

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety
Washington, D.C. 20594

March 14, 2022

Attachment 1 - Metallurgical Report

Powerplants

ENG20LA046



ENGINE SN 143016

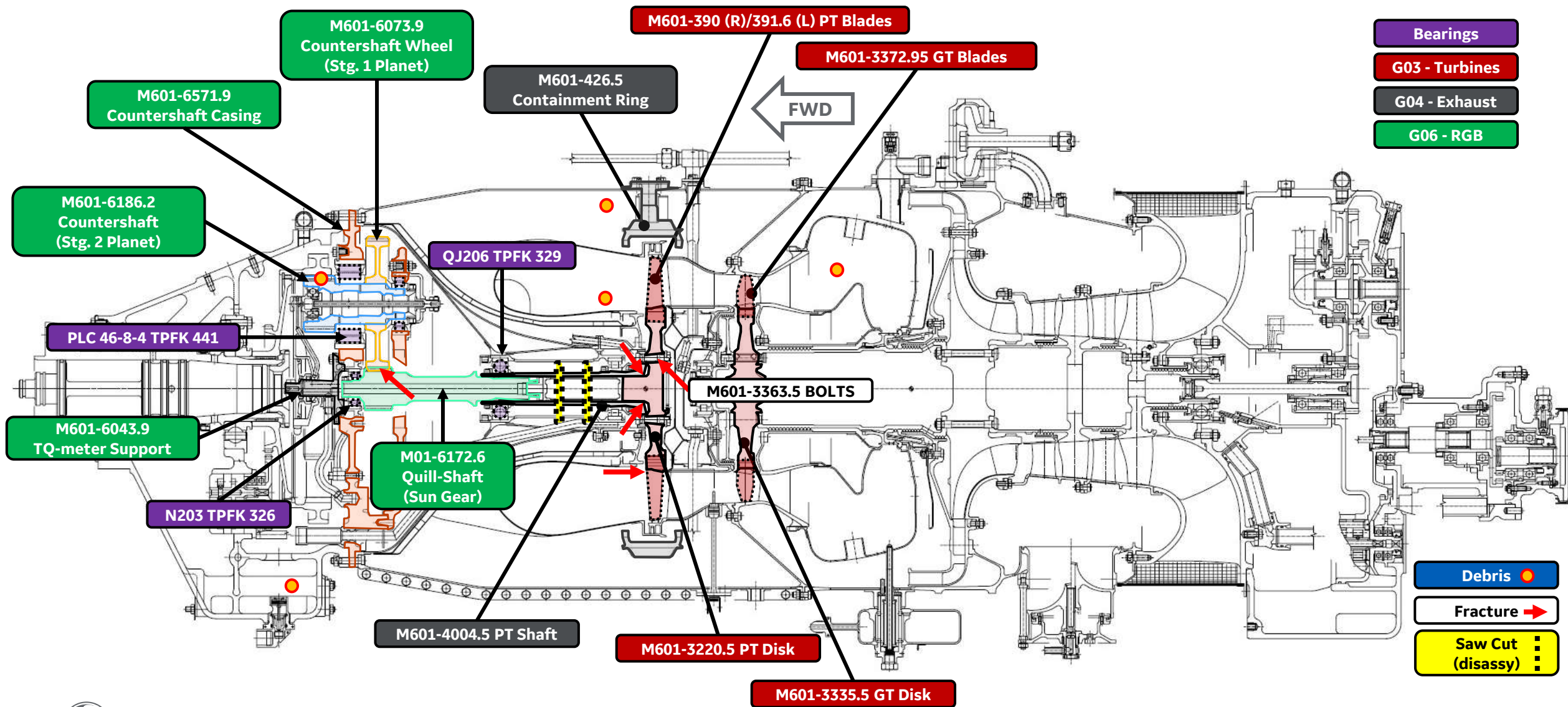
Spring Creek Aviation LLC / Donalsonville GA, USA / Thrush Aircraft 510G (registration N6216K)
METALLURGICAL REPORT

Background Information

Date of occurrence (DD/MM/YYYY):	28/09/2020
X-Fracas Event (if applicable):	GEAC-576
Event Narrative/Occurrence Sequence:	ACCIDENT – Pilot reported an engine power loss during flight without any previous indication. The pilot performed an emergency landing in the field. Pilot reported that the aircraft had approximately 2800 hours. There were no reported injuries. From the provided pictures of the airplane, it is visible that aircraft had a propeller strike and left side (aft looking forward) of the aircraft fuselage at engine location is damaged and engine suffered from exhaust case rupture.
ENGINE RECORDS	
Operator/Location/Aircraft:	Spring Creek Aviation LLC / Donalsonville GA, USA / Thrush Aircraft 510G (registration N6216K)
Engine Type:	H80-100
Engine S/N:	143016
TSN/CSN (TSO/CSO):	2760/3013



Background Information: Engine X-section



Material Engineering Statement

On Sept. 28th, 2020 Thrush Aircraft 510G (registered N6216K) operated by Spring Creek Aviation LLC experienced a Power Loss in Donalsonville GA (USA) and pilot performed an Emergency Landing in the Field. Visual examination of engine model H80-100 S/N 143016 indicated exhaust case breach (4 o'clock, FLA) & decoupled PT rotor with low energy debris release.

The present report gathers the results of Metallurgical Examination conducted on down-selected hardware relevant to the Root-Cause Analysis.

The metallurgical investigation results are consistent with the 360° teeth liberation on Sun Gear that led to the mechanical decoupling of PT from RGB and subsequent PT Loss of Load. Fractography conducted on stage 1 RGB gearing (i.e. Sun Gear & Planetary Gear in position 1 – 12.00 o'clock) supports a high contact stress condition initiation to fracture teeth in the vicinity of root land. Higher alternating stress propagation until full teeth liberation was underlined by coarser striation pattern and high density of secondary cracking. Stage 1 Planetary Gear suffered 8 consecutive teeth liberation at root radii, whose fatigue region aspect suggest a damage sequence from tooth N₀ (first liberated) to tooth N₇ (last liberated) as a result of mis-meshing following tooth N₀ liberation.

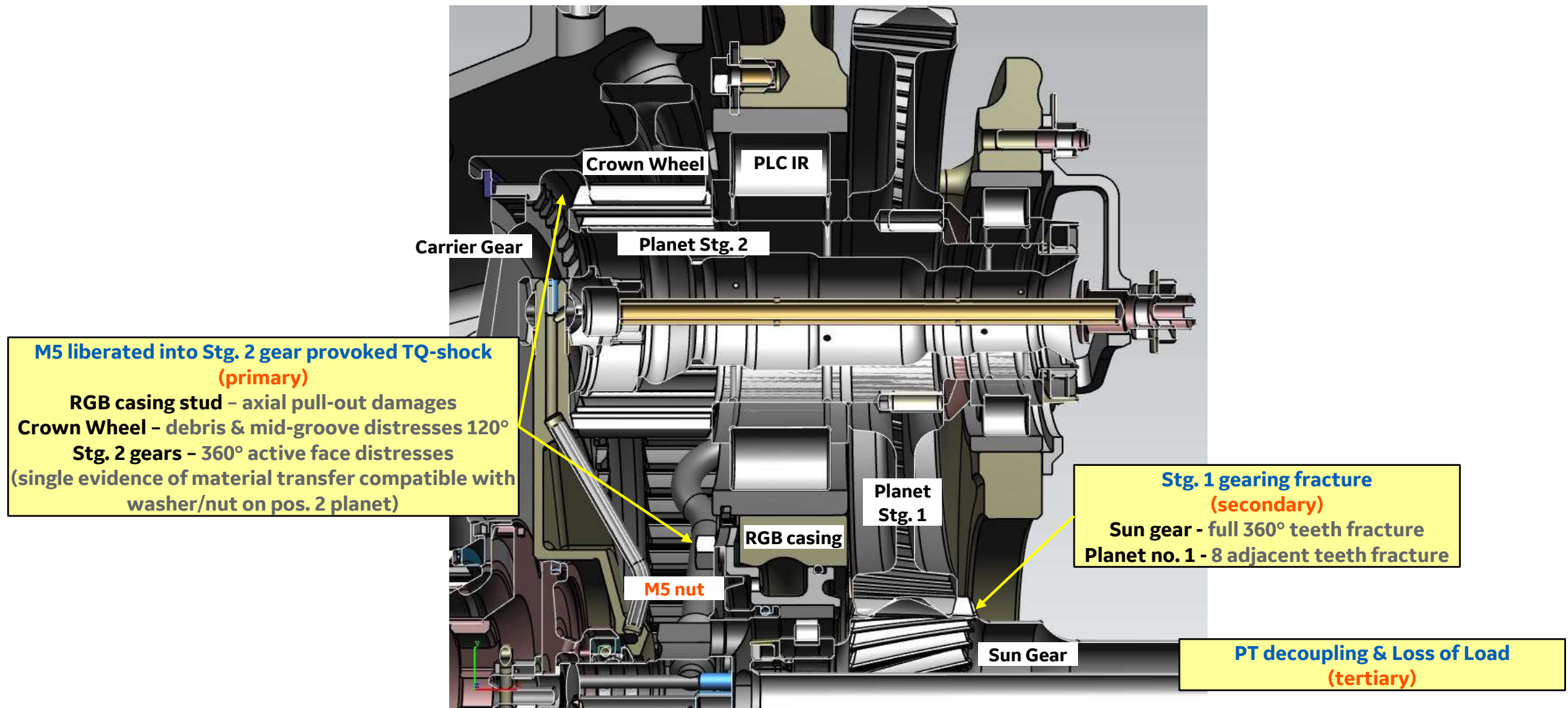
The metal debris collected on crown wheel forward groove was determined to match M5 nut material also reported missing at 3.00 o'clock FLA on TQ-meter flange during RGB disassembly. The nut most likely liberated prior to the event (**PRIMARY**) when taking into consideration 1) the limited axial displacement (forward direction) of M5 * 20 stud countershaft casing (sole CW location measured to be within drawing tolerance out of 6 studs on TQ-meter flange) and 2) the absence of axial pull-out damage of the thread. The M5 nut have easy access to fall by gravity into stage 2 gearing (between Crown Wheel and Countershaft teeth). Such a Domestic Object Damage (DOD) driven torque shock would eventually favor the failure of stage 1 gearing (**SECONDARY**) owing to its lower modulus (1.75) and helical design. This seems to be overall consistent with deeper imprint marks on active faces of stage 2 gears accounting for higher contact stress condition and further embodied by indications of radial misalignment. Such lever effect resulted in position 1 PLC bearing OR spalling with evidence of sub-surface microstructure alteration in line with higher contact stress condition.

The Power Turbine (PT) overspeed and PT disk separation from PT shaft flange is considered **TERTIARY**.

The above failure sequence is developed further in following pages.



Material Engineering Statement (Cont'd)



Material Engineering Statement (Cont'd)

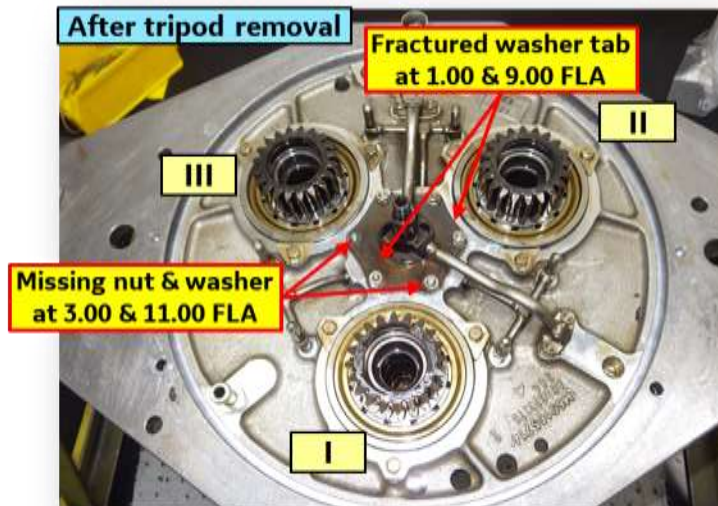
1. PRIMARY – TORQUE-METER SYSTEM M5 NUT LIBERATION INTO STAGE 2 GEARING (RGB)

TQ-meter Flange

Reported missing two (2) M5 nuts and two (2) securing tab washers at locations 3.00 and 11.00 (ALF) during RGB disassembly

- Thorough examination indicated the following
 - Flange side edge/face contact pattern appears to be similar irrespective of clockwise position, hence supposing washer tabs were initially secured.
 - Measurements of the axial displacement of M20 studs of countershaft casing was shown to be within drawing tolerance at 3.00 o'clock location (FLA) only, while exceedance was the greatest at surrounding locations 1.00 and 5.00 (FLA). This feature might indicate a higher load-carrying as a result of either missing or loosen M5 nut, despite the presence of through crack of countershaft casing at these locations might also have contributed to the displacement.
 - Moreover, the relative elongation of stud was measured to be the highest at 11.00 (7.5%) and 7.00 (6.4%) compared to other locations ($\leq 3\%$), the same trend being noticed for axial flatness exceedance of TQ-meter flange (CMM) supporting uneven repartition of axial pulling force/load in fwd direction.

=> In light of the above and the absence of apparent pull-out damage indicators on the stud thread at 3.00 location (neither bending nor distortion component), the assumption of missing M5 nut at location 3.00 prior to event occurrence is concluded as pertinent.



Material Engineering Statement (Cont'd)

1. PRIMARY – TORQUE-METER SYSTEM M5 NUT LIBERATION INTO STAGE 2 GEARING (RGB)

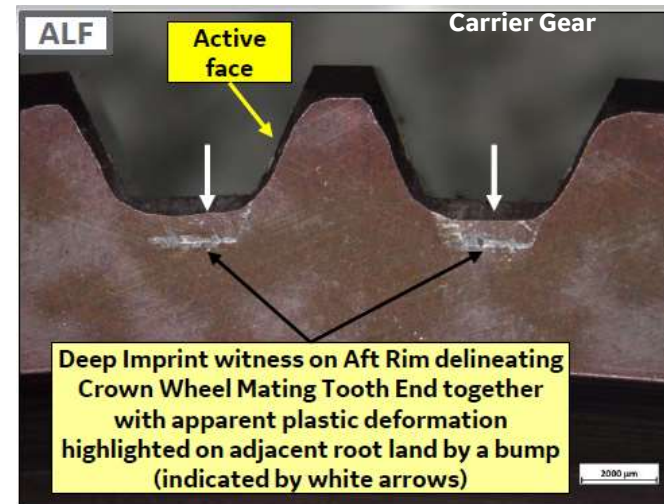
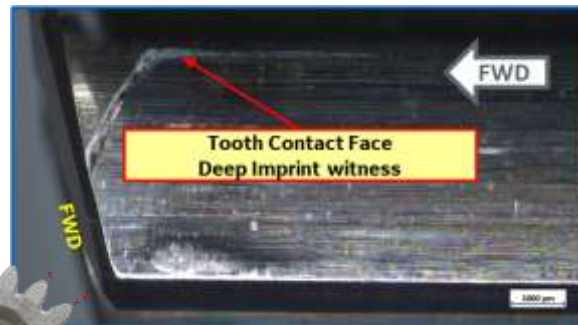
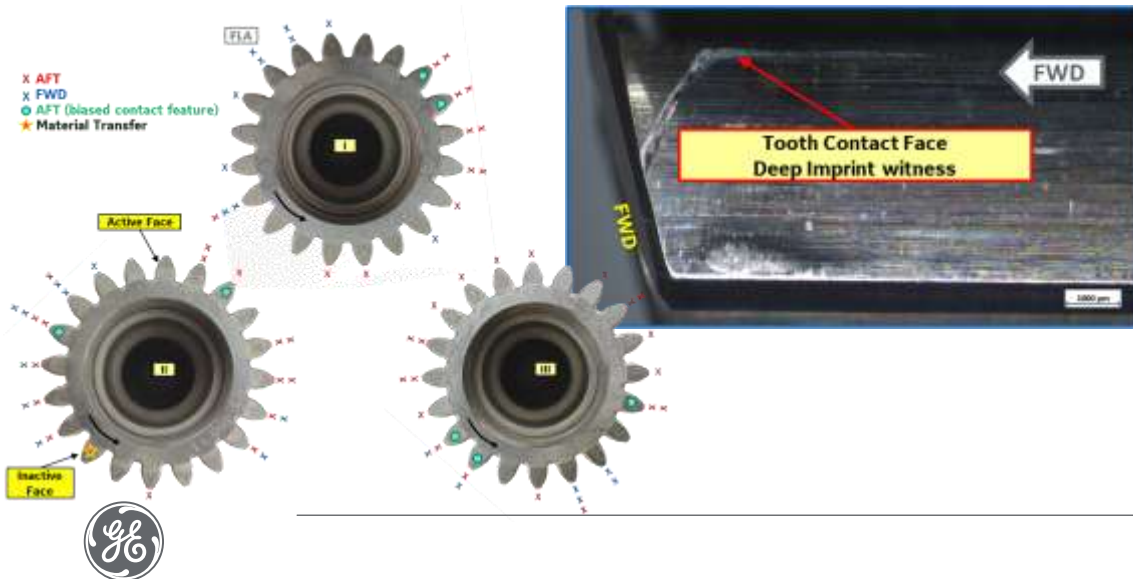
Stage 2 Planetary Gears

Active faces examination revealed the presence of **higher contact stress distresses 360°**, irrespective of the examined gear & RGB position

- **Damage map summary in FLA clocked positions: most distressed/rated segment appears to be synched to the single evidence of material transfer demonstrated on gear S/N 1530 (position 2) and compatible with washer &/or M5 nut (or combination thereof)**
- **Deeper imprint witnesses on gear S/N H1515 fwd end (position 1)** were not correlated to conclusive indications accounting of material transfer (**nut ingestion**)
- Note that the presence of biased contact imprints on active faces aft region might support radial misalignment with Crown Wheel

Debris, Crown Wheel and Carrier Gear

- The hypothesis of **Domestic Object Damage DOD** (i.e. liberated M5 nut) is further corroborated by the extensive work conducted on engine debris with a particular attention paid to **metal debris found on Crown Wheel** adjacent to local distressed observed on the fwd groove.
- Outcome is that parent material was **determined to be consistent with M5 nut material**, while the total mass of debris matching M5 nut (including a partially damaged and recovered M5 nut) appears to exceed the average representative mass of random damage-free nut, thereby indicating that a **M5 nut had to be crushed into the gearing (in line with 1 missing nut out of 22 expected in RGB after recount)**
- **Crown Wheel and Carrier Gear** also display unusual condition that supports **contact distress**



Material Engineering Statement (Cont'd)

2. SECONDARY – RGB STAGE 1 GEARING FRACTURE

Stage 1 Planetary Gear S/N 1815, position 1 – 12.00 o'clock

Visual examination revealed **8 consecutive fractured teeth (numbered from N_0 to N_7)** in the vicinity of root land/radius area with apparent **fatigue macro-features indicating primary origin on active/loaded teeth face**.

- **MPI** enabled to reveal **one (1) indication** emanating from fractured tooth root radius emerging on fwd rim and developing inboard the web ~ 25mm radial length.
- **Fractography** demonstrated **multiple surface-initiated cracking on teeth active faces span in the vicinity of root radius**.
 - Fatigue region morphological features indicate a **high alternating stress propagation** with **coarser fatigue striation pattern** and **secondary cracking** along the propagation direction towards inactive face of the teeth.
 - Additionally, a **minor fatigue component emanating from teeth inactive face** was also noted. A narrow band of tensile overload was locally observed when intersecting main fatigue front emerging from active faces in the absence of excessive smearing.
 - The **striation density** was assessed and determined to **vary between 50-70k striations/inch** (resolved beyond ~ 0.5mm from crack edge) to **20-30k striations/inch** as the crack progresses, hence **within the range of a higher alternating stress propagation condition**.
 - **Crack edge** of all active faces (fractured or not) display common **witness of high contact stress initiation condition** * emphasized by the presence of significant deformation (original machined lines vanished). Note also the occurrence of numerous secondary cracking underlying the main fracture plane and initiated primarily by ratchet marks and along original machined lines.



OTHER

- **Planetary Gears S/N 1818 and S/N 1838** respectively at 8.00 o'clock (RGB position 2, FLA) and 4.00 o'clock (RGB position 3, FLA) only exhibited secondary damages with locally embedded teeth debris without apparent fatigue indicators.
- **Two (2) small MPI indications** ~ 3mm length were also reported on **Planetary Gear S/N 1818** on both active and inactive face root radii of the only partially damaged tooth (secondary).

* **Replicas carried out on active/inactive faces** also support a **high contact stress pattern 360°** on teeth root land region for the three (3) Planetary Gears

Material Engineering Statement (Cont'd)

2. SECONDARY – RGB STAGE 1 GEARING FRACTURE

Stage 1 Planetary Gear S/N 1815, position 1 – 12.00 o'clock

Among the pool of consecutive fractured teeth, the **tooth N₀** adjacent to the 1st “damage-free” tooth displays peculiar features, i.e. smoother fatigue region with absence of apparent macro-beachmarks.

- In contrast, subsequent teeth fractures exhibit more pronounced topography and higher density of secondary cracking, while having steeper crack entry & propagation plane (~45 degree), thereby supporting **damage sequence from tooth N₀ to tooth N₇** in the rotation direction. This seems to be in line with the generic evolution of fatigue region aspect implying a **contact pattern offset toward aft** side of teeth and consistent with anticipated consequence of **meshing issue on helical gear following the liberation of tooth N₀**.
- **Recovery and sequencing of liberated Planetary Gear teeth debris** did not show relevant indications of any significant prior face distresses but high contact stress witness with sun gear teeth in the vicinity of face root

=> **This observation tends to spot on the sudden nature of the event occurrence in good agreement with fractography observations (also supported by fresh metal fracture and absence of oil varnishing).**

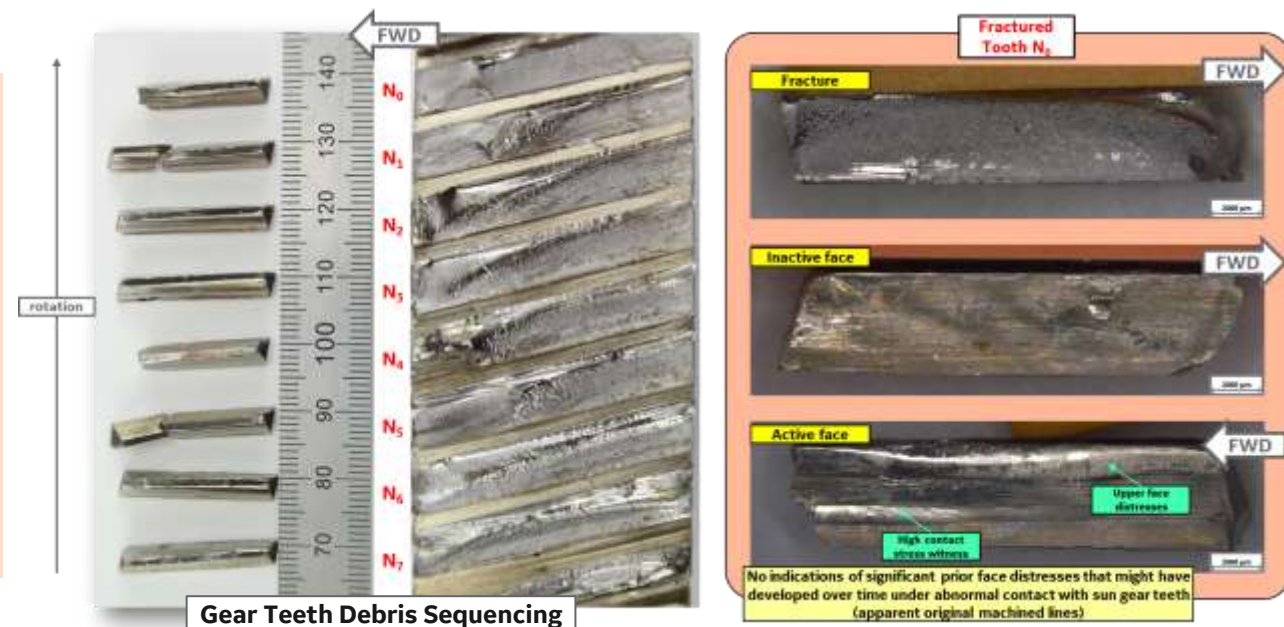
OTHER

PLC 46-8-4 Roller Bearing TPFK 441

- Varnished portion of the running track appears to be in line with high load segment according to stress model prediction and observations on other single engine RGB without abnormal extent
- Presence of a narrow but relatively deep (~ 0.3 mm dist. from original surface) **fatigue spalling on running track of bearing outer ring** in position 1 combined to the presence of **sub-surface butterflies** (altered bearing steel microstructure) demonstrated by step-polishing through spalled region also indicates an **abnormal contact stress occurrence (limited radial clearance)**
- No material structure anomaly and conforming micro-hardness

N203 TPFK 326 Roller Bearing

Sanity check was conducted on bearing elements and did not show any apparent indication of distresses nor malfunction prior to the event



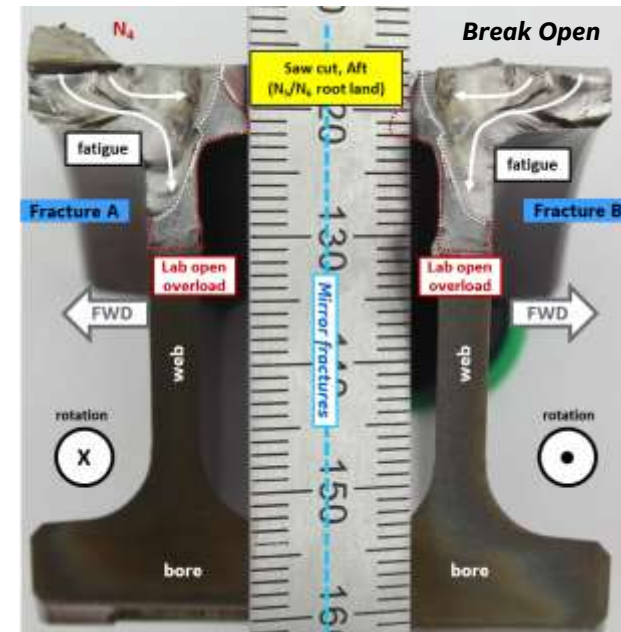
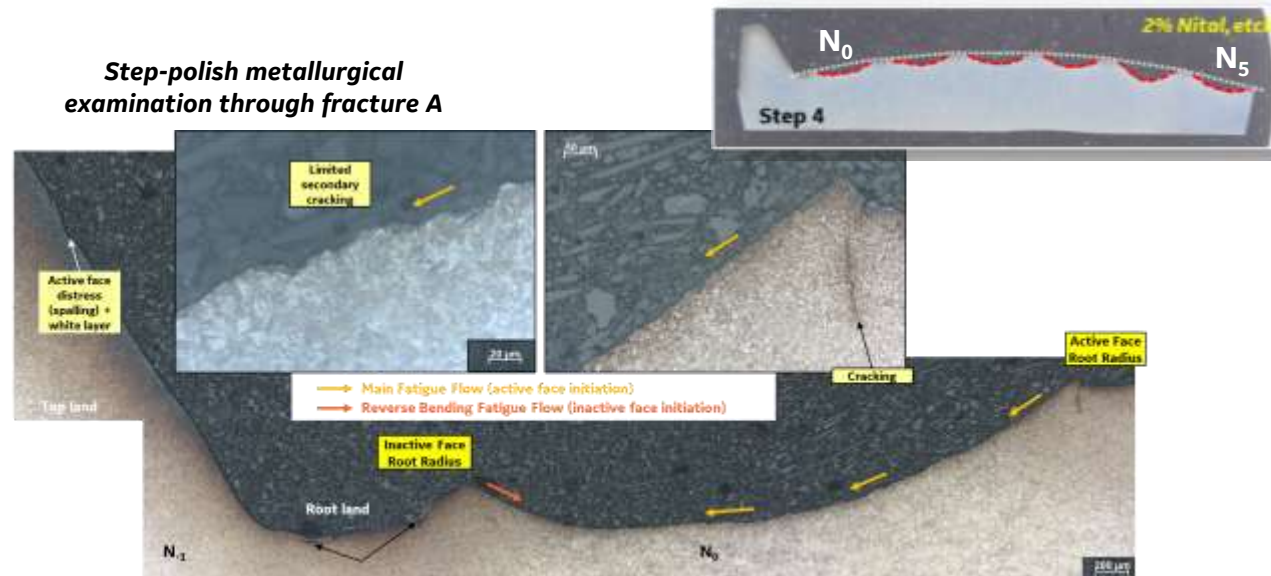
Material Engineering Statement (Cont'd)

2. SECONDARY – RGB STAGE 1 GEARING FRACTURE

Stage 1 Planetary Gear S/N 1815, position 1 – 12.00 o'clock

Lab break open of Planetary Gear S/N 1815 secondary cracking revealed by MPI between teeth N_4 & N_5 allowed to document the fatigue crack propagation inboard the gear web initiated from tooth N_4 fwd root radius and developing through adjacent tooth N_5 (the extent of smear damages prevented a thorough fractography work).

