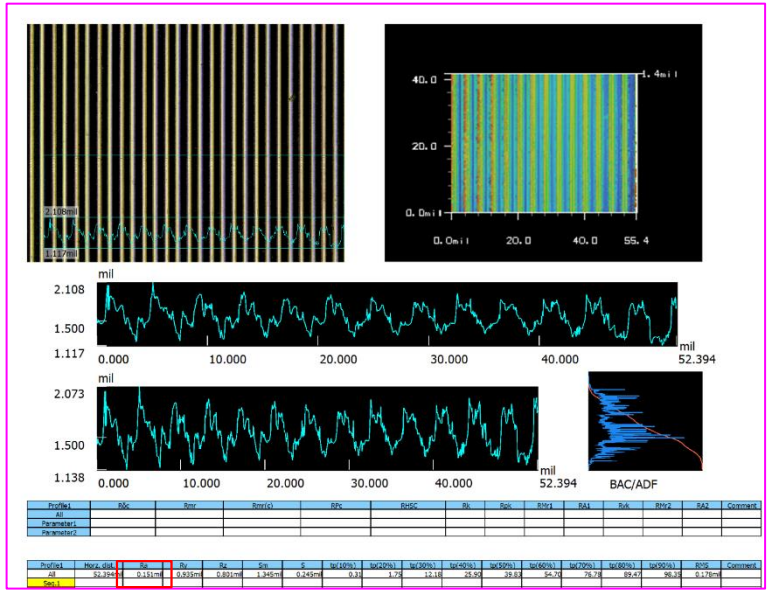




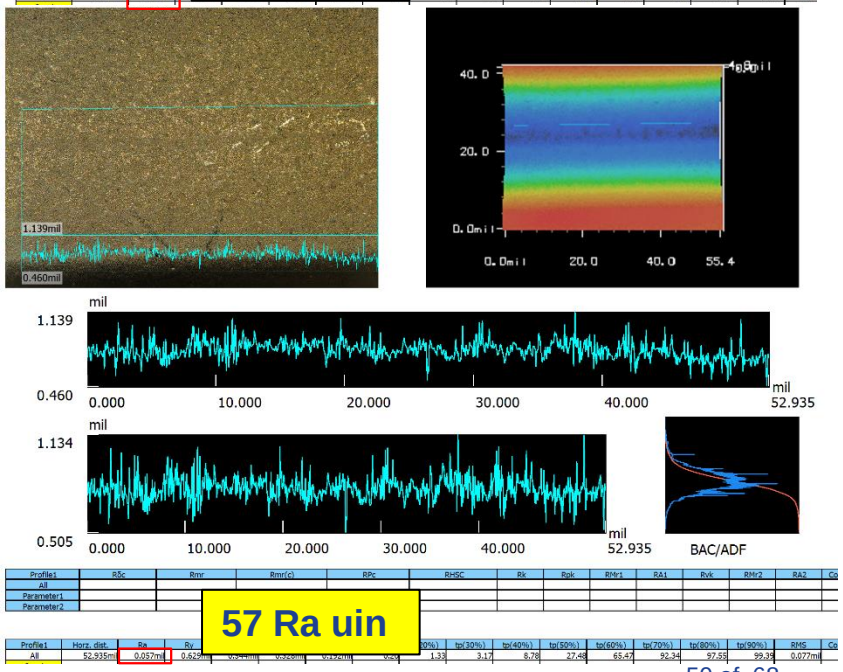
72 Ra uin

Calibration Block

151 Ra vs. 117 Ra uin



959-374



57 Ra uin

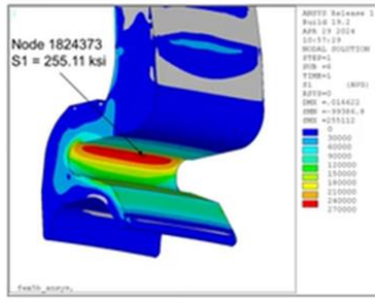
Appendix C

R65 Retainer Feature Testing

EMS Material Behavior

Basic Steps to Run Feature Test

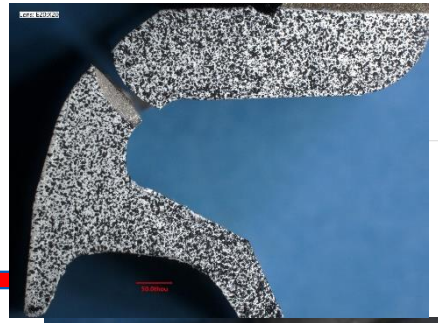
Form team & determine goal → **Determine Stresses/loads** → **Determine Estimated lives** → **Procure materials and design/make fixture**

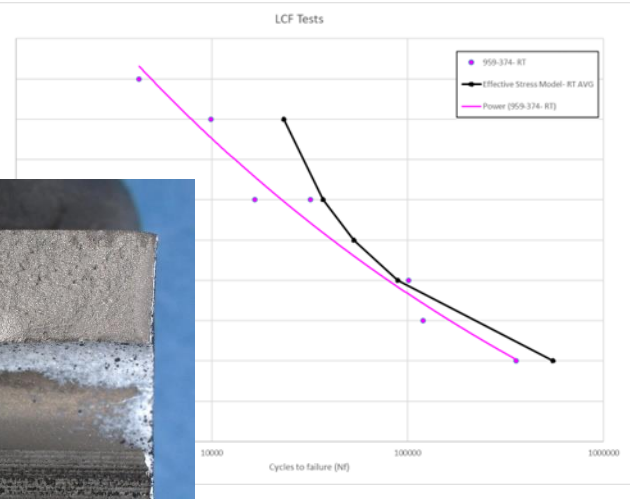


Min Load (lb)	b)	R Ratio	Collet Max Centroid Effective Stress (ksi)	Temp = 1200F R65 - S203798A1 Hold = 0 Avg LCF Life (cycles)	Temp = 1200F R65 - S20379801 Hold = 0 Min LCF Life (cycles)	Temp = 1200F R65 - S203798A1 Hold = 300 sec Avg SPLCF Life (cycles)	Temp = 1200F R65 - S20379801 Hold = 300 sec Min SPLCF Life (cycles)
40	400	0.1	157	Redacted			
50	500	0.1	**198**				
55	550	0.1	**219**				
60	600	0.1	**239**				
70	700	0.1	280				

