

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



ERA23FA025

MATERIALS LABORATORY

Factual Report 23-066

December 22, 2023

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A. ACCIDENT INFORMATION

Location: Brentwood, Tennessee
Date: October 18, 2022
Vehicle: Piper PA-32-300, N600JG
Investigator: Brian Rayner, AS-ERA

B. COMPONENTS EXAMINED

Crankshaft, connecting rod assemblies, number 6 piston and cylinder assemblies, main and connecting rod bearings, bags of debris collected from the oil sump and the oil screen, front oil seal, and exemplar magneto bumpers.

C. EXAMINATION PARTICIPANTS

Specialist	Matthew R. Fox, Ph.D. NTSB Washington, DC
IIC	Brian Rayner NTSB Washington, DC
Group Member	Ryan Enders Lycoming Engines Williamsport, Pennsylvania
Group Member	Charles Russo Lycoming Engines Williamsport, Pennsylvania
Group Member	Robert Martellotti Piper Aircraft Vero Beach, Florida

D. DETAILS OF THE EXAMINATION

An overall view of the submitted components from the Lycoming Engines model IO-540-K1A5 engine is shown in figure 1. The crankshaft was fractured through the number 6 connecting rod journal adjacent to the forward cheek as shown in figure 2. The number 6 connecting rod was fractured in the beam section near the small end. The big end of the number 6 connecting rod was separated from the crankshaft but remained intact. The remaining connecting rods were intact and were attached to the crankshaft, rotating freely on their respective journals. The

number 6 cylinder assembly was damaged at the barrel skirt, and the number 6 piston assembly was trapped within the cylinder barrel. The submitted components also included the main bearings and bags of assorted debris from the oil sump and the oil screen. A bag containing exemplar magneto bumpers was also included with the bag of oil screen debris as shown in the inset image in figure 1.

Markings on the side of the crankshaft flange read "LW 10842 M06M 03P S166505-2", indicating that it was Lycoming part number LW-10842, serial number S166505-2, with main journal diameters that had been ground 0.006 inch undersize and connecting rod journal diameters that had been ground 0.003-inch undersize. According to engine manufacturer representatives, crankshaft LW-10842 was made obsolete in 1979. Crankshaft LW-10842 and crankshafts that superseded part number LW-10842 were certified for use in multiple variants of the IO-540 series engines including the -AA1A5, -K1C5, -K1F5, -K1J5, and -S1A5, but the list of certified variants did not include the accident engine model, IO-540-K1A5.

According to maintenance records, the crankshaft had been exchanged at the last engine overhaul on October 1, 2012. At the last annual inspection on October 4, 2022 (two weeks before the accident), the engine had 101.3 hours time in service since overhaul.

The interior and exterior surfaces of the main bearings are shown in figure 3 labeled M1 through M5. The bearings were marked as Federal Aviation Administration (FAA) parts manufacturer approval (PMA) bearings with a part number that was consistent with the accident engine using a crankshaft with 0.006-inch undersize main journal diameters. The Babbitt material on the interior surfaces of the bearings was intact with isolated debris and circumferential drag marks (comet tails). Coked oil deposits were present on the engine case contact surfaces on the back face of bearing M5 and on the oil channel surfaces on the back face of bearing M4. The edges of the oil channel holes were deformed on bearings M4 and M5 as indicated with arrows in the lower image in figure 3 consistent with contact with corresponding dowels in the engine case. The deformation was located at the aft sides of the holes on bearing M4 and the forward sides of the holes in bearing M5.

A view of the number 6 piston assembly as received within the cylinder barrel is shown in figure 4. The small end of the fractured number 6 connecting rod was attached to the piston pin, and a closer view of the fracture surface is shown in the right image in figure 4. The fracture surface had smeared features and deformed lips at the edges of the fracture surface consistent with ductile overstress fracture with bending and twisting loads.

A transverse cut was made through the number 6 cylinder barrel just below the head to facilitate inspection of the cylinder combustion chamber and to remove the piston assembly from the barrel. The deposits in the combustion chamber and piston crown appeared consistent with normal operation. The piston was removed from the

cylinder barrel. The piston rings were intact. The piston had some uneven wear patterns on the sides, but no evidence of erosion was observed on the piston crown or sides. The intake valve was removed from the cylinder assembly, and length measurements from reference points on the valve were measured using an optical shadowgraph. The resulting measurements were consistent with engineering specification, consistent with the absence of deformation from valve stretching.

No part numbers were observed on the connecting rods. However, a forging part number LW-13756 was observed, and connecting rods for use in the accident engine are made from that forging part number.

The number 6 connecting rod was separated from the crankshaft as shown in figure 1. The big end of the connecting rod was darkened consistent with heat tinting, but the big end remained intact. The corresponding connecting rod bearing was destroyed showing deformation, fracture, and high heat damage. Smeared bearing material was observed on the interior surfaces of the number 6 connecting rod big end, and bearing remnants were observed adhering to the crankshaft as indicated in figure 2. Smaller pieces of bearing remnants were observed in the oil sump and oil screen debris.

The connecting rods were labeled with etched numbers on the sides of the straps and the caps. The connecting rod in the number 3 position was labeled number 4, and the connecting rod in the number 4 position was labeled number 3. Connecting rods 2 through 5 were disassembled from the crankshaft. The corresponding connecting rod bearings, labeled C2 through C5, had oil on the surfaces that was wiped away with a clean cloth. Views of bearings C2 through C5 after disassembly and wiping are shown in figure 5. The bearings were marked SL74309A M03F 08-11 FAA-PMA K-795", indicating they were a FAA PMA part for use on a crankshaft with 0.003-inch undersize connecting rod journal diameters. According to the Superior Air Parts website, the SL74309A M003 connecting rod part number is eligible for use in multiple variants of Lycoming IO-540 series engines, including a Lycoming IO-540-K1A5D engine, but the list did not include the IO-540-K1A5 engine.¹

As shown in figure 5, the Babbitt material on the interior surfaces of bearings C2 through C5 was intact with isolated debris and comet trails. The back faces mostly had a shiny appearance consistent with light rub. The anti-rotation tabs on the bearings were intact.

The counterweights on the fractured crankshaft were intact, and no remarkable features were noted in the examination. Two washers on the forward side of one ear were cracked on the counterweight attachments.

¹ www.superiorairparts.com, Superior Air Parts, Coppell, Texas, accessed October 3, 2023.

The crankshaft fracture shown in figure 2 was relatively smooth with curving crack arrest lines, features consistent with fatigue. The fracture features emanated from an origin area in the fillet radius between the journal and the cheek at the forward end of the journal. The origin area on the aft side of the fracture was obliterated by post-fracture contact, so additional examination of the fracture surface focused on the forward side of the fracture shown in the left image in figure 2.

To facilitate further examination of the fracture surface, the counterweights were disassembled from the crankshaft. Then a transverse cut was made through the number 5 connecting rod journal. The fracture surface was then gently cleaned using a soft bristle brush dipped in a solution of Alconox detergent and warm water followed by rinsing with water followed by ethanol.

Views of the fracture surface after the initial disassembly, sectioning, and cleaning are shown in figure 6. Brackets in figure 6 indicate the fatigue origin area located in the number 6 connecting rod journal fillet radius near the runout for the cheek. Additional cracks were observed extending from the fracture area into the counterweight attachment ear, and crack locations are indicated with brackets labeled with letters in figure 6.

In order to examine the fracture surfaces associated with cracks A through D and to facilitate an SEM examination of the origin area shown in figure 6, the crankshaft piece was sectioned in several locations including the numbered cuts indicated in figure 7. After cut 1 was made through crack A along with a back cut to the tip of crack A (not shown), the exposed portion of crack A showed crack arrest lines that showed the direction of crack growth away from the origin area as indicated with an arrow within bracket A in figure 6. Additionally, the crack path revealed by the cut showed that the portion of crack A penetrating through the thickness of the cheek turned more than 90 degrees and propagated along the path indicated by bracket B.

Cut 2 was made through a location where tips of cracks B and C intersected and through secondary cracks located in the cheek closer to the journal fracture. Once cuts 1 and 2 were complete, the portions of cracks A, B, and C between the fracture surface and cut 1 were exposed. The resulting piece with exposed crack surfaces was then cleaned using an ultrasonic cleaner while submerged in a solution of Alconox and warm water.

A view of the resulting fracture surface after opening the cracks and ultrasonic cleaning is shown in figure 8. The locations of cracks A, B, and C are indicated in figure 8 for reference. Crack D, a smaller crack parallel to crack A, was contained within the piece that had been removed in the process. Unlabeled arrows in figure 8 indicate local directions of fatigue crack propagation. Fracture features all emanated from the origin area that was originally exposed by the fracture as shown in figures 6 and 8.

To facilitate closer views of the origin area using an optical microscope and a scanning electron microscope (SEM), cut number 3 (see figure 7) was made through the fracture surface. An optical image of the origin area is shown in figure 9 showing additional detail of fracture features emanating from the indicated origin area.

The fracture surface remained lightly oxidized. To assist in an SEM examination of the surface, the piece with the origin area was submerged in Evapo-Rust for a few minutes, and the surfaces were lightly brushed with a soft-bristle brush to remove oxides on the surface. The piece was then rinsed with water followed by ethanol. An overall view of the fracture surface and adjacent cheek after oxide removal is shown in figure 10.

Optical images of the origin area after deoxidation were obtained and processed using a Keyence VHX-7000 optical microscope as shown in figures 11 and 12. In figure 11, the fracture surface was imaged using high dynamic range (HDR) processing to remove reflections and glare on the fracture surface. The image in figure 12 was obtained using the shadow mode to remove color and highlight topographical features. The images show a relatively rough fracture topography near the surface within 0.023 inch of the surface. A fracture region with smoother features was observed extending up to 0.083 inch deep approximately perpendicular to the fillet radius surface. Step features extended radially outward from the boundary of the smoother region and prominent crack arrest marks were observed, features consistent with fatigue crack growth on slightly offset planes emanating from the origin area.

SEM images of the origin area are shown in figure 13. The upper image is a montage of SEM images stitched together to show a wider view, and the lower images show closer views of fracture features next to the surface near the middle of the origin area. Fracture features at the origin area showed mechanical damage from rubbing. However, the relatively rough area at the surface had a granular appearance suggestive of an intergranular fracture.

The relatively rough intergranular region near the origin had a curving boundary that had cusps that appeared to coincide with small radial features. The boundary shape and radial features were consistent with multiple origins in a broad origin area located at the fillet radius surface. The intergranular region extended up to 0.023 inch deep as shown in figure 14. Beyond that region, a smoother region with a similar curving boundary was observed up to a depth of 0.032 inch, also indicated in figure 14.

A piece of the crankshaft was cut from the origin area to facilitate a metallographic examination. The sectioned piece is shown in figure 15 after the cuts were made, and unlabeled arrows point to the cut surface that was polished and etched using 2% nital etchant. A metallographic image of the typical core

microstructure is shown in figure 16. The typical lath microstructure associated with tempered martensite appeared transformed with spheroidization.

Metallographic images of the polished cross-section at the origin area are shown in figure 17 in the as-polished and etched conditions. The images show the fracture location in the journal radius. A secondary crack was observed at the location of the runout for the journal radius into the cheek. In the etched condition, a white layer was observed at the surface of the cheek and journal radius consistent with nitride hardening. The remainder of the cross-section had a microstructure consistent with tempered martensite.

Closer views of the origin area are shown in figure 18. The surface adjacent to the fracture was deformed inward over the fracture surface consistent with post-fracture damage. Additionally, the fracture showed step features at the deformed lip and at a location near the boundary of the surface-hardened region. A closer view of the surface at the location of the secondary crack is shown in figure 19 in the etched condition.

Next, the metallographic mount was sputter coated with a thin layer of a gold/palladium alloy to facilitate an SEM examination of the sample. Note that the SEM images are mirror images of optical images taken with the inverted metallograph as presented in figures 16 through 19. An SEM image of the fatigue origin area is shown in figure 20, and views of the secondary crack are shown in figure 21. Near the surface, both the fracture surface and the secondary crack showed crack paths along prior austenite grain boundaries.

Frictional heating from rubbing damage can produce a layer of untempered martensite that etches white with a nital etch. However, the white layer next to the secondary crack and further away in the cheek showed elevated levels of nitrogen when analyzed using energy dispersive x-ray spectroscopy (EDS), consistent with a nitride layer. EDS line scans through the white layers at these locations showed higher counts associated with the nitrogen peak relative to the underlying material as shown in figures 22 and 23. A similar line scan in the journal radius near the fracture surface as shown in figure 24 did not reveal a similar trend associated with the white layer, but disturbed metal associated with rubbing that can produce untempered martensite also was not observed.

Additional cracks were observed in the number 5 connecting rod journal. On the cheek surface at the aft end of the number 5 connecting rod journal, a series of radially oriented cracks (ladder cracks) were observed in a rubbed area of the cheek that corresponded to sliding contact with the aft side of the number 5 connecting rod assembly. Rub marks from sliding contact with the forward side of the number 5 connecting rod assembly was also observed on the forward cheek, but ladder cracks were not observed in the rubbed area in that case. However, cracks were observed in the fillet radius as indicated in figure 26. The cracks were oriented at an angle

between the circumferential and radial directions and did not appear to be associated with any rubbing damage, scoring, or pits. Small pits were observed in the fillet radius at the aft end of the number 5 connecting rod journal as indicated in figure 25, but no cracks were observed associated with the pits.

