

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



DCA23FA417

MATERIALS LABORATORY

Factual Report 24-015

September 26, 2024

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A. ACCIDENT INFORMATION

Location: Santa Ana, California
Date: August 20, 2023
Time: 23:15 Pacific daylight time
06:15 coordinated universal time
Vehicle: Boeing 737-890, N516AS
Investigator: Michael Hauf, AS-10

B. COMPONENTS EXAMINED

Pieces of a main landing gear trunnion pin

C. EXAMINATION PARTICIPANTS

Specialist Erik Mueller, Ph.D., P.E.
Office of Research and Engineering - Materials Laboratory Division
NTSB, Washington, DC

D. DETAILS OF THE EXAMINATION

On August 20, 2023, Alaska Airlines flight 1288, a Boeing 737-890, sustained damage when the left main landing gear collapsed after landing on runway 20R at John Wayne-Orange County Airport (SNA). The 112 passengers and crew evacuated the airplane via stairs onto a taxiway with no reported injuries. A post-accident examination found the left main landing gear assembly was found to have failed, as illustrated in Figure 1.

From the on-scene examination, the left-hand main landing gear aft trunnion pin was found to have fractured, as illustrated in Figure 2 through Figure 4. The aft section of the trunnion pin, shown from the opposite side, was more accessible and extracted first (see Figure 5). This fragment was sent to Boeing Equipment Quality Analysis (EQA) in Seattle, WA, for examination. Later, the forward portion of the fractured trunnion pin was removed and examined at both the NTSB Materials Laboratory and Boeing EQA.

This trunnion pin was made of Type 4340M alloy steel, then coated externally with a chromium electroplated layer, and internally with a cadmium-titanium alloy electroplated layer with chromate treatment.

Figure 6 shows the aft remnant of the fractured aft trunnion pin, as received at Boeing EQA. This remnant was between 4.5 and 5.0 inches in length, and it exhibited the following markings shown in Figure 7:

161A1192-4 E5514

P/N: 161A1192-13

S/N: E5514

The fracture surface of the forward trunnion pin fragment is shown as received in Figure 8. Most of the fracture surface exhibited a rough surface with a dull gray luster, and much of the edges featured small shear lips, except for the lower left corner. The surface exhibited river patterns and chevron marks that indicated fracture from an area on the bottom left of Figure 8. This corner of the fracture surface contained a thumbnail crack with crack arrest marks, consistent with an initial crack propagation region.

The part had been inspected visually, as well as with Barkhausen noise inspection (BNI), fluorescent penetrant inspection (FPI), and magnetic particle inspection (MPI).¹ The BNI probes were calibrated to a specially designed shot-peened steel standard that had simulated grinding burn regions, created from an induction heating process. The thickness of the chromium electroplated layer of the pin pieces was inspected and used to determine a shim thickness for more accurate calibration. The BNI detected areas of elevated readings near the fracture surface. These readings were directly labeled onto the part, as illustrated in Figure 9 and Figure 10. The highest readings exceeded 100, whereas many of the base readings were as low as 34. The highest readings were in areas with visible physical damage to the pin surface and near the thumbnail crack in Figure 8.

FPI and MPI inspections were performed on the forward fragment of the pin. Figure 11 and Figure 12 show some of the images under ultraviolet light of the FPI. From this inspection, no indications of an abnormal network of cracks (such as “chicken wire” cracks) were observed on the surfaces of the parts. Small cracks parallel and adjacent to the fracture surface were found in the chromium electroplated layer. These cracks were observed near the fracture origins (Figure 12). Additional indications were observed on the surface, in areas that exhibited impact damage to the surface (indicated by the bright circumferential area in Figure 11b and the U-shaped area under the fracture in Figure 11a).

Figure 13 shows a closer view of the thumbnail crack on the forward pin remnant fracture surface. This thumbnail crack exhibited diverse colors visually and crack arrest marks (see Figure 14). These features were consistent with pre-existing progressive cracking in this pin section.

¹ Barkhausen noise inspection is a nondestructive testing technique that measures the noise in the magnetic output of a ferromagnet when the magnetizing force applied to it is changed, due to rapid changes in the size of magnetic domains. This technique can be used to locate the degradation of mechanical properties in magnetic materials, such as high-strength steels that have undergone damage from grinding.

Figure 13 and Figure 14 show the forward thumbnail crack before and after cleaning with acetone, and Figure 15 shows a dark-field image of the region. These different views demonstrate the crack arrest marks, seen bowing convexly into the pin cross-section from the surface. There were also vertically oriented ratchet marks, consistent with crack initiation along multiple sites. A rectangular region of faceted features was located between the crack arrest mark features of the thumbnail crack and the pin surface. This region appears dark in Figure 14 and Figure 15 and lighter in Figure 16: an adherent shiny external layer and a subsurface darker, faceted region.

Figure 17 shows the aft remnant of the aft trunnion pin, as received by the NTSB Materials Laboratory. This remnant measured between 5.25 and 6 inches in length. The features of the aft fracture surface mirrored those of the forward side, including the thumbnail crack along the edge, shown in Figure 18 through Figure 20.

The thumbnail crack dimensions were measured with a digital optical microscope, as annotated in Figure 21. The crack measured 0.144 inches deep, with a linear length on the outer diameter (OD) of 0.391 inches. This subsurface intergranular region measured 0.016 inches deep by 0.290 inches long inside the thumbnail crack.

The darker, brownish-colored subsurface intergranular area is shown closer in Figure 22. Smaller ratchet marks were present on the progressive region of the thumbnail crack adjacent to the intergranular area. This crack area was examined using a field-emission scanning electron microscope (SEM), as shown in Figure 23 and Figure 24. This region was below an area of the fractured external chromium electroplating layer, shown in more detail in Figure 25. The plating layer exhibited layered fan-shaped characteristics, with radiating or tongue features, as typified in Figure 26. The intergranular region is shown in more detail in Figure 27. The faceted morphology of the area was consistent with fracture between grain boundaries. Much of the intergranular surfaces exhibited ridged or smooth surface features, with clear triple points and some secondary cracking, typified in Figure 28.

Beyond the intergranular region, the thumbnail crack exhibited fatigue striations, as shown in Figure 29. These features were consistent with fatigue crack propagation. As shown in Figure 30, these striations originated along the edge of the intergranular region of the fracture surface. The ratchet marks, indicative of multiple initiation sites, indicate that the fatigue crack started along stress concentrations created by the tortuous morphology of the initial intergranular zone. There was no indication of mixed mode features, such as dimpled rupture or intergranular cracking within the fatigue regions of the darker portions of the thumbnail crack.

At the terminus of the fatigue thumbnail crack (Figure 31), there was an abrupt change in fracture features. Outside the striations comprising the fatigue crack in Figure 32, the fracture surface exhibited dimpled rupture, consistent with subsequent

overstress fracture of the pin during the final fracture upon the accident landing event.

Overall, the fracture features of the thumbnail crack were consistent with multiple crack initiation sites along the facets of the intergranular region. These smaller cracks had coalesced during early crack propagation, as evidenced by the ratchet marks in that portion of the fatigue crack.

The various regions of the fracture surface were examined using energy-dispersive X-ray spectroscopy (EDS). The EDS data were consistent with the prescribed material composition, Type 4340M alloy steel. EDS examination of the thumbnail areas was all consistent with each other, and exhibited elevated levels of O, C, Ca, and Al. These elements are typically found on oxidized fracture surfaces of landing gear components made of this steel alloy.

Figure 33 shows the different pieces of the trunnion pin sections, including the later recovered forward fragment, after sectioning of various areas for metallographic and microscopic examination. Figure 34 shows the aft remnant, with data from a Barkhausen noise inspection (BNI) written directly on the cylindrical surface. The highest numbers were areas of potential excessive heat input for the part (Figure 34).

After calibrating the equipment with a shim to simulate the chromium electroplating layer thickness, the areas of most severe potential damage exhibited reading between 100 and 120. Most of the rest of the trunnion surfaces with no indications of damage exhibited readings between 5 and 7. The areas of highest readings were concentrated in areas near the fatigue crack initiation site, along a longitudinal area of the pin, and an area of visible impact damage on the lower portion near the part edge.

The aft remnant was also inspected using FPI and MPI, as exemplified in Figure 35 and Figure 36, respectively. These nondestructive examinations revealed similar areas of surfaced damage, most notably with areas of visible impact damage consistent with post-fracture damage. Some of these areas are highlighted in the tow figures, visible at parallel ladder cracking on the exterior electroplating layer.

The aft fragment of the fractured pin was bisected along the thumbnail crack, and the section to the left was examined with a temper etch inspection using a 2% Nital bath solution. This section underwent a stripping process to remove the chromium electroplated layer, using an electrolytic solution of sodium hydroxide (NaOH) and sodium carbonate (NaCO₃), held at 100 °F with 4 - 6 V.

Figure 37 shows the main surface of the aft remnant following the etching process. The two primary indications are a longitudinal elongated oval of dark contrast with a central white area, and a 45° angled wider dark indication that intersected the

fracture surface edge at the location of the fatigue crack and its initiation sites. The darker regions correspond to localized elevated iron carbide content, indicative of localized overtempering, consistent with heat exposure. In addition, the temper etch inspection found a longitudinal indication of white-etched material surrounded by darker-etched regions. This region was consistent with an area of undertempering from lighter-etching martensite, consistent with localized heat input exceeding 727 °C (1340 °F).

Of note was the angled dark region, which corresponded to the parallel ladder crack indications found from FPI. As illustrated in Figure 38 and Figure 39, the center of this angled dark band coincided with the center of the fatigue crack initiation site (which had been bisected in Figure 39). When contrasted with mating forward section of the trunnion pin, the areas of highest Barkhausen noise readings were located on an angle along the path of the dark band from the temper etch inspection (Figure 40).

A portion of the cross-sectioned pin was mounted, polished, and etched with a 2% Nital solution. Figure 41 shows a cross section through the surface, showing the surface-facing chromium electroplating layer. Microscopic measurements found this layer averaged about 0.005 inches (5 mils) in thickness. For the most part, this layer was intact and adherent. However, there were indications of surface cracking, as demonstrated from the exterior in Figure 42.

A cross-section through this cracking found it perpendicular to the surface and branched, but the branching was flat and generally parallel to each other. These features were consistent with the morphology seen on the fracture surface with the electroplating, shown in Figure 43. Within the steel body of the pin, the crack was absent such branching, progressing in a mainly transgranular manner through the tempered martensite microstructure. Other cross-sectioned surface cracks exhibited similar features, as illustrated in Figure 44.

Submitted by:

Erik M. Mueller
Materials Research Engineer

E. FIGURES



Figure 1. View of the fractured and damaged areas of the main landing gear taken in scene.



Figure 2. View of the fractured trunnion pin of the main landing gear on-scene.



Figure 3. View of the fracture surface of the aft remnant of the aft trunnion pin remnant, on-scene.



Figure 4. View of the mating fracture surface of the forward half of the aft trunnion pin, on-scene.



Figure 5. View of the opposite end of the forward remnant of the aft trunnion pin shown in Figure 3.

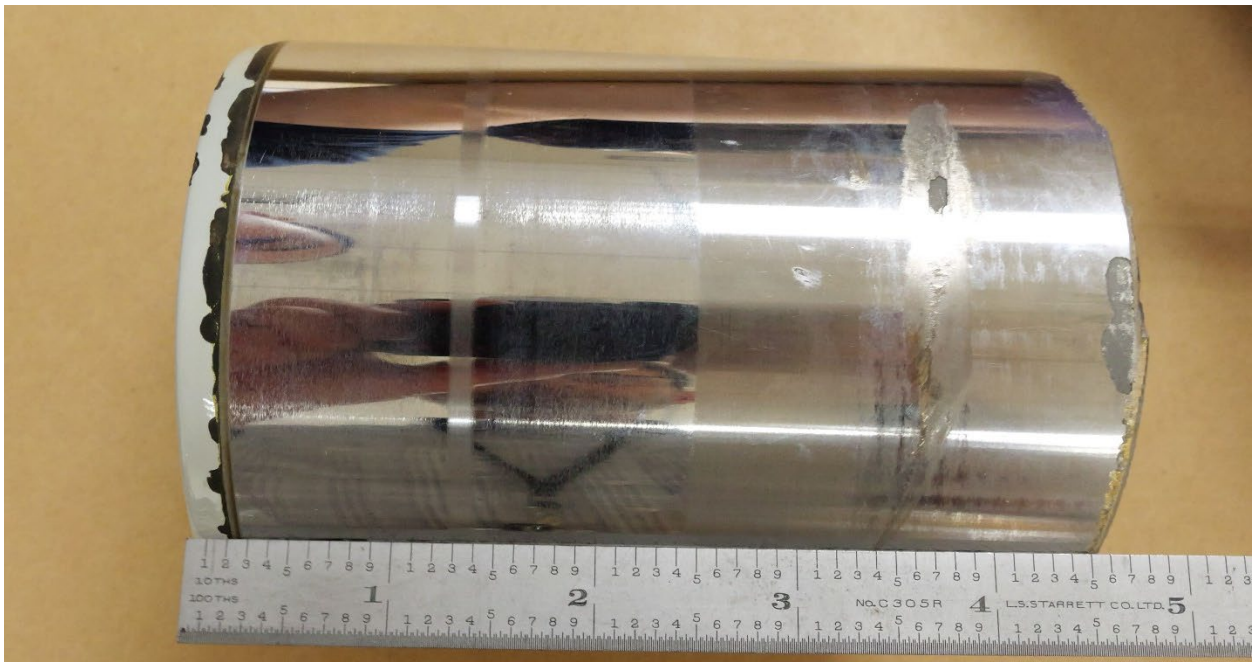


Figure 6. Side view of the aft remnant of the aft trunnion pin, after removal and receipt at Boeing EQA (courtesy: Boeing).