- **Metallographic step-polishing into Planetary Gear S/N 1815 fracture A** consisting of consecutive teeth from N_{-1} , i.e. 1st “damage-free” tooth adjacent to N_0 , to N_4) **did not reveal any material microstructural anomalies of base material** (*axial polish perpendicular to teeth axis - from mid span toward aft side of the gear teeth*). The apparent increase of secondary cracking density and crack-entry steepness from tooth N_0 to N_7 noted during surface fractography was further confirmed as well as the **trans-granular nature of crack propagation**.
- Worth mentioning the surface distresses specifically observed on root land adjacent to 1st fractured tooth N_0 with the alteration of its original dimensions and microstructure (thin superficial white layer, plastic deformation) implying contact with top land of mating Sun Gear.
- The 1st “damage-free” tooth shows relatively thick and even white layer on its top land as well as thin and discontinuous white layer and surface-initiated cracking/spalling on its loaded face only.



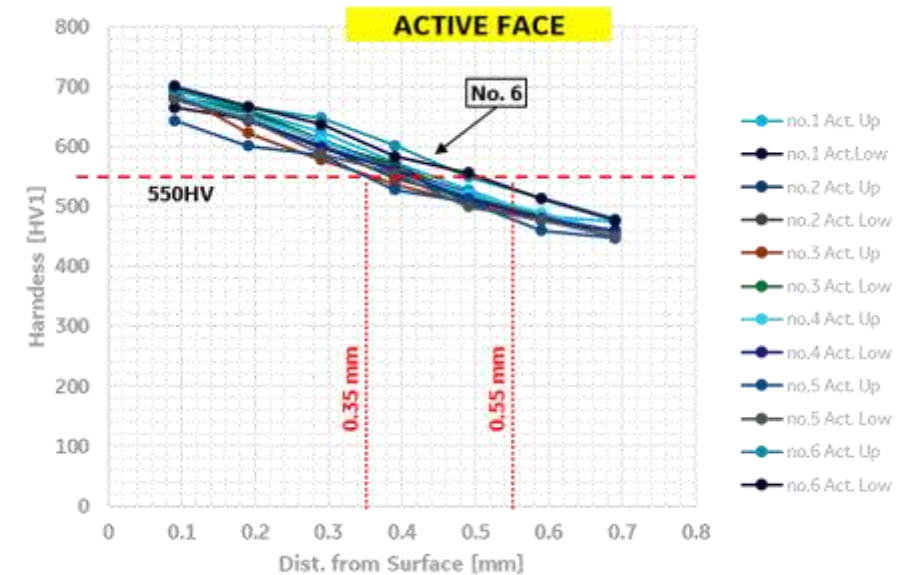
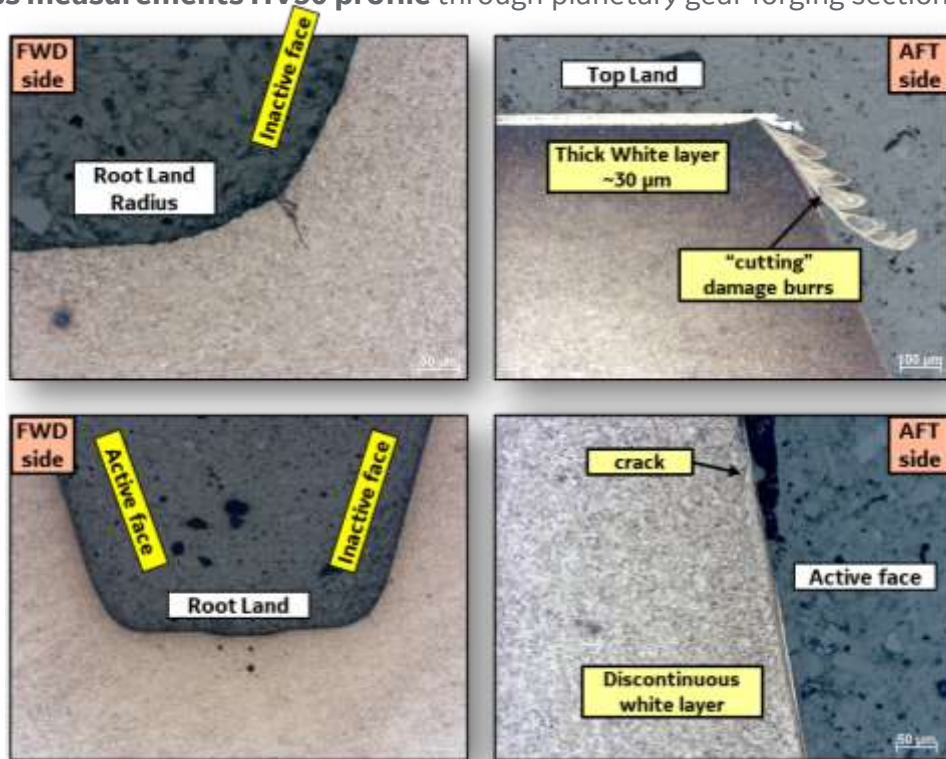
Material Engineering Statement (Cont'd)

2. SECONDARY – RGB STAGE 1 GEARING FRACTURE

Stage 1 Planetary Gear S/N 1815, position 1 – 12.00 o'clock

Metallurgical cut-up prepared on segment 4.00-5.00 away from the main fracture and damage zone indicated comparable distress on contact/loaded faces, i.e.:

- surface-initiated cracking and spalling)
- top land (thick and even white layer with presence of “cutting damage” burrs on edges)
- numerous occurrences of crack initiation on root radii of inactive faces
- **CHD measurement results** conforming to requirements for new-make parts irrespective of measurement location.
- **Micro-hardness measurements HV30 profile** through planetary gear forging section **did not reveal abnormality.**



CHD measurements stack (active faces)

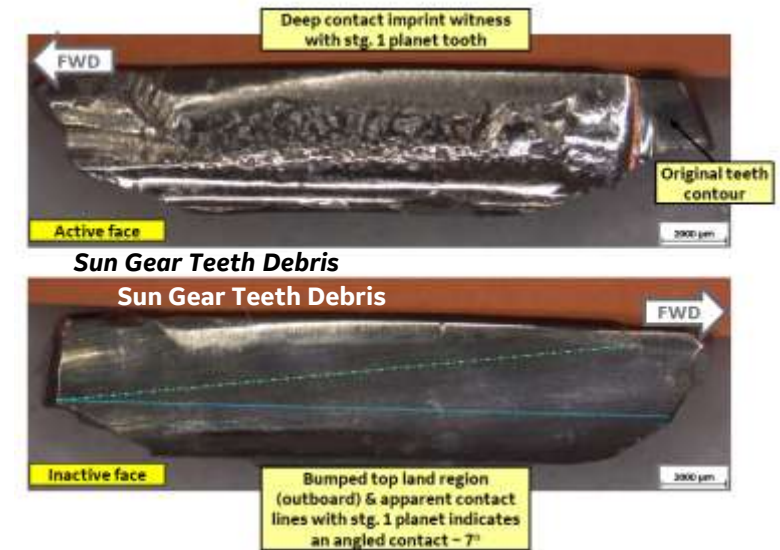
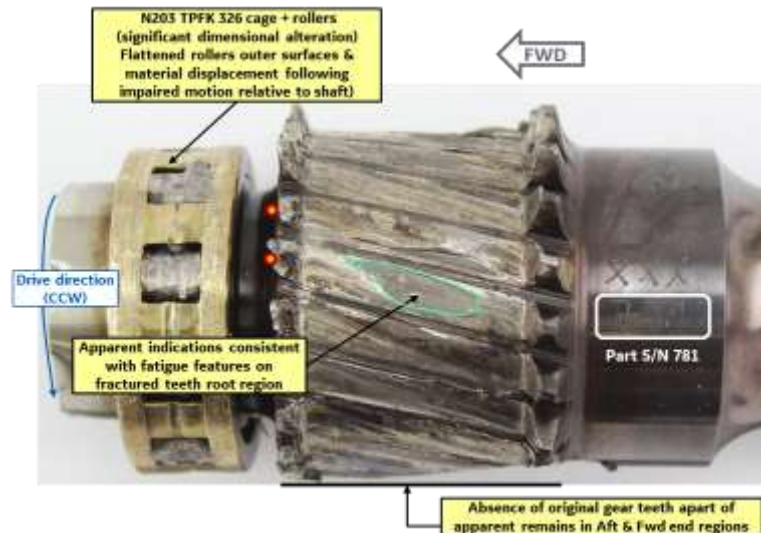
Material Engineering Statement (Cont'd)

2. SECONDARY – RGB STAGE 1 GEARING FRACTURE

Sun Gear S/N 781

Visual examination indicated the **absence of teeth 360°** (root land fractures) and apparent **fatigue macro-features emanating from the active/loaded face** on a limited number of teeth in the absence of secondary damages.

- The extent of wear on spline active faces does not appear to be excessive compared to average single engine application RGBs with comparable life.
- The aft spline coupled to the PT rotor shows both bending and torsion components measured to be ~ 21° and 4°, respectively.
- **MPI** did not reveal any interpretable indications
- **Fractography** demonstrated comparable features to those reported for Planetary Gear and consisting of
 - **1) multiple surface initiation** with apparent indications of **high contact stress condition** with severe deformation and material displacement on crack edges
 - **2) high alternating stress propagation condition.**
- A limited number of **Sun Gear liberated teeth debris were recovered** and emphasized
 - **1) high contact stress** with the presence of **planetary Gear teeth contour imprint witness**
 - **2) apparent indications of contact mismatch with radial offset** documented on inactive teeth faces that might suggest a **sudden TQ-transfer shock.**
- **Microstructure and micro-hardness** were demonstrated to be conforming to new-make requirements.



Material Engineering Statement (Cont'd)

3. TERTIARY – PT OVERSPEED & PT DISK SEPARATION FROM PT SHAFT FLANGE

PT Shaft S/N 008

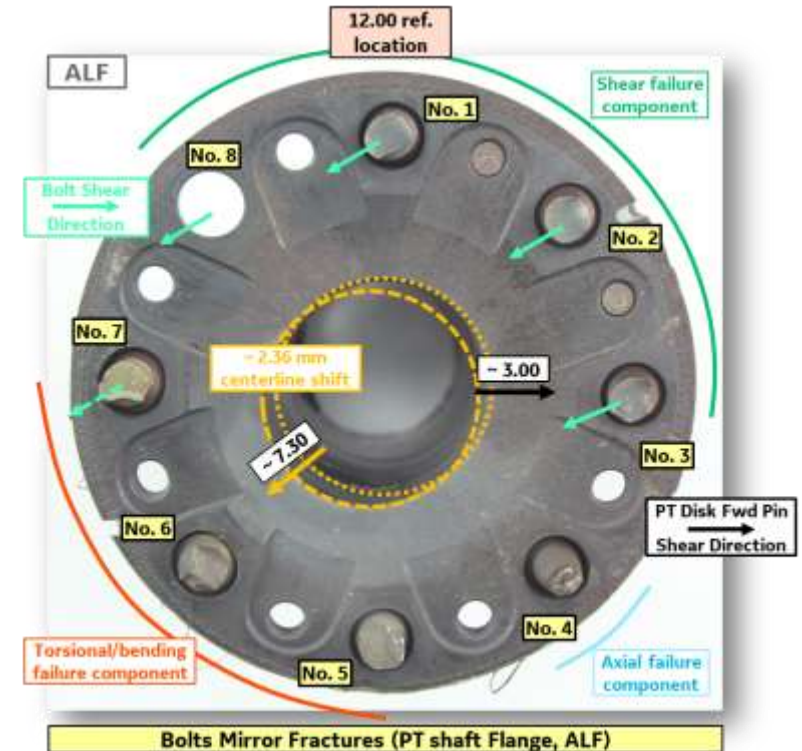
Separated from the PT rotor disk on the bolted flange had to be cut in 2 locations for disassembly purpose.

- **Altered circularity and outboard deformation from bending** is observed on fwd end ~ 7.30 location (FLA) in line with Quill-Shaft spline condition (connected to Quill-Shaft through spline coupling)
- Shaft Aft End also displays deformation component at ~ 7.30 (ALF) and relates to the PT disk fwd pin deformation direction
- **Mapping of seized T-head bolts fracture aspect features (ALF) allowed to demonstrate to presence of two (2) main failure component, i.e.**
 - Shear / angled 45°: primarily from 3.00 (bolt no. 3) to 9.00 (bolt no. 7)
 - Torsional/bending / flatter: from 6.00 (bolt no. 5) to 7.00 (bolt no. 6) ⇔ associated with ovalized flange bolt hole (tangential direction to rotation)
 - Axial / necking: at 5.00 o'clock only (bolt no. 4)
- Flange contour also indicates greater damage and deformation between bolts no. 4 (5.00) to no. 7 (9.00) supporting higher axial load component
- In light of the above, a **damage sequence might be derived** as follows: **1) shear seizure** of bolts no. 3 to 8 (3.00 to 11.00 o'clock); **2) torsional overload** of bolts no. 5 to 7 (6.00 to 9.00 o'clock) and **3) axial pull with apparent necking and overload**

PT Disk S/N 813 404 – 1019

Severe damages 360° and apparent rub marks ~180° FLA. Two (2) bolt nuts in position (no. 4 & 7), no. 4 being removable without applying force

- **Fractured Fwd pin sheared outboard** at ~ 3.00 o'clock ALF and **blue tinted**
- Bolt holes show features consistent with observations made on PT shaft flange & seized T-head bolts



OTHER

PT blades debris

Inter-dendritic fractures in the vicinity of dovetails

QJ206 TPFK 329 Ball Bearing

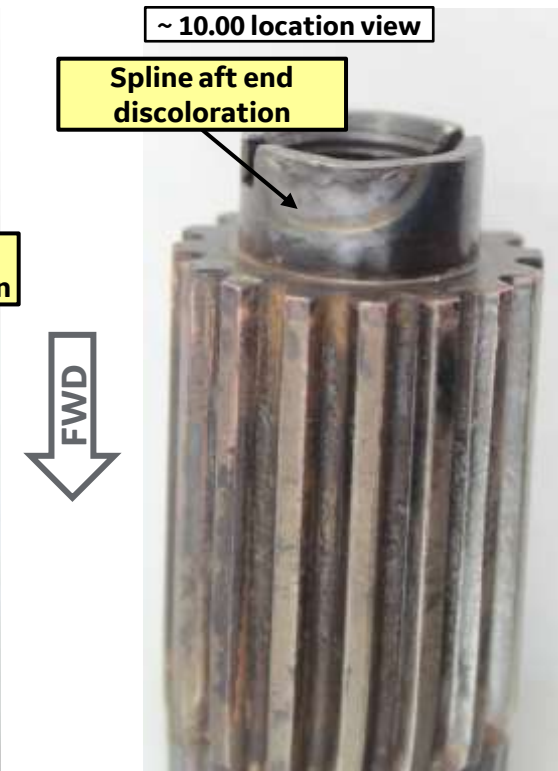
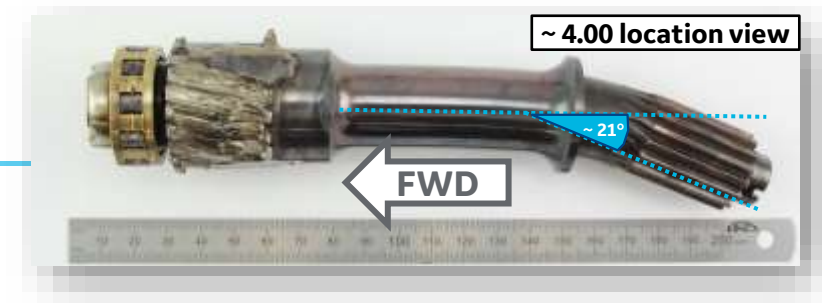
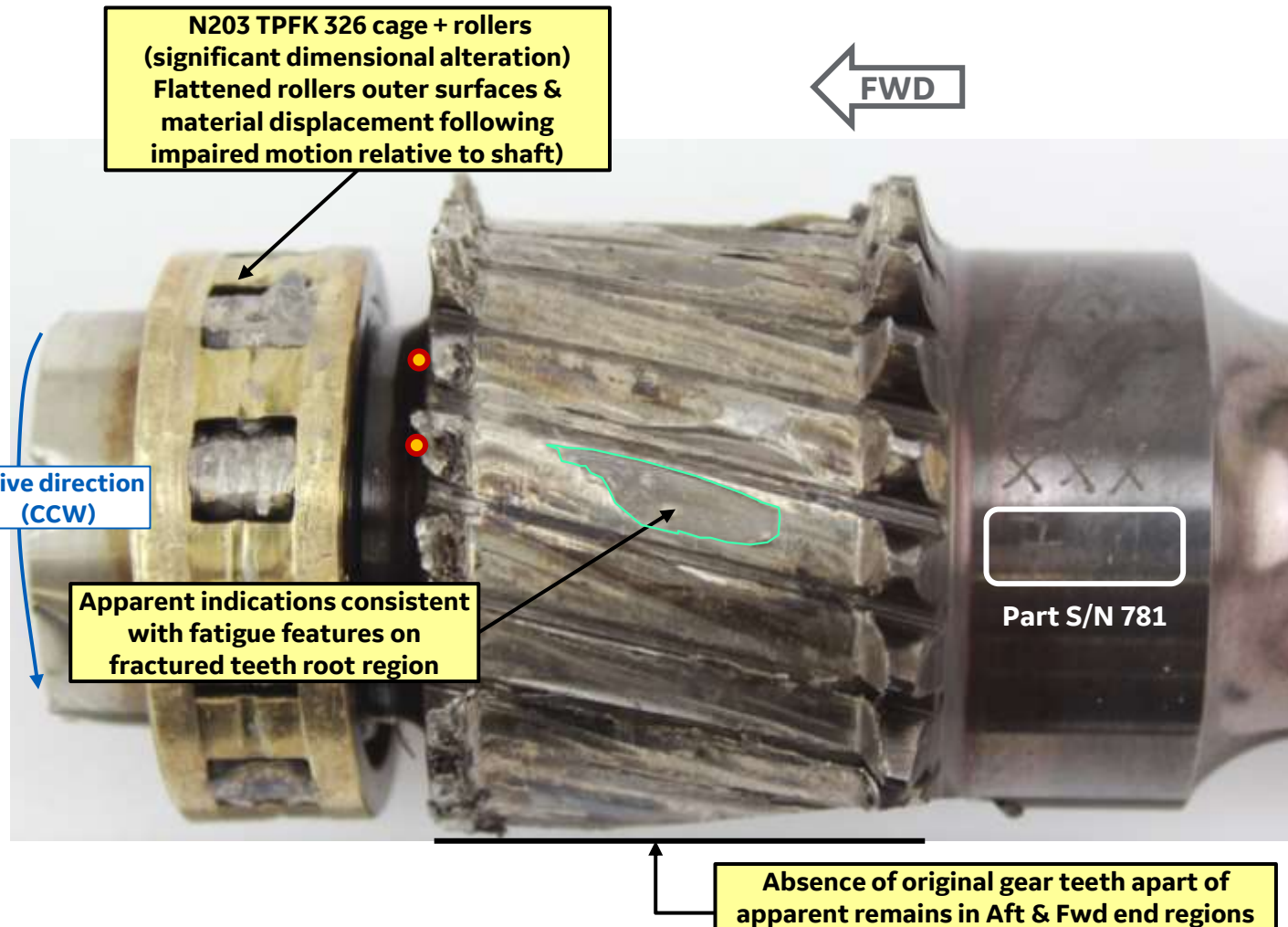
Sanity check was conducted on bearing elements and did not show any apparent indication of distresses nor malfunction prior to the event

RGB STG. 1 GEARING

SUN GEAR

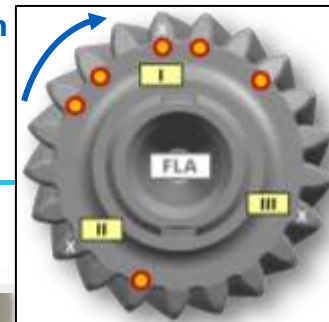


Visual Inspection (as-received)



Visual Inspection (as-cleaned)

Drive rotation
(CW, FLA)



12.00

3.00

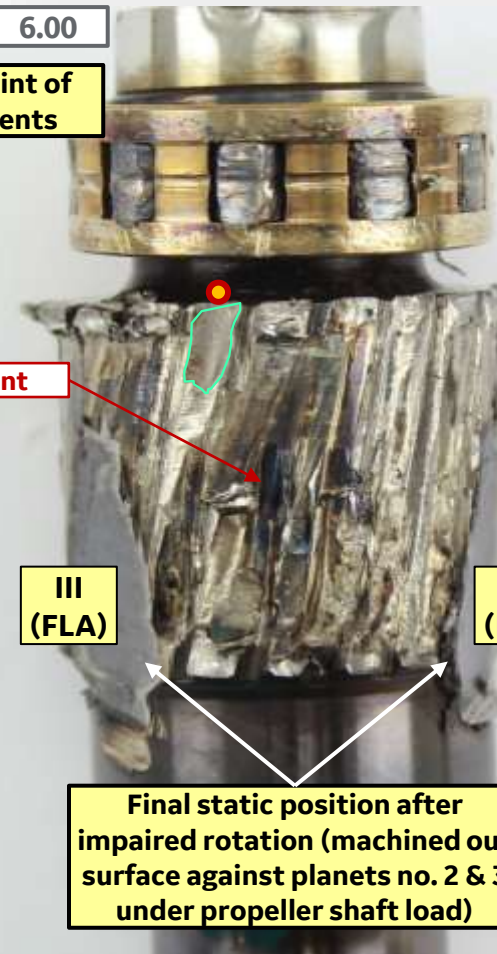
6.00

9.00



Limited heat tint of
bearing elements

Heat tint



Final static position after
impaired rotation (machined out
surface against planets no. 2 & 3
under propeller shaft load)



Apparent macro-fractographic features ●



Visual Inspection (as-cleaned)



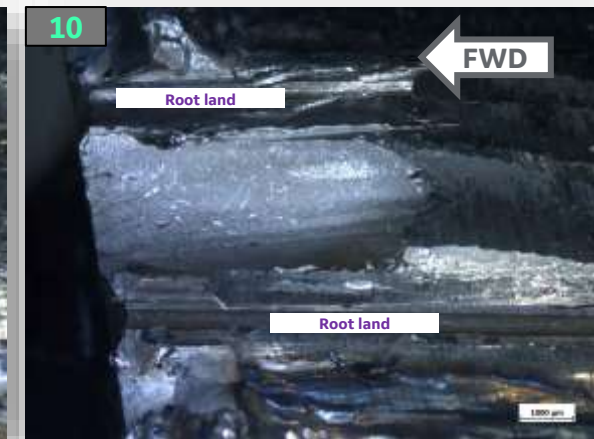
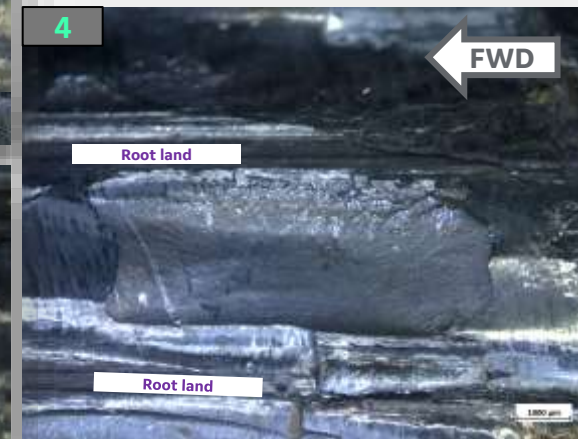
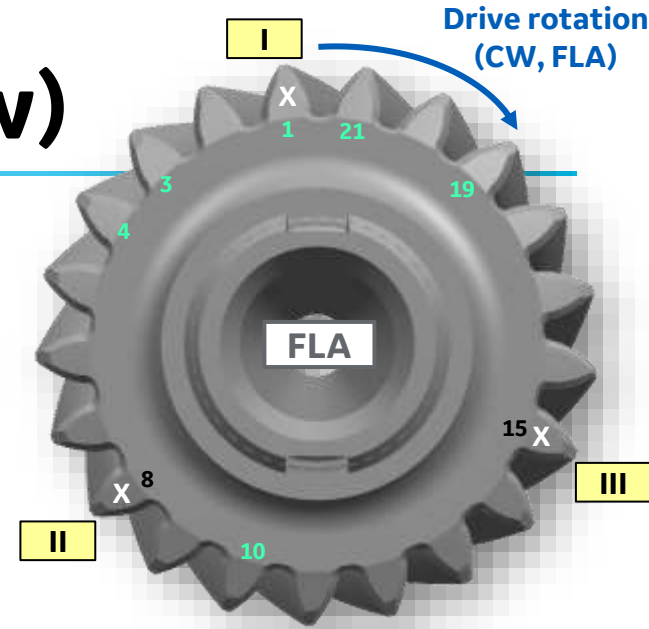
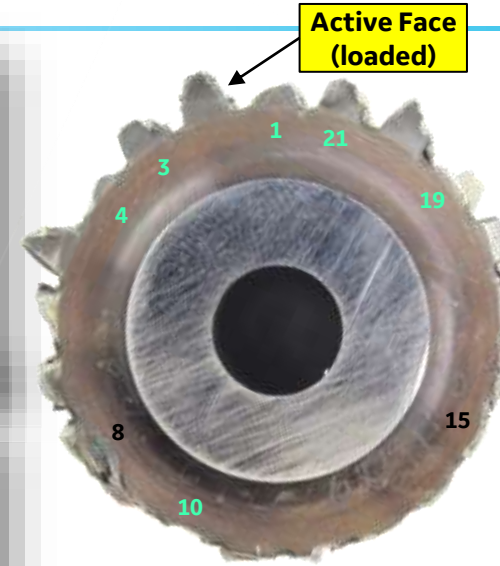
Stereo-micrograph (fracture overview)