Evidence of sliding contact damage was observed on each of the cheeks at the forward and aft sides of the connecting rod journals. Corresponding rub marks were observed on the sides of the connecting rod assemblies. On the crankshaft, the heaviest contact damage was generally located where the cheek transitioned to the adjacent connecting rod or main journal. On the connecting rod assemblies, the heaviest rub contact was generally located at the middle of the arc for the cap and was associated with local heat tinting. The side faces of the numbers 2 through 5 connecting rod caps are shown in figure 27, and arrows point to sliding contact damage on the sides of the caps. Local heat tinting and sliding contact damage was also observed on the number 1 connecting rod cap that remained assembled on the crankshaft.

Sliding contact damage was also observed on the outer surfaces of the connecting rod caps. A view of typical damage as observed on the number 3 connecting rod cap is shown in figure 28. Circles indicate sliding contact damage on the outer surface likely associated with contact with the engine case. Although the number 6 connecting rod cap experienced more extensive contact damage, similar areas of sliding contact damage were observed shown circled in figure 29. The damaged areas were stained dark with coked oil, which generally appeared darker in these areas relative to other areas of contact damage.

Diameters of the number 2 through 5 connecting rod journals and numbers 1 through 3 main journals were measured using a micrometer at 4 locations on each journal. The diameter was measured at 2 locations on M4 due to coked oil on the surface. Diameters were measured at the forward and aft ends of the journal in a direction parallel to the edges of the adjacent cheeks and in a direction transverse to the first measurement. Results of the measurements are shown listed in table 1, and values that were outside the respective specified ranges for that journal are highlighted in yellow.

The main journal diameter measurements were generally within the specified range for 0.006-inch undersize journals, ranging from 2.6193 inches to 2.6196 inches on M1 and M2 and 2.6196 inches to 2.6198 inches on M3 and M4. The specified ranges are 2.6190 to 2.6195 inches for M1 and M2 and 2.619 inches to 2.620 inches for M3 through M5. One of 4 measurements on M1 was 0.0001 over the maximum specified value.

Connecting rod journal diameter measurements were mostly within specification for 0.003-inch undersize journals. Measurements ranged from 2.2467 inches to 2.2472 inches. The specified range is 2.246 inches to 2.247 inches.

One of 4 measurements on CR2 and CR4 were each 0.0002 inch above specification, and two measurements at the aft end of CR3 were 0.0001 inch above specification.

Table 1. Journal Diameter Measurements

Journal	Diameter, FWD end, parallel (inches)	Diameter, FWD end, perpendicular (inches)	Diameter, Aft end, parallel (inches)	Diameter, Aft end, perpendicular (inches)
M1	2.6194	2.6196	2.6194	2.6194
M2	2.6193	2.6193	2.6193	2.6193
M3	2.6197	2.6197	2.6196	2.6197
M4	2.6196		2.6198	
CR2	2.2472	2.2469	2.2470	2.2470
CR3	2.2468	2.2469	2.2471	2.2471
CR4	2.2470	2.2470	2.2470	2.2472
CR5	2.2468	2.2467	2.2469	2.2462

The fillet profile at the aft end of connecting rod journal 5 was examined using a backlit optical image as shown in figure 29. The fillet had smooth transitions to the journal and cheek surfaces. The fillet radius measured 0.149 inch, which is within the specified range of 0.140 inch to 0.156 inch.

The distance between the cheeks was measured for connecting rod journals 2 through 4. The length measured 1.3389 inches, 1.3399 inches, and 1.3385 inches for connecting rod journals 2, 3, and 4, respectively. All lengths were within the specified range of 1.337 inches to 1.341 inches.

The widths of the caps from connecting rods 2 through 5 were measured at three locations; the middle of the arc and at each end of the arc where it mated to the connecting rod straps. For clarification, the cap width dimension is indicated in figure 28. Results of the width measurements are listed in table 2. The specified width of the caps for the part number connecting rod assembly associated with the forging number observed on the accident connecting rods and specified for use in this engine were 1.331 inch to 1.333 inches. Measured values that exceeded the

specified maximum value are highlighted in table 2. All caps had a conforming width at the ends of the arcs, but caps from connecting rods 2, 3, and 4 had widths that exceeded the maximum design at the middle of the arc. Although the cap from connecting rod 5 had a conforming dimension at the middle of the cap, it was also the most extensively rubbed and the only connecting rod that was also associated with ladder cracks in the corresponding crankshaft surface.

Table 2. Connecting Rod Cap Widths

CR Cap	Width at one end of the arc (inch)	Width at the middle of the arc (inch)	Width at the other end of the arc (inch)
2	1.3315	1.3355	1.3318
3	1.3314	1.3384	1.3315
4	1.3309	1.3339	1.3314
5	1.3307	1.3307	1.3308

A pair of radial cuts were made through the number 5 connecting rod journal to facilitate a metallographic examination of the nitride case and to measure the hardness profile from the surface to the core by microindentation. Rockwell hardness measurements were also taken in the core after the metallographic examination was completed.

A view of the microstructure near the surface of the number 5 connecting rod journal is shown in figure 30. The sample was etched using Marble's reagent, which produces a darker etch for the nitride case. As shown in figure 30, the case depth as measured optically was 0.033 inch. The case depth as noted in the engineering drawing for the crankshaft was specified to be 0.018 inch to 0.026 inch (or 0.0165 inch to 0.0245 inch for a surface with 0.003 inch removed from the original diameter). However, according to maintenance records for the accident engine, the crankshaft was replaced, and the replacement crankshaft that was installed in the engine at overhaul had been renitrided.

The hardness profile was measured by microindentation at varying depths from the number 5 connecting rod journal surface using a Leco AMH55 hardness tester. The hardness was measured using a Vickers indenter, and the results were reported as converted to the Rockwell C scale. The case hardness profile decreased approximately linearly from 56 HRC at a depth of 0.003 inch to 29 HRC at a depth of 0.038 inch as shown in figure 31. Hardness was also measured in the core using a

Rockwell indenter, and the average hardness measured 29.5 HRC. According to the engineering drawing for the crankshaft, the specified core hardness range is 32 HRC to 37 HRC.

Another radial segment of the number 5 connecting rod journal was sectioned with two longitudinal cuts to fabricate a specimen to be used to produce a laboratory-induced overstress fracture. Next, a cut was made in the circumferential plane to create a notch on the side opposite the journal surface, and cracks were opened at the journal surface by squeezing the notch closed within a vise.

A view of the fracture features near the connecting rod surface as produced by the lab-induced overstress fracture are shown in figure 32. Within approximately 0.015 inches of the surface, the fracture surface had an intergranular fracture features as shown in figure 33. Further from the surface, between 0.015 inches and 0.030 inches deep, the fracture had transgranular cleavage features as shown in figure 34. The remainder of the lab-induced fracture had ductile dimple features.

An overall view of debris recovered from the oil screen and sump are shown in figure 35. Material recovered from the sump was mostly consistent with bearing remnants. A dowel pin was included in the sump debris, but a corresponding installation location in the accident engine for a dowel pin of that dimension and configuration could not be determined. Debris from the oil screen included metallic and nonmetallic debris. The nonmetallic debris generally had similar color and surface textures, and the larger pieces had dimensional features that were consistent with a magneto bumper. The forward seal was fractured as shown in figure 35 but was not examined in detail.

Submitted by:

Matthew R. Fox, Ph.D.
Chief Technical Advisor - Materials

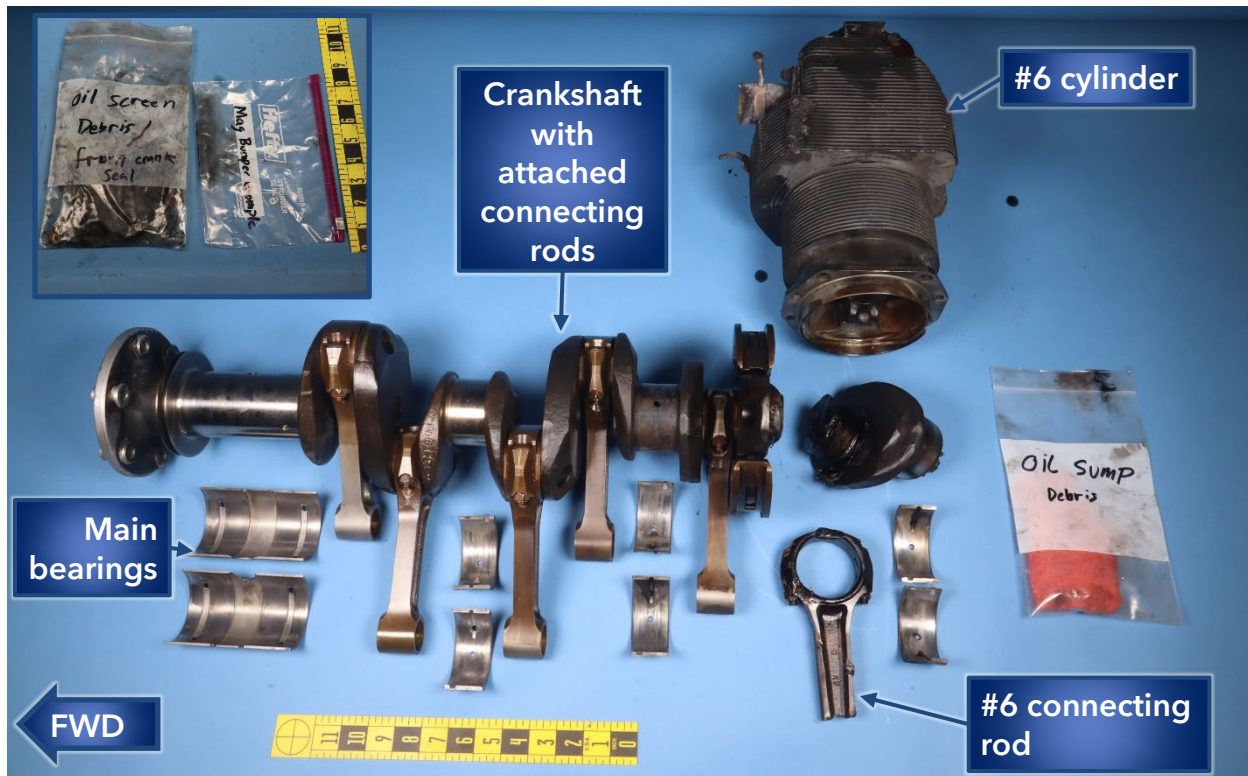


Figure 1. Overall view of the submitted engine components and bag of oil sump debris with an inset image of the bagged oil screen debris, front seal, and intact magneto bumpers as received.



Figure 2. Mating sides of the crankshaft fracture at the number 6 connecting rod journal forward cheek showing the forward side in the left image and the aft side in the right image.



Figure 3. Views of the main bearing interior (upper image) and exterior (lower image) surfaces. Arrows in the lower image indicates elongation at the edges of the oil supply holes.

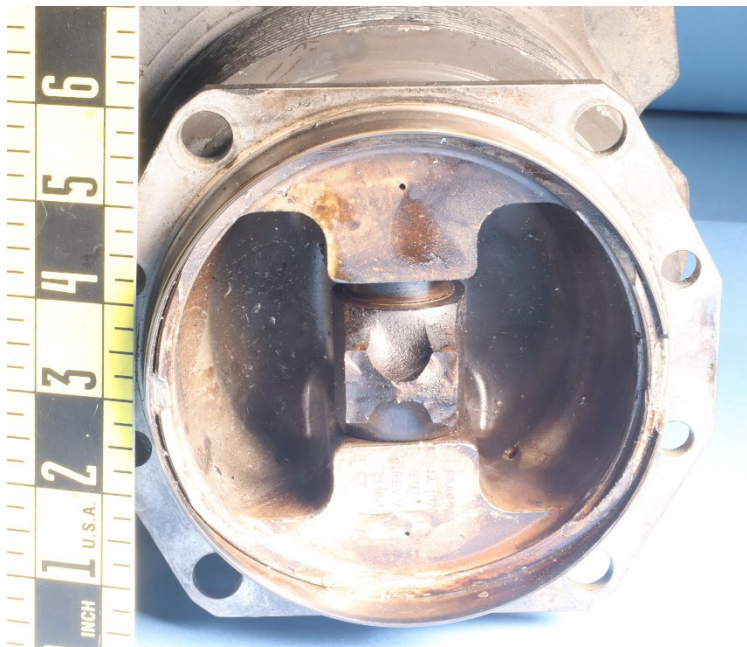


Figure 4. Lower end of the number 6 cylinder assembly (left image) with a trapped piston assembly and fractured connecting rod. The right image shows a closer view of the fracture surface on the number 6 connecting rod.

