

NATIONAL TRANSPORTATION SAFETY BOARD

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



June 23, 2020

MATERIALS LABORATORY FACTUAL REPORT

Report No. 20-014

1. ACCIDENT INFORMATION

Place : Denver, Colorado
Date : December 22, 2019
Vehicle : Boeing 737-800, N87513
NTSB No. : DCA20LA047
Investigator : Dan Bower, AS-10

2. COMPONENTS EXAMINED

Remnants of a main landing gear trunnion pin

3. DETAILS OF THE EXAMINATION

On December 22, 2019, a Boeing 737-800 operated by United Air Lines (UAL) collapsed during a landing in Denver, CO.¹ The collapse occurred in the left main landing gear assembly. After examination of the wreckage, the left-hand main landing gear aft trunnion pin was found fractured. This pin connected the main landing gear beam and outer cylinder. The pin sat inside the trunnion, attached with a cross bolt. According to the personnel on scene, the forward section of the trunnion pin was still in place inside the trunnion, held in place by a damaged but intact cross bolt. The aft pin section had separated and was located with the beam.

The pieces of this component were sent to Boeing Equipment Quality Analysis (EQA) in Seattle, WA for group examination, which was performed from January 22 to 24, 2020. Additional testing and examination were performed at the NTSB Materials Laboratory and Boeing Research and Technology Laboratories in the following months after the group examination.

The trunnion pin, P/N 161A1192-13 and S/N 65780-0066, had been examined by United Airlines personnel prior to the group examination. The trunnion pin was made of Type 4340M alloy steel, and then coated externally with a chromium electroplated layer, and internally with a cadmium-titanium alloy electroplated layer with chromate treatment. The part had been inspected visually, as well as with Barkhausen noise inspection (BNI), fluorescent

¹ The Boeing 737-800 is a variant of the 737 Next Generation family of jet airplanes, which are narrow-body aircraft powered by two engines and produced by Boeing Commercial Airplanes, headquartered in Seattle, WA.

penetrant inspection (FPI) and magnetic particle inspection (MPI).² The Barkhausen noise inspection found some areas of elevated readings away from the fracture surface. No additional indications were noted from the FPI and MPI.

The trunnion pin had fractured into two pieces, as shown in Figure 1 and Figure 2. The pin had fractured approximately perpendicular to the length of the pin at midspan. The separated aft piece of the pin contained remnants of white paint on the beveled bottom of the pin opposite the fracture surface (Figure 2). The forward piece of the pin that was found inside the trunnion had green enamel primer on the beveled face opposite the fracture surface (Figure 1).

The mating fracture surfaces are shown in Figure 3. The majority of the mating pin fracture faces exhibited a rough, fibrous surface with a dull gray luster. This surface exhibited flow lines consistent with fracture of the part from the bottom of the fracture in Figure 3 around the pin cavity upward. The flow lines emanated from a small thumbnail crack, approximately located at the 12 o'clock (upward-facing) position of the pin (shown on the bottom of Figure 3a and Figure 3b).

The outer diameter surfaces of the pin pieces were examined using Barkhausen noise inspection. The probes were calibrated to a specially designed shot-peened steel standard that had simulated grinding burn regions, created from an induction heating process. The thicknesses of the chromium electroplated layer of the pin pieces were inspected and used to determine a shim thickness for more accurate calibration.

The BNI readings were taken on the outer surface of both pin pieces (see Figure 4 and Figure 5). The data showed readings above the calculated baseline near the fracture surface of both halves—this was concentrated near the fracture origin on the forward pin piece (Figure 5a and Figure 5b) and 180° opposite on the aft pin piece (Figure 4a). In addition, the aft piece exhibited elevated readings above the calculated baseline about 1 inch below the fracture surface origin (Figure 4b). This area was approximately 2 inches along the circumferential direction and 0.5 inch in the longitudinal direction.

The parts were then inspected using MPI and FPI. MPI was able to be performed in the coil and head shot directions for the aft piece, but could only be performed in the coil direction for the forward piece. In both cases, the coil shot direction would be able to detect circumferential/transverse crack indications. Neither MPI orientation revealed any indications of cracks (as typified in Figure 6).

FPI inspection was performed on both pieces (see Figure 7). From this inspection, no indications of an abnormal network of cracks, (such as “chicken wire” or “ladder” 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 not observed near

² 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 degradation of mechanical properties in magnetic materials, such as high-strength steels that have undergone damage from grinding.

the fracture origins. These cracks were consistent with cracks in the chromium electroplated layer that would form as the pin separated at the time of the accident.

The fracture surface was examined and documented. A small thumbnail crack was present on the approximate 12 o'clock position of the forward pin piece fracture surface. This thumbnail crack exhibited diverse colors visually, along with crack arrest marks (see Figure 8). These features were consistent with pre-existing progressive cracking in this section of the pin. The majority of the rest of the fracture surface exhibited river patterns and chevron marks, which flowed from the small thumbnail crack. Some limited shear lips were observed in the upper half of the fracture, along the outer diameter surface. These features were consistent with subsequent overstress fracture during the accident landing event.

The thumbnail crack dimensions were measured with a digital optical microscope, as annotated in Figure 9. The crack measured 0.154 inches deep, with a linear length on the outer diameter (OD) of 0.275 inches. There was a discolored region that measured 0.105 inches deep by 0.216 inches long inside the thumbnail crack (see Figure 9). There was an adherent shiny external layer, and a subsurface darker, faceted region (see Figure 10). These different regions of the fracture surface will be detailed further below.

The thumbnail crack on the aft side had been damaged along the edge, consistent with post-fracture impact damage with another component (see Figure 11). The mating forward fracture surface was relatively undamaged, and it was selected for further microscopic examination. The aft fracture surface was used for metallographic examination, along with a temper etchant inspection.

A section encompassing the forward piece thumbnail crack was examined in a scanning electron microscope (SEM), as shown in Figure 12. This crack was examined after MPI and FPI, and again after using successive cleaning with acetone, cellulose acetate tape, and Alconox.³ Examination using the SEM found an outer adherent chromium electroplated layer, approximately 0.005 inches in thickness, upwards of 0.006 inches thick at the crack initiation site (Figure 13). The chromium electroplated layer was generally adherent, with no indications of corrosion or pitting. The chromium electroplated area along the fracture surface exhibited faceted fracture features (Figure 14).

A thin layer of intergranular cracking was present below the chromium electroplating layer (see Figure 15). This intergranular cracking area was consistent with the location of the origin of the thumbnail crack (Figure 16). Internal to this intergranular region was a series of small ratchet marks, consistent with multiple small cracks coalescing as they propagated inward. The intergranular region measured approximately 0.011 inches deep and was approximately 0.074 inches in width.

Figure 17 shows a closer view of one of the facets in the intergranular region. This area exhibited a secondary crack, which was a crack that had propagated perpendicular to the fracture surface. Just above the middle facet highlighted in Figure 17 was the transition to

³ Alconox is a powdered cleaning detergent, containing primarily sodium bicarbonate and sodium alkylbenzene sulfonate, manufactured by Alconox, Inc., White Plains, NY.

different fracture features. As highlighted in Figure 18, these features were sequential bands parallel to the intergranular facet, consistent with fatigue striations.

The remainder of the thumbnail crack exhibited fatigue striations, consistent with fatigue crack propagation (Figure 19). 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. In the outer areas of the thumbnail crack (those not discolored visually), some bands of dimpled rupture were observed among fatigue striations.

Outside of the thumbnail crack, dimpled rupture was observed—these features were consistent with subsequent overstress fracture that occurred during the final fracture upon the accident landing event (Figure 20). Along the edge of the fracture surface, the thumbnail crack bowed, consistent with lateral as well as depth-wise crack propagation (see Figure 21). These areas also exhibited fatigue striations. There were indications of striations along the chromium electroplated layer, as shown in Figure 21.

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 were 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.

The thumbnail crack on the aft pin remnant was bisected with a small angle cut underneath to remove a wedge section (see Figure 22). The remainder of the aft pin remnant underwent a stripping process to remove the chromium electroplated layer, using an electrolytic solution of sodium hydroxide (NaOH) and sodium carbonate (NaCO_3), held at 100 °F with 4 – 6 V. The process was interrupted in intermediate steps to examine the underlying chromium electroplated layer. This process had removed the outer smeared layer revealing microcracking of the chromium electroplated layer. The plating exhibited multiple cross-cracks, typical of hard chromium electroplated layers (see Figure 23). This microcracking was multidirectional in nature and did not exhibit cracking patterns consistent with “ladder cracking” or “chicken-wire cracking.” The remainder of the chromium electroplated layer on the aft side was then completely stripped electrochemically.

The stripped aft section of the pin was examined using MPI (illustrated in Figure 24). This nondestructive inspection revealed longitudinal ladder cracks, located in the area of material transfer and elevated Barkhausen noise indications, shown in Figure 4b. This cracking pattern was consistent with those observed from a subsequent FPI inspection, as illustrated in Figure 25.

The stripped surfaces were then etched in a 2% Nital bath. As shown in Figure 26, there were two areas exhibiting darker contrast on the surface, consistent with localized elevated iron carbide content, indicative of localized overtempering. There was an area approximately 0.5 inches from the fracture origin, and an area noted adjacent to the fracture surface. These marks were consistent with heat exposure, typical of a previous grinding operation. The stripped material transfer area also exhibited more pronounced darker regions, consistent with overtempering (Figure 27). This area was consistent with the location of the ladder cracks identified by MPI.

The wedge section shown in Figure 22b was mounted and polished for metallographic examination. This specimen was then etched using a 2% Nital solution to reveal the microstructure.⁴ Examination of the cross section through the aft thumbnail crack revealed the outer chromium electroplated layer up to the damaged edge of the thumbnail crack (Figure 28 and Figure 29).

The chromium electroplated layer adjacent to the beveled edge of the thumbnail crack exhibited through cracking (Figure 30 through Figure 32). This cracking was present only in the areas consistent with post fracture impact damage. No indications of secondary cracking were found emanating from either the fracture surface or the outer diameter (plated) surface of the cross section (compare with Figure 28). The beveled area closest to the fracture surface was absent chromium electroplated layer and exhibited a localized area of a lighter-etching microstructure, consistent with untempered martensite (Figure 33). This damage mirrored that observed macroscopically on the mating aft pin remnant (shown in Figure 34 after chromium electroplated layer stripping and acid etching).

Overall, the microstructure of the aft thumbnail cross section was consistent with tempered martensite. The area of the underlying etched steel microstructure exhibited a darker color in response to the etch underneath the chromium electroplated layer (left side of Figure 29). A closer view of this subsurface darker region is highlighted in Figure 35.

The hardness was examined using a microindentation hardness method using a 100 gram load for Vickers hardness (HV_{100}), consistent with ASTM E384.⁵ The data were converted per ASTM E140.⁶ The hardness in the core averaged 55 to 56 HRC (595 to 613 HK_{100}). The hardness of the core material adjacent to the chromium electroplated layer measured 52 HRC (540 HK_{100}).

A similar cross section was taken through the darker colored region in the etch aft pin outer diameter surface region, highlighted in Figure 26. Figure 37 shows the microindentation hardness indents in this cross section. Whereas the core regions (away from the outer

⁴ Nital etchant is a solution of 2% concentrated nitric acid in ethanol.

⁵ ASTM E384 – *Standard Test Method for Knoop and Vickers Hardness of Materials*. ASTM International, West Conshohocken, PA

⁶ ASTM E140 – *Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness*. ASTM International, West Conshohocken, PA

diameter surface) exhibited an average hardness between 55 to 56 HRC, the areas closest to the surface exhibited a lower hardness of 53 HRC (556 HK₁₀₀).

The regions just under the chromium electroplated layer exhibited a darker color, consistent with a different etching response than the rest of the pin steel. This darker region was consistent with an area of higher iron carbide content, indicative of localized overtempering.

Erik M Mueller
Materials Research Engineer

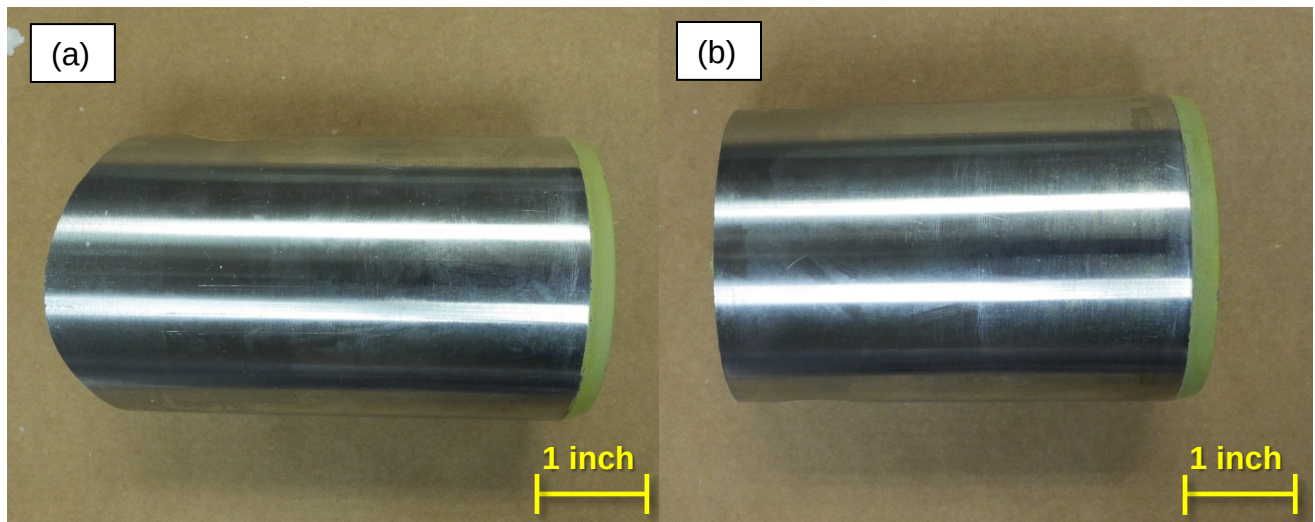


Figure 1 – The forward fractured section of the trunnion pin, as received, viewed from (a) the approximately 6 o'clock position and (b) the approximately 12 o'clock position.

