

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594



September 29, 2014

MATERIALS LABORATORY FACTUAL REPORT

Report No. 13-086

1. INCIDENT INFORMATION

Place : Charleston, South Carolina
Date : July 28, 2012
Vehicle : Boeing 787-8, ZA238
NTSB No. : DCA12IA114
Investigator : Dave Helson, AS-10

2. COMPONENTS EXAMINED

- GENx engine fan midshafts (ESN 956-121 and ESN 956-175)
- Fan midshaft retaining nuts (ESN 956-121 and ESN 956-175)
- Center vent tube (ESN 956-121)

3. DETAILS OF THE EXAMINATION

3.1. Background and Timeline of Events

On July 28, 2012, a Boeing 787-8 airplane experienced a loss of thrust in the right engine during a pre-flight, low speed taxi test at Charleston International Airport in Charleston, South Carolina. The test was aborted when the engine reached 78% N1 when commanded to 95.4% N1.¹ The engine was a General Electric (GE) GENx-1B turbofan engine, engine serial number (ESN) 956-121. Borescope inspection of the engine revealed the low-pressure turbine (LPT) rotor had shifted aft causing extensive damage to the LPT section of the engine. Further examination of the engine revealed the forward end of the fan midshaft (FMS) had separated from the aft portion of the shaft at the aftmost external thread.

The fractured forward end of the FMS assembly with the forward lock nut and center vent tube still in place was removed from the engine and sent to GE Aviation in Evendale near Cincinnati, Ohio, for dimensional inspection and metallurgical examination. The engine was subsequently removed from the airplane and sent to GE Aviation in Cincinnati for disassembly and examination. The examination of the shaft remnant and the removed engine was performed under the guidance of the NTSB, with participating party members present. The engine had not yet been operated in flight, having only been operated during post-assembly tests at GE and post-installation ground runs at Boeing in Charleston. The fan midshaft had undergone 634 days of total

¹ N1 refers to the rotating speed of the innermost rotating shaft with the fan/booster and low-pressure turbine sections of the engine, here given as a percentage of maximum RPM.

time clamped to the adjacent components and 18 hours (2 cycles) under power before fracture.

Because of the ongoing investigation into the FMS separation that occurred on ESN 956-121 at Charleston, GE developed and validated a field ultrasonic (UT) inspection to scan the forward end of the FMS under the threads where the fracture occurred from the forward side of the engine. These inspections were performed on all GENx FMS in the field and in storage. On August 13, 2012, another GENx-1B engine, ESN 956-175, installed on a 787-8 airplane that had not yet flown was field UT inspected. The inspection revealed an indication in a similar location on the FMS as the incident engine.

Like ESN 956-121, this engine had not been operated in flight. The fan midshaft had undergone 106 days of total time clamped to the adjacent components and no flight hours under power before detection of the crack indication. The engine was removed from the airplane and shipped to the GE Aviation facility in Durham, North Carolina, for disassembly with a total clamp time of 114 days. Further ultrasonic tests confirmed the crack indication. The FMS was removed from the engine and shipped to GE in Cincinnati for further inspection and examination.

3.2. Cincinnati Group Examination

The failed shaft, the second cracked shaft, and an exemplar shaft were inspected, non-destructively and destructively, at the GE Aviation engine facility in Evendale, Ohio near Cincinnati. The following metallurgical group representatives were present for at least part of the investigation:

- Erik Mueller, NTSB
- Wesley D. Pridemore, GE Aviation
- Walt Buttrill, GE Aviation
- Dale Weires, The Boeing Company
- Jim Kachelries, The Boeing Company
- Terry Khaled, FAA

The forward end of the fan midshaft arrived separate to the GE Evendale facility before the rest of the GENx engine 956-121 arrived. This engine was disassembled under the direction of Jim Hookey, NTSB AS-40, in order to observe and document other damage to the engine while the metallurgical group analyzed the fan midshaft fracture. As the investigation took place, several specimens were sent to outside labs for further testing. Much of this testing information is detailed in *NTSB Materials Lab Report 13-087*. In addition, when the crack indication was found in the second fan midshaft from engine 956-175, this part was sent to the Evendale facility for further inspection and analysis. The results of this analysis are detailed below in Section 3.3.3.

3.3. Failure Analysis Investigation

The parts examined during this investigation were as follows:

- ESN 956-121
 - Coupling Nut: P/N 2331M28P01
 - Forward Fan Shaft: P/N 2321M44P01
 - Shim Washer: P/N 2331M29P01 (0.1968 inch)
 - Fan Midshaft: P/N 2331M20G02, S/N JHVAY014
- ESN 956-175
 - Coupling Nut: P/N 2331M28P01
 - Fan Midshaft: P/N 2331M20G02, S/N JHVAA268

3.3.1. Investigation Teardown and Initial Investigation (ESN 956-121)

The fracture of the fan midshaft was located at the aft most full thread root, forward of the outboard shaft splines. This fracture of the FMS allowed the LPT section to move aft causing significant secondary engine damage. However, the FMS splines remained engaged with the forward fan shaft splines that kept the fan and LPT modules rotating at the same speed.

The fan midshaft was approximately 8 ft long and was comprised of GE1014 ultrahigh strength steel.² The shaft threads were coated with a cured thermosetting dry film lubricant, Everlube 9002.³ The fan midshaft included turned buttress threads on interior and exterior surfaces that allowed it to mate with adjacent components. The buttress threads possessed 7° and 45° flanks. The inside of the fan midshaft was coupled to a center vent tube using interior threads. The fan midshaft coupled the forward fan shaft to the rear low-pressure turbine section. The assembly was fastened together on the forward end using a forward lock nut and shim washer (see Figure 1). The lock nut was made of Marage 250 with the inside threads coated with Everlube 9002.⁴ During assembly, petrolatum graphite grease was used to aid in assembly. The forward lock nut was clamped to a specified load.

Borescope inspection of ESN 956-121 revealed a separation in the fan midshaft adjacent to the lock nut face as shown in Figure 2. Figure 3 shows the forward FMS fracture half with lock nut and center vent tube (CVT) assembly upon arrival at GE-Aviation. The FMS fracture and inside region of the FMS were still covered in engine oil. Examination of the FMS fracture revealed distinct color differences, consistent with multiple failure modes: one progressive and one instantaneous. The progressive

² GE1014 is a type of ultrahigh duplex strengthened steel developed for applications requiring high yield strength and fatigue properties, developed by General Electric. *M.A. Rhodes, E.L. Raymond, W.M. Garrison, High Strength, High Fatigue Structural Steel. US Patent 5,393,488 filed August 6, 1993 and issued February 28, 1995.*

³ Everlube 9002 is a heat-cured, lead-free, molybdenum disulfide solid film lubricant used at temperatures below 700°F produced by Everlube Products, Peachtree City, GA.

⁴ Marage 250, or MAR 250, is a maraged low-carbon, iron-nickel martensitic steel which is precipitation strengthened by intermetallic compounds.

regions generally showed two separate origin regions, located approximately 180° apart.⁵ The mating aft FMS fracture surface mirrored the pattern of the forward side (see Figure 4). The oil-covered aft fracture surface was rinsed with acetone, and the liquid was captured for further examination (see *Report 13-087*).

Figure 5 illustrates the forward segment of the fan midshaft and lock nut still attached to the center vent tube after the assembly was removed from the engine. The center vent tube was sectioned approximately 5 inches aft of the fracture to examine the forward fracture face of the FMS. Figure 6 shows the forward FMS fracture in a lightly cleaned condition with the lock nut attached. The lock nut appeared to have been properly secured. The fracture surface was cleaned with a light methanol and acetone rinse to remove residual engine oil and small wear debris. No evidence of fretting, wear, or abnormal contact damage was observed on the contact faces. Per the applicable drawings, all forward FMS threads and lock nut threads were coated with Everlube 9002 dry film lubricant with a subsequent application of graphite grease used to aid assembly.

As shown in Figure 6, two fracture origins were identified on the FMS fracture surface—these origin regions were labeled A and B for the purpose of this investigation. This view shows the progressive fracture regions, which contained visible crack arrest and ratchet marks. Figure 7 and Figure 8 show the forward FMS fracture segment after removal of the lock nut. The fracture emanated from the aft most thread root progressing primarily through the thicker (~0.6 inch) cross-section portion. After more extensive cleaning, the forward FMS fracture face showed a discolored region encompassing ~85% of the FMS cross-section (see Figure 9). Comparable fracture features were noted on the aft FMS fracture surface (see Figure 4).

Closer views of the fracture highlighting numerous discolored, thumbnail-shaped sites at origin regions A and B are shown in Figure 10, Figure 11, and Figure 12. The average thumbnail region depth measured 0.062 inch in origin region A and 0.059 inch in origin region B. Greater discoloration present on progressive regions near the fracture origin regions was consistent with longer exposure times to the local environment in the thread root region. The thumbnail-shaped origin regions exhibited multiple crack arrest, or beach mark, features consistent with progressive crack growth. Crack arrest marks outside of the thumbnail appeared more widely spaced, consistent with a change in the crack growth rate.

Additional views of origin region A are shown in Figure 12 and Figure 13. Cracking was also noted in the adjacent thread root along the circumferential direction of the root. As seen in Figure 13, this cracking resulted in liberation of a small thread fragment. Near this origin area for cracking region A, a triangular-shaped “island” was present bearing features consistent with the inner instantaneous fracture regions. As detailed in Section 3.3.2, this region was consistent with monotonically-increasing load to failure (overstress), as opposed to the surrounding progressive features.

⁵ A progressive fracture is the result of a crack that grows in length under the influence of time under continuous or variable stress prior to final fracture.

On the opposite side of the fracture (region B) away from the origin area of region A, other smaller thumbnail features emanating from the aft thread root were observed (see Figure 14 through Figure 16). Beach marks were more evident within the progressive region contrasted with the fracture outside of the thumbnail region. The presence of multiple ratchet marks around the periphery of the thumbnail region was consistent with later crack propagation from the thumbnail boundary.

Replicating silicon rubber was used to evaluate the profile of the thread roots before destructive inspection. A cross-section of one area is shown in Figure 17. Initial thumbnail regions were angled at $\sim 50\text{--}55^\circ$ with respect to the 7° thread flank angle. The deepest thumbnail shaped region associated with origin region A measured 0.075 inch. The radius of curvature of the thread roots was consistent with specification requirements.

3.3.2. Failure Analysis of Fractured Fan Midshaft (ESN 956-121)

The forward FMS was sectioned in order to examine the fracture surface using scanning electron microscopes (SEM), as shown in Figure 18. Evidence of faceted, quasicleavage fracture was observed emanating from the aft most thread root region as shown in Figure 19. These facets showed small cleavage “tongues” which generally faced inward, but in some locations were oriented in sporadic directions. Similar fracture morphology along with prevalent secondary surface cracking was observed just inboard of the thread root region. This fracture morphology was consistent with environmentally assisted cracking (EAC) in certain ultrahigh strength steels, such as the fan midshaft material, GE1014.⁶ No evidence of fatigue striations was found.⁷ Inspection using energy dispersive X-ray spectroscopy (EDS) found the FMS material to be consistent with GE1014.⁸ No evidence of any corroding elements, namely chlorine and other halogens, was detected on the fracture surface. Major levels of carbon and oxygen were commonly detected on the discolored fracture surface.

A distinct boundary was observed between the progressive EAC cracking and the triangular-shaped area shown in Figure 11 and Figure 12. Dimple rupture, consistent with failure by overstress, was seen within the triangular patch as shown in Figure 20. A continuation of the predominantly transgranular EAC fracture morphology, with an occasional smooth intergranular facet, was observed at areas inward of the triangular patch, as shown in Figure 21 and Figure 22. Distinct crack initiation sites were observed adjacent to the aftmost thread (see Figure 23 and Figure 24). The innermost regions displayed dimple rupture, consistent with instantaneous ductile overstress (Figure 25).

⁶ Environmentally assisted cracking is progressive failure of a normally ductile material in which the corrosive effect of the environment.

⁷ Fatigue striations are parallel lines observed microscopically on fracture surfaces indicative of failure by repeated or fluctuating stresses less than the ultimate tensile strength of the material (fatigue).

⁸ See *NTSB Materials Lab Report 13-087* for more information on environmental testing of GE1014.

The progressive region on the opposite side of the FMS fracture surface showed fracture features consistent with EAC. Multiple-origin, quasicleavage cracking was again observed emanating from the thread root region (see Figure 24). Fracture outside of the initial thumbnail region, consistent with progressive EAC, continued inward abruptly transitioning to an overstress region. In addition, a thin band with fracture morphology consistent with EAC was observed progressing in an inward direction parallel to the inner diameter surface, just prior to the final overstress fracture at the edge (Figure 25).

EDS was used to analyze the surface of the FMS fracture from EAC region A after light cleaning to remove residual engine oil in an attempt to identify underlying surface contaminants. The data obtained was consistent with decreasing carbon (C) and oxygen (O) levels while moving radially inward from the discolored initial thumbnail region. No indications of elevated molybdenum (Mo) or antimony (Sb) were found along the fracture surface—these elements are constituents in the Everlube 9002 dry film lube.

Additional SEM examination was performed to characterize the thread root at the origin region as shown in Figure 26. This cross-section revealed the initial thumbnail fracture regions angled between $\sim 49^\circ$ and $\sim 59^\circ$ with respect to longitudinal axis of the FMS. The fracture angle transitioned to approximately 90° further inward of the FMS cross-section. Secondary cracking was observed adjacent to the thread root region, with additional secondary cracking found emanating from the thumbnail fracture that had progressed back towards the adjacent thread root, as shown in Figure 27. The end of the secondary crack exhibited a branched appearance consistent with EAC. A closer view of transgranular, secondary cracking below the primary fracture surface in the center region of the fracture is shown in Figure 28. The appearance of cracking observed during metallographic examination was consistent with EAC cracking mechanisms in high strength steels.

Fracture features consistent with EAC cracking were also observed emanating from the aft most thread root. EDS analysis did not reveal any typical corrodants, such as chlorine, or constituent elements present in the dry film lube on the initial fracture surface. EDS did reveal areas within the thread root regions that yielded only spectra consistent with GE1014 material with no indications of the dry film lubricant. In general, the dry film lubrication coating was incomplete in thread root region but continuously coated on both the 7° and 45° thread flanks. A similar trend of incomplete DFL coating coverage was found in other forward thread roots. No evidence of any typical corroding elements, namely chlorine, was detected in the other thread roots.

The thread root region adjacent to the cracking showed thin dry film lubrication thicknesses measuring less than the prescribed minimum, particularly certain regions on the 45° flanks (Figure 29). Some regions within the thread root appeared bare, consistent with previous observations. These thread roots also exhibited areas with shallow semi-circular features resembling pits. However, features were filled with mounting material rather than foreign debris or corrosion products, as shown in Figure

30. No evidence of abusive machining or other material anomalies was noted in the thread roots.

The dry film lubrication coating thickness generally met the drawing requirements on the 7° thread flank, but tapered down to below minimum thicknesses closer towards the thread root. EDS evaluation of debris within the thread root beneath DFL coating did not reveal any evidence of chlorides or other typical corrodants. The root radius of the non-fractured thread roots met drawing requirements.

The overall FMS microstructure was consistent with tempered martensite. Both the average prior austenite grain size and hardness (56 HRC) met drawing requirements.

A portion of the fracture surface from origin region A was sent to GE Global Research Center (GRC) in Niskayuna, NY for focused ion beam (FIB)⁹ and Auger electron scanning¹⁰ surface analysis to characterize the discolored surface debris layer. The outermost layer of the fracture surface specimen (under the protective platinum layer) consistently exhibited elevated carbon and oxygen peaks, with no evidence of chlorides or other similar species, consistent with previous EDS results obtained from the fracture surface. However, trace amounts of chlorine were detected under the outermost layer after sputtering (see Figure 31).