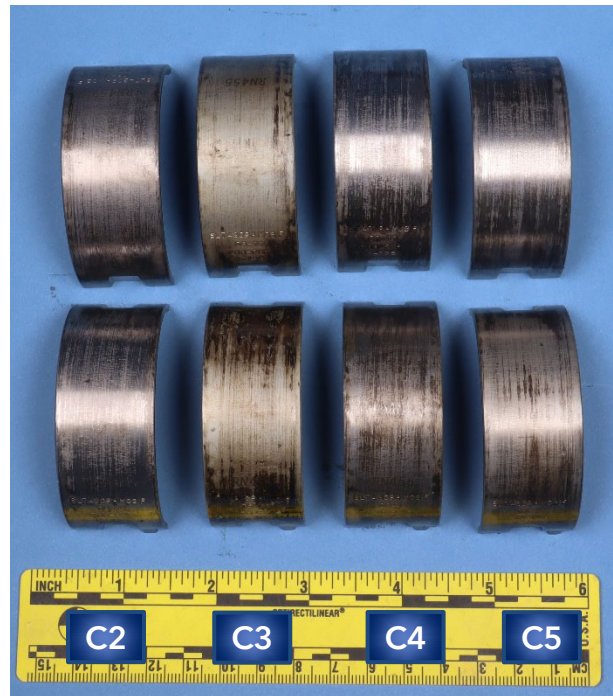
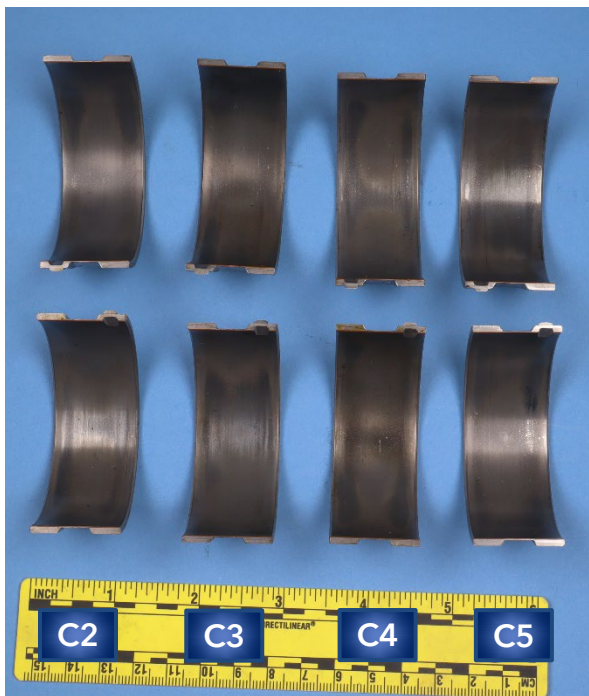


Figure 5. Interior (left image) and exterior (right image) surfaces of the number 2 through 5 connecting rod bearings.

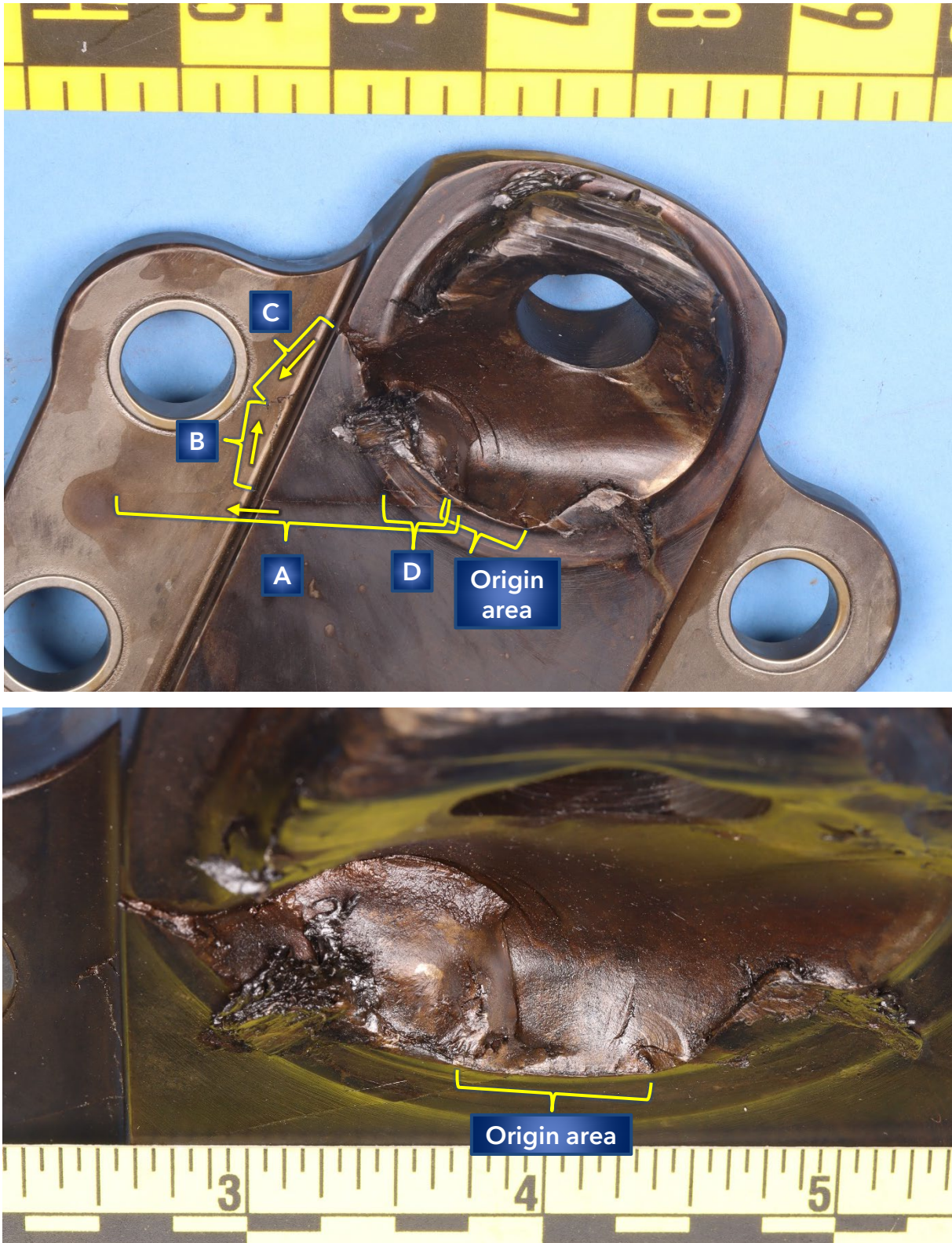


Figure 6. Forward side of the crankshaft fracture showing the origin area. Lettered brackets indicate locations of unopened cracks extending from the origin area, and arrows within the brackets indicate the direction of crack growth.



Figure 7. Crankshaft piece showing cuts made to separate unopened cracks and to facilitate SEM exam of the origin area. Numbered arrows point to saw cuts.

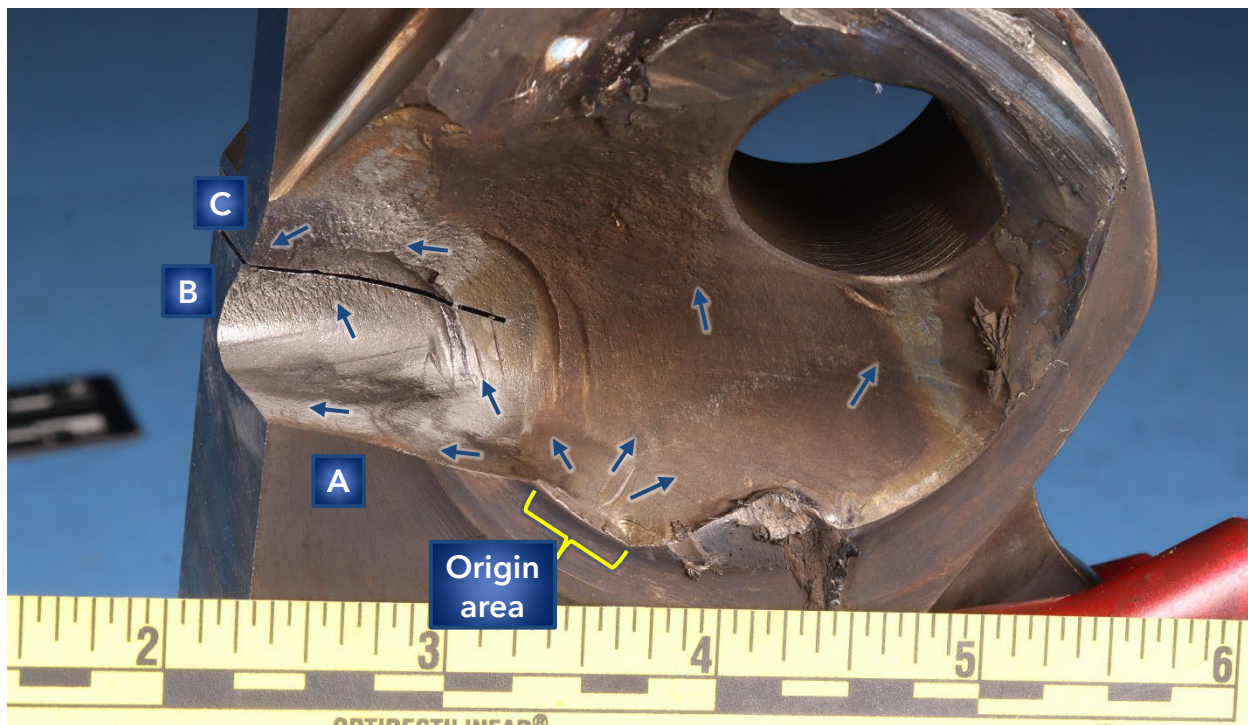


Figure 8. Optical image of the origin area after separating the unopened cracks and before cutting for the SEM examination. Unlabeled arrows indicate the local directions of fatigue crack propagation.

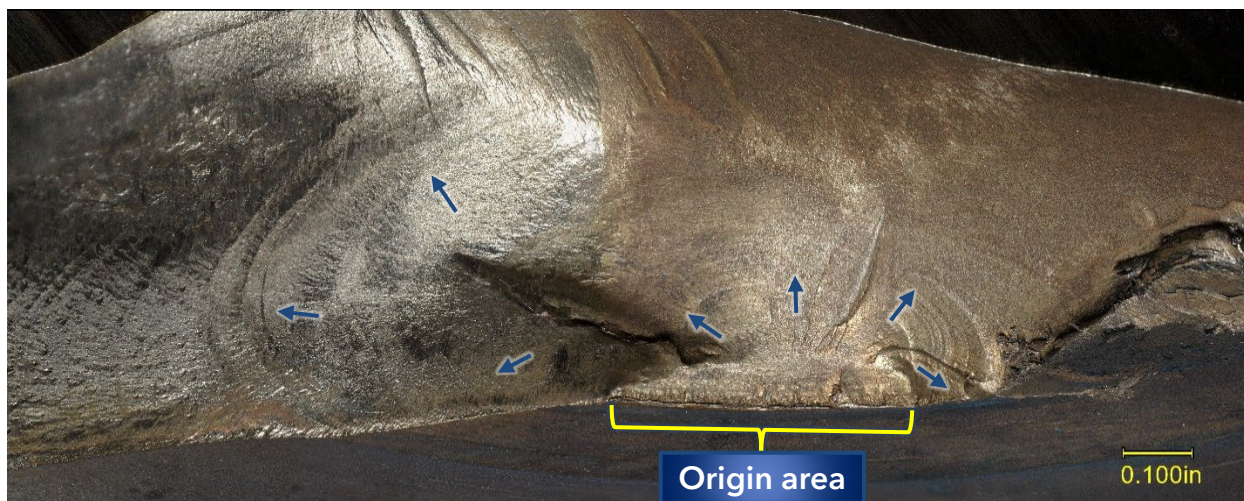


Figure 9. Another optical view of the origin area after separating the unopened cracks. Unlabeled arrows indicate the local directions of fatigue crack propagation.

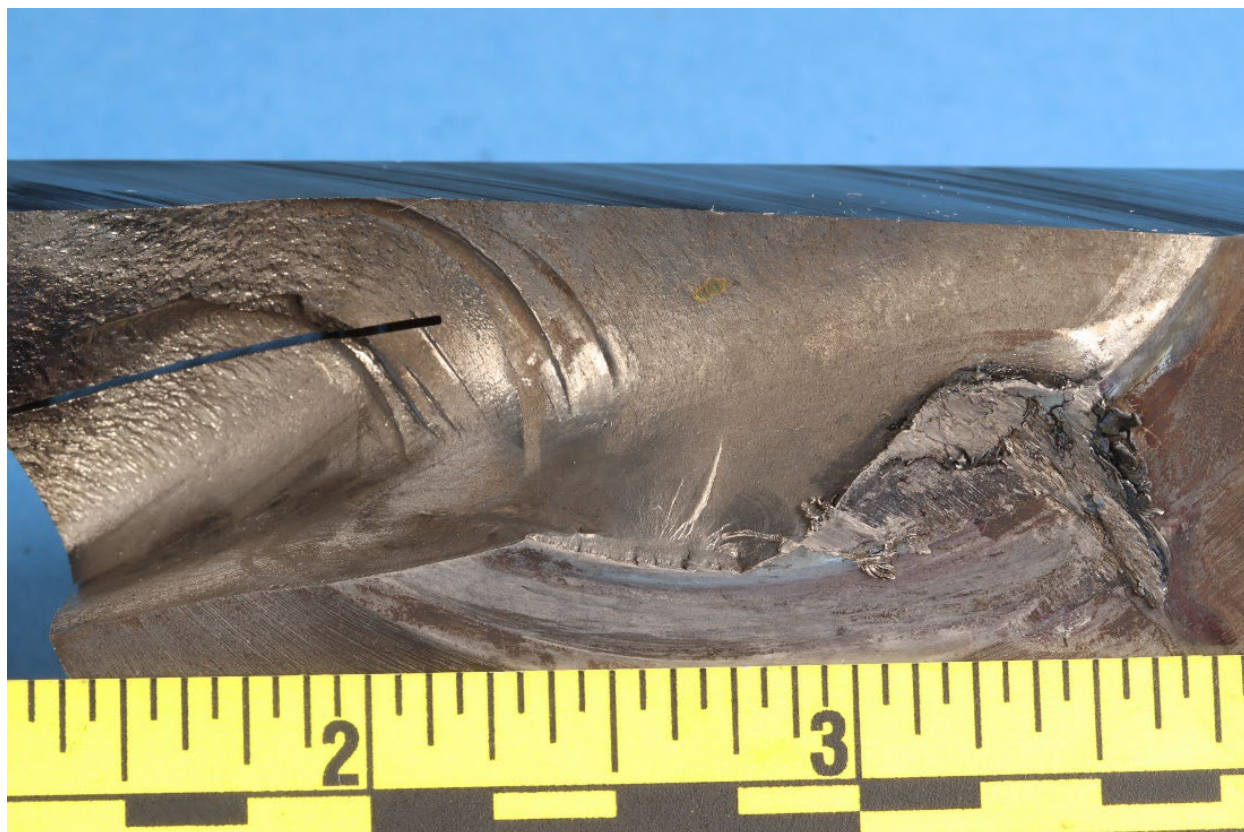


Figure 10. View of the origin area after sectioning and cleaning using Evapo-Rust.