~ 18 mm dist. from tooth fwd end

Drive direction

~ 13 mm dist. from tooth fwd end

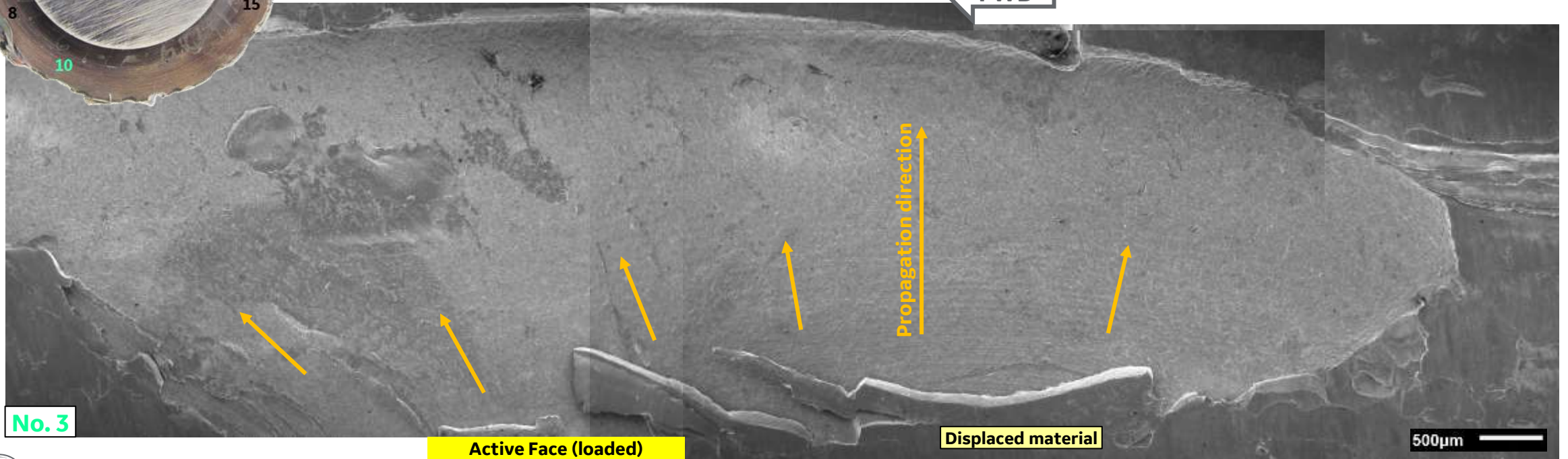
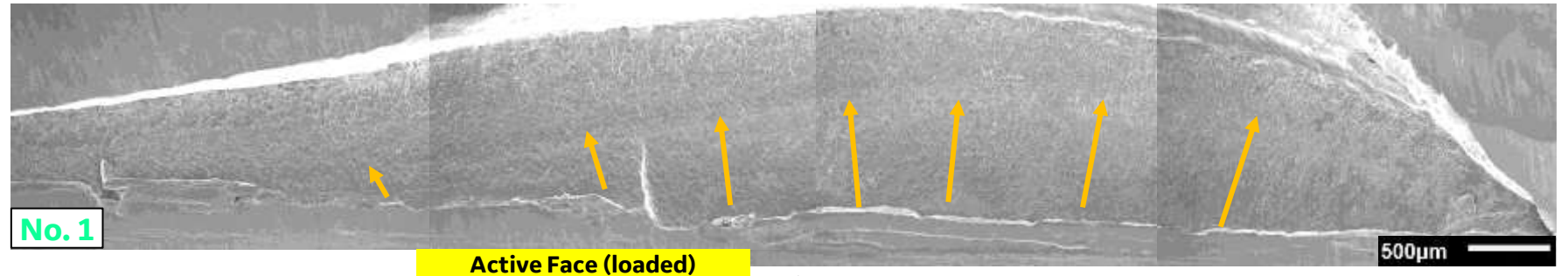
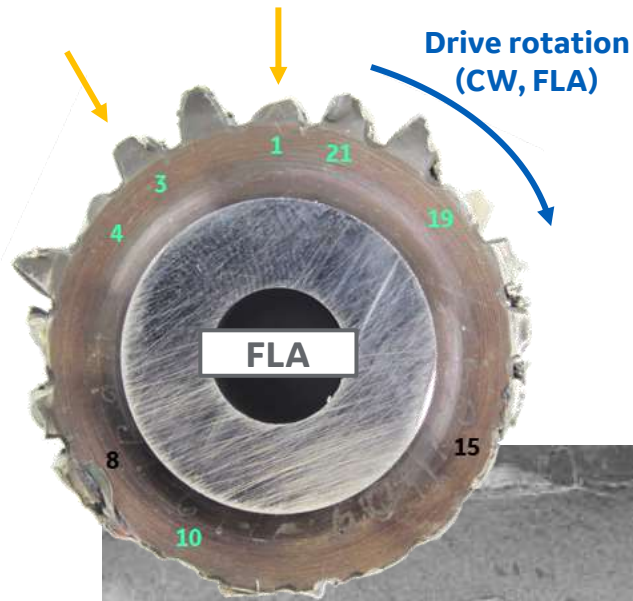
~ 16 mm dist. from tooth fwd end



~ 17 mm dist. from tooth fwd end



Fractography (teeth no. 1 & 3 overview, FLA)



Drive direction

Metallurgical Examination

Micro-hardness HV30 summary

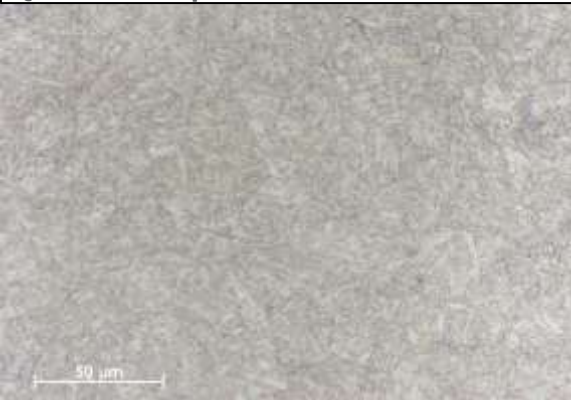
Quill-Shaft M601-6172.6

- 415 ± 7 in transverse direction
- 432 ± 2 in axial direction

PT Shaft M601-4004.5

- 371 ± 5 in transverse direction
- 388 ± 2 in axial direction

Quill-shaft (representative microstructure)



PT shaft (representative microstructure)

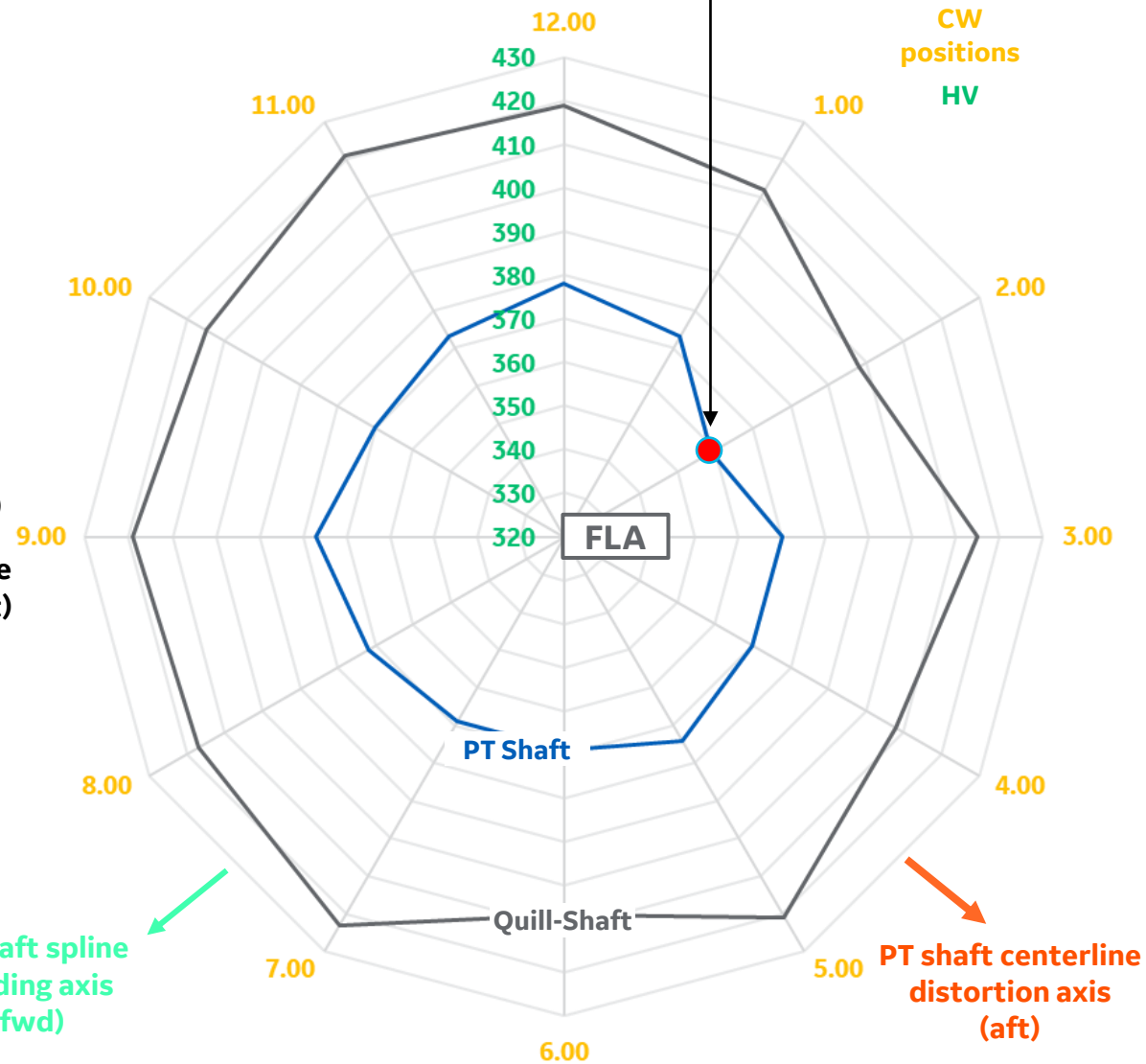


PT disk pin
shear axis (fwd)
←
Quill-shaft Spline
bending axis (aft)

PT shaft spline
bending axis
(fwd)

PT shaft centerline
distortion axis
(aft)

Significance of clocked micro-hardness drop at 2.00 & PT shaft HV30 < LSL (363HV) likely related to bending axis



Metallurgical Examination

Homogeneous martensitic structure containing
tempered martensite & partially retained austenite
ASTM E112 finer than GS 5.0 min. requirement

Quill-Shaft M601-6172.6 (L-TER.4 alloy)



PT Shaft M601-4004.5 (1.6722.9+T alloy)



RGB STG. 1 GEARING

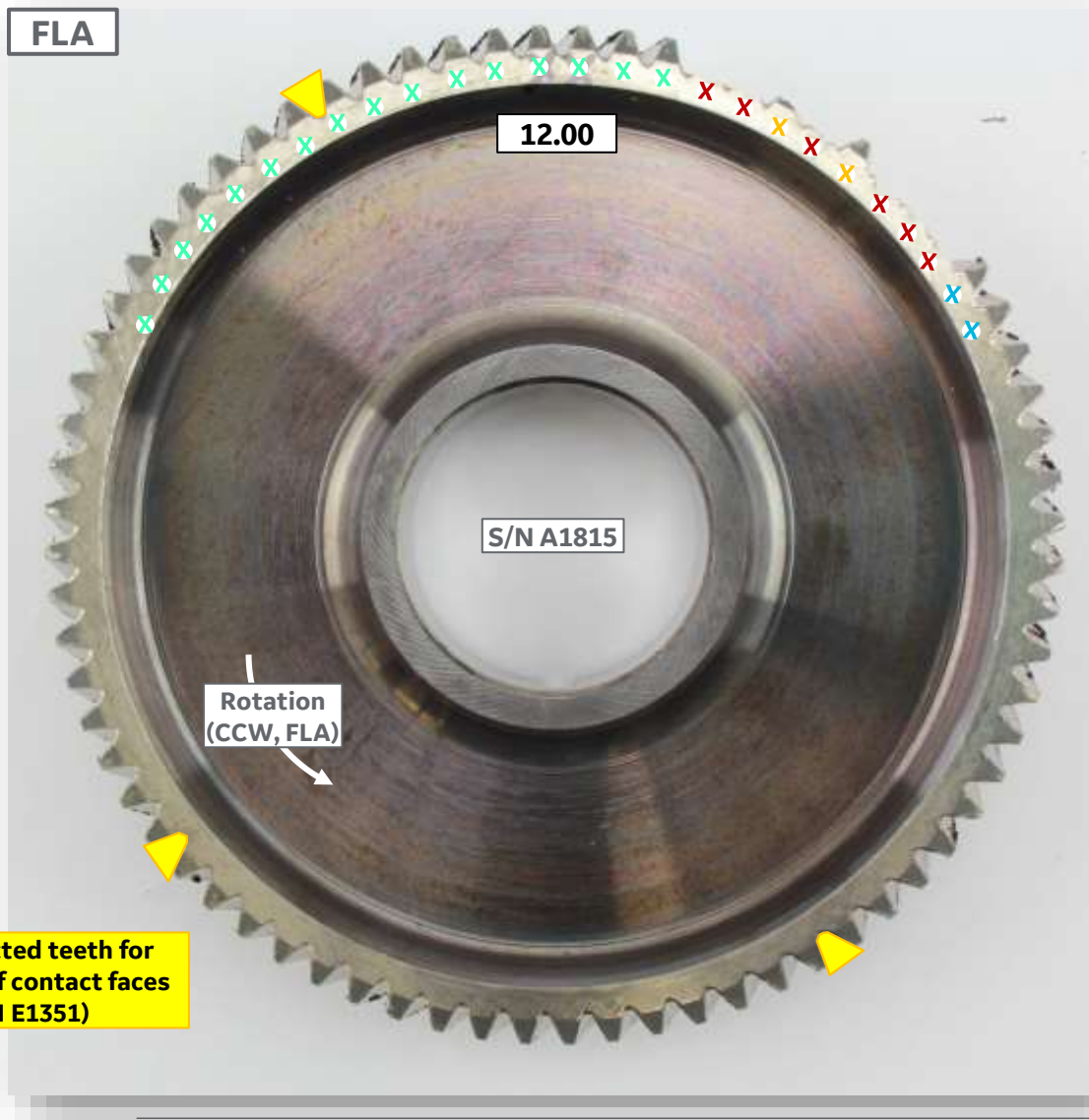
PLANETARY GEARS



Visual Inspection (as-cleaned, pos. I)

Teeth Damages Nomenclature

- ✗ Fracture | Root - Full length
- ✗ Fracture | Root - Partial length
- ✗ Fracture | Mid-Chord - Partial length
- ✗ Secondary | Large Top Land Track



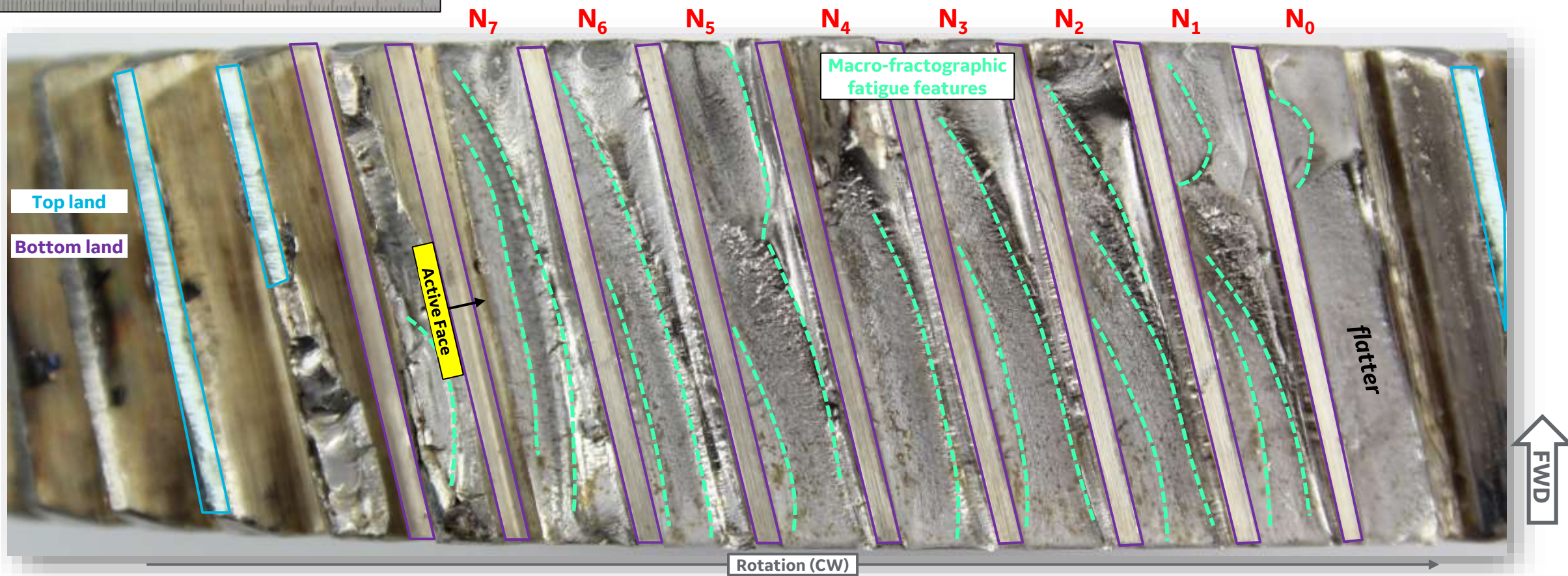
Down-selected teeth for replication of contact faces (ASTM E1351)



Visual Inspection (as-cleaned, A1815, pos. I)



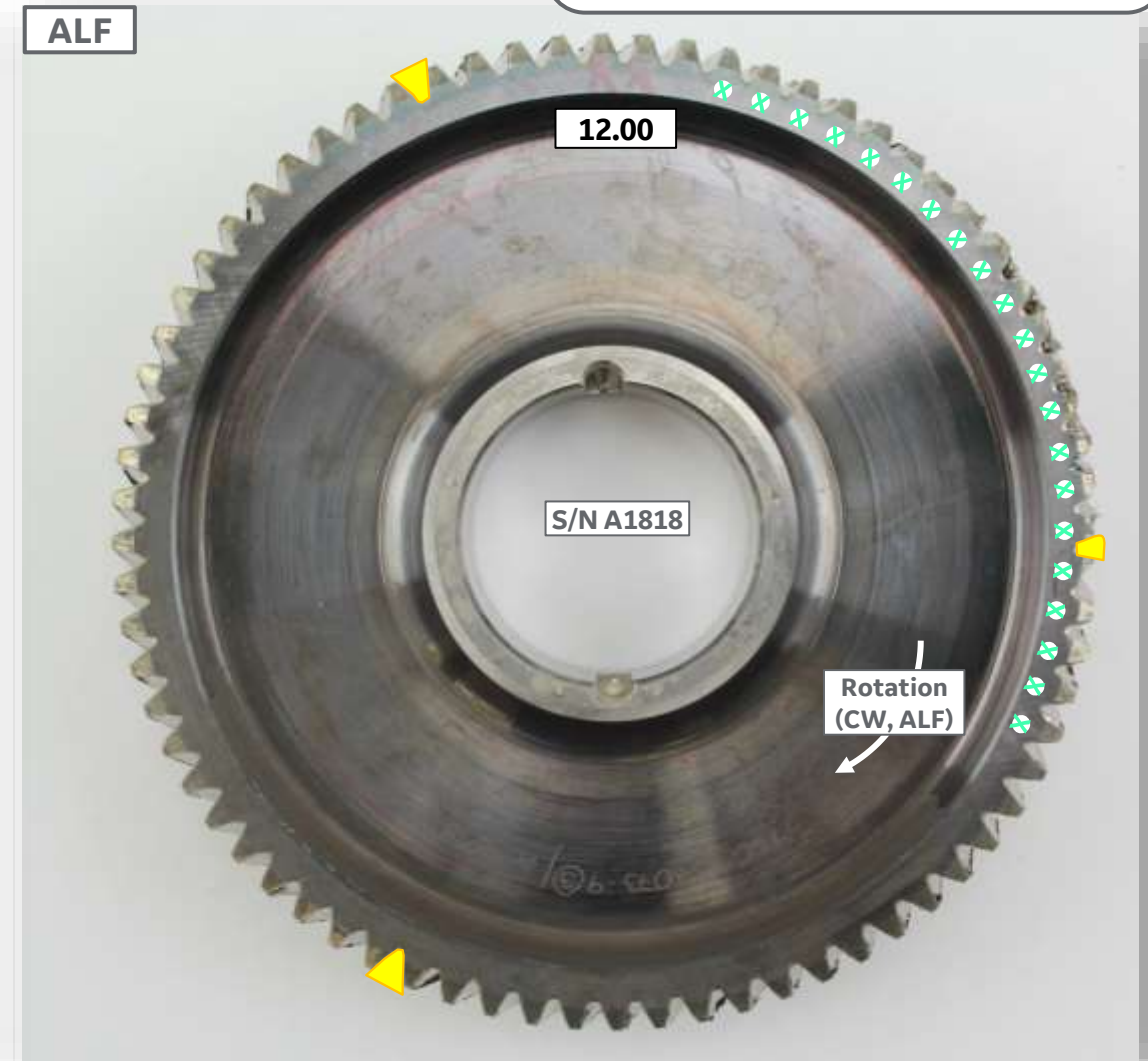
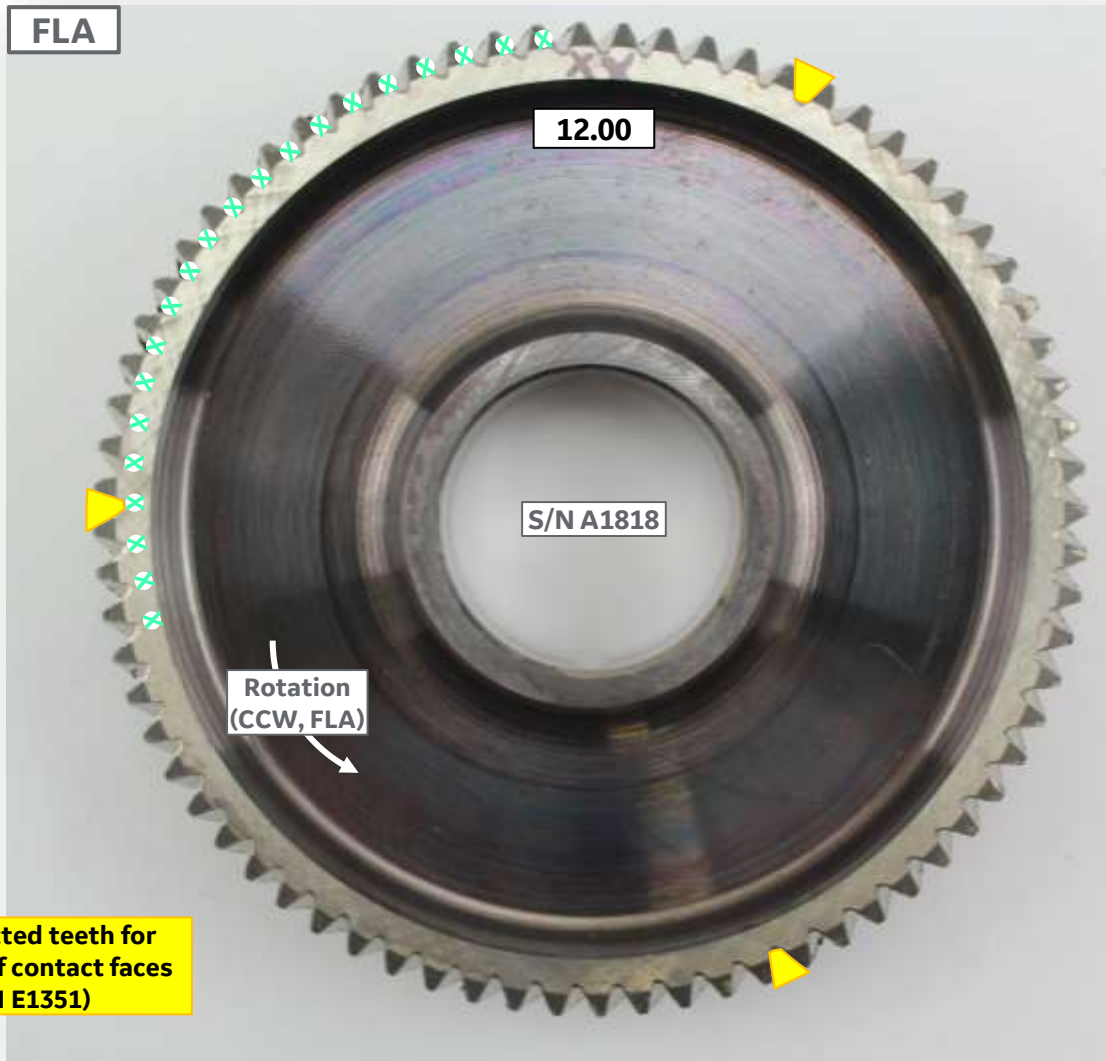
- Macro-fractographic features indicating fatigue fracture emanating from root area on active faces of teeth (multiple origin) – note flatter fracture on N_0
- Smoother initiation region & transition to greater apparent topographical changes along crack propagation ($\Leftrightarrow$ cycles)



Visual Inspection (as-cleaned, **pos. II**)

Teeth Damages Nomenclature

- X Fracture | Root - Full length
- X Fracture | Root - Partial length
- X Fracture | Mid-Chord- Partial length
- X Secondary | Large Top Land Track

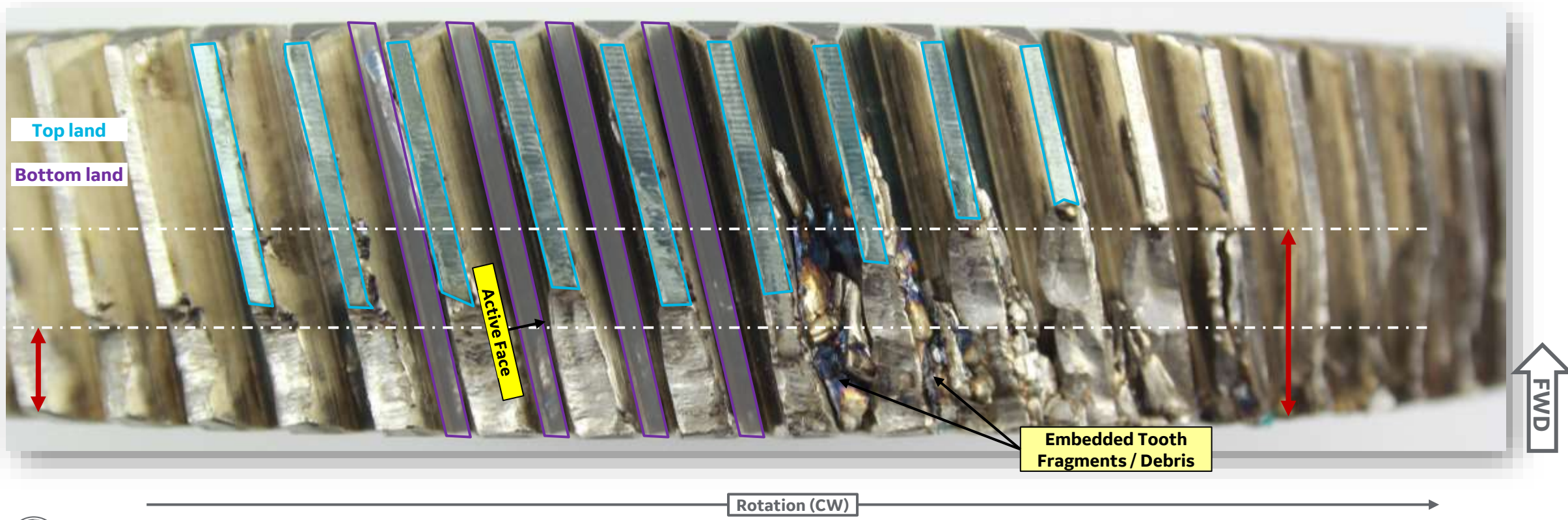


Down-selected teeth for
replication of contact faces
(ASTM E1351)

Visual Inspection (as-cleaned, A1818, pos. II)