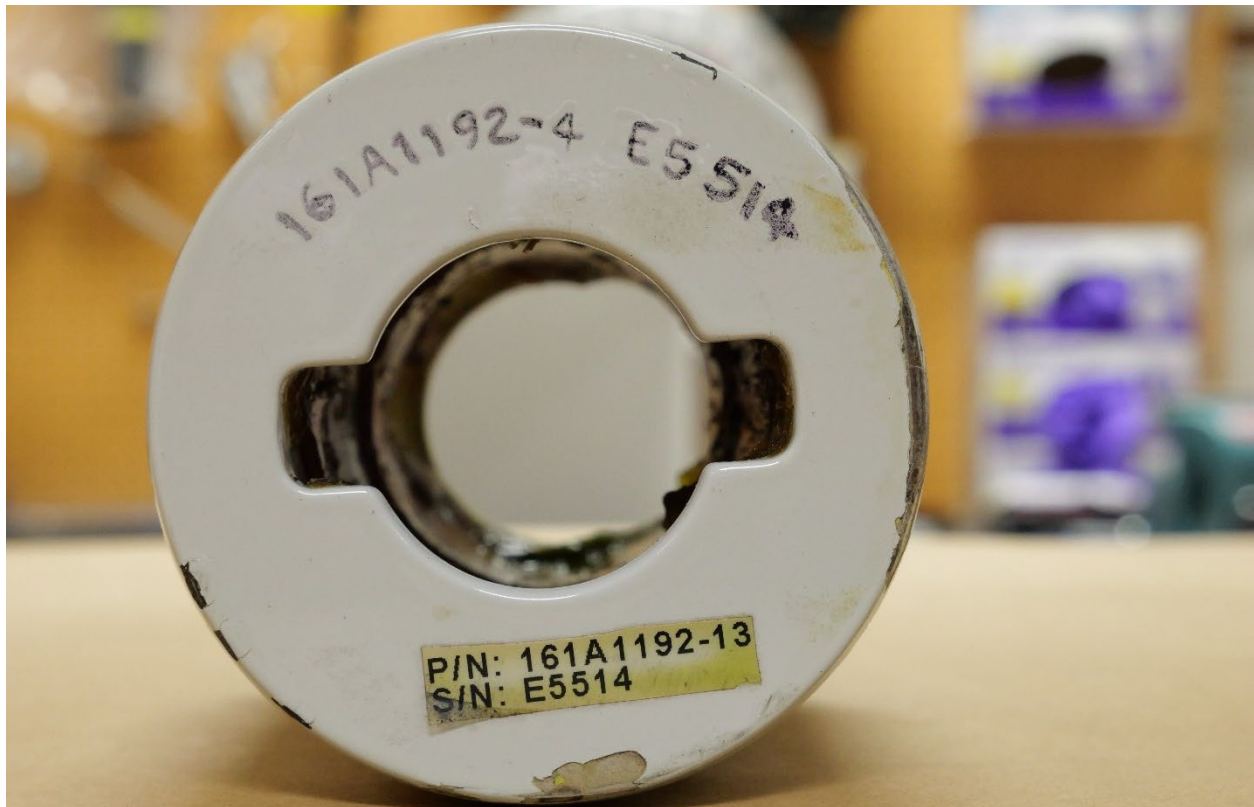


Figure 7. View of the flat, painted end opposite the fracture surface of the aft remnant of the aft trunnion pin, showing part markings.

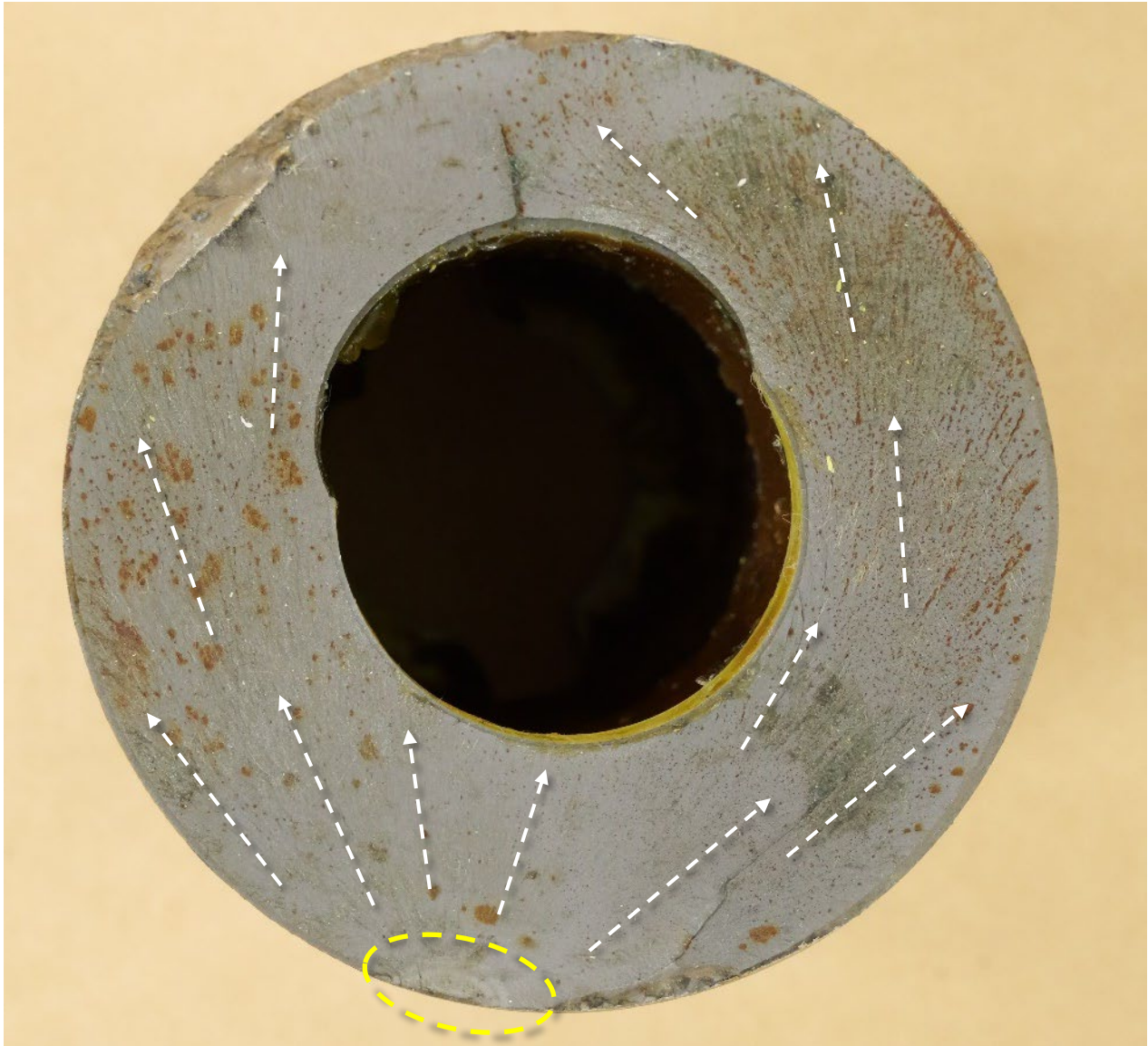


Figure 8. View of the fracture surface of the aft remnant of the aft trunnion pin, annotated to show the initial thumbnail crack (oval) and the later fracture directions (arrows) (courtesy: Boeing).

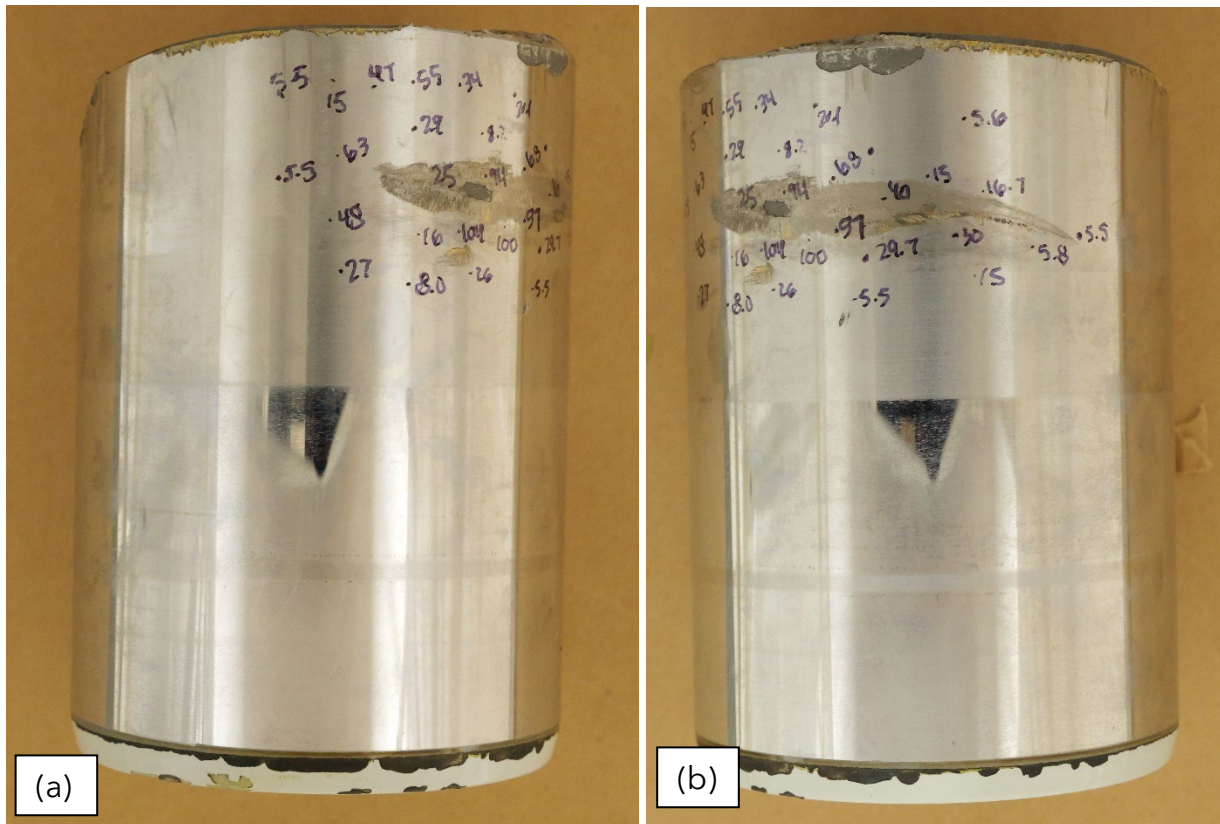


Figure 9. View of the aft trunnion pin remnant opposite the thumbnail crack edge, showing Barkhausen data directly on the exterior surface (courtesy: Boeing).

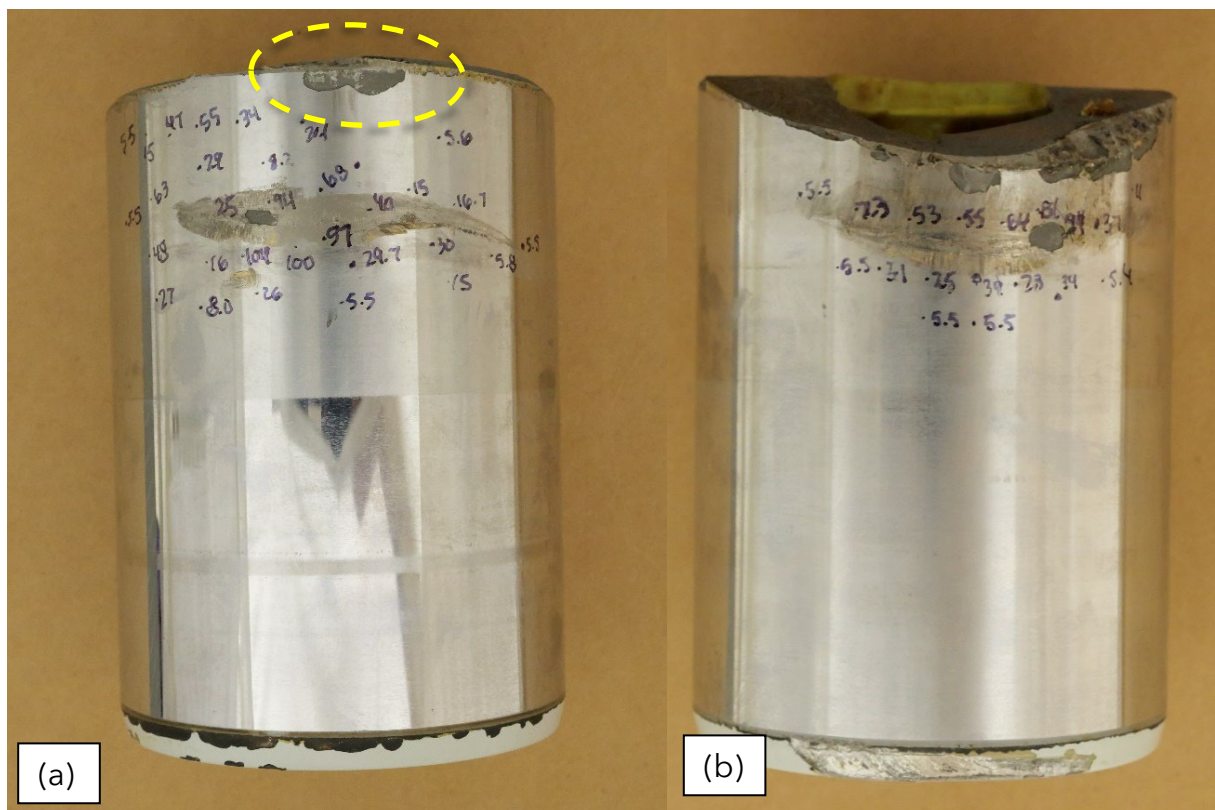


Figure 10. Side view of the aft trunnion pin remnant on the thumbnail crack edge (circled) showing the Barkhausen data directly on the surface.

