

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



ERA23LA293

MATERIALS LABORATORY

Factual Report 24-030

July 5, 2024

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A. ACCIDENT INFORMATION

Location: Waldorf, Maryland
Date: July 9, 2023
Vehicle: Hughes 369D, N5027P
Investigator: Chihoon Shin, AS-40

B. COMPONENTS EXAMINED

Overrunning clutch assembly part number 369A5350-605

C. EXAMINATION PARTICIPANTS

Specialist Matthew R. Fox, Ph.D.
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Engineering Technician Edward Komarnicki
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Washington, DC

D. DETAILS OF THE EXAMINATION

An overall view of the submitted overrunning clutch subassembly and housing are shown in figure 1. The clutch outer race was fractured near the forward end of the hollow shaft portion of the outer race, and the splined input end of the shaft was separated from the rest of the clutch subassembly. The clutch inner race was intact at the output end of the clutch subassembly. The nut appeared tight against the outer race, and crimps in the lock washer were in place in the respective grooves in the nut and outer race.

Markings on the clutch outer race read "369A5352-5 REV K S/N 5304-0945 Heat Lot No. 250963 M NE", consistent with the clutch outer race for the part number 369A5350-51 overrunning clutch subassembly. The clutch outer race is made of alloy 9310 steel. As manufactured, the input shaft splines and the sprag raceway on the clutch outer race are hardened by carburization while the remainder of the surfaces are plated with copper to mask the surfaces from the carburization treatment. At the end of the carburization treatment, the clutch outer race is quenched and tempered to a core hardness of 39 to 41 HRC, and the surfaces are stripped of the copper plating. Next the outer race is inspected with an acid etch inspection quickly followed by an 8-hour oven bake. The part is subsequently inspected by magnetic

particle inspection (MPI). Next, the outer race is then balanced by removing material adjacent to the locking washer as needed, and then the outer race receives another MPI. Finally, the part receives a black oxide treatment that is followed by another oven bake if the part is pickled in the process.

The accident clutch outer race was delivered new to MD Helicopters in March 2017. The clutch outer race had passed MPIs for cracks when new and during the last overrunning clutch subassembly overhaul that had been conducted on June 19, 2021. The overhaul record listed three bearings and seals that were replaced, but the sprag assembly was not included in the replaced parts list. The time in service since new (TSN) for the clutch outer race at the time of the overhaul was not recorded in the available maintenance records.

The accident overrunning clutch assembly had been removed from another helicopter in February 2023 to accomplish Airworthiness Directive (AD) 90-19-02. For helicopters with a hook installed, AD 90-19-02 requires disassembly of the overrunning clutch subassembly to inspect the condition of the clutch inner race, clutch outer race, and sprag assembly at 300-hour intervals with replacement of the sprag assembly at 1,800 hours TSN. A non-routine work card for the accident helicopter dated June 9, 2023, indicated the accident overrunning clutch subassembly was installed on the accident helicopter with 1,199.4 hours TSN on the sprag assembly. At the time of the accident, the overrunning clutch had accumulated an additional 22 hours time in service since installation on the accident helicopter following the AD inspection. During operation, the overrunning clutch outer race rotates at approximately 6,200 rpm.

An overall view of the forward side of the clutch outer race fracture is shown in figure 2. A portion of the fracture surface had relatively smooth fracture features with curving crack arrest lines, features consistent with fatigue fracture. Unlabeled arrows in figure 2 indicate the overall direction of the fatigue crack growth counterclockwise (as viewed looking forward unless otherwise specified) around the shaft wall. Fatigue fracture features emanated from the fillet area where the forward end of the shaft transitioned to a shoulder on the larger-diameter portion of the outer race. The fatigue features showed propagation through the thickness at the forward end of the exposed fracture surface as shown in figure 3 and propagated aft as the crack propagated counterclockwise, forming a spiral orientation to the fracture consistent with fatigue fracture under torsion loading. At the aft end of the spiral, the fracture transitioned to a nearly circumferential fracture with rubbing damage and twisting deformation consistent with ductile overstress fracture of the remaining ligament under torsion loading.

A circumferential crack was observed in the fillet radius as shown in figure 4 extending clockwise around approximately 40 percent of the circumference from the exposed fracture surface. The fillet radius forward of the spiral portion of the fracture is shown in figure 5. The surface had an etched appearance with circumferential

scratches that disturbed the surface finish. However, the circumferential crack to the clockwise side of the spiral fracture was not associated with the observed scratches. A backlit image of the intact portion of the fillet radius is shown in figure 6 showing a smooth radius of curvature.

To facilitate further examination of the overrunning clutch subassembly and fractured clutch outer race, the subassembly was disassembled as shown in figure 7, where the labeled parts are displayed in their relative positions in the assembly. The clutch outer race was then cleaned using an ultrasonic cleaner while submerged in a beaker of acetone. Views of the interior surfaces of the outer race after cleaning are shown in figures 8 and 9. Wave washer contact marks were observed at the forward end of the interior cavity as indicated in figure 8. The shoulder associated with contact with the sprag cage is also indicated. The sprag cage contact face had a slightly rubbed surface appearance, and part markings on the aft side of the sprag cage were observed transferred to the corresponding shoulder on the clutch outer race. The part markings were repeated at multiple locations around the circumference consistent with relative rotation between the sprag cage and the clutch outer race.

Sprag element contact marks were observed on the sprag raceway on the clutch outer race as shown in figure 9. The ends of the sprag element contact marks varied in axial position. Additionally, some marks were observed angled relative to the longitudinal axis. Unlabeled arrows in figure 9 indicate several sprag contact marks that were angled relative to the longitudinal axis.

The wave washer had markings at the wave peaks corresponding to contact with the clutch outer race on the aft side of the washer and with the aft sprag bearing on the forward side of the washer. On the forward side of the washer shown in figure 10, multiple distinct contact marks were observed at each contact location corresponding to contact with the inside diameter edge of the aft sprag bearing outer race.

The aft end of the clutch inner race with attached aft sprag bearing and sprag assembly is shown at the right in figure 10. The aft sprag bearing outer race had markings that read "FAFNIR MS8K C2" on the aft face and "369A5363B" on the outside diameter. The sprag assembly cage was marked "CL7605-81-5 2639" followed by a circled M symbol on the aft side and "369D25351-E FORMSPRAG USA CL42315 S/N 9870" with an arrow between the E and F pointing toward the F on the forward side. Rub marks corresponding to contact with the inside diameter edge of the wave washer were observed on the aft sprag bearing cage as indicated in the right image in figure 10.

The width of the sprag assembly cage was 0.8665 inch, which conforms to the maximum cage width as reported by a representative for the sprag assembly manufacturer. The same representative also reported the manufacture completion

date for the Formsprag part number CL42315 sprag assembly with serial number 9870 was February 8, 2019.

The forward sprag bearing was marked "2770 MRC R20 Japan" on the aft side of the outer race. As installed on the inner race, a gap was observed between the aft side of the forward bearing and the adjacent shoulder on the inner race as shown in figure 11. The gap measured approximately 0.040 inch.

The inner race, sprag, and bearing assembly was mounted vertically on a measuring table, and the total length between the aft face of the aft sprag bearing to the forward face of the forward sprag bearing was measured at 7 locations around the circumference using a digital height caliper. The overall length between the bearing faces measured between 1.728 inches and 1.730 inches. The width of the forward sprag bearing was 0.375 inch, and the thickness of the ring spacer was 0.620 inch.

Selected dimensional measurements were taken on the clutch outer race and compared to the engineering drawing. At the location of the aft sprag bearing, the inside diameter measured 1.6254 inches, and the diameter of the sprag raceway measured 2.1557 inches; both were within drawing specifications. The length of the sprag raceway was 0.8805 inch, and the length from the shoulder for the ring spacer to the shoulder for the wave washer was 1.311 inches, also within drawing specifications. The outside diameter of the input shaft on the clutch outer race measured 1.125 inches, which was consistent with the engineering drawing. The inside diameter of the input shaft measured 0.9361 inch, which was below the specified diameter of 0.938 inch.

The clutch outer race was sectioned using water-cooled abrasive saws to facilitate a more detailed examination of fracture features. After sectioning, the inner race with attached bearings and sprag assembly were placed in the sectioned clutch outer race as shown in figure 12. Based on measurements of the length of the sprag raceway on the clutch outer race and the length of the sprag assembly cage, the combined total gap on each side of the sprag assembly was 0.014 inch with the ring spacer tight against the corresponding shoulder on the clutch outer race. At the aft face of the aft sprag bearing, the gap for the wave washer was calculated to be 0.018 inch to 0.020 inch. The thickness of the wave washer was 0.0160 inch.

Multiple cuts were made through the clutch to reveal fracture features for examination. Several longitudinal cuts were made with water-cooled abrasive saws, and then handheld metal hacksaws, jeweler's saws, and files were used to make wedge-shaped backcuts into the wall toward the circumferential crack tip on each piece. The pieces containing the cracks were then bent and pinched as needed in a vice and with pliers to facilitate the opening of the cracks. A view of the clutch outer race after lab fractures were completed is shown in figure 13.

An overall view of the circumferential crack that was opened by lab-induced fractures is shown in figure 14. A portion of the crack had relatively dark features emanating from a broad origin area near the middle of the circumferential crack region. An unlabeled bracket in figure 14 indicates the approximate origin area. The fatigue features in the spiral fracture portion of the fracture shown in figures 2 and 3 emanated directly from the counterclockwise end of the exposed circumferential crack.

Closer views of the circumferential crack features are shown in figure 15. The fracture surface had a flat region oriented perpendicular to the fillet surface extending into the outer race to the boundary indicated with a dashed blue line. The fracture surface showed signs of progressive fracture consistent with fatigue. A portion of the fracture was relatively dark covering most of the fatigue region in the upper image and a lesser portion of the fatigue region toward the clockwise end of the crack. Unlabeled arrows in figure 15 indicate local fatigue crack propagation directions, which emanated from a broad origin area as indicated with unlabeled brackets on either side of a longitudinal cut made to facilitate the lab-induced fractures.

A closer view of crack fracture features at the clockwise end of the fatigue origin area is shown in the lower image in figure 15. Adjacent to the external surface, the fracture surface had a rock candy appearance consistent with intergranular fracture features. Yellow dashed lines in figure 15 indicate the extent of the observed intergranular fracture features.

The fracture surface shown in the middle image in figure 15 was cleaned using an ultrasonic cleaner while submerged in acetone. The fracture surface was then examined using a scanning electron microscope (SEM). An SEM image of the fracture surface at the clockwise end of the origin area is shown in figure 16. Intergranular fracture features were observed adjacent to the exterior surface as shown in figure 17 extending up to 0.00921 inch (234 micrometers) deep. The fracture then transitioned to a flat transgranular fracture with feathery features typical of high-cycle fatigue in steel.

Deposits of nonconductive material that appeared relatively dark in at low magnification and showed charging effects at higher magnifications¹ were observed across the surface near the origin area, including low points in the fracture surface between grains in the intergranular region and scattered across the transgranular fracture surface mostly within 0.04 inch (1 mm) of the external surface. The deposits were analyzed using energy dispersive x-ray spectroscopy (EDS) with the electron

¹ Imaging contrast in the SEM can be affected by atomic weight, where materials composed of elements with lower atomic weight appear relatively darker than those having elements with higher atomic weight. Charging is the accumulation of negative charge on the surface that develops during electron imaging of nonconductive samples in a SEM under high vacuum and can result in distorted and overexposed images.

beam energy set at 10 kV. The upper image in figure 18 shows a typical EDS spectrum for the dark deposits showing high peaks of carbon and oxygen with smaller peaks of elements commonly associated with additives used in grease. For comparison, an EDS spectrum obtained in the lab-induced overstress region of the fracture surface is shown in the lower image in figure 18.

Typical intergranular fracture features in the origin area of the circumferential crack adjacent to the exterior surface are shown in figure 19. Within 2 to 3 grains of the surface, the microstructural features of the individual grains were revealed on the fracture surface. While visible using the secondary electron detector that primarily reveals fracture topography (upper image in figure 19), the microstructural features became more visible when viewed using the backscatter detector in composition mode (lower image in figure 19). When imaging with the backscatter detector in composition mode, materials with lower atomic weight appear darker than materials with higher atomic weight. As shown in figure 19, the microstructural features revealed on the grain surface were most evident on grains adjacent to the surface and were mostly absent from grains more than approximately 3 grains deep.

Another SEM image of the circumferential crack origin area showing intergranular fracture features adjacent to the exterior surface is shown in figure 20. Step features were observed on some of the exposed intergranular surfaces highlighted with rectangles in the upper image in figure 20 and shown at higher magnification in figures 20 and figure 21. Grain surfaces with similar step features were observed on intergranular fracture surfaces in other isolated areas scattered throughout the origin area.

Post-fracture contact damage consistent with relative motion associated with torsion loading was observed throughout the circumferential crack fracture surfaces. Sliding contact marks on several grains are indicated with unlabeled arrows in the upper image in figure 20, consistent with the mating aft side of the fracture moving clockwise relative to the forward side shown in figure 20.

A view of typical circumferential crack fracture features where the intergranular fracture transitioned to transgranular fracture is shown in figure 22. Another view of typical fracture features in the transgranular portion of the crack is shown in figure 23. The transgranular fracture features had feathery features with limited secondary crack openings consistent with high cycle fatigue. In the lab-induced overstress region, ductile dimple features were observed as shown in figure 24.

The intergranular features associated with the circumferential crack varied in depth and were discontinuous at the exterior surface. An SEM image of the fracture features adjacent to the exterior surface at the clockwise end of the origin area is shown in figure 25. Transgranular fatigue features emanating from the intergranular features at the right side of the image intersect the exterior surface and an adjacent region of intergranular fracture shown at the left side of the image. Further from the

origin near the clockwise end of the circumferential crack, the intergranular fracture features were limited to several grains deep or less (up to 0.0024 inch or 60 microns deep) as shown in figure 26. The image in figure 26 shows the clockwise end of the intergranular fracture features where fatigue fracture propagation extending clockwise from the intergranular region had transgranular fatigue fracture features intersecting the exterior surface.