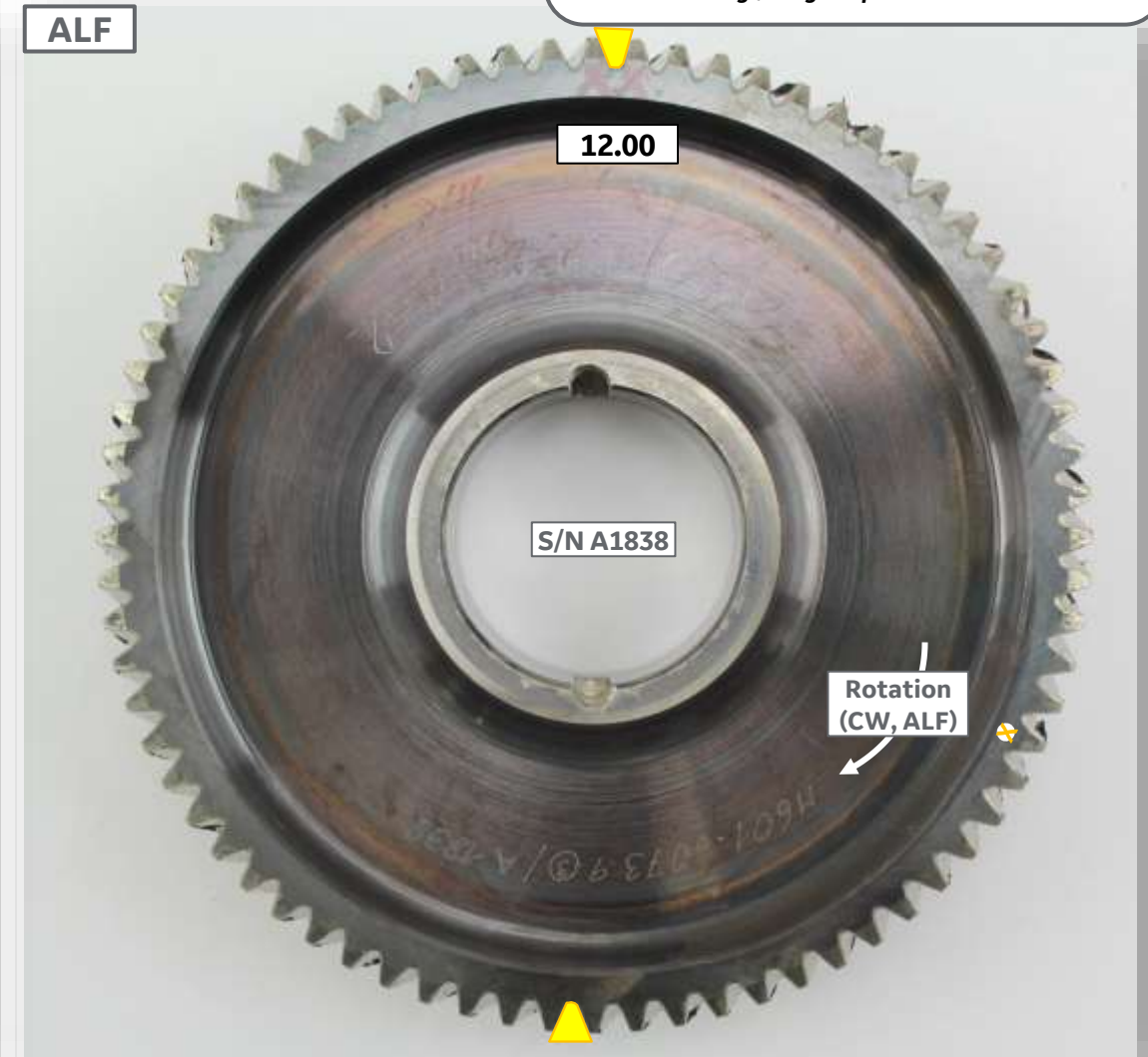
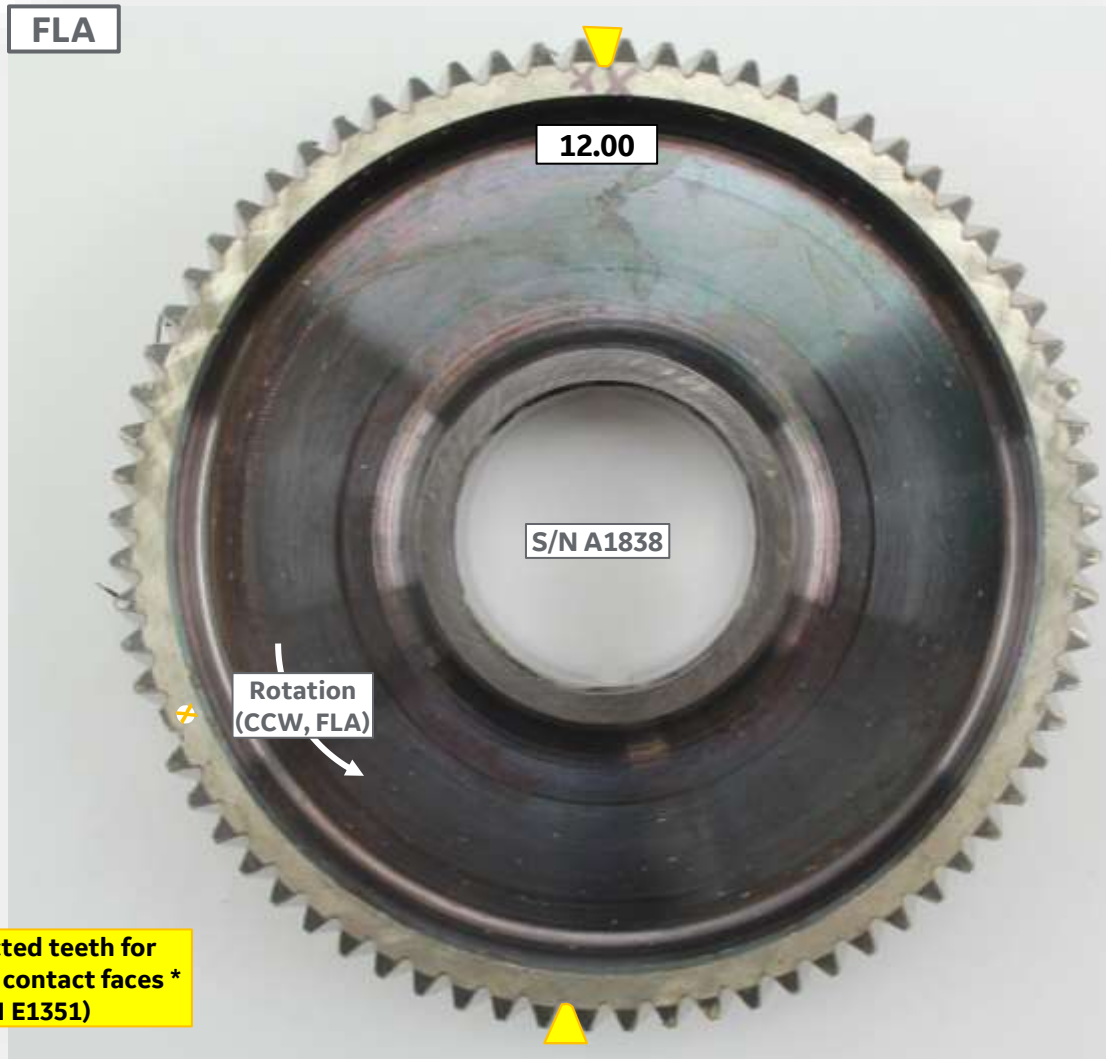
- Expanding span of teeth damages towards forward direction
⇔ wheel rotation direction
- Secondary damages



Visual Inspection (as-cleaned, **pos. III**)

Teeth Damages Nomenclature

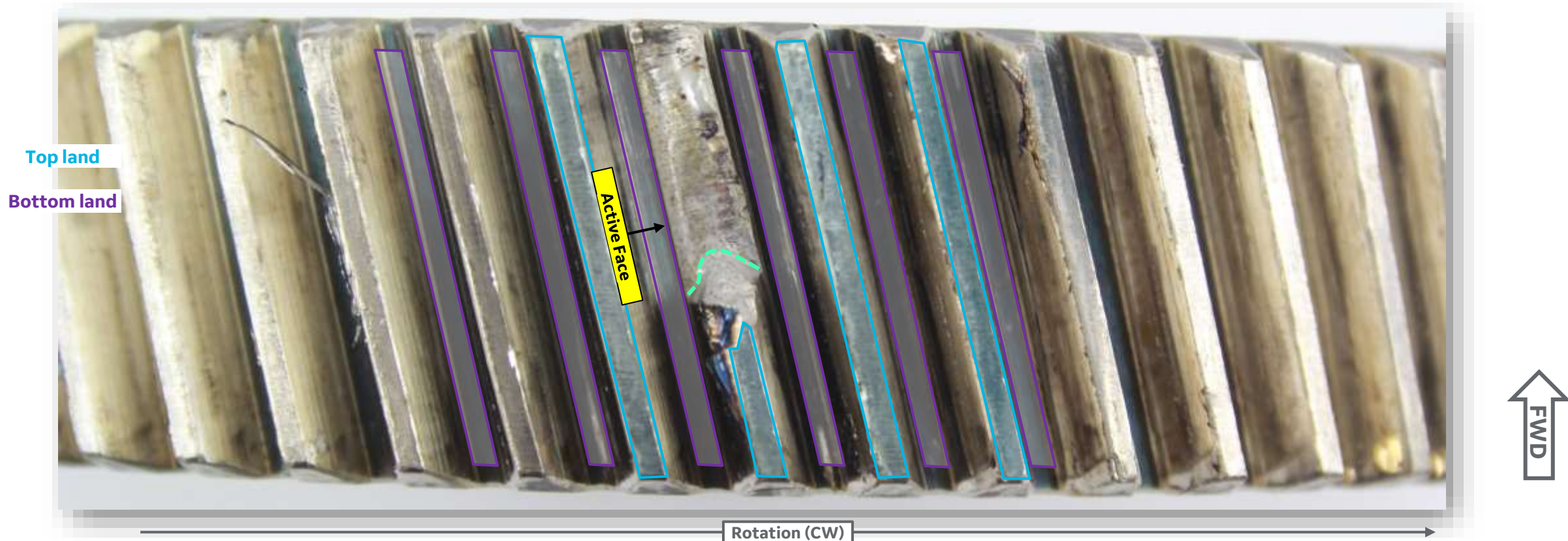
- X Fracture | Root - Full length
- X Fracture | Root - Partial length
- X Fracture | Mid-Chord - Partial length
- X Secondary | Large Top Land Track



Visual Inspection (as-cleaned, **A1838**, **pos. III**)



- Partial tooth liberation under mid-chord plane ($>$ root radius) surrounded by teeth with minor distresses comparatively
- Secondary damages

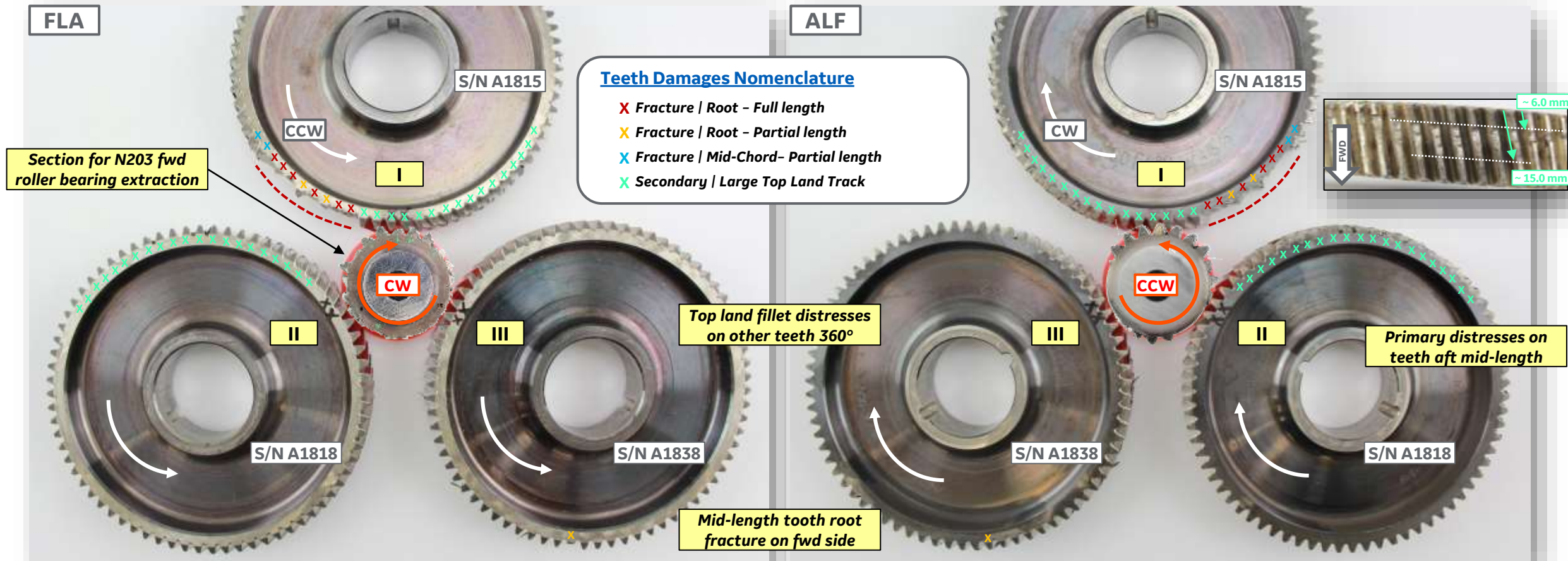


Visual Inspection (as-cleaned)

* Seven (7) revolutions of Sun Gear to return to initial clocking with Planets
(Sun gear - 21 teeth | Planet - 72 teeth)

Countershaft wheels clocking (quill-shaft sun gear center position - XXX marking coincides with position I wheel XX marks per dwg. definition in initial assy condition *)

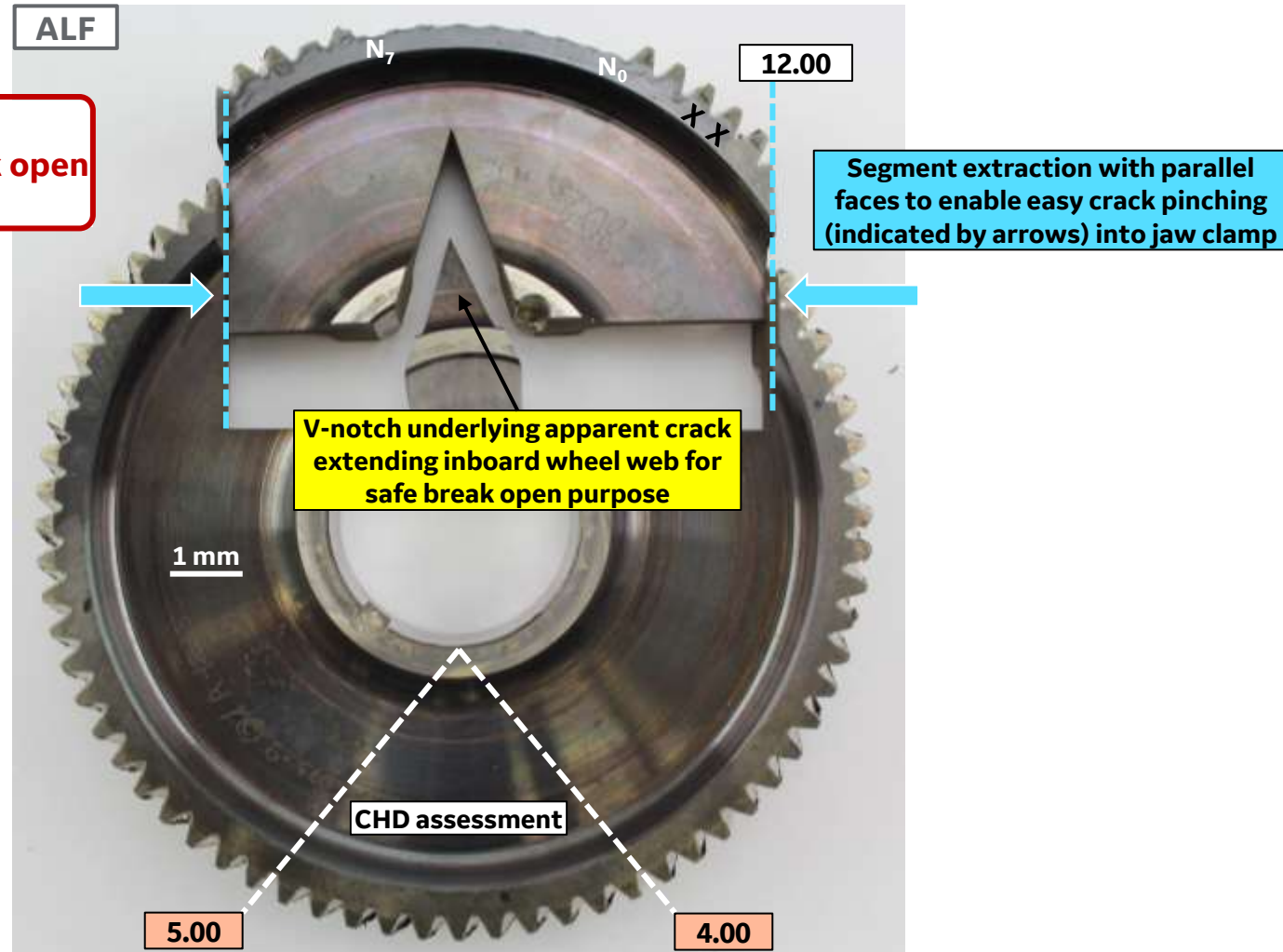
- **Position 1:** Primary damages with eight (8) adjacent teeth fractured in the root area
- **Position 2:** Secondary fractures & Top Land Track + Inter-teeth Debris
- **Position 3:** One (1) tooth fracture (loose Inner Ring of mid-shaft roller bearing PLC 46-8-4) + Inter-teeth Debris



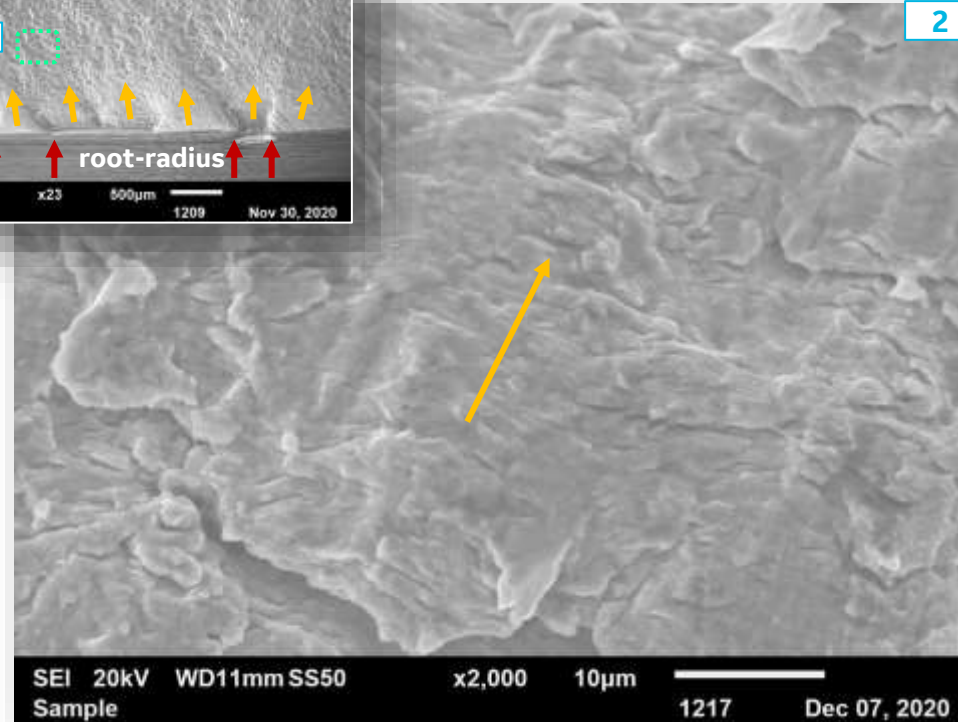
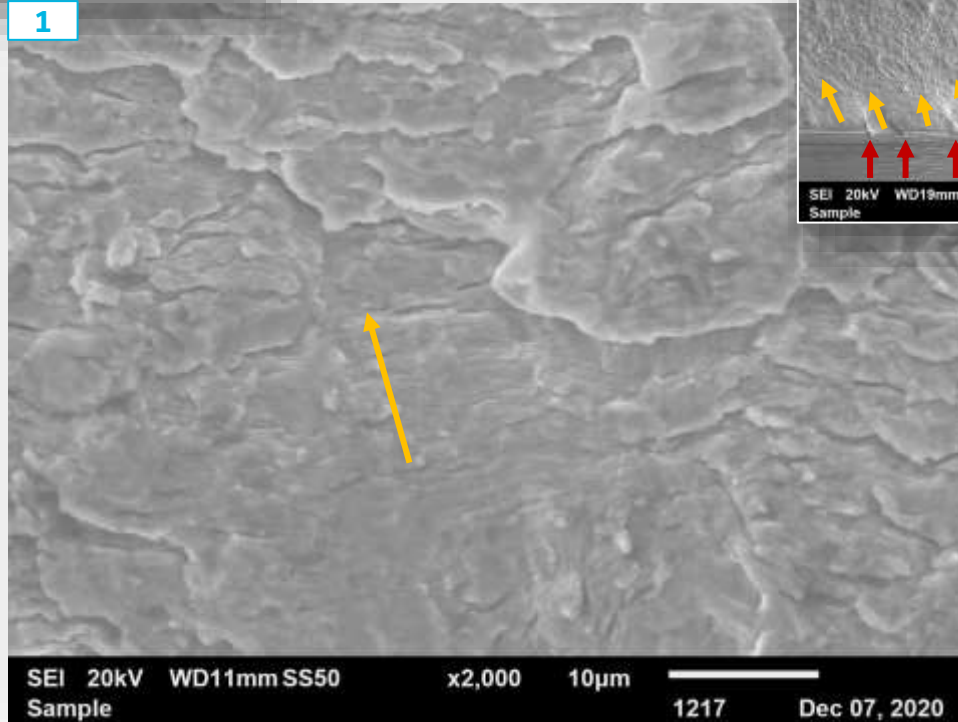
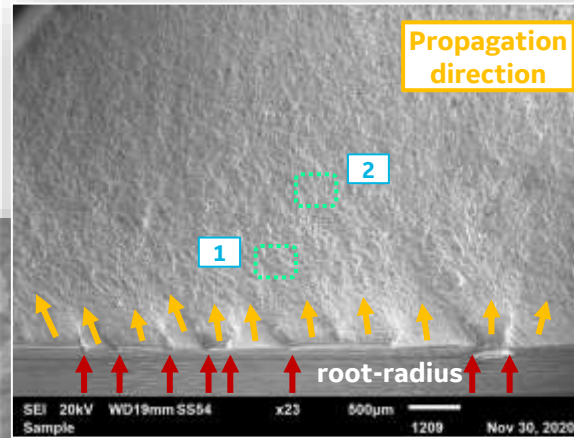
Fractography & Metallography (wheel S/N A1815)

Wheel segments extraction scheme

- 1) Fractography purpose prior to crack open
- 2) Metallurgical examination & CHD

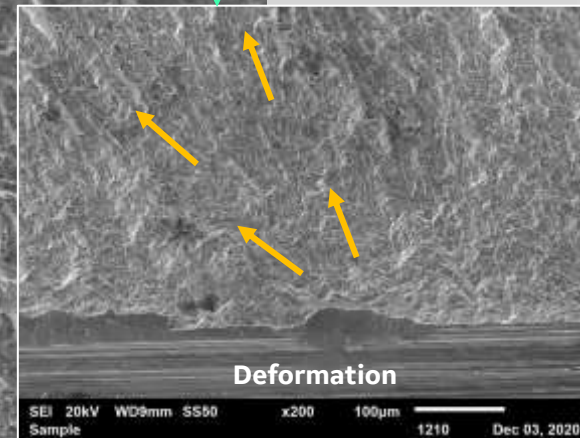
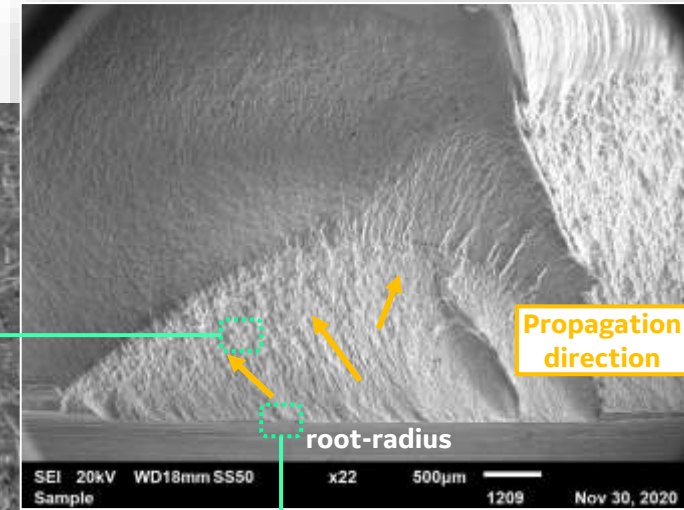
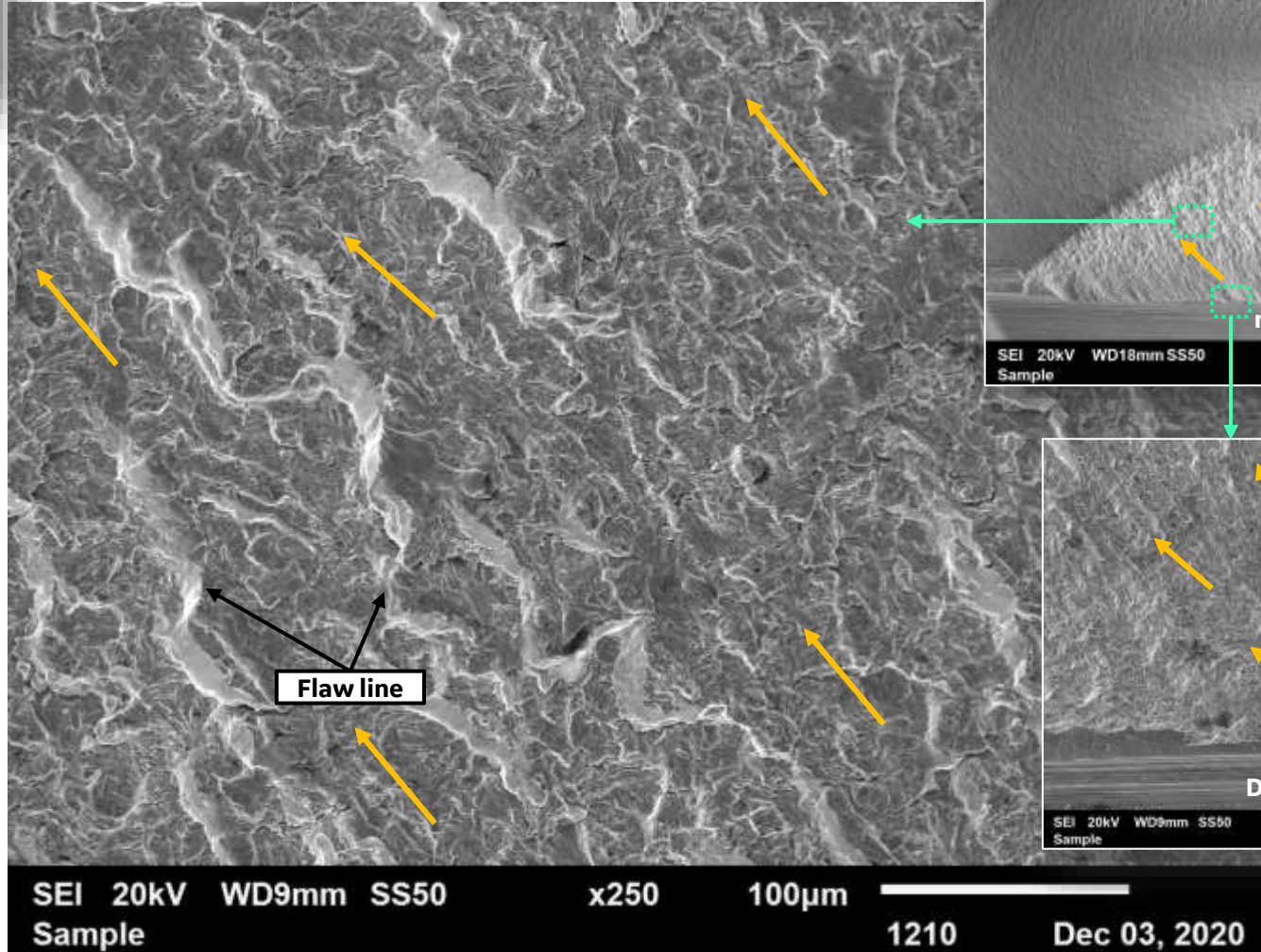


Fractography (wheel S/N A1815, tooth N₀)