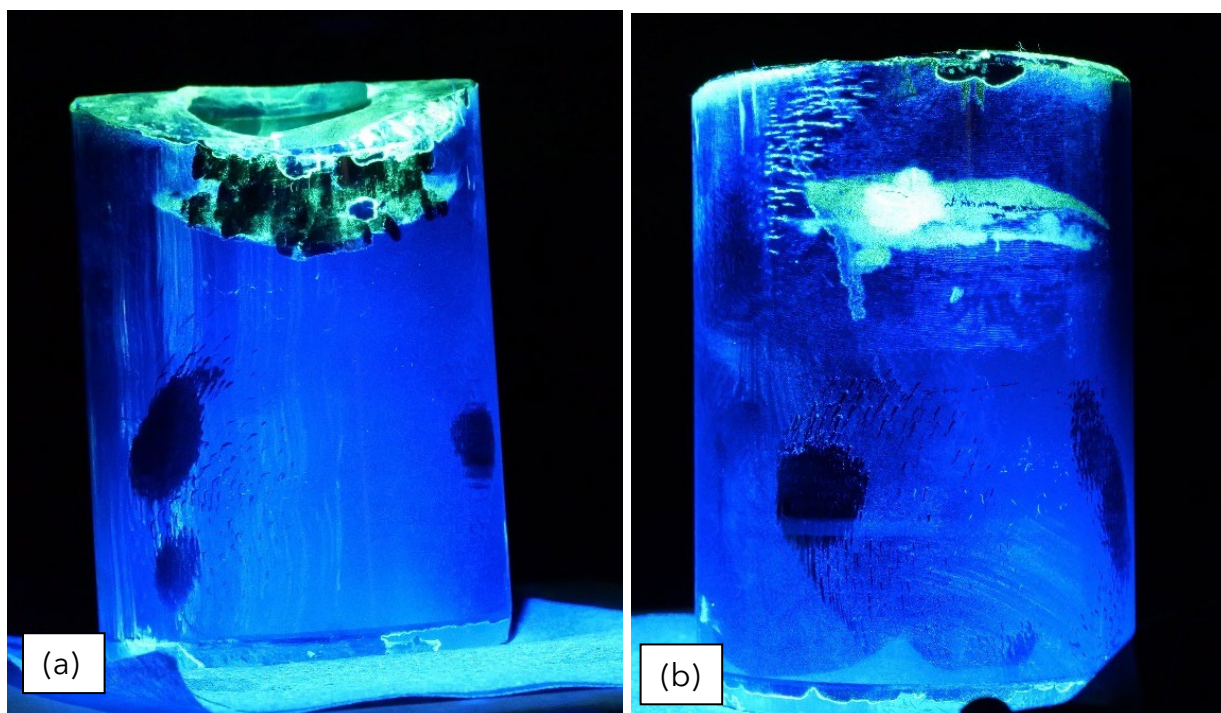


Figure 11. Ultraviolet light images of the aft pin remnant from (a) the thumbnail crack side and (b) the opposite side during FPI (courtesy: Boeing).

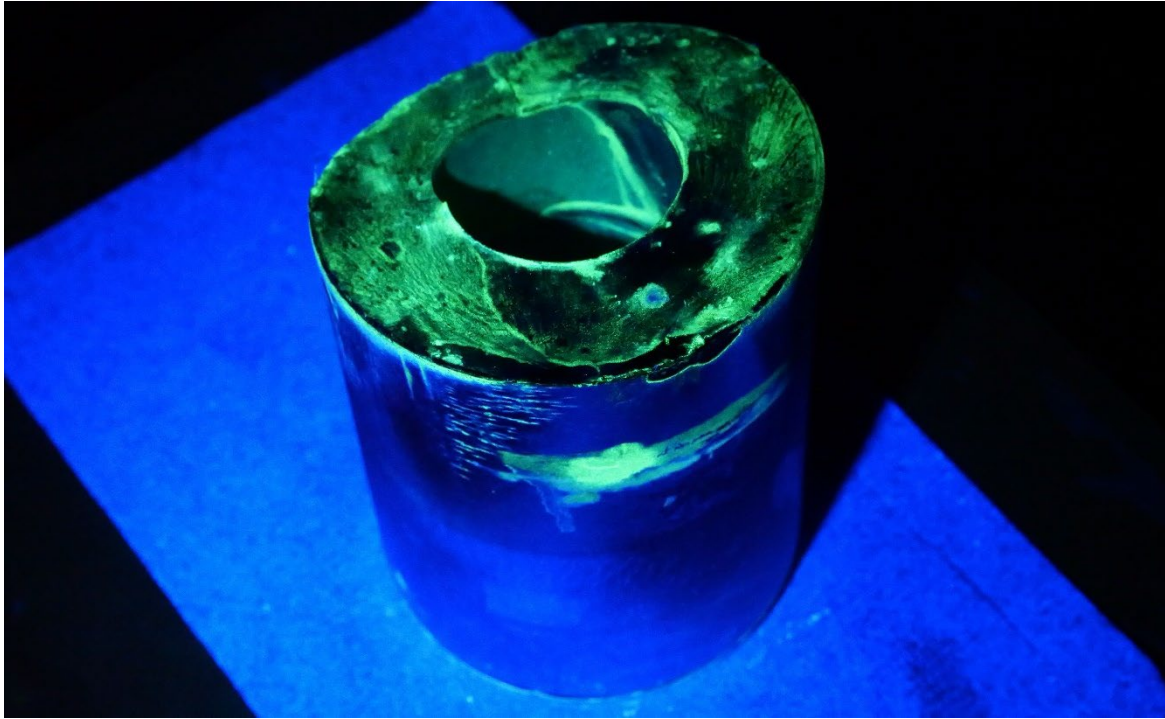


Figure 12. Ultraviolet view of the edge of the fracture surface with the thumbnail crack under FPI inspection (courtesy: Boeing).

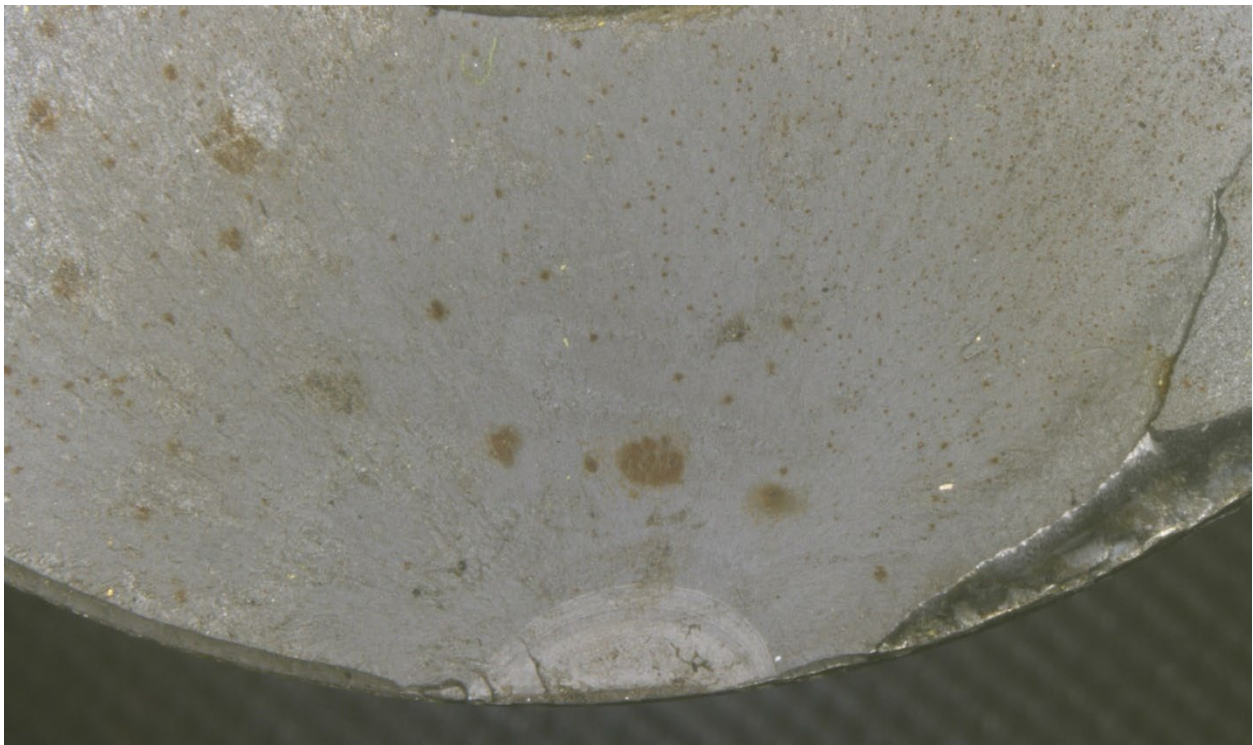


Figure 13. The edge of the fracture surface, showing the thumbnail crack and adjacent shear lips (courtesy: Boeing).



Figure 14. Closer view of the thumbnail crack in **Figure 13**, showing crack arrest marks (courtesy: Boeing).

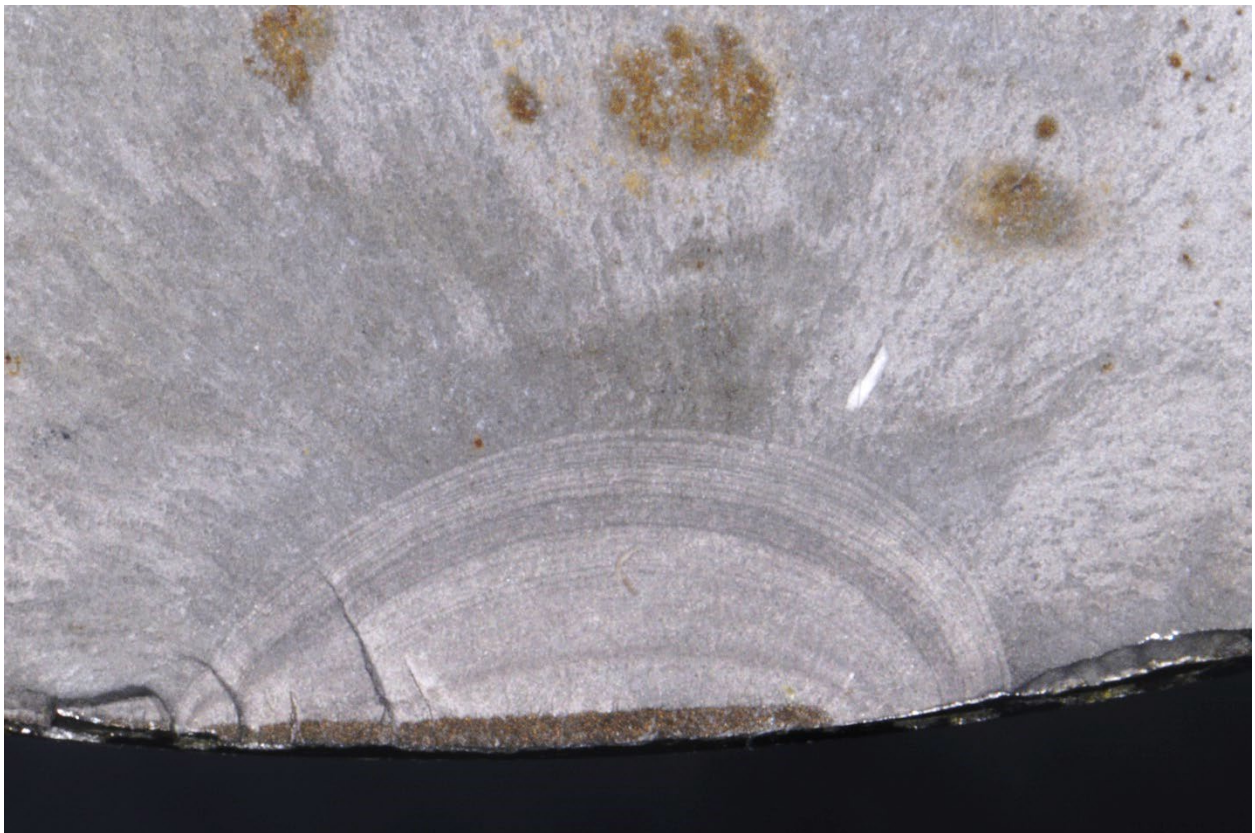


Figure 15. Closer view of the thumbnail crack after cleaning (courtesy: Boeing).

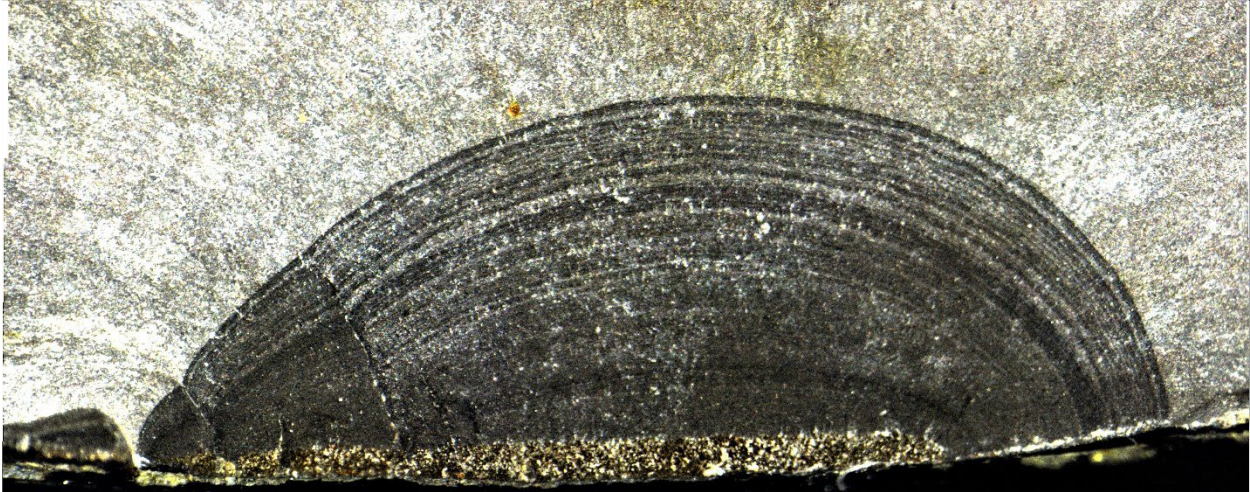


Figure 16. Angled dark field lighting view of the thumbnail crack in , highlighting the major arrest marks and subsurface rough zone of the fracture (courtesy: Boeing).