Auger electron analysis performed on the debris layer revealed the presence of carbon and oxygen, as well as GE1014 constituent metal elements and platinum from the FIB plating. Auger analysis of the underlying debris revealed a trace amount of chlorine within a local region of debris as shown in Figure 31. Auger depth (sputter) profiles were performed within the initial thumbnail fracture surface. After sputtering, both carbon and oxygen were confirmed within the debris layer, along with sporadic areas containing trace amounts of chlorine.

The lock nut used to torque the forward end of the FMS was also examined. The forward region of the nut contained enough graphite grease material to coat the entire inner threaded surface. Shear damage was noted on the last aft thread of the nut. This damage corresponded to a region on FMS fracture where the crack was observed to have overlapped. EDS analysis of the graphite grease removed from the forward side revealed primarily carbon with minor amounts of molybdenum and antimony, consistent with constituents in the dry film lubrication. No evidence of any typical corroding elements, such as chlorine, was detected in any of the removed debris.

⁹ FIB is a technique analogous to SEM that uses a gallium ion beam to sputter and analyze a specimen. The technique typically places a layer of protective platinum on the desired surface to protect it while the ion beam bores a trough cross-section through the specimen.

¹⁰ Auger electron spectroscopy is a chemical and surface analysis technique that identifies atoms present in a layer by measuring characteristic energies of their Auger electrons. Auger electrons are emitted from an atom with an inner shell vacancy and possess characteristic energies specific to atomic number.

3.3.3. Failure Analysis of Cracked Fan Midshaft (ESN 956-175)

The field ultrasonic inspection data illustrating the observed crack indications from the forward FMS threaded region on GENx-1B ESN 956-175 is shown in Figure 32. A closer view of the UT inspection data highlighting the largest indication is shown in Figure 33. After the inspection, the engine was removed from the aircraft and the fan midshaft was removed and examined at the GE facility in Evendale, Ohio. The graphite grease was removed from the forward threads using engine oil and acetone with light bristle brush. The liquid was collected and examined by Fourier Transform Infrared (FTIR) analysis for organic compounds (see *NTSB Materials Lab Report 13-087*).

This cleaning was performed to facilitate subsequent fluorescent penetrant inspection (FPI) to better identify the locations and boundaries of the crack indications. The FPI examination performed after cleaning confirmed an approximately 2 inch circumferential crack indication in the aft most thread root. The indication was located between FMS forward castellations #2 and #16 previously found during field UT inspection as shown in Figure 32. No other crack indications were detected in the aft most thread root via FPI.

The FMS was sectioned just aft of the splined region and subjected to magnetic particle inspection (MPI). The MPI inspection confirmed the approximately 2 inch indication located between castellations #2 and #16. In addition, the MPI inspection identified other crack indications, two of which were located at castellations #8 and #9. All indications detected via MPI were marked on the FMS shoulder with a grease marker. All of these indications were observed along the aft most thread root.

The FMS was sectioned just forward of the spline shoulder to allow full immersion ultrasonic inspection in mineral oil. Additional crack indications were identified during immersion UT inspection, with the largest crack indication located between castellation #2 and #16. This region of the FMS was sectioned, backcut, and intentionally overstressed to expose the crack faces. Multiple initial thumbnail regions were found emanating from the aft most thread root, as shown in Figure 34. Figure 35 shows a closer image of one of the initial thumbnail regions prior to any cleaning.

EDS analysis was performed on the discolored fracture surface in Figure 35. As with the 956-121 FMS, elevated levels of carbon and oxygen on the progressive crack face were observed. No evidence of typical corroding elements, namely chlorine, was observed on the fracture surface in the uncleansed condition. Incomplete dry film lube coating was noted in the thread root region with local bare regions of GE1014 commonly observed.

The initial thumbnail regions of the fracture surface displayed faceted, quasicleavage features consistent with progressive environmentally assisted cracking emanating from the thread root region. Re-examination of the lab-opened fracture surface at castellations #2 through #16, following cleaning, revealed multiple discolored initial thumbnail-shaped regions, as shown in Figure 36 and Figure 37. The fracture surface morphology in the progressive cracking regions was comparable to the

progressive regions on the 956-121 fracture surface. The initial thumbnail regions tended to be relatively uniform in crack depth and measured approximately 0.041 to 0.047 inch deep. The maximum overall EAC crack depth measured 0.107 inch for the FMS from ESN 956-175. The intentionally overstressed regions inboard of the crack faces are shown in Figure 38. The dimple rupture morphology was comparable to the overstress regions in the fractured ESN 956-121 FMS.

The smaller double indication, detected via MPI and immersion ultrasound inspection at the castellation #11 location (right side of Figure 31), was sectioned, backcut, and intentionally overstressed. Separate, discolored thumbnail regions were observed measuring 0.035 and 0.038 inch deep, as shown in Figure 39.

Examination of the fracture surface prior to any cleaning revealed multiple origin, transgranular EAC cracking emanating from the aft most thread root. This fracture morphology was present up to the boundary with the intentionally overstressed region. Evidence of the dry film lubricant constituents was observed in the thread root region. Closer examination of the aft most thread root revealed regions of bare GE1014 material, as shown in Figure 40 and Figure 41. EDS analysis of debris removed earlier from the aft most thread root revealed no evidence of chlorine or other similar elements.

Examination of a metallographic cross-section through the aft most thread root revealed areas of dry film lube coating coverage less than the minimum coating requirements (Figure 42). The thread root radius measured 0.0051 inch, which met drawing requirements. Evaluation of the forward thread flank face also revealed a thin dry film lube coating, exhibiting a coating thickness greater than the requirement on the 45° flank angle surface (Figure 43).

Metallographic cross-sections through one of the discolored, thumbnail origin sites, from cracking between castellations #2 through #16, are shown in Figure 44. The initial thumbnail crack was angled at ~60° with respect to the longitudinal direction, similar to that observed with fractured FMS in ESN 956-121. No evidence of abusive machining or other material anomalies were noted at the origin region.

The FMS microstructure was consistent with tempered martensite. Both the average prior austenite grain size and hardness (55 HRC) met the prescribed drawing requirements.

A portion of uncleansed fracture surface from the intentionally opened crack at castellation #11 was sent to GRC in Niskayuna, NY for focused ion beam and Auger electron analysis. The sample sent to GRC and FIB sample extraction from the discolored thumbnail region is shown in Figure 45. Auger analysis confirmed the presence of carbon (C) and oxygen (O) as well as the GE1014 base metal elements associated with thin debris layer. No chlorine was detected during Auger analysis at any of the points analyzed.

The forward lock nut from ESN 956-175 was inspected. As with the forward lock nut from ESN 956-121, the forward region of the nut contained enough graphite grease

to cover all the internal surfaces. EDS analysis of the graphite grease removed from the FMS revealed mainly carbon with small particles of molybdenum and antimony, consistent with constituents from the dry film lubricant. No evidence of typical corroding elements, such as chlorine, was detected in the removed debris.

Optical comparison was performed on the forward lock nuts from both engine fan midshafts. The DFL coverage appeared more uniform on the lock nut from ESN 956-121 as opposed to the lock nut removed from ESN 956-175. The lack of lubricant coverage was most noticeable on the five aftmost threads on the lock nut from ESN 956-175. SEM examination of specimens from both lock nuts threads further demonstrated a lack of dry film lubricant uniformity and coverage, with some local areas measuring below the minimum thickness drawing requirements. Local bare spots of Marage 250 nut base metal were observed in the aft-most thread root of lock nut from ESN 956-175.

Erik M Mueller
Materials Research Engineer

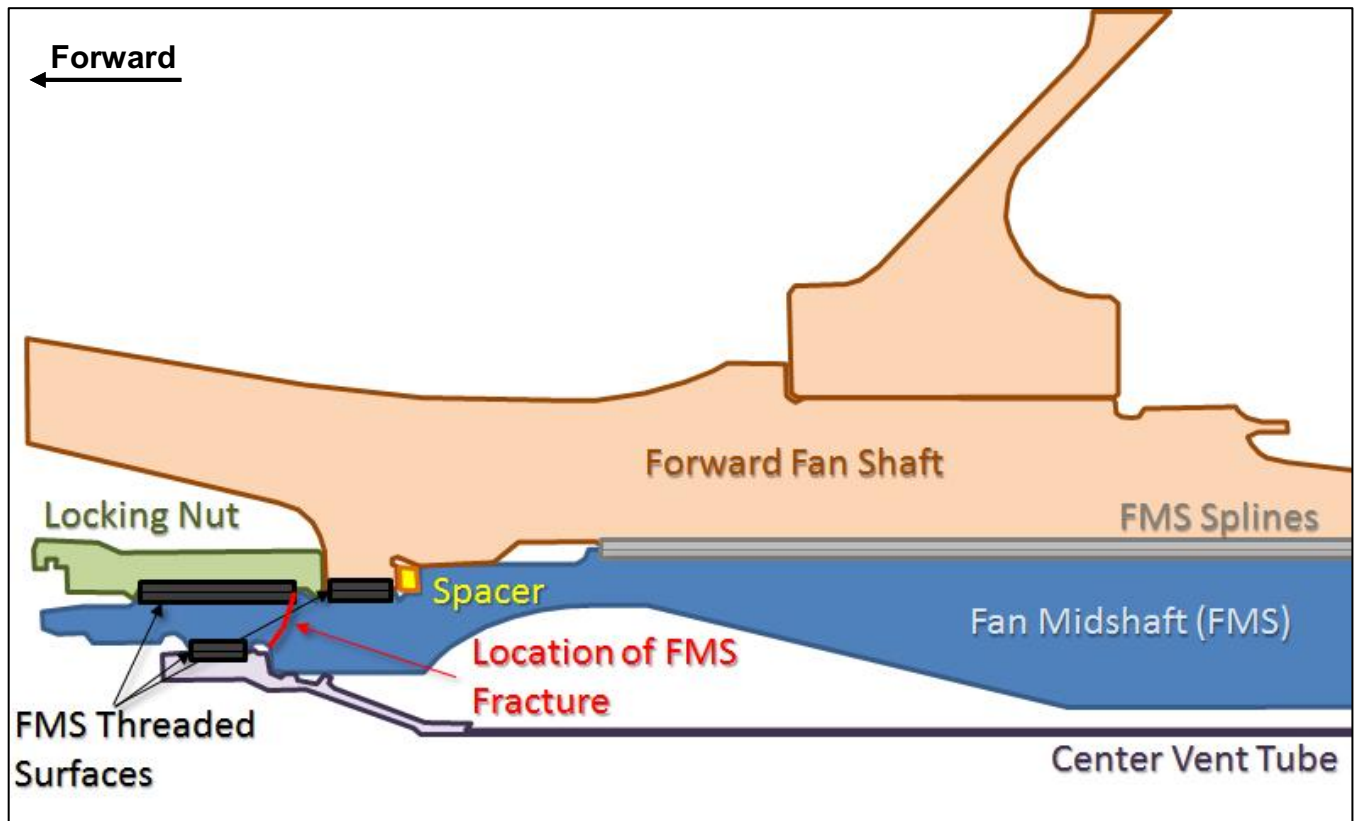


Figure 1 – Schematic illustration of the configuration of the fan midshaft in relation to forward adjacent components. The FMS has threaded connections with the forward fan shaft, center vent, tube, and the locking nut. The FMS also connects to the forward fan shaft via splines on the FMS outer surface further aft.



Figure 2 - Initial borescope image of fractured fan midshaft while inside the GENx engine (ESN 956-121), aft looking forward.

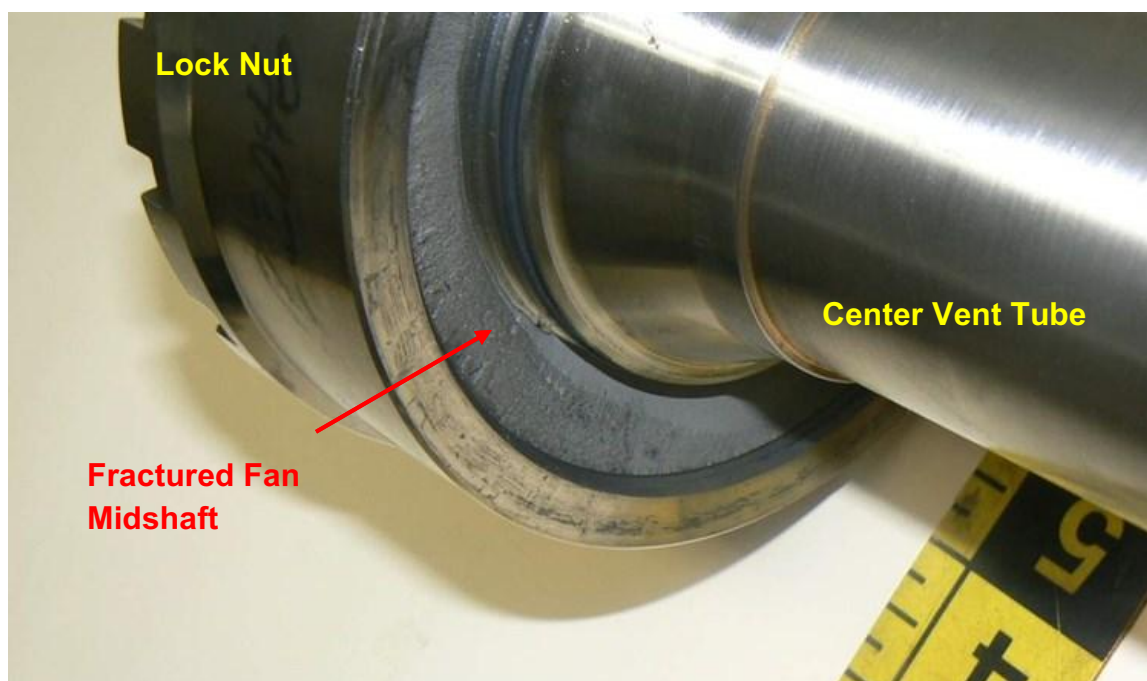


Figure 3 – Fracture surface of the forward segment of the fan midshaft, still held in the coupling nut.