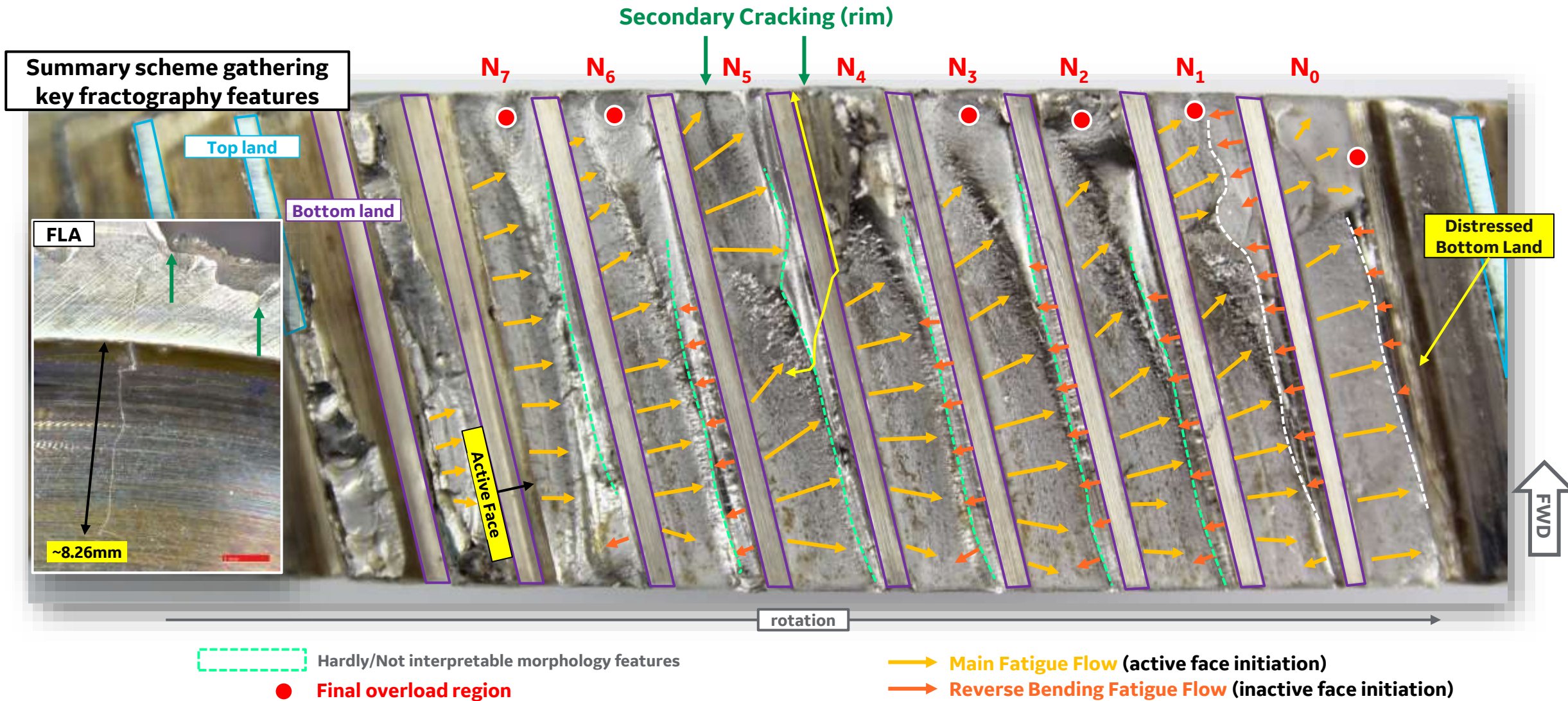


- ❑ Multiple surface initiation (depicted by orange arrows) along original machined line in the vicinity of root-land radius to contact face lower region (red arrows underline ratchet marks)
- ❑ Relatively coarse striation pattern (high alt. stress condition) & apparent secondary cracking

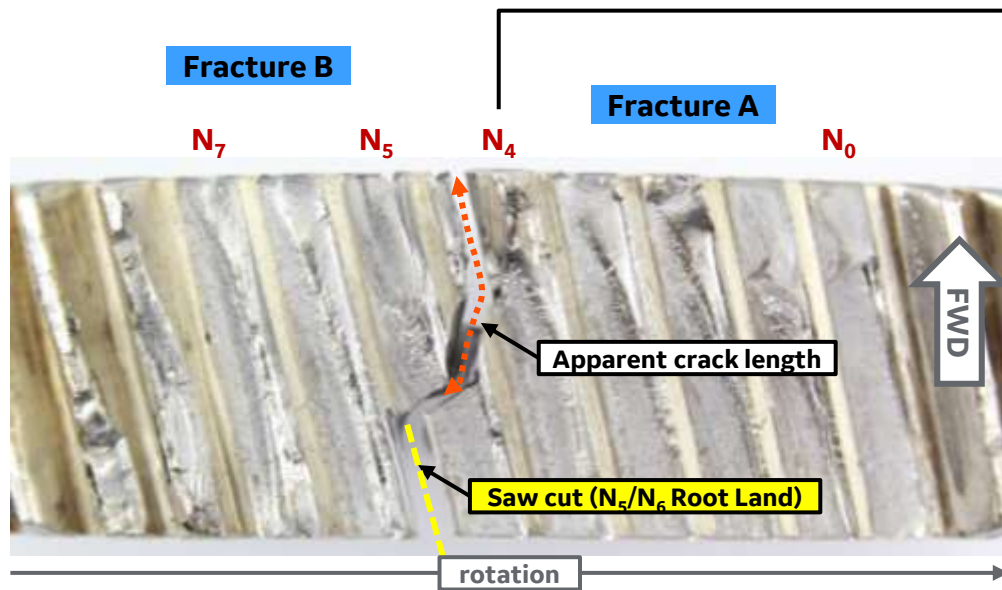
Fractography (wheel S/N A1815, tooth N₀)



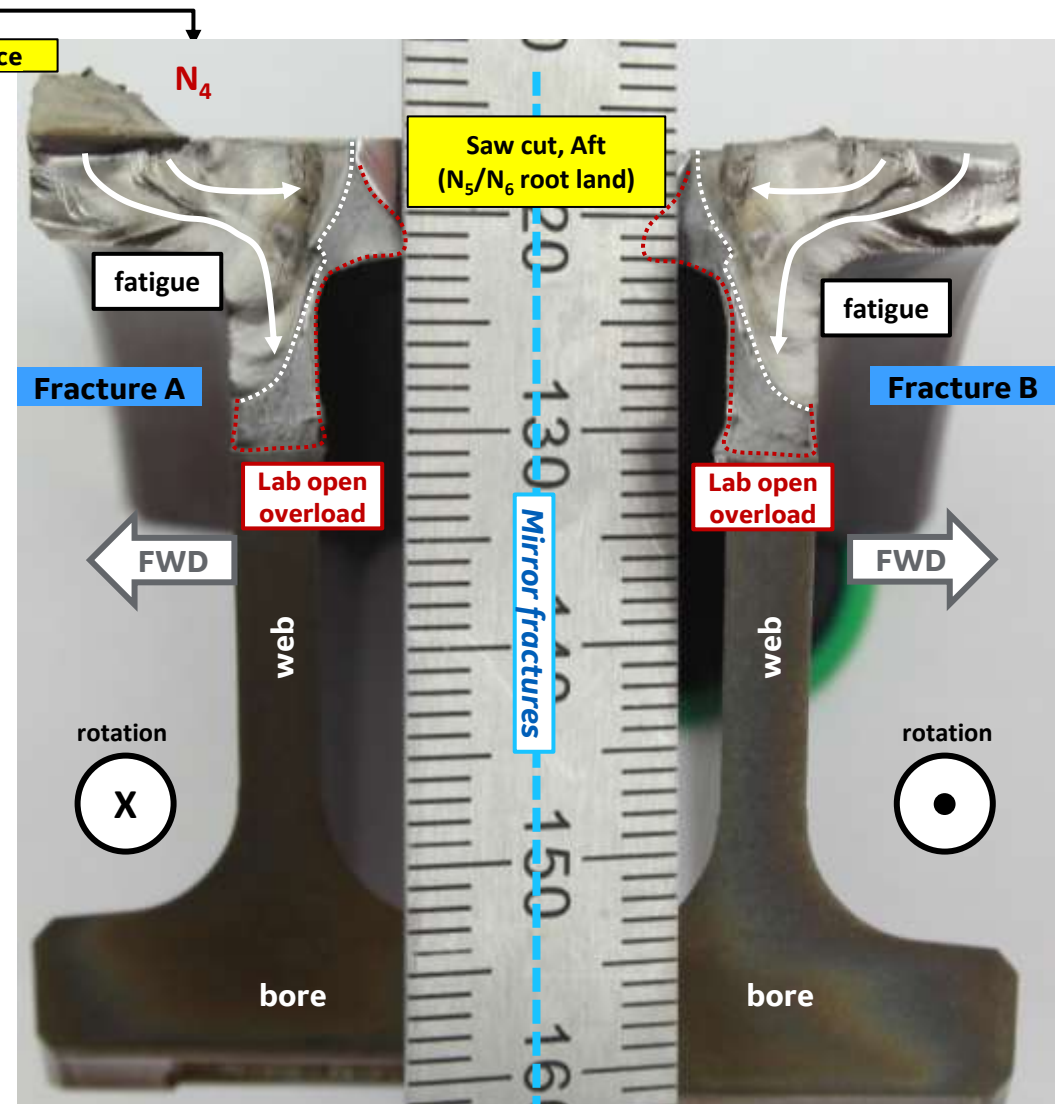
Fractography (wheel S/N A1815): Summary



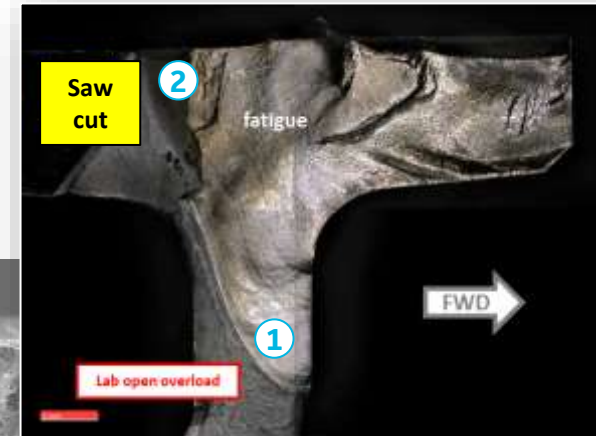
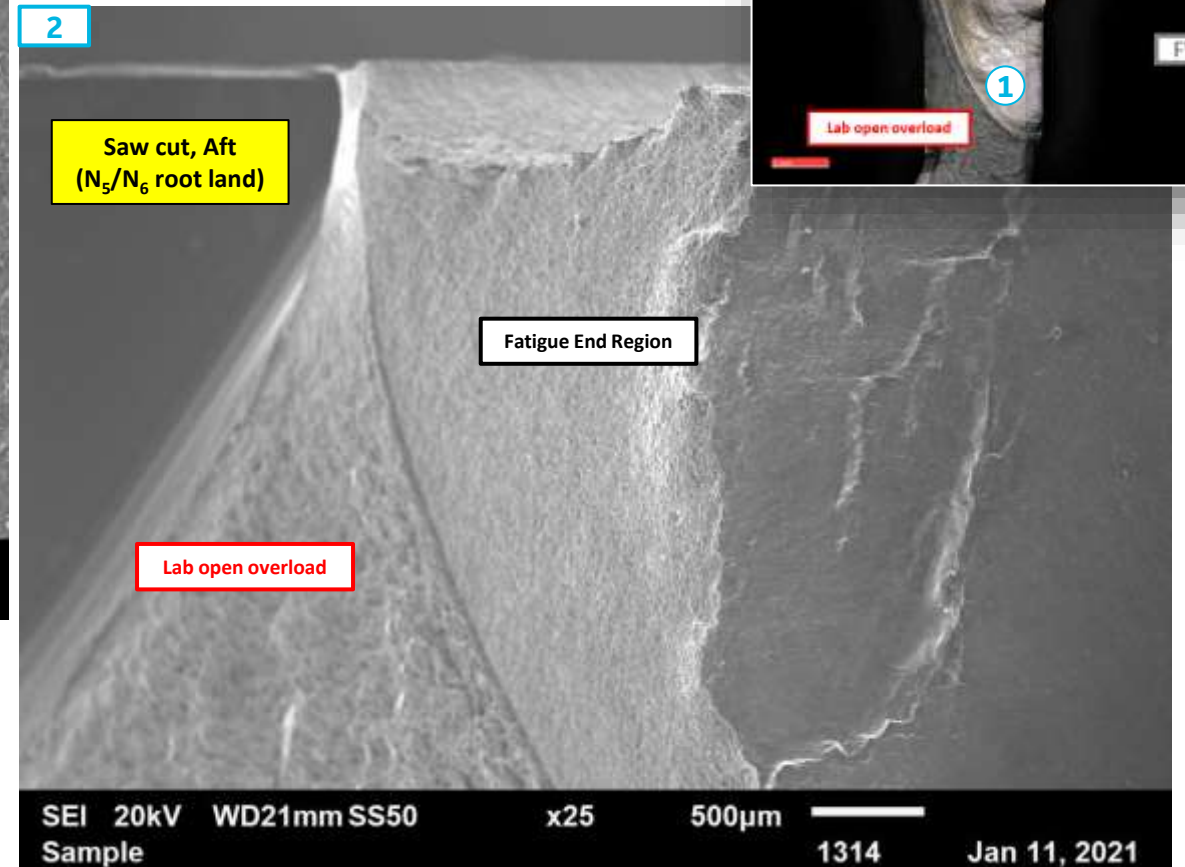
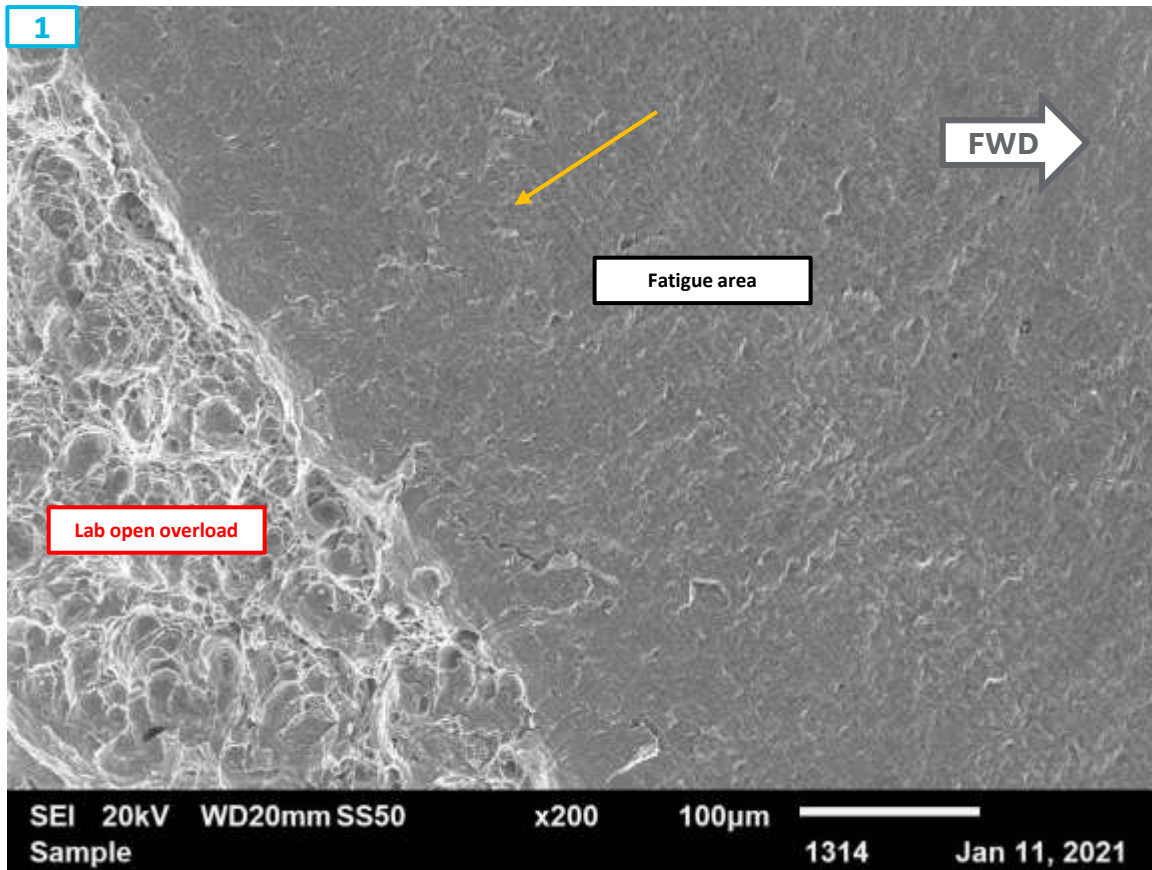
Fractography (wheel S/N A1815): Break Open



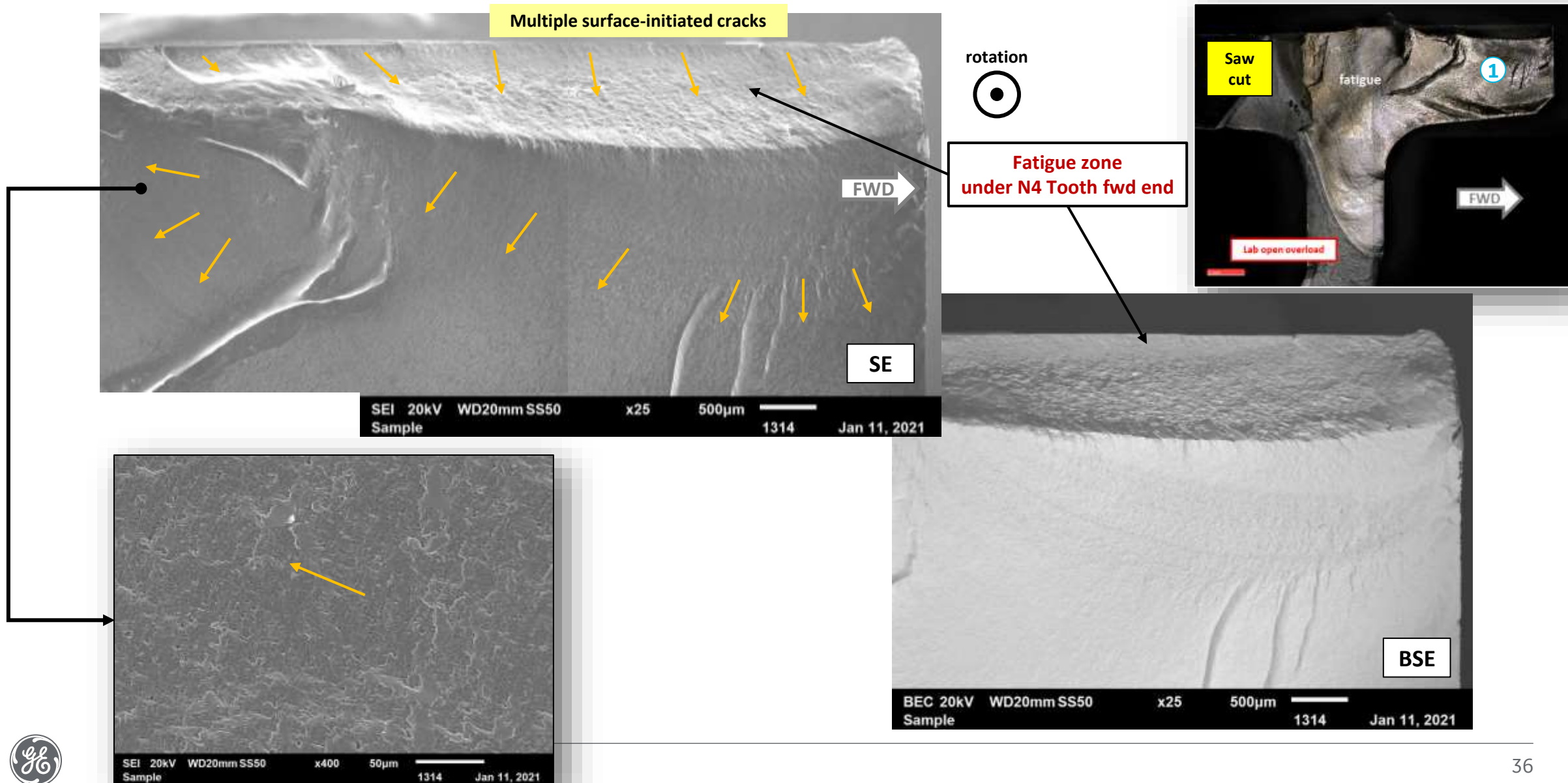
- Saw cut carried out on N₅/N₆ aft root land region & force open
- Fatigue Propagation Inboard Wheel Web ~12 mm from Tooth Fwd End



Fractography (**wheel S/N A1815**): Break Open “B”

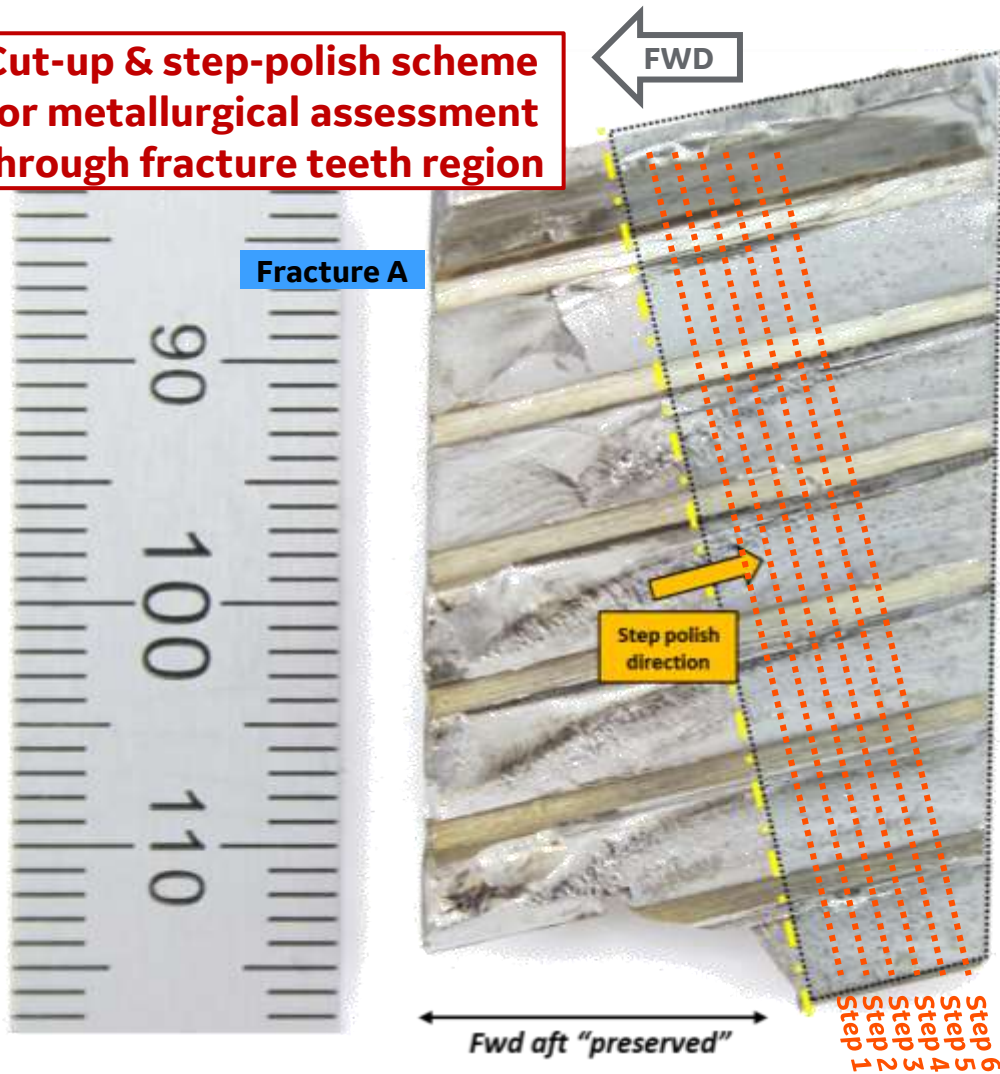


Fractography (**wheel S/N A1815**): Break Open “B”



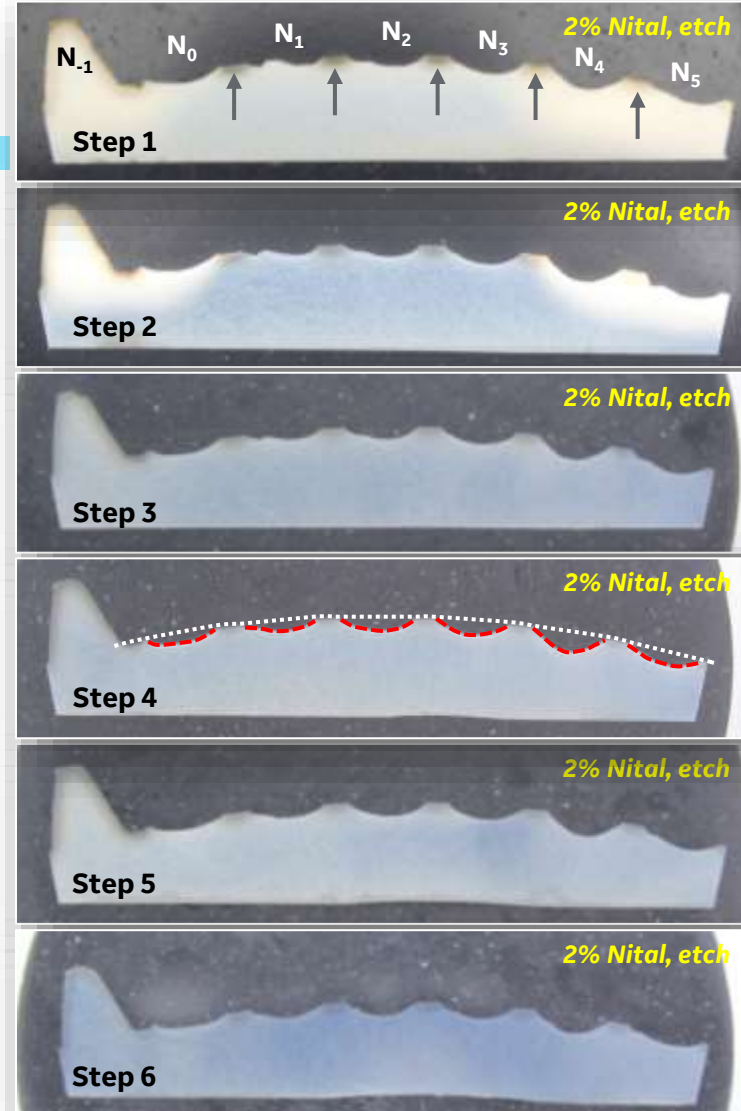
Metallurgical Examination: fracture A step polish

Cut-up & step-polish scheme for metallurgical assessment through fracture teeth region



CHD check
(@ step polish no. 6)