Figure 11. Close view of the origin area using a Keyence VHX-7000 in depth-up HDR mode.

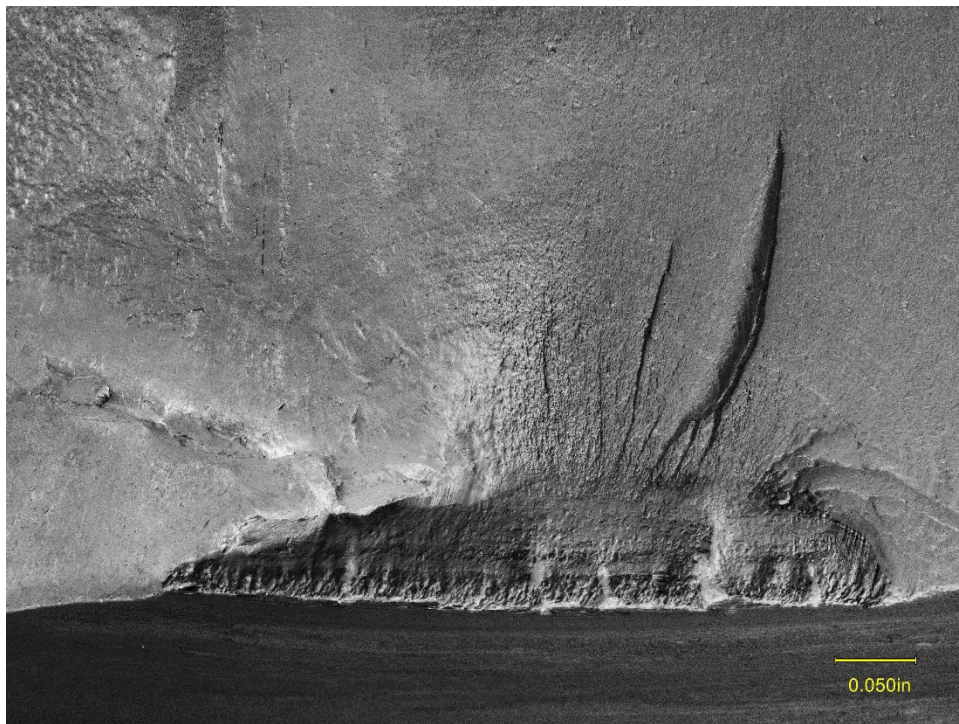
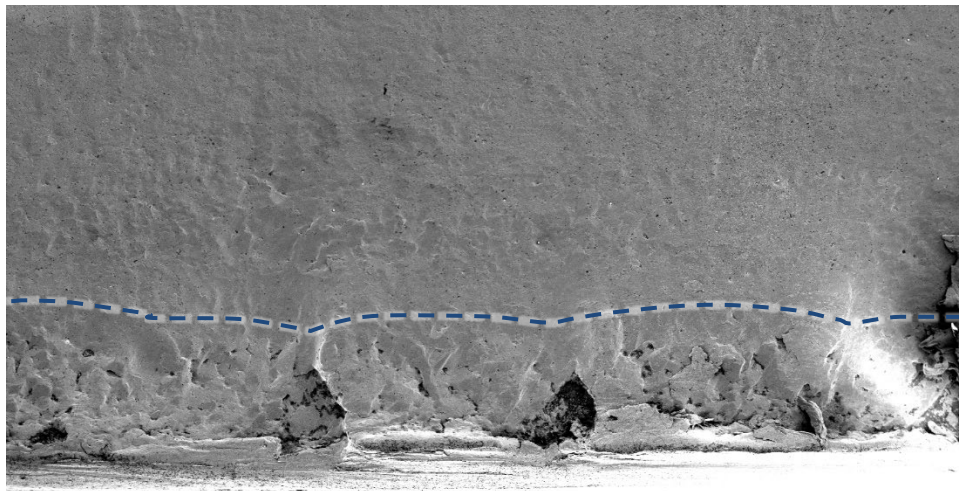
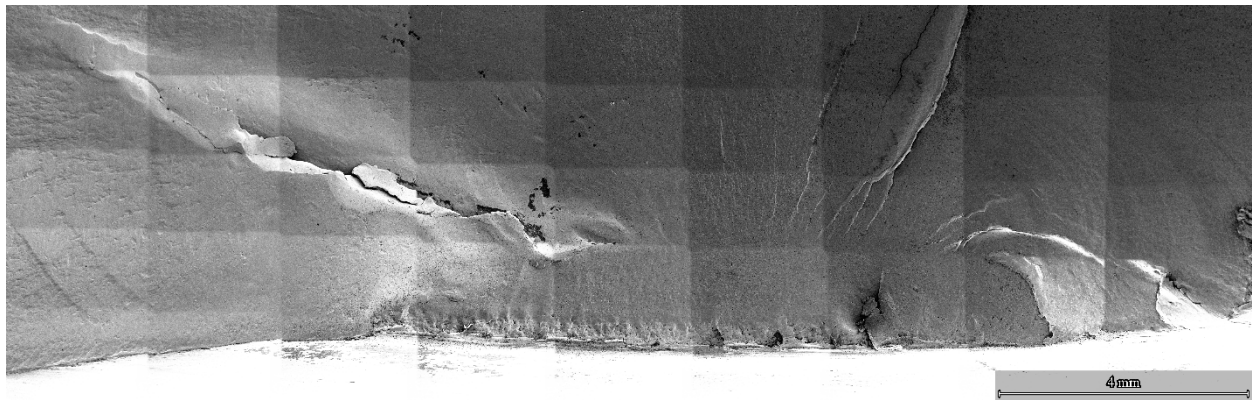
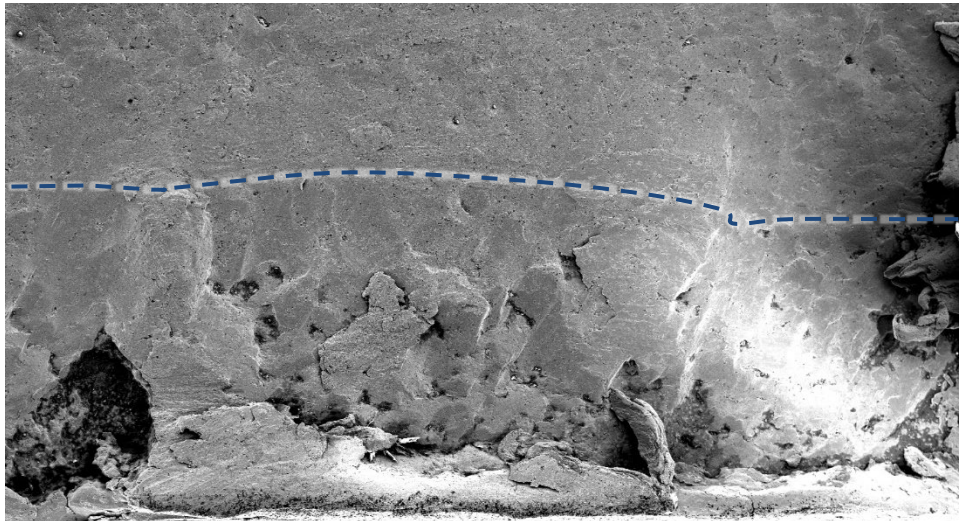


Figure 12. Optical image of the origin area using a Keyence VHX-7000 in depth-up optical shadow mode.



NTSB	8/21/2023	HV	det	mode	mag	WD	use case	500 μ m
	4:33:02 PM	10.00 kV	ETD	SE	35 $\times$	29.5 mm	OptiPlan	Materials Laboratory



NTSB	8/21/2023	HV	det	mode	mag	WD	use case	300 μ m
	4:39:18 PM	10.00 kV	ETD	SE	80 $\times$	29.3 mm	OptiPlan	Materials Laboratory

Figure 13. A montage of stitched SEM images of the origin area (upper image) with closer views near the middle of the origin area (middle and lower images).

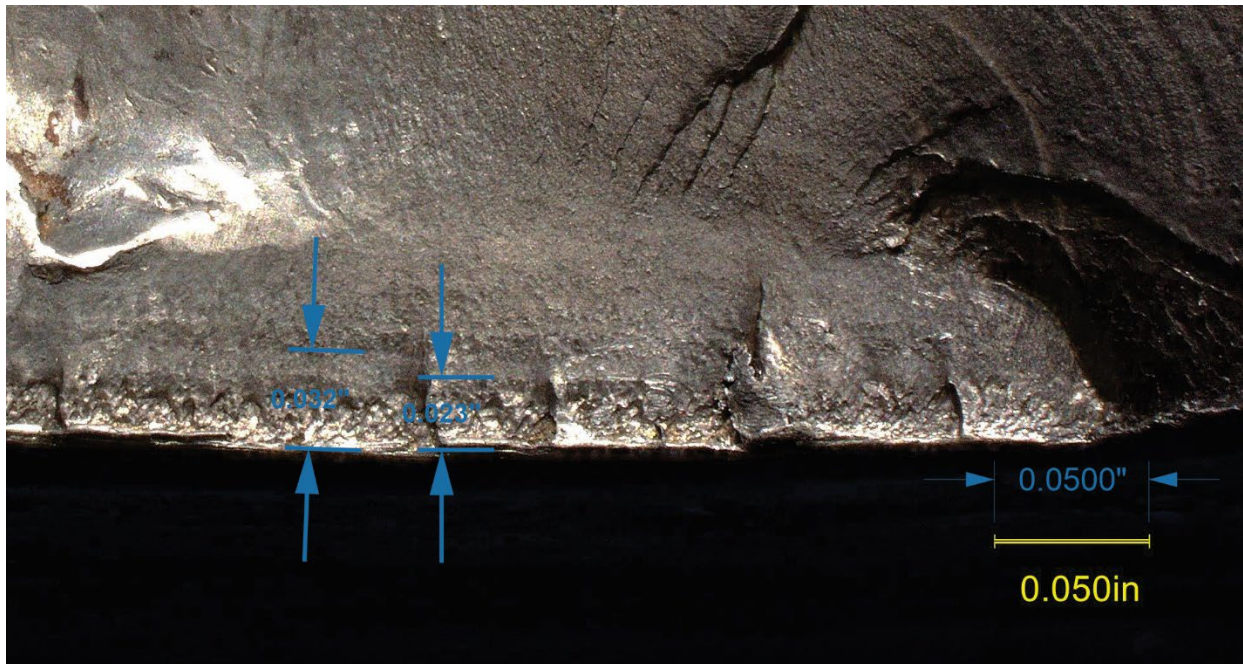


Figure 14. Optical image showing regions with different fractographic textures at the origin area with boundaries at depths of 0.023 inch and 0.032 inch as shown.

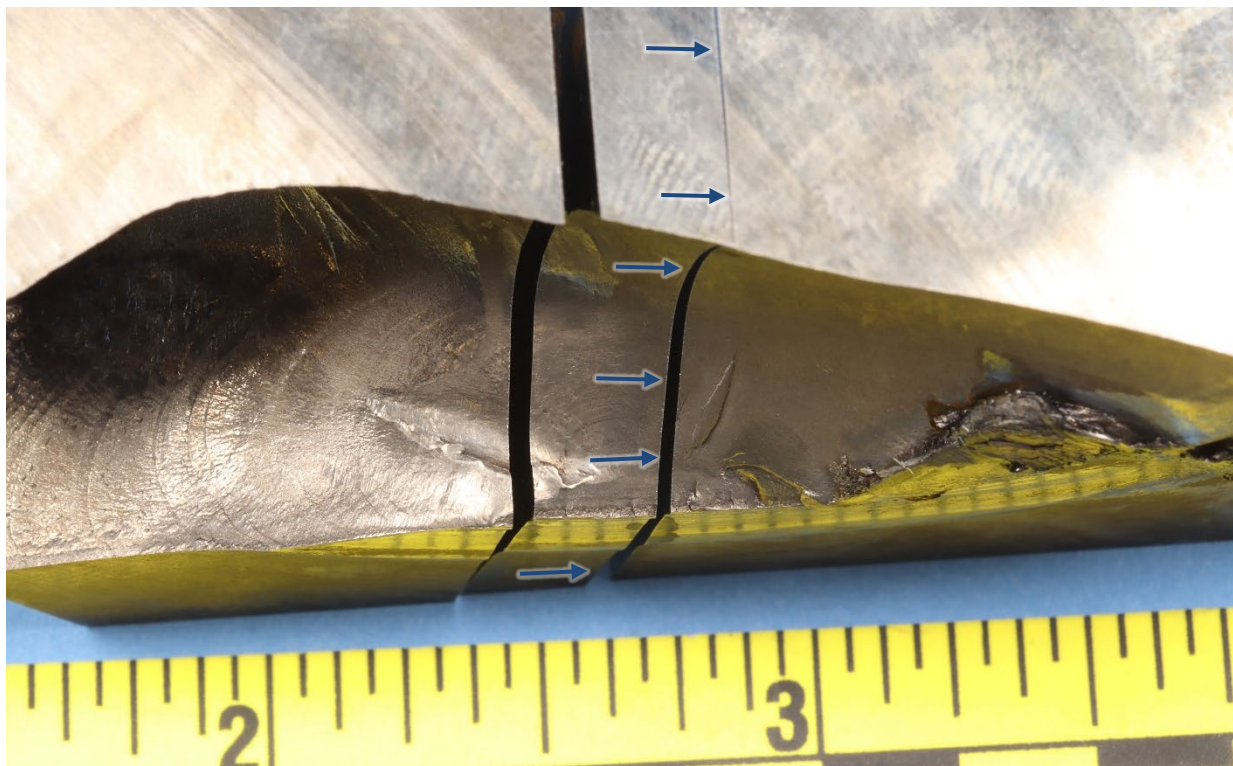


Figure 15. View of the fracture surface after sectioning for metallographic examination. Arrows point to the prepared surface.