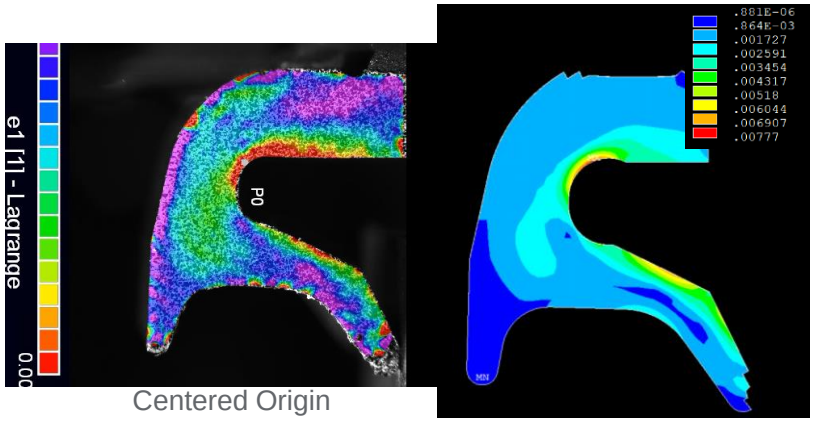
Likely Iteration

Validate/Trial at RT





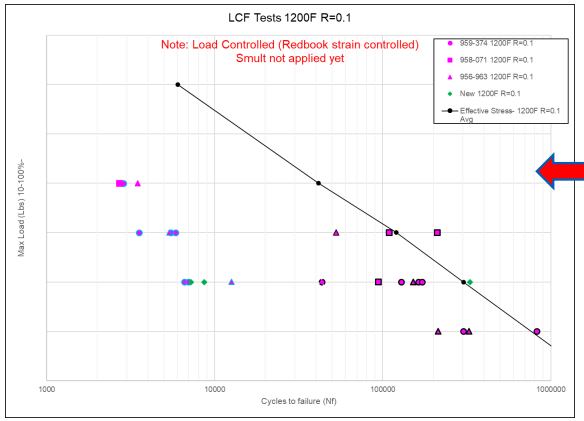
Validate Strains/Stresses



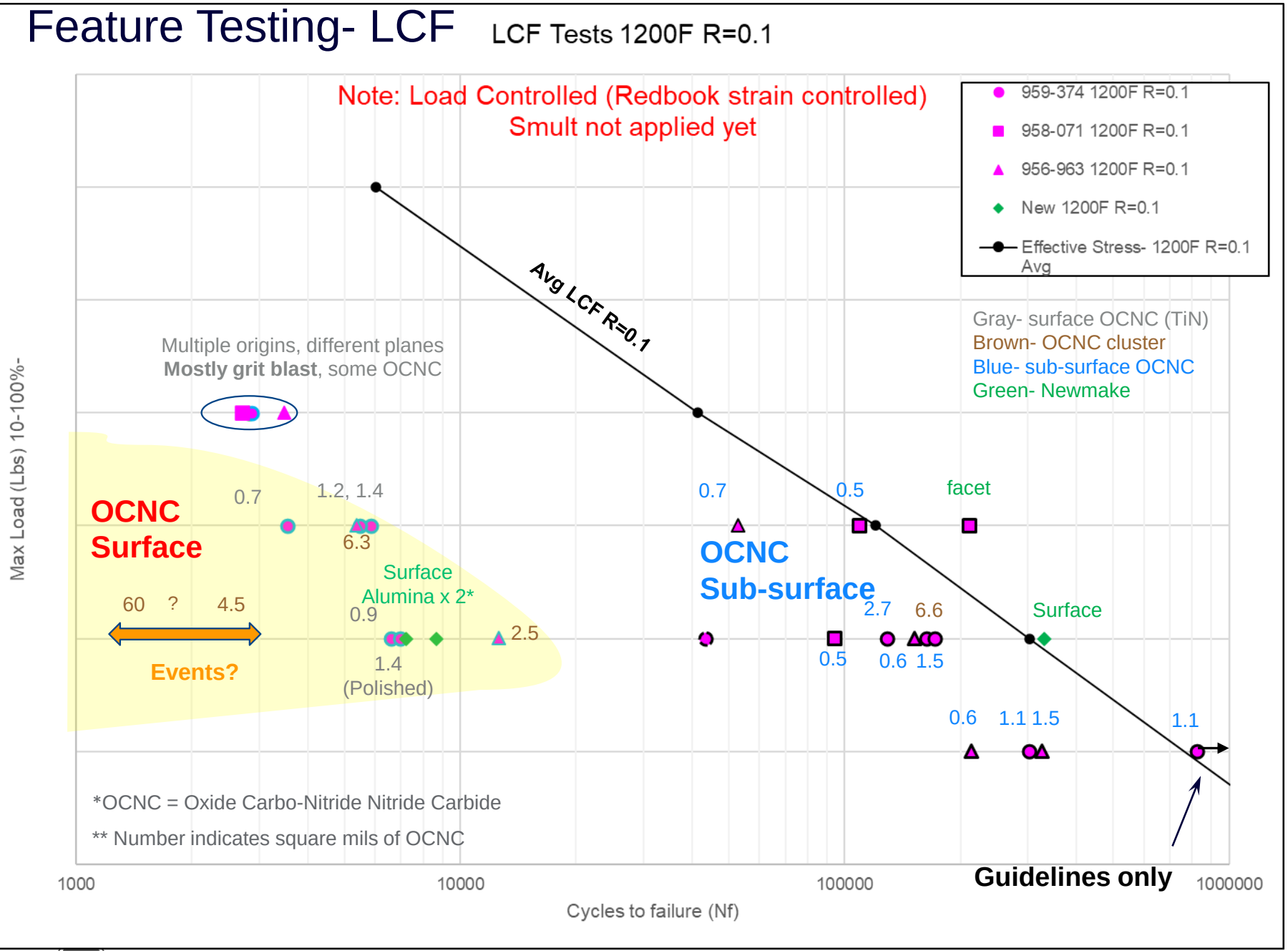
Centered Origin
Edge Strains ~0.5%

Use strain gauge or DIC

Generate Data/Draw Conclusions

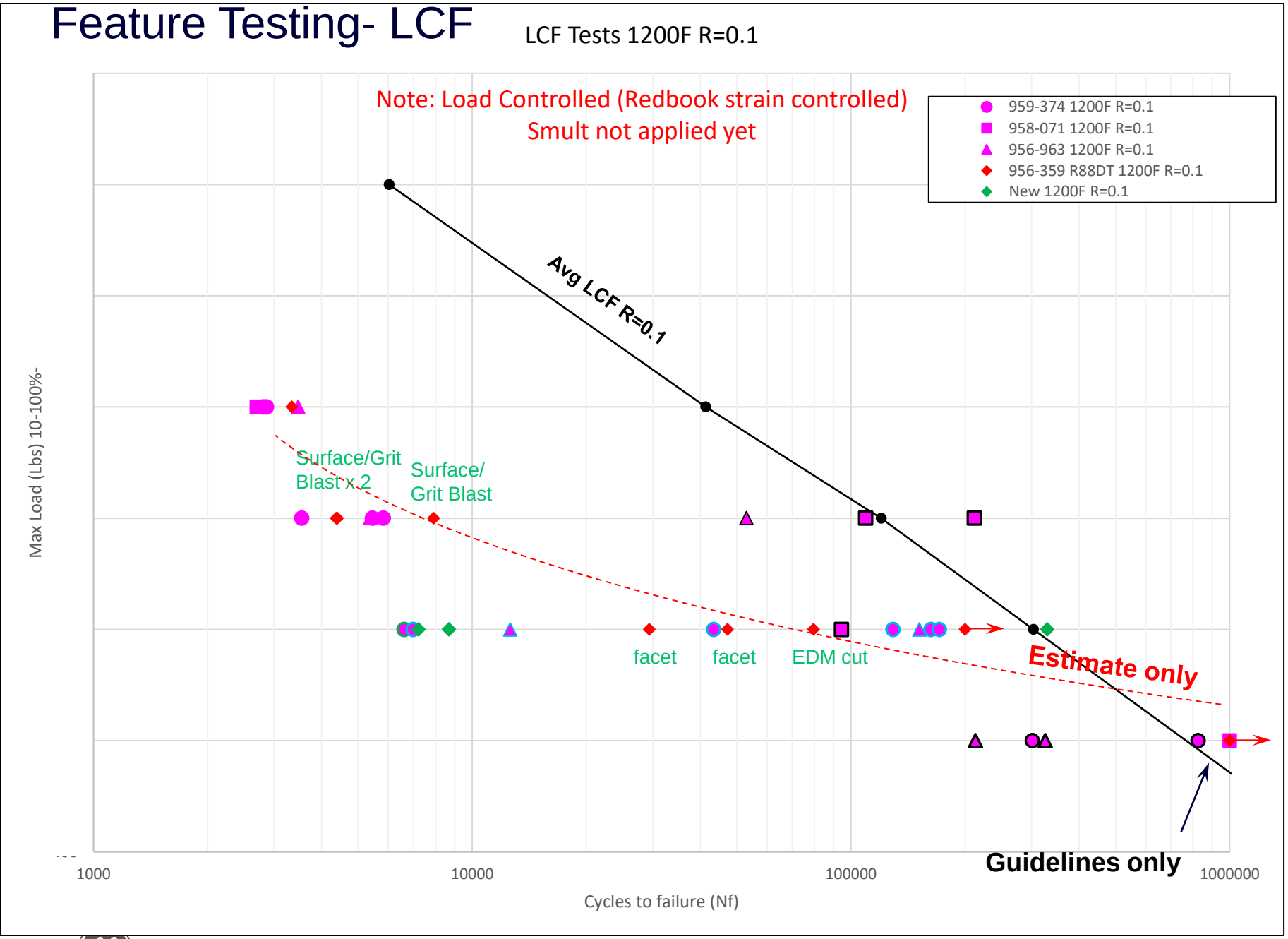


Feature Testing- LCF



1) Loading
   - At very high stress: All had multiple origins at the surface initiating from the surface, grit blast particles, or OCNCs. They did not look similar to the event parts.
   - At high stress: The lives had a **bimodal** distribution and either initiated with low lives at **surface OCNCs**, or subsurface at higher lives near average expectations.
   - At intermediate loads : **All** 5 specimens initiated **sub-surface** with average expected lives.
2) The feature test specimens initiated at more **OCNCs** at surface compared to smooth uniaxial test bars.
3) 2 out of 35 tests initiated at OCNC clusters at the surface (3 total). Both confirmed event/shop find parts had OCNC clusters.
4) The largest tested surface OCNC was **6.3 square mils**, but most were closer to 1 square mil.
5) A **new** retainer also had a bimodal distribution, but initiated at surface grit blast media (vs oxidized OCNCs on the fielded specimens).