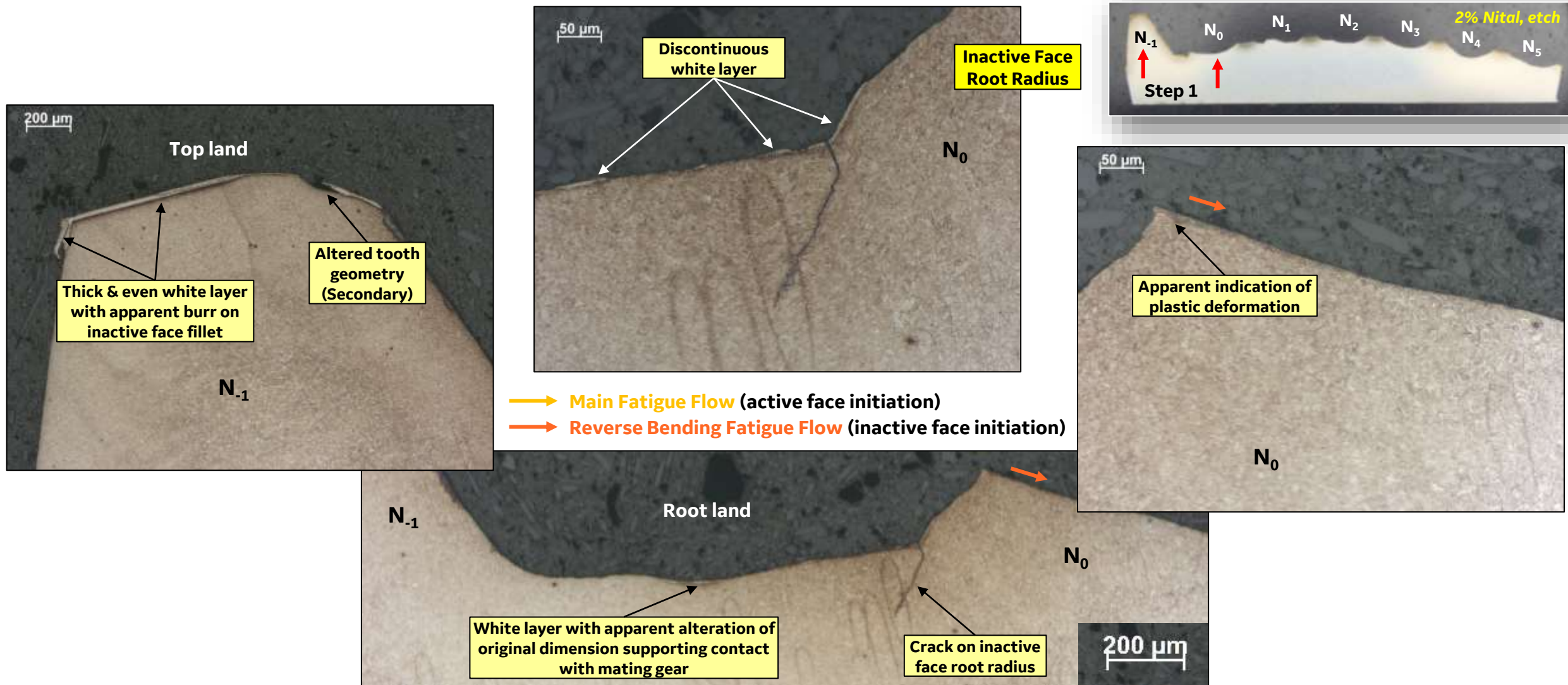
Step
polish



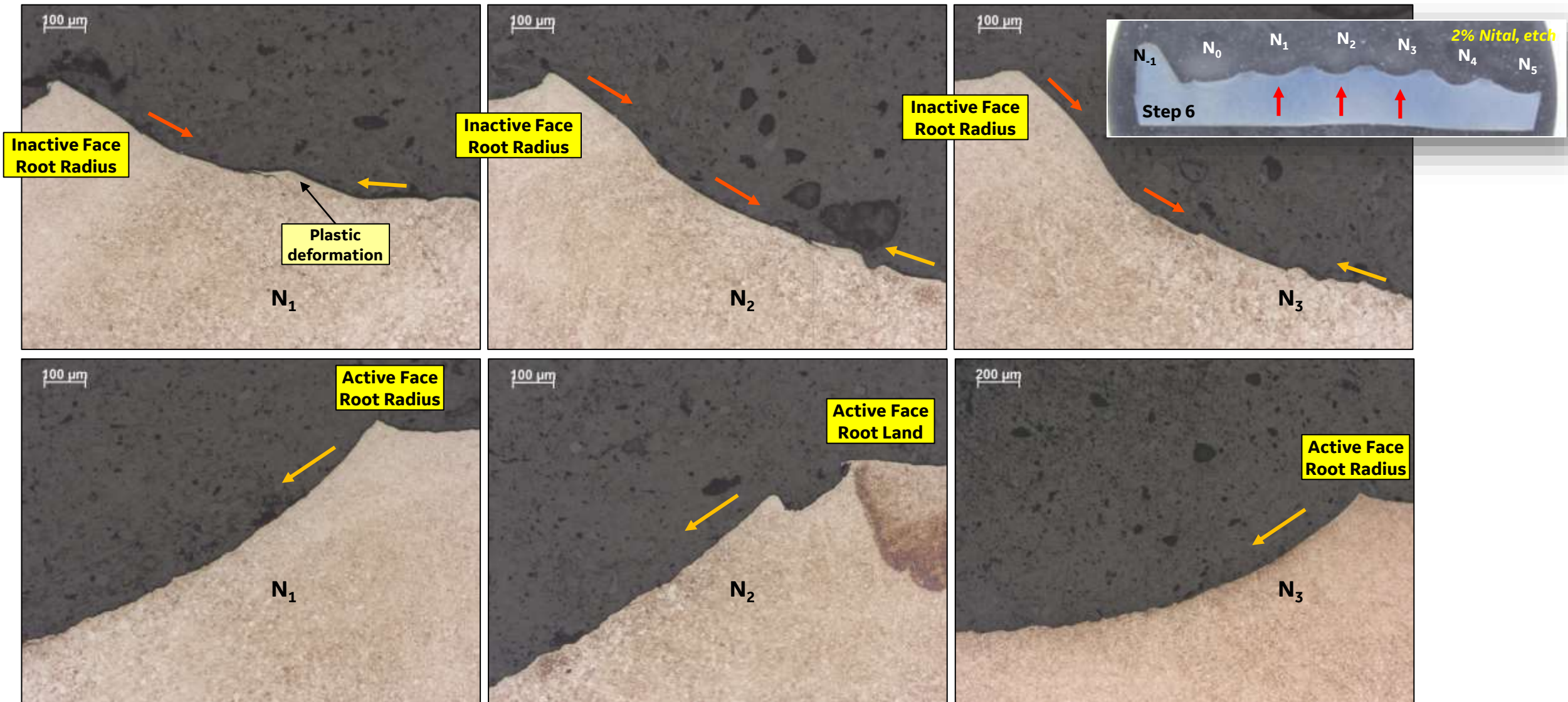
Darker contrasted
root-land indicated by
arrows underlines
remnant of carburizing

Increased fracture
steepness with teeth
liberation progression
 $N_0 \rightarrow N_5$

Metallurgical Examination: fracture step polish 1

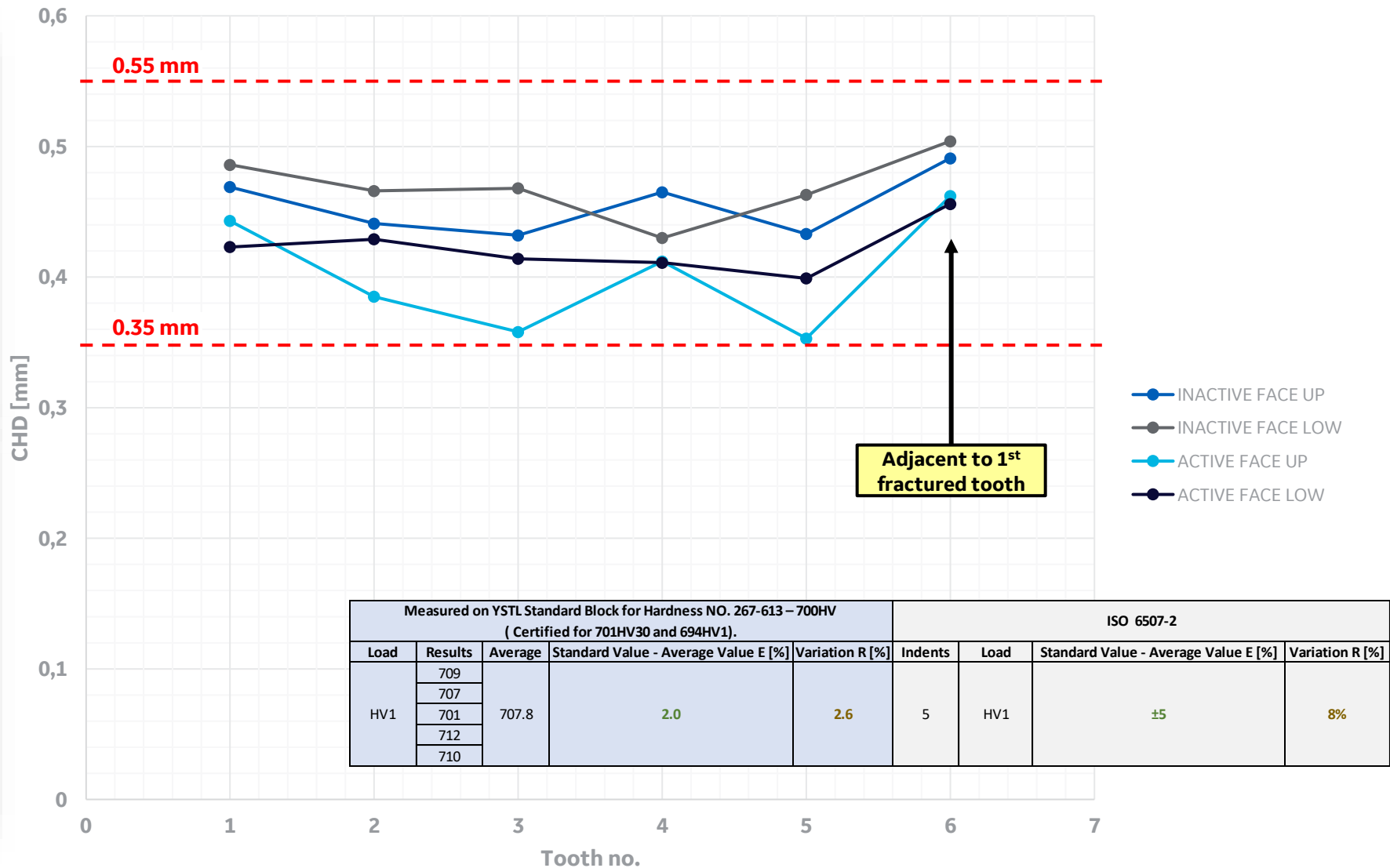
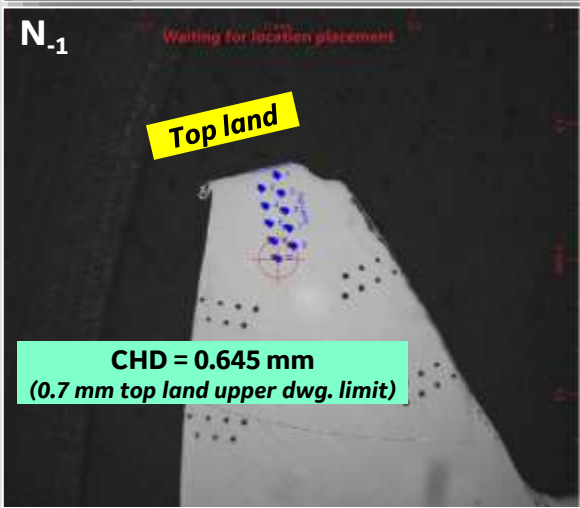
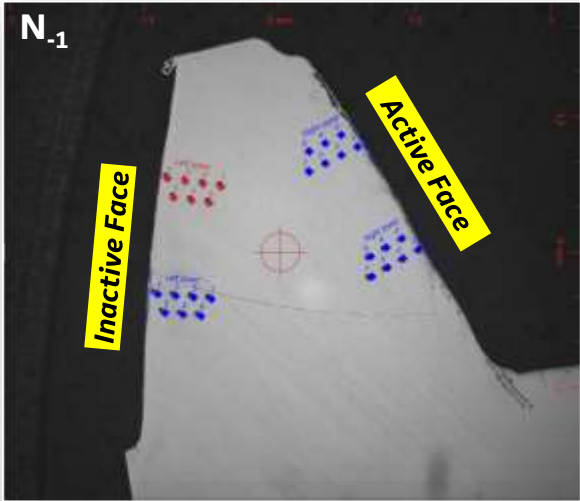


Metallurgical Examination: fracture step polish 6

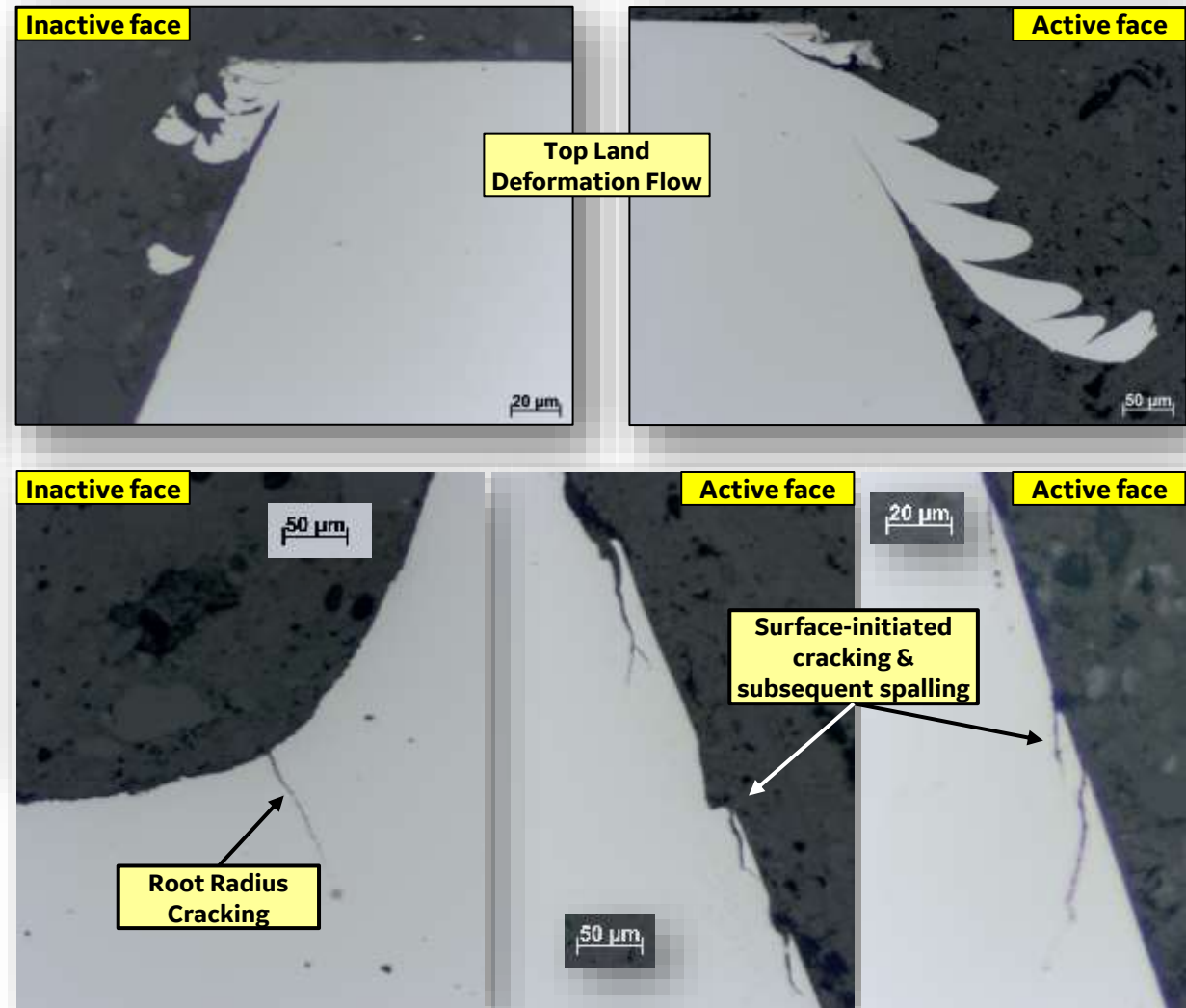
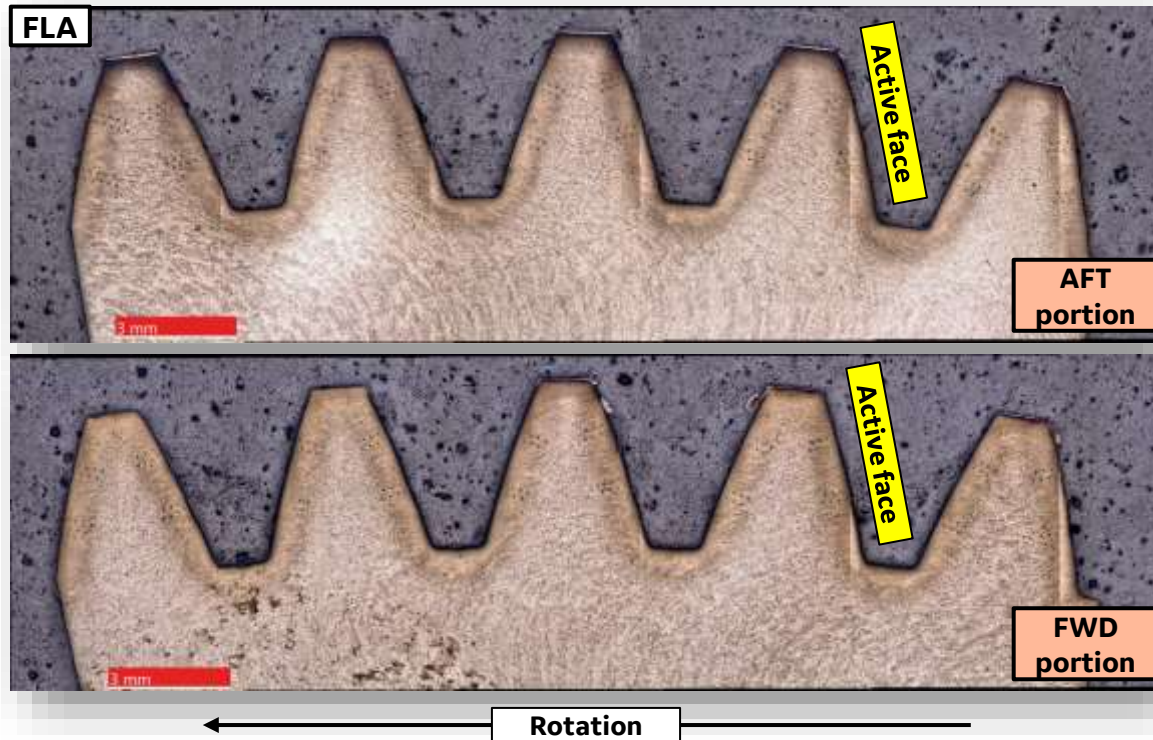


Metallurgical Examination: CHD

Teeth no. 1 to 5 (4.00 – 5.00 CW)
Tooth no. 6 = N₋₁ (12.00 CW)



Metallurgical Examination: 4.00 - 5.00 segment

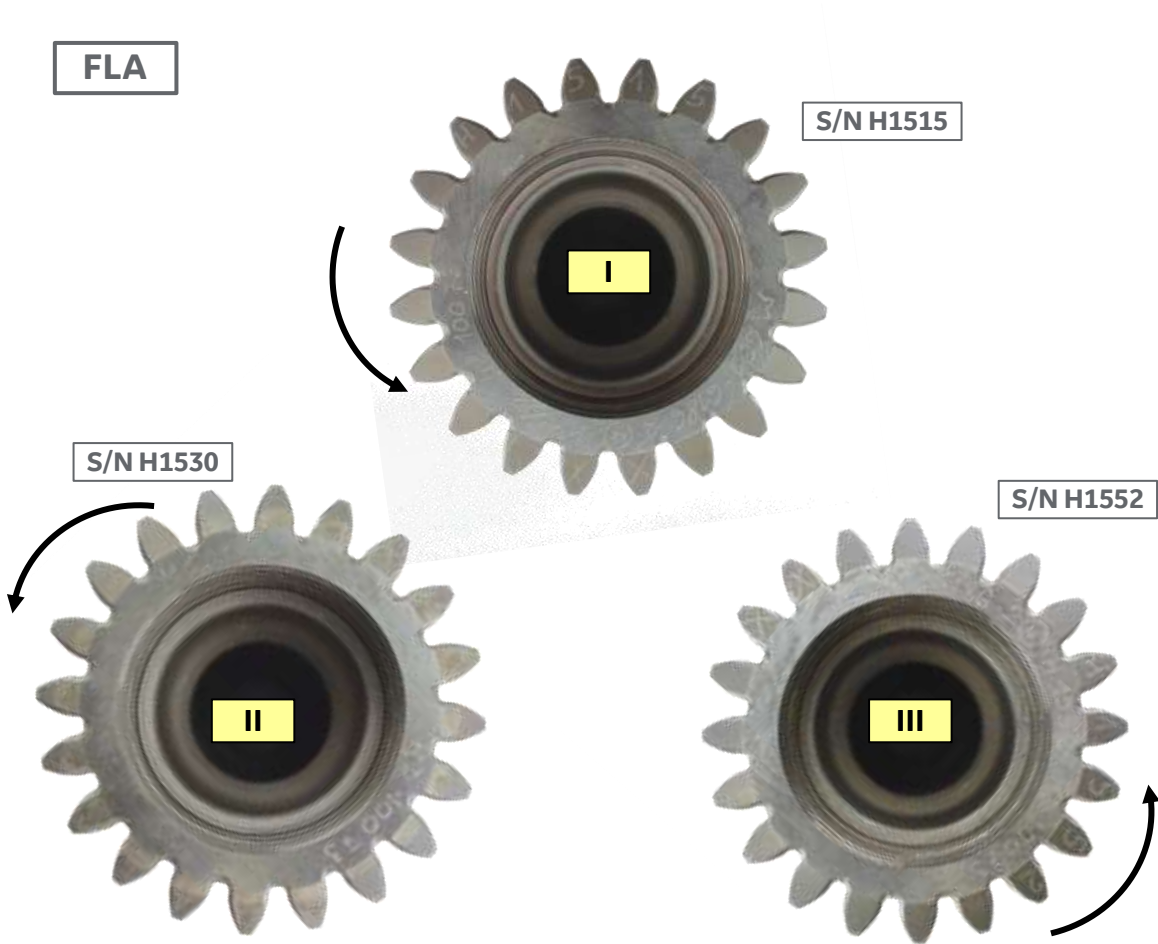


RGB STG. 2 GEARING

PLANETARY GEARS

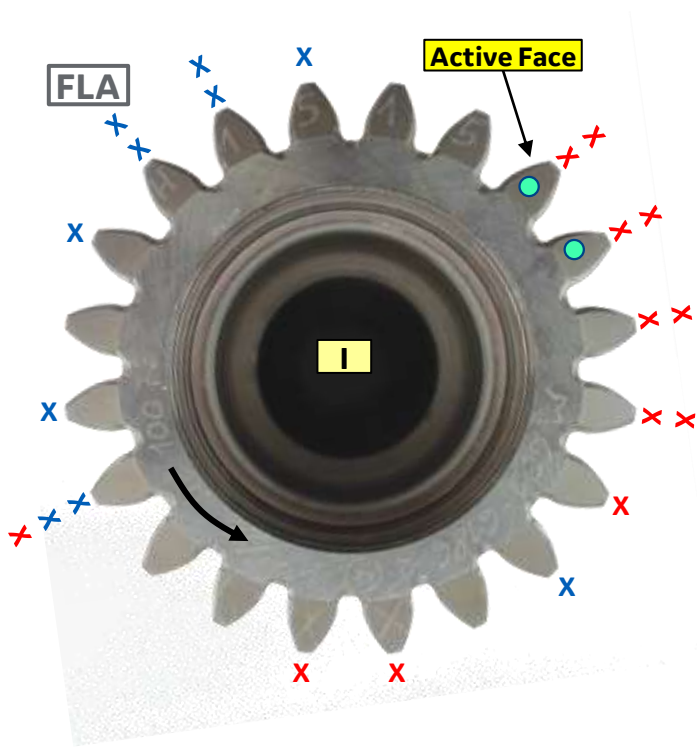


Visual Inspection (as-received)

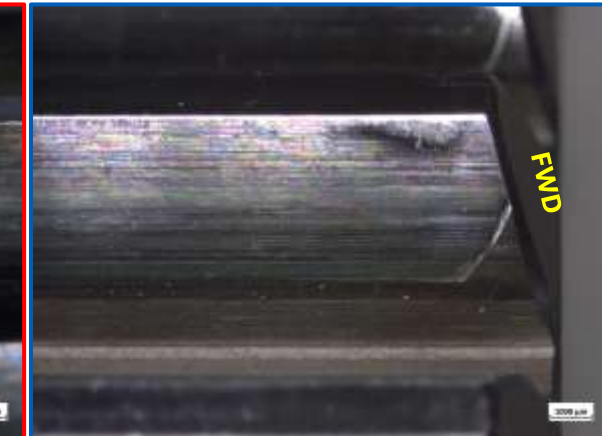
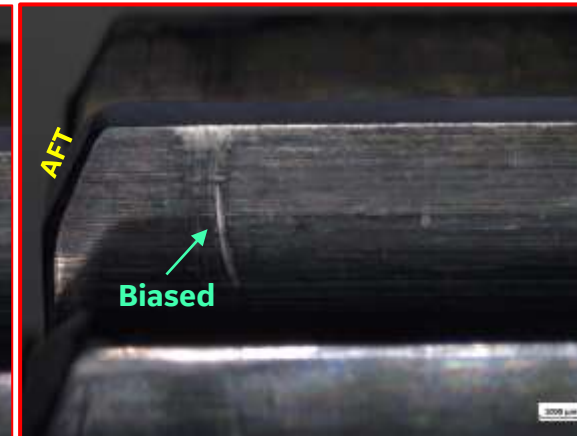
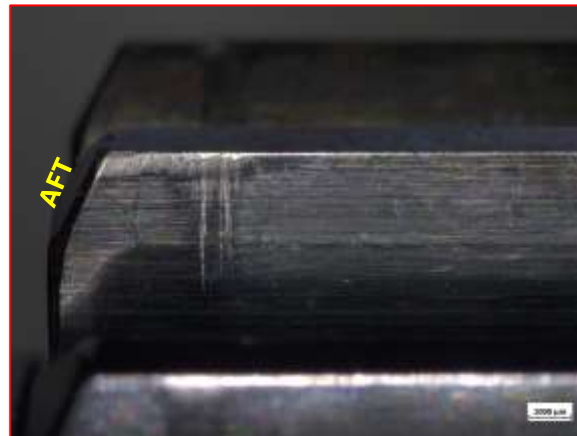
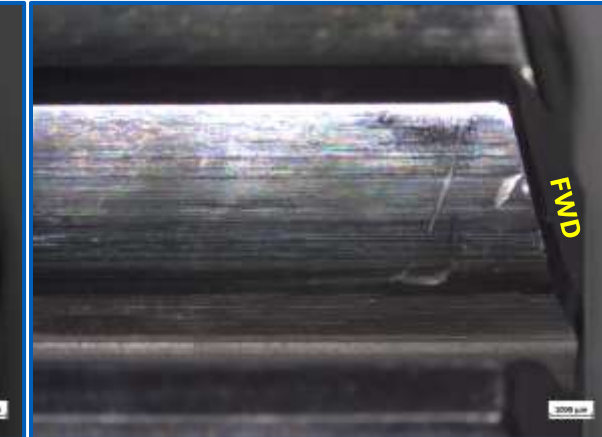
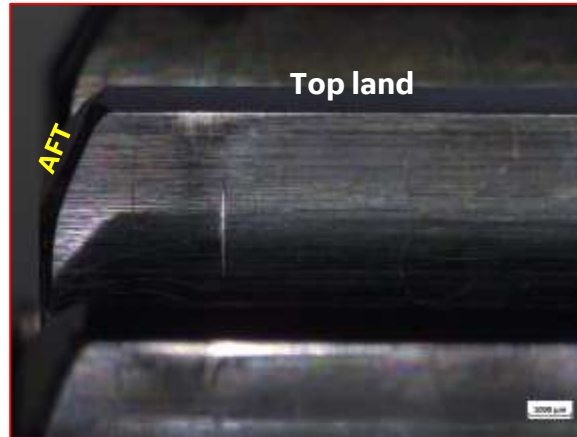