In the process of opening the portion of the circumferential crack shown in the upper image in figure 15, the input shaft wall aft of the crack was bent to a curved shape. As the input shaft wall was bent, a series of parallel secondary cracks and microcracks opened on the exterior surface. The bent piece was cleaned with acetone, and the secondary cracks and microcracks were examined using the SEM. A series of secondary microcracks on the external surface of the bent input shaft piece at the forward end near the fillet are shown in figure 27. The microcracks had intergranular fracture paths along the surface. Some of the microcracks were gaped open, showing ductile deformation at the tip of the intergranular fracture features. A closer view of one of these opened microcracks is shown in figure 28. As shown in figure 28, the intergranular features typically extended 1 to 2 grains deep near the forward end of the shaft adjacent to the fillet. Cracks in the fillet area appeared to extend deeper, but the cracks were also not opened as wide to view the extent of cracking. Further aft on the shaft surface, the external surface had a more rippled appearance consistent with plastic deformation with intermittent areas of shallow intergranular microcracks.

The intact fillet radius on the clutch outer race forward of the spiral portion of the fracture was examined using the SEM. The fillet radius surface is shown in figure 29 as viewed using the secondary electron detector (upper image) and the backscattered electron detector in composition mode (lower image). Unlabeled arrows in figure 29 indicate the approximate circumferential plane associated with the circumferential crack on the opposite side of the clutch outer race. In the upper image, circumferential scratch marks are shown interrupting the surface texture, indicating they occurred after the overrunning clutch had been etched during the manufacturing process. The lower image shows slight variations in contrast appearing as a cell-like network of compositional difference likely associated with the black oxide treatment applied at manufacture. At higher magnification, a network of possible intergranular microcracks were observed on the surface as indicated with unlabeled arrows in figure 30. These possible microcrack features were observed to be most concentrated near the middle of the fillet radius.

A piece of the clutch outer race at the clockwise end of the origin area was sectioned to produce a metallurgical cross-section through the forward side of the circumferential crack and a portion of the clutch outer race forward of the crack. The sectioned piece was mounted, polished, and etched using a solution of concentrated nitric acid diluted in alcohol (2% nital). As shown in figures 31 and 32, the etched microstructure had an appearance consistent with tempered martensite with a similar

appearance adjacent to the external surface (figure 31) as in the core away from the surface (figure 32). The opened circumferential crack showed an intergranular fracture path extending from the external surface that appeared to follow the prior austenite grain boundaries. Some crack branching was observed as indicated, but the branching cracks were generally limited less than 2 grains from the main crack path. A secondary microcrack with limited branching and an intergranular fracture path extending approximately 2 grains deep in the polished plane was observed emanating from the external surface in the fillet area adjacent to the primary crack as shown in figure 31.

The metallographic sample shown in figure 31 was further examined using the SEM. Images of the typical etched microstructure are shown in figures 33 through 35 as imaged using the backscattered electron detector in composition mode. The microstructure adjacent to the exterior surface in the fillet region is shown in figure 33, and the microstructure adjacent to the surface further forward on the shoulder for the clutch outer race is shown in figure 34. Both areas had similar microstructural features, and both were similar to the microstructure deeper into the wall thickness adjacent to the circumferential crack surface where the crack had a transgranular fracture path as shown in figure 35.

A piece of the bent shaft wall that had the series of opened secondary cracks shown in figures 27 and 28 along with the aft side of the opened circumferential crack was mounted and polished for metallographic examination of the cross-section. A montage of optical images stitched to show an overall view of the surface aft of the opened circumferential crack is shown in the upper image in figure 36. As shown in the stitched image, a series of secondary cracks with intergranular fracture paths were observed at the exterior surface that generally extended deeper in the fillet radius and generally became shallower further aft on the shaft. As shown in the lower right image in figure 36, a secondary crack was observed extending up to 0.0083 inch deep adjacent to the opened circumferential crack. The secondary crack had a jagged fracture path consistent with intergranular fracture and showed crack branching that was generally limited to one grain away from the main crack path.

The lower left image in figure 36 shows secondary microcracks in the shaft portion of the clutch outer race just aft of the fillet radius. The microcracks were shallower (0.002 inch deep or less), appearing to extend approximately 1 to 2 grains deep, and many of the cracks were gaped open with blunt crack tips.

The as-polished metallographic sample shown in figure 36 was coated with a thin coating of gold palladium alloy to facilitate an SEM examination of the cracks at the surface in the fillet radius and along the shaft wall.² Images of two of the microcracks are shown in figure 37 and 38 as viewed using the backscatter electron

² The conductive coating was applied to eliminate charging effects from the nonconductive material used in the metallurgical mount.

detector in composition mode. The cracks had apparent intergranular fracture paths. At the surface, a thin coating with a relatively darker shade of gray was observed consistent with the black oxide layer applied during manufacturing of the clutch outer race. As indicated in the lower images in figures 37 and 38, the darker gray layer appeared to extend onto the crack surface with tapering thickness along the apparent grain boundary for the first grain. In many of the microcracks, dark microcrack-like features extended from the grain boundary into the grains in the first two grains from the surface. These dark branching microcrack-like features appeared to correspond to the dark microstructural features observed on the grain surfaces as shown in figure 19. When analyzed using EDS in spot mode, the dark branching microcrack-like features had a relatively high peak of oxygen when compared to the adjacent areas of the grain cross-section.

Several EDS spectra were obtained from areas at the tip of one of the microcracks. When acquiring the EDS spectra, the SEM beam was set to spot mode with the spot aimed in the microcrack near the crack tip. The resulting spectra were compared to a baseline spectrum obtained deeper in the cross-section away from the surface. A comparison of the EDS spectra is shown in figure 39. The EDS spectra obtained in the microcrack showed elevated peaks of oxygen compared to the baseline spectrum. Peaks for the remaining elements were similar to the baseline spectrum.

Core hardness measurements were conducted on the mounted and polished cross-section through the clutch outer race with the forward side of the circumferential crack. Superficial Rockwell hardness measurements were taken near the middle of the wall thickness in the shoulder adjacent to the input shaft section, along the wall next to the forward sprag bearing, and in the wall forming the sprag outer race. The average core hardness was 39.7 HRC (59.3 HR30N), which is within the core hardness range specified for the clutch outer race.

Submitted by:

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

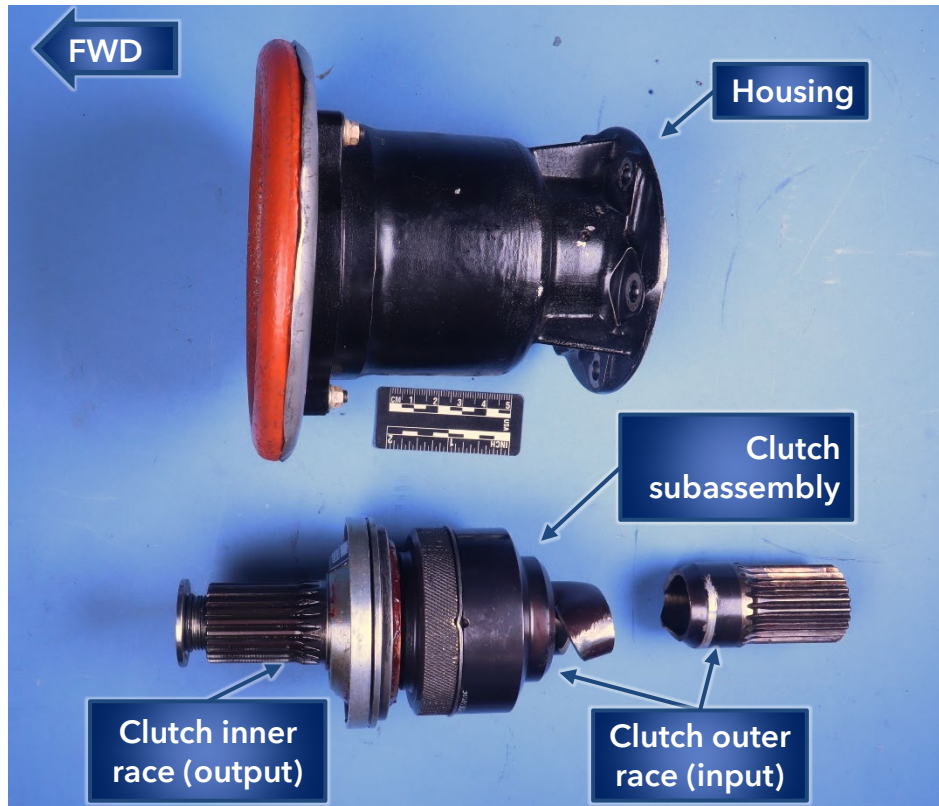


Figure 1. Overall view of the submitted overrunning clutch assembly as received.



Figure 2. Visible portion of the forward side of the fracture surface in the clutch outer race. Unlabeled arrows next to the fracture surface indicate the direction of fatigue propagation on the spiral portion of the fracture.

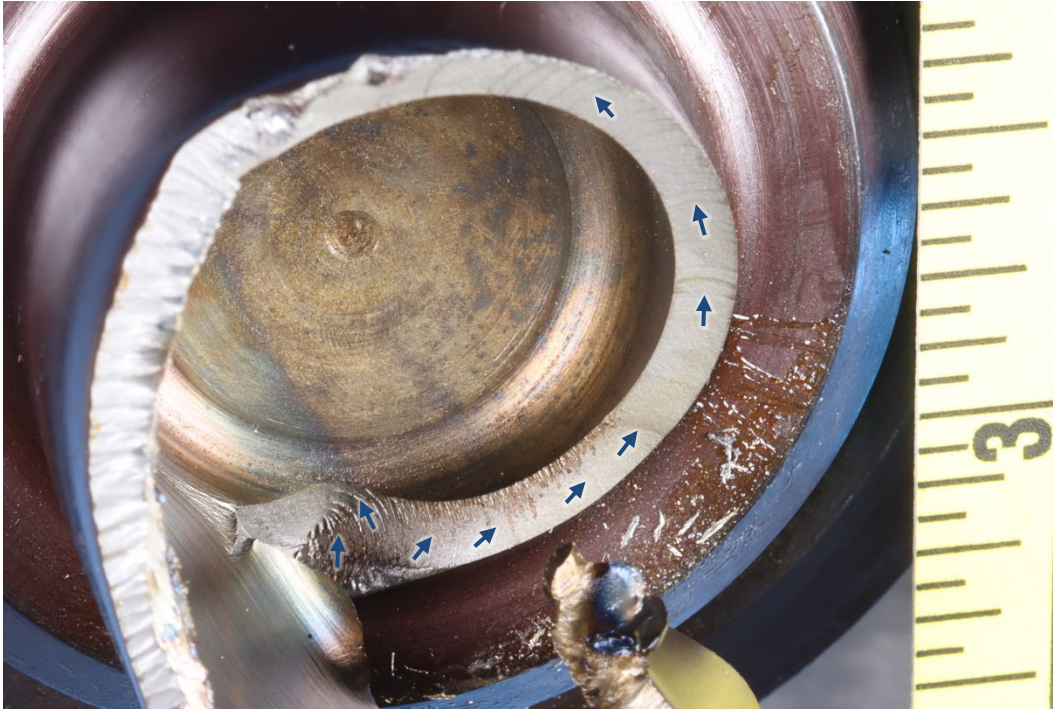


Figure 3. Another view of the visible portion of the fracture in the clutch outer race. Unlabeled arrows indicate local fatigue propagation directions.

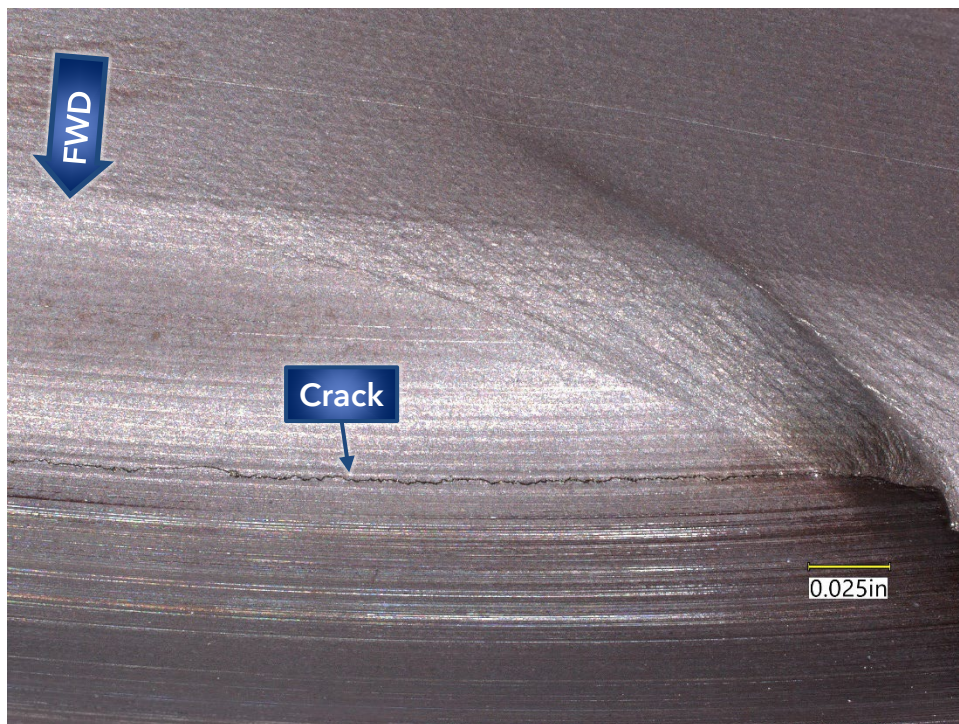


Figure 4. Crack in the fillet radius between the clutch outer race shaft and adjacent shoulder. The crack intersects the visible portion of the fracture at the right side of the image.



Figure 5. Intact fillet radius between the input shaft and adjacent shoulder on the clutch outer race forward of the spiral portion of the fracture.