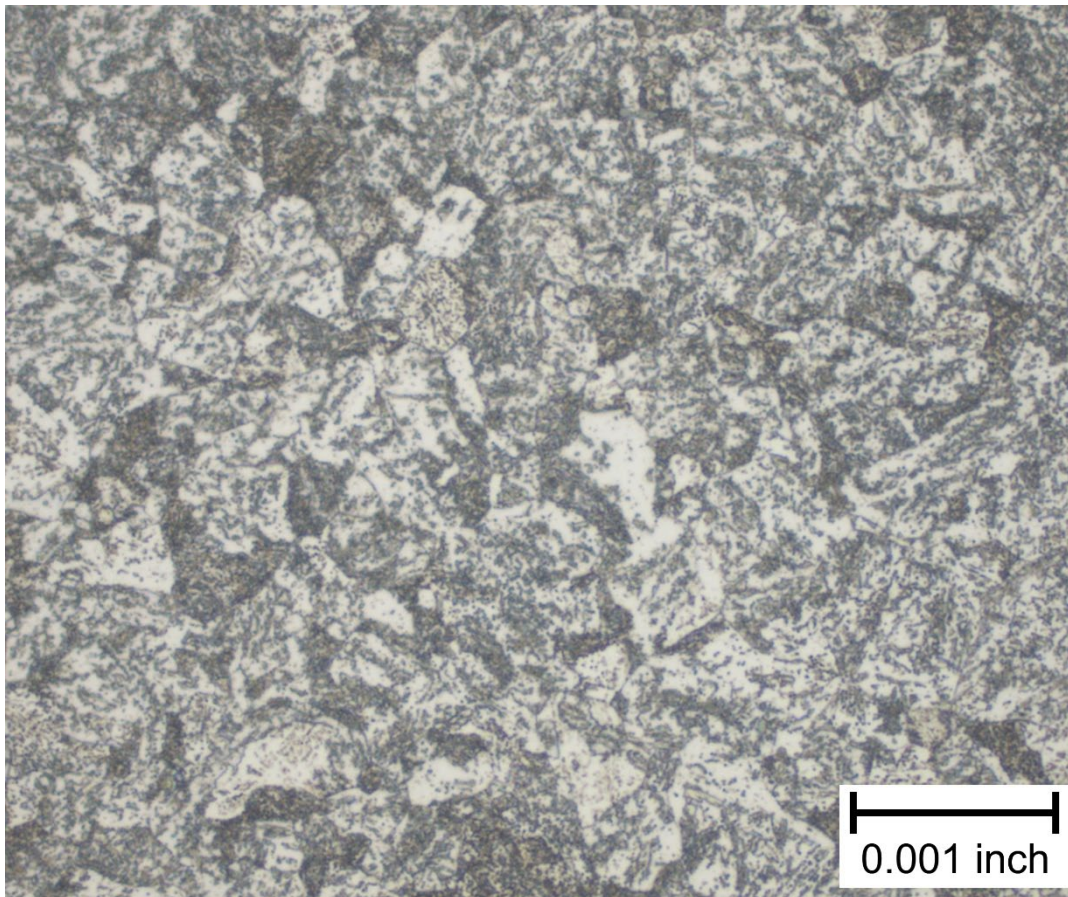


Figure 16. Metallographic image of the typical core microstructure observed on the crankshaft cross-section after etching with 2% nital.

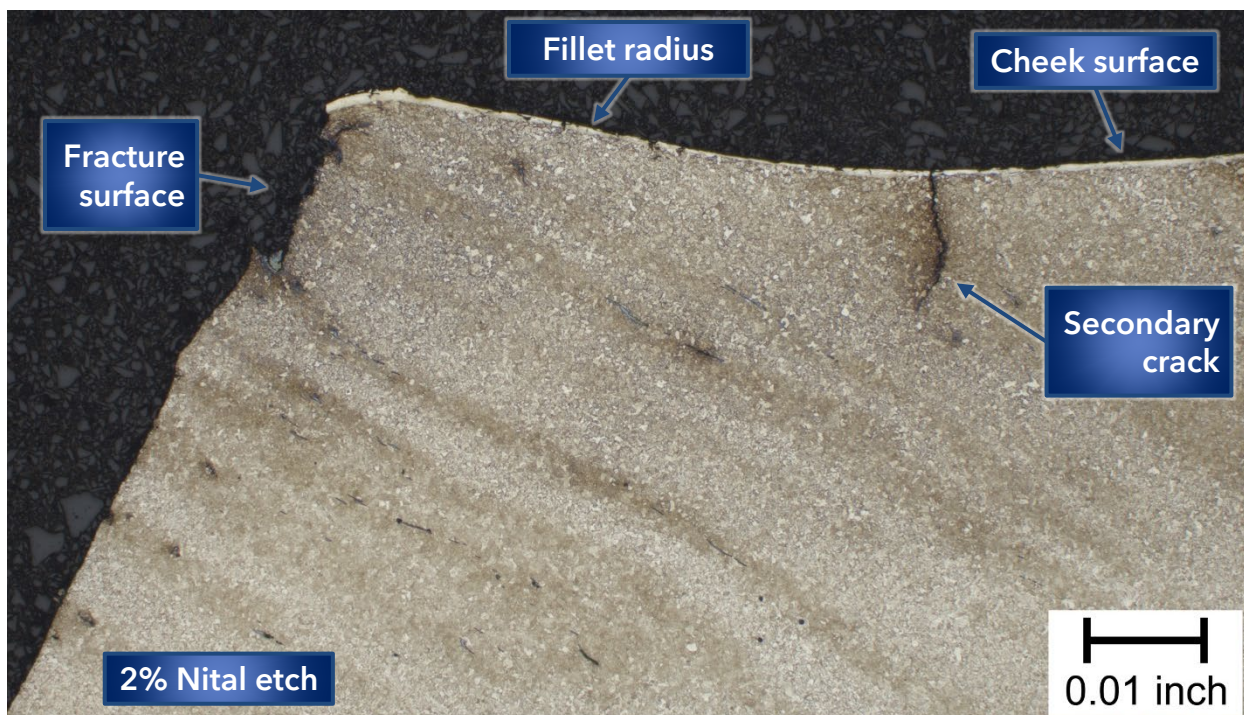
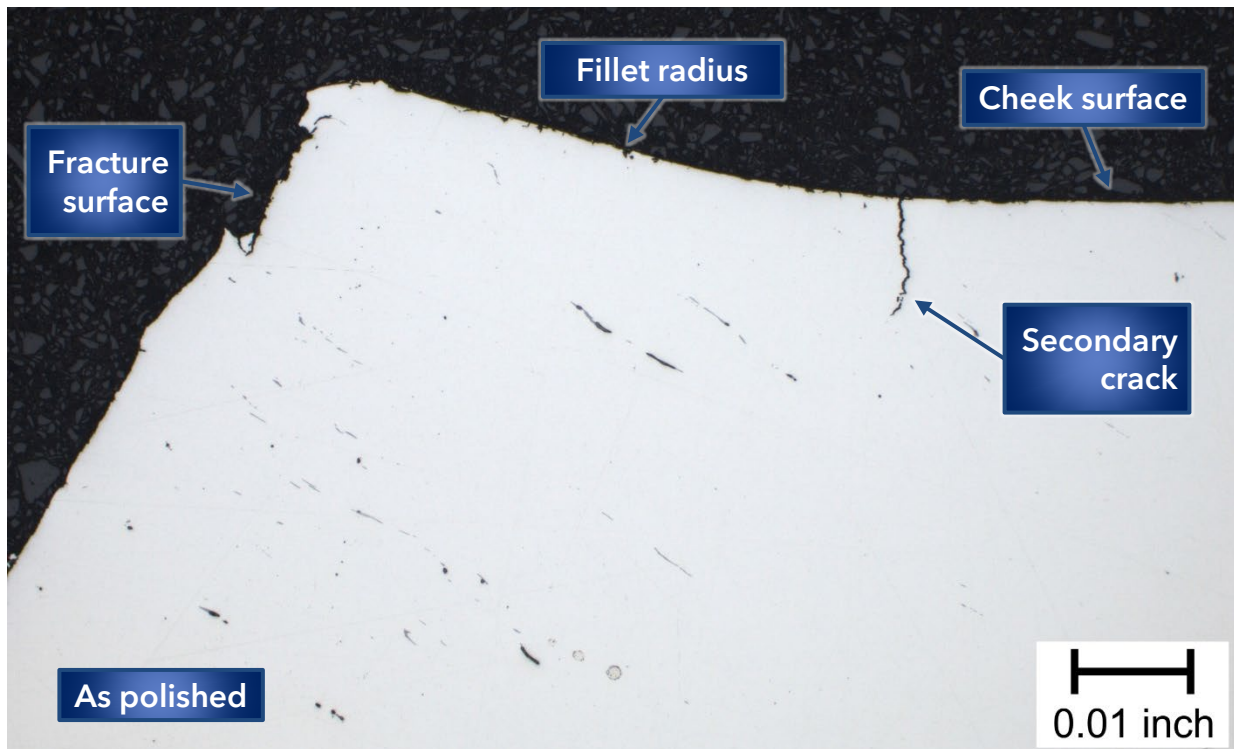


Figure 17. Metallographic images of the cross-section through the fatigue origin area as polished and after etching with 2% nital.

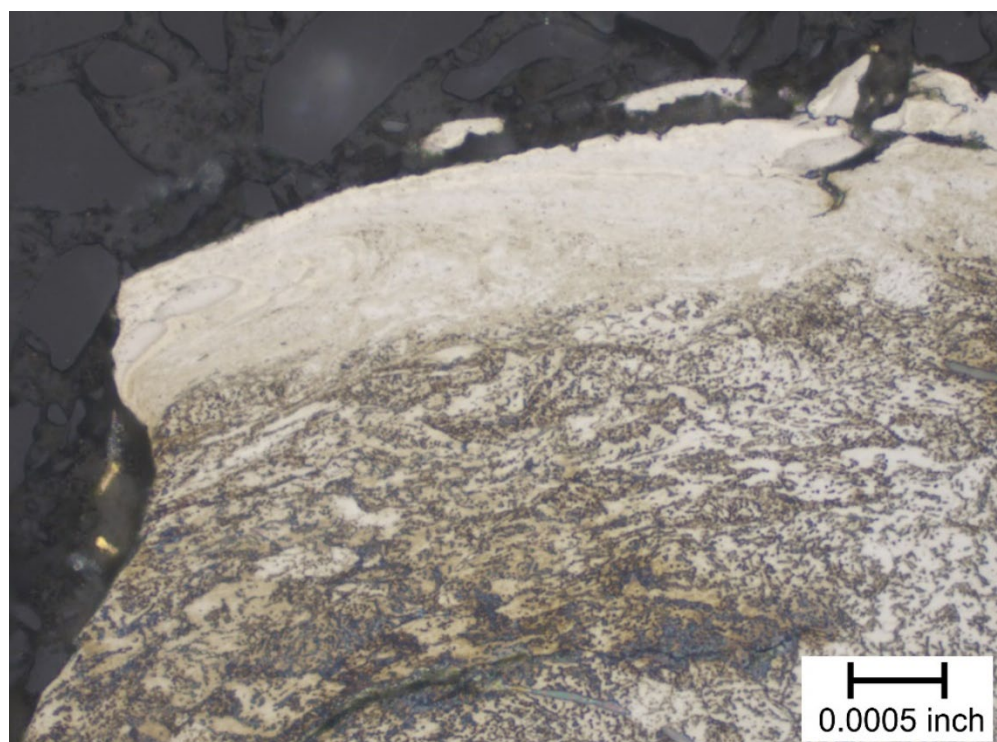
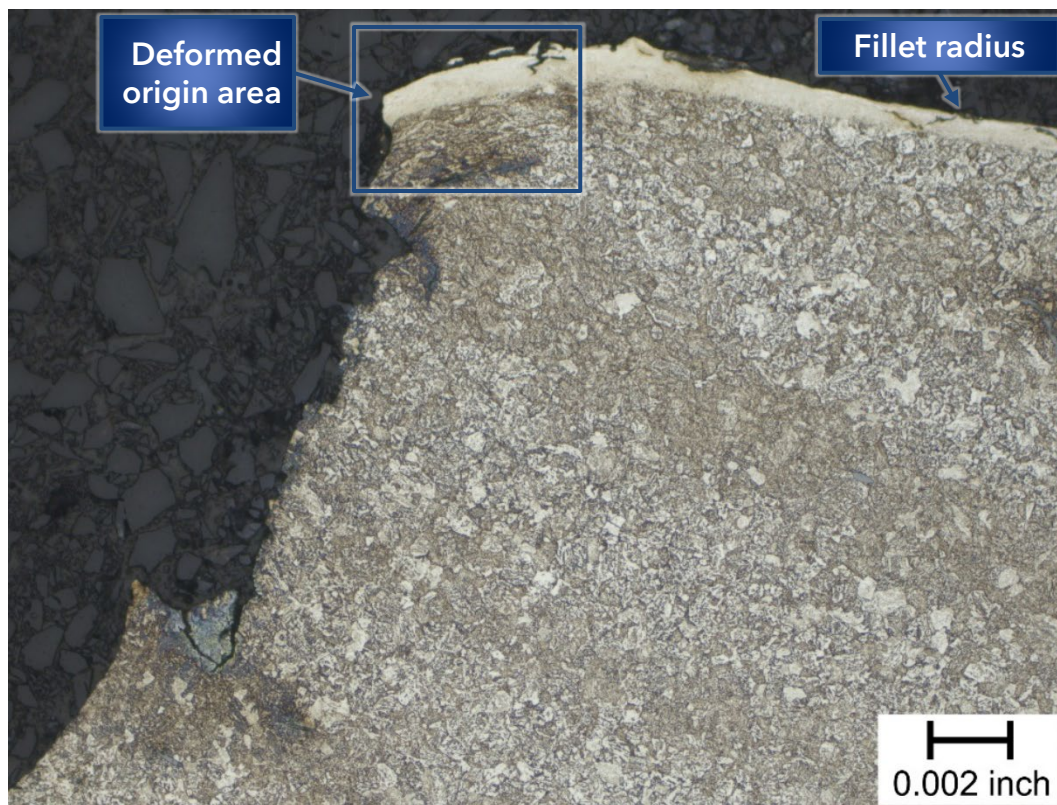


Figure 18. Closer views of the fatigue origin area in the metallographic specimen. Etched with 2% nital.