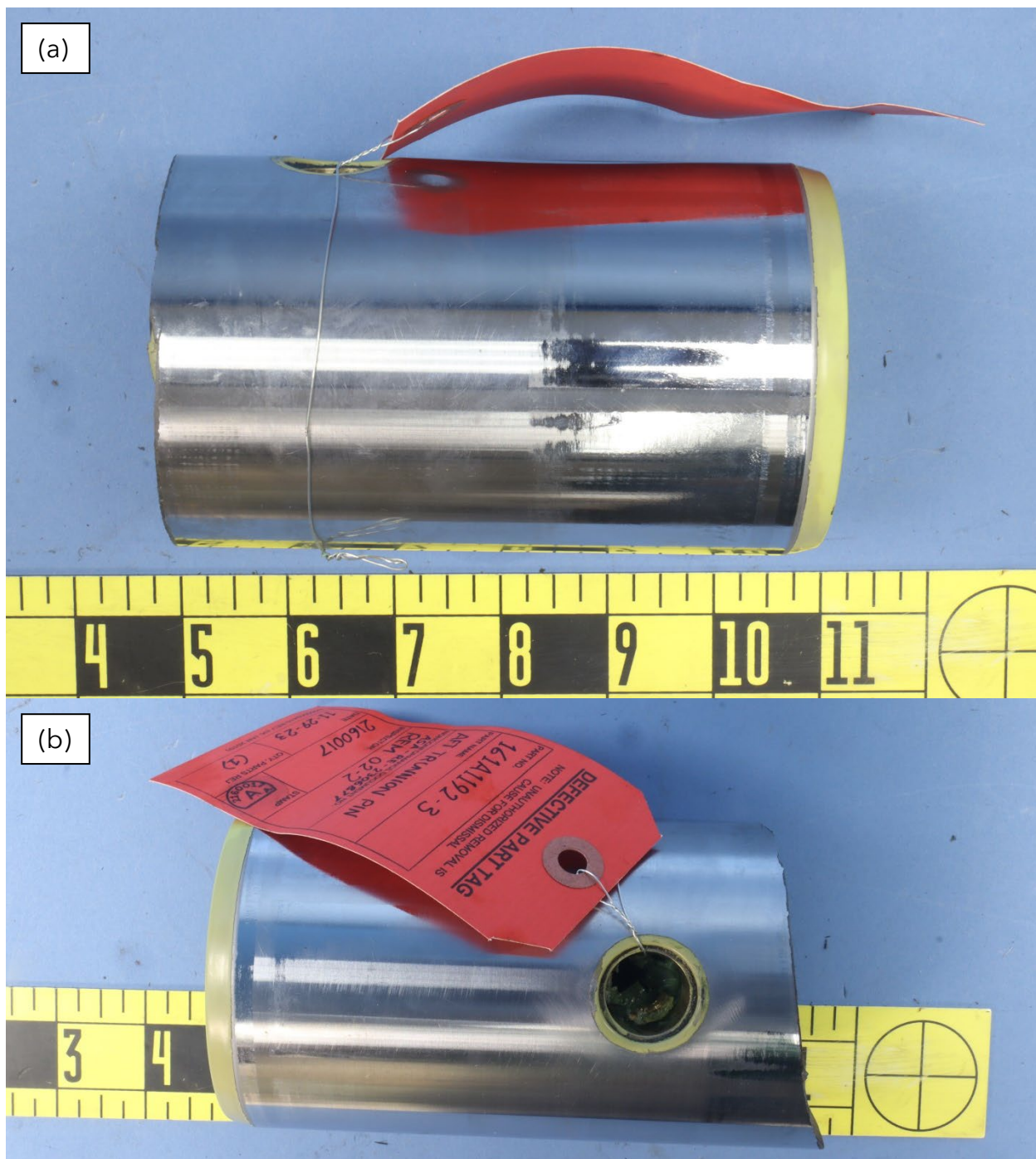


Figure 17. Side view(s) of the forward remnant of the aft trunnion pin, as received.

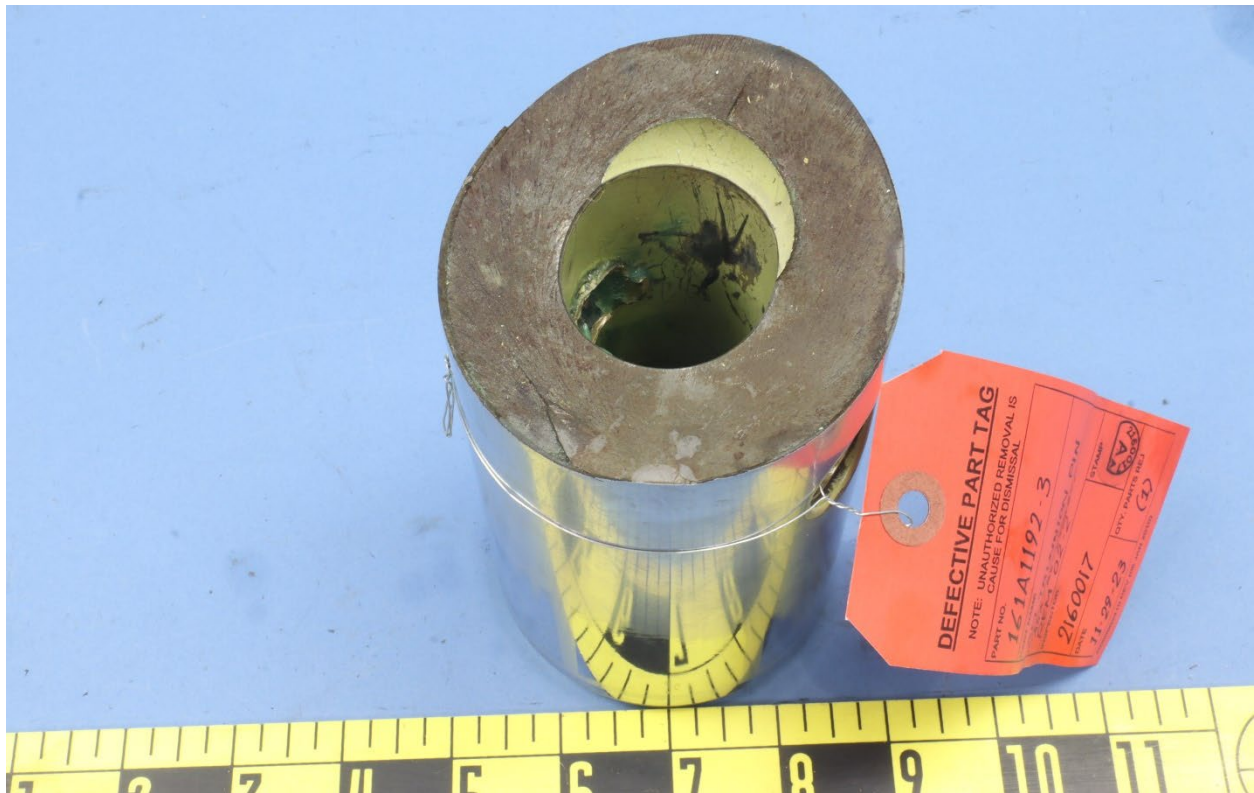


Figure 18. View of the forward pin remnant fracture surface, with the thumbnail crack positioned on the bottom edge.

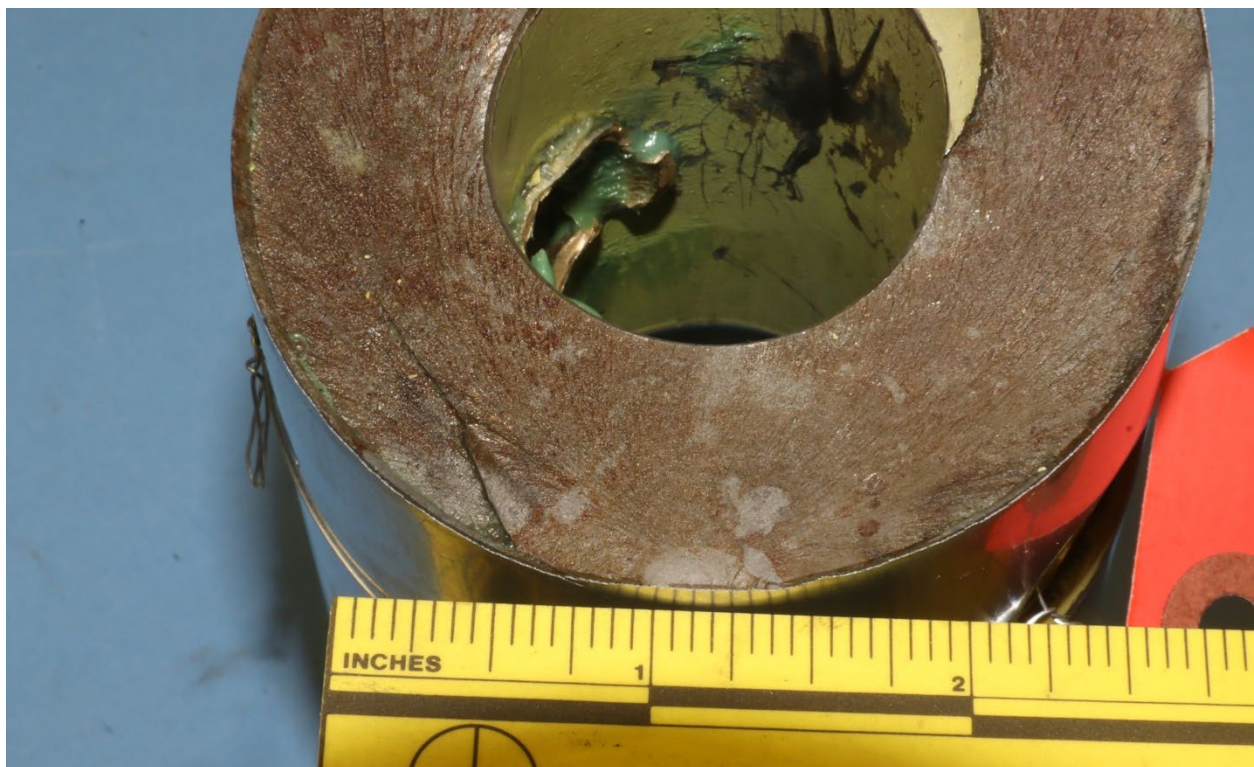


Figure 19. Closer view of the edge with the thumbnail crack from **Figure 18**.



Figure 20. Close-up view of the thumbnail crack on the forward pin remnant.

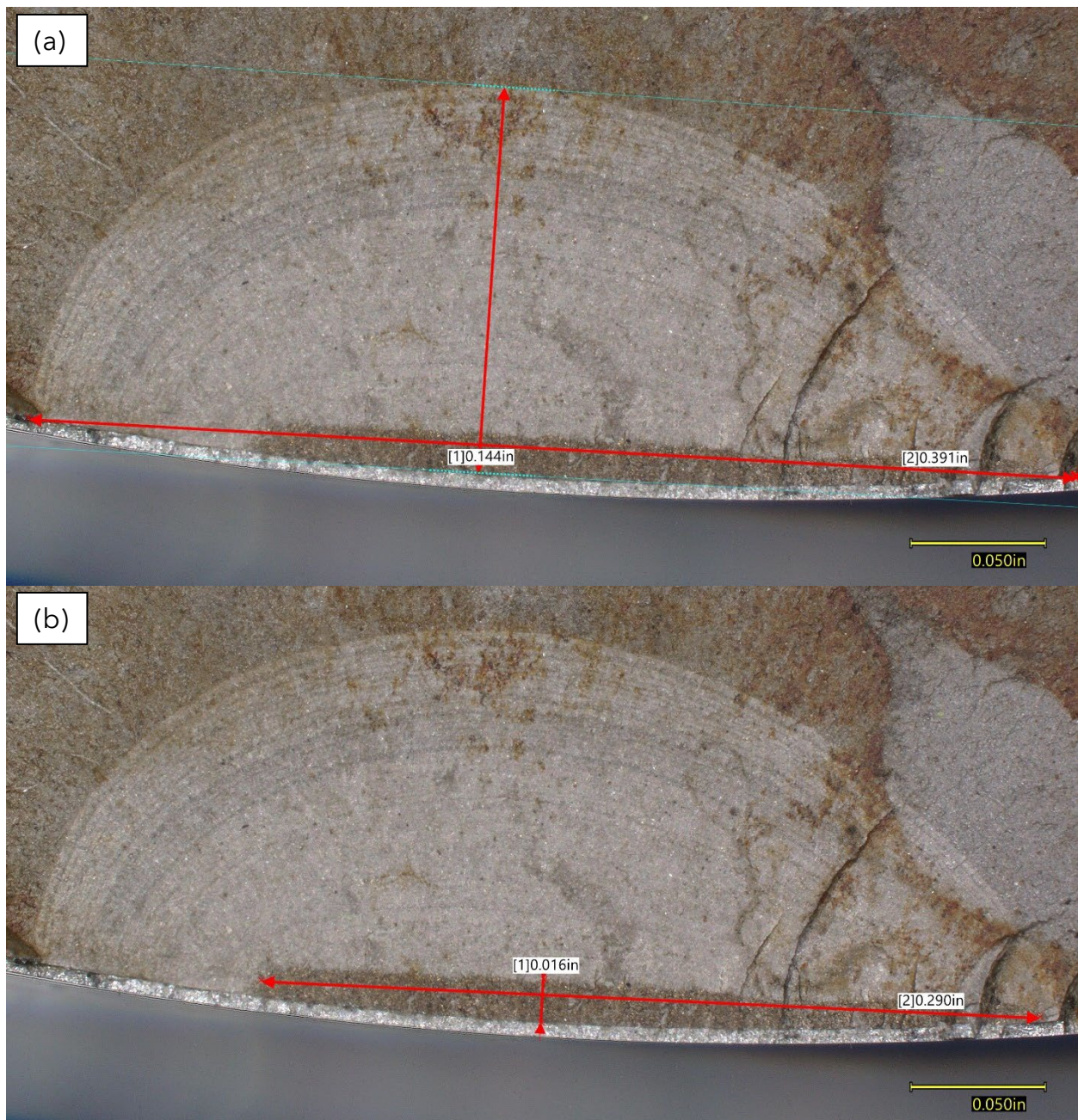


Figure 21. Measurements of various dimensions on the thumbnail crack image in **Figure 20**.



Figure 22. Closer view of the initiation region of the thumbnail crack, showing the Cr-plating surface layer and the darker subsurface intergranular layer.