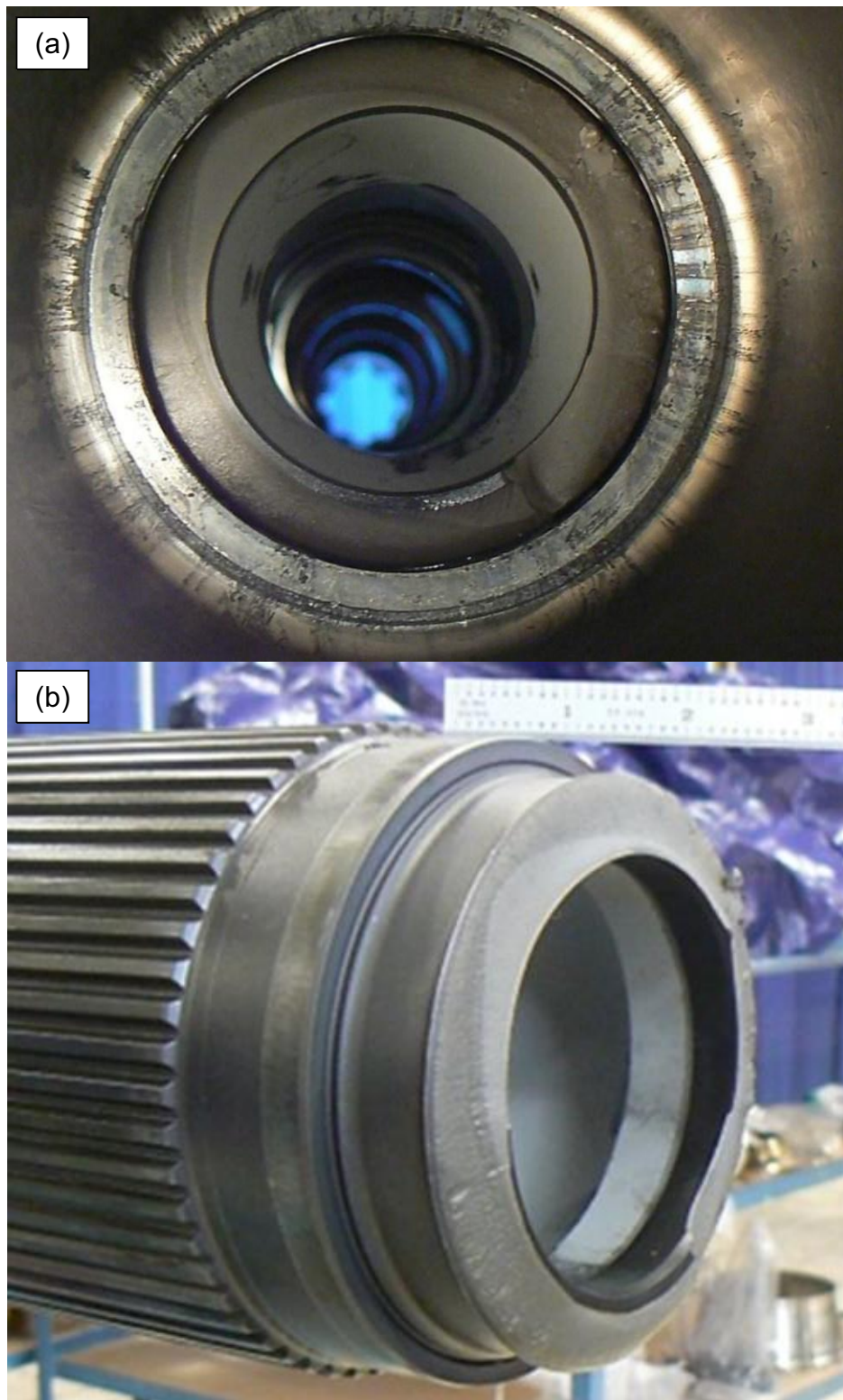


Figure 4 – The aft section of the fan midshaft, still inside the engine center after removal of the forward fan midshaft section and center vent tube (a) inside the engine and (b) after removal.

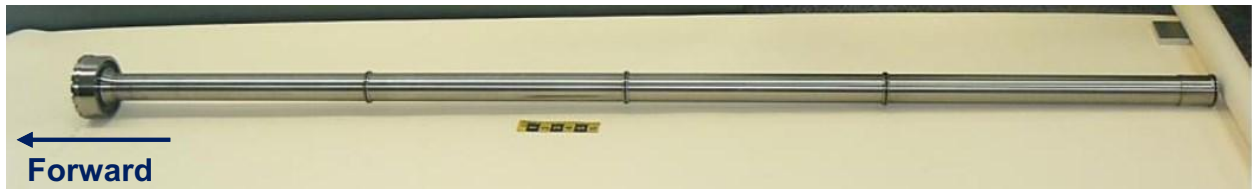


Figure 5 – The fan midshaft forward segment in the coupling nut attached to the center vent tube (CVT).



Figure 6 – The fracture surface of the fan midshaft forward section, aft looking forward. The fracture surface shows features consistent of two modes of failure: one progressive and one overstress.



Figure 7 – The forward fan midshaft section illustrated in Figure 6, after removal of the coupling nut with the center vent tube still attached.



Figure 8 – The forward fan midshaft segment, showing a break in the aft most outer thread at the location of the fracture.

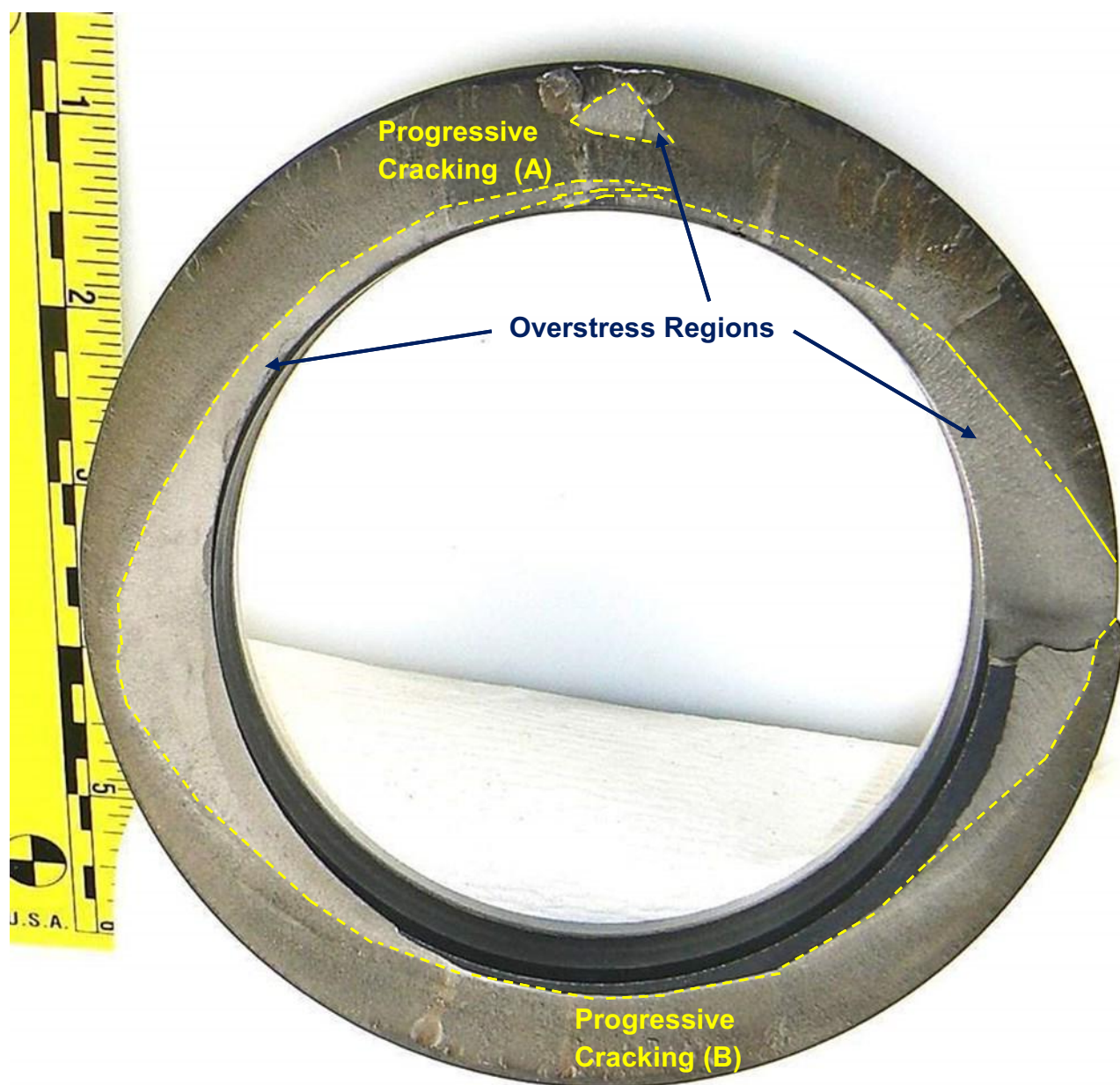


Figure 9 – The forward fan midshaft fracture surface, after removal of the lock nut and center vent tube. The different failure mode regions are identified, with the progressive regions labeled A and B.



Figure 10 – Thumbnail features on the fracture surface (after cleaning).

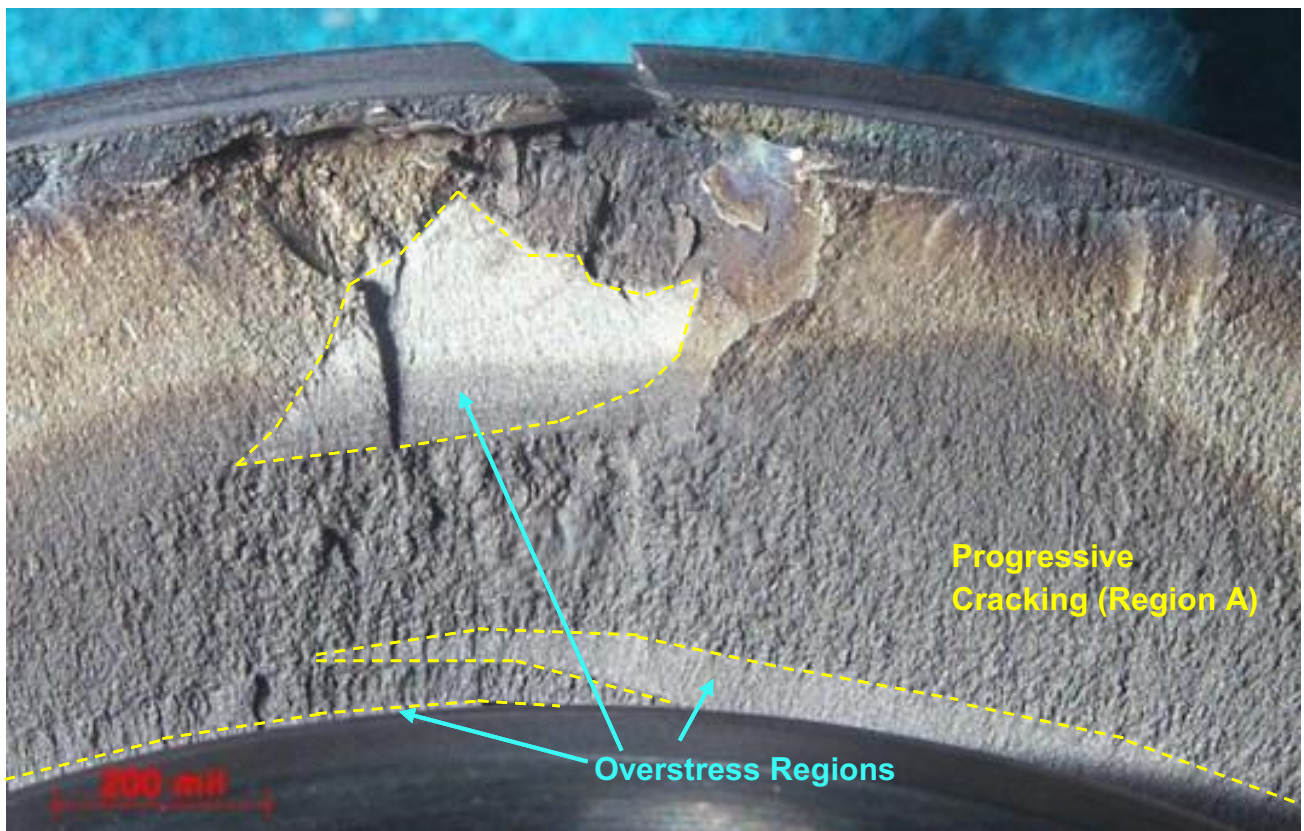


Figure 11 – Forward fan midshaft fracture surface near the aft broken thread, showing thumbnail, discoloring, and crack arrest features. These surrounded an area of rough, cleaner looking region inside of the fractured thread (before cleaning). The dashed lines represent the boundaries of the progressive cracking regions from the overstress regions.



Figure 12 – Closer look at the fracture surface from Figure 11.

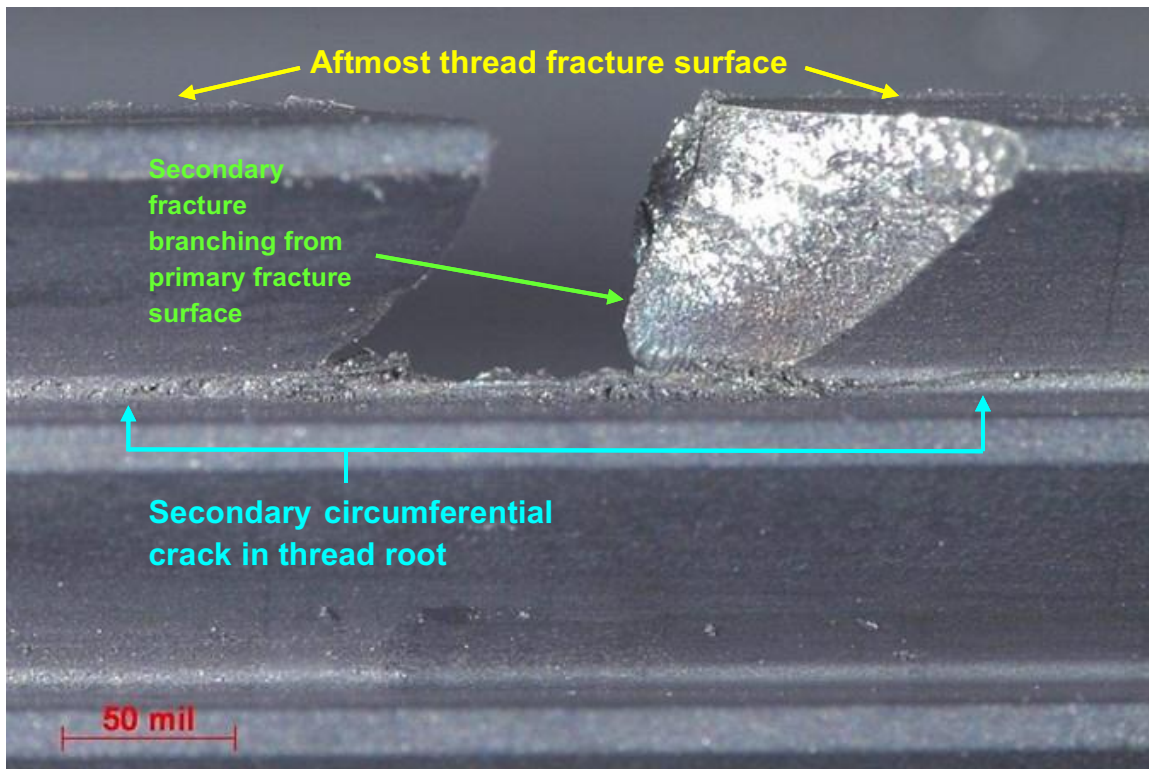


Figure 13 – View of the aft most fractured thread root, from above.



Figure 14 – Closer view of the thumbnail feature near the thread root depicted in Figure 10a.

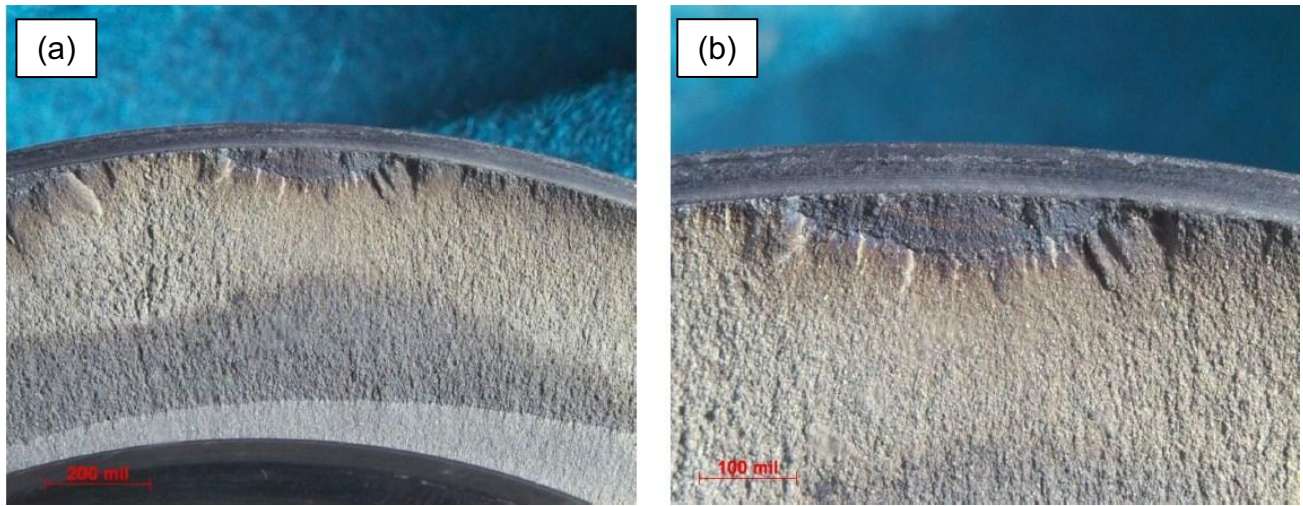


Figure 15 – Two other thumbnail features and discoloration approximately 180° away from the larger crack front on the forward fan midshaft fracture surface.