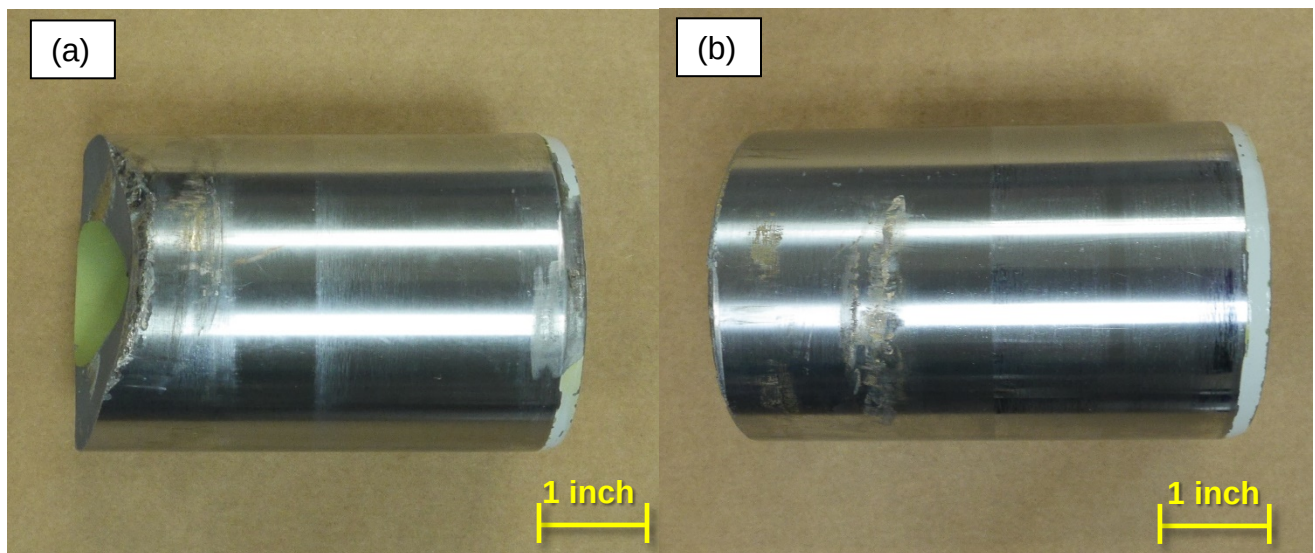


Figure 2 – The aft fractured section of the trunnion pin, as received, viewed from (a) the approximately 6 o'clock position and (b) the approximately 12 o'clock position.

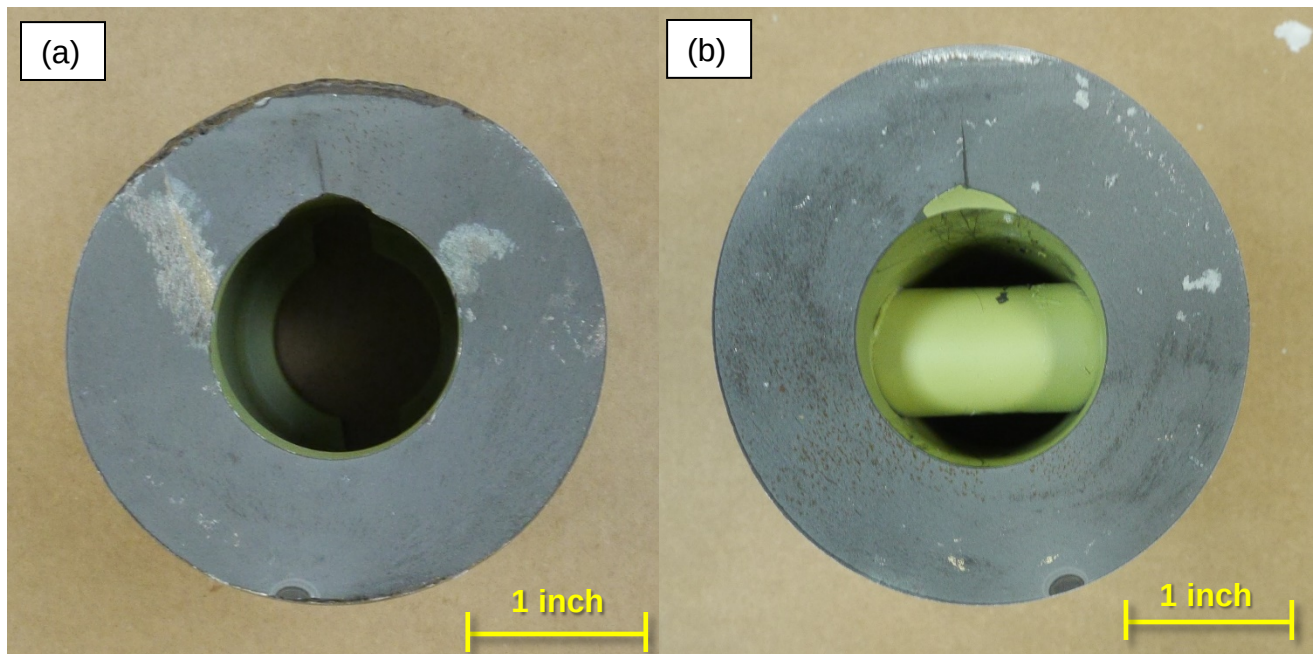


Figure 3 – The mating fracture surfaces of the trunnion pin from (a) the aft and (b) forward sides.

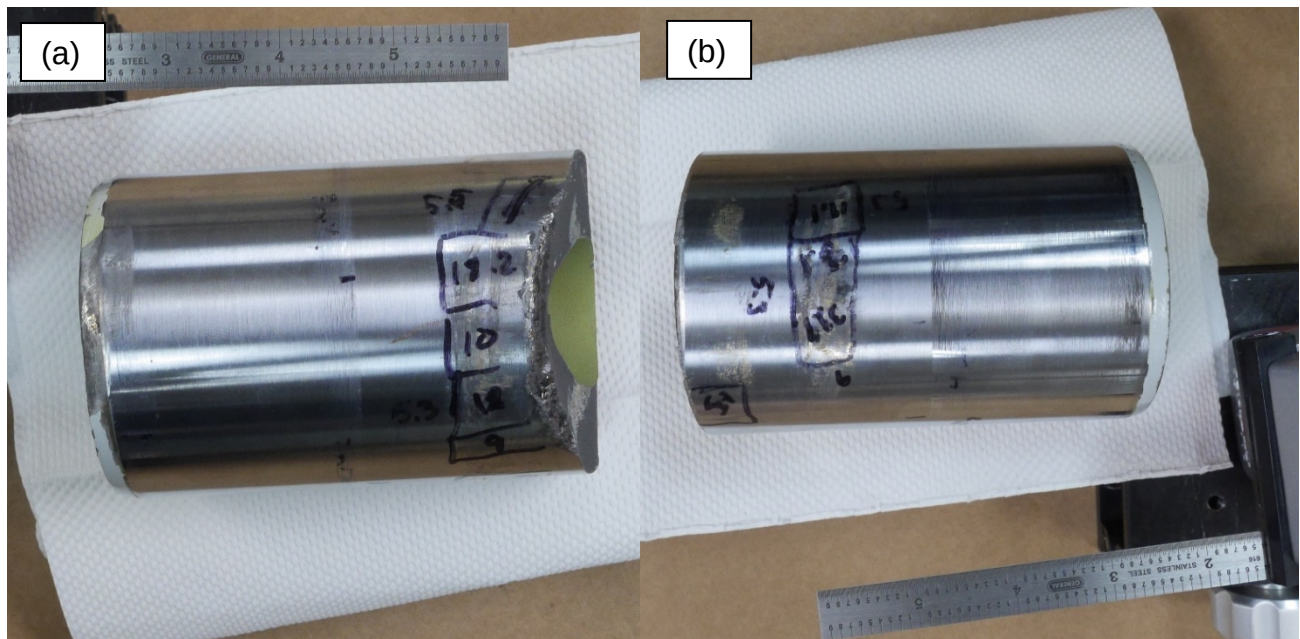


Figure 4 – The aft trunnion pin remnant, from (a) the 6 o'clock and (b) and 12 o'clock positions, after examination using Barkhausen noise inspection.

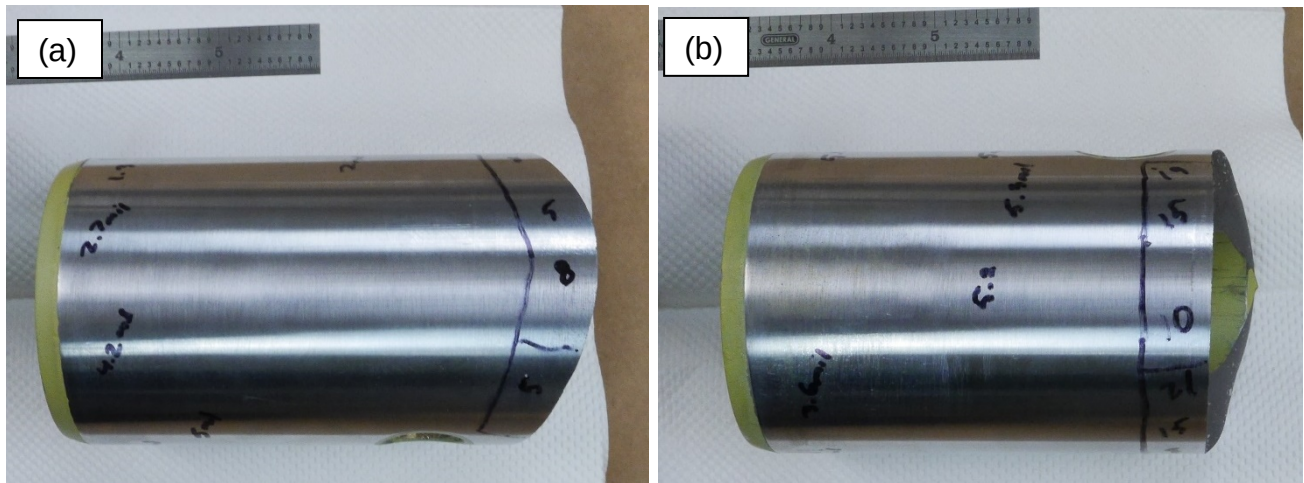


Figure 5 – The forward trunnion pin remnant, from (a) the 6 o'clock and (b) and 12 o'clock positions, after examination using Barkhausen noise inspection.

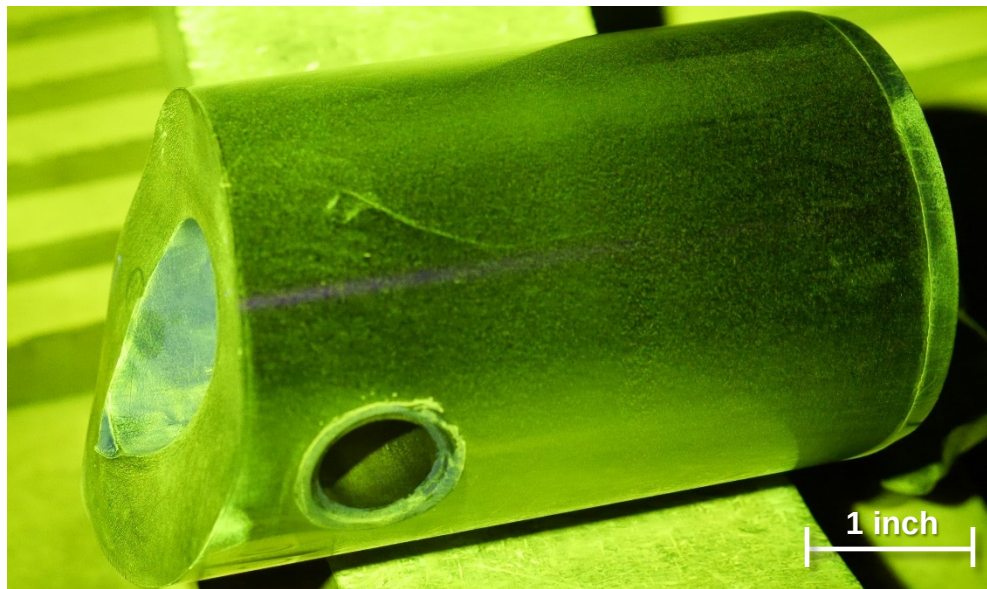


Figure 6 – View of the forward trunnion pin piece under UV light after MPI. The indication observed was consistent with a post-fracture scratch.