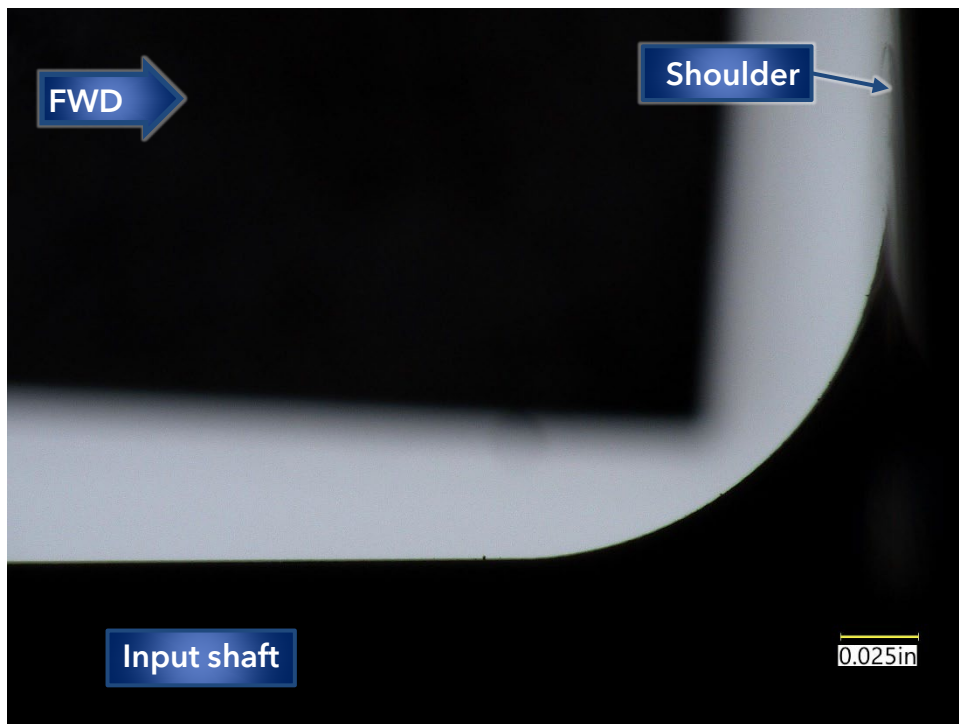


Figure 6. Backlit image of the clutch outer race showing the fillet radius between the input shaft and the adjacent shoulder.



Figure 7. Disassembled pieces of the overrunning clutch subassembly.

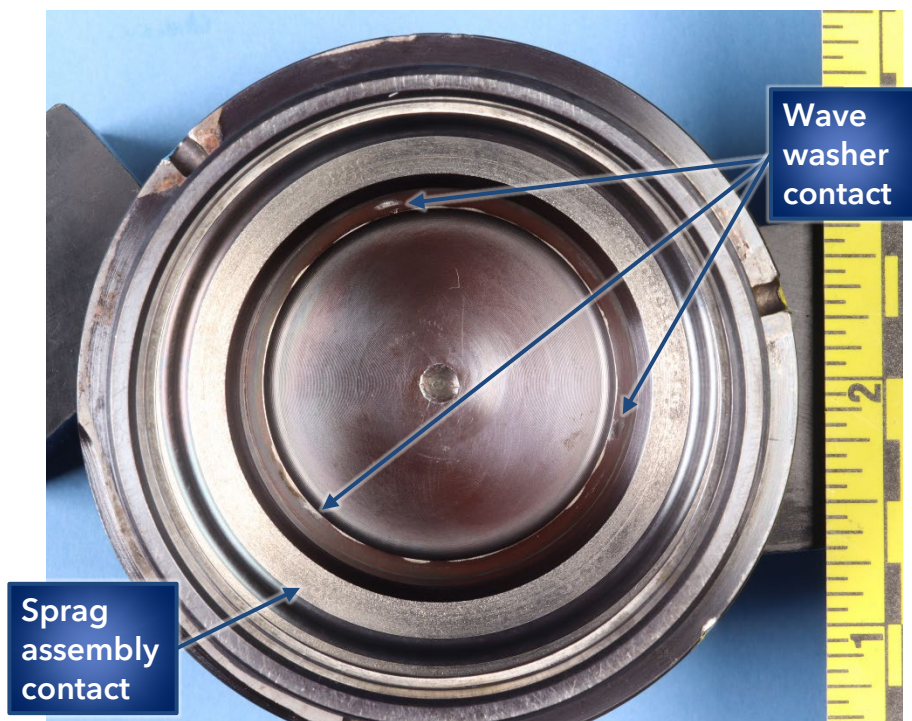


Figure 8. Forward side of the clutch outer race showing wave washer contact areas and marks from contact with the aft face of the sprag assembly.



Figure 9. Sprag element contact marks on the clutch outer race. Unlabeled arrows point to several off-axis sprag element contact marks.

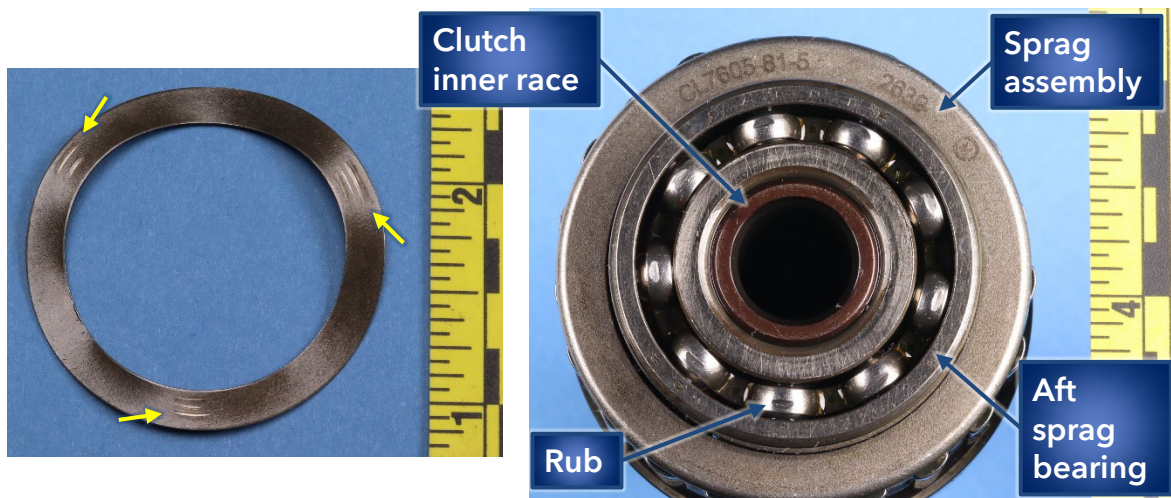


Figure 10. Forward face of the wave washer (left image) and aft end of the clutch inner race with attached sprag assembly and aft sprag bearing (right image). Unlabeled arrows in the left image point to circumferential contact marks corresponding to contact with the aft sprag bearing outer race.

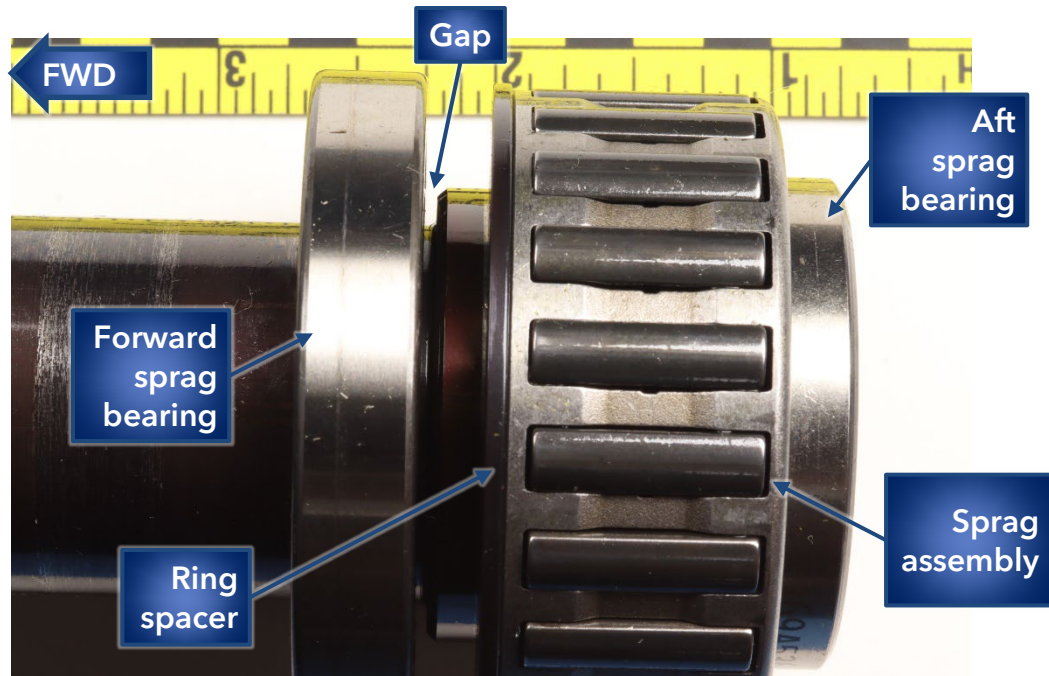


Figure 11. Side view of the clutch inner race, sprag assembly, and sprag bearings showing a gap between the forward sprag bearing and adjacent shoulder for the sprag inner race.

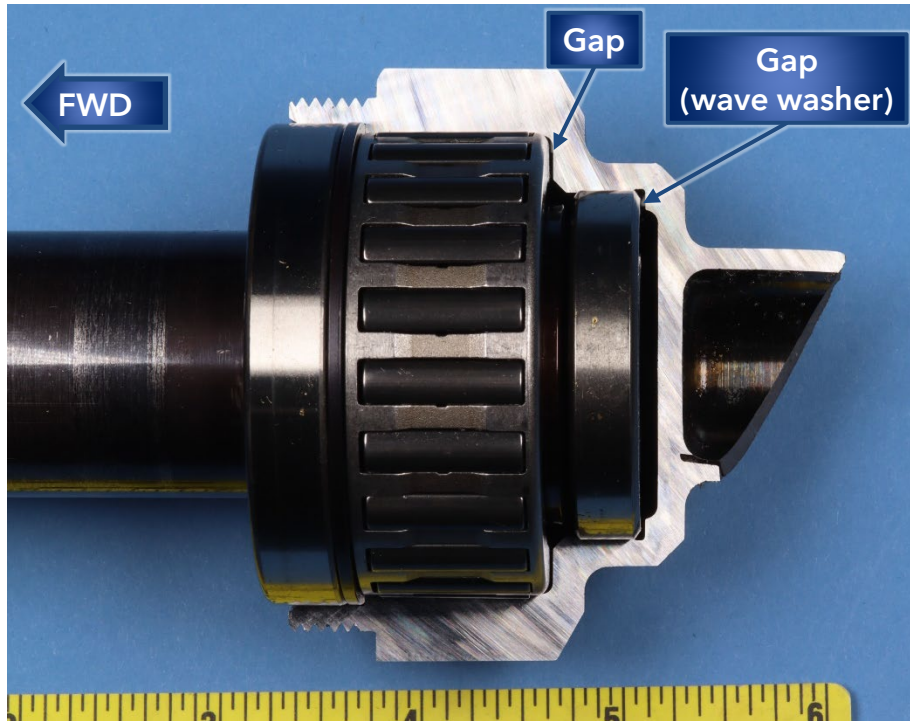


Figure 12. View of the clutch inner race and attached sprag assembly and sprag bearings positioned in the sectioned clutch outer race.

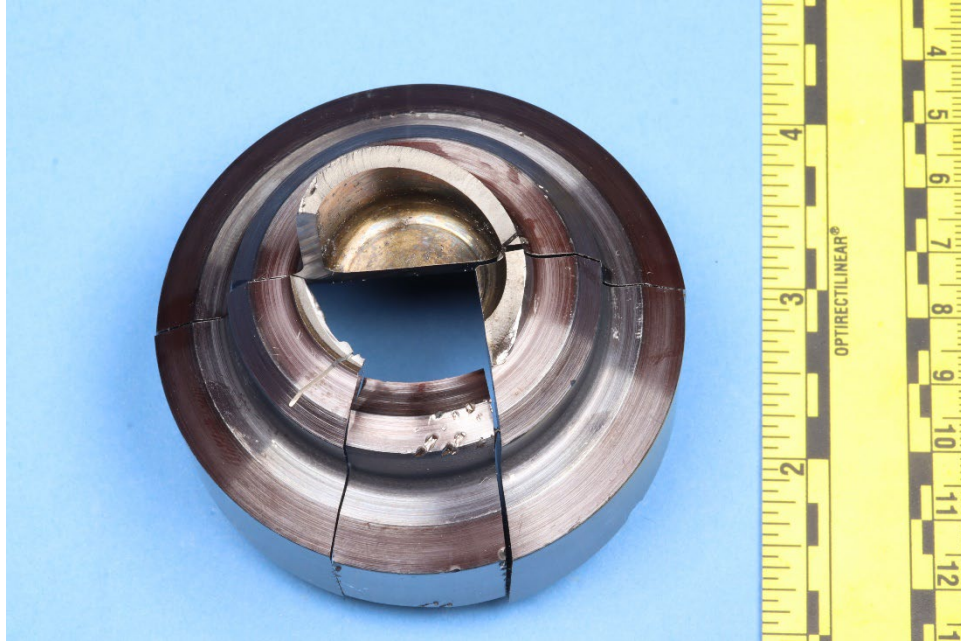


Figure 13. Clutch outer race after sectioning and subsequent lab-induced fractures to open the circumferential crack in the fillet radius.

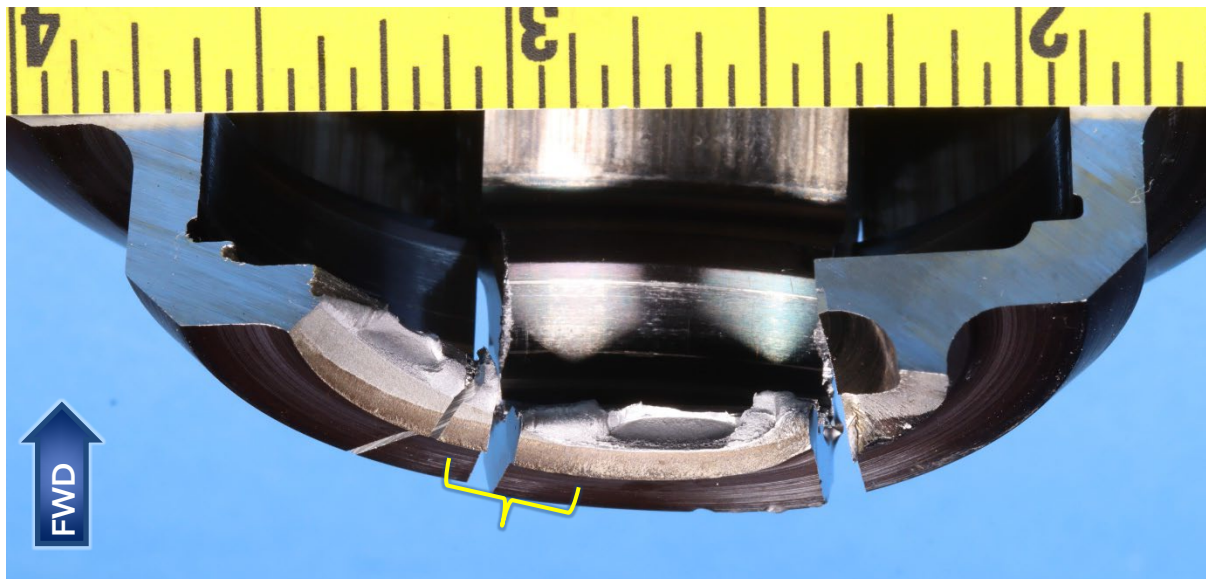


Figure 14. Overall view of the fatigue origin area after lab fracture of the circumferential crack. A bracket indicates the approximate fatigue origin area.