Figure 16 – Closer view of the thumbnail feature and discoloration in Figure 15b.

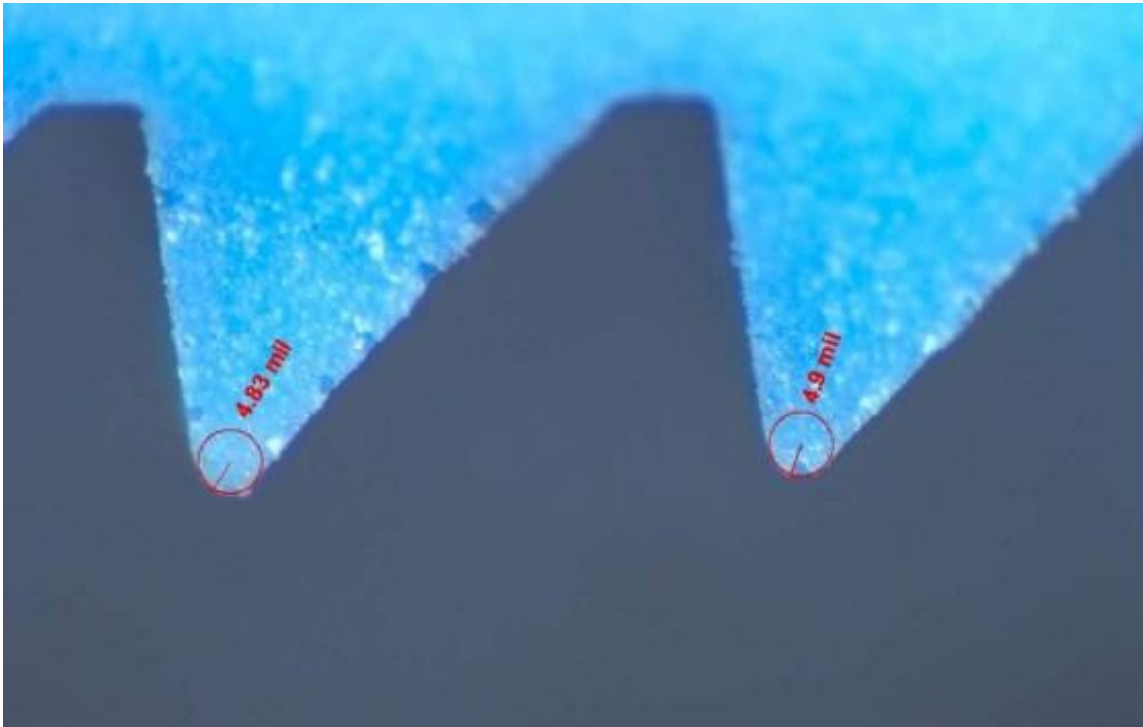


Figure 17 – Cross-section a replica of the thread roots adjacent to the aft most thread (right), created to determine the minimum radius of the roots.

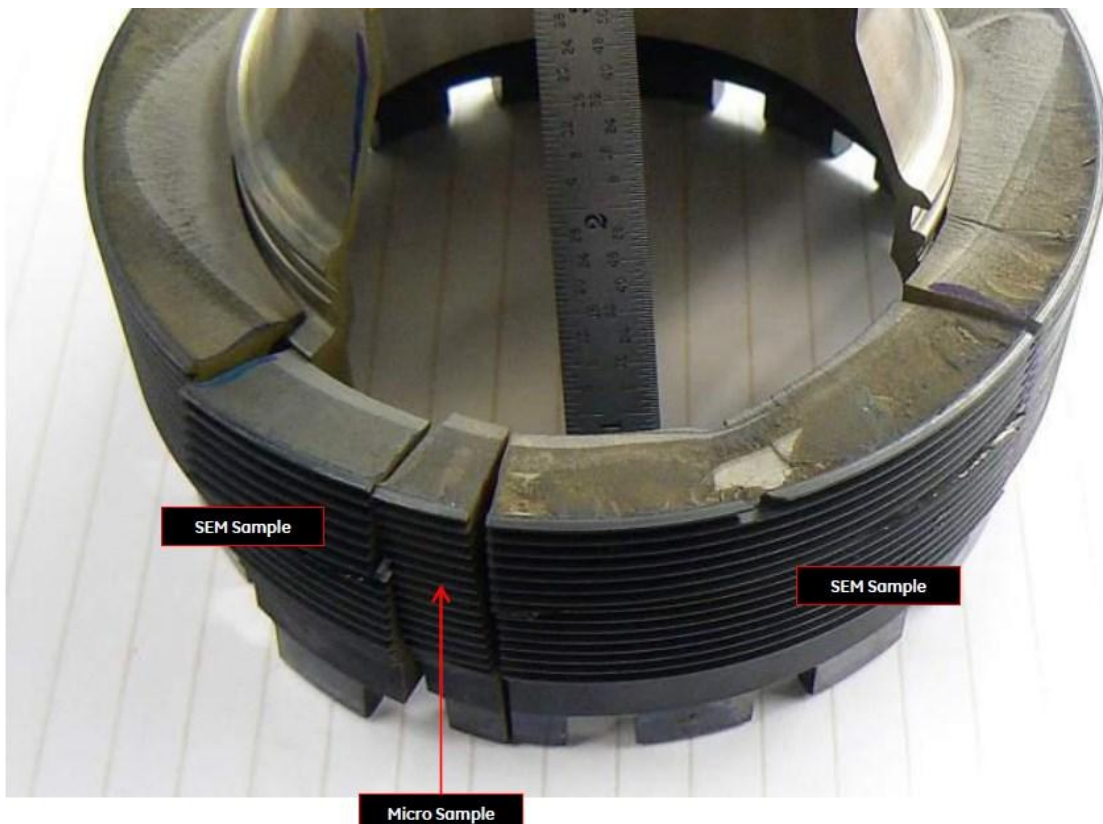


Figure 18 – The forward fan midshaft segment after sectioning areas of interest for further analysis.

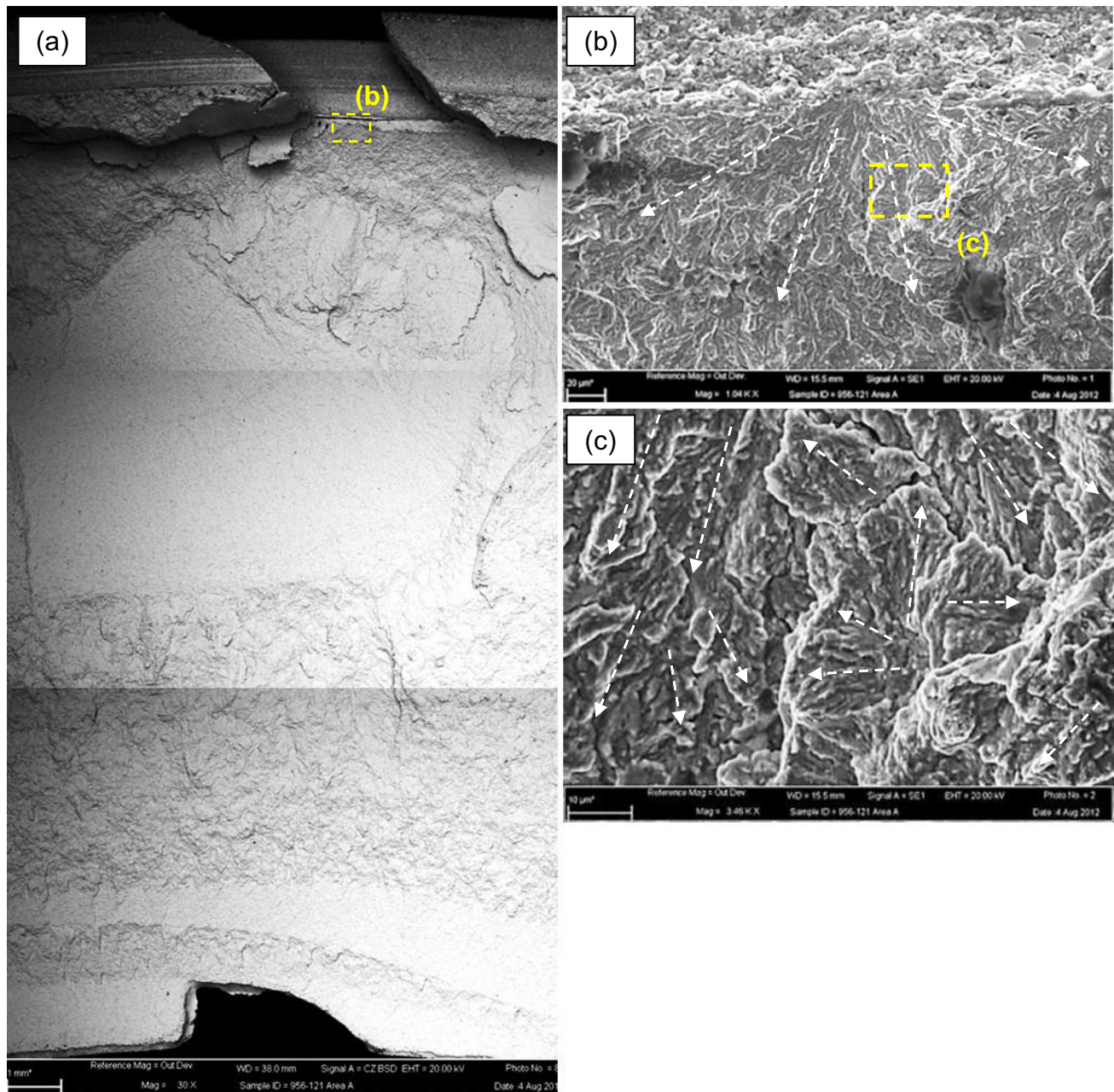


Figure 19 – The forward fan midshaft fracture (a) showing a backscattered electron (BE) micrograph montage of the area depicted in Figure 11, (b) showing a secondary electron (SE) micrograph of the fracture near the initiation site, and (c) showing a closer view of (b). The fracture surface shows a faceted, quasicleavage morphology (crack direction in arrows).

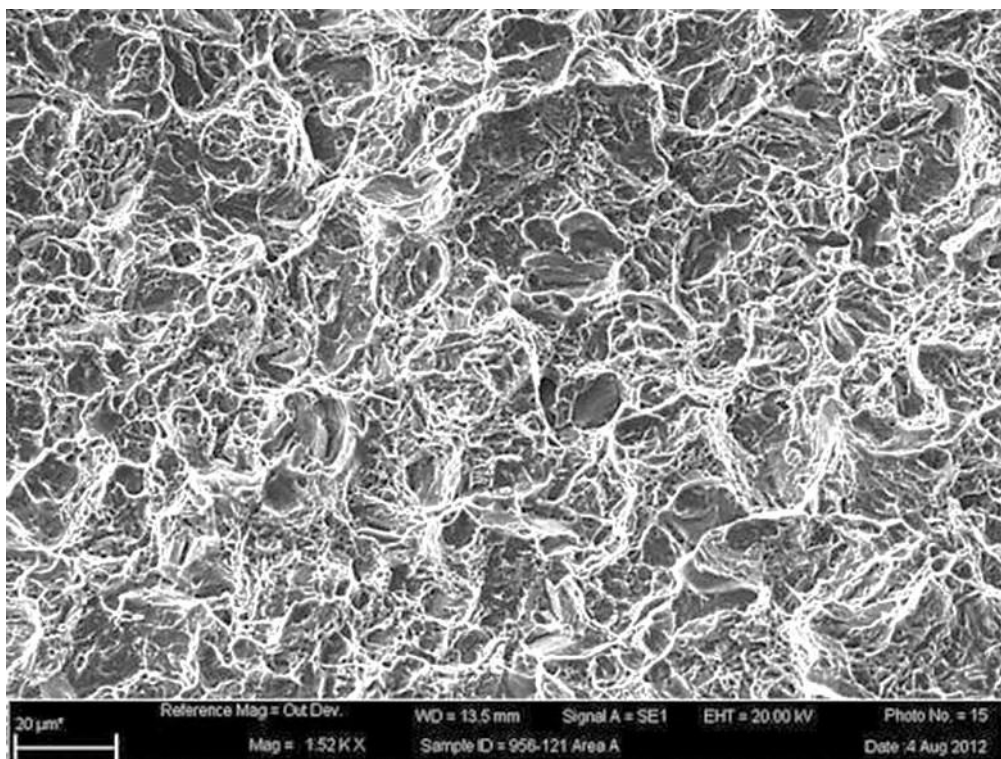


Figure 20 – SE micrograph of the triangular-shaped feature in Figure 19a, showing dimple rupture indicative of overstress.

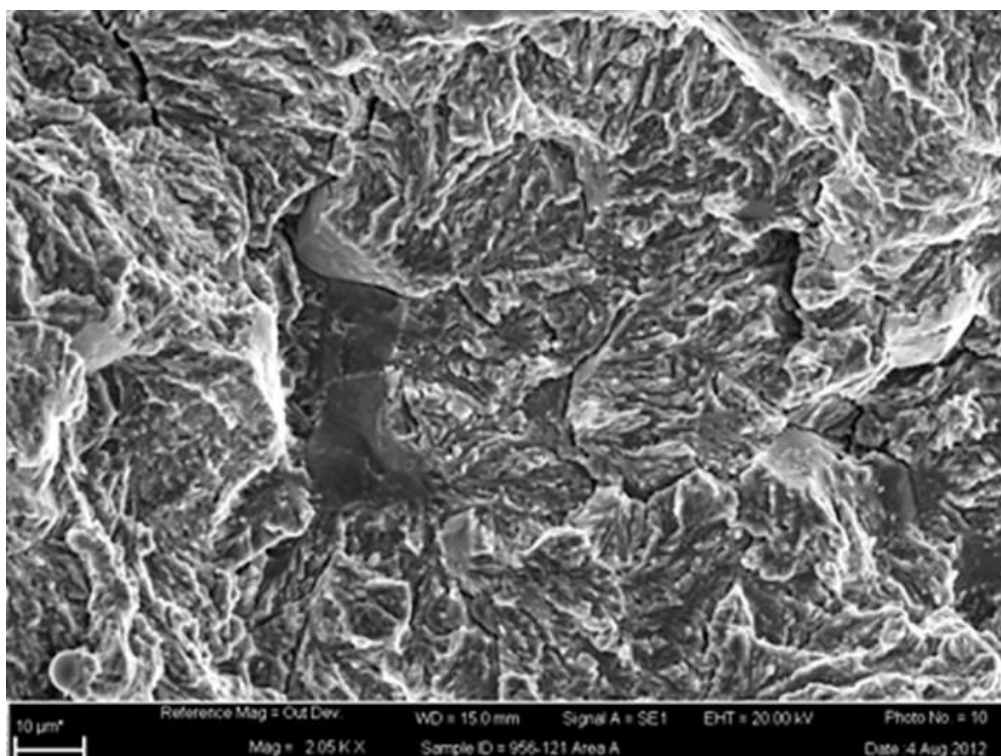


Figure 21 – SE micrograph of the fracture surface outboard of the triangular-shaped feature, showing intergranular facets in the EAC region.