Feature Testing- LCF

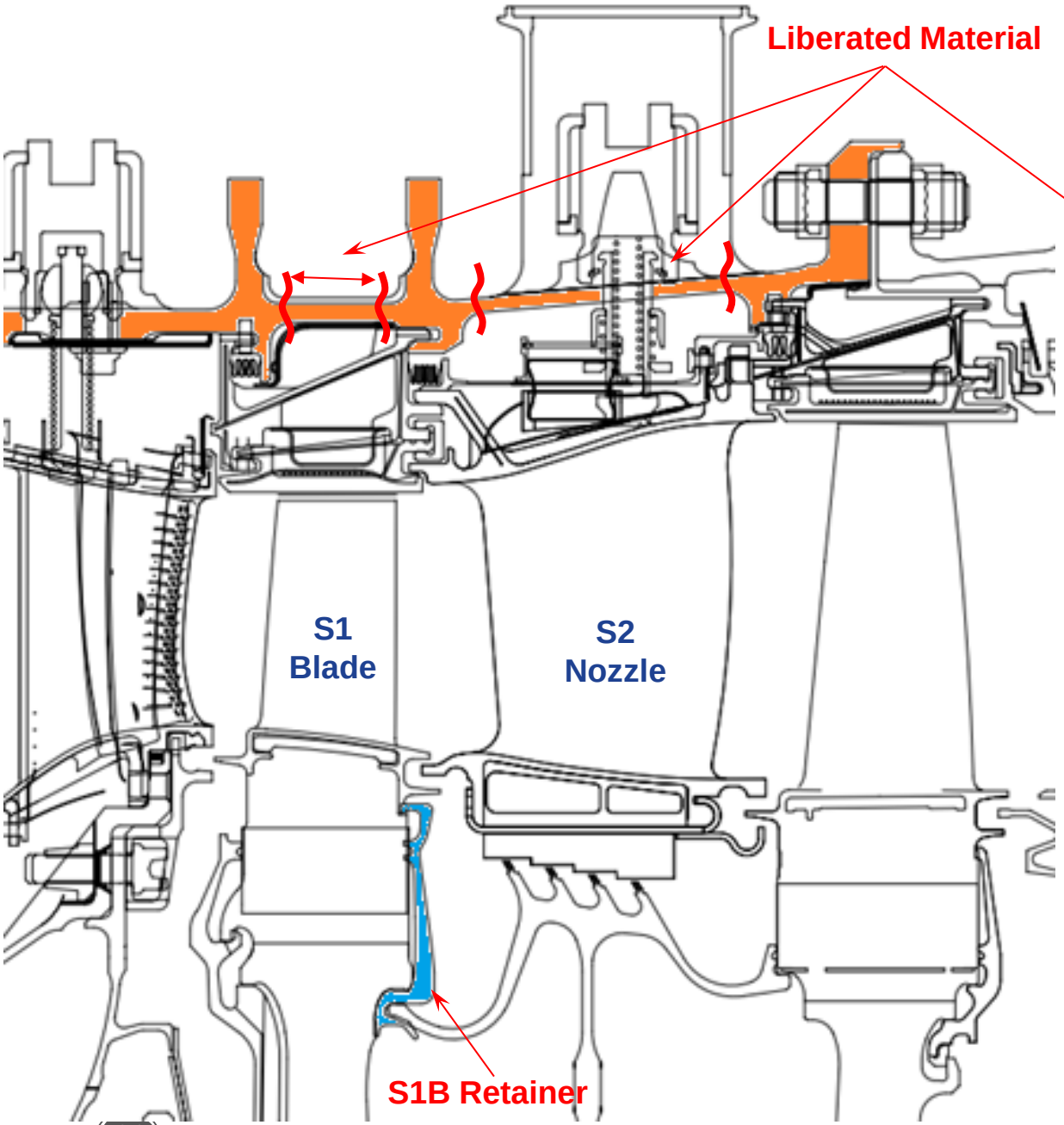


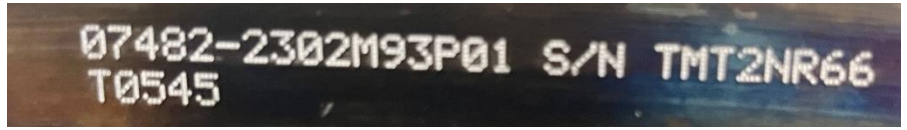
Comparing R88DT (red) to R65 showed that at very high loads the lives were similar, but as the stress decreased the lives were improved without the very low data points (differences in OCNC/inclusion type/distribution/sizes).