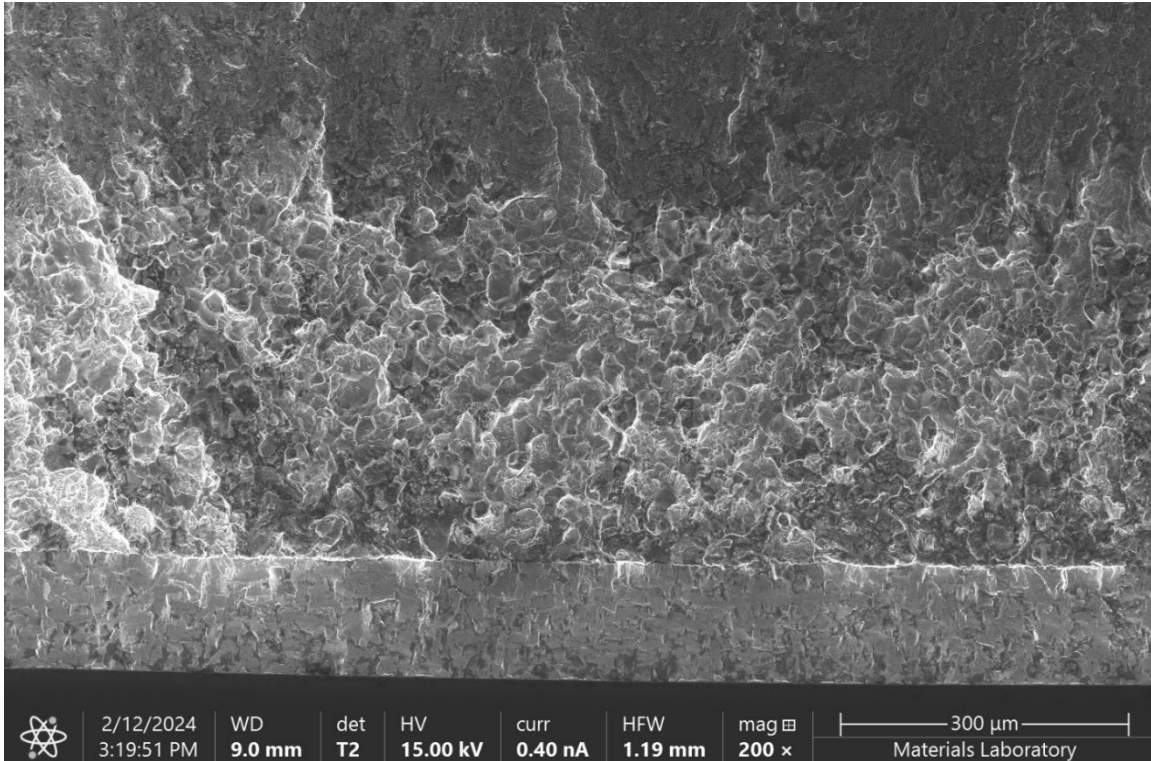


Figure 23. Secondary electron (SE) micrograph of the intergranular region of the initial crack.

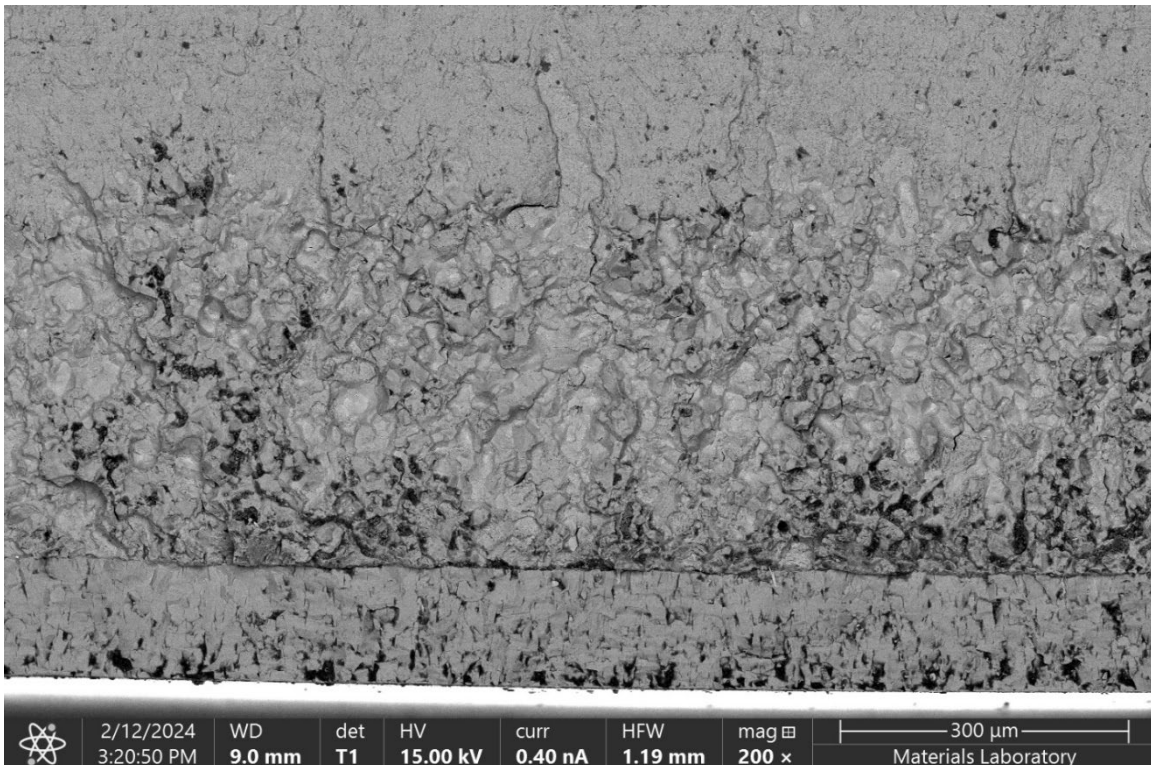


Figure 24. Backscattered electron (BE) micrograph of the intergranular and Cr-plating region of the thumbnail crack in **Figure 23**.

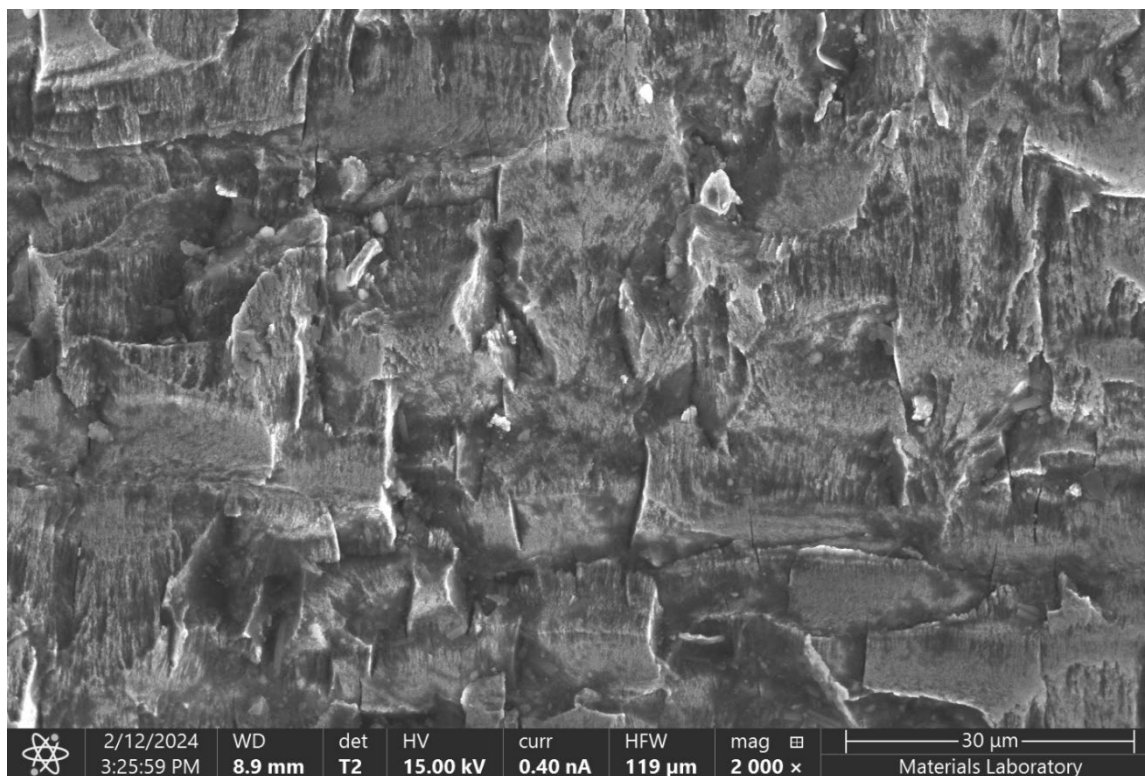


Figure 25. SE micrograph of the fractured Cr electroplating surface coating.

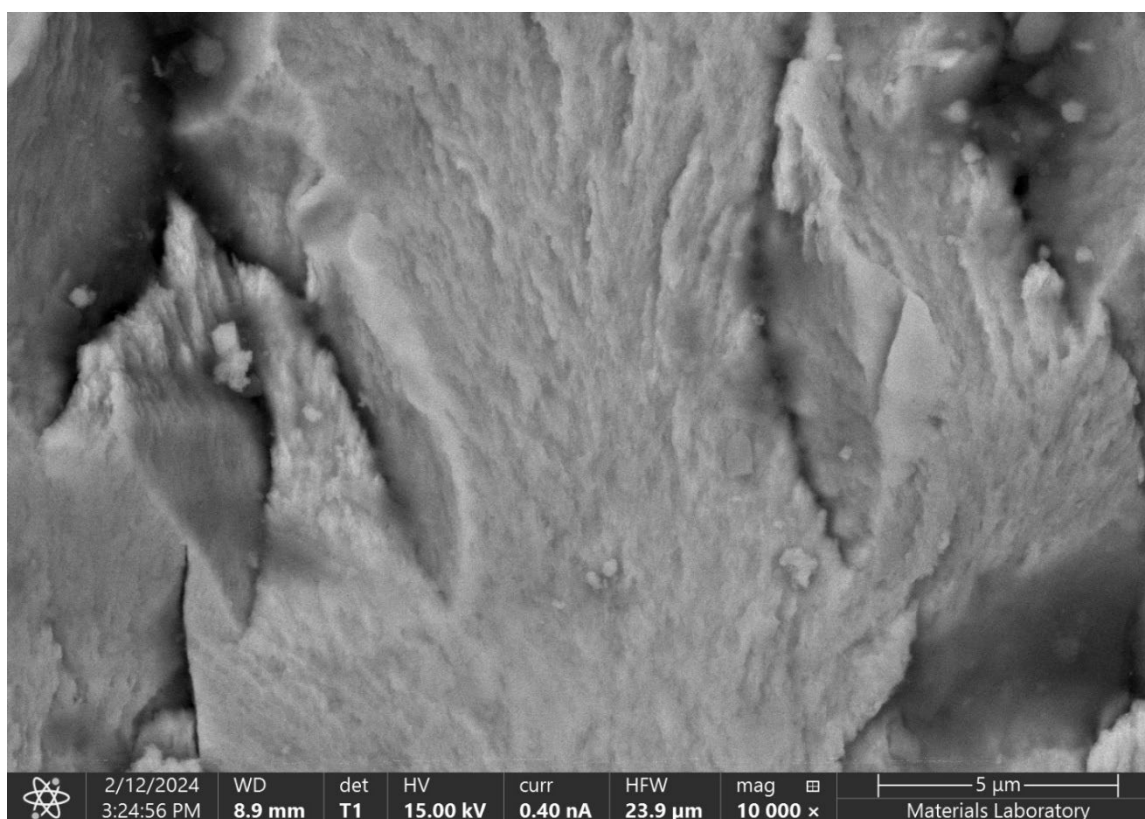


Figure 26. BE micrograph of one of the facets in **Figure 25**.

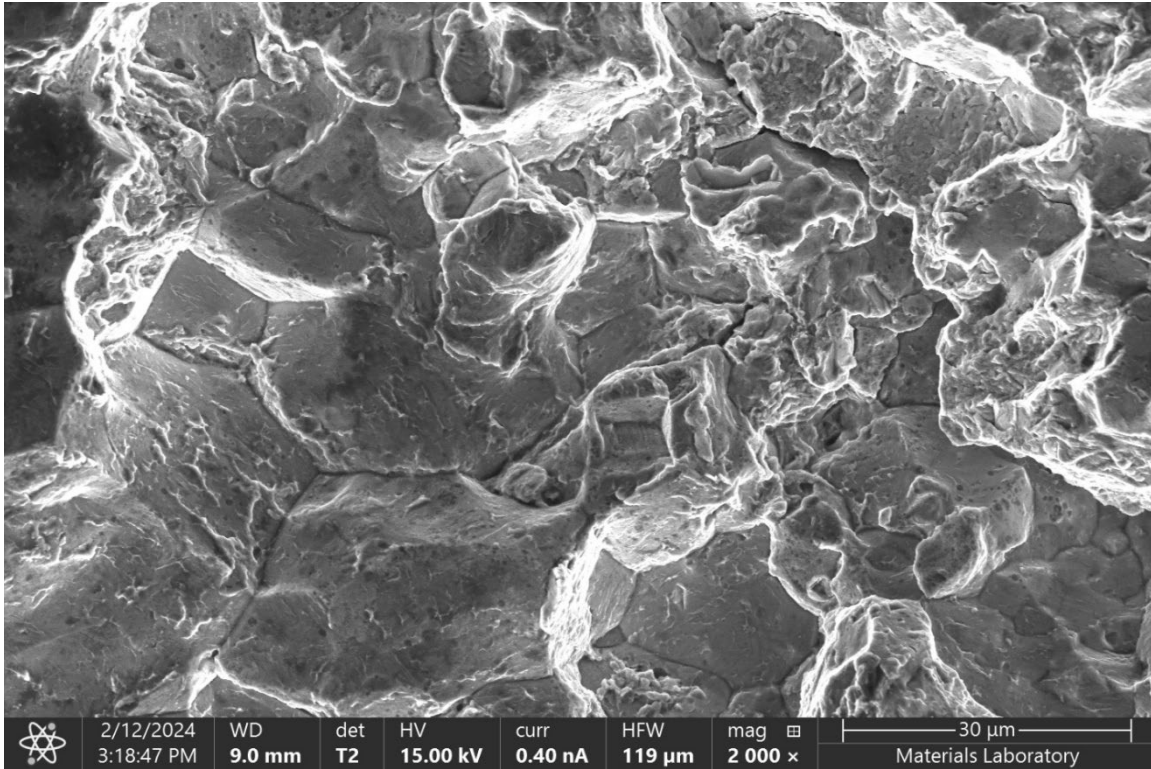


Figure 27. SE micrograph of a typical area of the initial intergranular region.