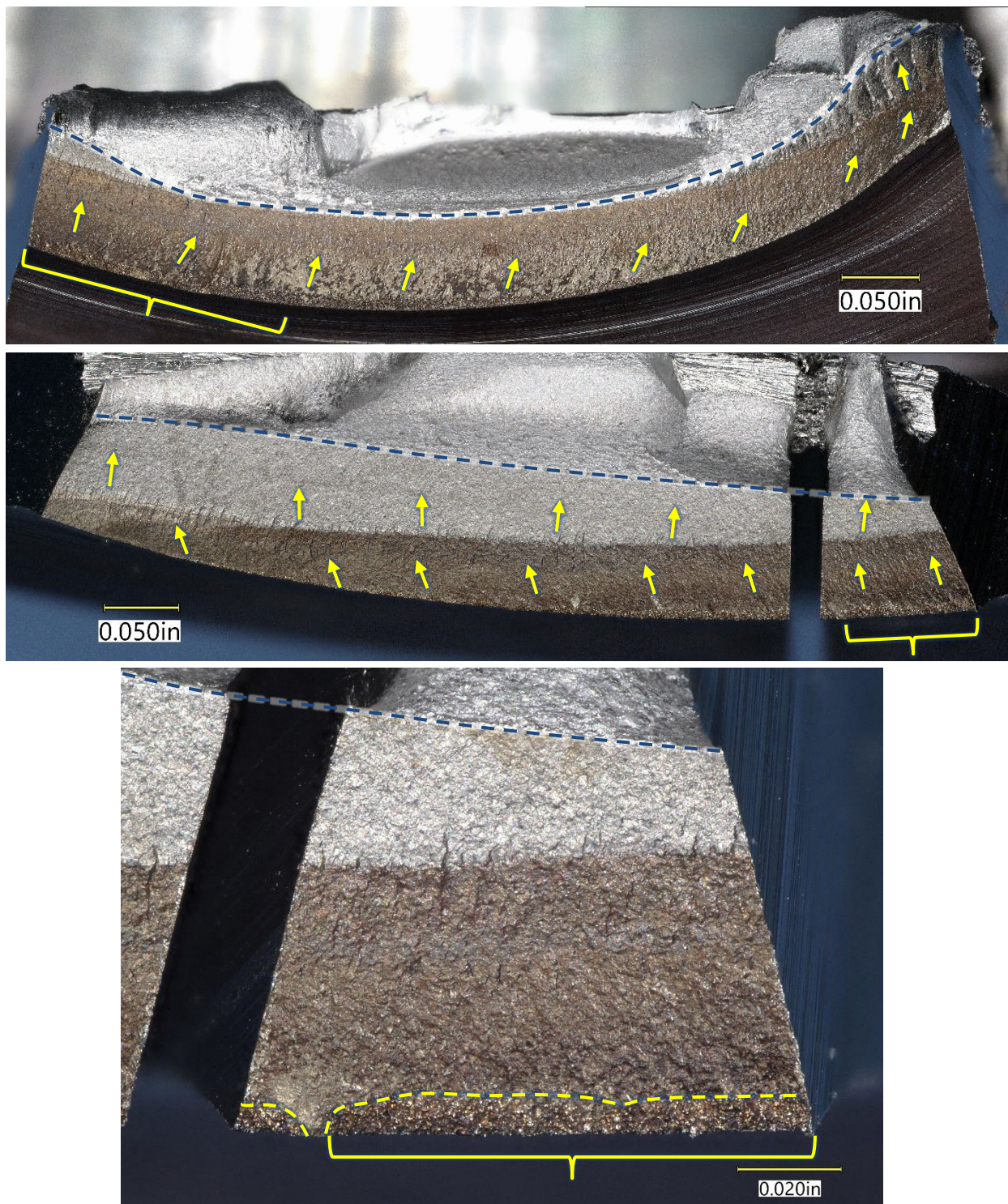


Figure 15. Optical images of the circumferential crack after opening (upper and middle images) with a closer view of the fatigue region near the origin area at the left side of the middle image. Blue dashed lines indicate the fatigue boundary, yellow dashed lines indicate the transition from intergranular to transgranular fracture. Unlabeled arrows indicate local fracture propagation directions, and brackets indicate approximate fatigue origin areas.

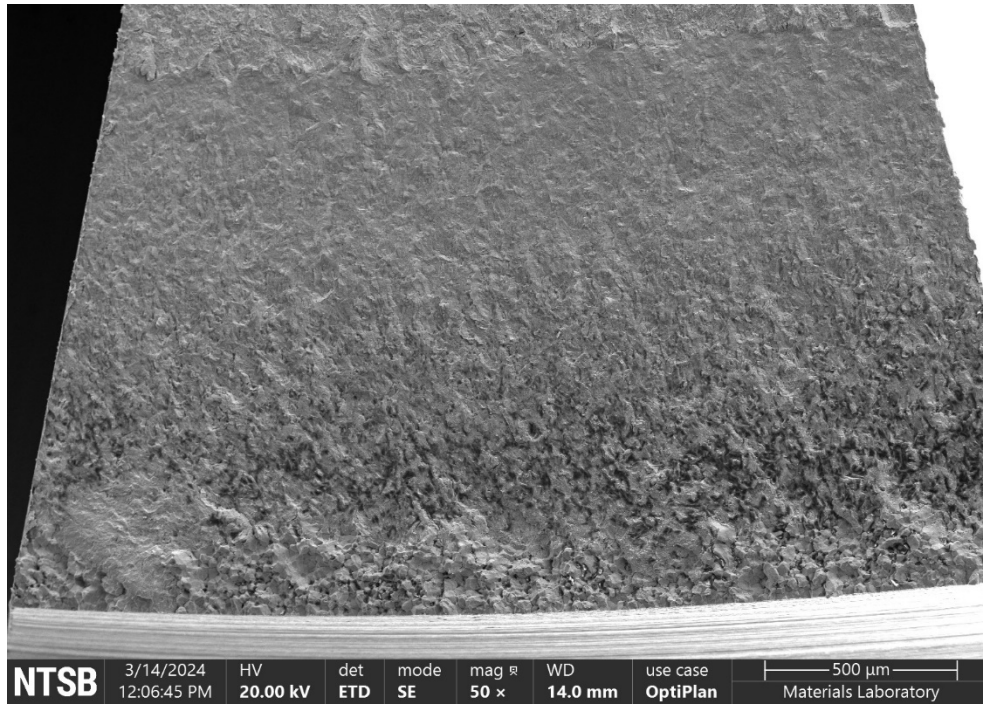


Figure 16. SEM image of the fatigue region shown in the lower image in the previous figure.

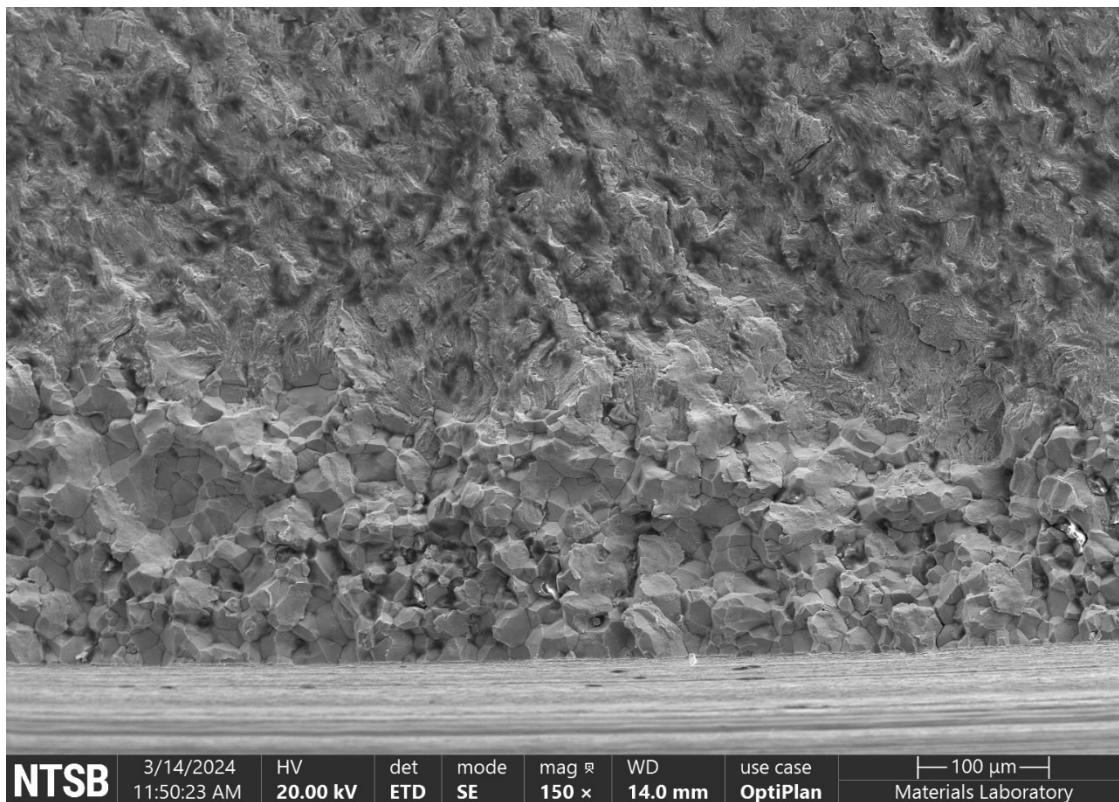


Figure 17. SEM image of the intergranular fracture region near the exterior surface in the fatigue origin area.

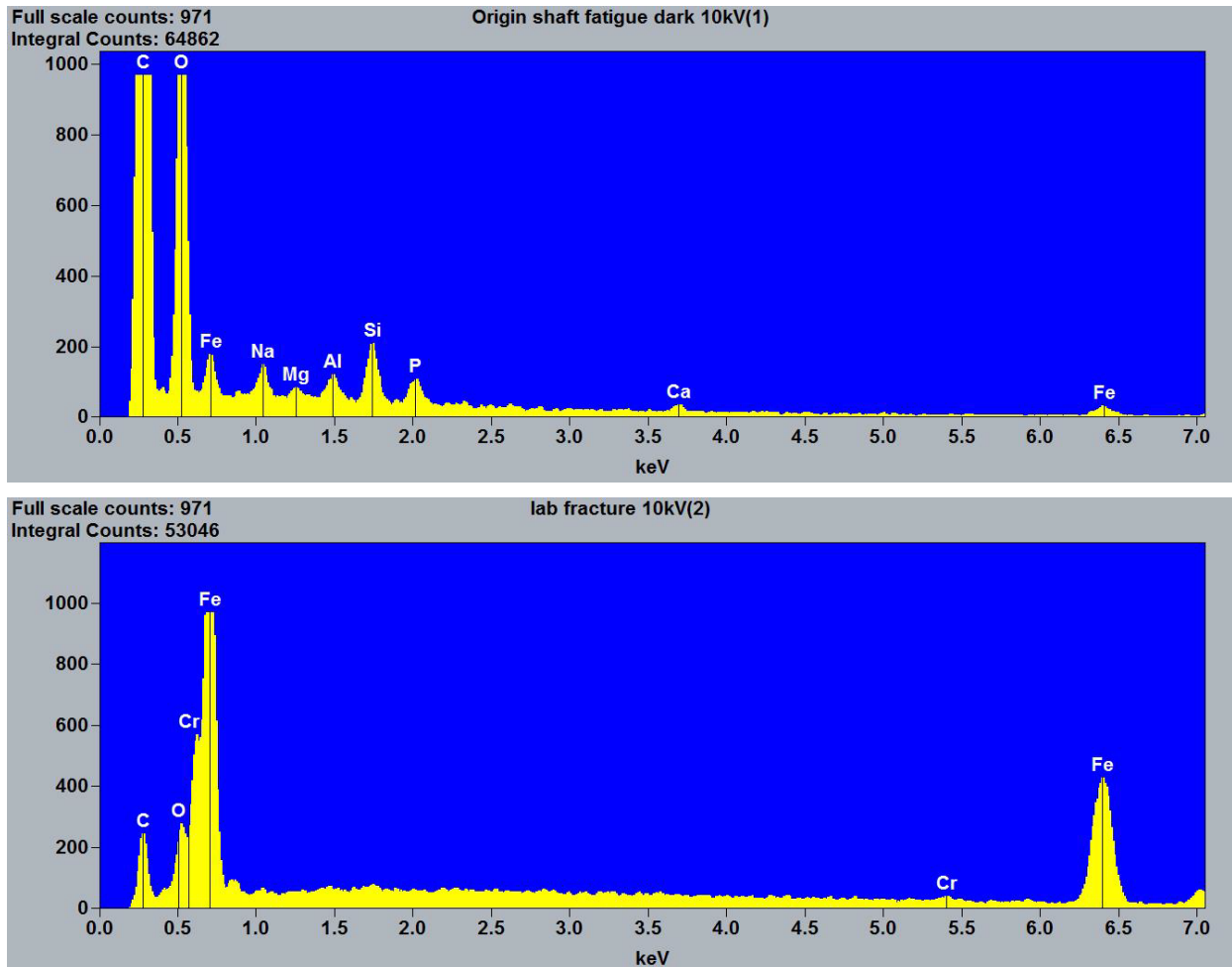


Figure 18. EDS spectra of dark non-conductive deposits on the fracture surface (upper spectrum) and of fracture features in the lab-induced overstress fracture region (lower spectrum) obtained with a 10 kV electron beam energy setting.