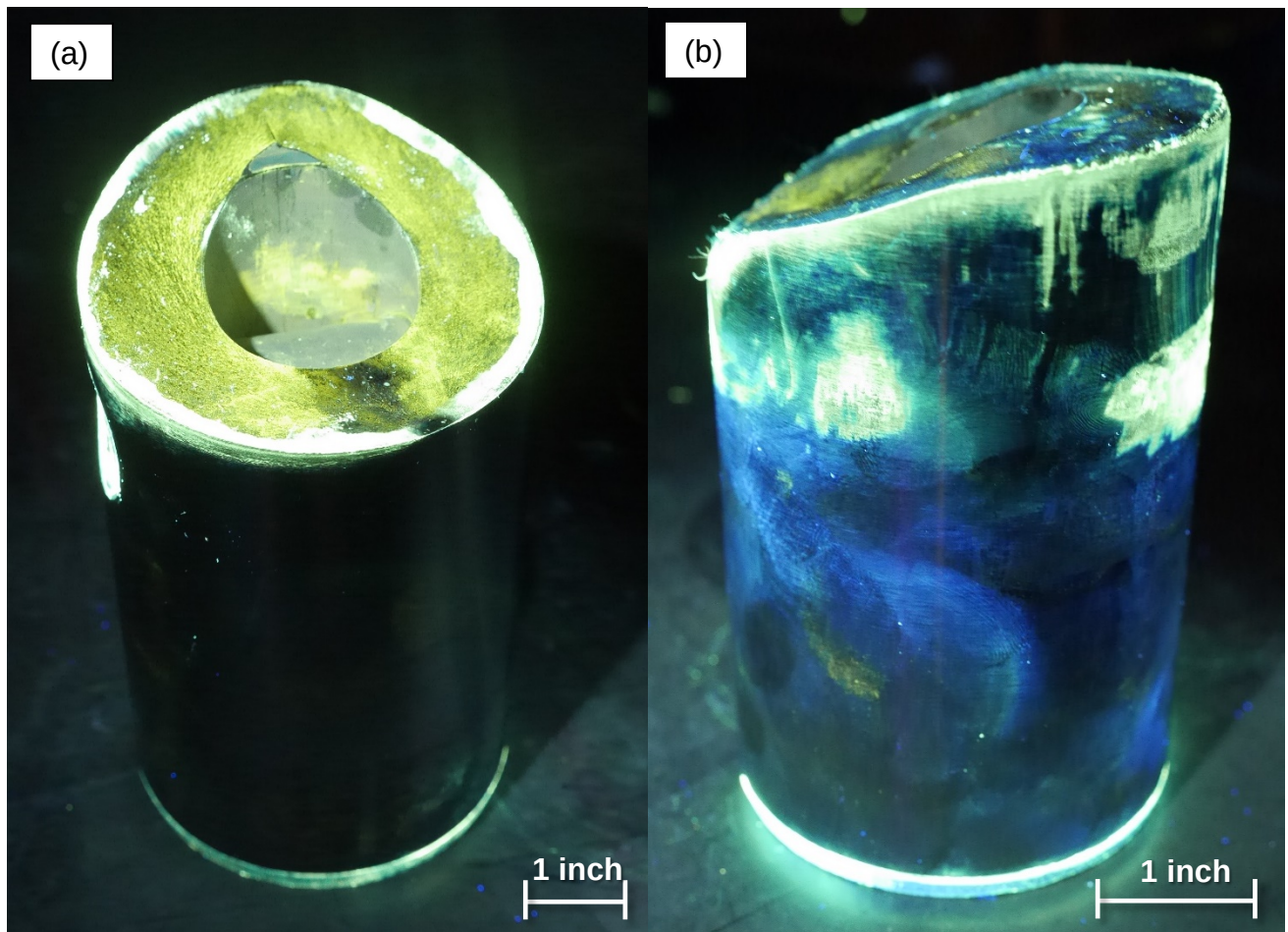


Figure 7 – View of the (a) forward and (b) aft trunnion pieces viewed under UV light during FPI.

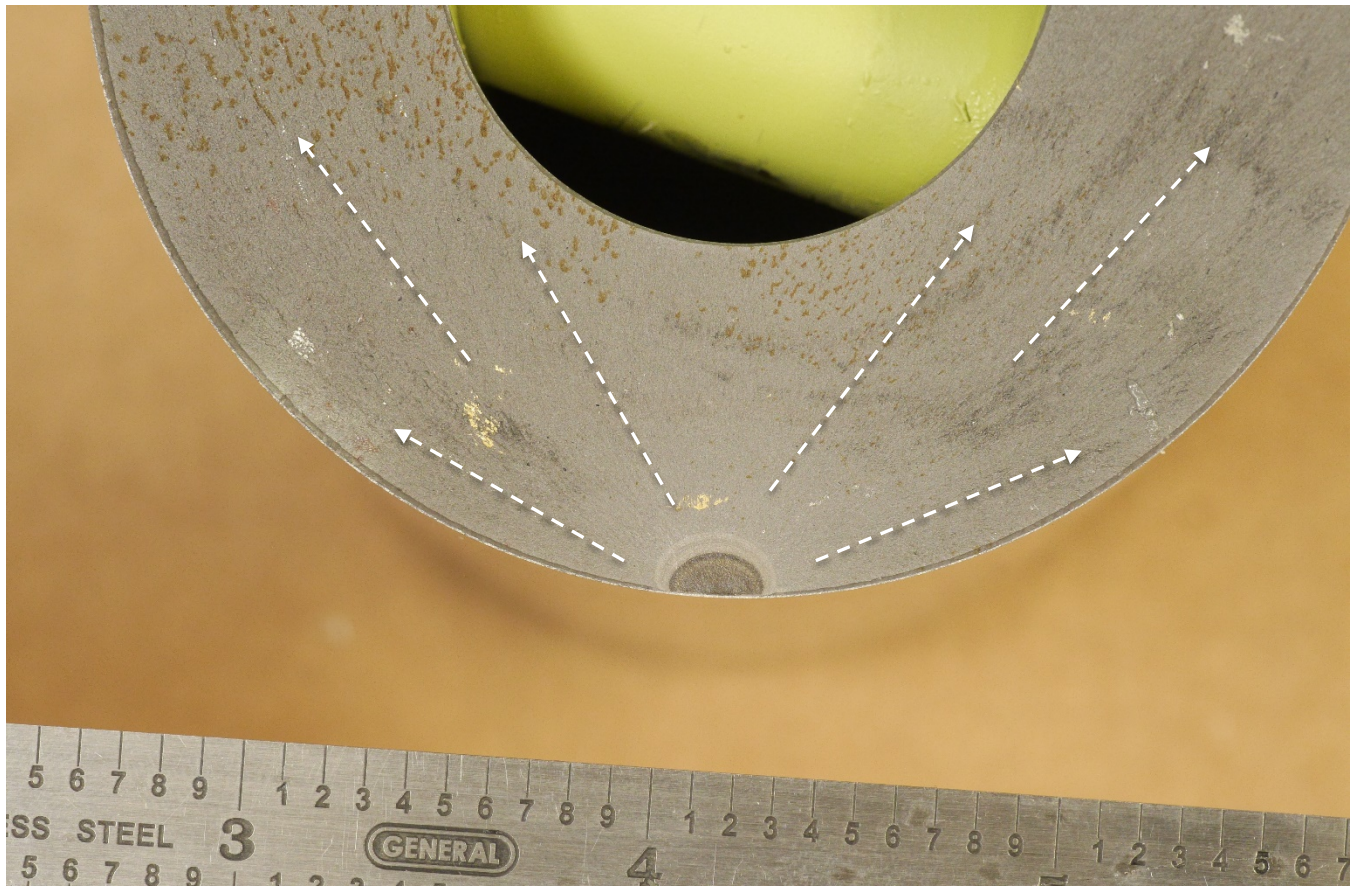


Figure 8 – Fracture surface of the forward pin fracture surface, showing a thumbnail crack at the 12 o'clock position. White dashed arrows denote the fracture direction from the thumbnail.

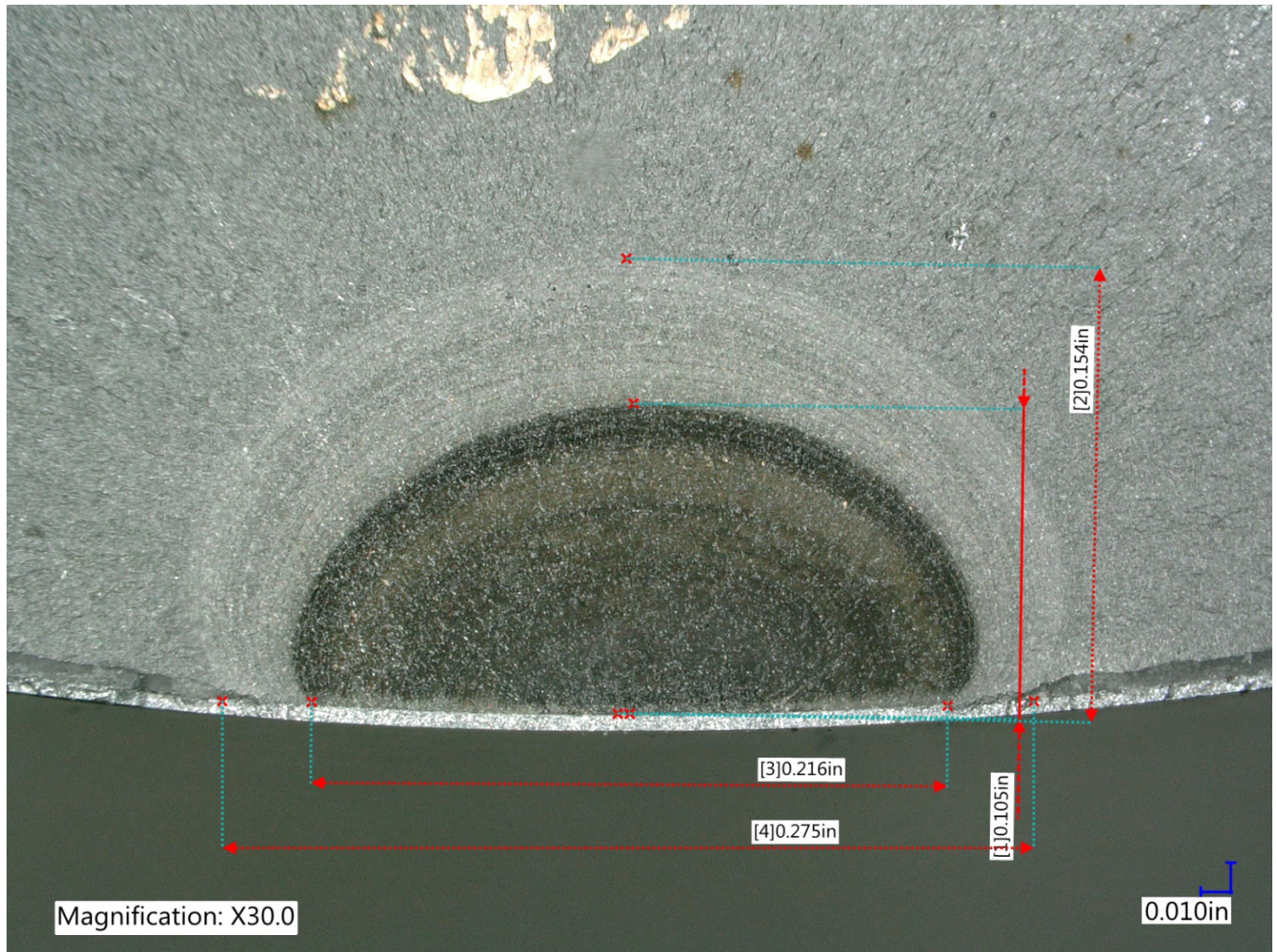


Figure 9 – Microscopic view of the thumbnail crack in Figure 8, annotated to show various dimensions.