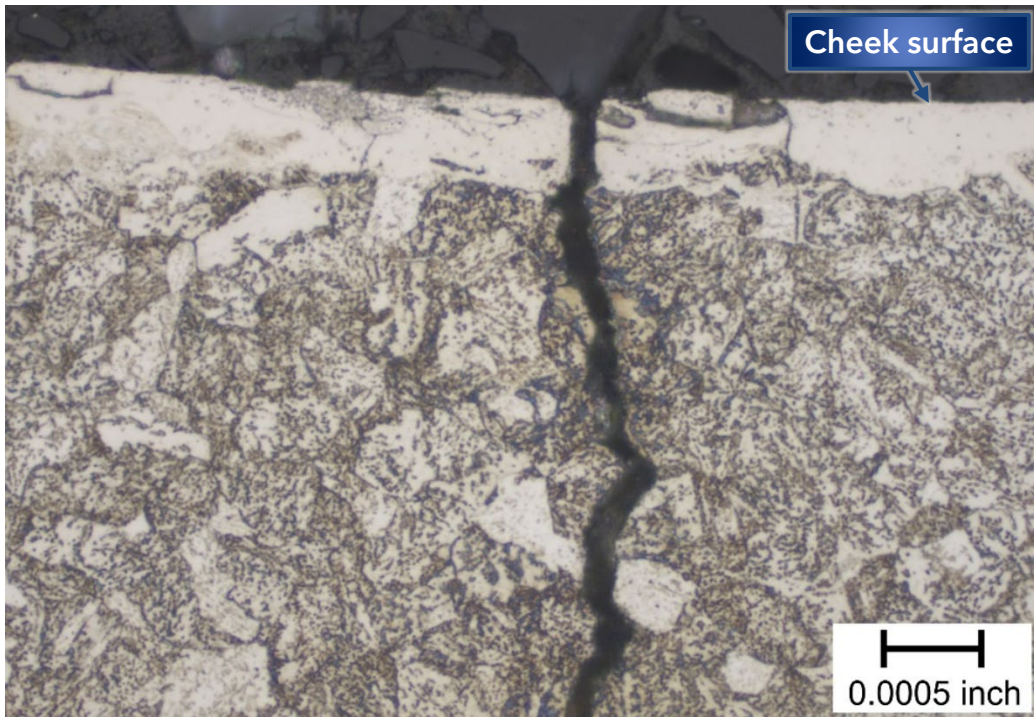


Figure 19. Closer view of the secondary crack where it intersected the number 6 journal cheek surface in the metallographic section shown in figure 15. Etched with 2% nital.

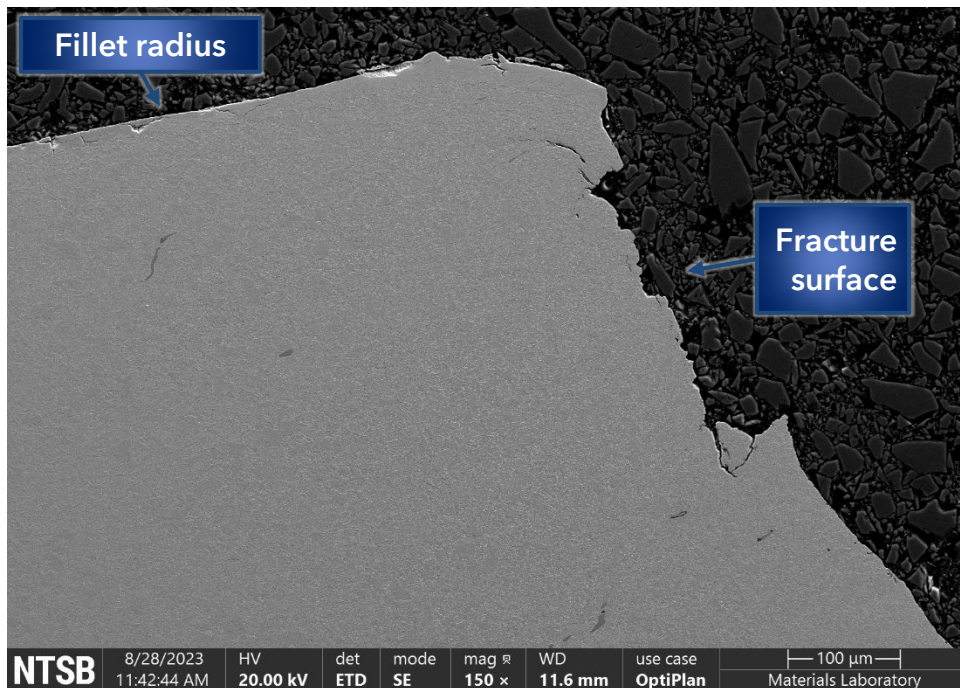


Figure 20. SEM image of the metallographic section through the fracture origin area. Etched with 2% nital.

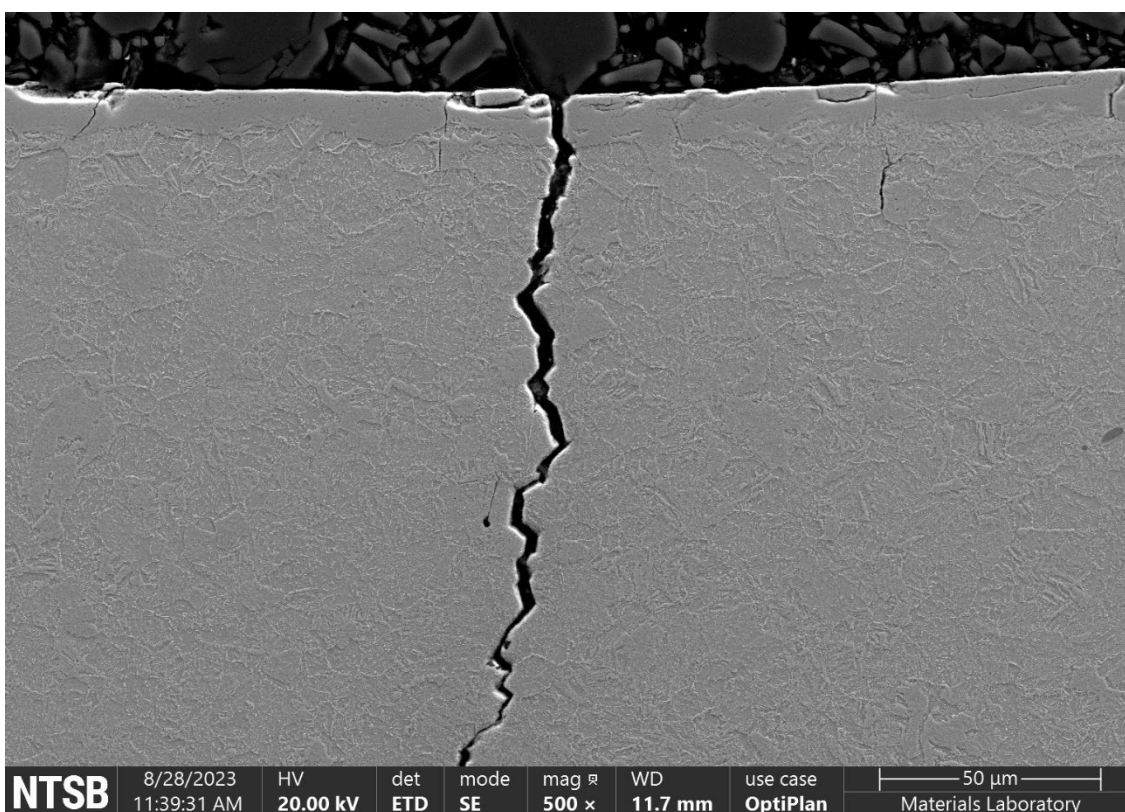
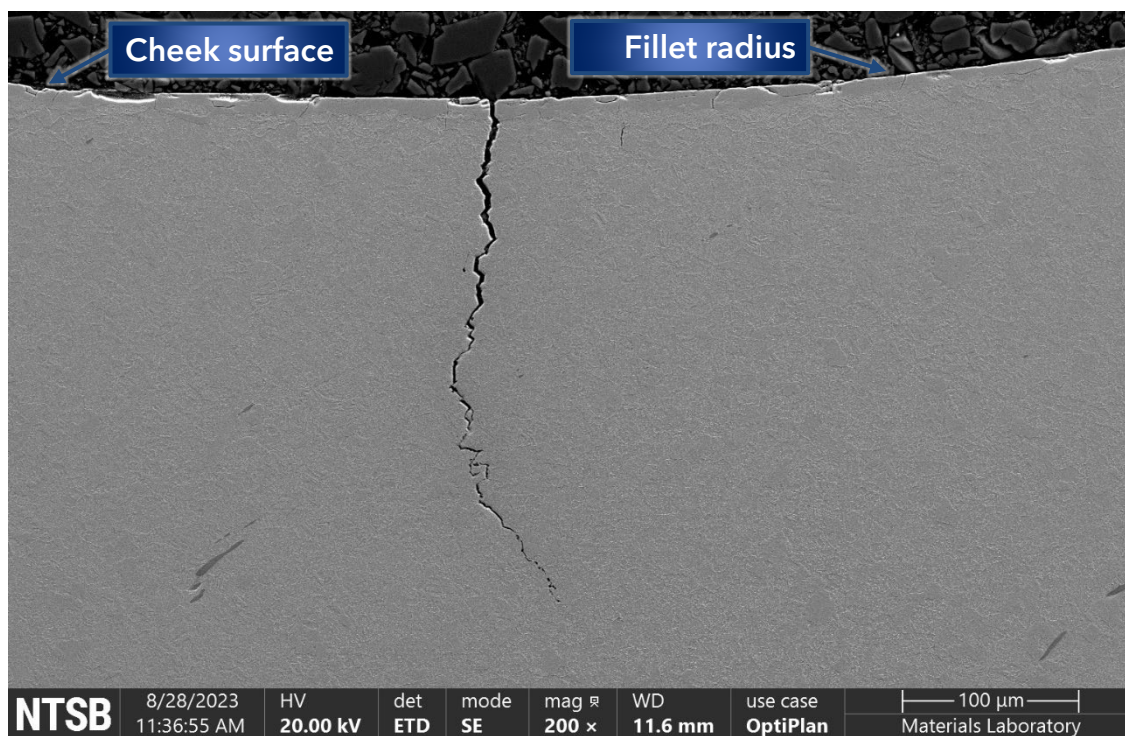


Figure 21. SEM images of the secondary crack in the number 6 journal cheek showing an intergranular fracture path. Etched with 2% nital.

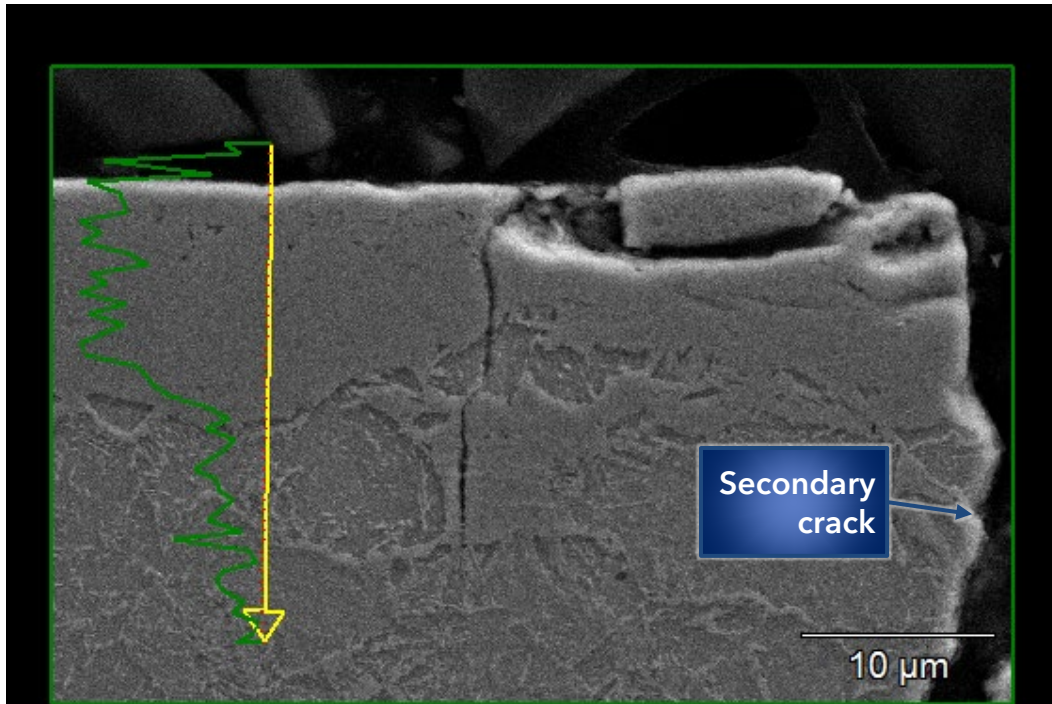


Figure 22. Nitrogen concentration profile determined using an EDS line scan at the cheek surface adjacent to the secondary crack. Etched with 2% nital.