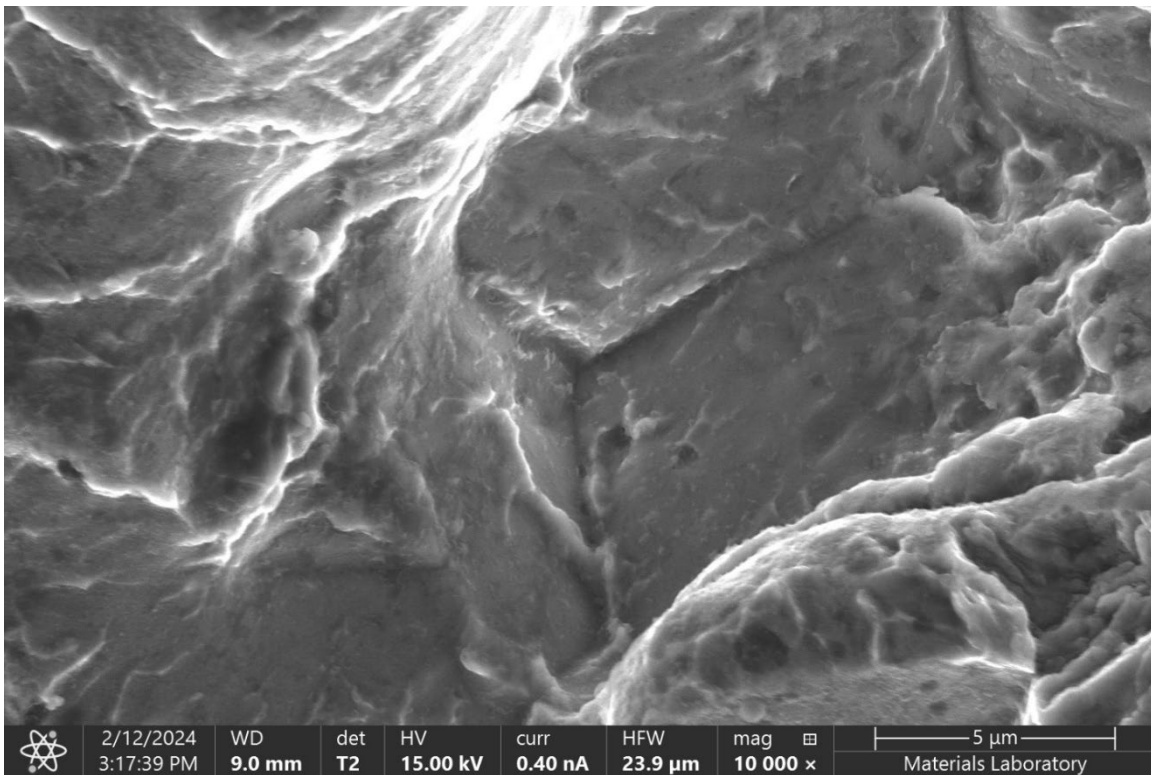


Figure 28. SE micrograph of a triple point in the intergranular region in **Figure 27**.

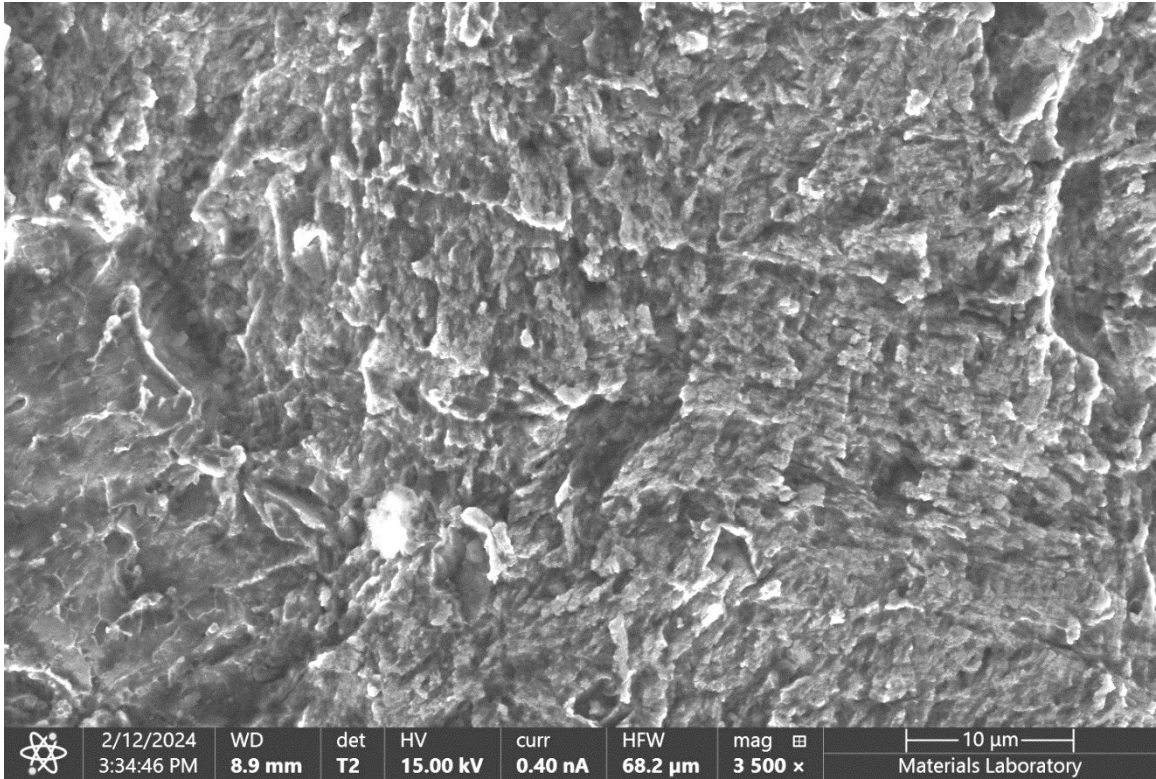


Figure 29. SE micrograph of a typical area of fatigue crack propagation in the thumbnail crack of the forward pin remnant fracture surface.

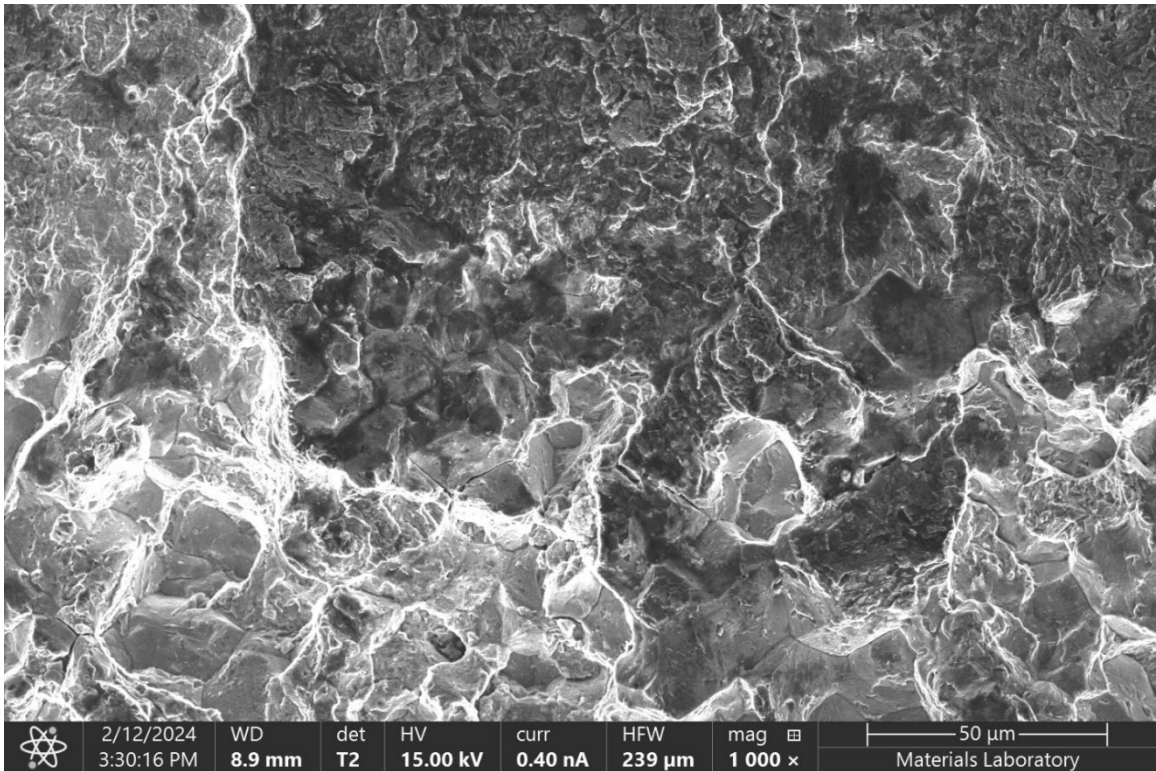


Figure 30. SE micrograph showing fatigue initiation sites off the intergranular region.

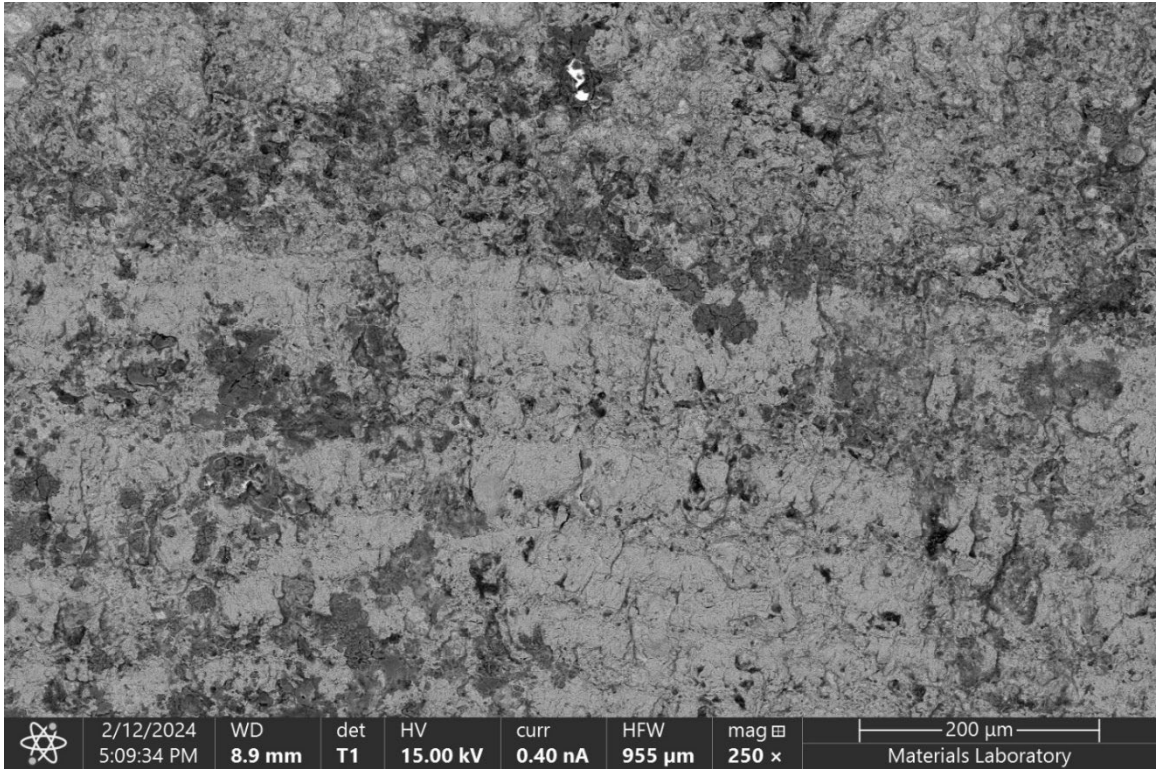


Figure 31. BE micrograph showing the terminus of the fatigue thumbnail crack.

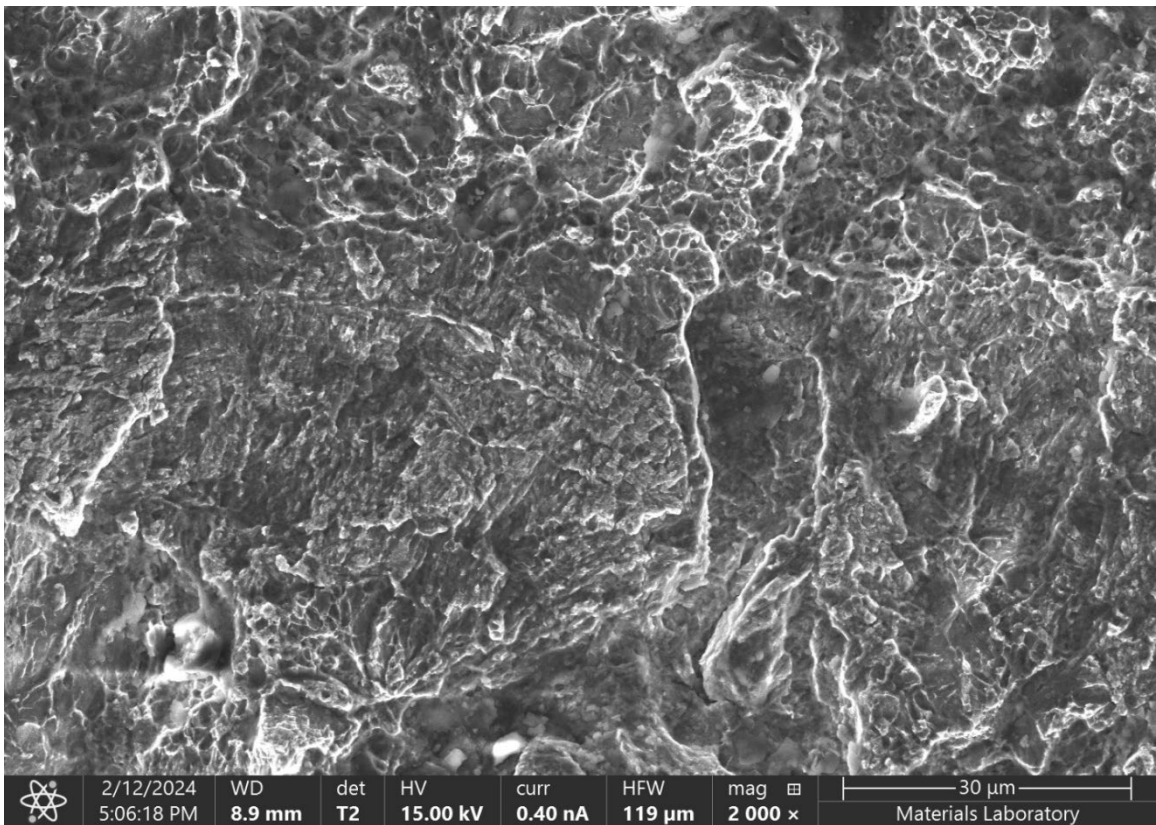


Figure 32. SE micrograph of the end of the fatigue thumbnail crack.



Figure 33. View of all the remnants and sections of the aft trunnion pin, taken after receipt and sectioning of the aft remnant (courtesy: Boeing EQA).