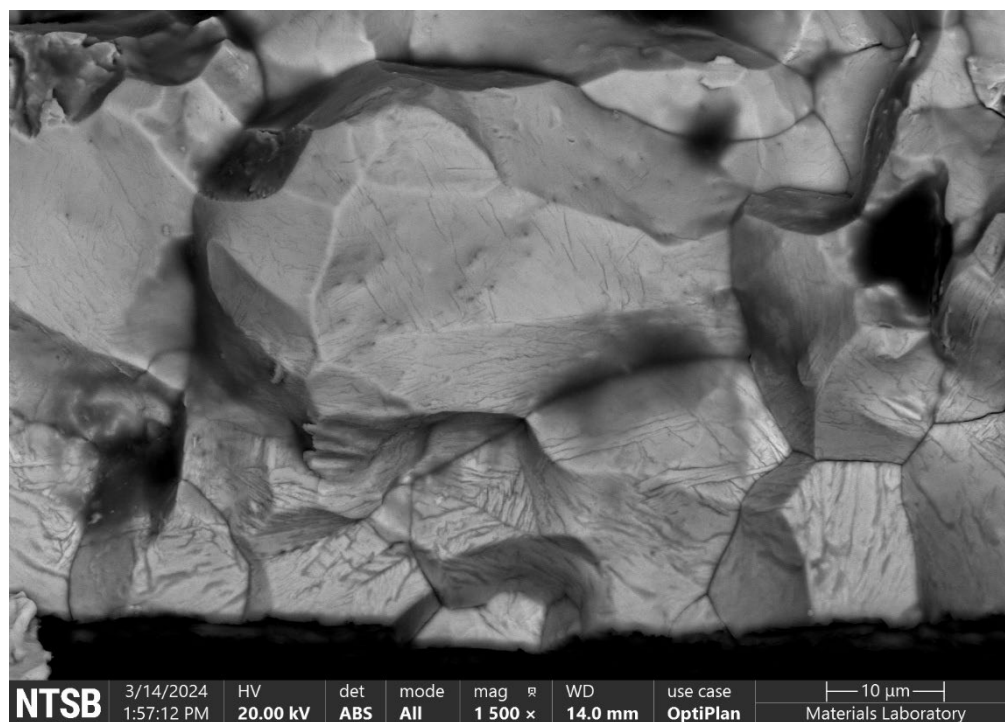
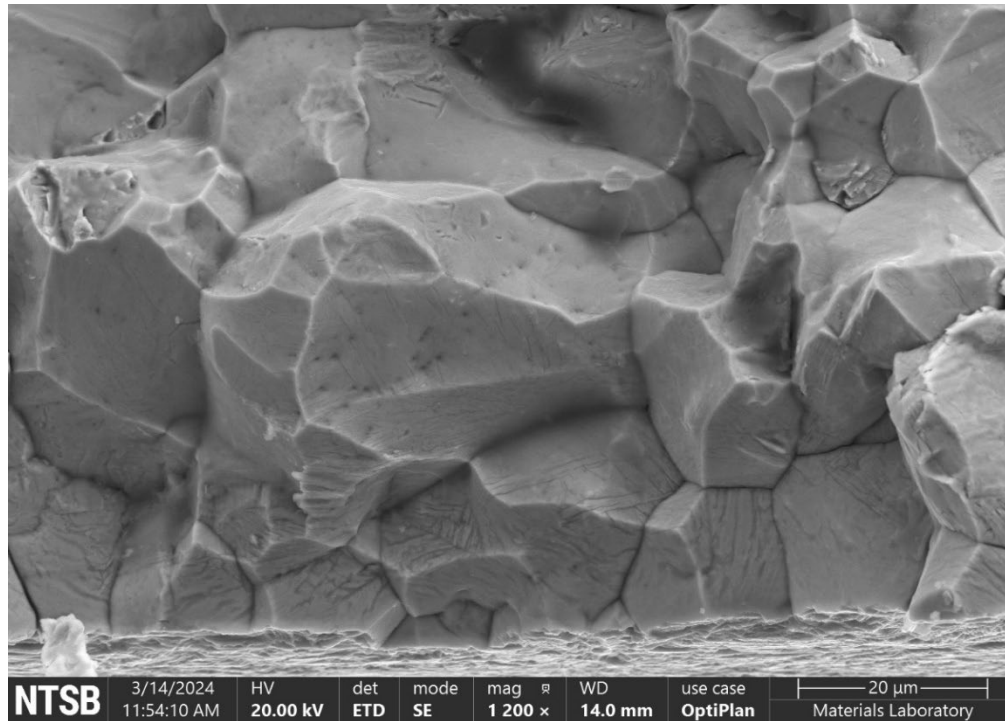


Figure 19. SEM images of typical intergranular fracture features adjacent to the exterior surface as viewed using the secondary electron detector (upper image) and the backscattered electron detector in composition mode (lower image).

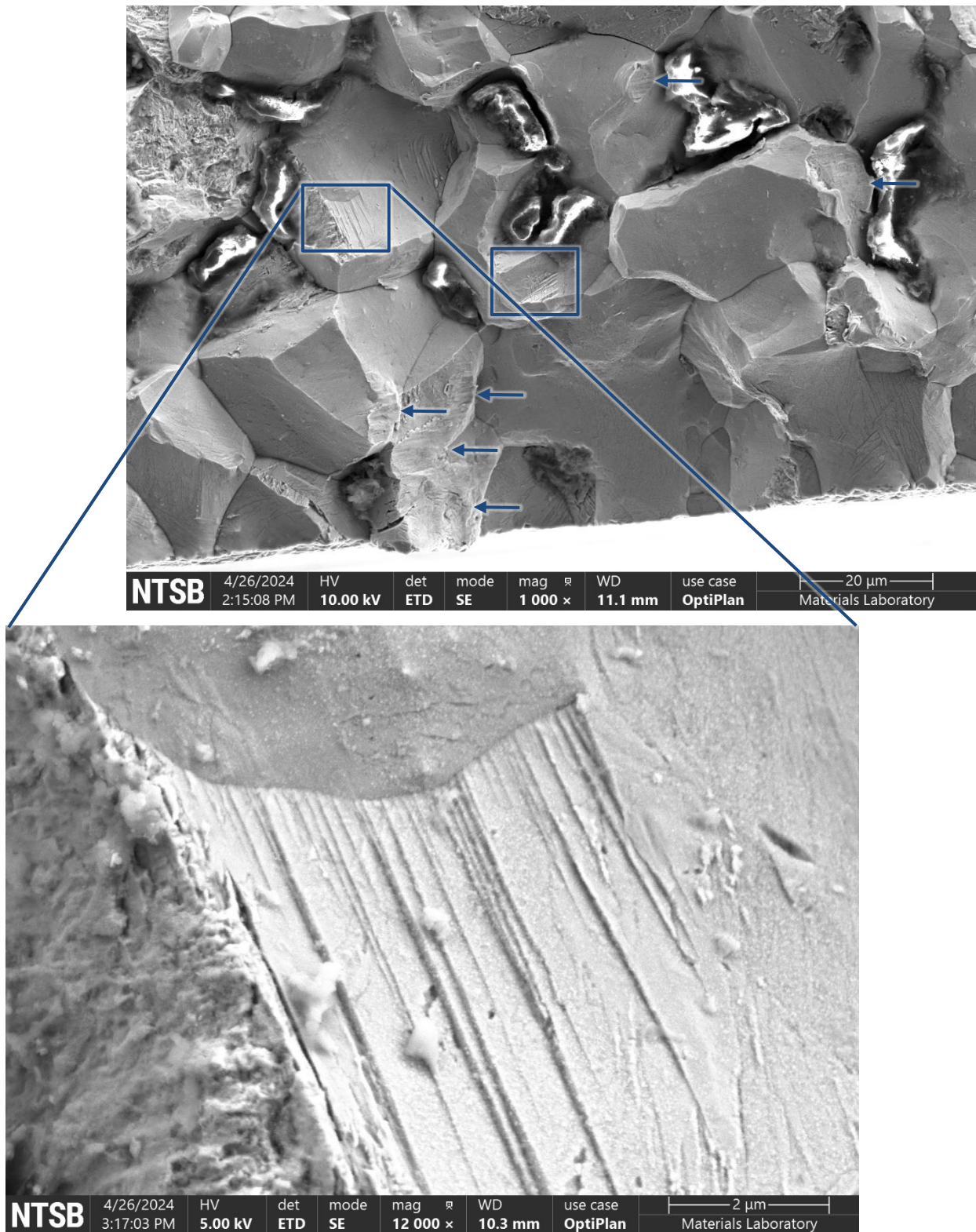


Figure 20. Intergranular fracture surface adjacent to the exterior surface (upper image) showing areas with crystallographic step features magnified in the lower image of this figure and in the next figure. Unlabeled arrows in the upper image point to sliding contact damage from the mating fracture surface.

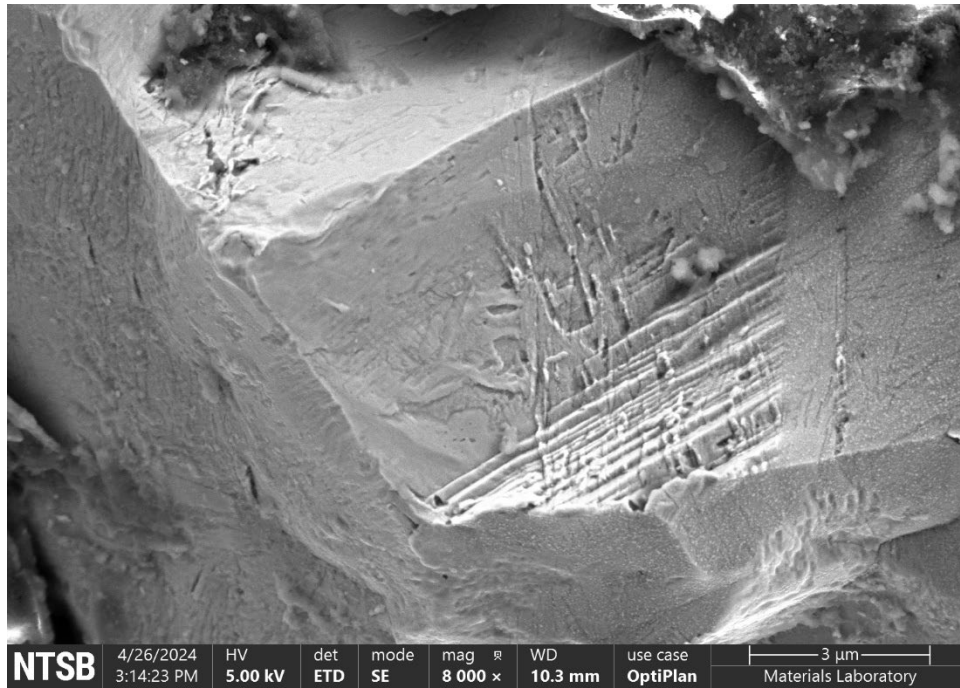


Figure 21. Crystallographic step features on the intergranular fracture surface in the area indicated in the previous image.

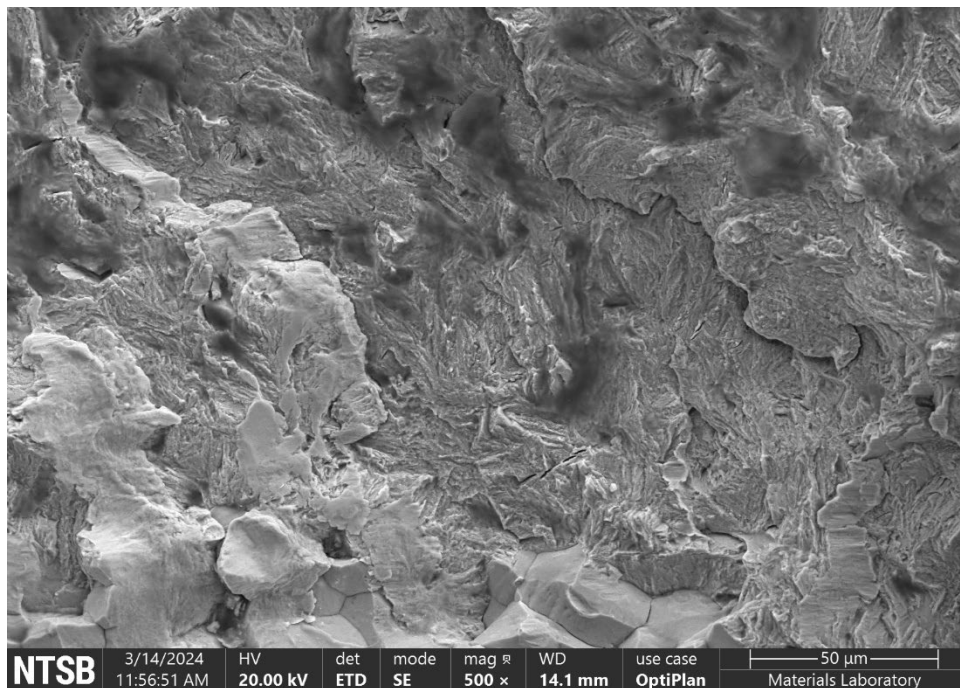


Figure 22. SEM image of typical fracture features at the transition from intergranular to transgranular fracture.

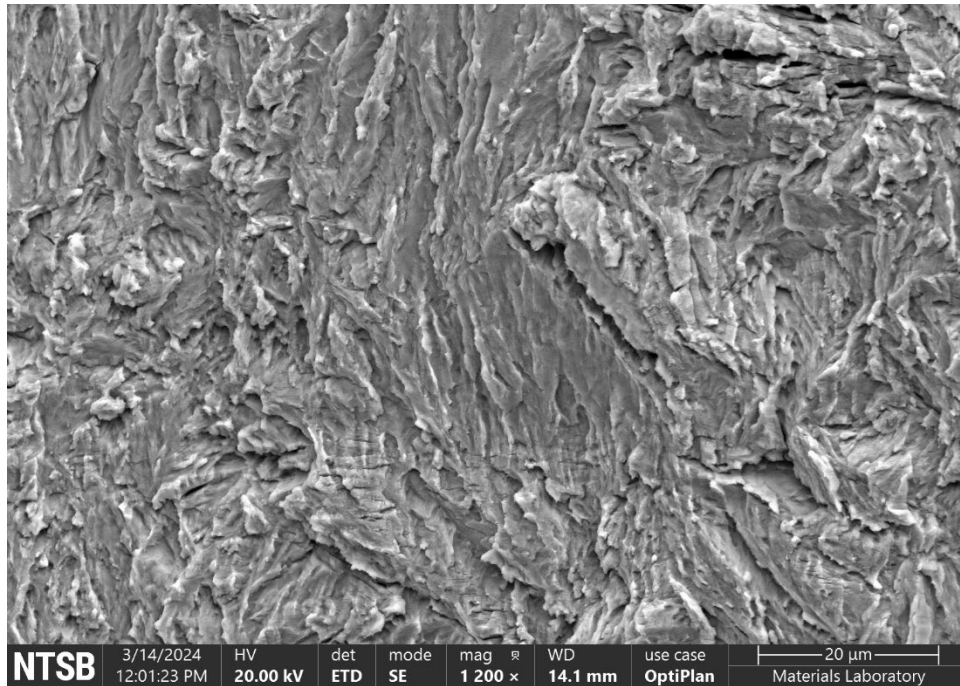


Figure 23. Typical transgranular fatigue fracture features through the thickness of the clutch outer race input shaft.