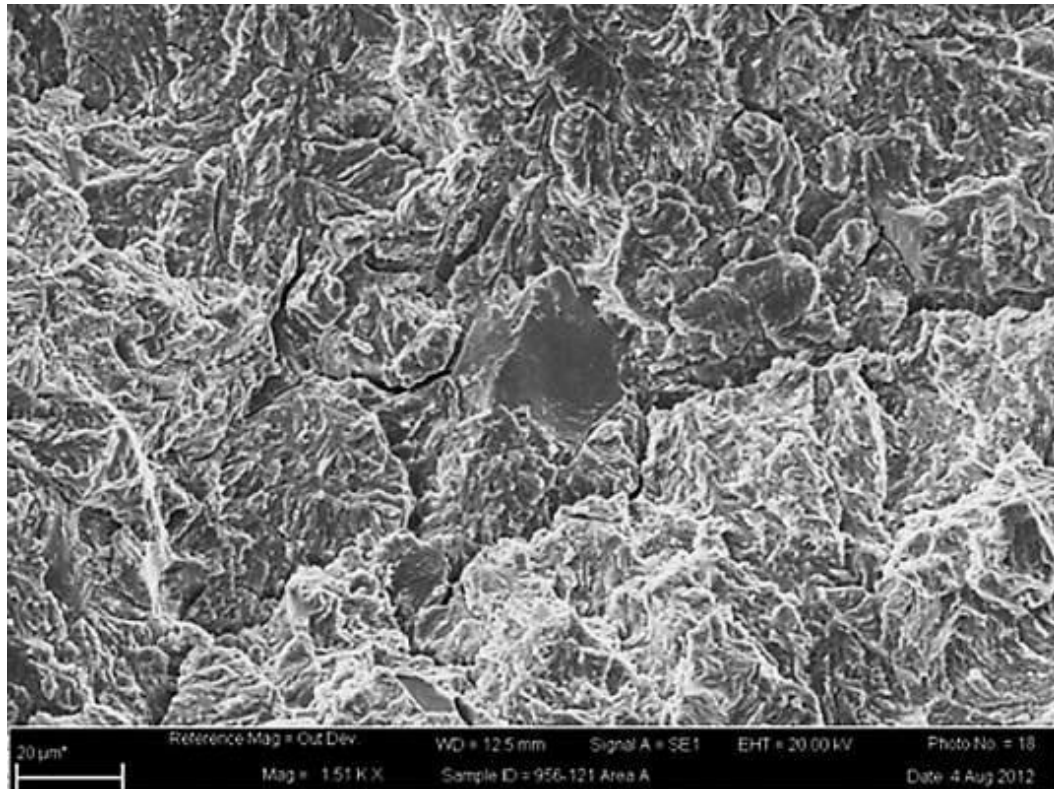


Figure 22 – SE micrograph of the fracture surface inboard of the triangular-shaped feature, showing intergranular facets and comparable features to Figure 21.

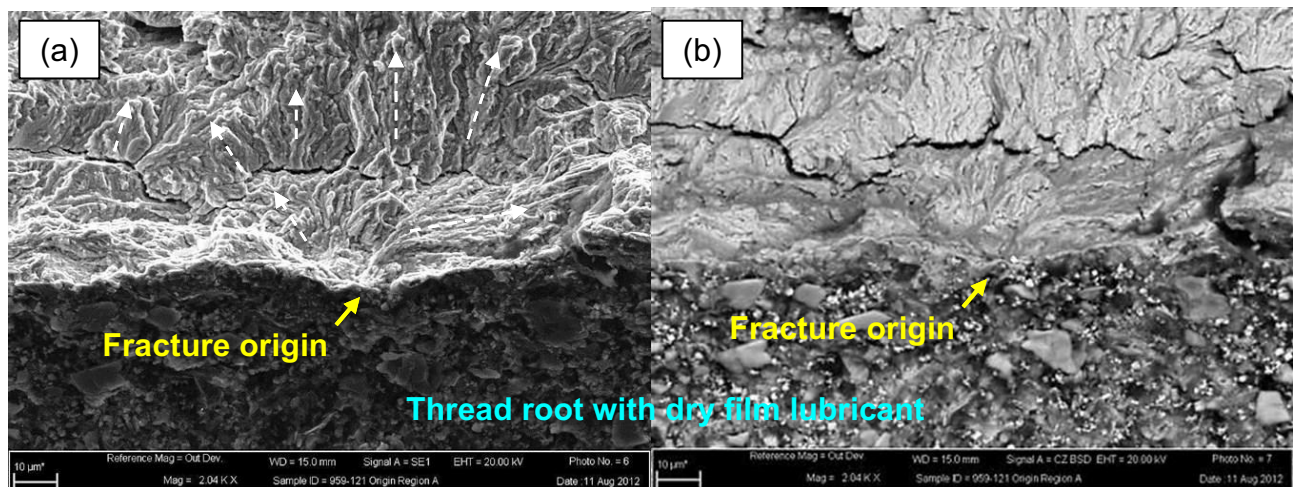


Figure 23 – Progressive crack origin at a thread root in the aft most thread using (a) secondary and (b) backscattered modes. The lower sections show the thread root with the dry film lubricant.

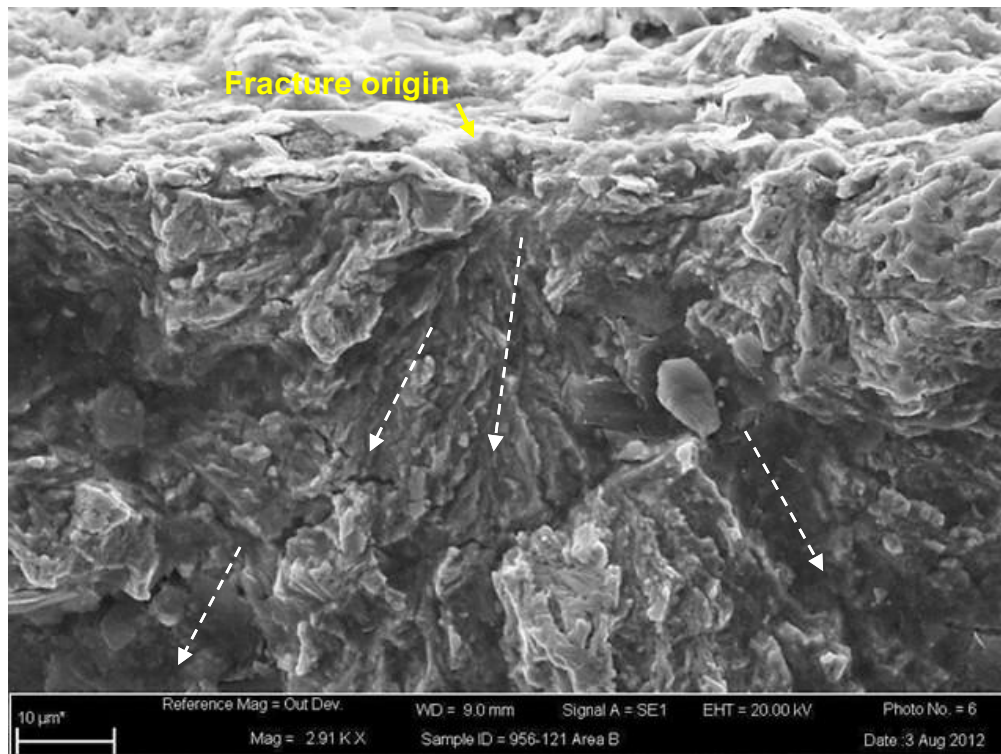


Figure 24 – SE micrograph of a crack initiation site on the region B thumbnail shown in Figure 16, with arrows showing crack growth directions.

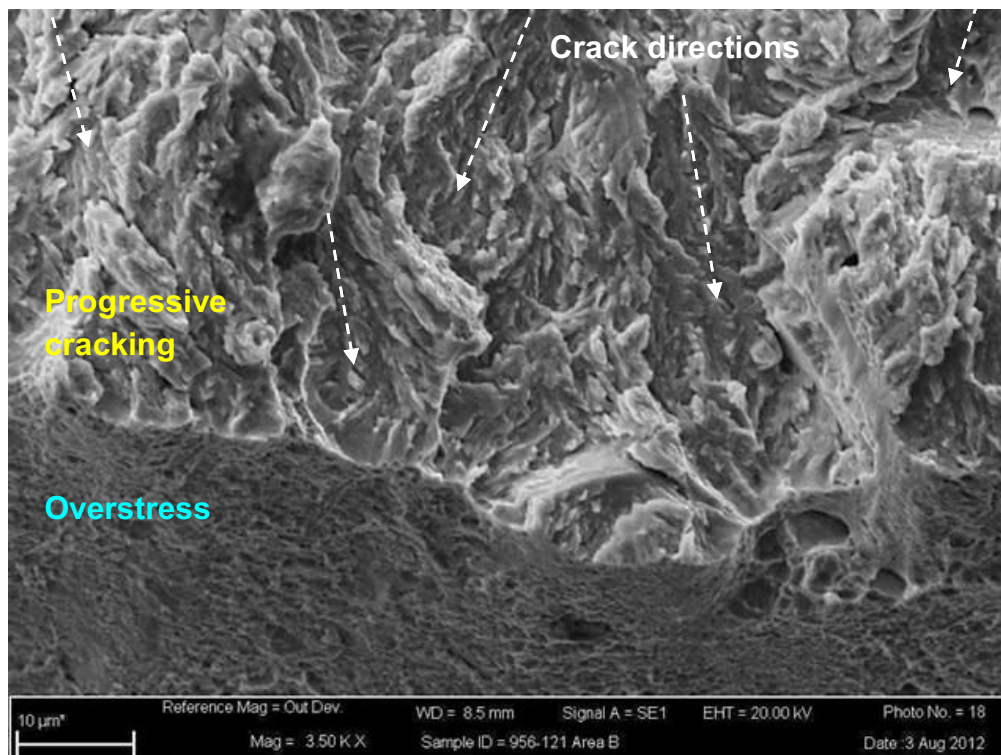


Figure 25 – SE micrograph of the innermost portion of EAC cracking on Region B before overstress.

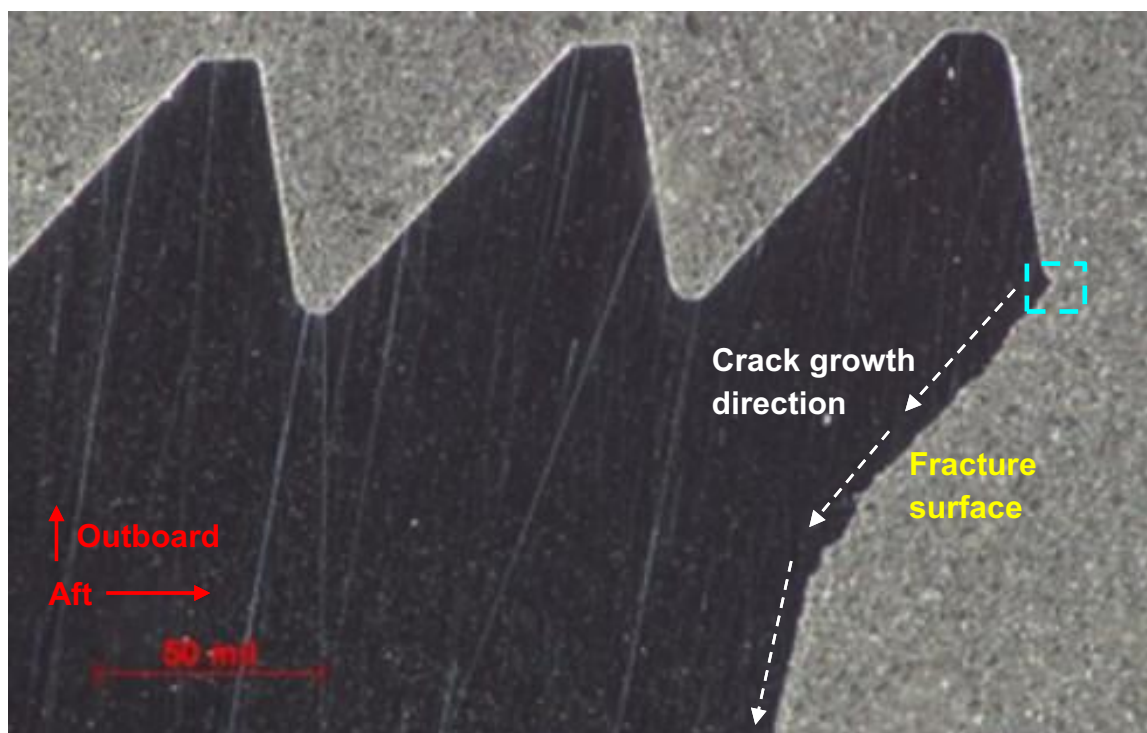


Figure 26 – Optical metallograph of a cross-section of forward end of the fan midshaft, showing the crack orientation. The boxed area is shown in Figure 29.

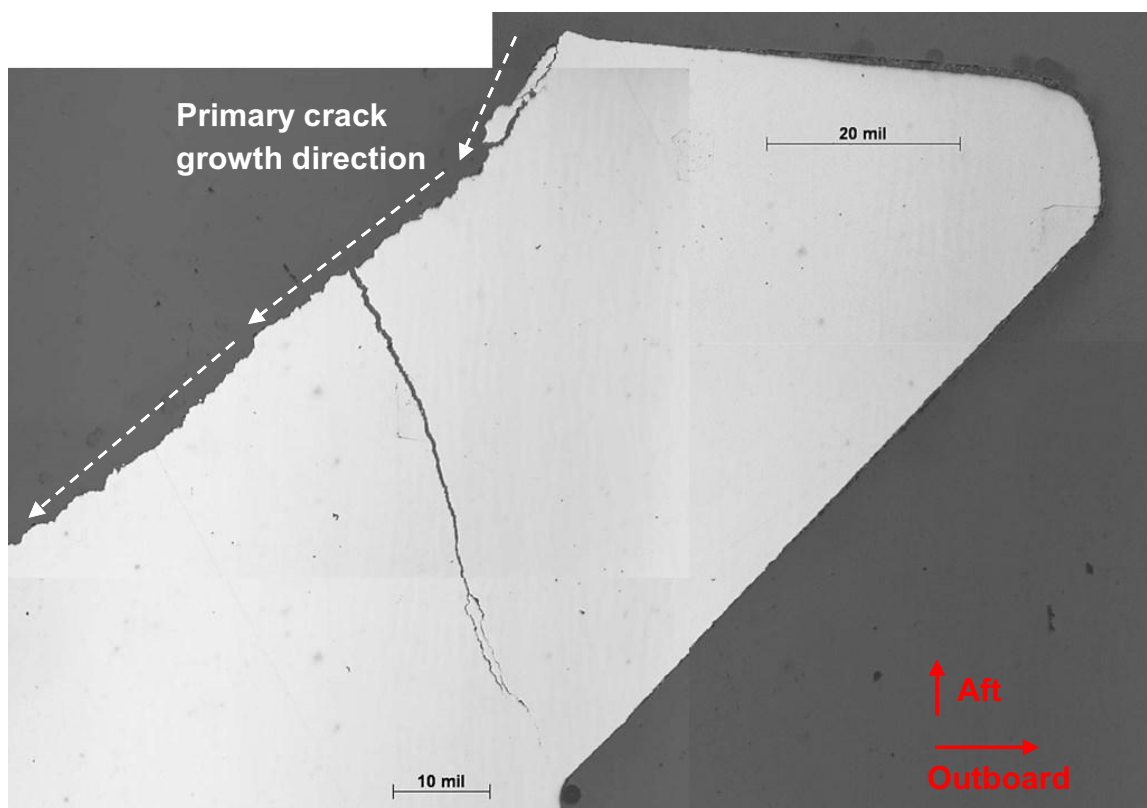


Figure 27 – Optical metallograph of the thread adjacent to the forward FMS fracture, showing a secondary crack growing under the thread.