Appendix D

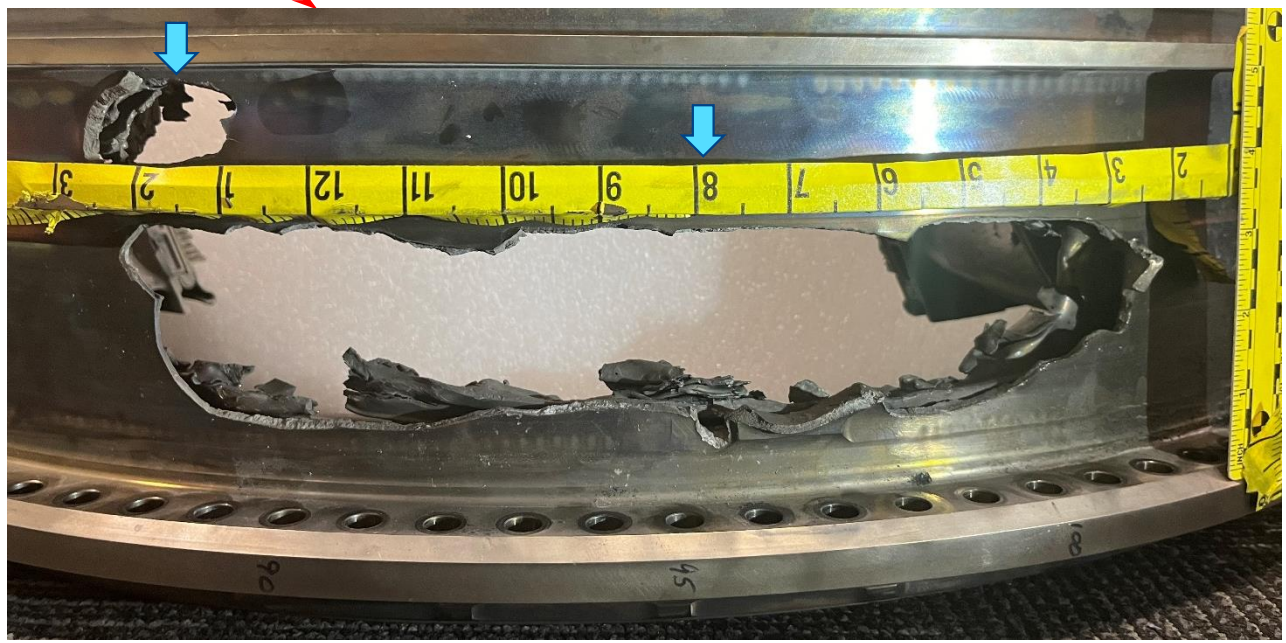
Other hardware from ESN 956-102

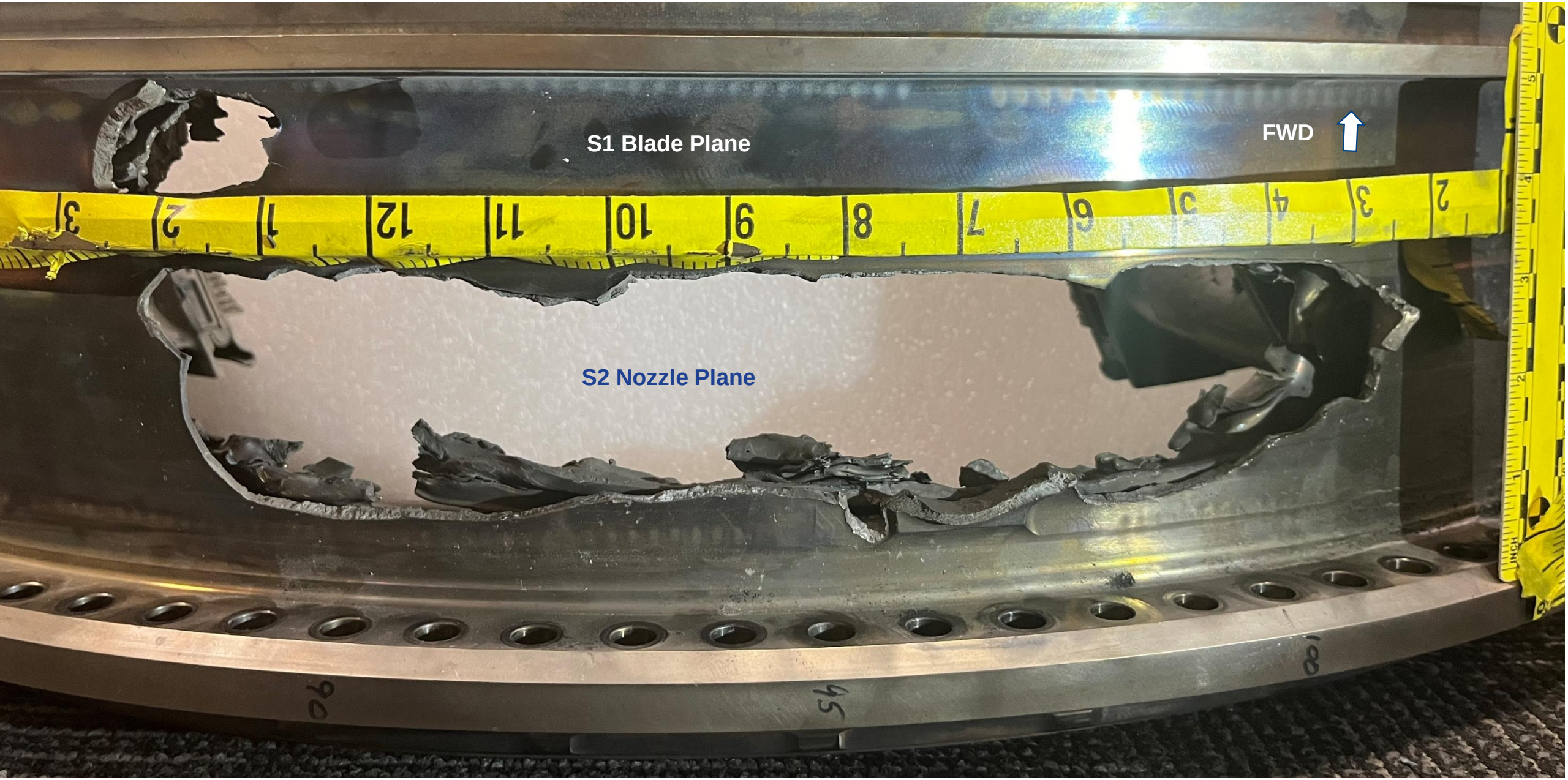
HPT Case

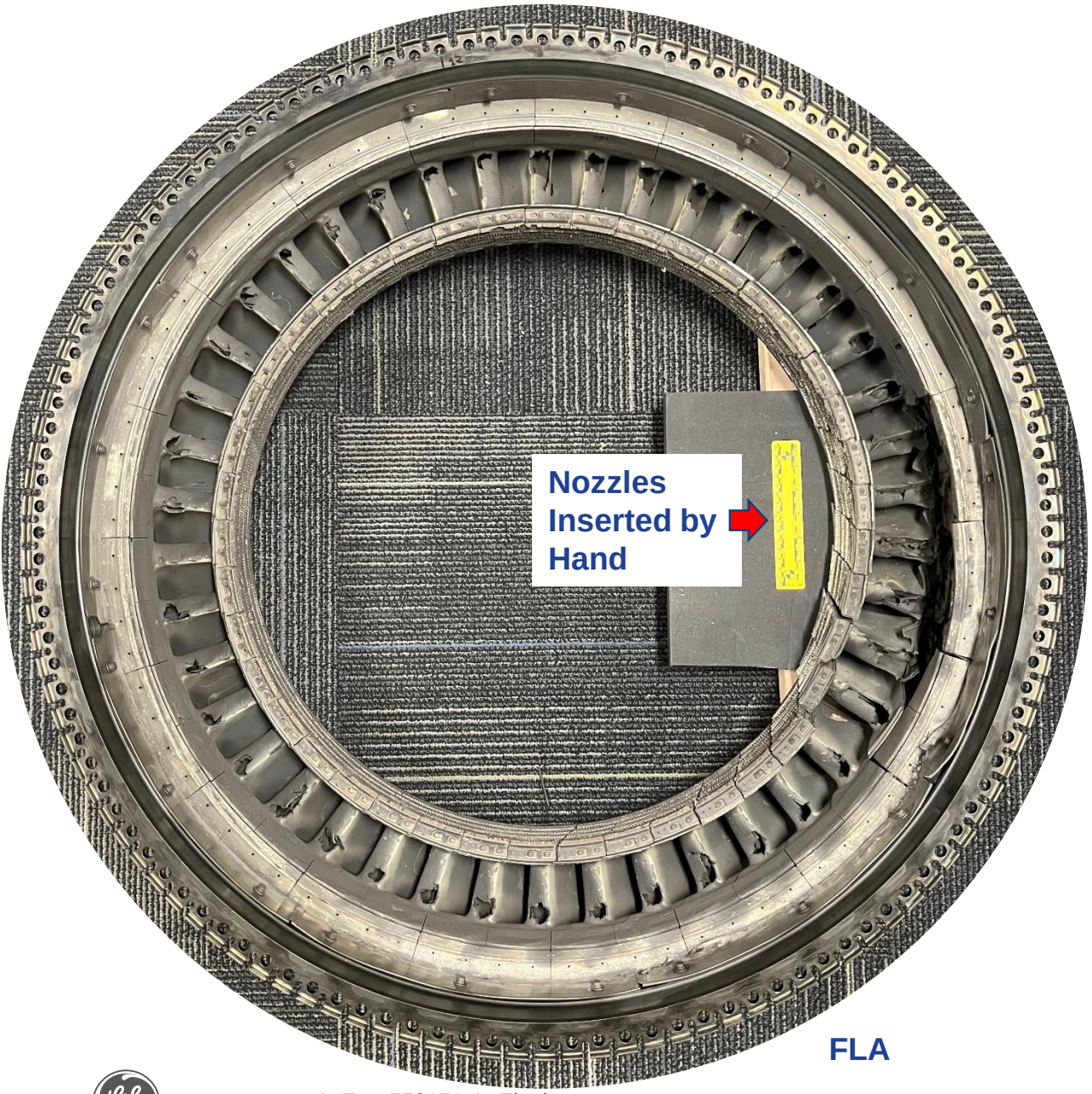

Liberated Material
S1
Blade
S2
Nozzle
S1B Retainer


07482-2302M93P01 S/N TMT2NR66
T0545

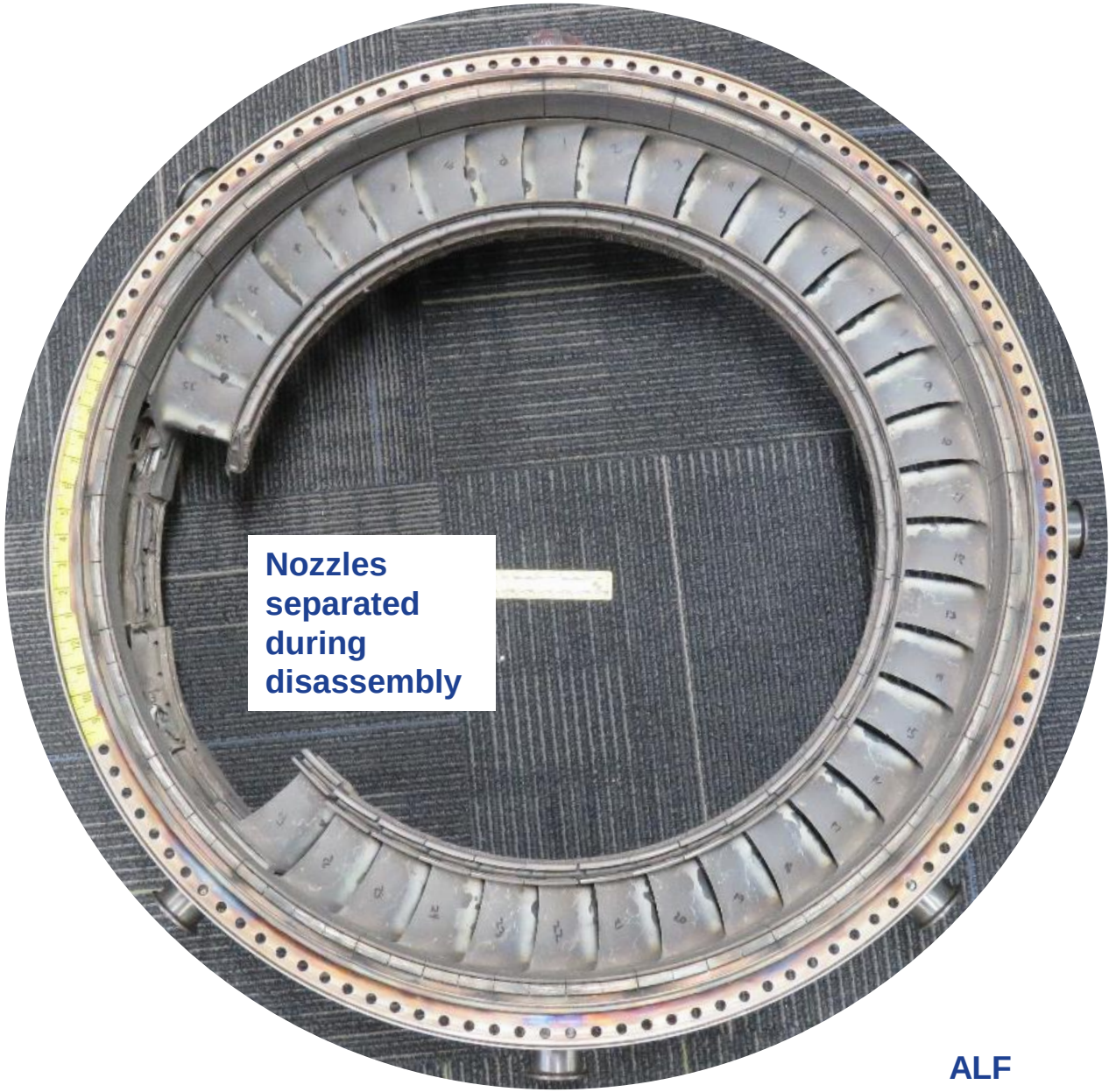