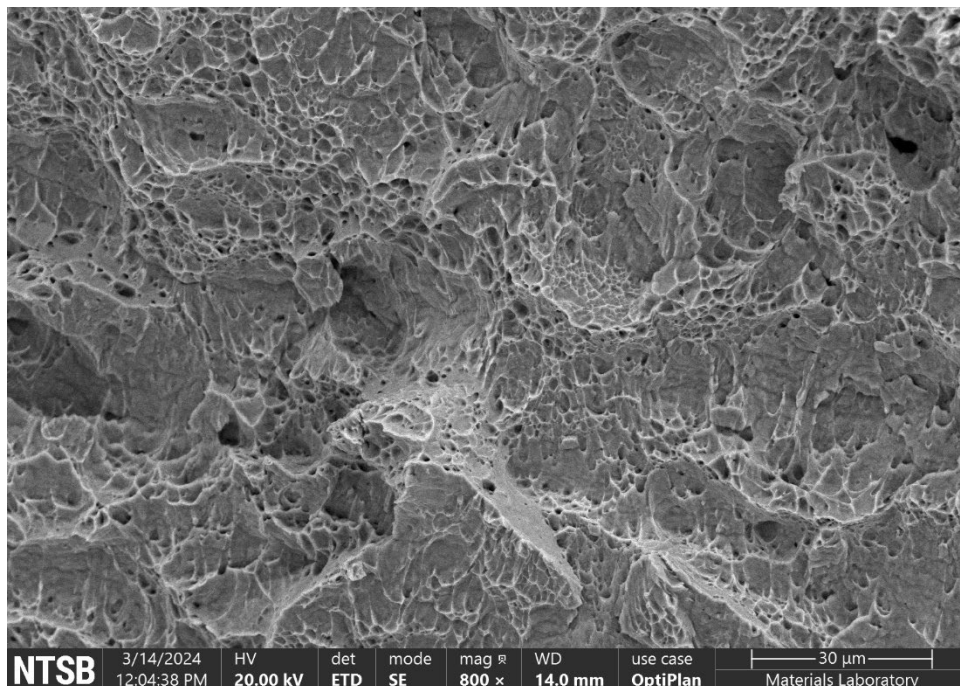


Figure 24. Typical ductile dimple fracture features in the overstress region in the lab-induced portion of the fracture.

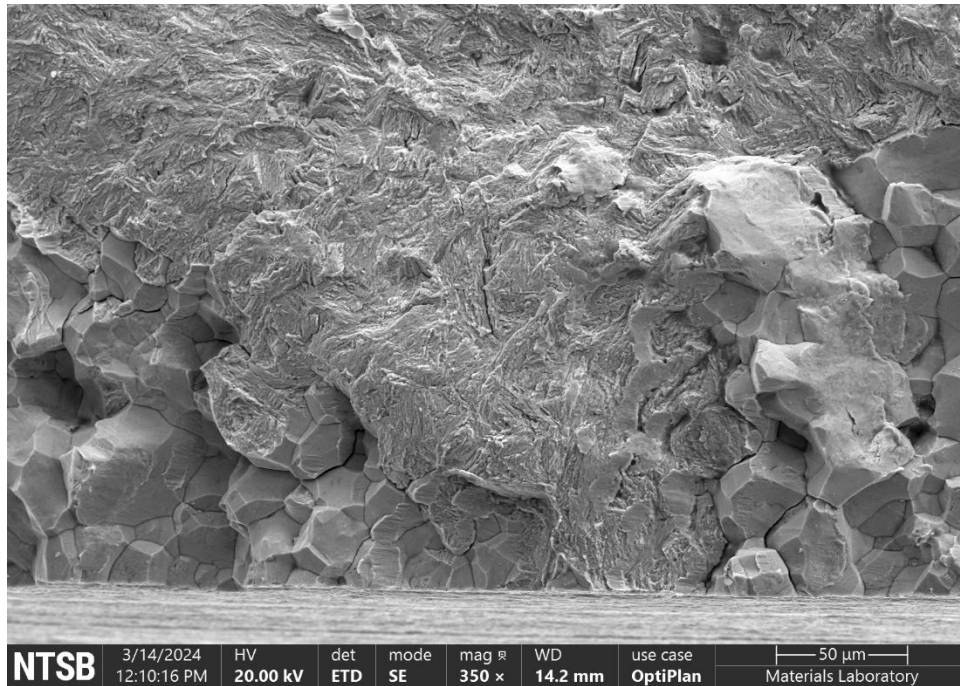


Figure 25. End of the fatigue origin area where transgranular fatigue features were observed intersecting the exterior surface between two regions of intergranular fracture features.

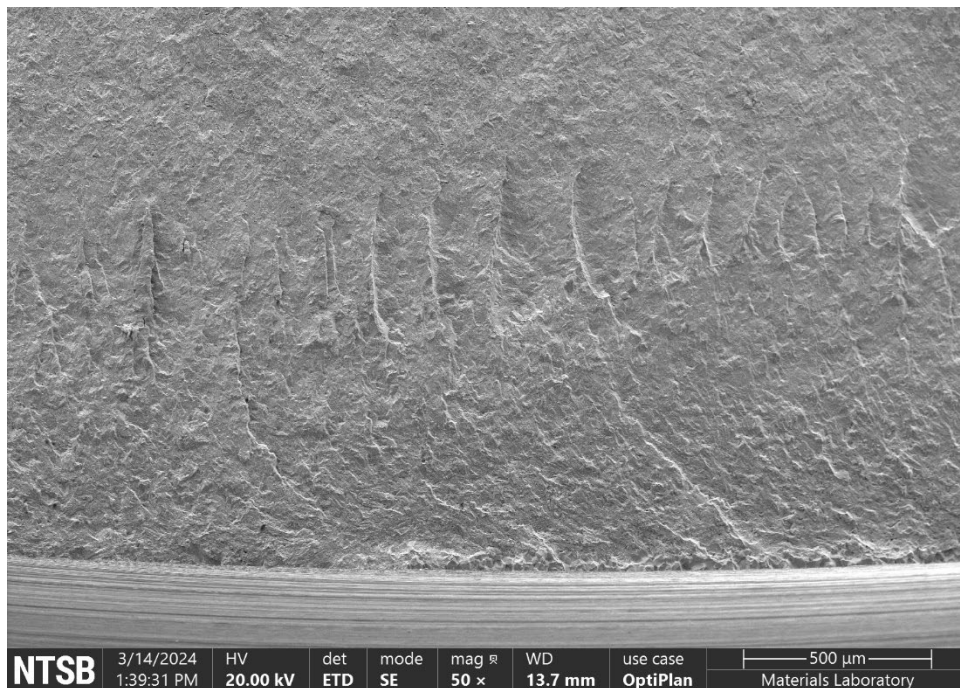


Figure 26. Overall view of the fracture features adjacent to the surface near the clockwise end of the circumferential crack showing a reduced extent of intergranular fracture at the origin area.

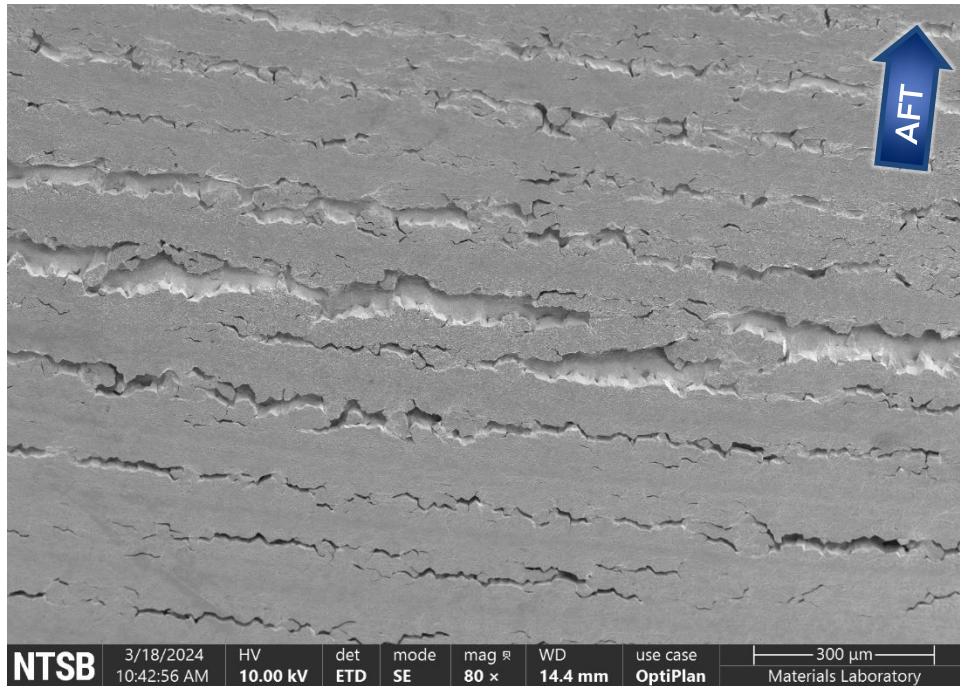


Figure 27. Secondary cracks on the shaft segment aft of the fillet radius that opened from lab-induced plastic deformation produced when exposing the circumferential crack.

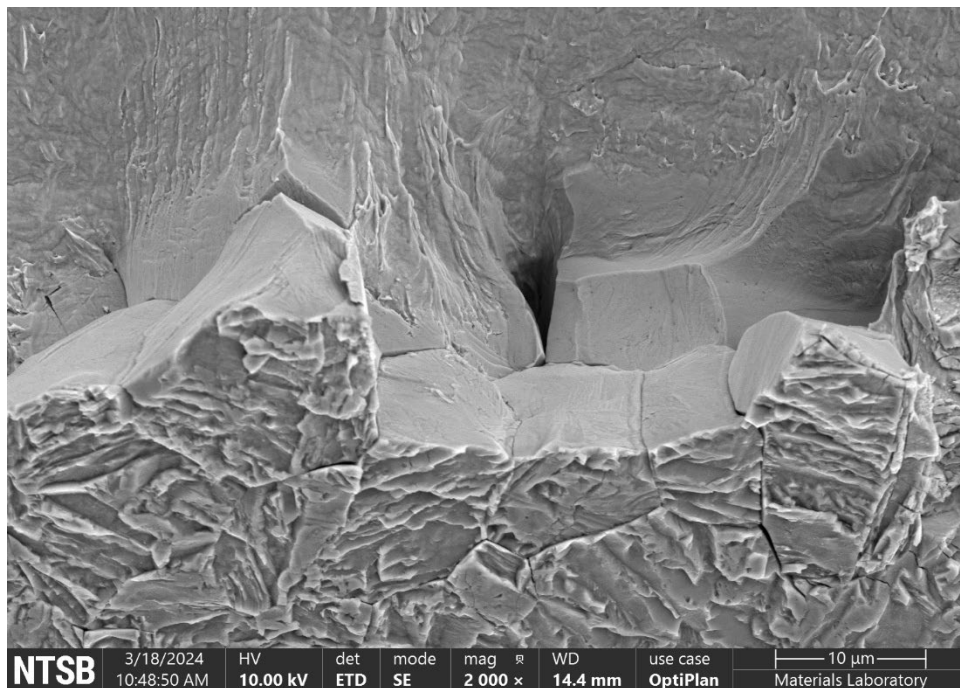


Figure 28. Intergranular fracture features across 1 to 2 grains typical of the opened secondary cracks shown in the previous figure.

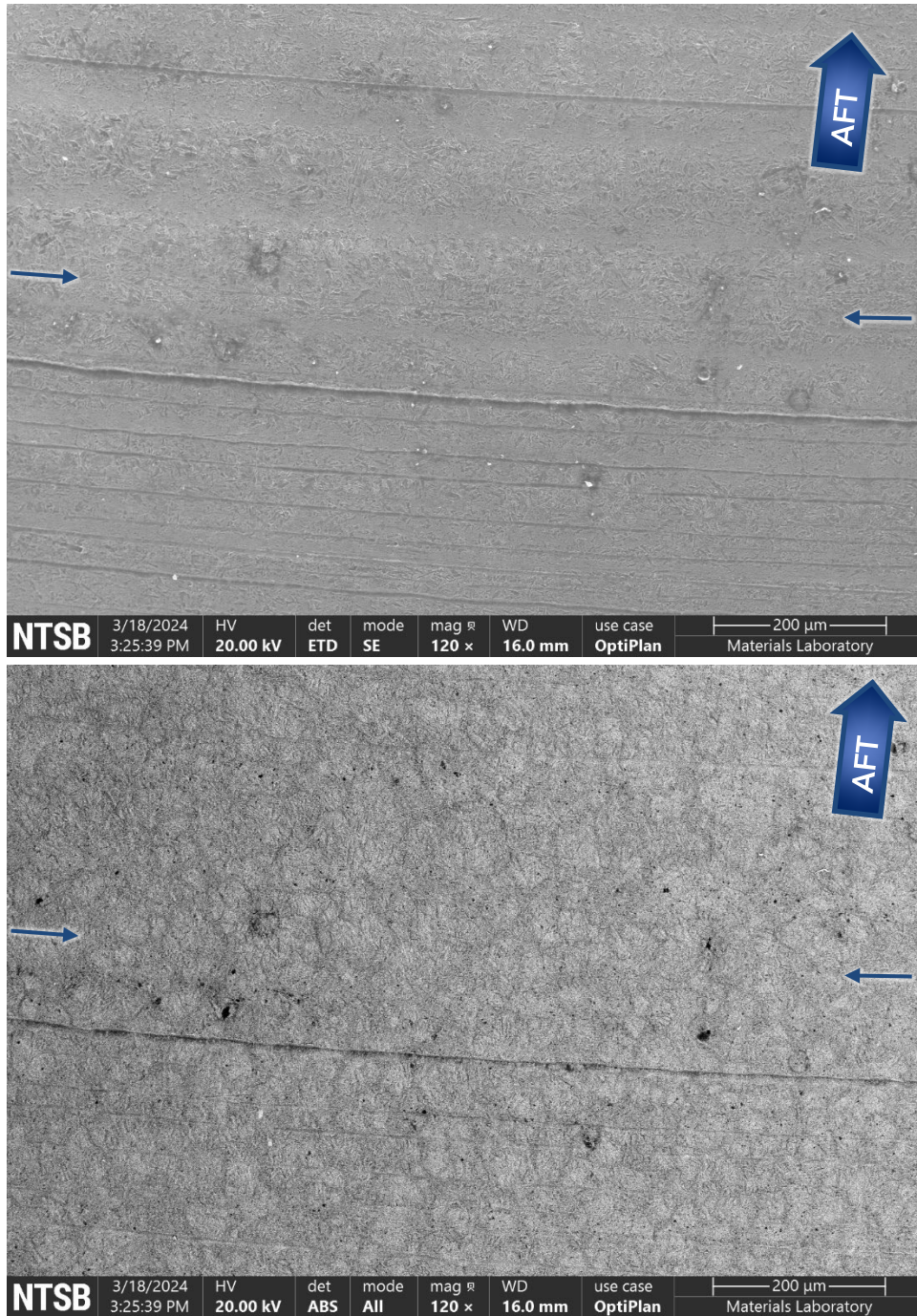


Figure 29. SEM images of the surface of the fillet radius in the intact side forward of the spiral fracture surface as viewed using the secondary electron detector (upper image) and the backscattered electron detector in composition mode (lower image). Arrows indicate the approximate location where the fillet was cracked on the opposite side of the clutch outer race.