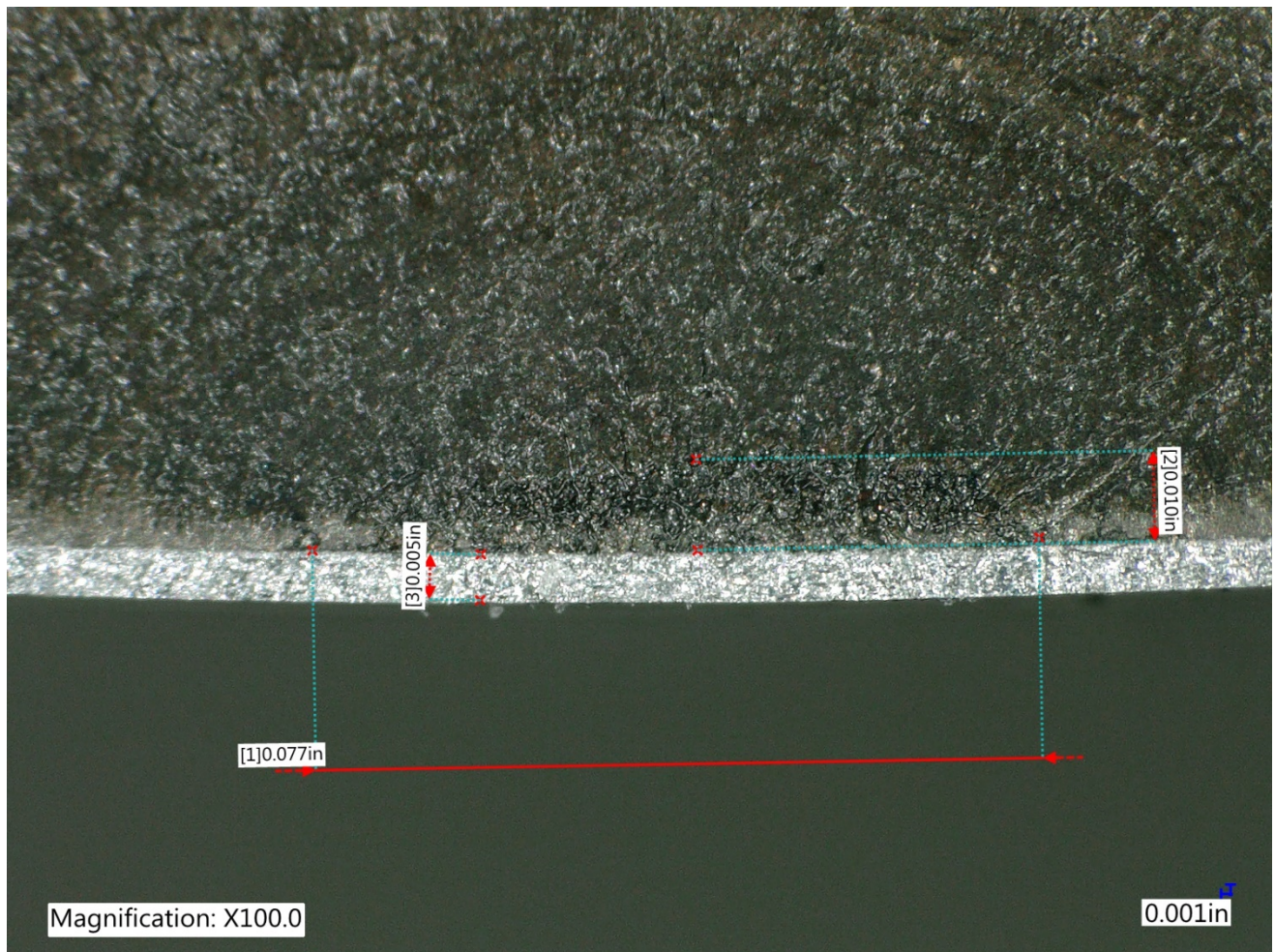


Figure 10 – Closer view of the initiation region of the thumbnail crack in Figure 9, with annotated measurements of the intergranular region (dark) and the outer chromium electroplating layer (light).

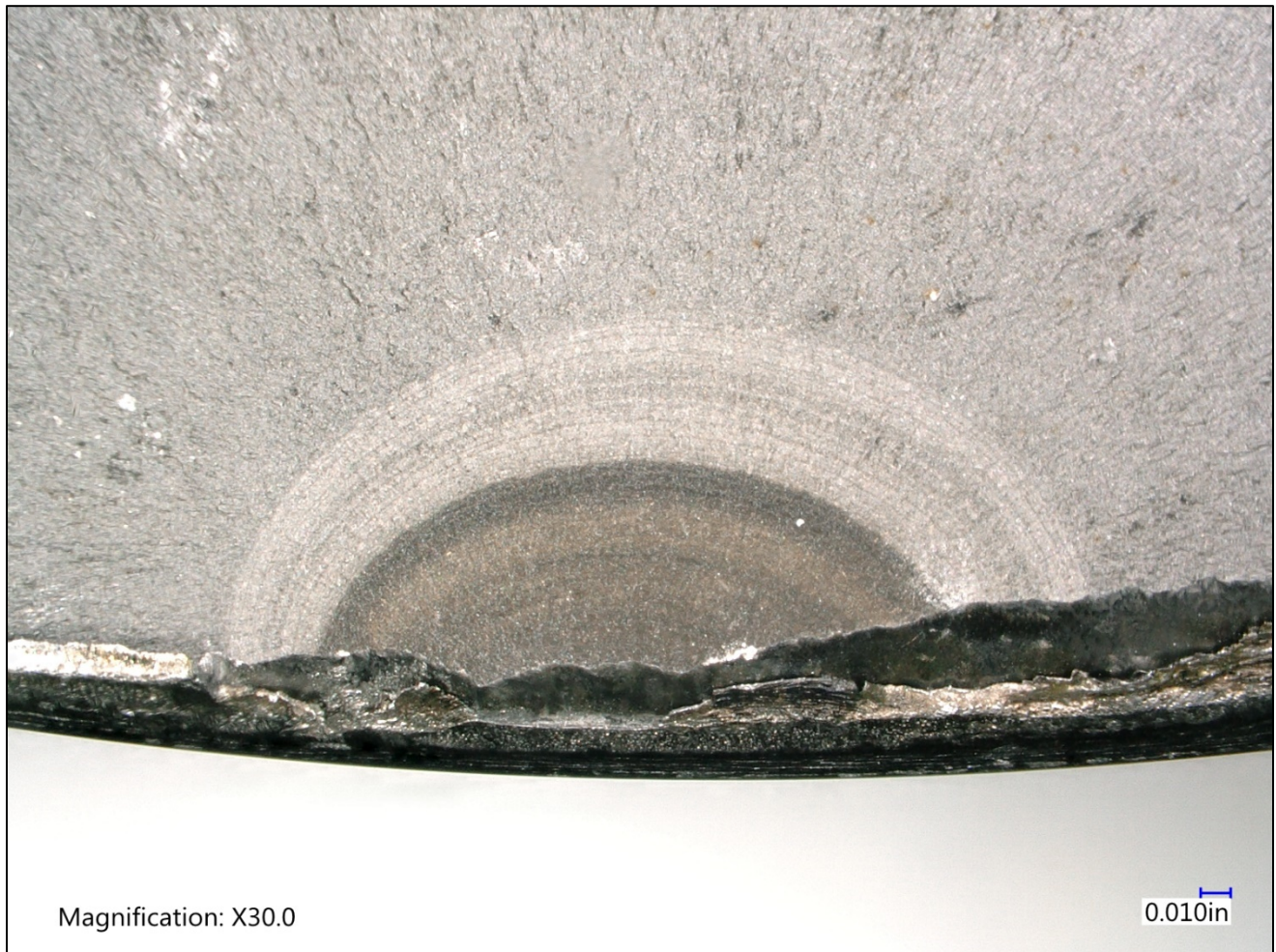


Figure 11 – View of the thumbnail crack on the aft fracture surface, showing the post fracture damage to the edge.

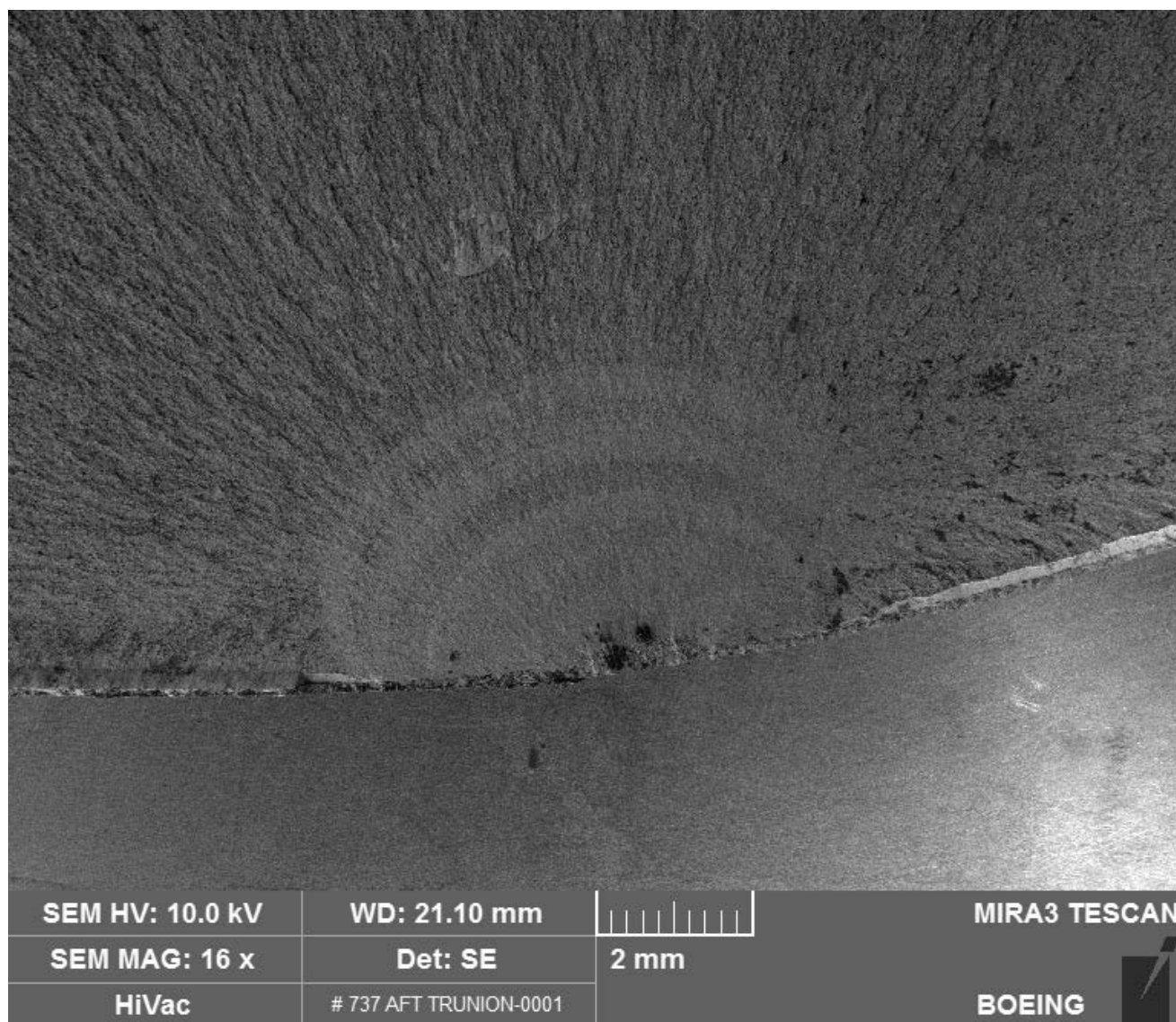


Figure 12 – Secondary electron (SE) micrograph of the forward side thumbnail crack.

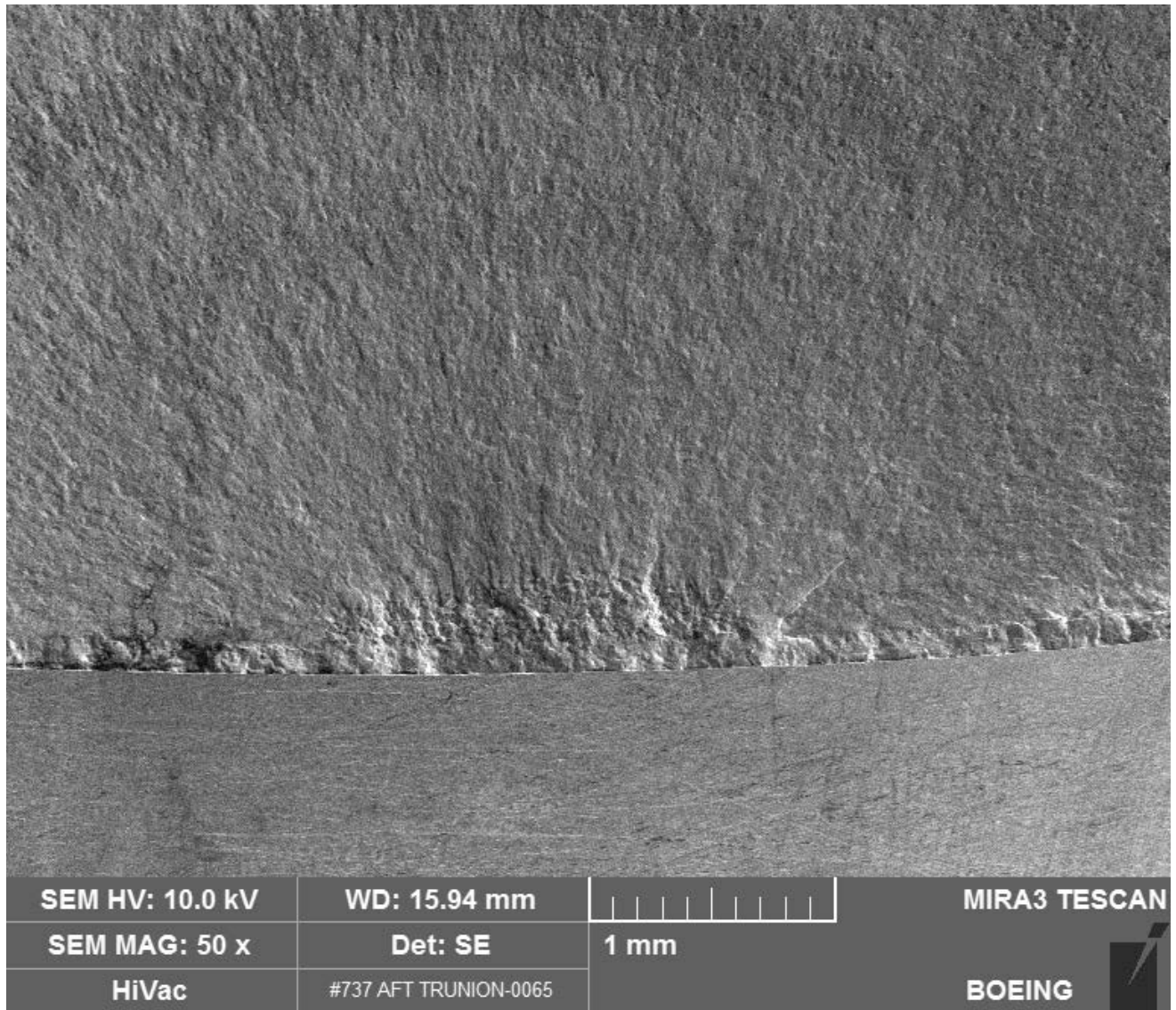


Figure 13 – SE micrograph of a closer view of the initiation site, angled to show the edge with the outer surface.