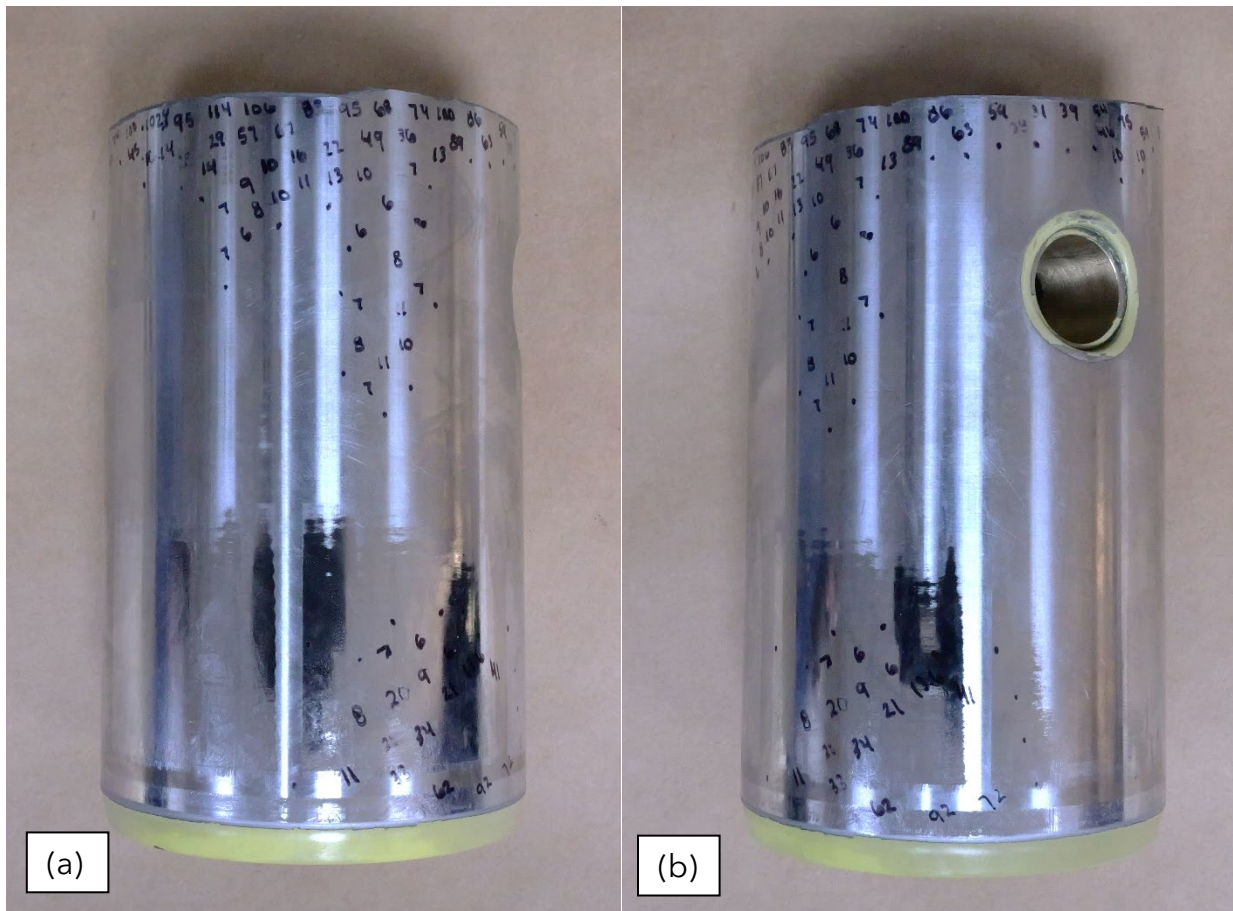


Figure 34. The aft remnant of the aft trunnion pin, with Barkhausen data written directly on the exterior surface (courtesy: Boeing EQA).

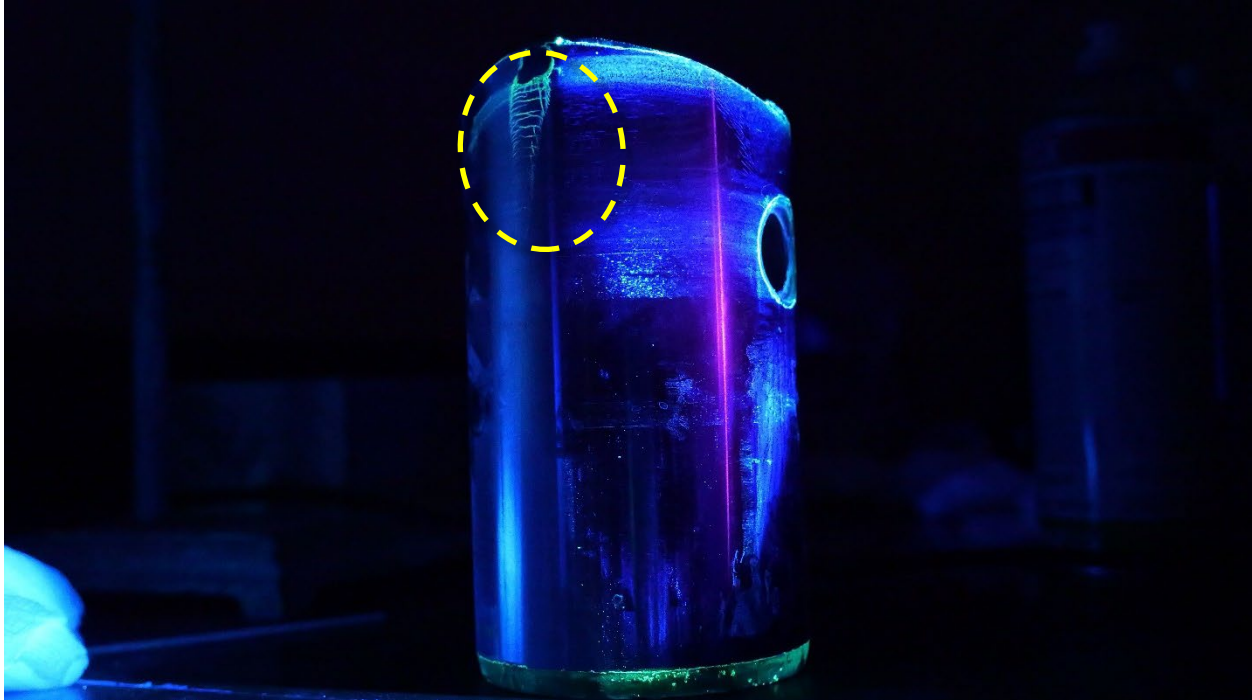


Figure 35. Ultraviolet light image of the aft pin remnant during FPI examination, with areas of parallel cracks highlighted (circle) (courtesy: Boeing EQA)

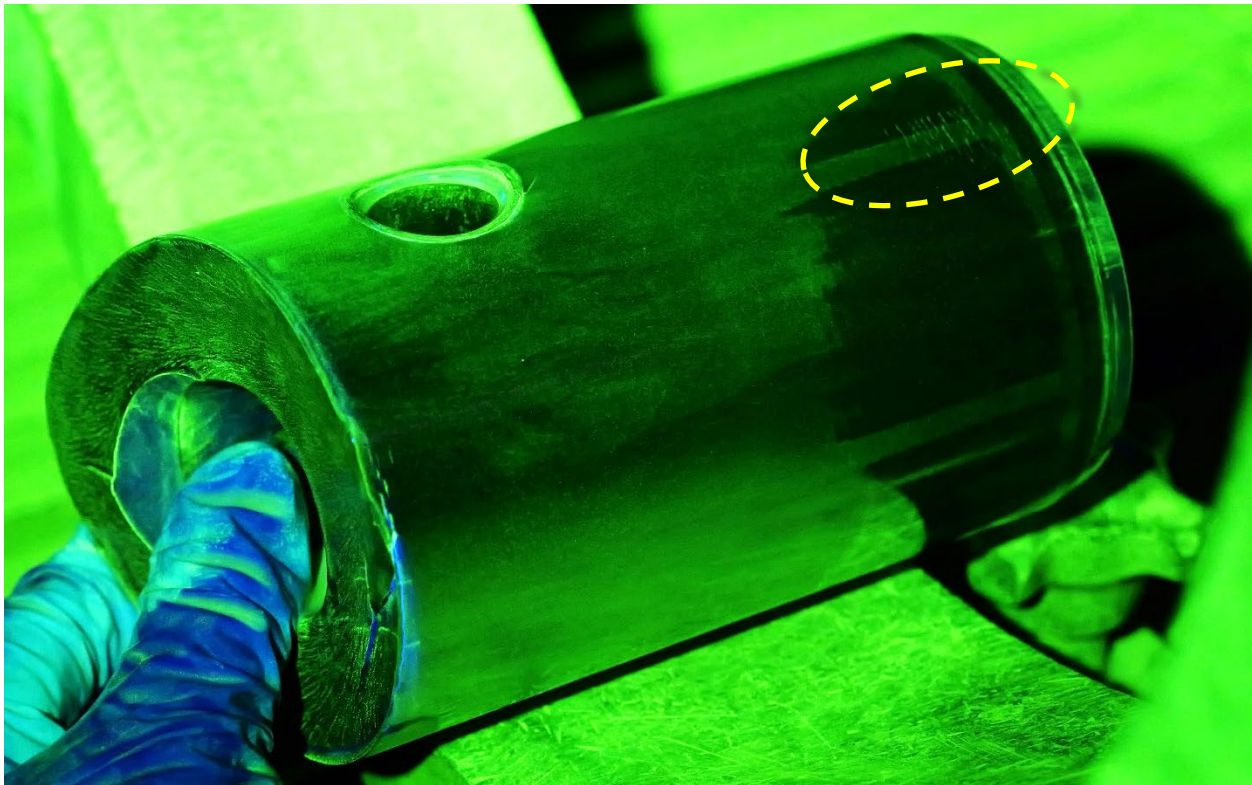


Figure 36. Ultraviolet light image of the aft pin remnant under MPI examination, with the area of parallel cracking circled (courtesy: Boeing EQA).



Figure 37. Images of the aft remnant of the aft trunnion pin showing temper etch surface contrast (courtesy: Boeing). The fracture surface is identified in the upper left.

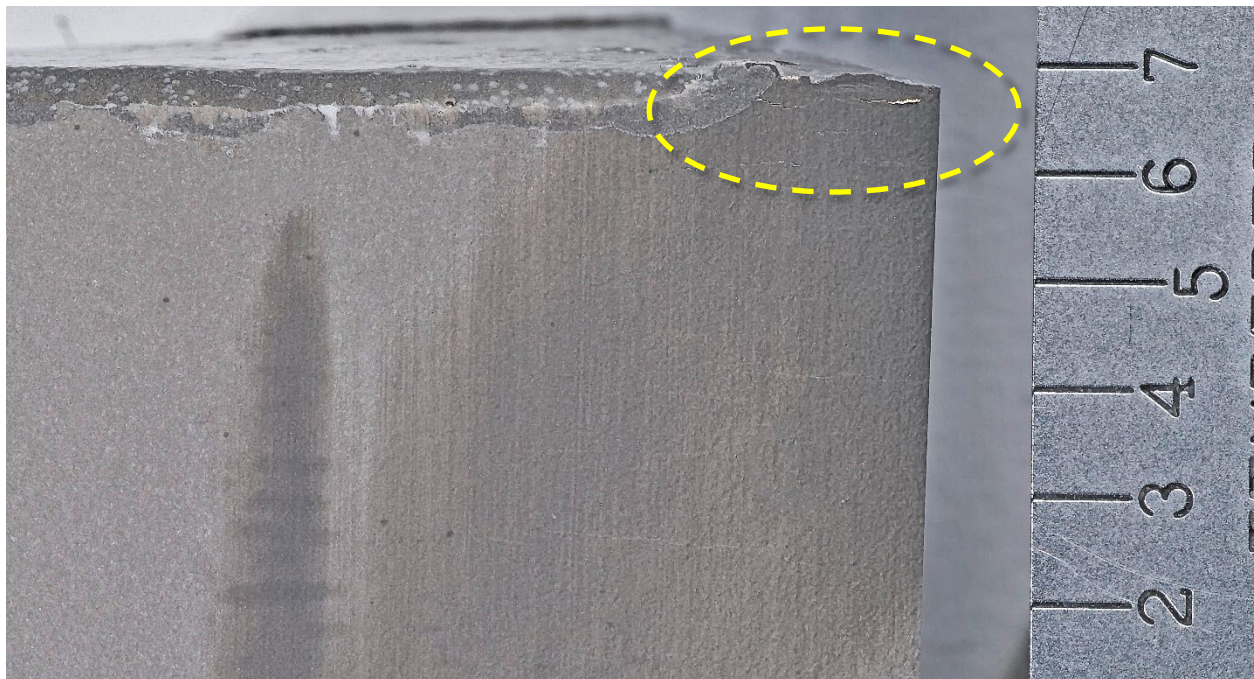


Figure 38. Closer view of the fatigue crack initiation site edge (circled) after temper etch.



Figure 39. View of the temper etch indications relative to the sectioned thumbnail crack of the aft pin remnant (courtesy: Boeing).

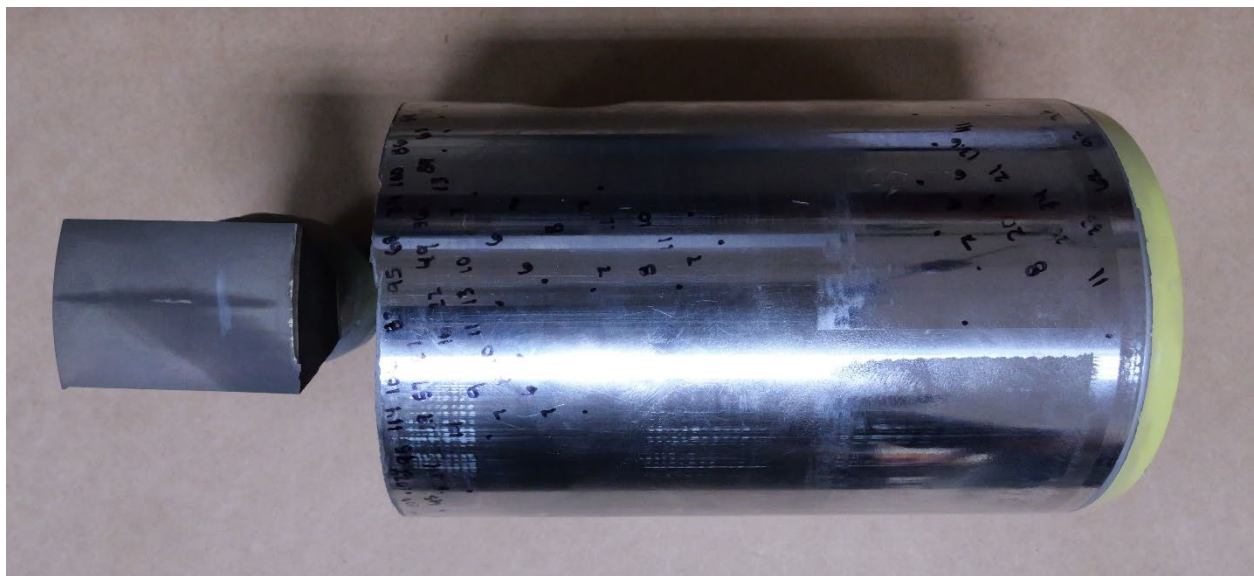


Figure 40. View of the mating sides of the fatigue crack portions of the fracture surface from the forward and aft remnants of the trunnion pin (courtesy: Boeing EQA).