FWD



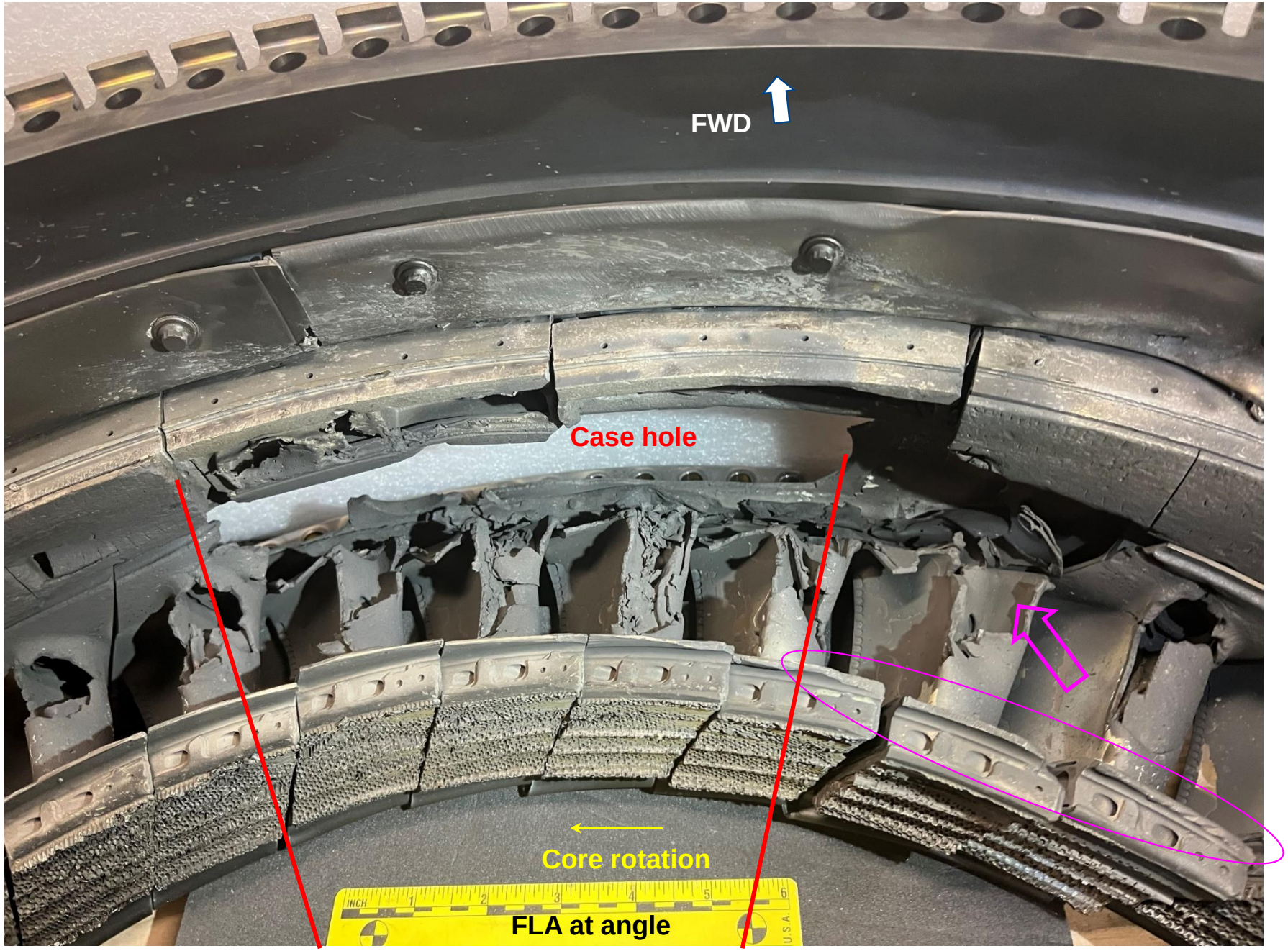

S1 Blade Plane
FWD
S2 Nozzle Plane


Nozzles Inserted by Hand

FLA


Nozzles separated during disassembly

ALF

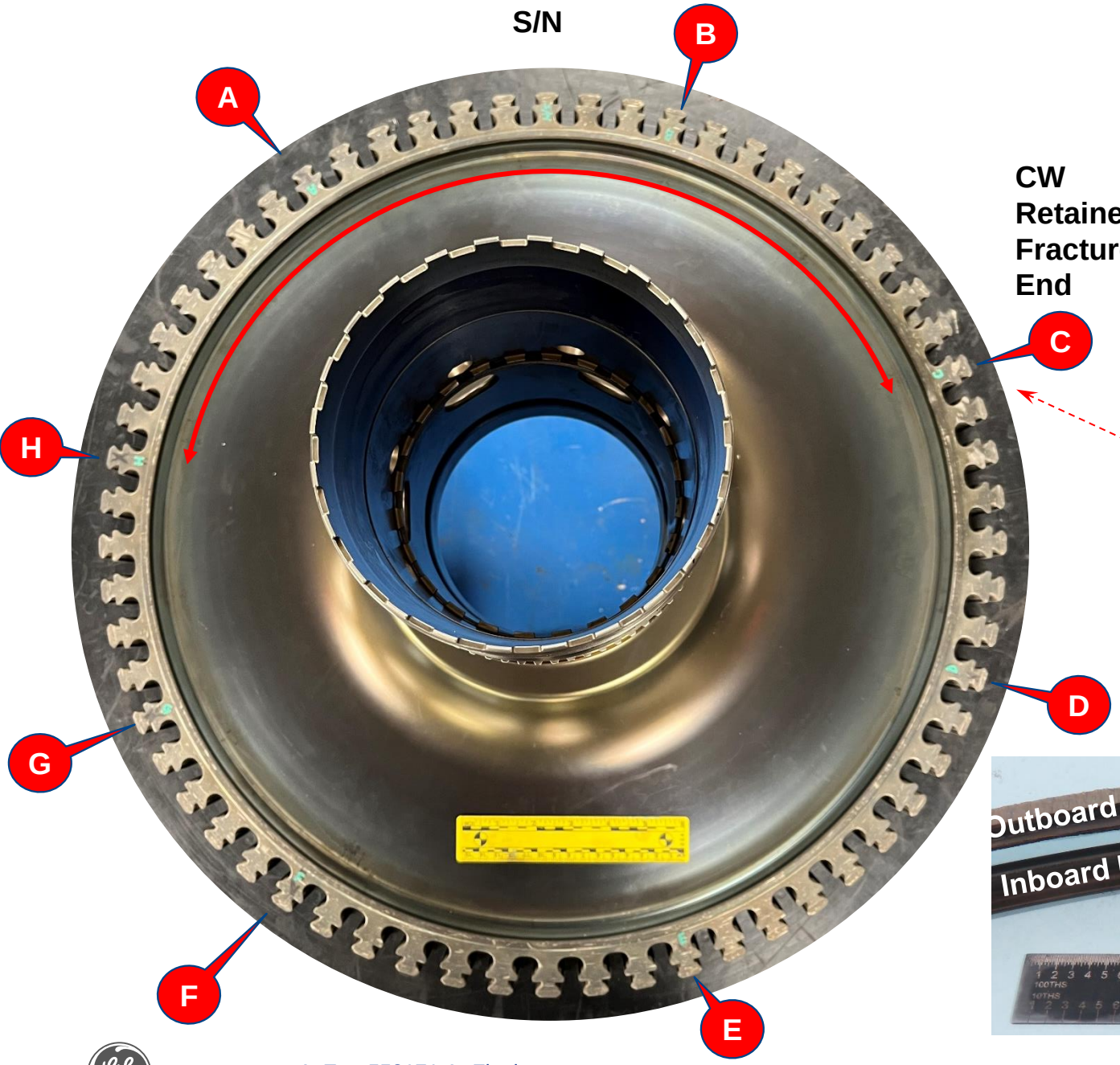


Circumferential offset of damage progressing from the retainer/S2 nozzle forward angel wing outward