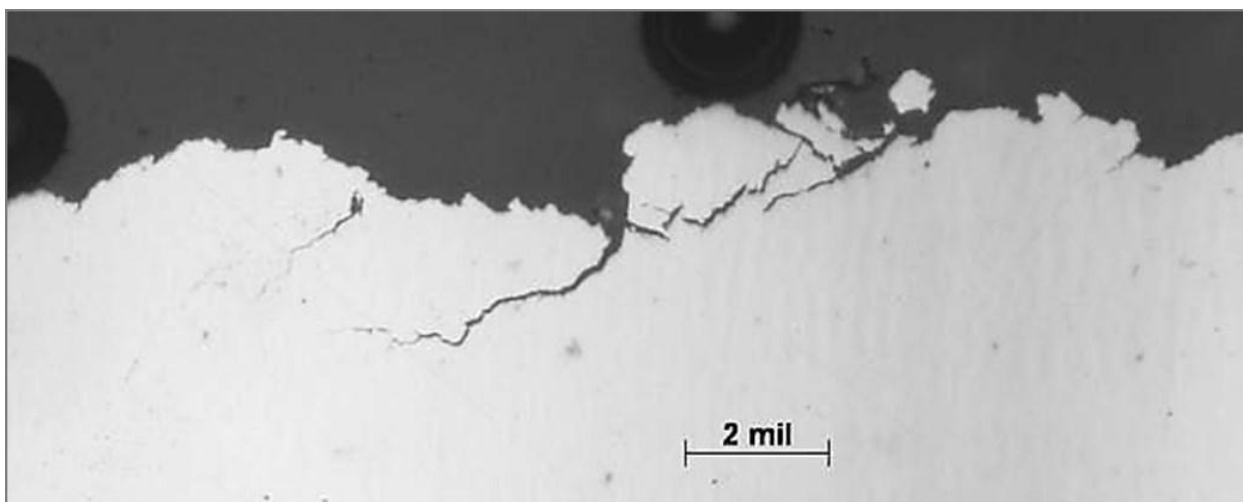


Figure 28 – Optical metallograph of a close-up of the forward FMS fracture surface, showing sub-surface cracking.

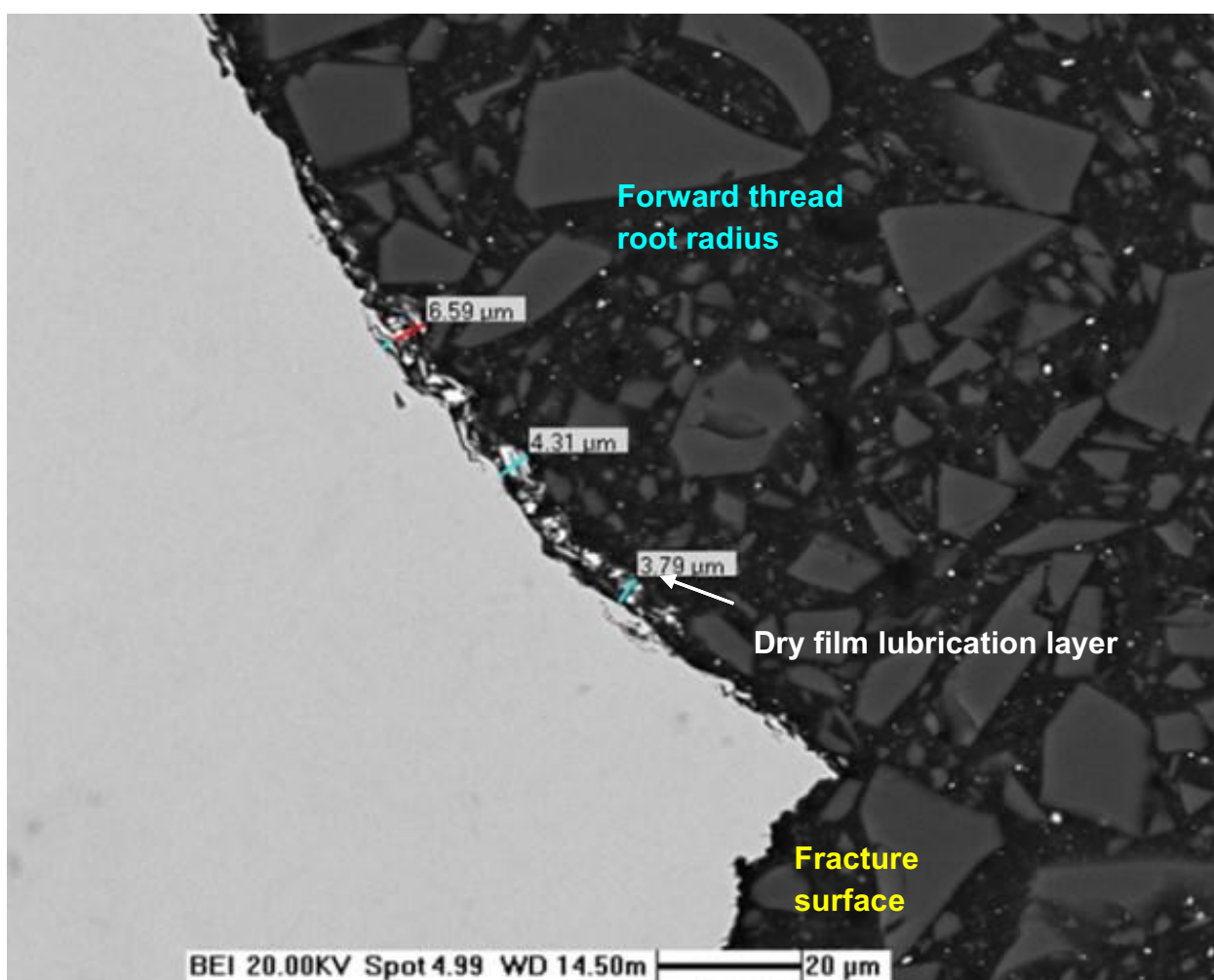


Figure 29 – BE micrograph of the thread root near the fracture, showing lack of complete dry film lubricant coverage.

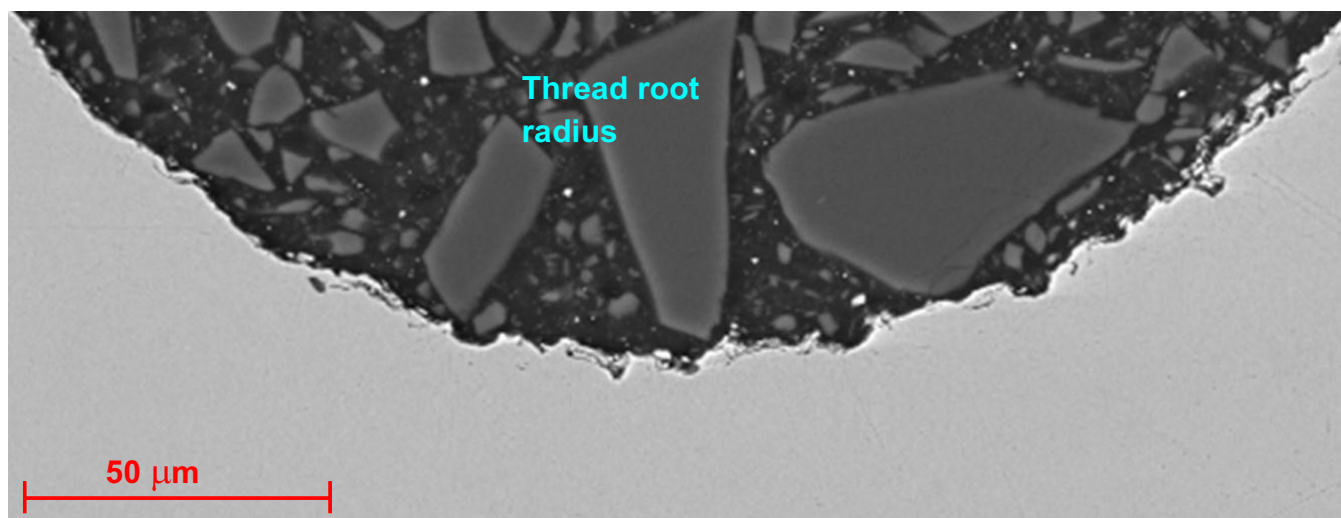


Figure 30 – BE micrograph of a close-up of a FMS thread root, showing pit-like divots at the surface.

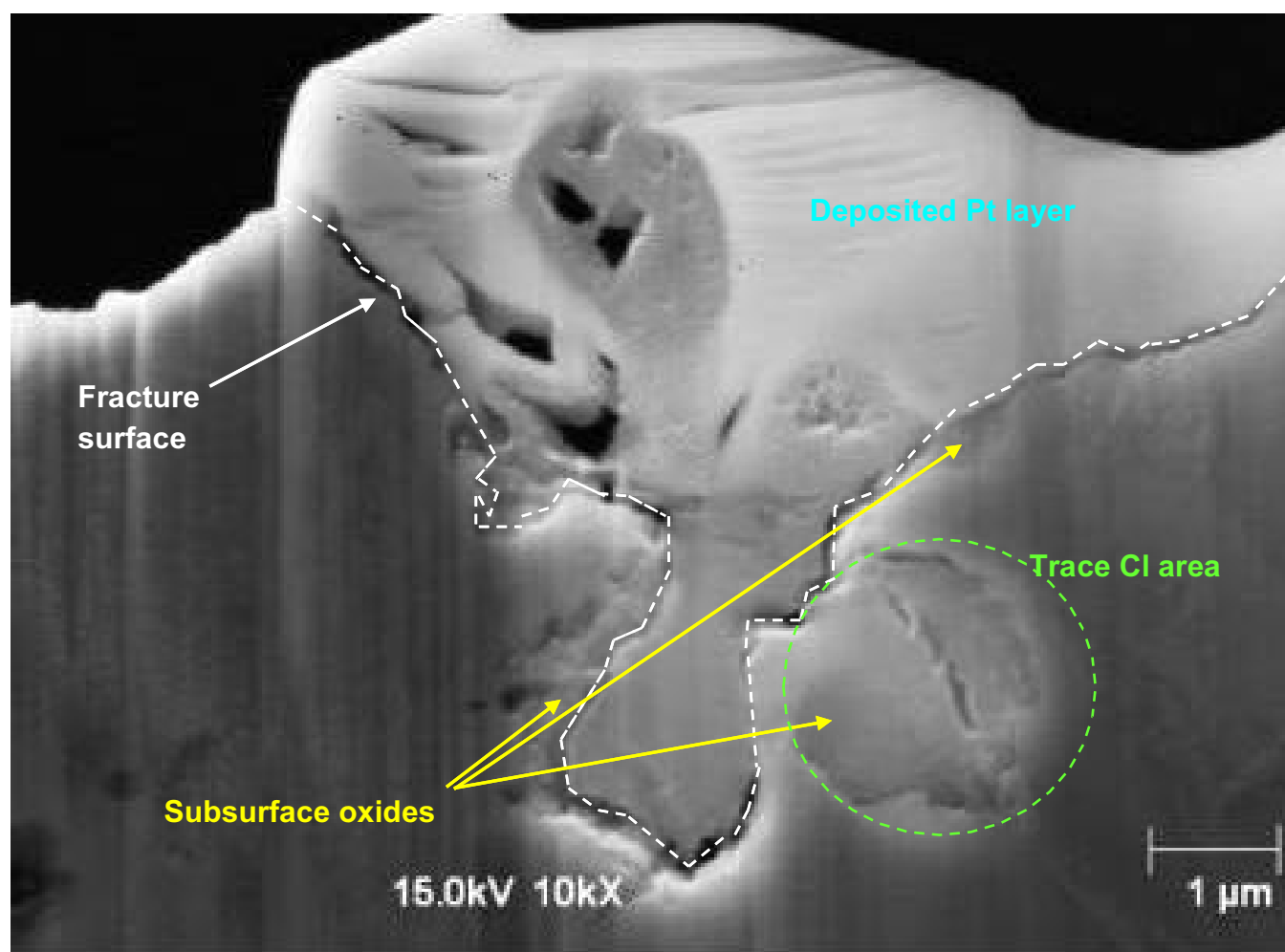


Figure 31 – SE micrograph of a focused ion beam (FIB) cross-section of the surface of progressive fracture region A.

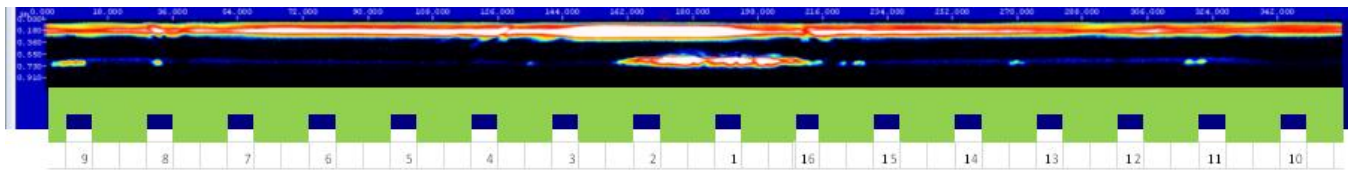


Figure 32 – UT scan of the 956-175, showing several crack indications around the forward thread root circumference.

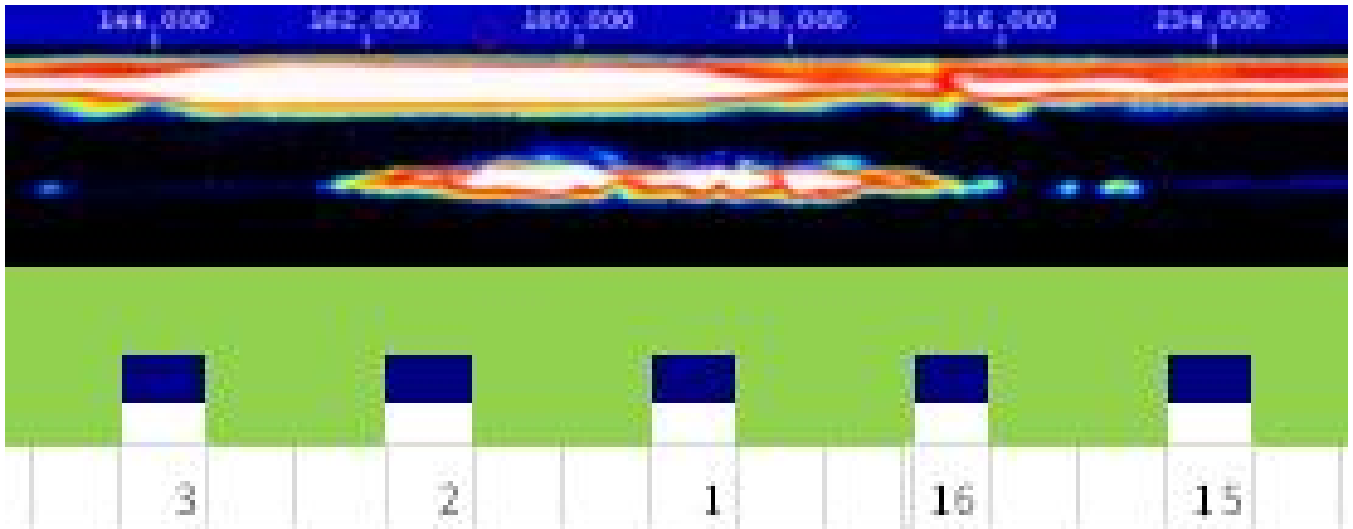


Figure 33 – Close-up of the UT scan showing the largest crack indication in the 956-175 fan midshaft between castellations #2 and #16.