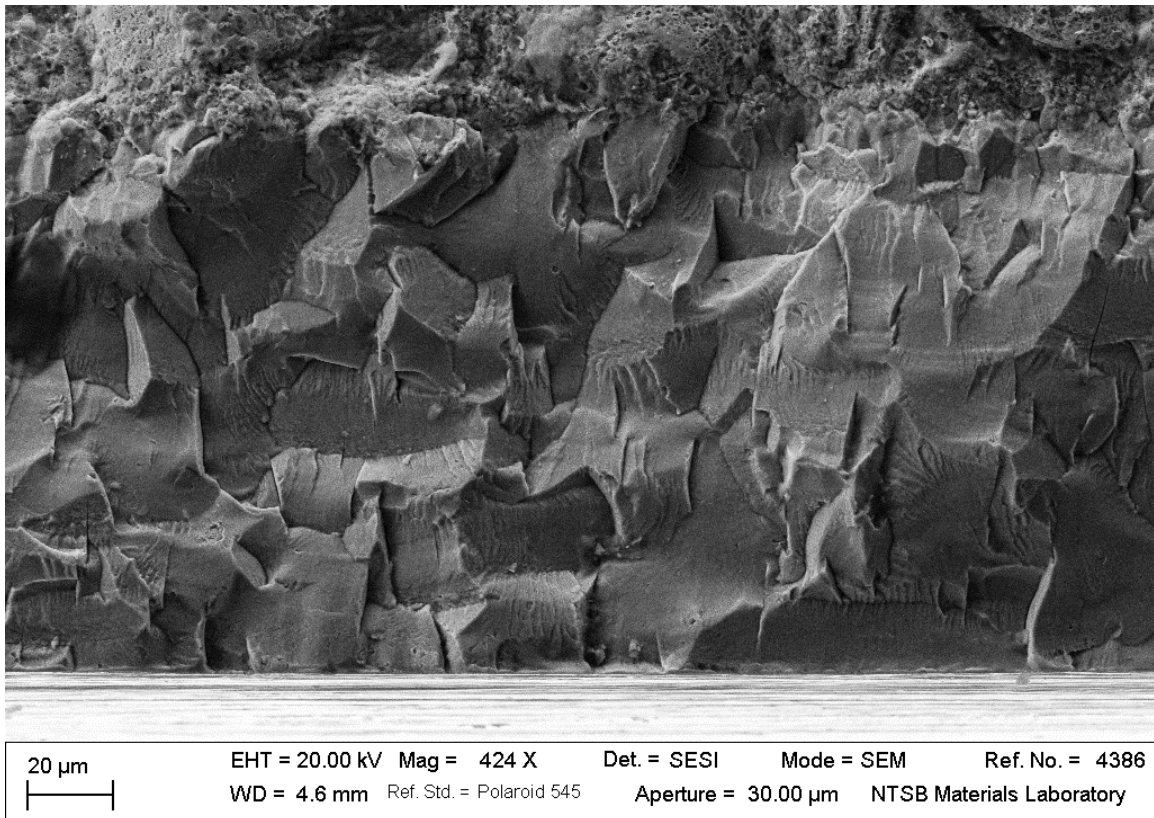


Figure 14 – SE micrograph showing a closer view of the faceted fracture features in the chromium electroplating layer.

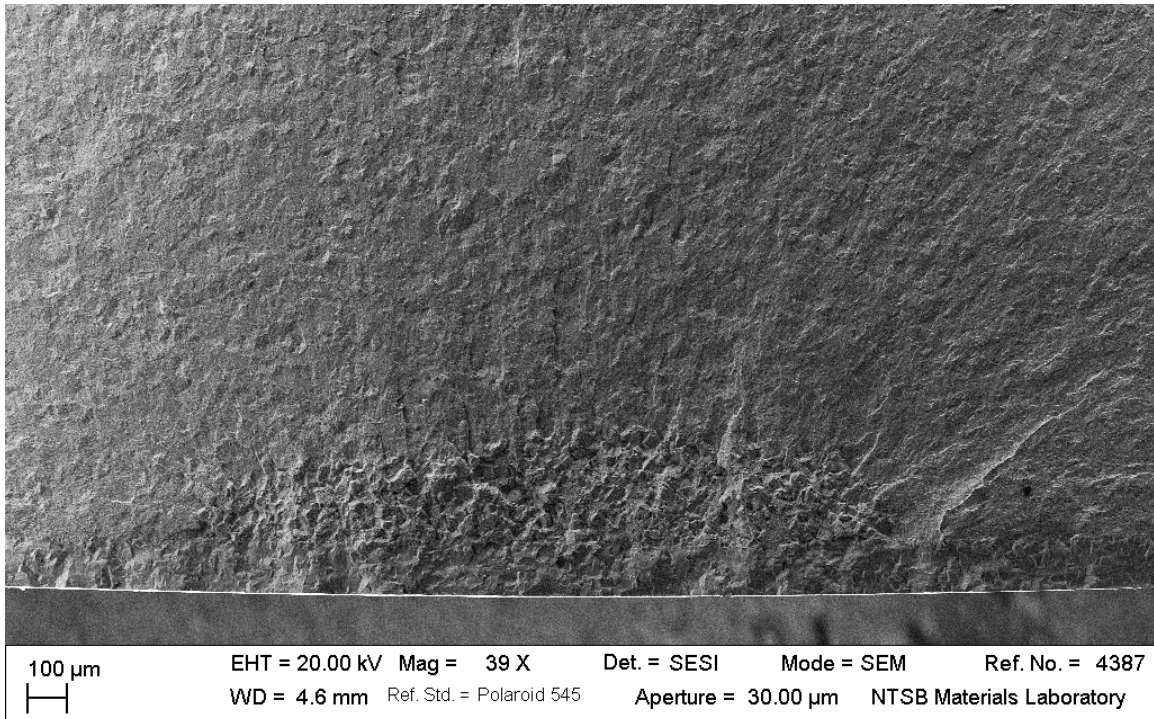


Figure 15 – SE micrograph showing the intergranular initiation region in Figure 13.

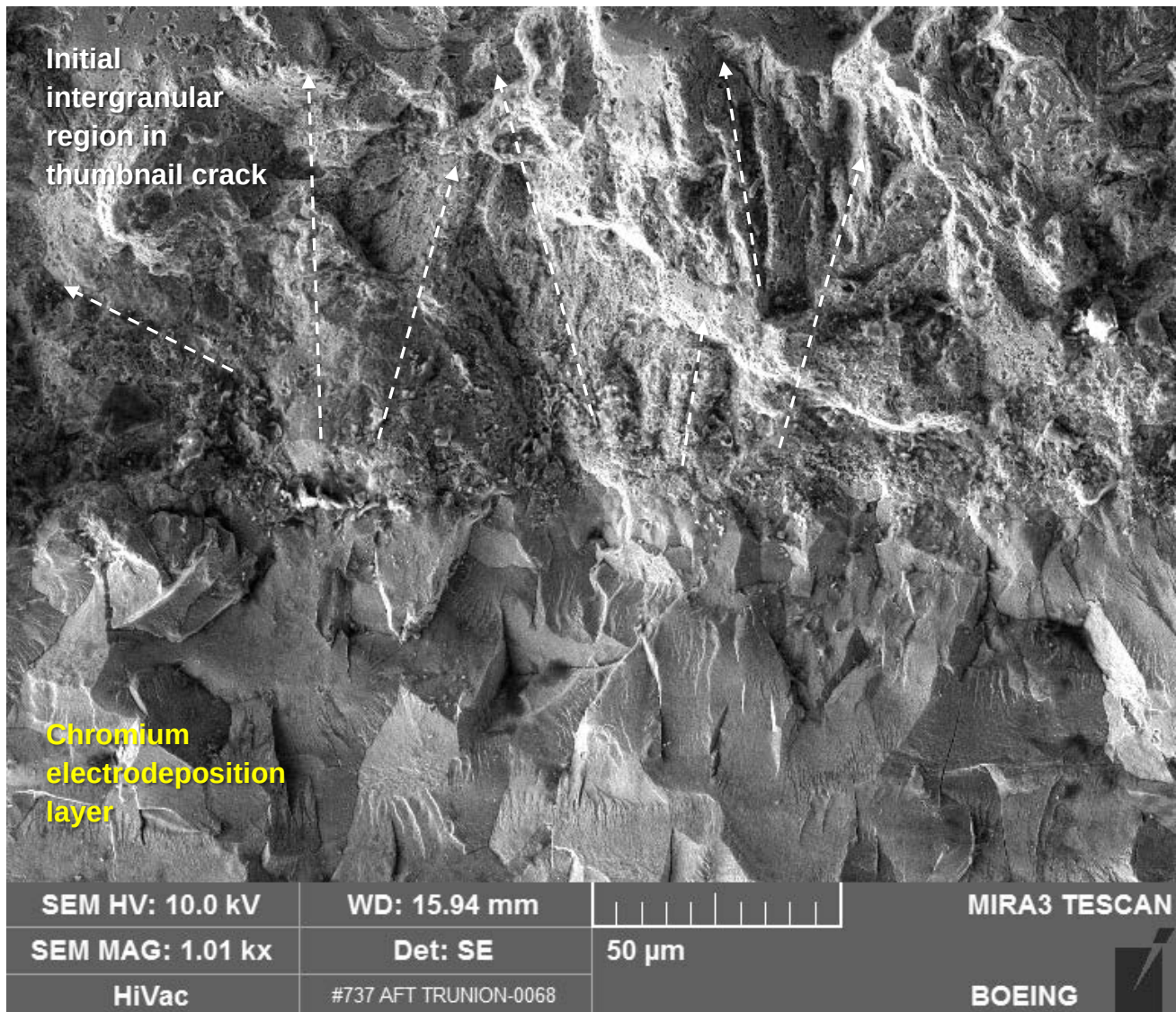


Figure 16 – SE micrograph of the transition between the faceted fracture in the chromium electrodeposition plating (lower) and intergranular region of the pin substrate (upper) in the thumbnail crack initiation area from the forward pin fracture surface, after two cleaning procedures. The white dashed arrows denote general fatigue crack propagation directions in this area.

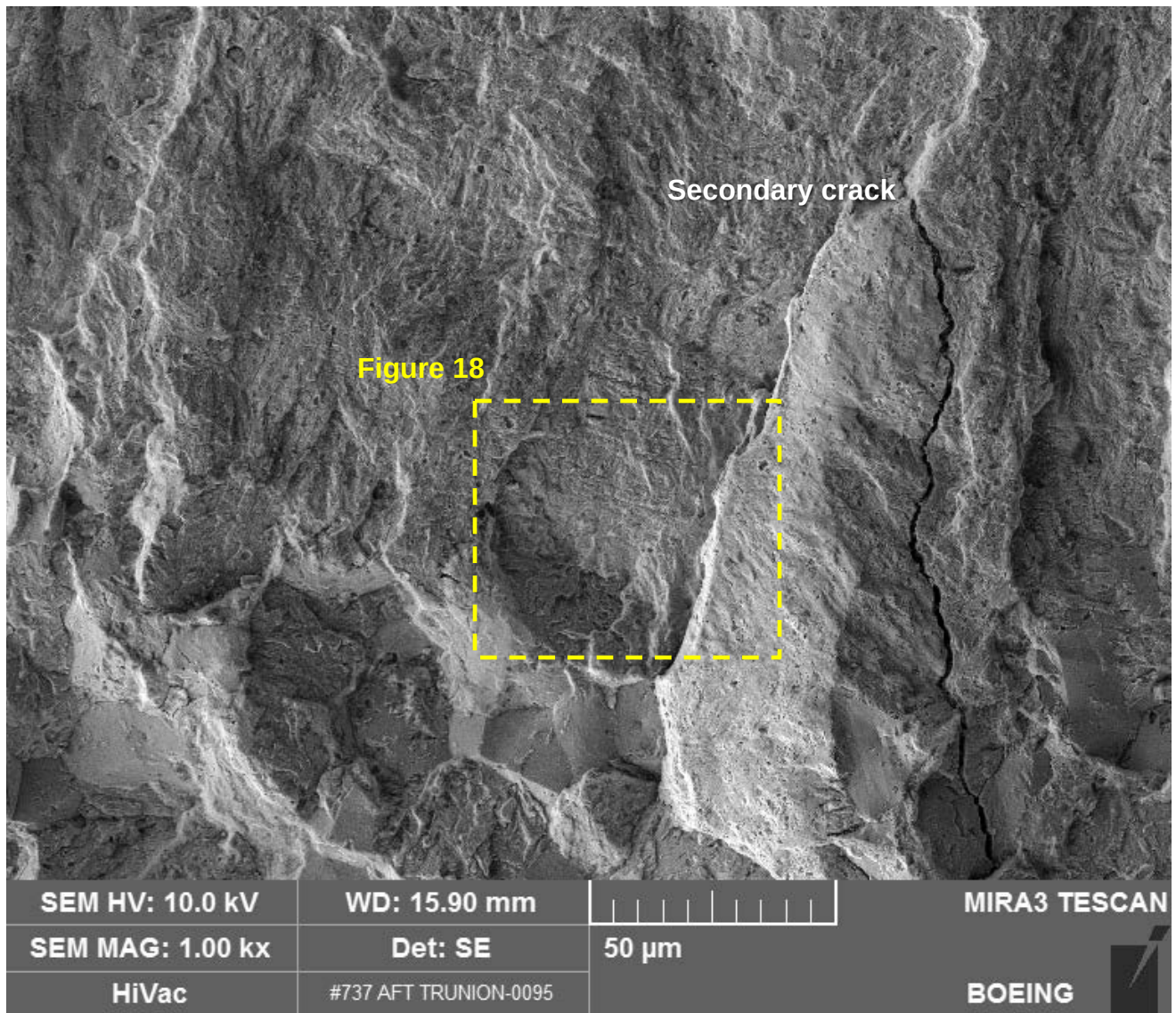


Figure 17 – SE micrograph showing an area of the edge of the intergranular region, with a secondary crack on one of the facets. The boxed area is shown in Figure 18.