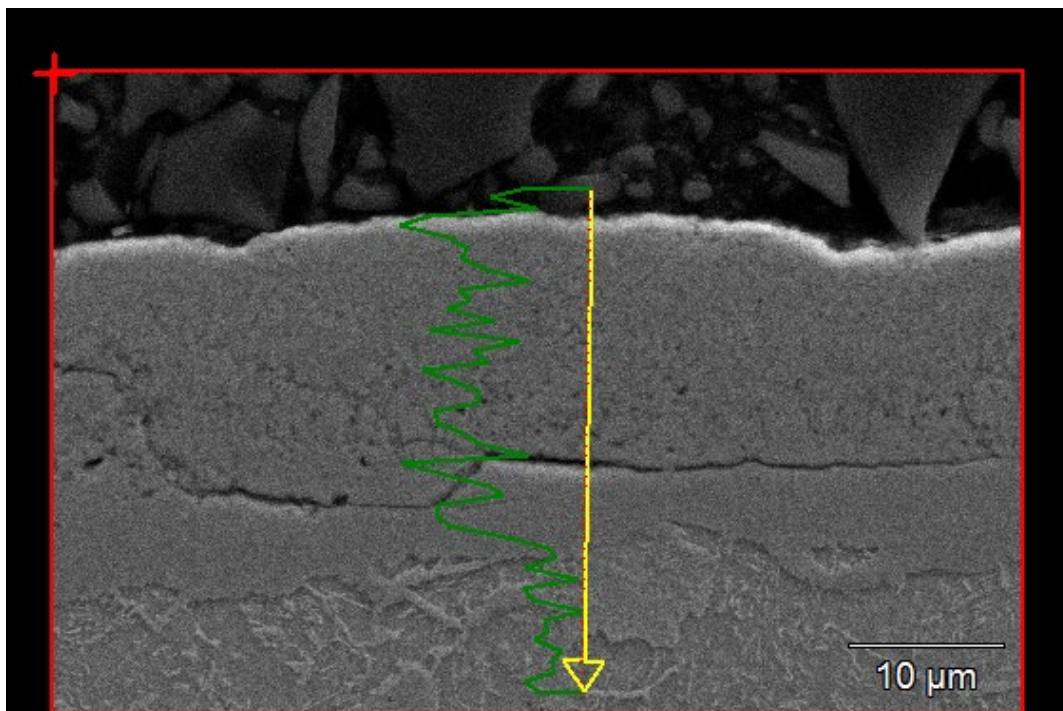


Figure 23. Nitrogen concentration profile determined using an EDS line scan at the cheek surface away from the potential connecting rod contact area. Etched with 2% nital.

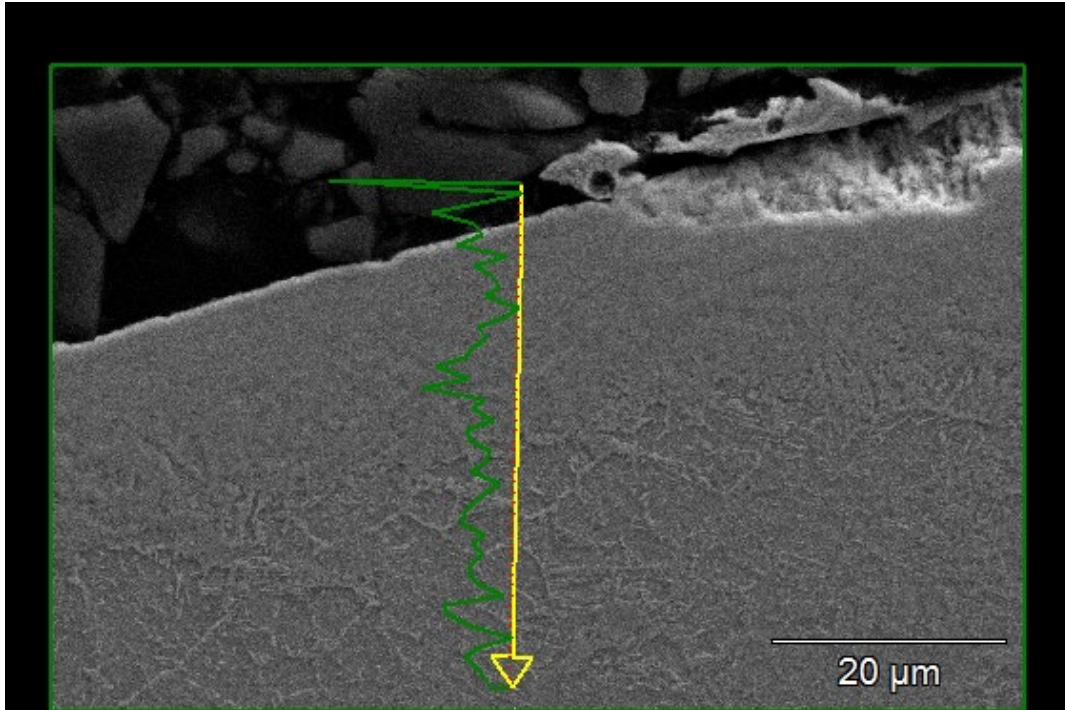


Figure 24. Nitrogen concentration profile determined using an EDS line scan at the journal radius near the fracture surface. Etched with 2% nital.

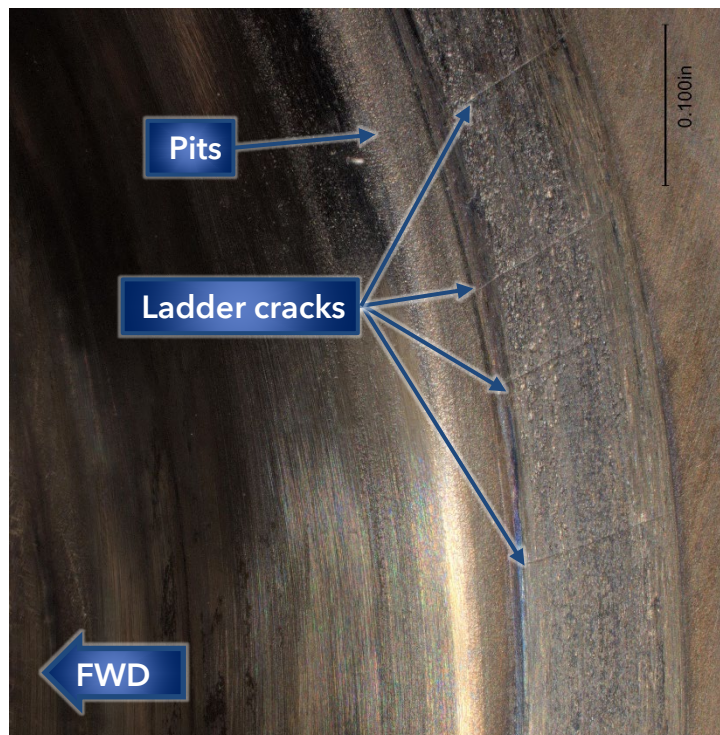


Figure 25. Number 5 connecting rod journal at the aft cheek showing ladder cracks from sliding contact with the connecting rod assembly and showing small pits in the journal fillet radius.

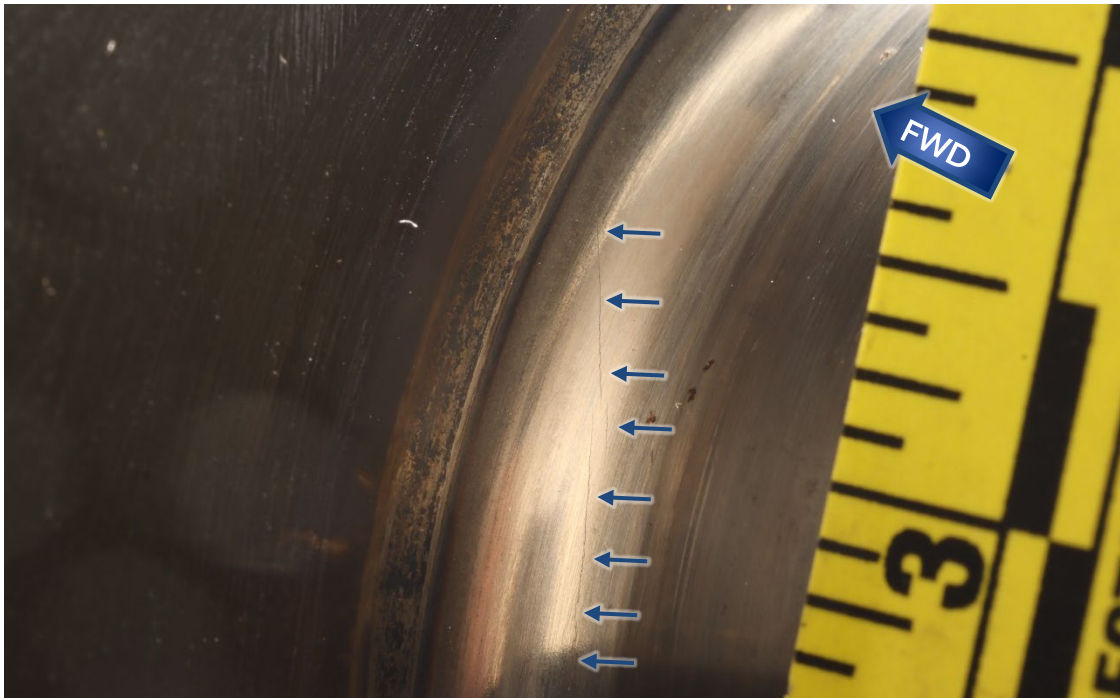


Figure 26. Number 5 connecting rod journal at the forward cheek. Unlabeled arrows point to several cracks in the fillet radius.

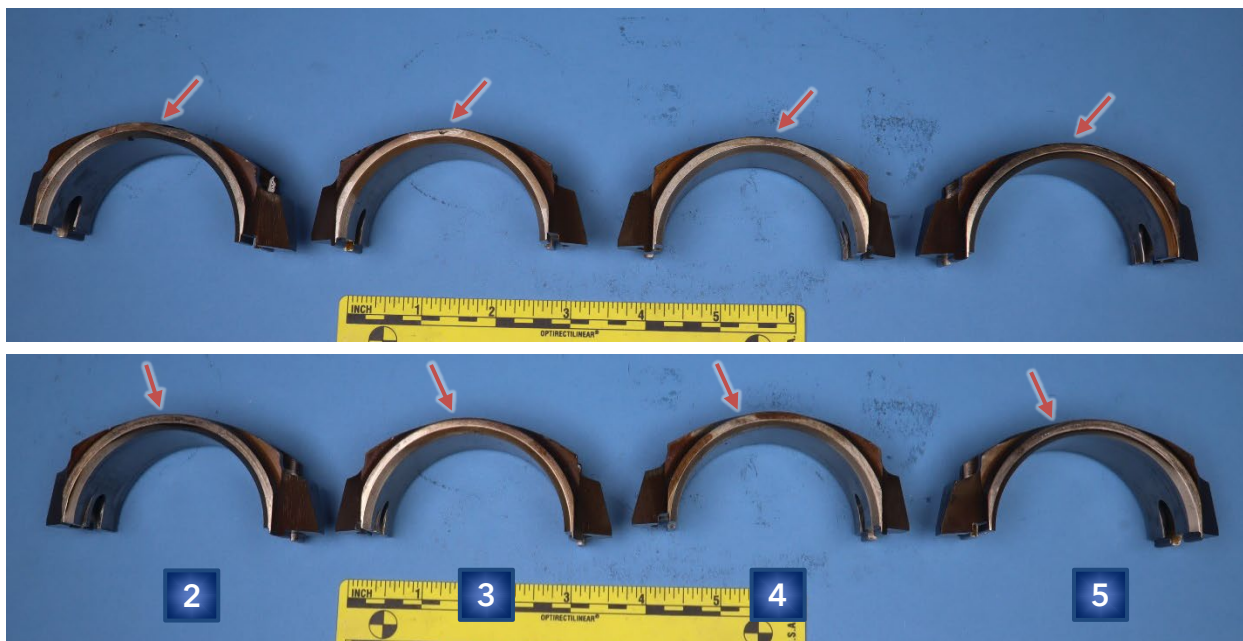


Figure 27. Sides of the connecting rod caps for rod assemblies 2 through 5 showing rubbing contact damage at the middle of the arc.