Rotation direction

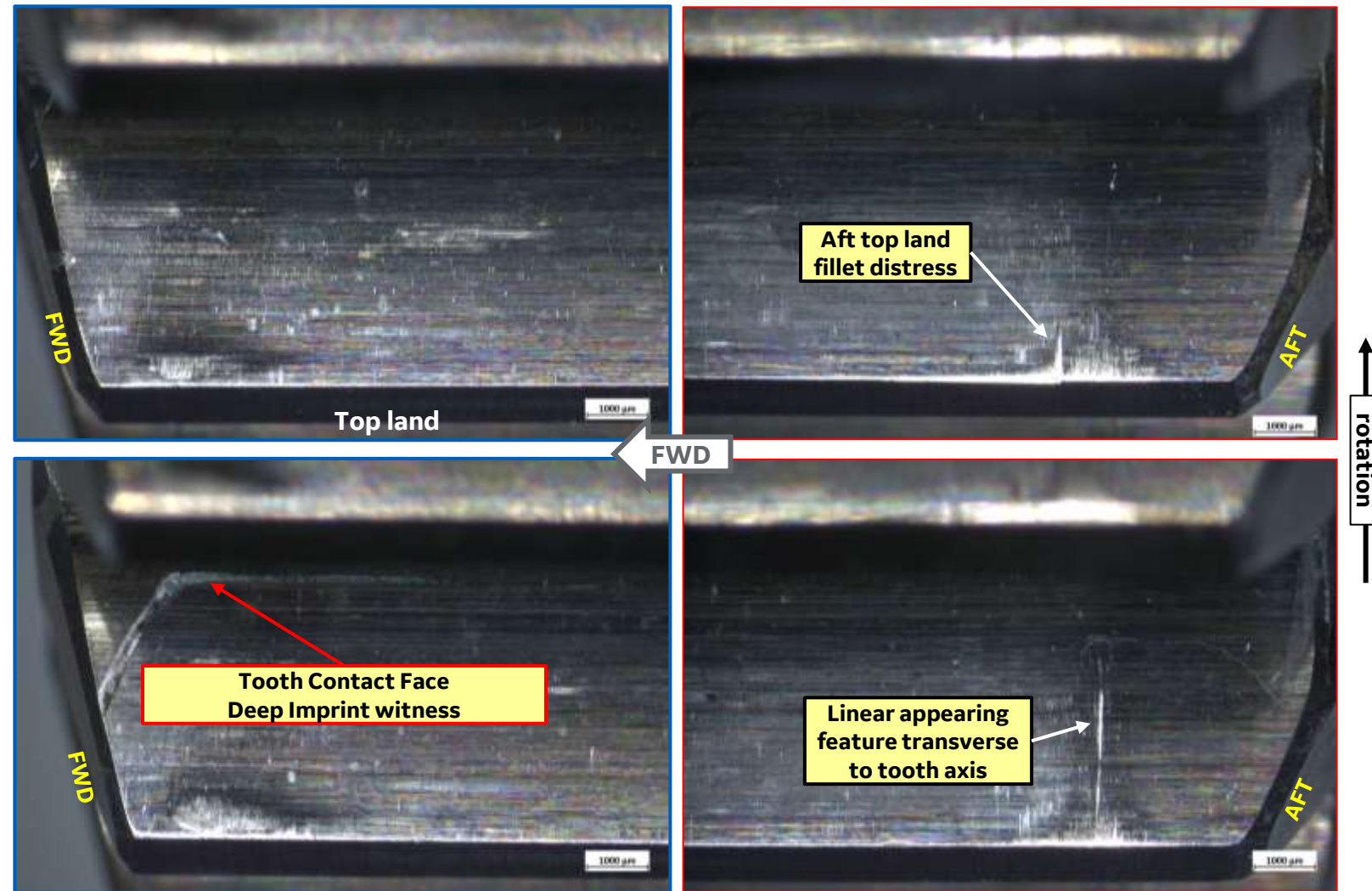
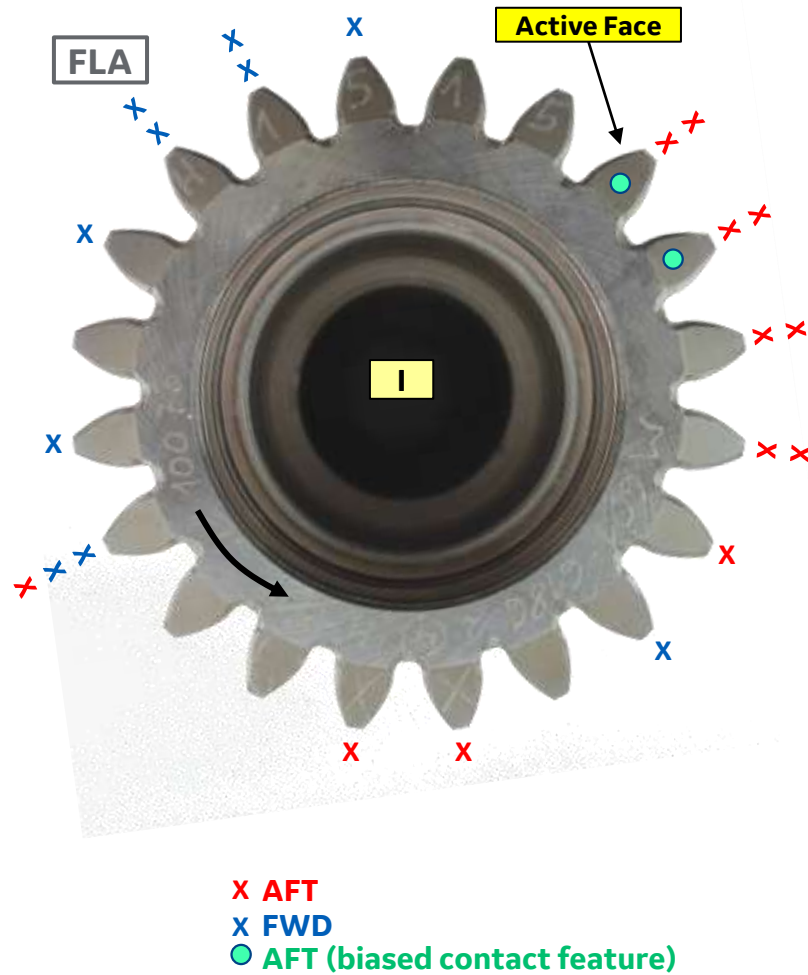
Stereo-micrographs (gear H1515, pos. 1)



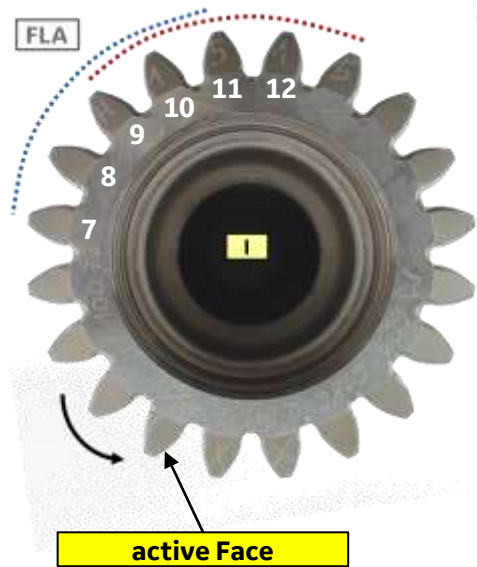
- x AFT
- x FWD
- AFT (biased contact feature)



Stereo-micrographs (gear H1515, pos. 1)



Stereo-micrographs (gear H1515, pos. 1)



Active Face

REPLICAS

Inactive Face



Axial marks on aft face portion



Contact Face Imprint witness comparable to observation on hdw.



Apparent contact imprint witness (compatible with crown wheel teeth fwd end shape)



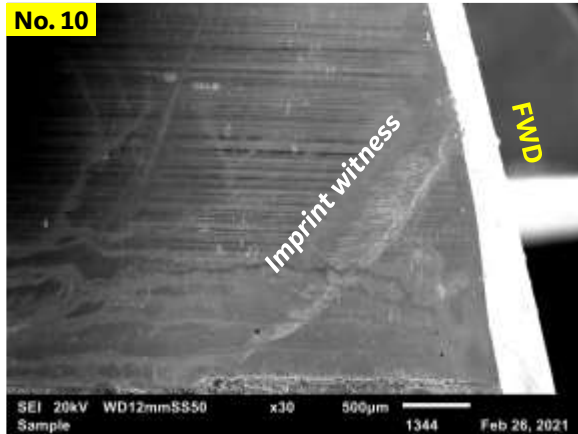
Top land



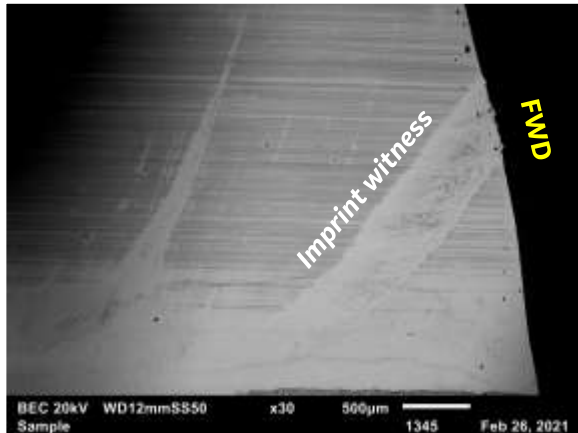
Root land

Stereo-micrographs / EDS (gear H1515, pos. 1)

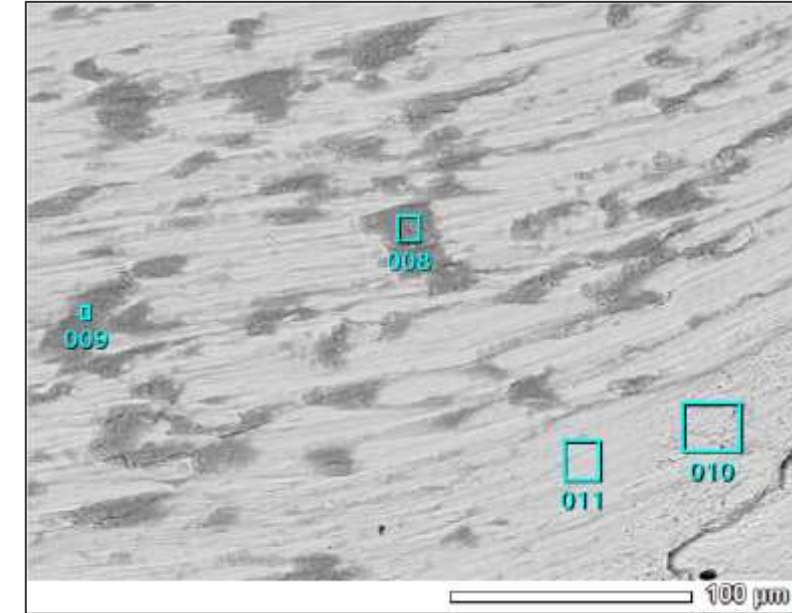
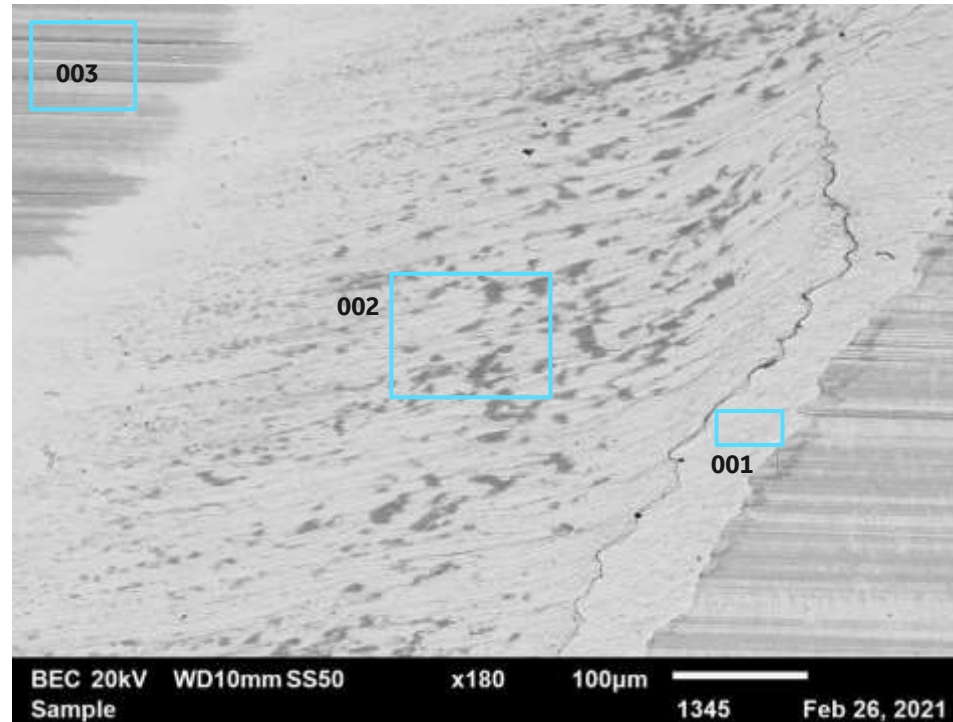
Active Face (SE)



Active Face (BSE)



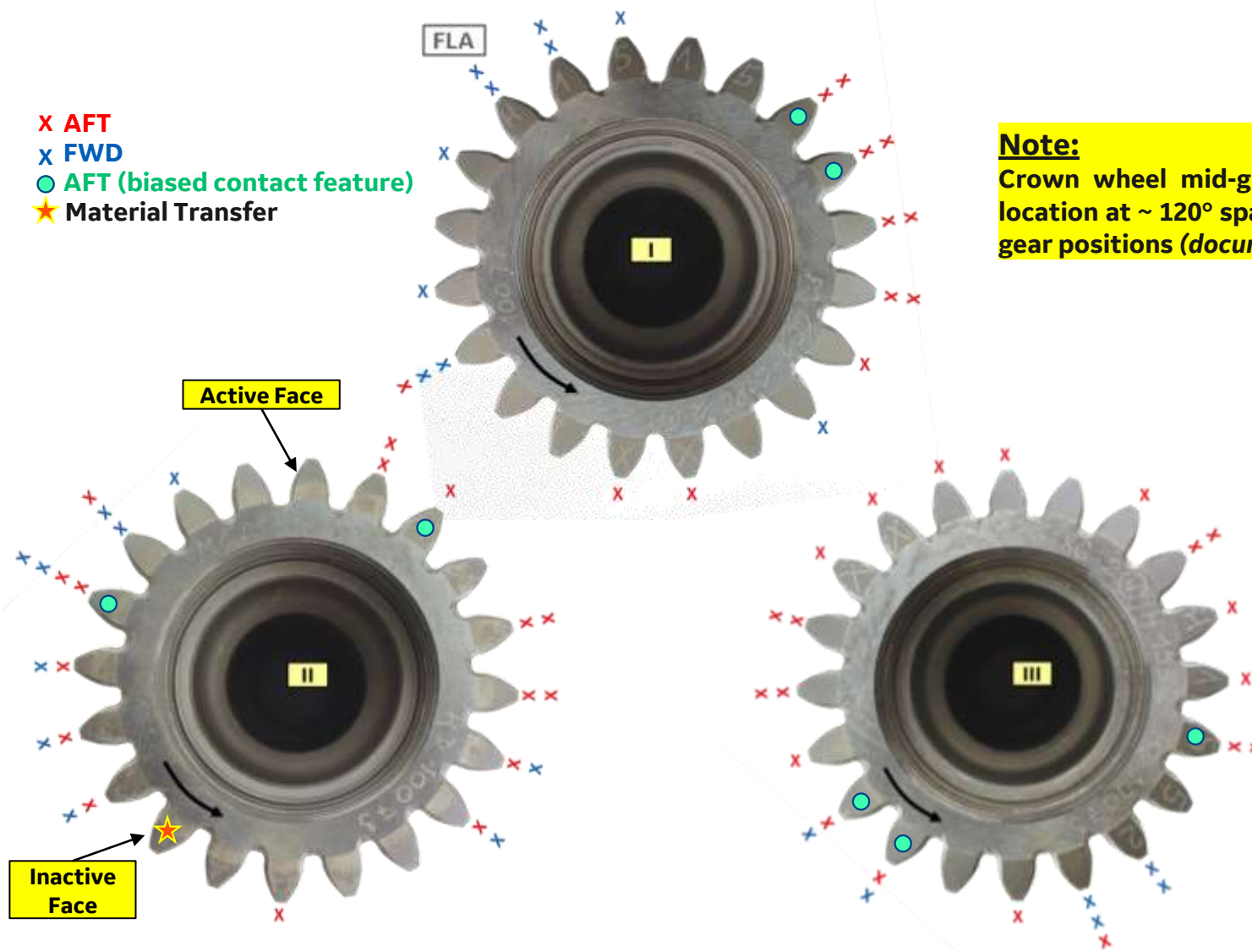
Mass%	O	Mg	Si	P	Ca	V	Cr	Mn	Fe	Ni	Cu	Mo	Total
008	21.35	0.33	0.77	0.20	0.53	0.28	4.18	0.60	71.26			0.49	100.00
009	20.33	0.27	1.24	0.30	0.44	0.37	3.87	0.58	72.20	0.40			100.00
010			0.28			0.17	2.34	0.43	96.24	0.34	0.21		100.00
011			0.29			0.19	2.50	0.52	96.50				100.00



Mass%	Si	Cr	Mn	Fe	Ni	Total
001	0.54	89.75	3.12	100.00		
002	0.29	1.55	0.51	95.95	1.70	100.00
003	0.47	0.86	0.49	94.60	3.59	100.00

=> No conclusive indication supporting a material transfer on teeth active face fwd end region
(note the presence of oxidation products within the distressed zone)

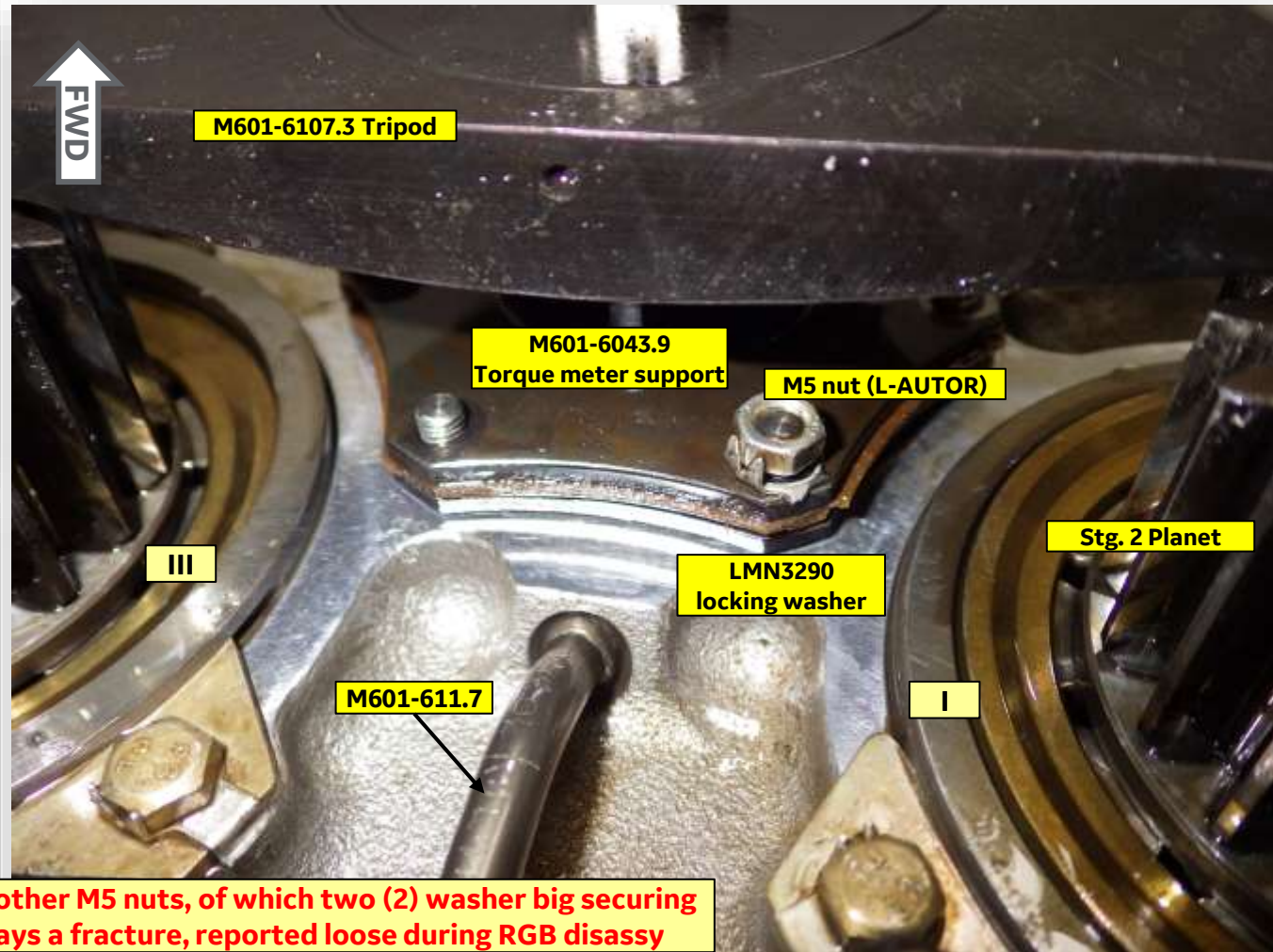
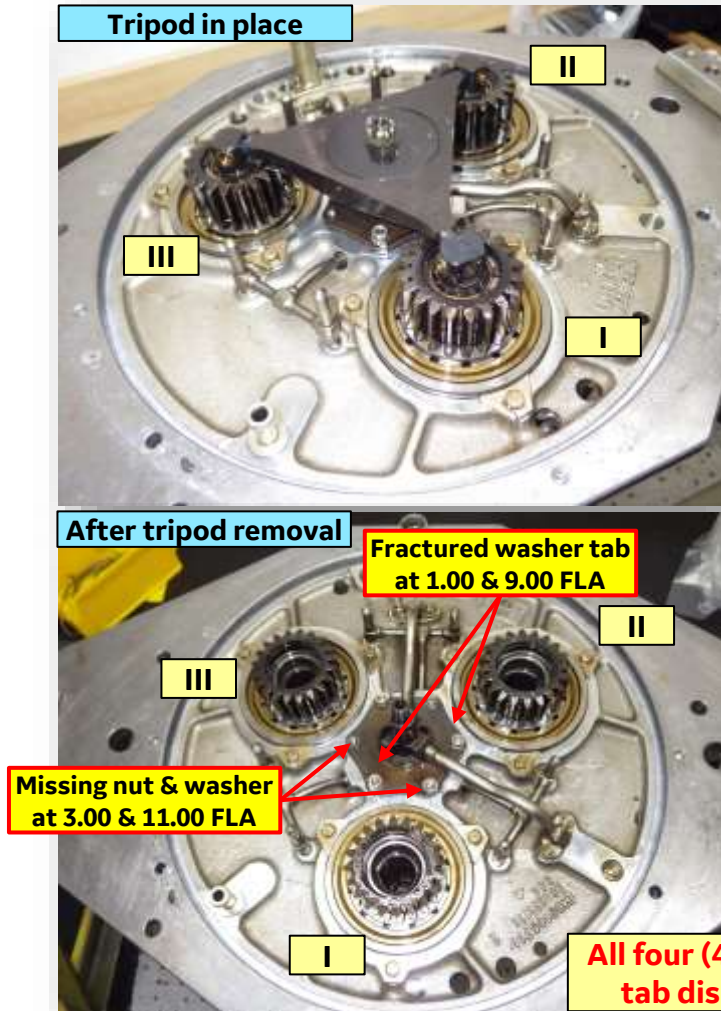
Active Teeth Damage Mapping Summary



RGB COUNTERSHAFT CASING



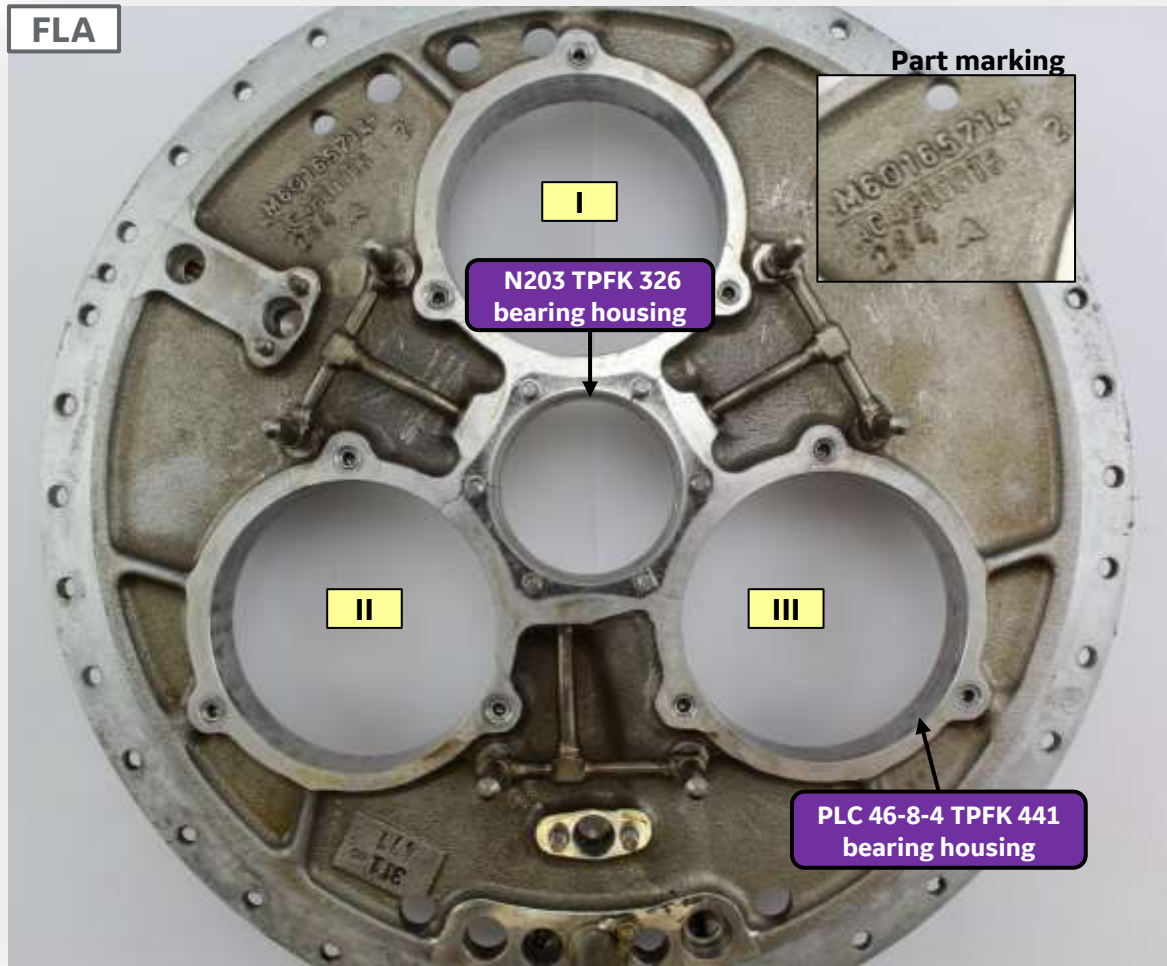
Visual Inspection (engine TDR)



All four (4) other M5 nuts, of which two (2) washer big securing tab displays a fracture, reported loose during RGB disassy