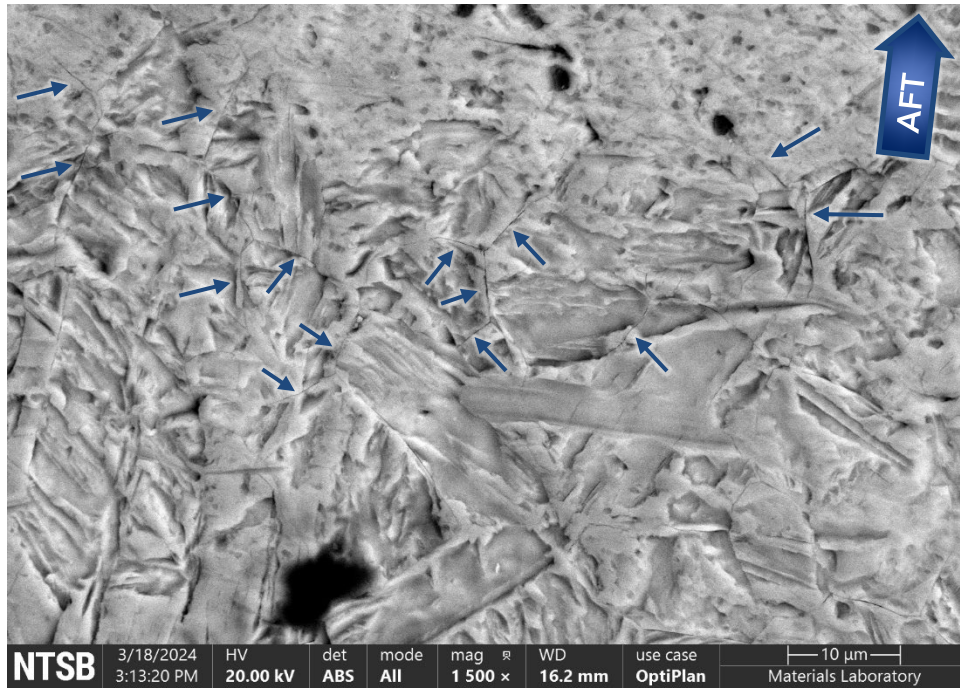


Figure 30. SEM image using the backscattered electron detector in composition mode showing intergranular crack features (indicated with unlabeled arrows) on the surface shown in the previous figure.

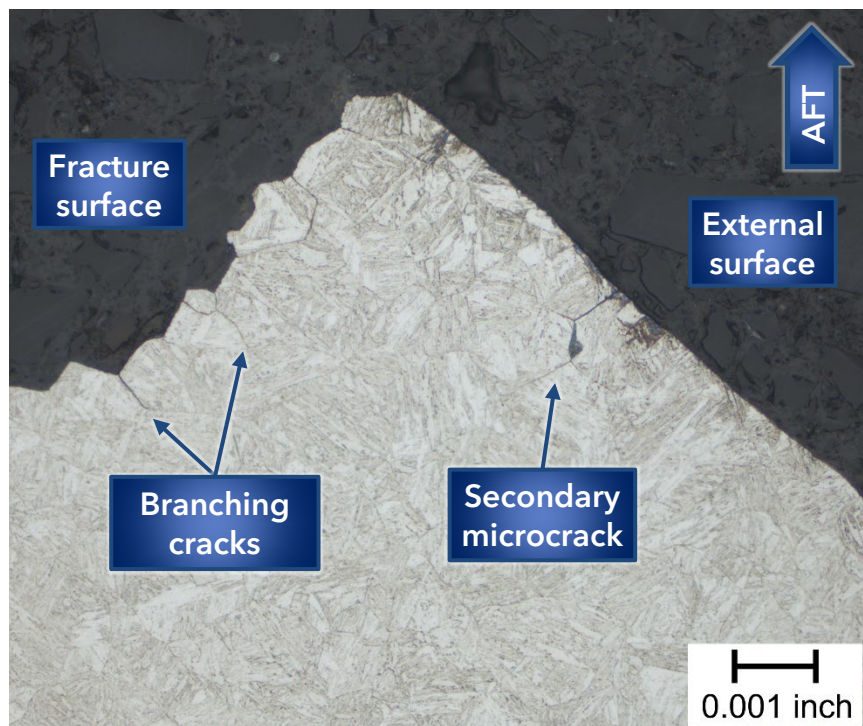


Figure 31. Optical micrograph of the polished and etched cross-section of the circumferential crack in the clutch outer race at the origin area. (Etchant: 2% nital)

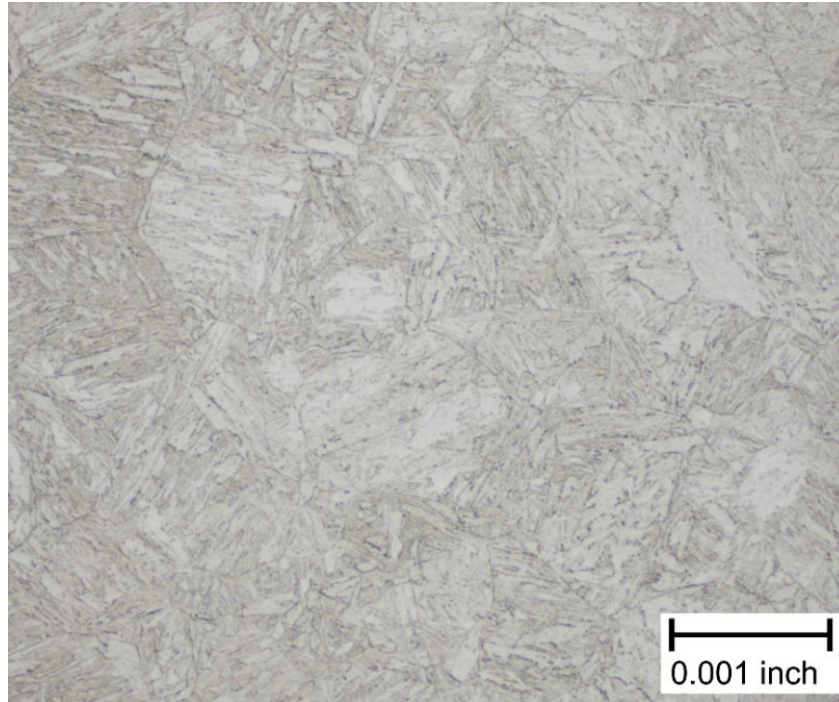


Figure 32. Optical micrograph of typical microstructural features at the core of the clutch outer race. (Etchant: 2% nital)

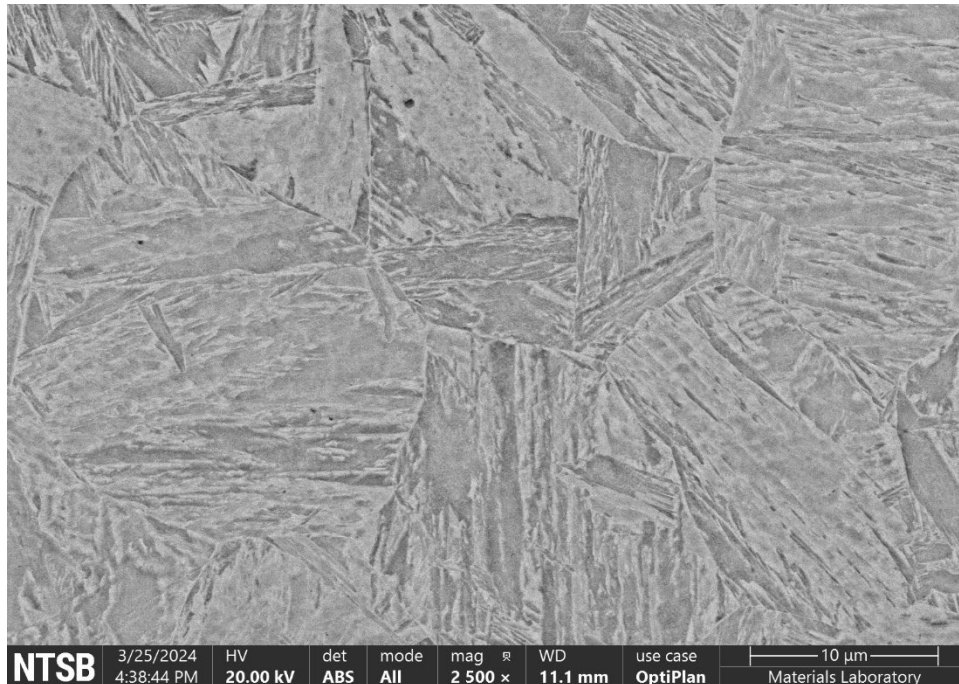


Figure 33. SEM image of typical etched microstructural features adjacent to the exterior surface in the fillet region viewed using the backscattered electron detector in composition mode. (Etchant: 2% nital)

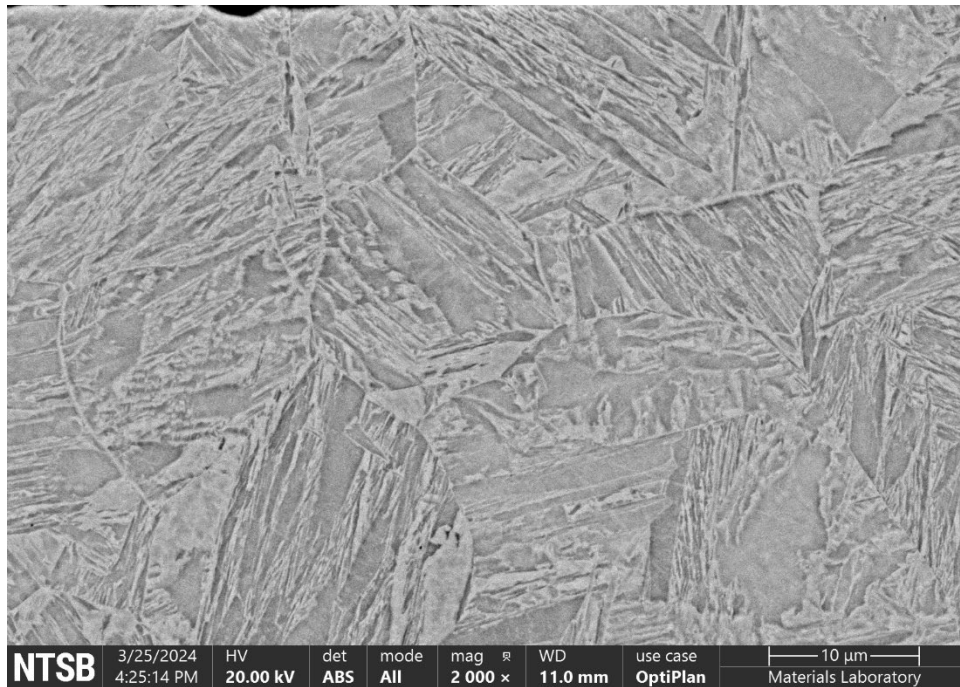


Figure 34. SEM image of typical etched microstructural features adjacent to the exterior surface in the shoulder forward of the fillet radius viewed using the backscattered electron detector in composition mode. (Etchant: 2% nital)

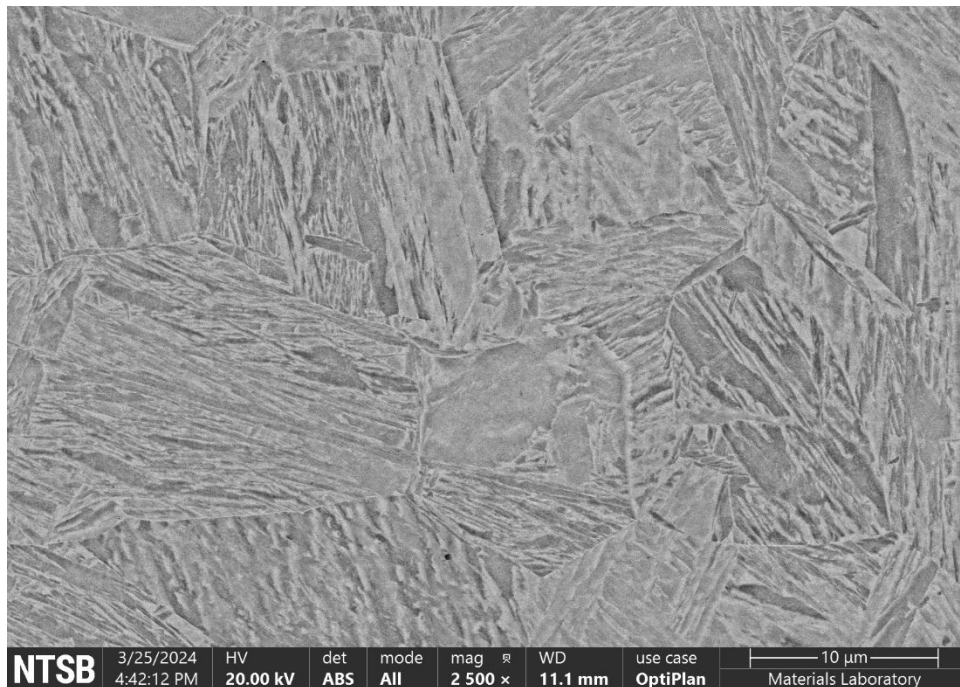


Figure 35. SEM image of typical etched microstructural features adjacent to the circumferential crack where the crack had a transgranular fracture path viewed using the backscattered electron detector in composition mode. (Etchant: 2% nital)