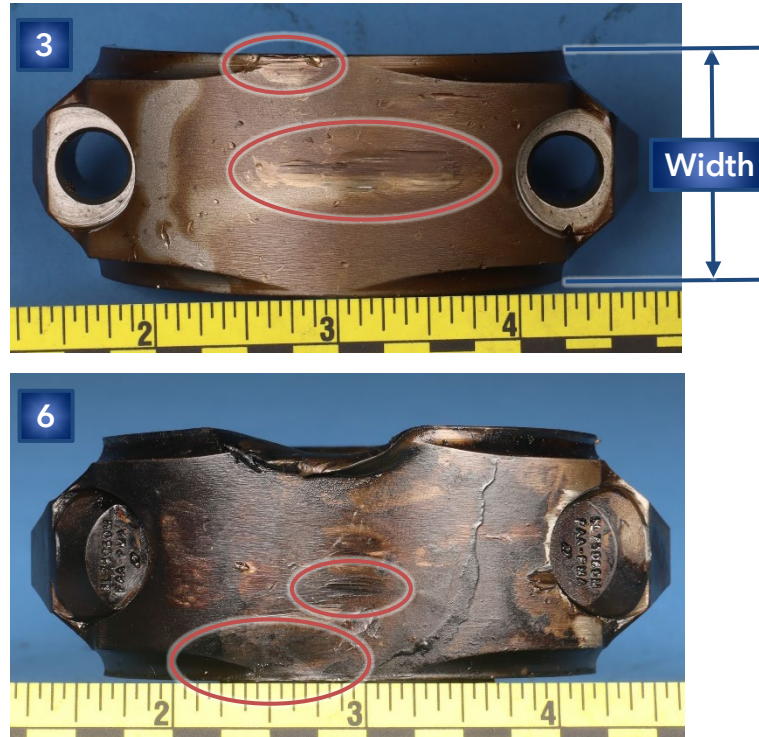


Figure 28. Rub damage on the outer surface of the caps from the number 3 and number 6 connecting rod assemblies.

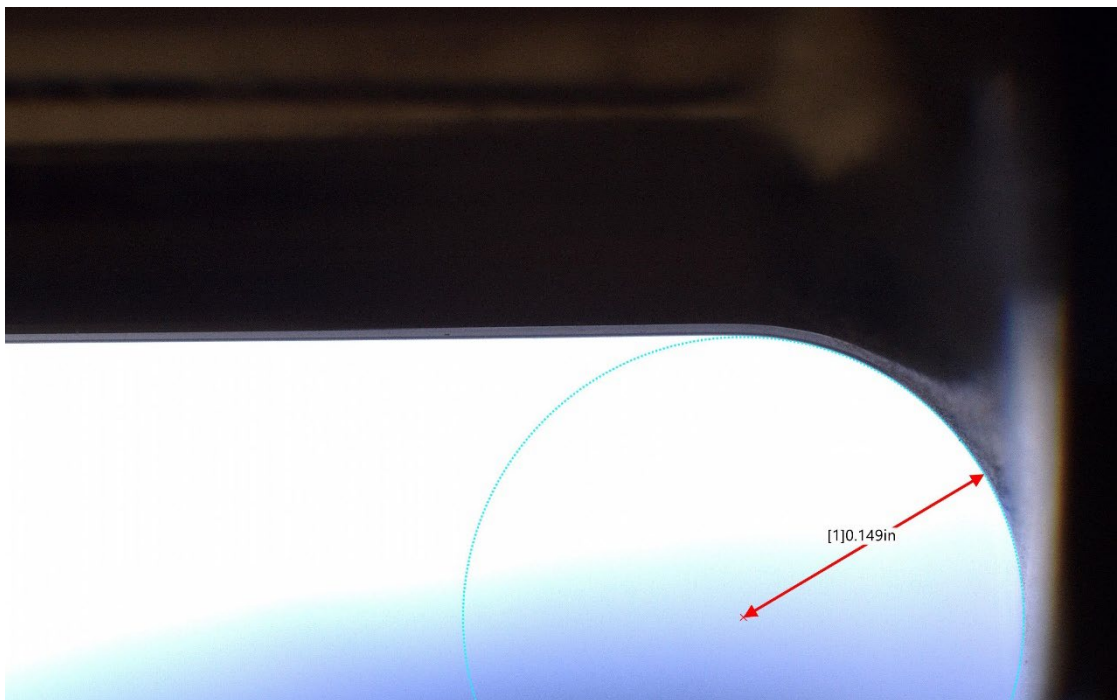


Figure 29. Number 5 connecting rod journal aft fillet radius measurement.



Figure 30. Nitride layer thickness at the number 5 connecting rod journal surface measured by optical means. Etched with Marble's reagent.

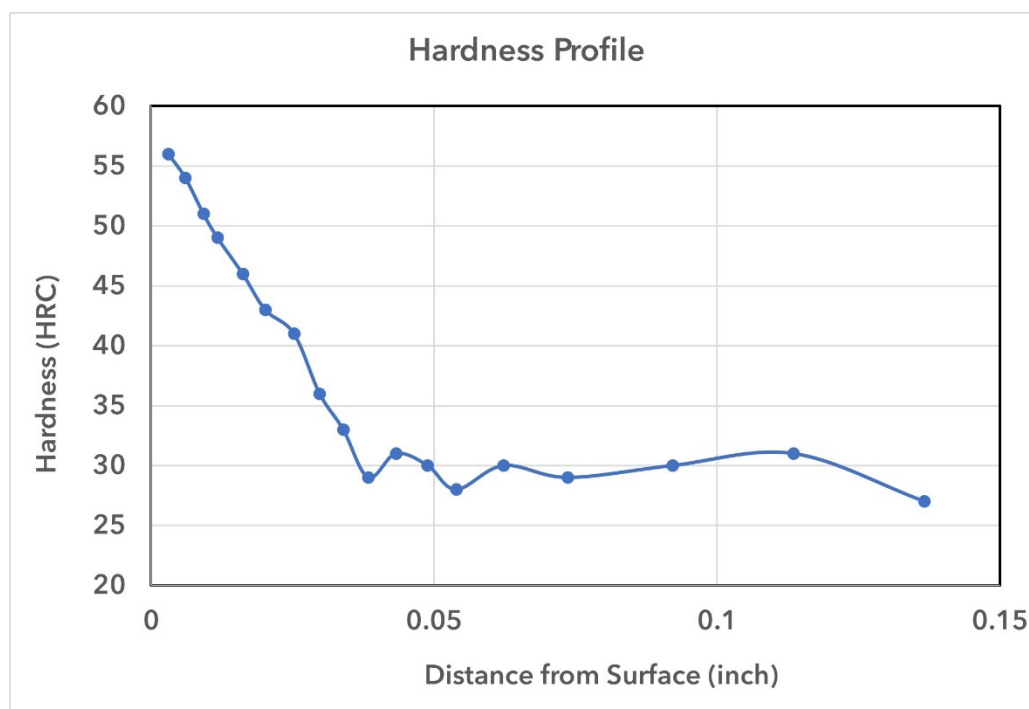


Figure 31. Hardness profile measured from the journal surface on the cross-section through the number 5 connecting rod journal.

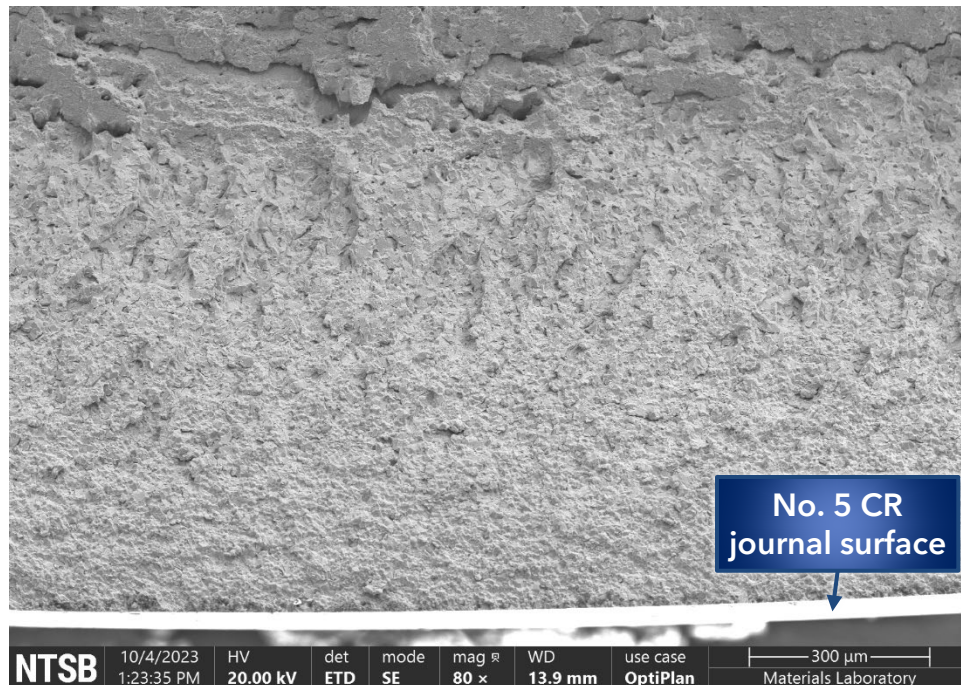


Figure 32. Lab-induced overstress fracture features adjacent to the number 5 connecting rod journal surface.

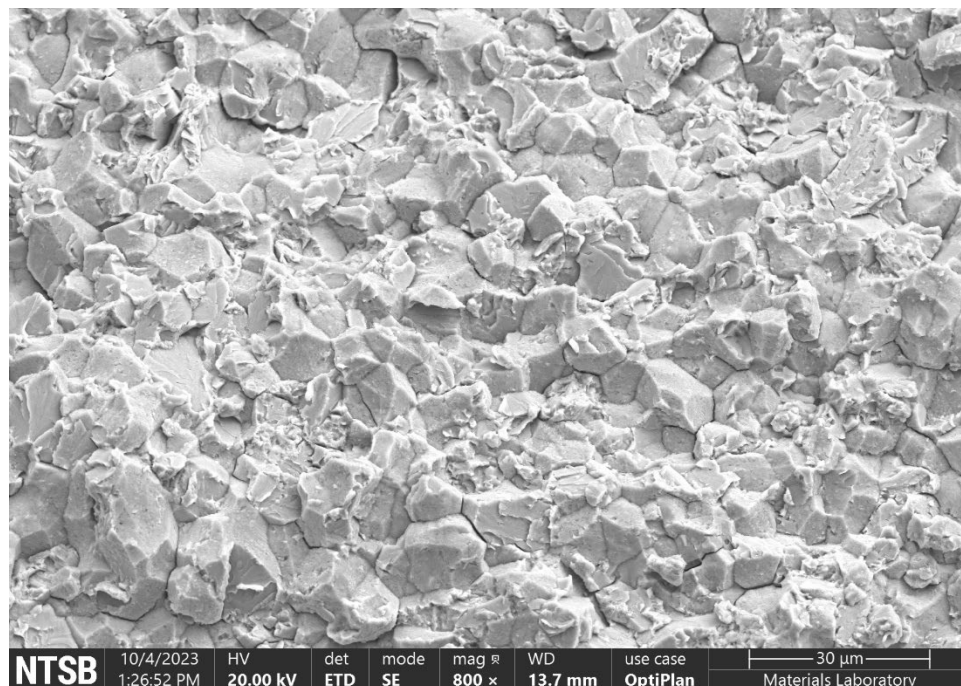


Figure 33. Intergranular fracture features on the lab-induced overstress fracture surface observed within 0.015 inch of the number 5 connecting rod journal surface.

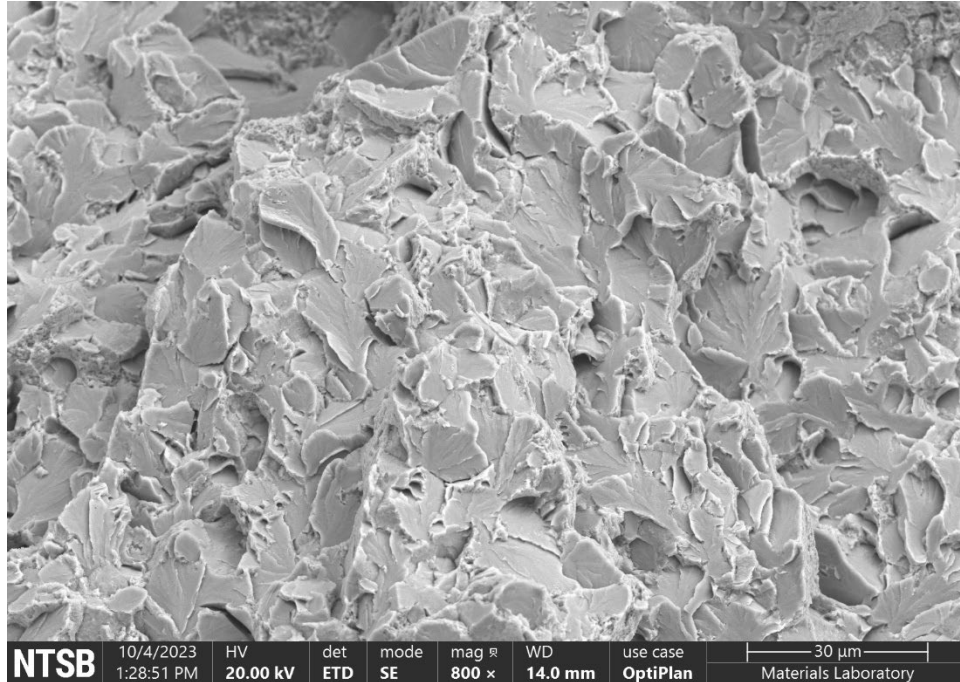


Figure 34. Transgranular cleavage fracture features on the lab-induced overstress fracture surface observed between 0.015 inch and 0.030 inch of the number 5 connecting rod journal surface.



Figure 35. Oil screen and debris recovered from the oil screen (on the green cloth on the left) and debris recovered from the oil sump (on the red cloth on the right). The front seal and intact magneto bumpers are also shown above the green cloth.