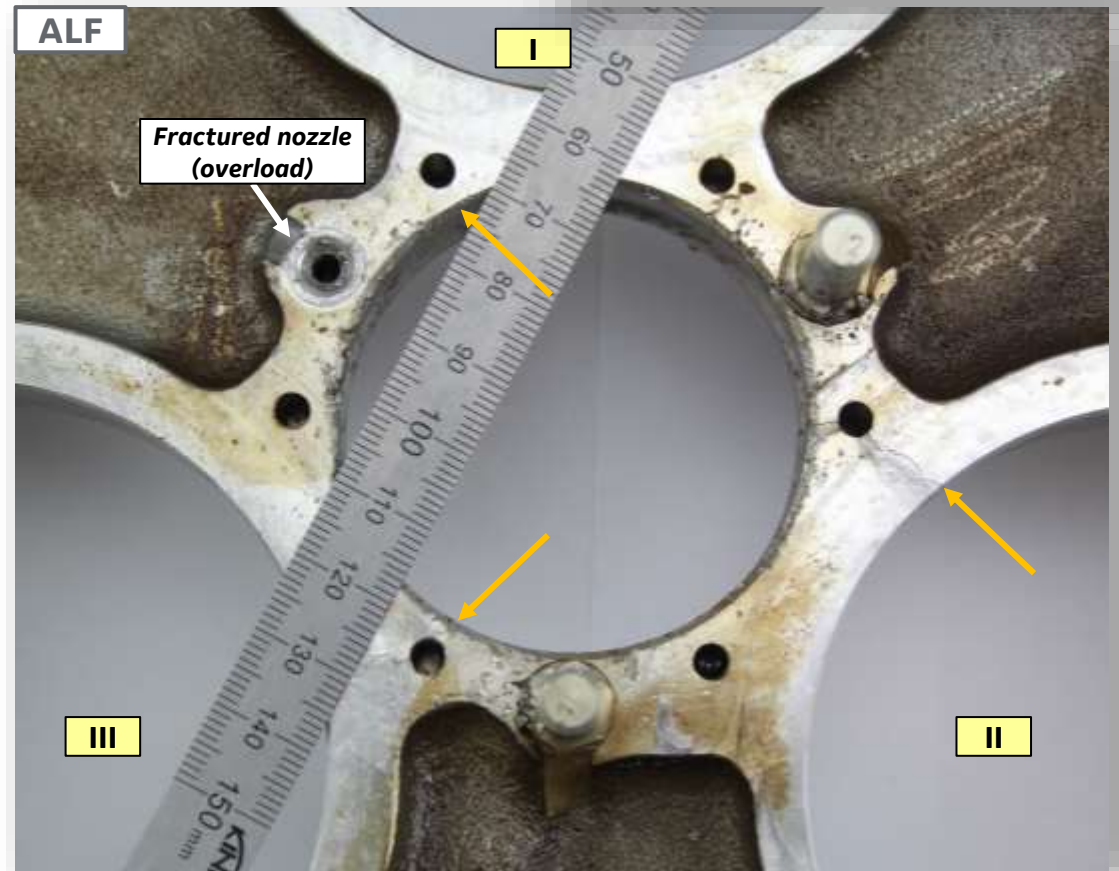
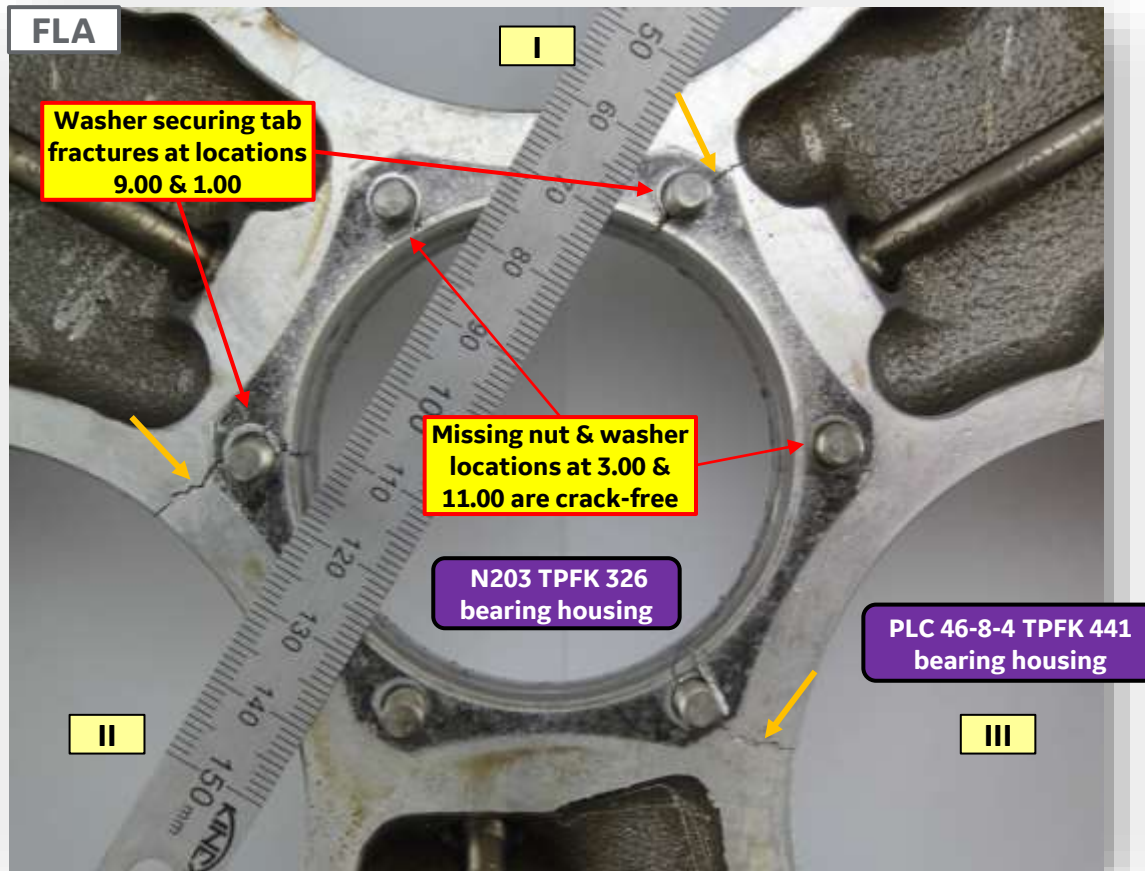
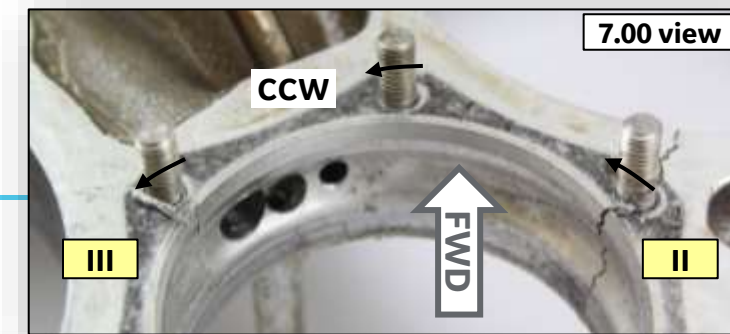
Fractured washer tab at 1.00 & 9.00 positions documented in Appendix 6

Visual Inspection (as-received)



Visual Inspection (as-received)

→ Apparent through cracking across pin location



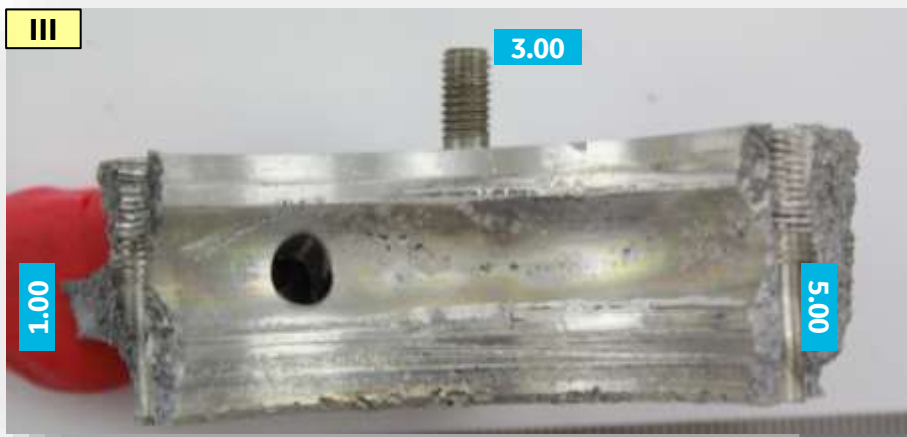
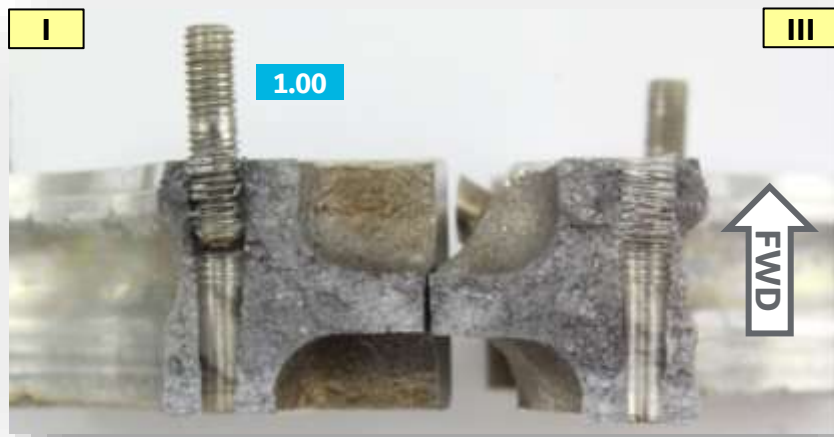
Fractured washer tab at 1.00 & 9.00 positions documented in Appendix 6

Visual Inspection (as-received)

 *Countershaft wheel marks
on casing OD (ALF)*

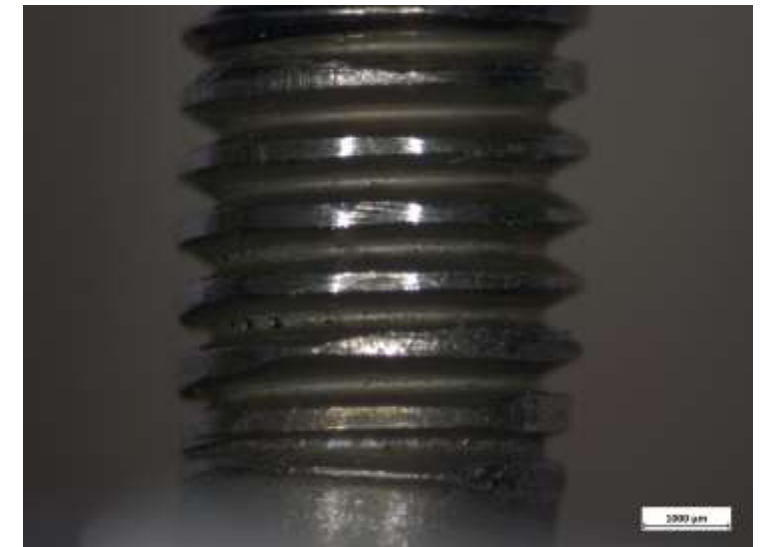
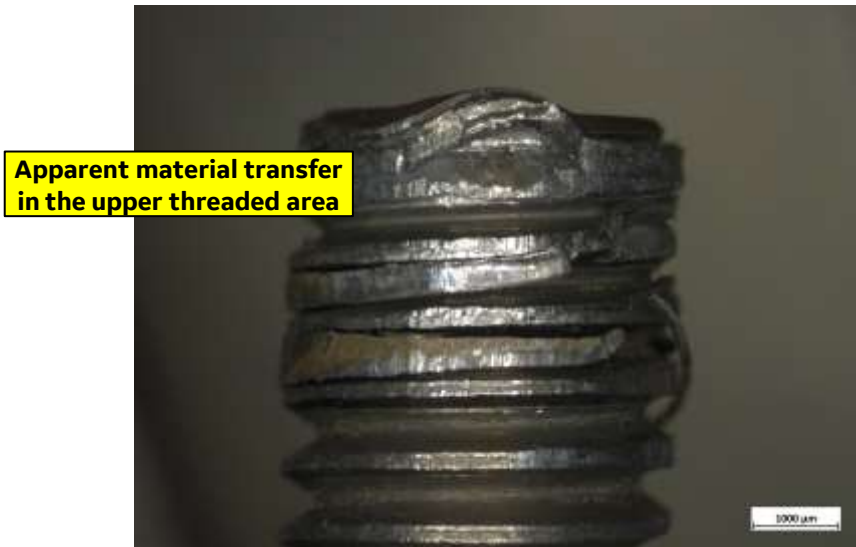
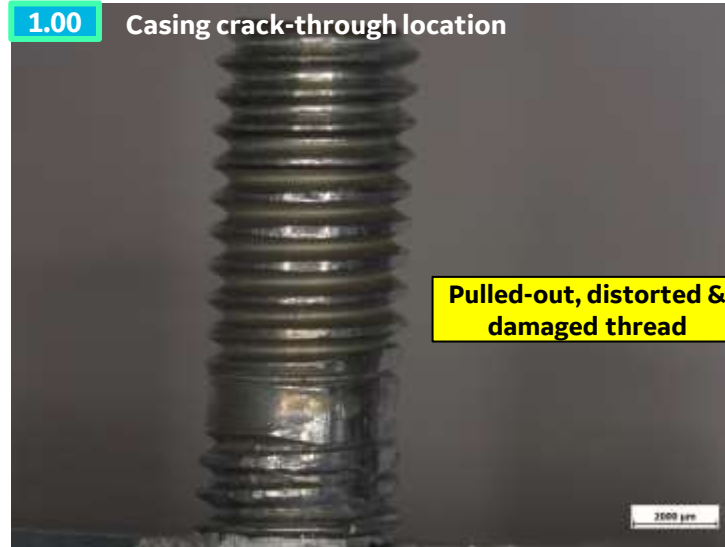
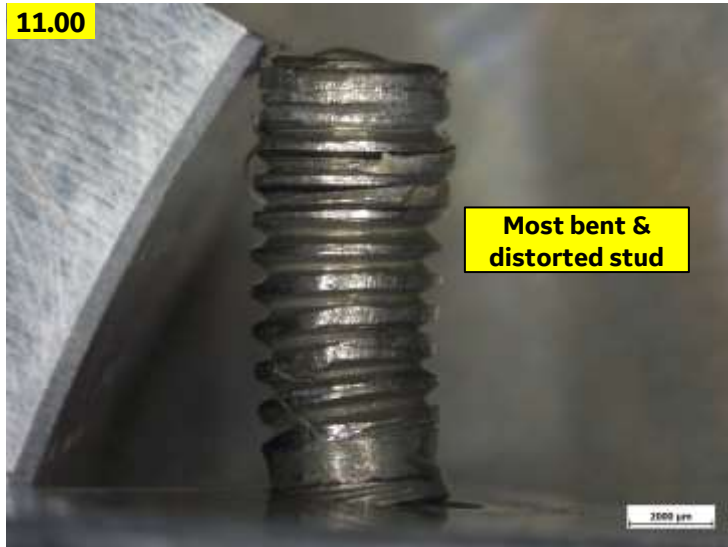


Visual Inspection (break open)



Stereo-micrographs (as-cleaned **studs**)

FLA CW positions
kept as reference

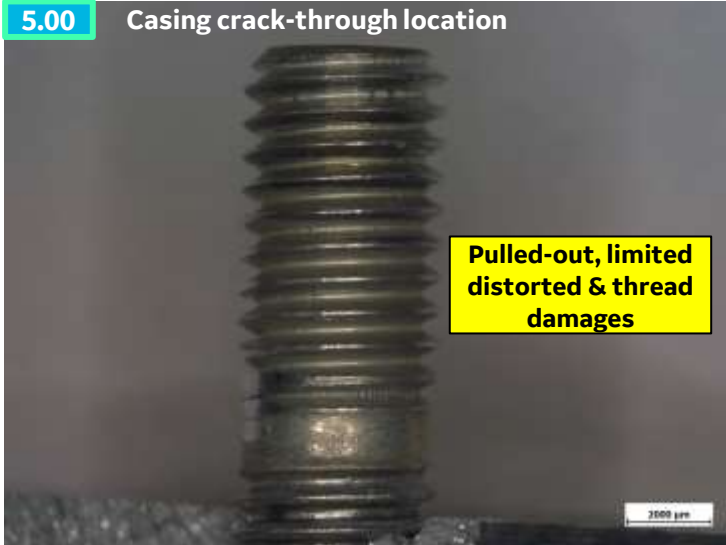


Stereo-micrographs (as-cleaned **studs**)

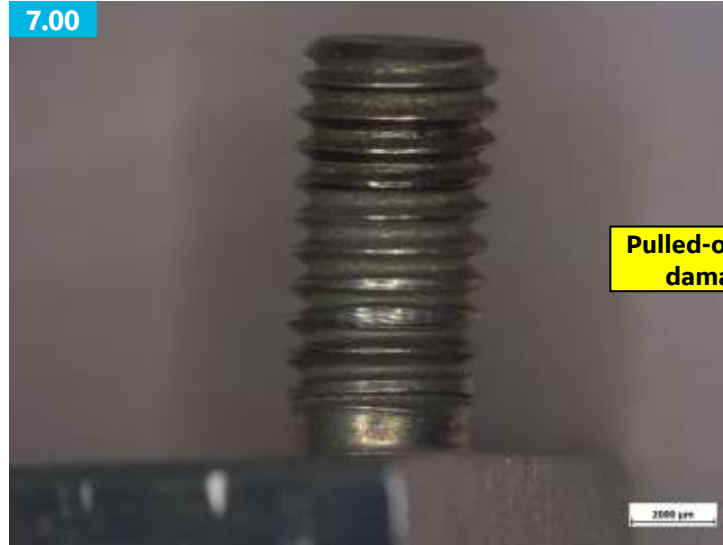
FLA CW positions
kept as reference

5.00

Casing crack-through location



7.00



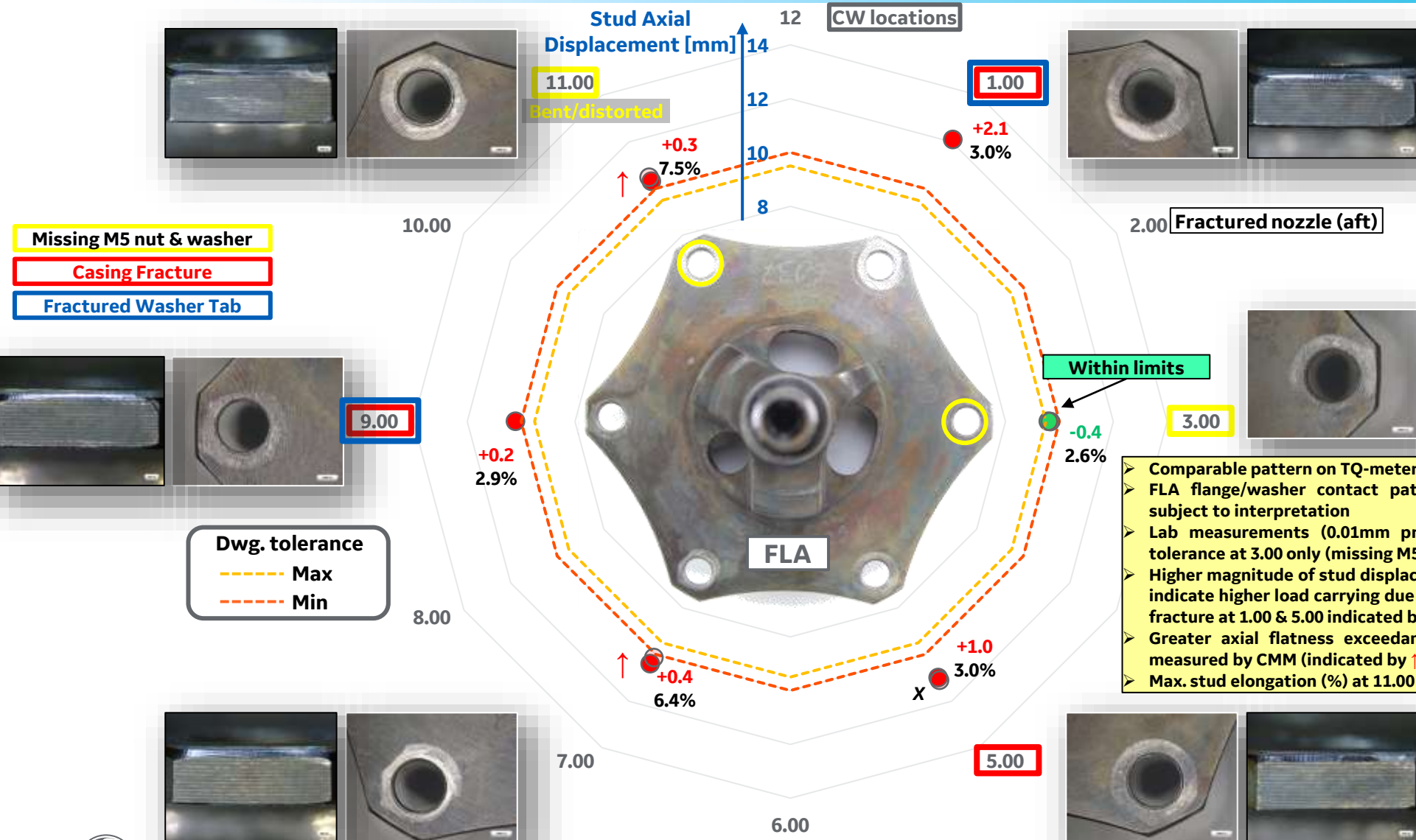
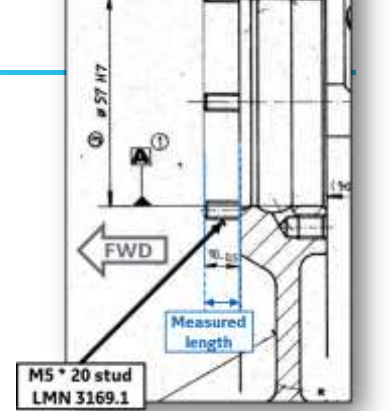
9.00

Casing crack-through location



TQ-meter Flange & Stud Assessment

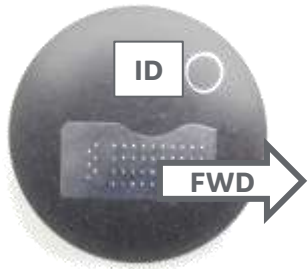
Measurements carried out with 0.01mm precision caliper



- Comparable pattern on TQ-meter flange edge/side face supporting initial tab securing
- FLA flange/washer contact pattern variation (indicated by tin-plating transfer) subject to interpretation
- Lab measurements (0.01mm precision) of stud axial displacement within dwg. tolerance at 3.00 only (missing M5 nut) & corroborated by CMM (indicated by "O") *
- Higher magnitude of stud displacement @1.00 & 5.00 locations adjacent to 3.00 might indicate higher load carrying due to missing/loosen nut (worth mentioning the casing fracture at 1.00 & 5.00 indicated by "X" as displacement contributor)
- Greater axial flatness exceedance at 11.00 & 7.00 locations of TQ-meter flange measured by CMM (indicated by ↑)
- Max. stud elongation (%) at 11.00 & 7.00 locations (0.01mm precision measurement)

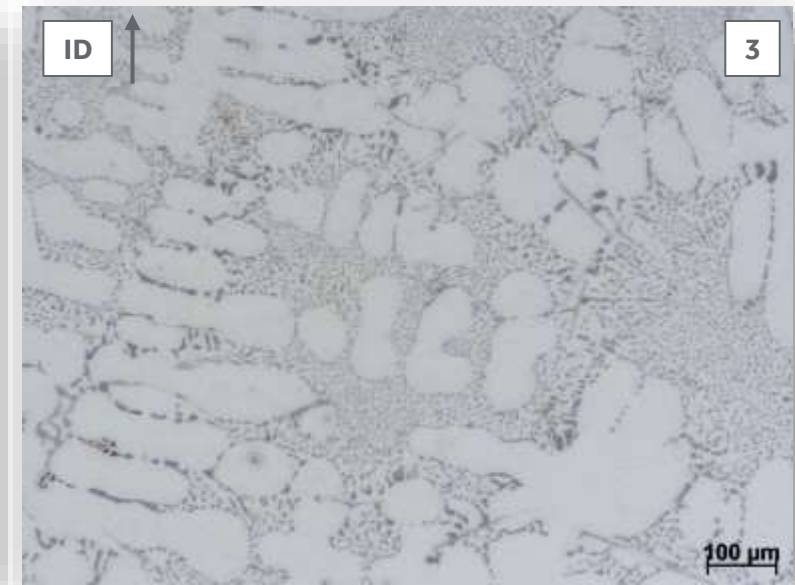
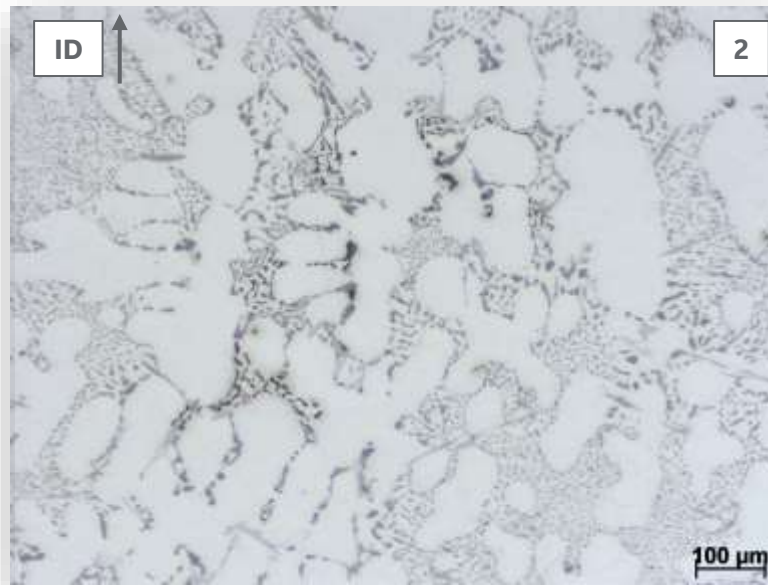
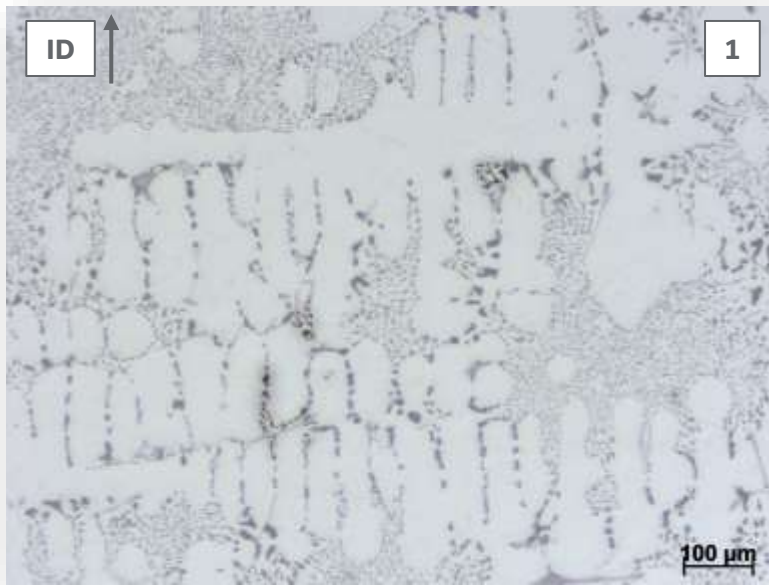
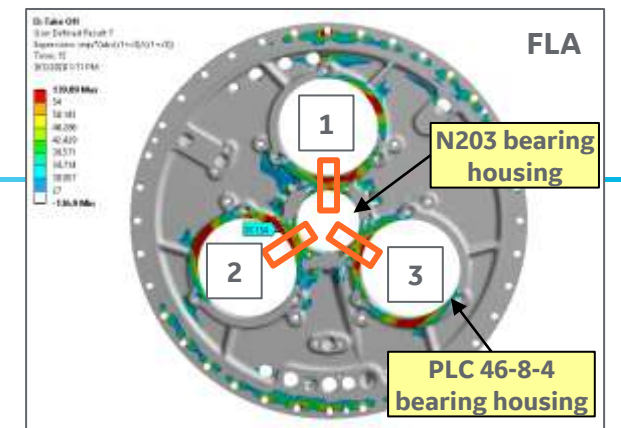
* compatible with missing M5 nut further connoted by the absence of pull-out damage indications on stud thread

Metallurgical Examination



- Radial cut-ups at critical locations CW positions (FLA)
 - 1 (12.00)
 - 2 (8.00)
 - 3 (4.00)
- 100 ± 10 HV5

=> Microstructure & micro-hardness conforming to technical specification TPF 01-2018-11 for EN AC-43100 casting in HIP & solution annealed + aged heat treat condition



Metallurgical Examination



- Tangential cut-ups at critical locations CW positions (FLA)
 - 1 (12.00)
 - 2 (8.00)
 - 3 (4.00)
- 101 ± 12 HV5

=> Microstructure & micro-hardness conforming to technical specification TPF 01-2018-11 for EN AC-43100 casting in HIP & solution annealed + aged heat treat condition