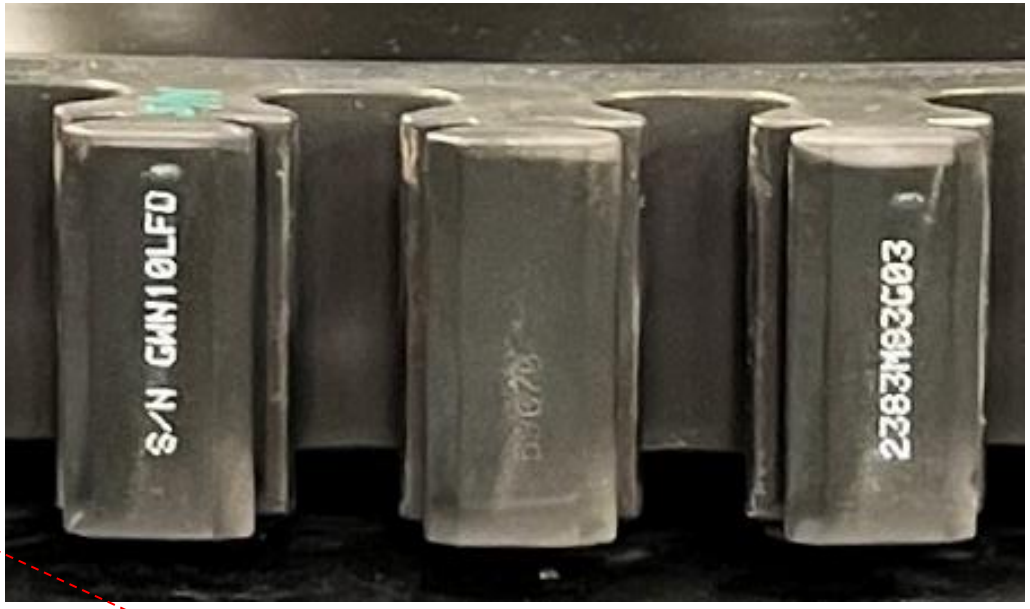
Missing/damaged S2N forward angel wing

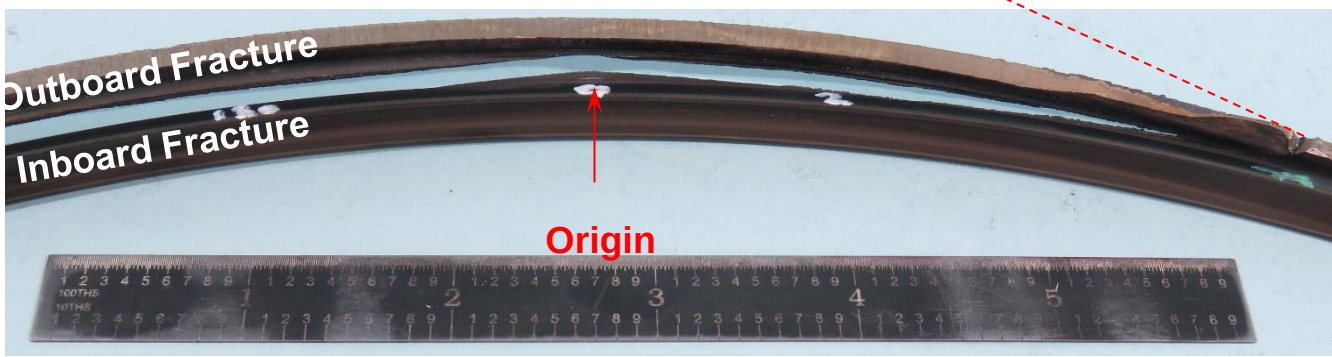
FWD
INCH
Looking Radially Outward

HPT Disk



CW Retainer Fracture End





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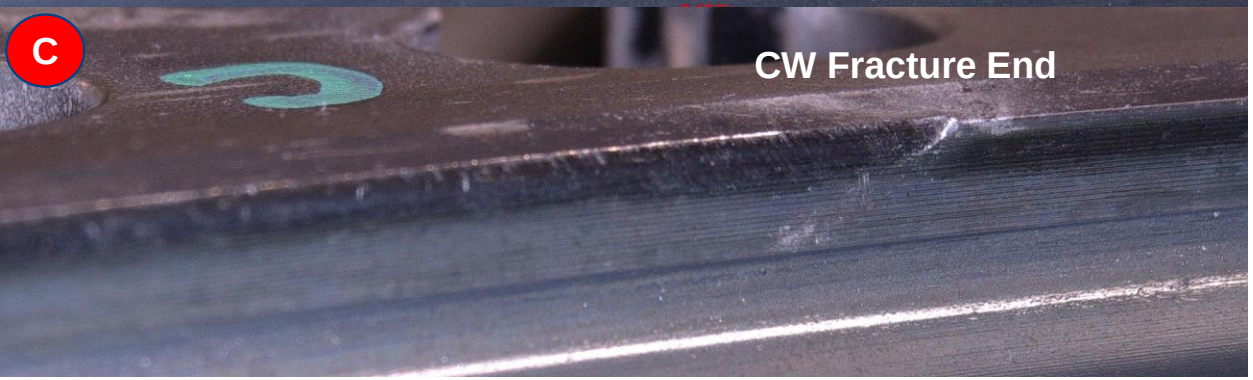
C
CW Fracture End