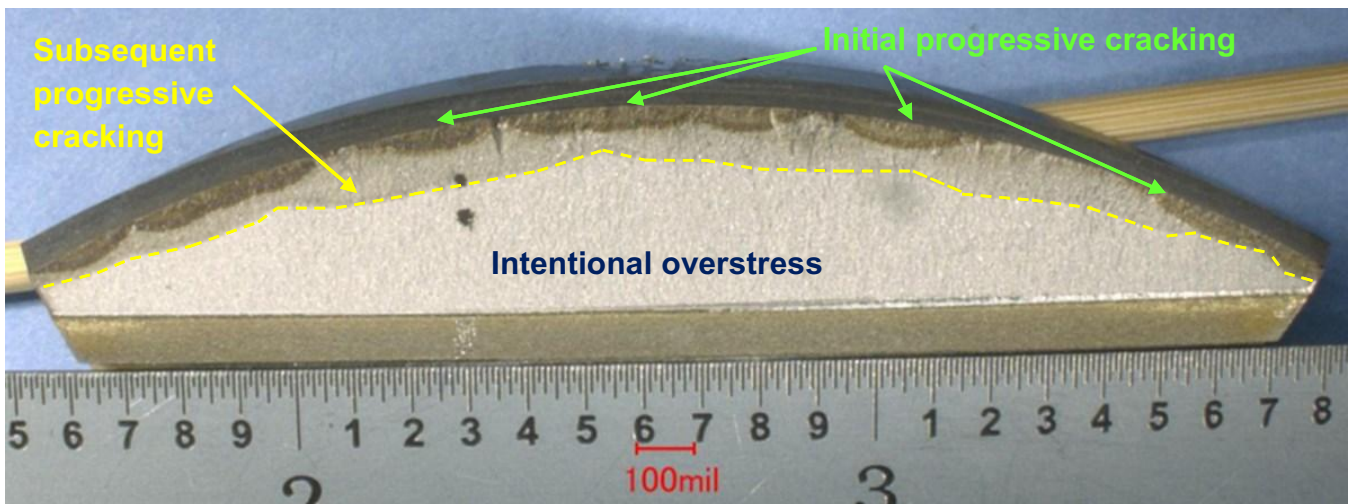


Figure 34 – The largest progressive crack in the 956-175 fan midshaft, after backcutting intentional overstressing. The dark areas are the pre-existing crack.

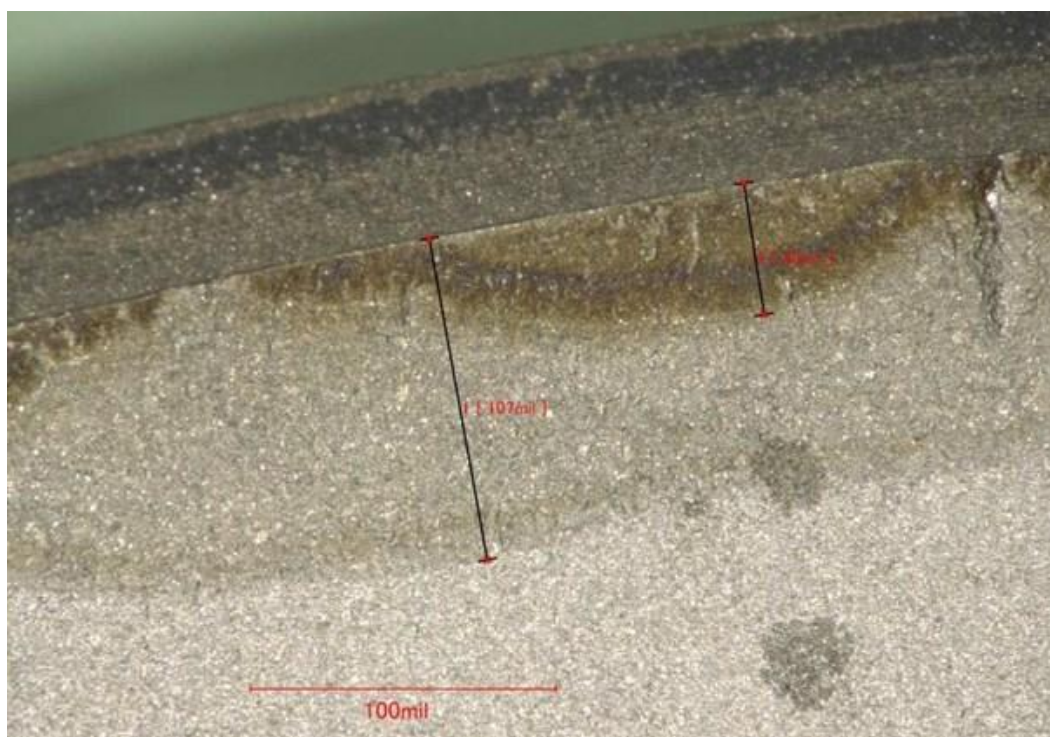


Figure 35 – Closer view of Figure 34, showing the depth of penetration of the progressive environmentally assisted crack.

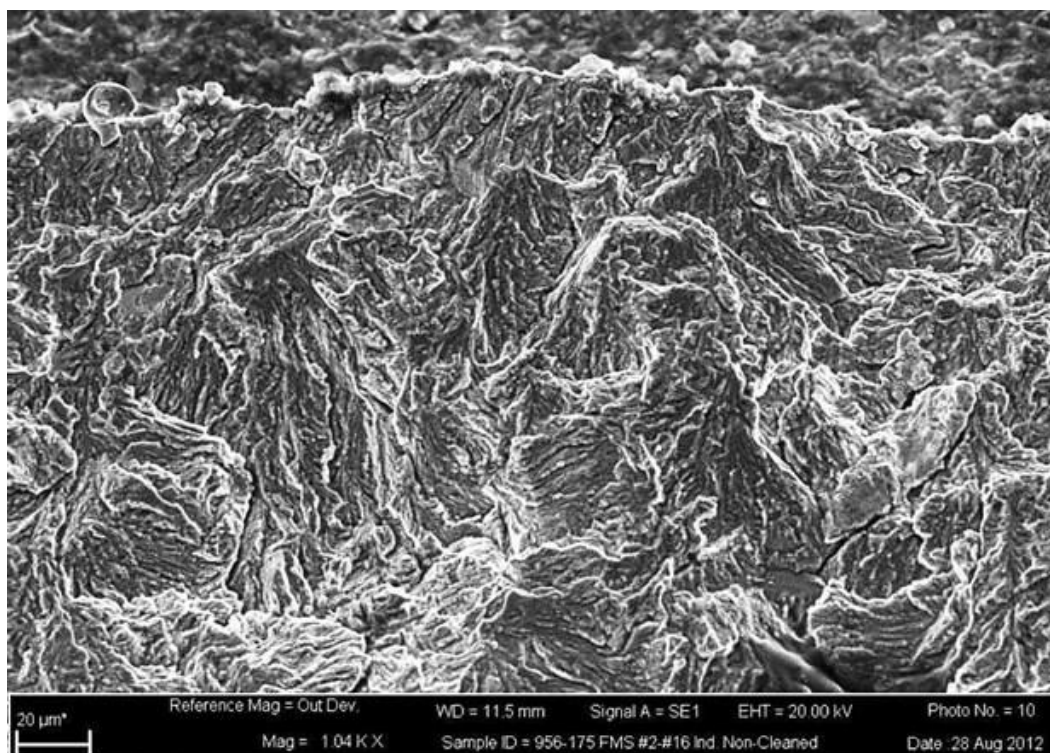


Figure 36 – SE micrograph of one of the initiation sites of the 956-175 progressive crack, comparable to the 956-121 fan midshaft fracture.

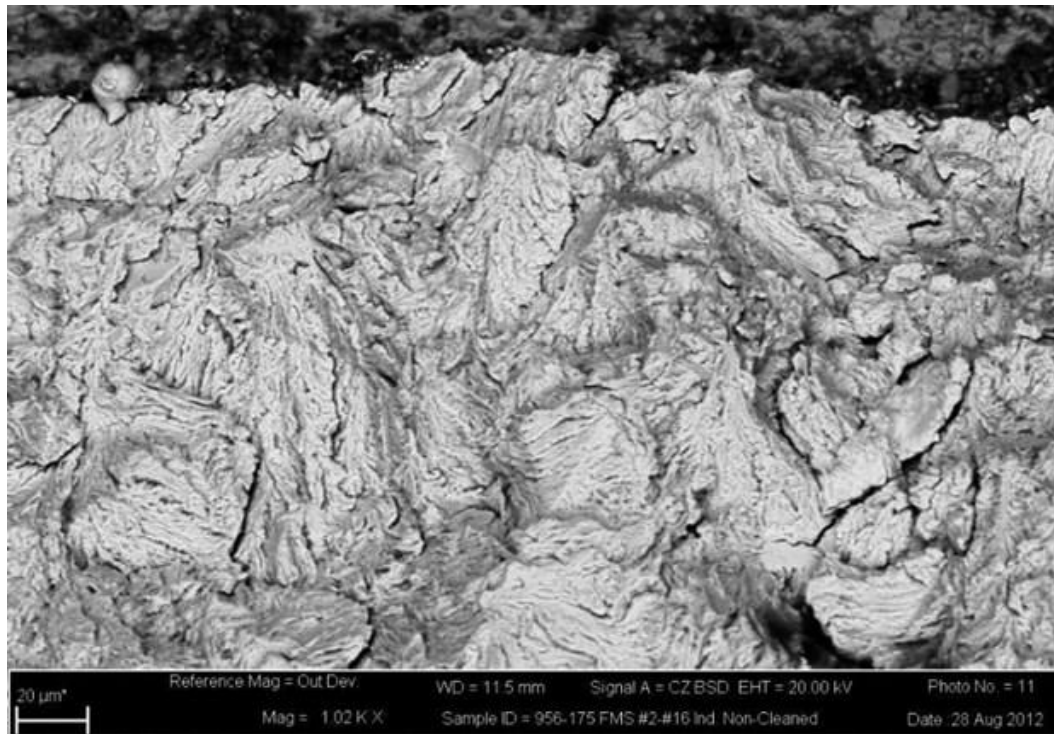


Figure 37 – BE micrograph of Figure 36, revealing the faceted morphology of the progressive crack surface.

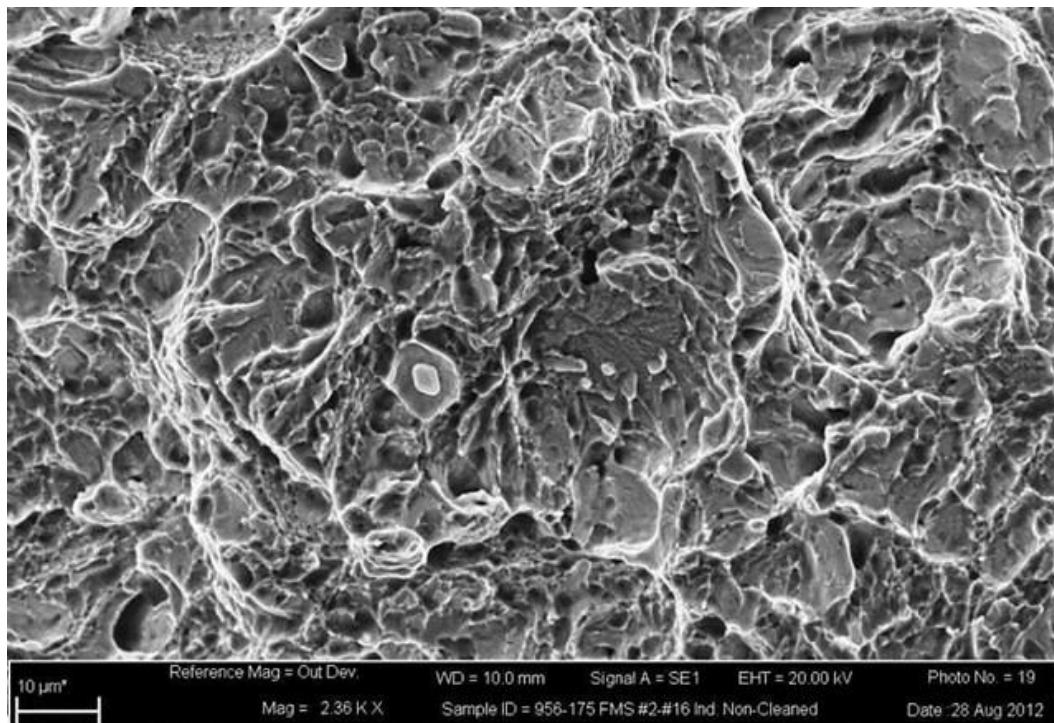


Figure 38 – SE micrograph of the 956-175 fracture surface inboard of the progressive area that was backcut, showing dimple rupture.

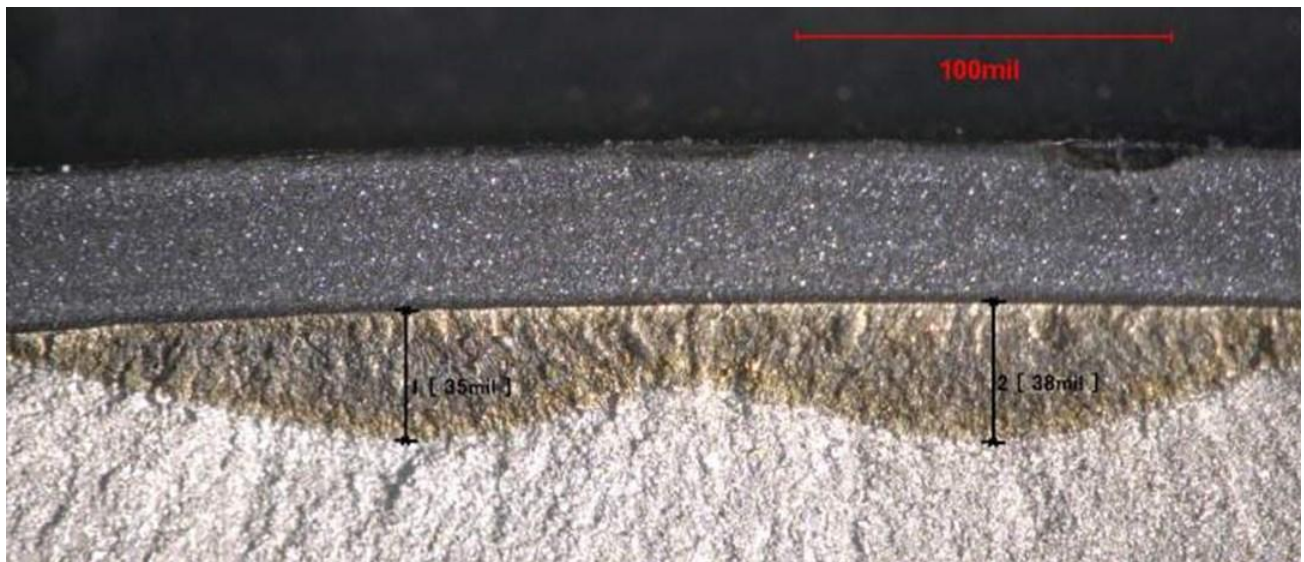


Figure 39 – The smaller crack located at castellation #11. The dark areas are the pre-existing crack.