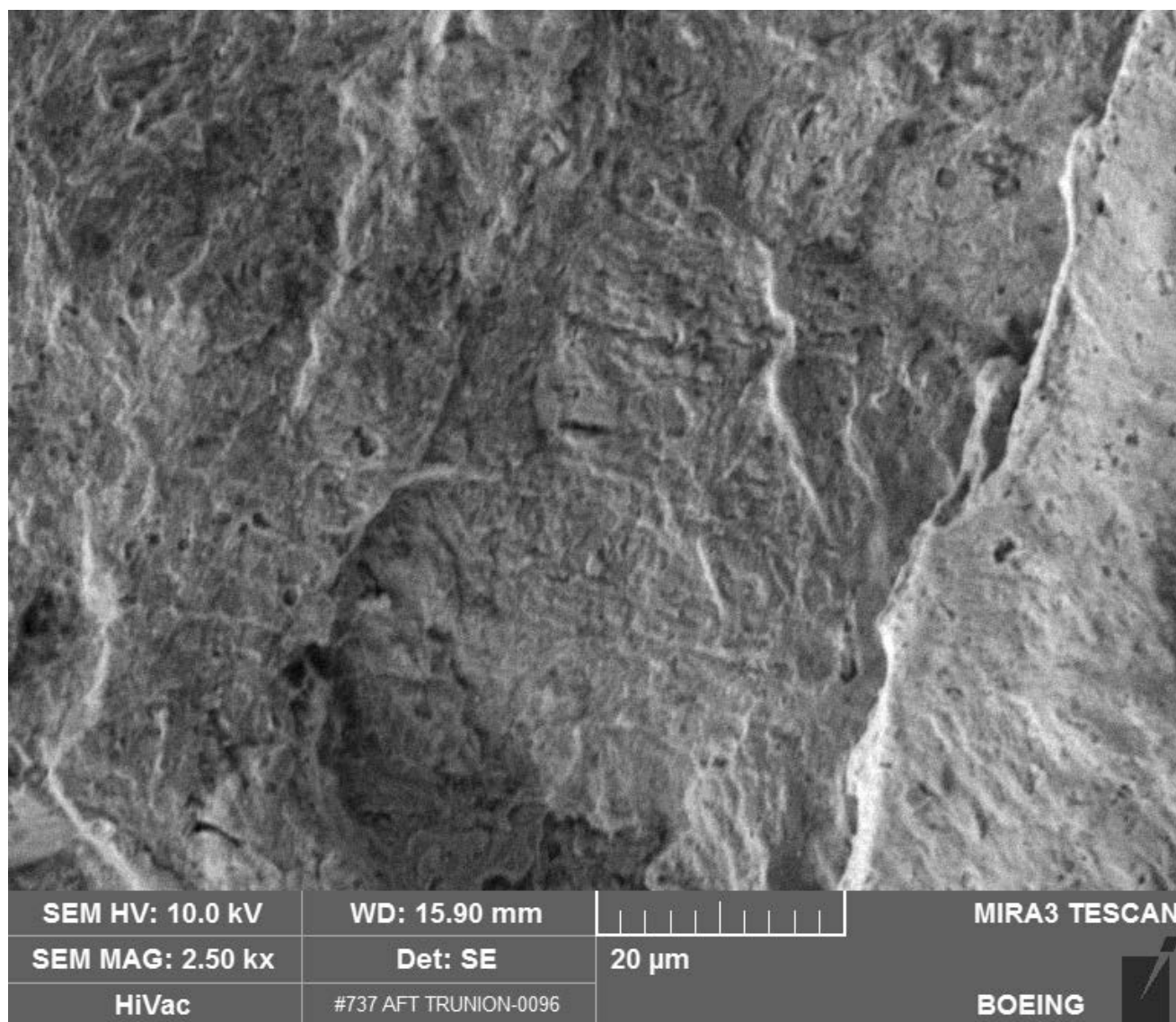


Figure 18 – SE micrograph of the boxed area in Figure 17, showing fatigue striations, propagating from lower left to upper middle in the figure.

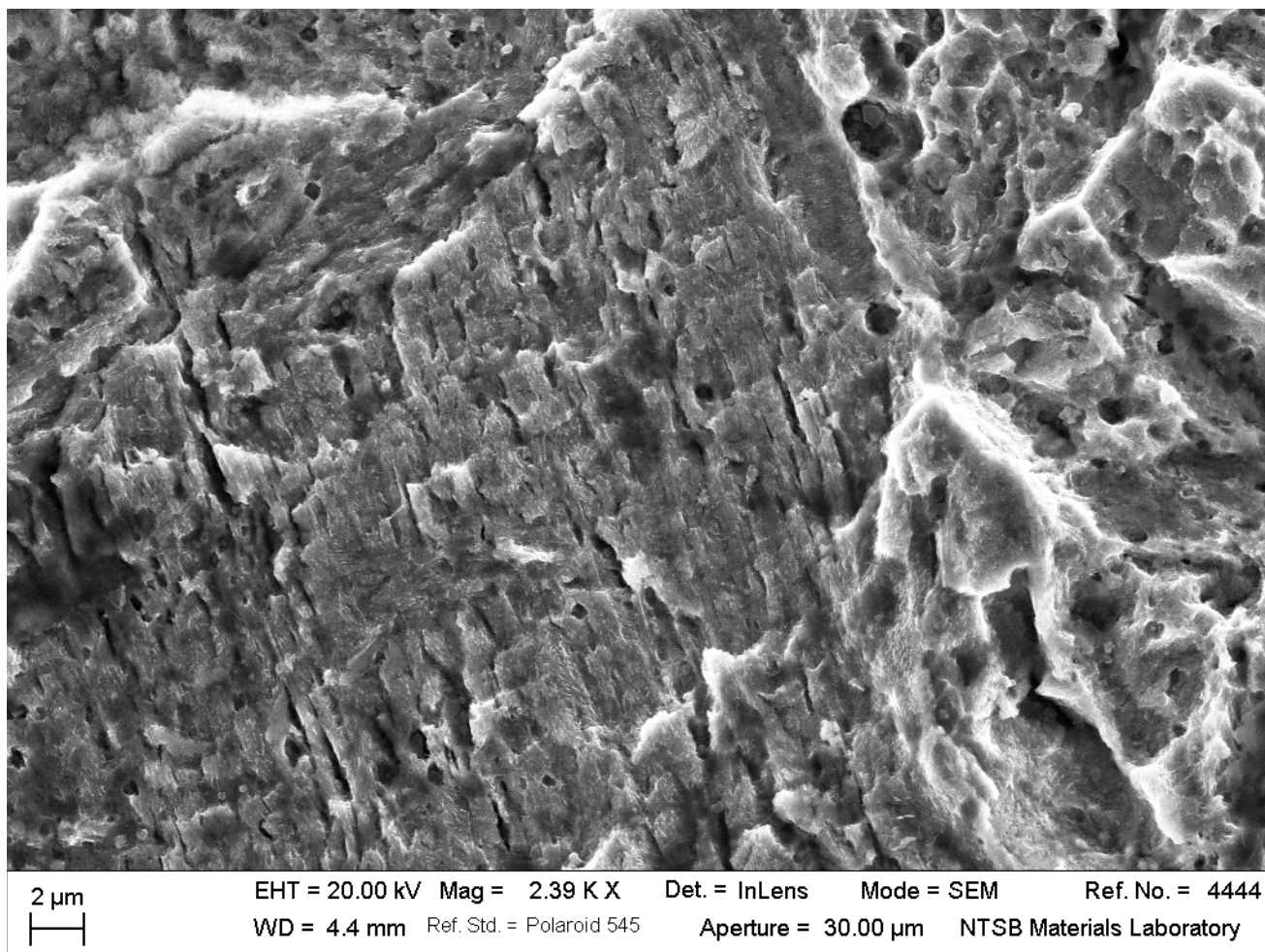


Figure 19 – SE micrograph of fatigue striations from the end of the fatigue thumbnail crack on the forward pin remnants fracture surface, after two cleaning procedures.

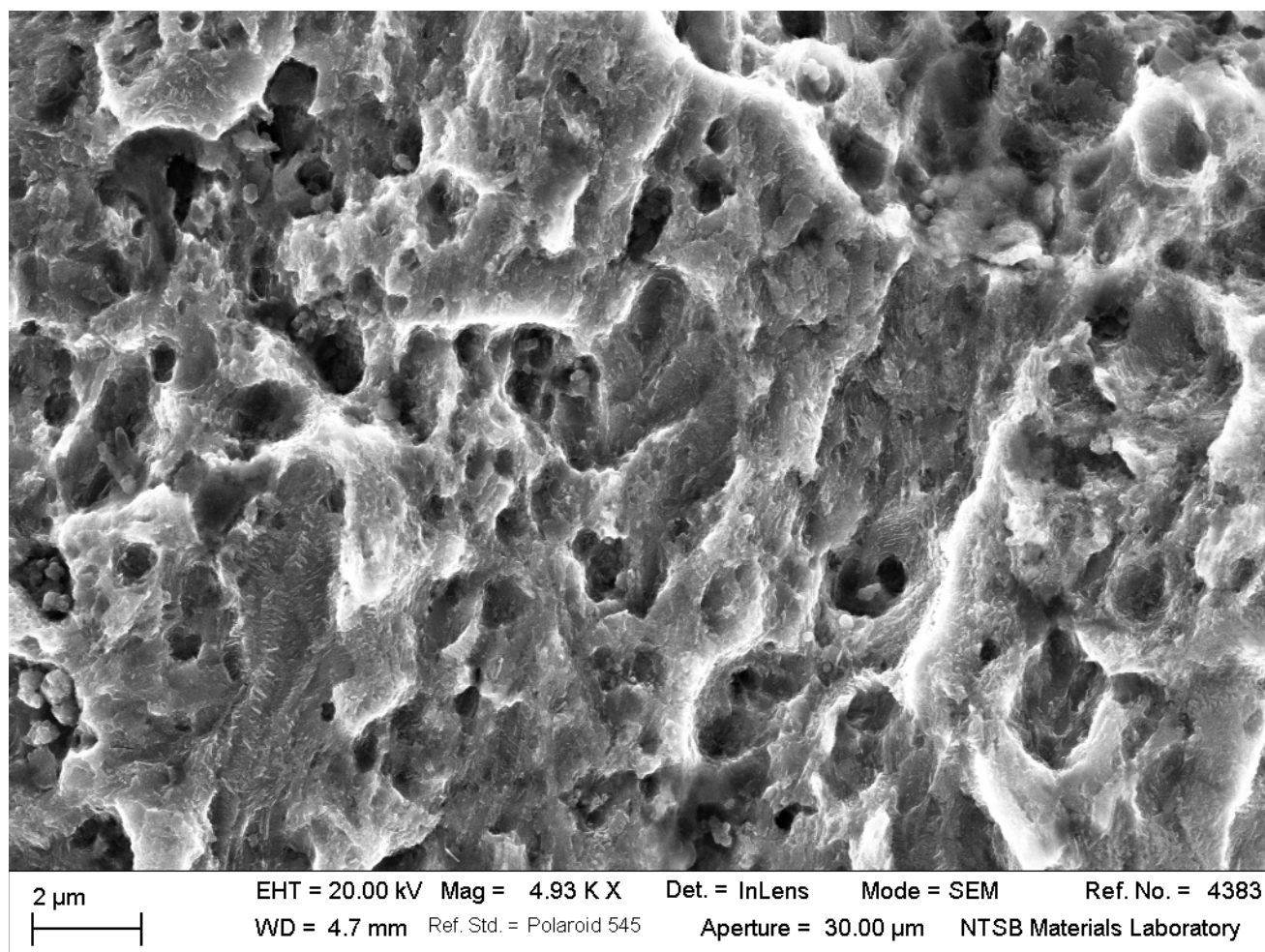


Figure 20 – SE micrograph of a typical area outside the fatigue thumbnail crack in Figure 9, showing dimpled rupture.