E
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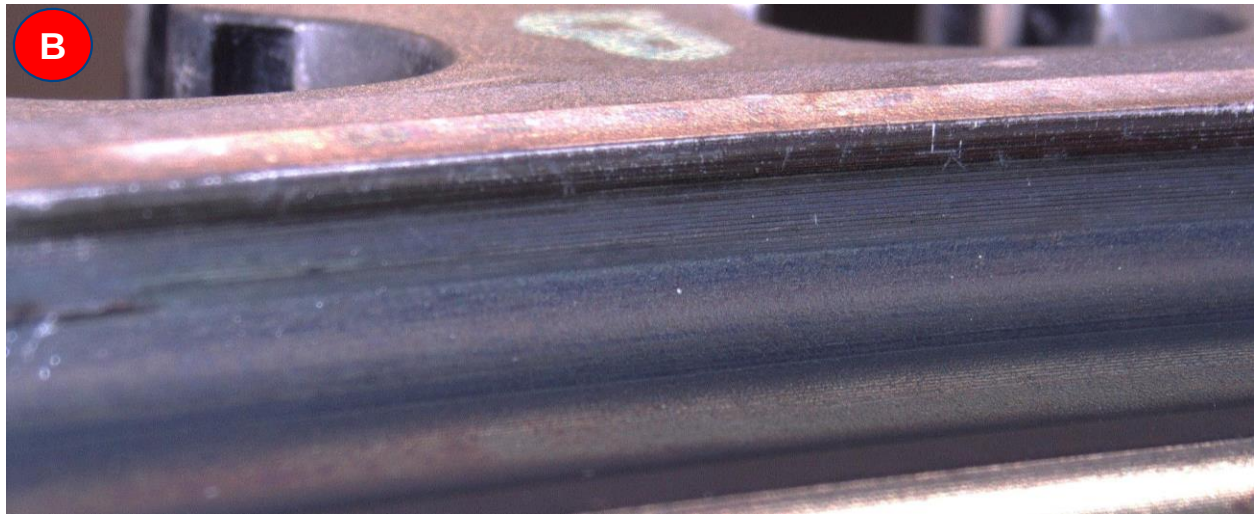
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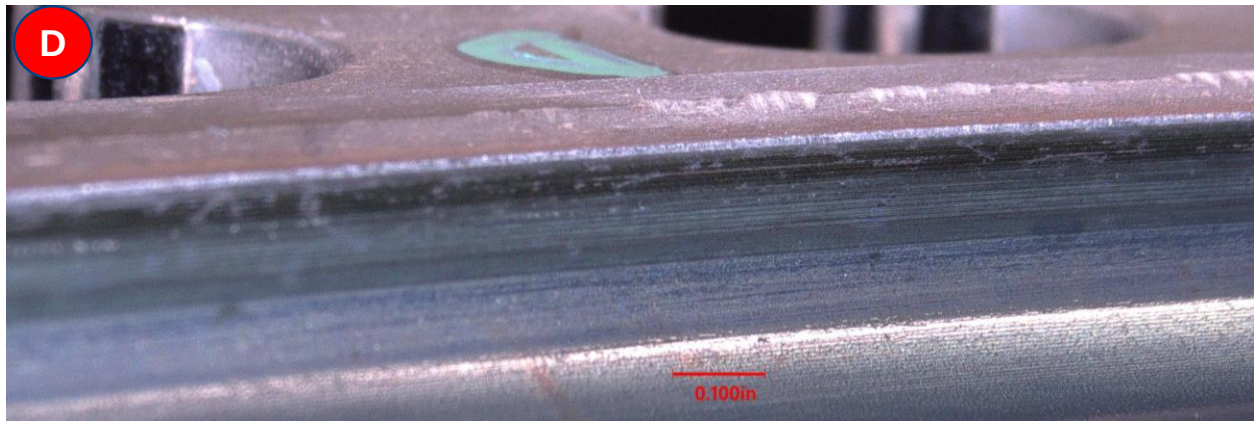
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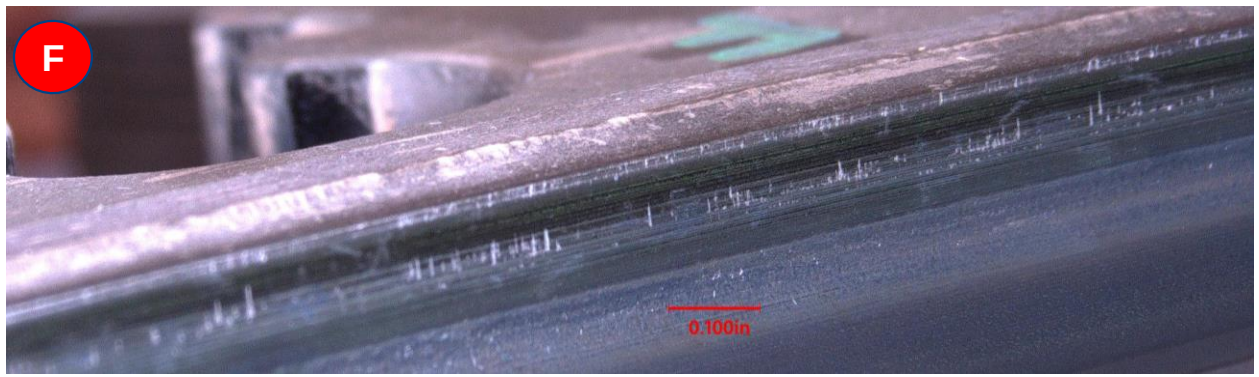
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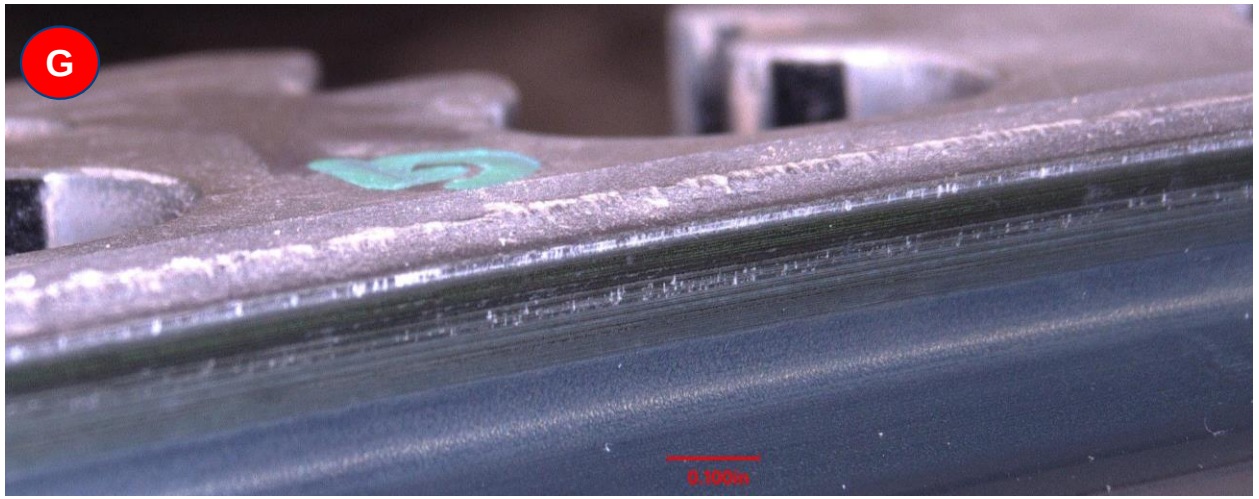
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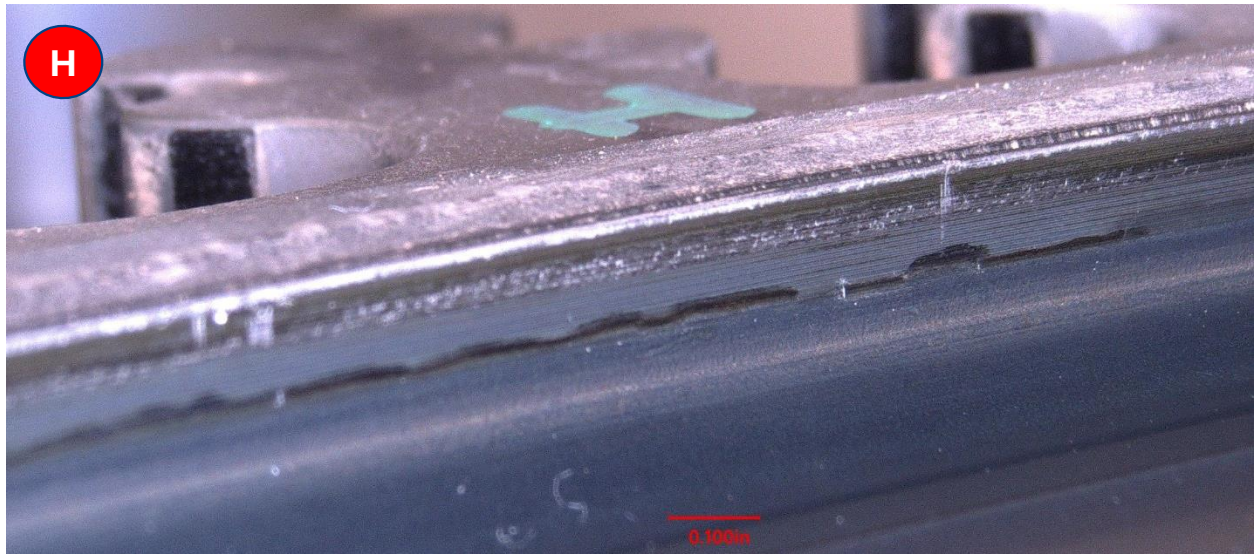
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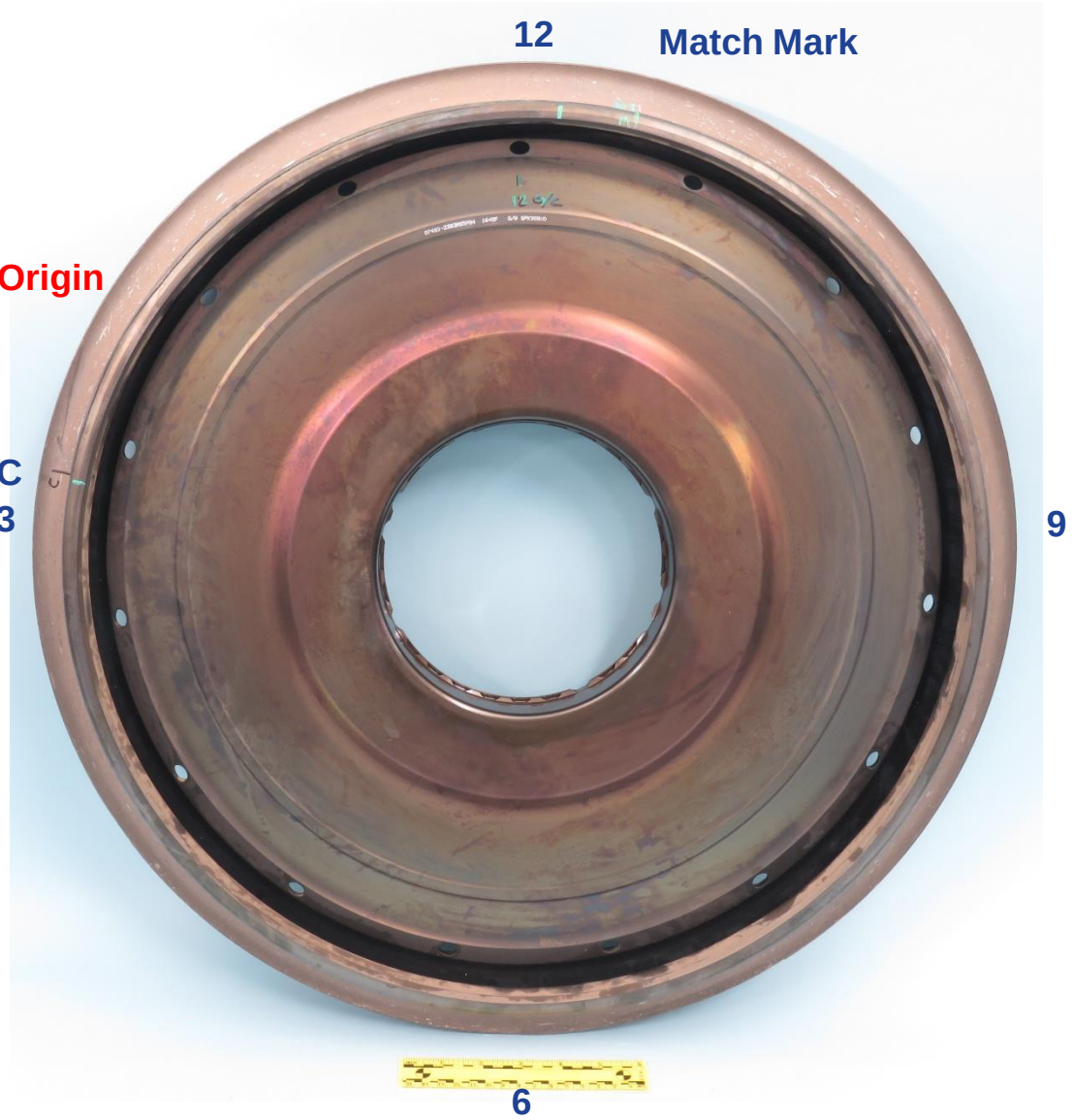
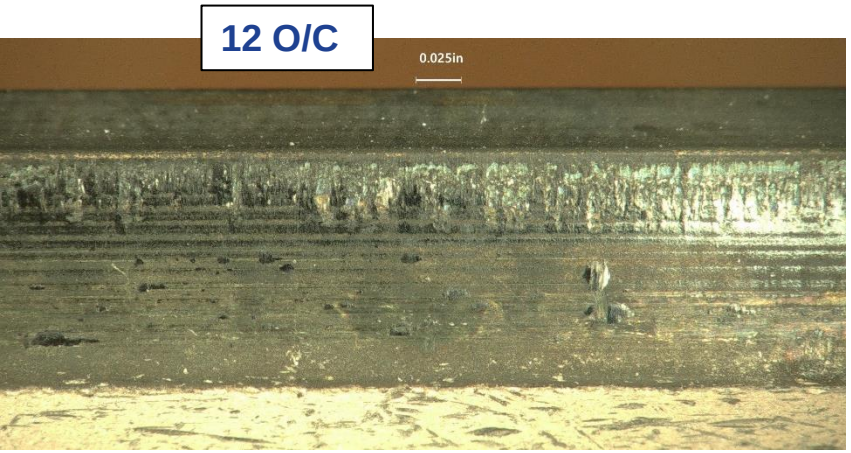
Mid-seal