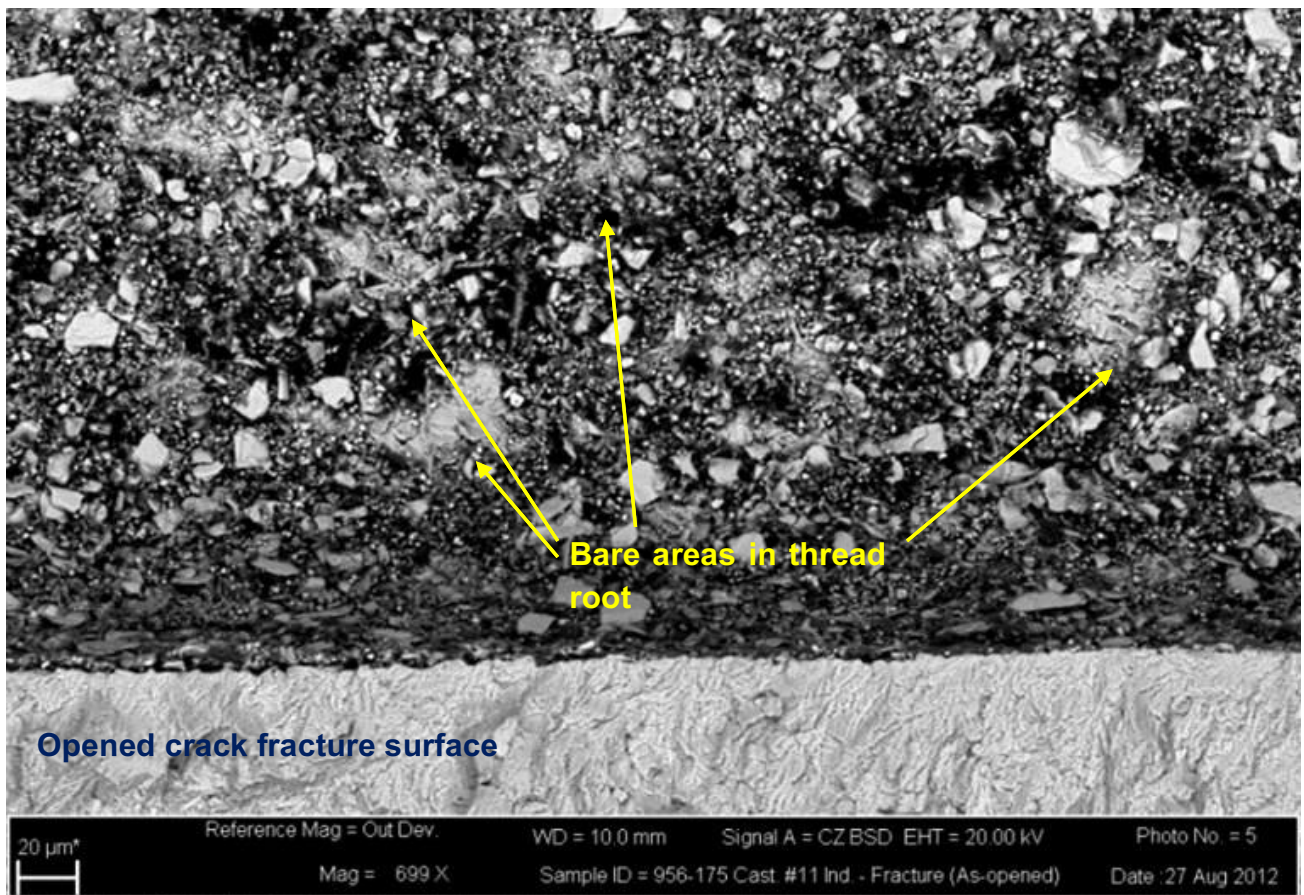


Figure 40 – BE micrograph of the thread root adjacent to the pre-existing crack. The circled areas show bare regions of the part surface.

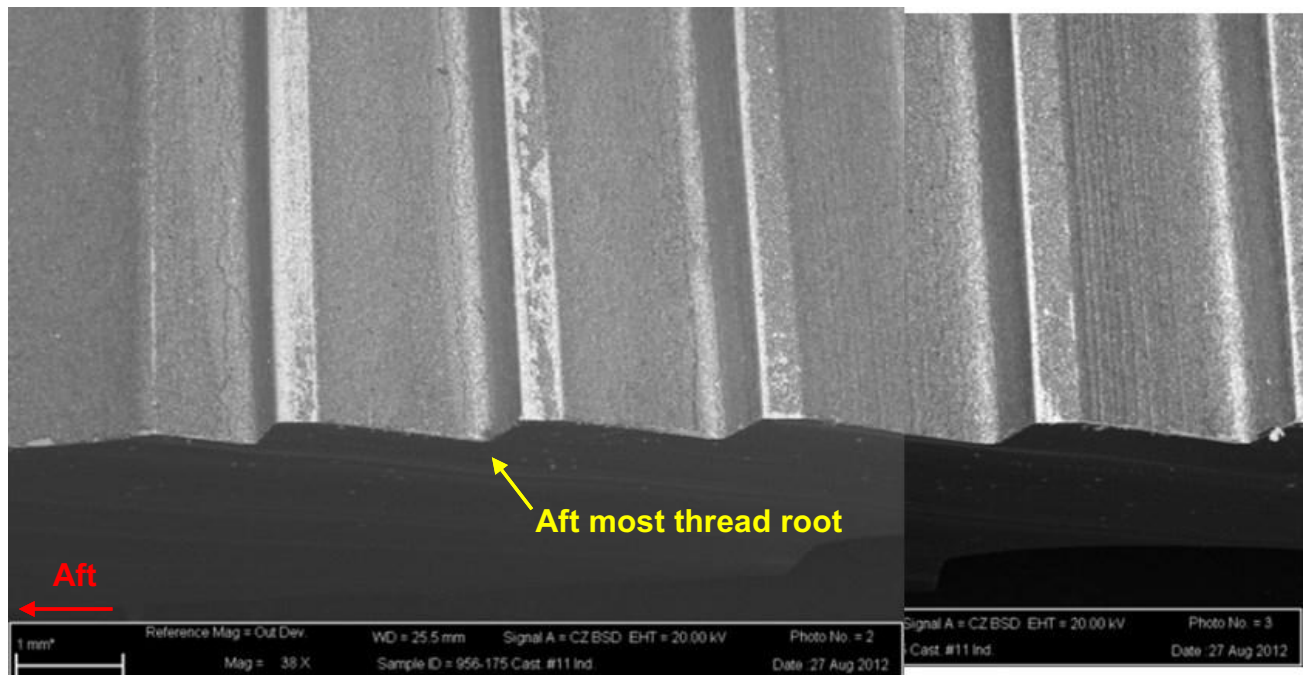


Figure 41 – BE micrograph showing bare areas (lighter shade) of the fan midshaft threads.

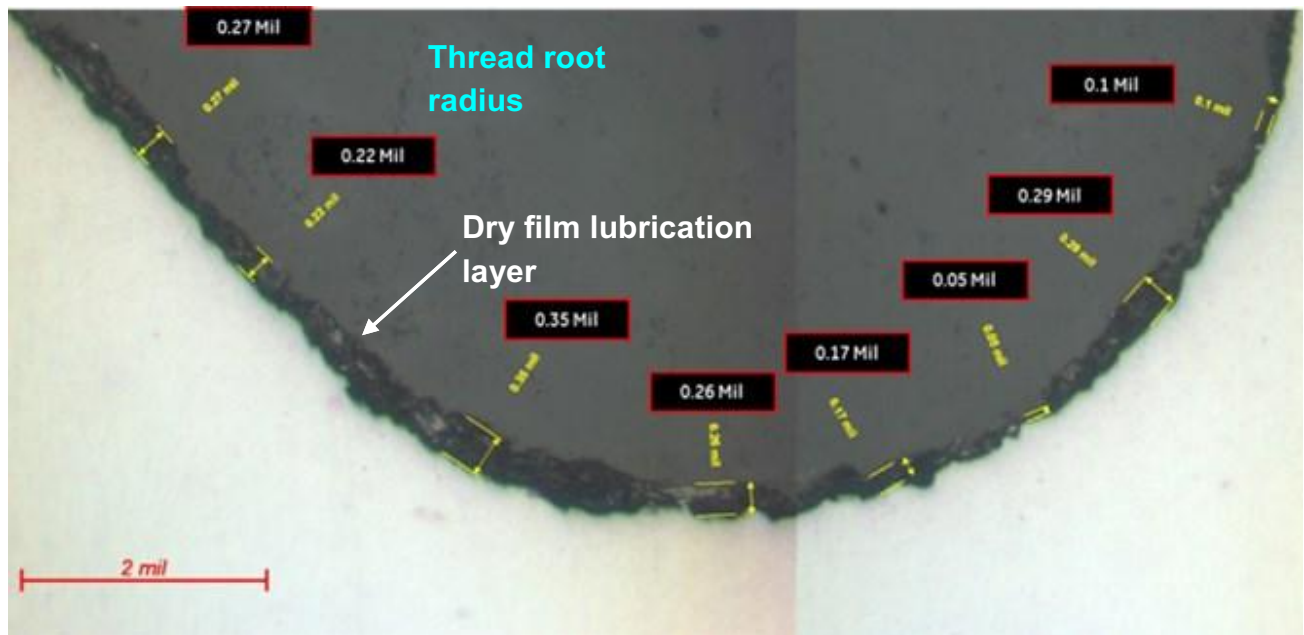


Figure 42 – Optical metallograph of a cross-section of the last thread root from 956-175 fan midshaft, showing the thickness of the dry-film lubrication layer.

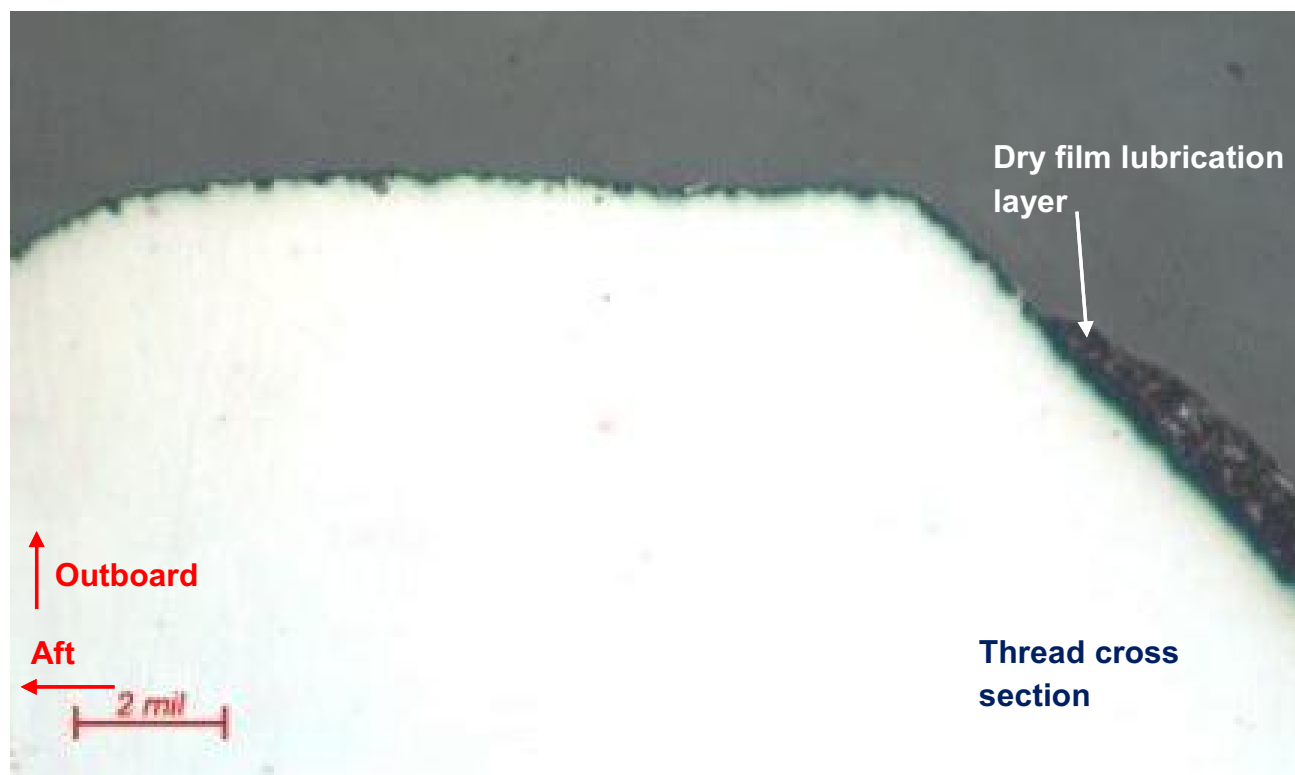


Figure 43 – Optical metallograph of a cross-section of the last thread of 956-175 FMS, showing a lack of dry film lubrication on the top of the thread crest.



Figure 44 – Optical metallograph of a cross-section of the largest fracture surface at the aft most thread root.

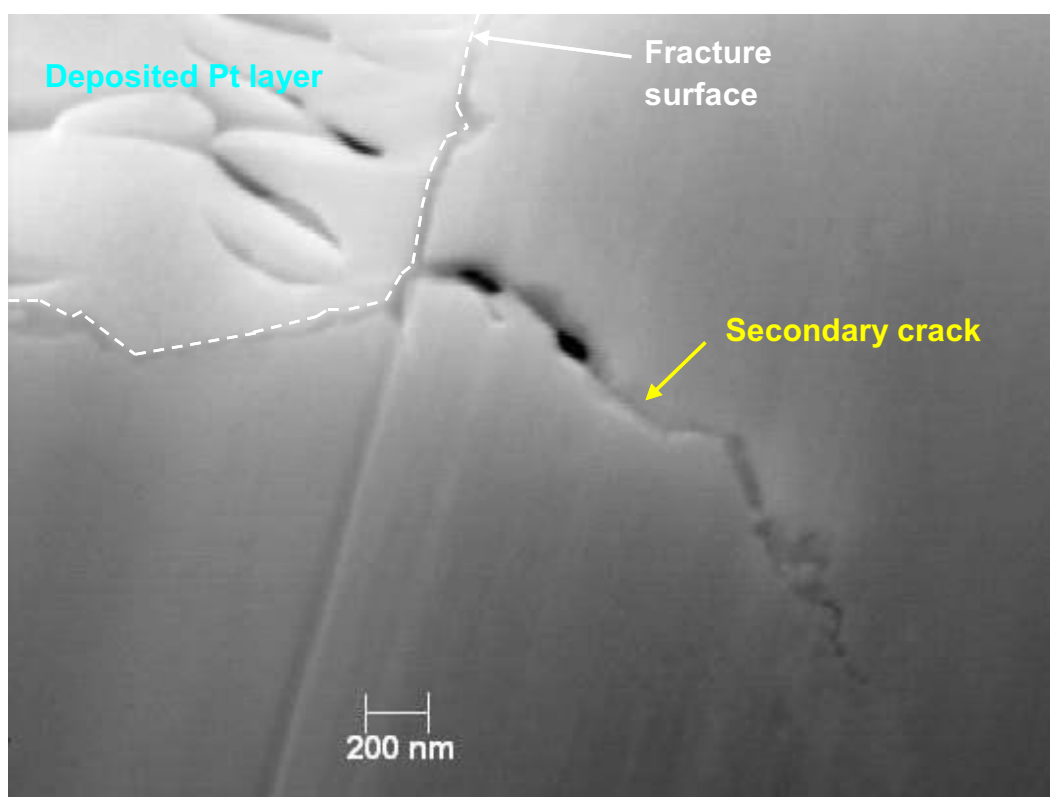


Figure 45 – SE micrograph of a FIB cross-section of the #11 castellation crack from ESN 956-175.