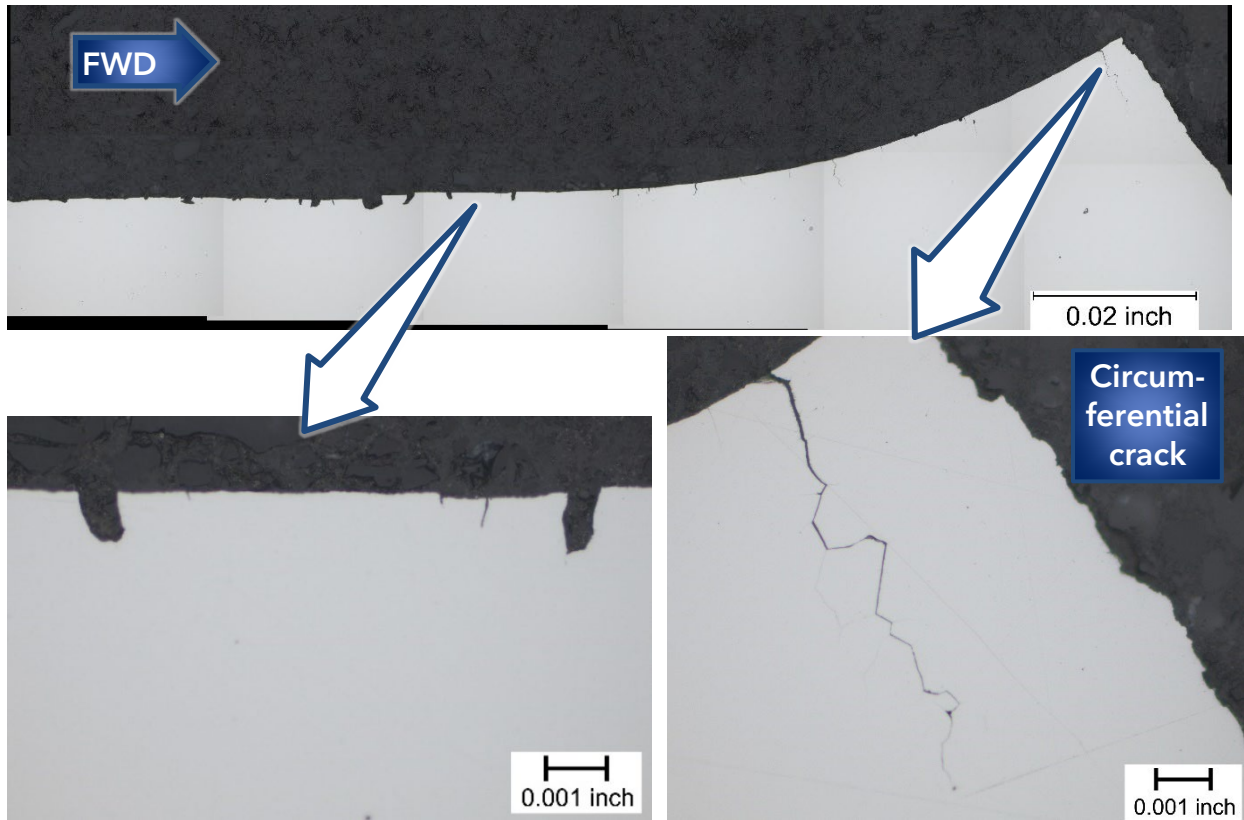


Figure 36. Polished cross-section through the clutch outer race shaft after opening the circumferential crack. The upper image is a montage of optical images stitched to show an overall view of the surface aft of the opened circumferential crack. The lower images show secondary microcracks with blunted crack tips approximately 1 to 2 grains deep on the shaft (lower left image) and a deeper intergranular secondary crack in the fillet radius near the opened circumferential crack (lower right image).

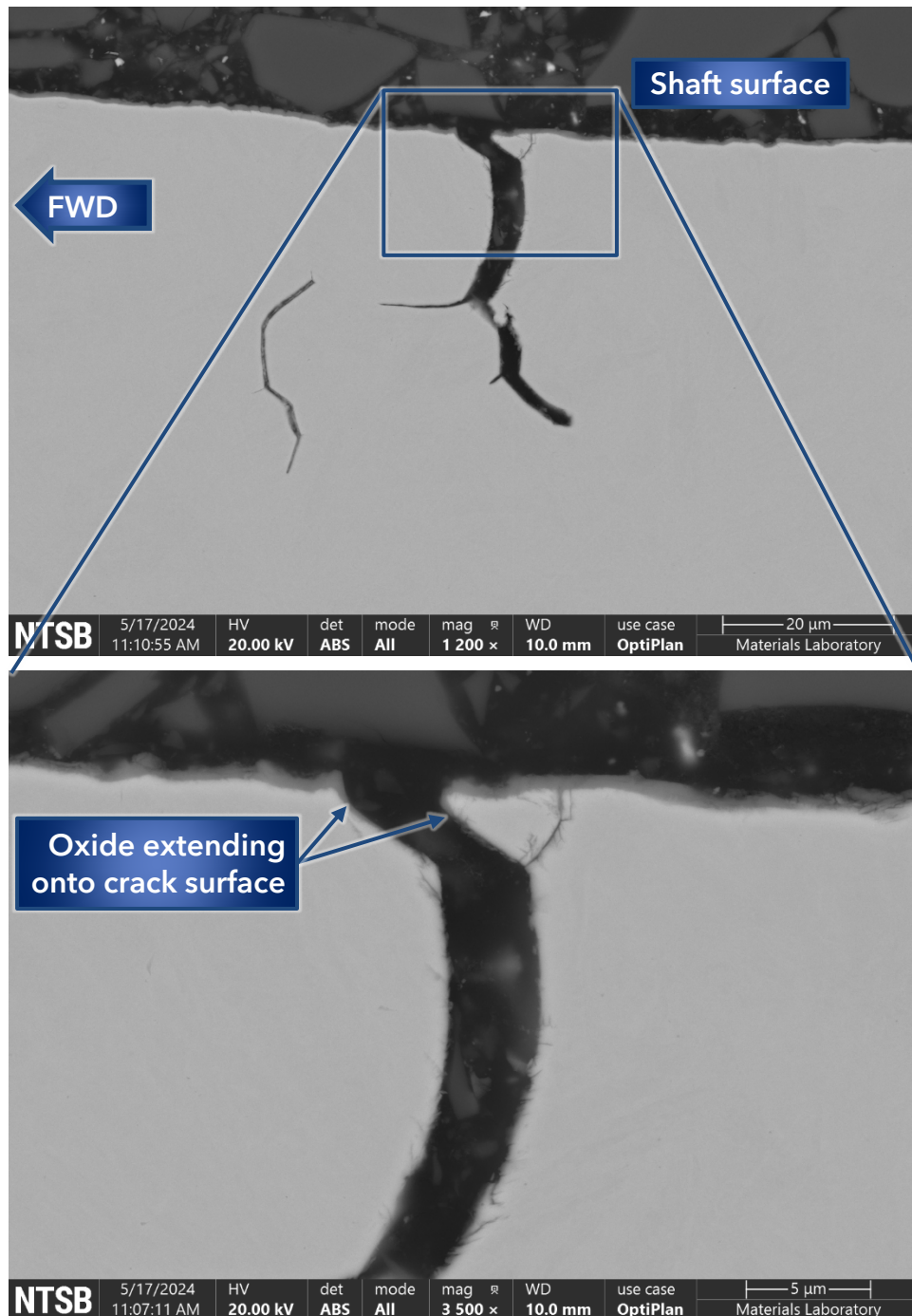


Figure 37. SEM images of a secondary microcrack in the as-polished metallurgical sample from the shaft portion of the clutch outer race after the lab-induced fracture of the circumferential crack.

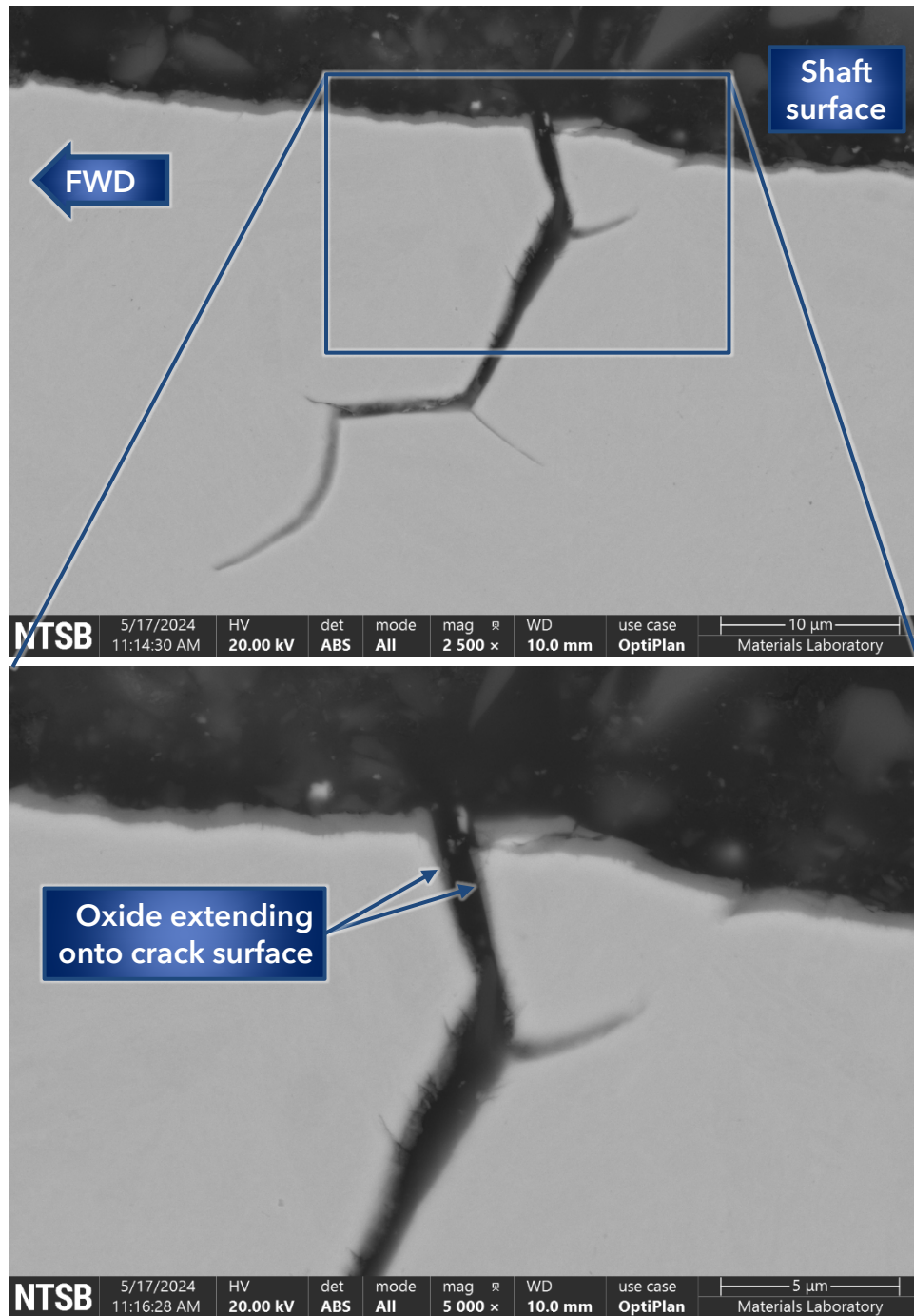


Figure 38. SEM images of a secondary microcrack in the as-polished metallurgical sample from the shaft portion of the clutch outer race after the lab-induced fracture of the circumferential crack.

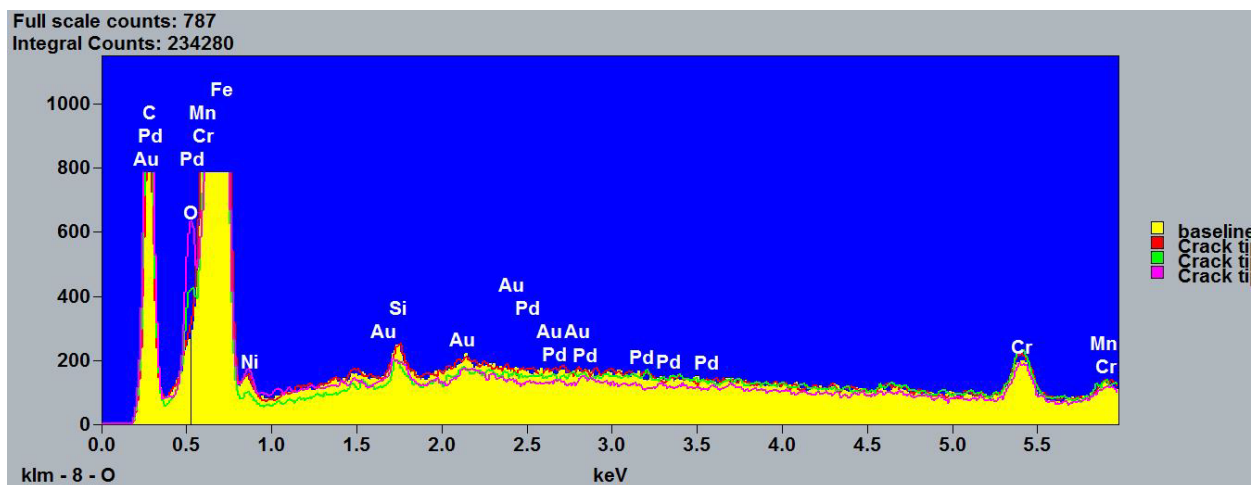


Figure 39. Baseline EDS spectrum (shown in yellow) of the clutch outer race material obtained from the gold/palladium coated metallurgical sample shown in figure 36 with overlaid spectra displayed as red, green, and magenta lines obtained in spot mode aimed in an intergranular crack near the crack tip.