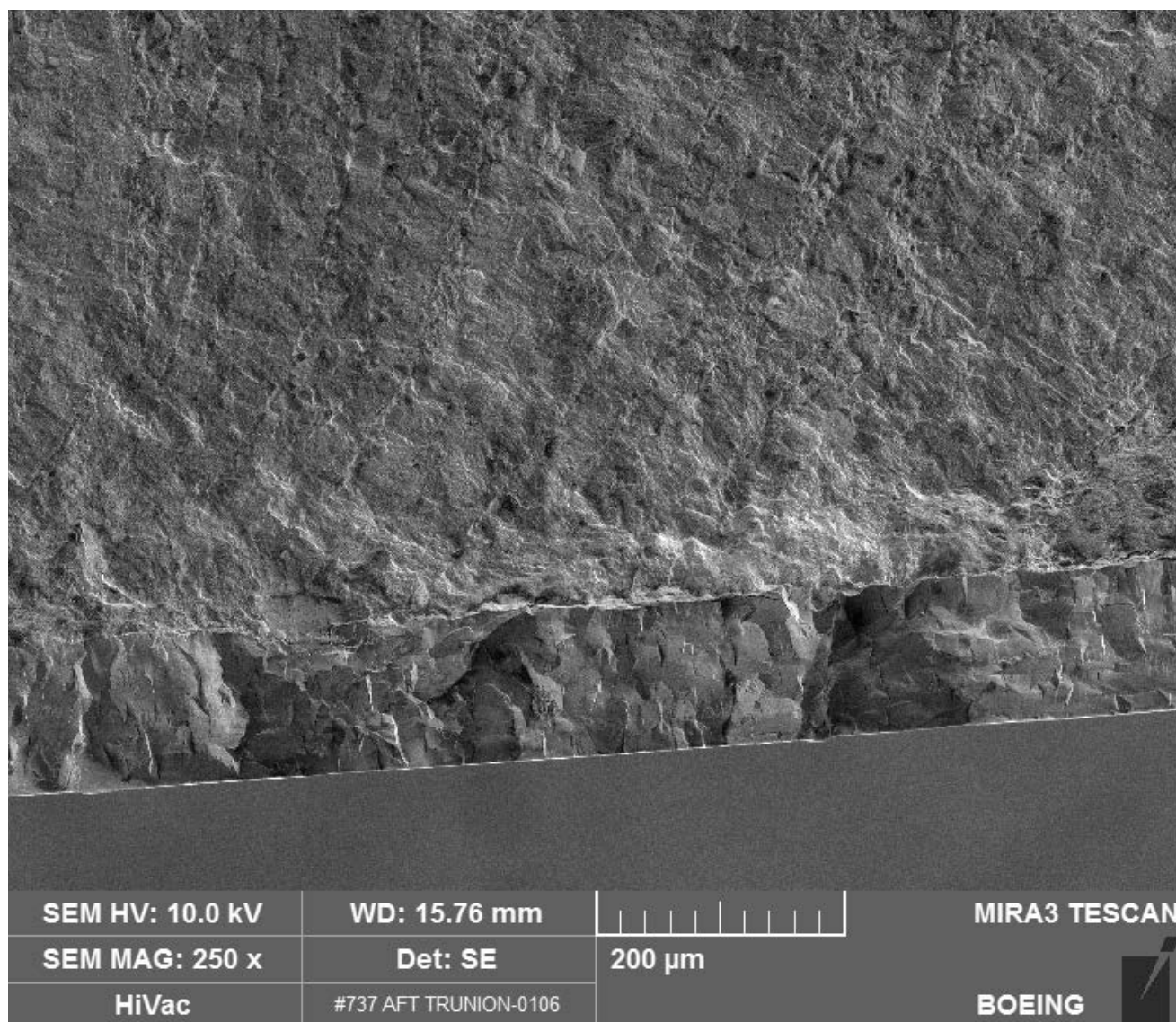


Figure 21 – SE micrograph of the end of the thumbnail crack along the edge, located right of the crack initiation region shown in Figure 15, showing the fracture features in the chromium electroplating layer.

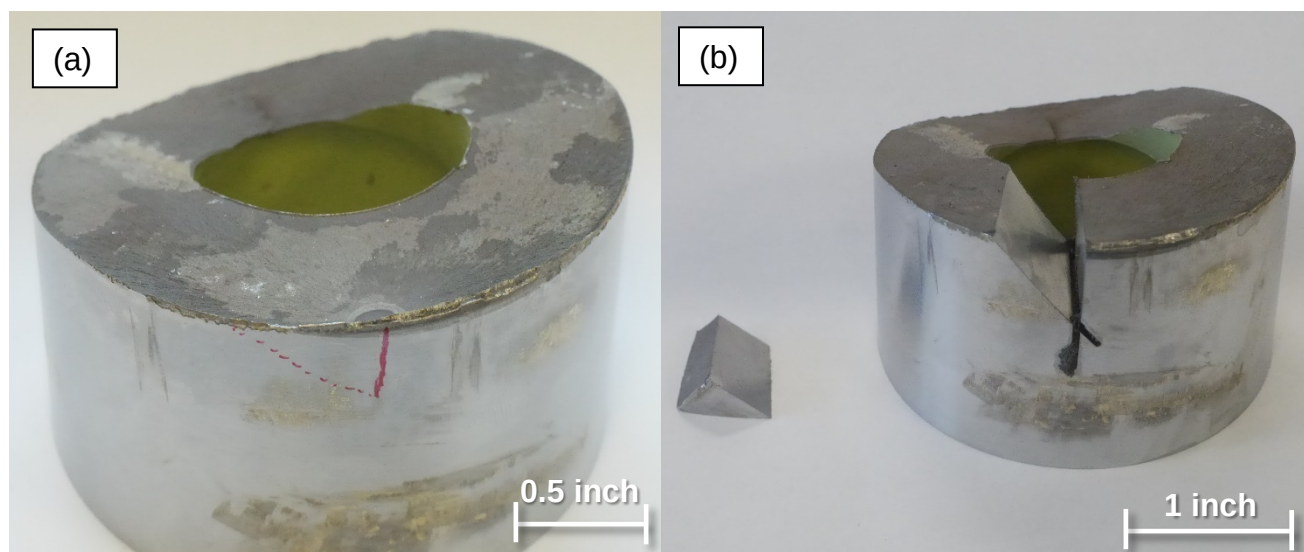


Figure 22 – A section of the aft trunnion piece, showing the location of the section removed for metallographic examination (a) as marked and (b) after sectioning.

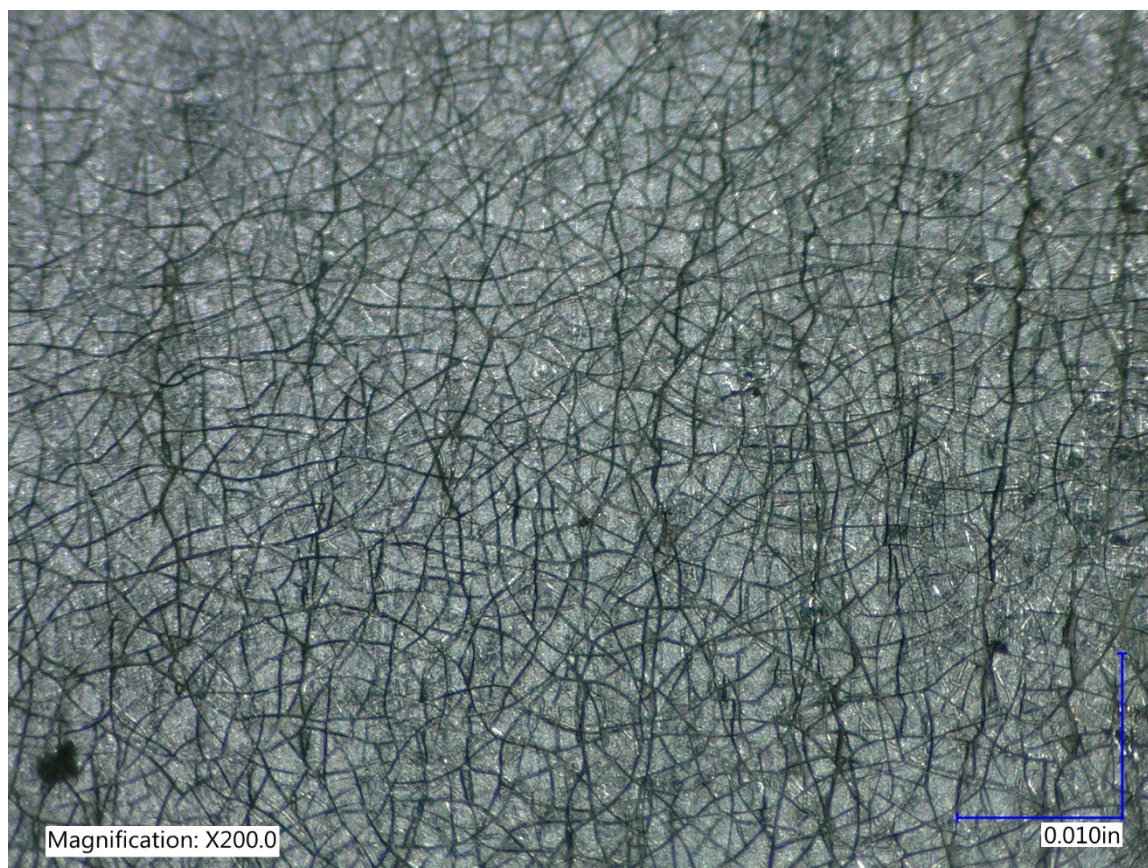


Figure 23 – View of the partially-stripped chromium electroplated layer from the aft pin remnant.

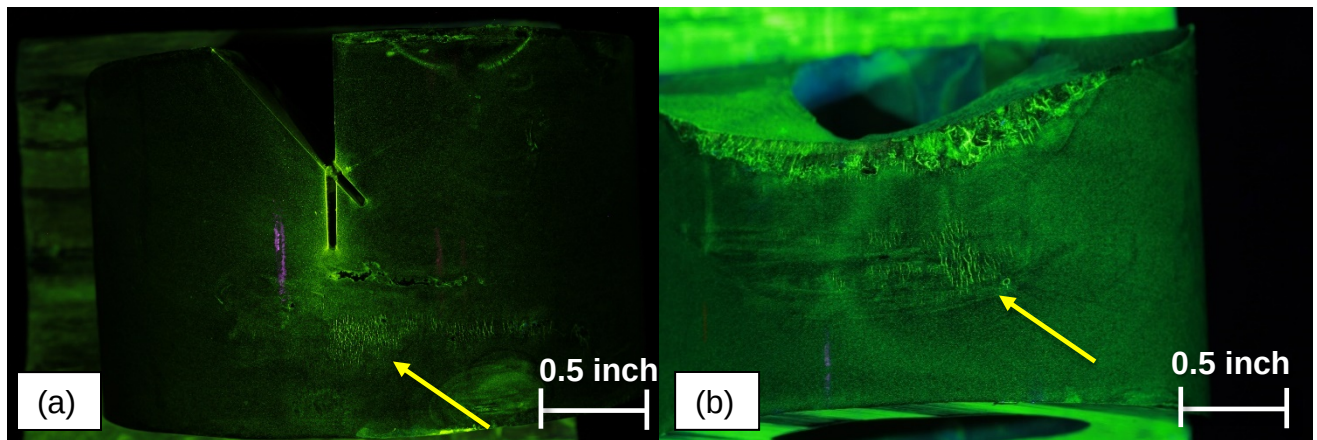


Figure 24 – The (a) 12 o'clock and (b) 6 o'clock faces of the aft trunnion piece, after sectioning in Figure 22, exposed to UV light after MPI, showing longitudinal cracking (arrows).

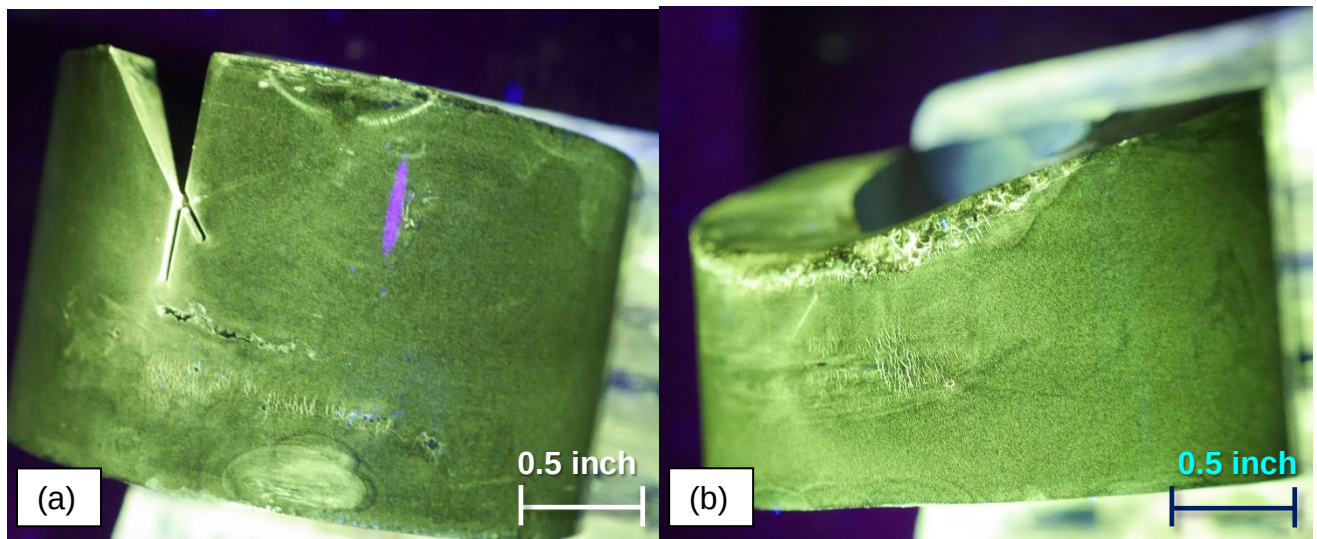


Figure 25 – The (a) 12 o'clock and (b) 6 o'clock faces of the aft trunnion piece, after sectioning in Figure 22, exposed to UV light after FPI, showing ladder cracking (arrows).