12
Match Mark
~Origin
C
3
9
6

~Origin

1
12 o/c
07482-2383M85P04 1645F S/N SPK98RUD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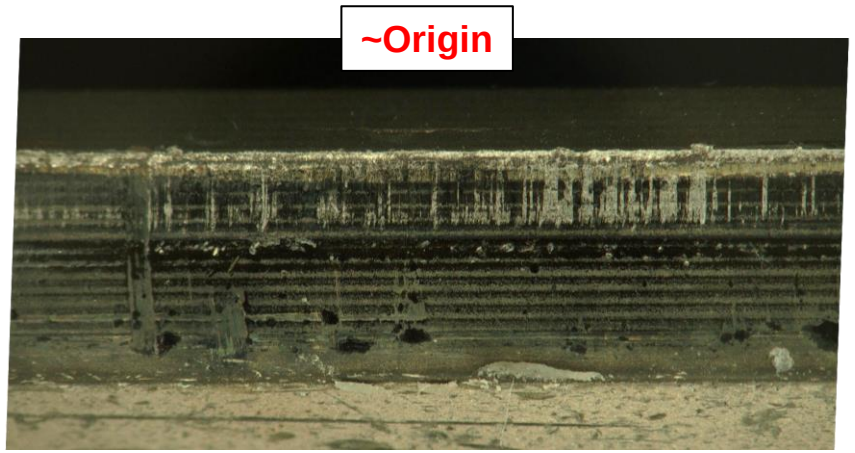
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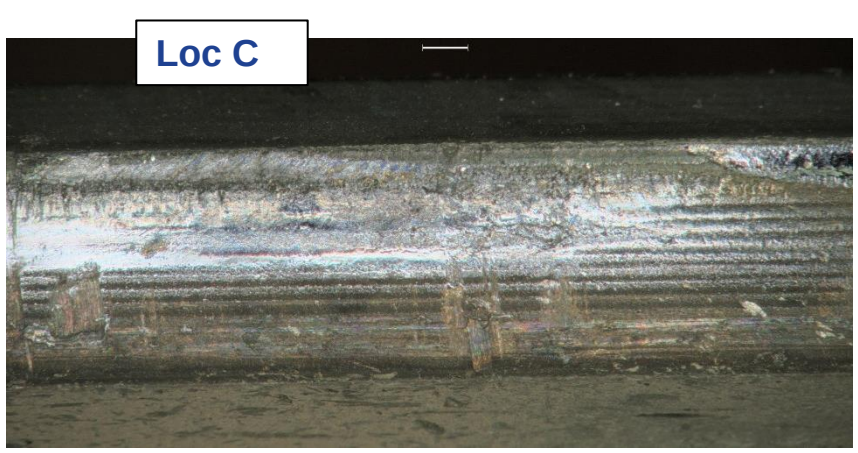
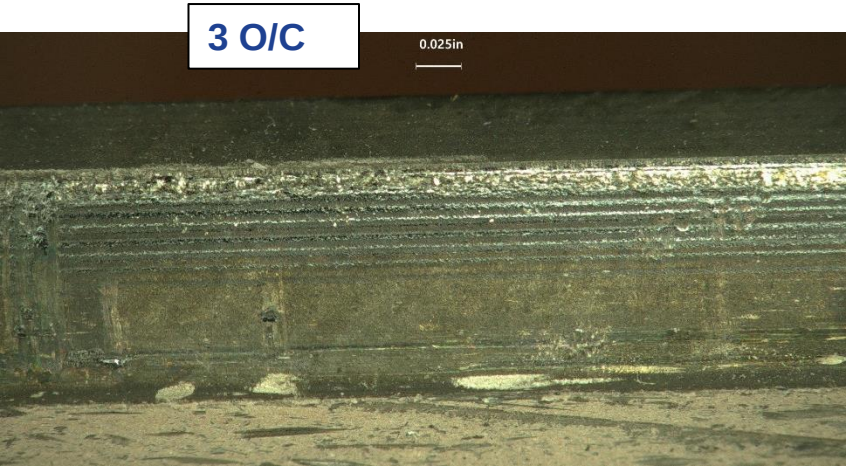

Loc C


3 O/C
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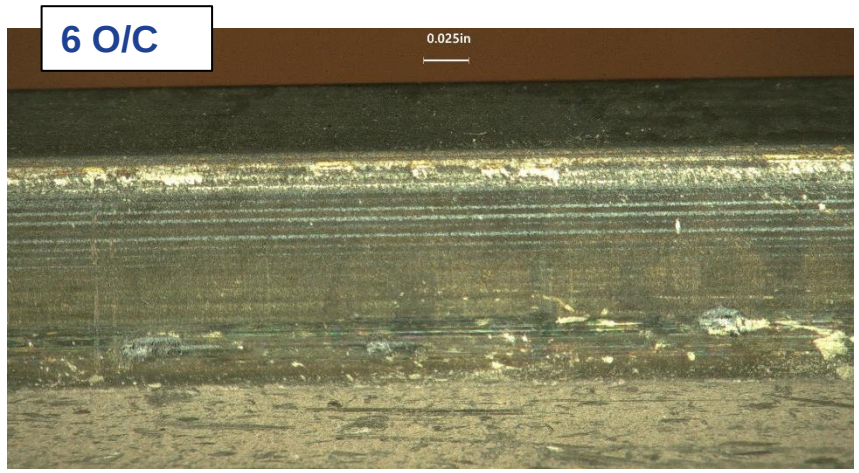
6 O/C
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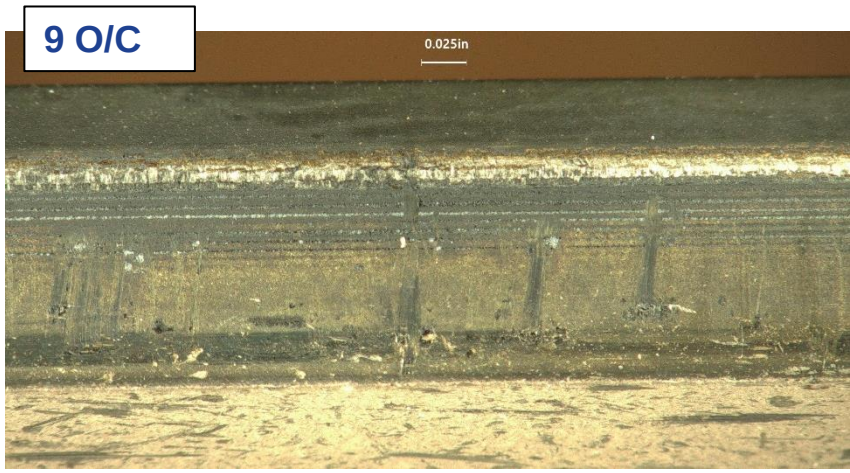
9 O/C
0.025in