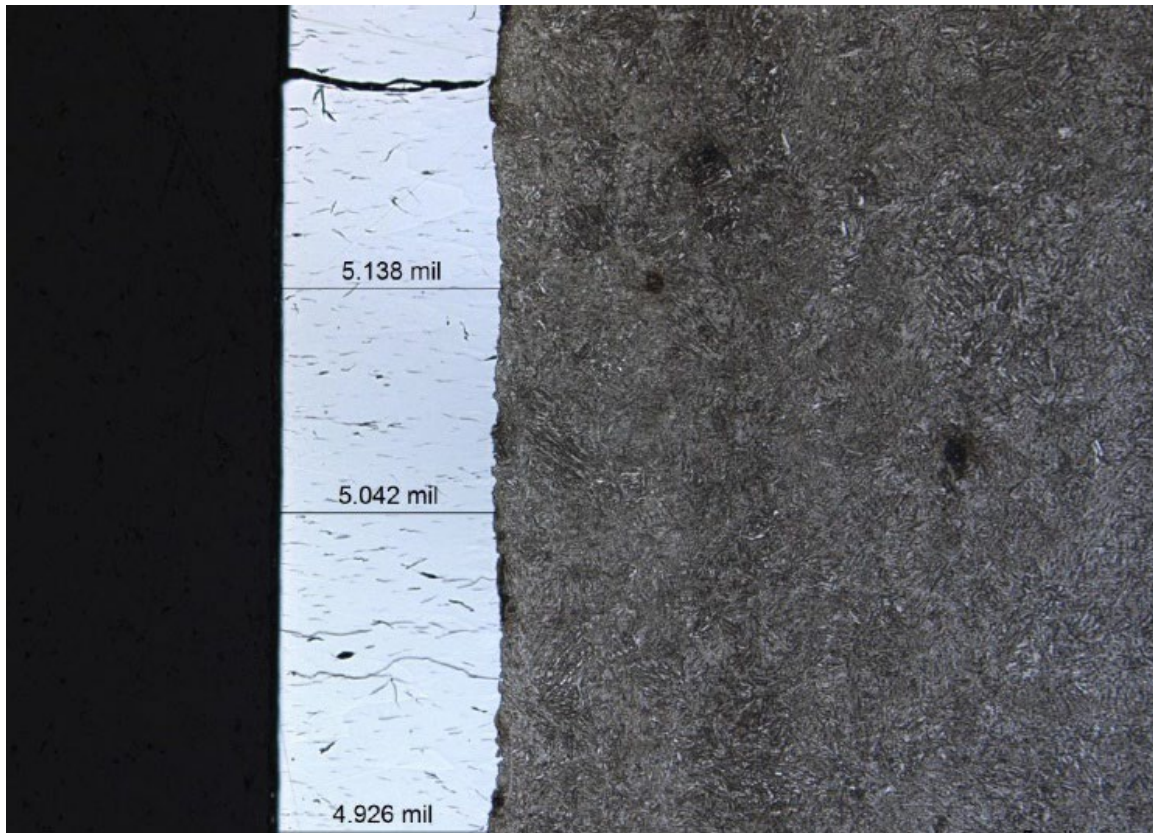


Figure 41. Bright-field (BF) optical micrograph through the surface of the aft pin remnant, showing the Cr electroplated surface layer, and annotated measurements (courtesy: Boeing EQA).

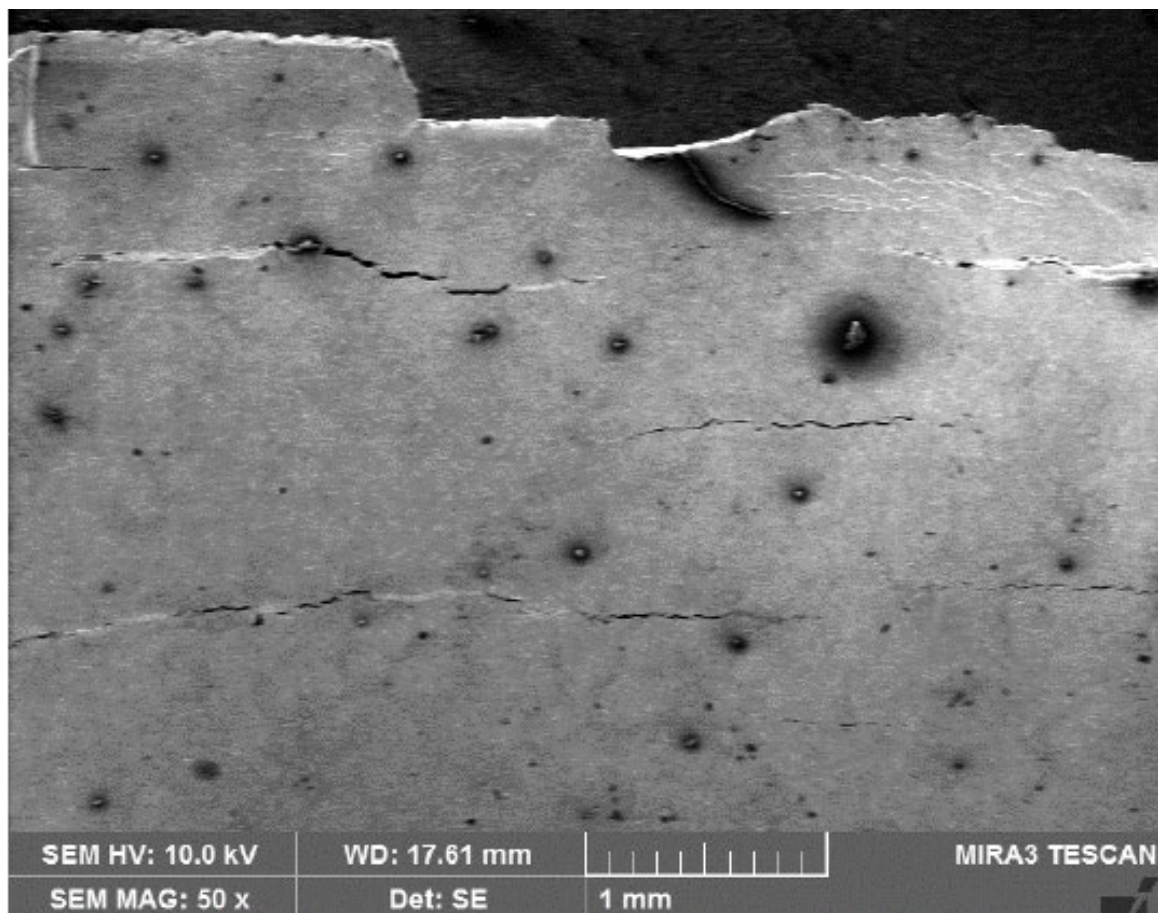


Figure 42. SE micrograph of surface cracks in the Cr electroplating layer near the thumbnail crack on the aft pin remnant (courtesy: Boeing).

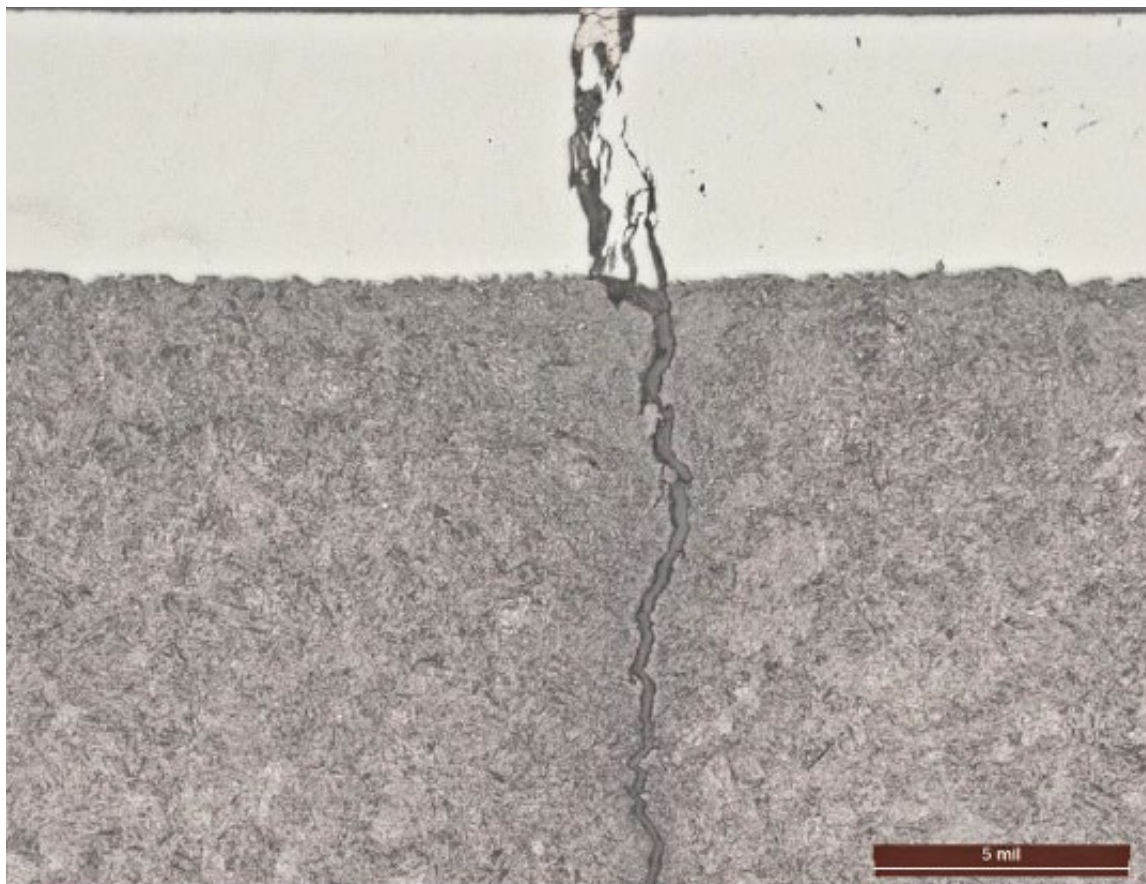


Figure 43. BF optical micrograph of a section through one of the surface cracks in **Figure 42** (courtesy: Boeing).

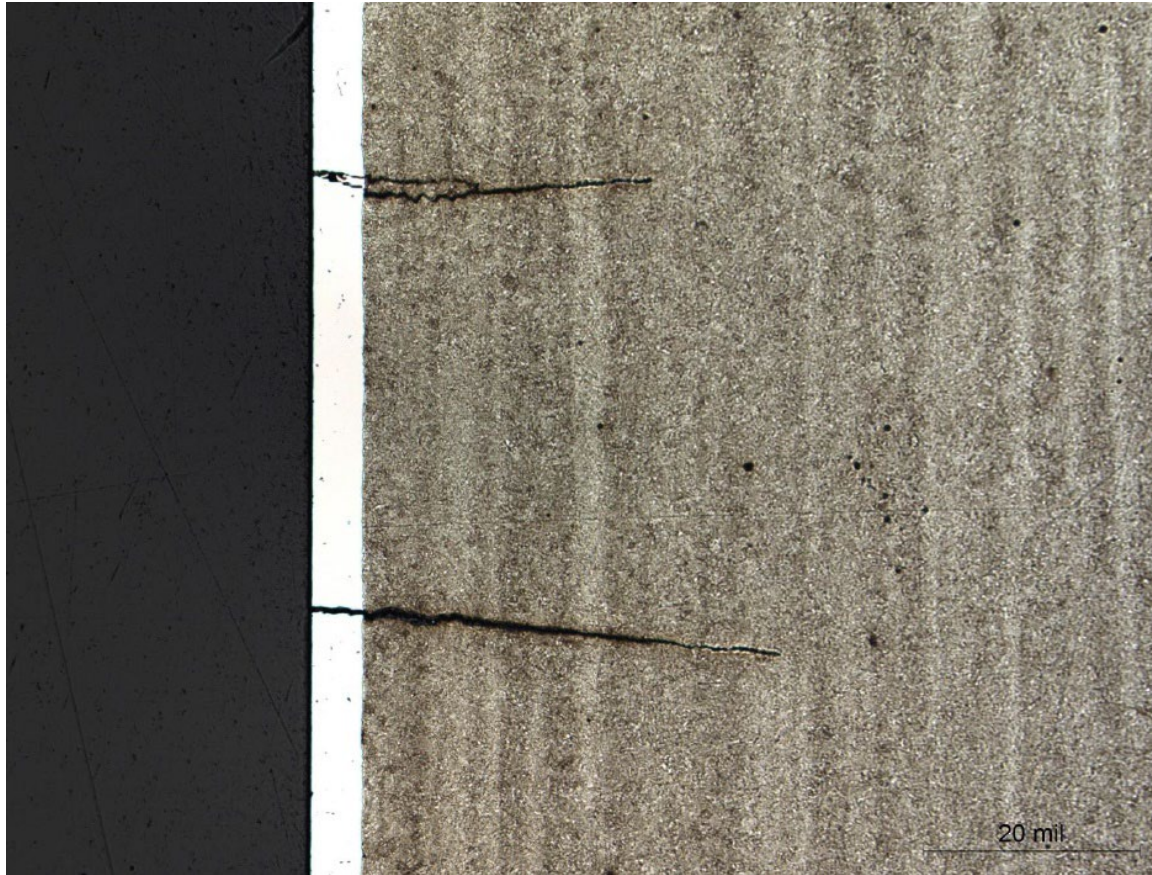


Figure 44. BF micrograph of additional cracks through the aft pin remnant surface (courtesy: Boeing).