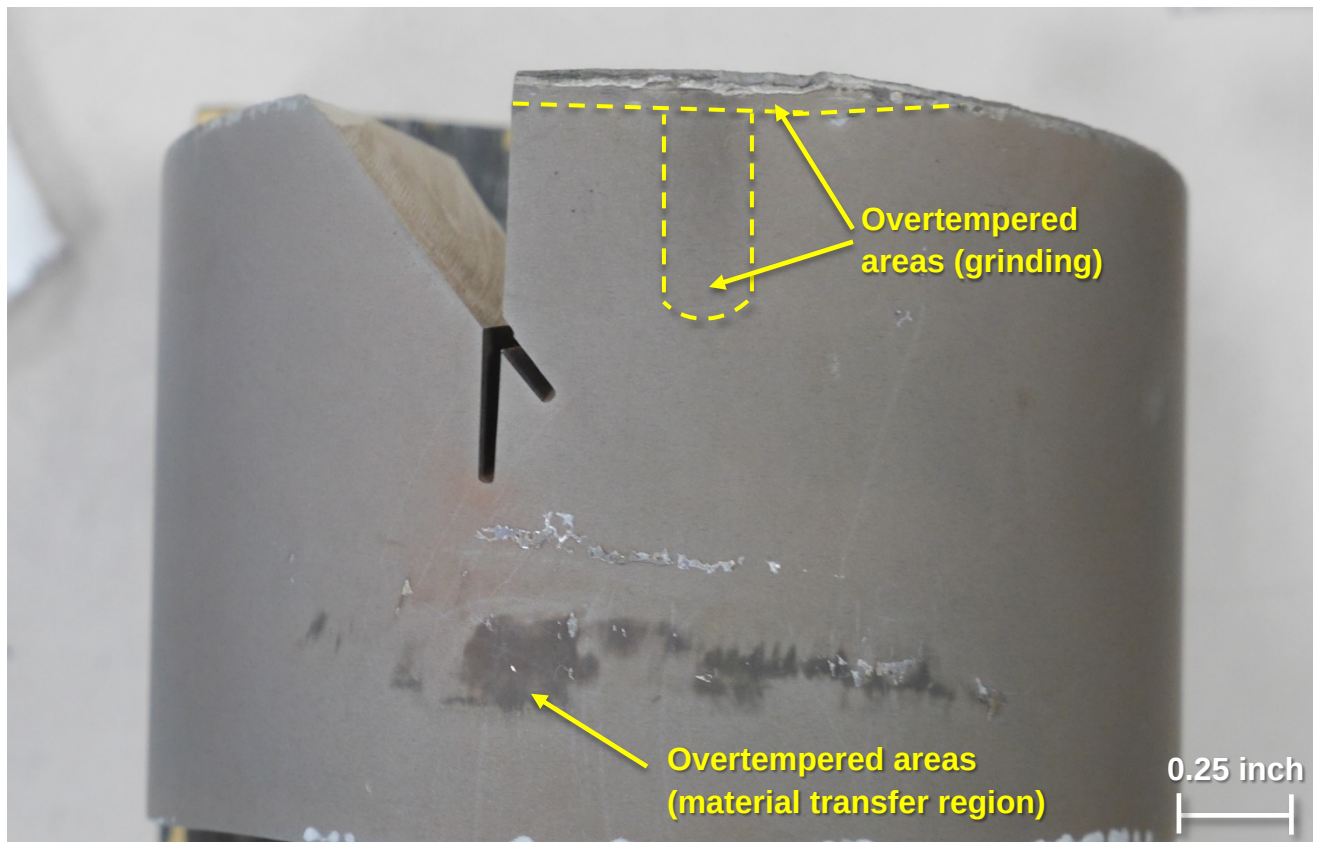


Figure 26 – The 12 o'clock face of the aft pin remnant, after temper etch using 2% Nital etch. The areas of noted overtempering are annotated.

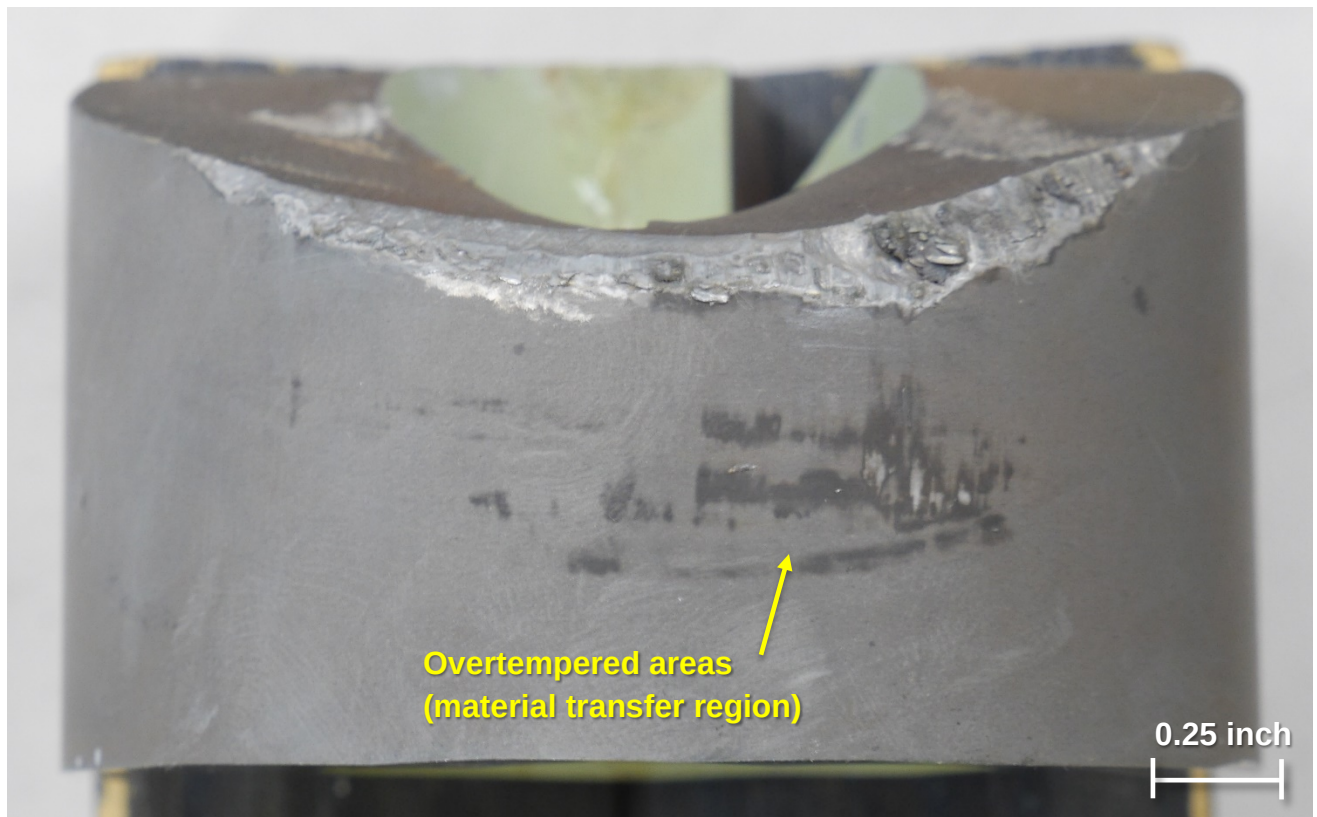


Figure 27 – The 6 o'clock face of the aft pin remnant, after temper etch using 2% Nital etch. The areas of noted overtempering are annotated.

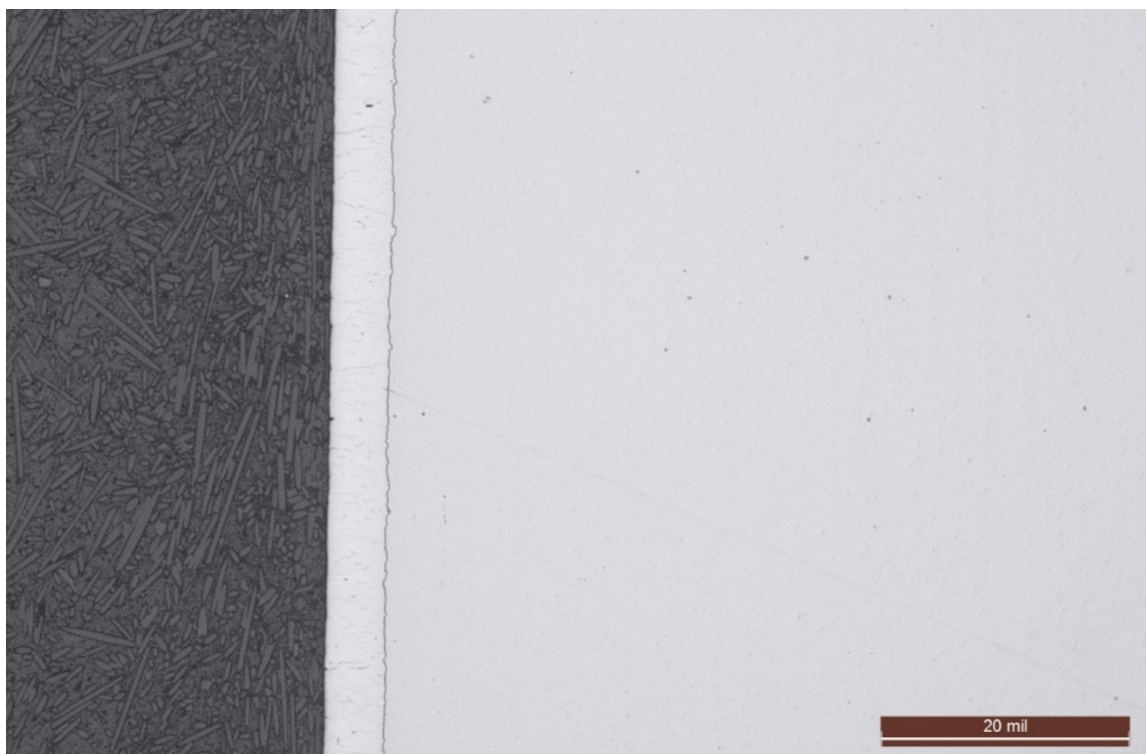


Figure 28 – Bright-field (BF) optical micrograph of an area away from the fracture surface, showing the adherent chromium electroplated layer (~50X, as-polished).

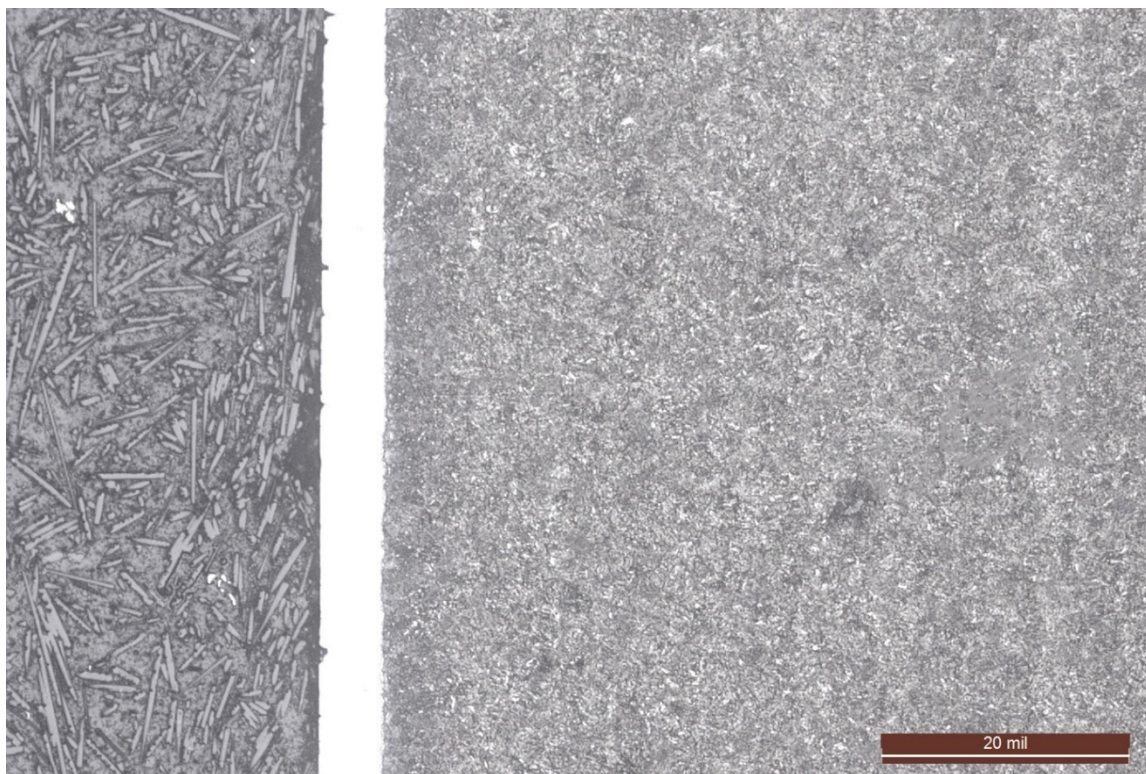


Figure 29 – BF optical micrograph of an etched version of Figure 28, showing the a darker etch response adjacent to the chromium electroplated layer (~50X, etched 2% Nital).

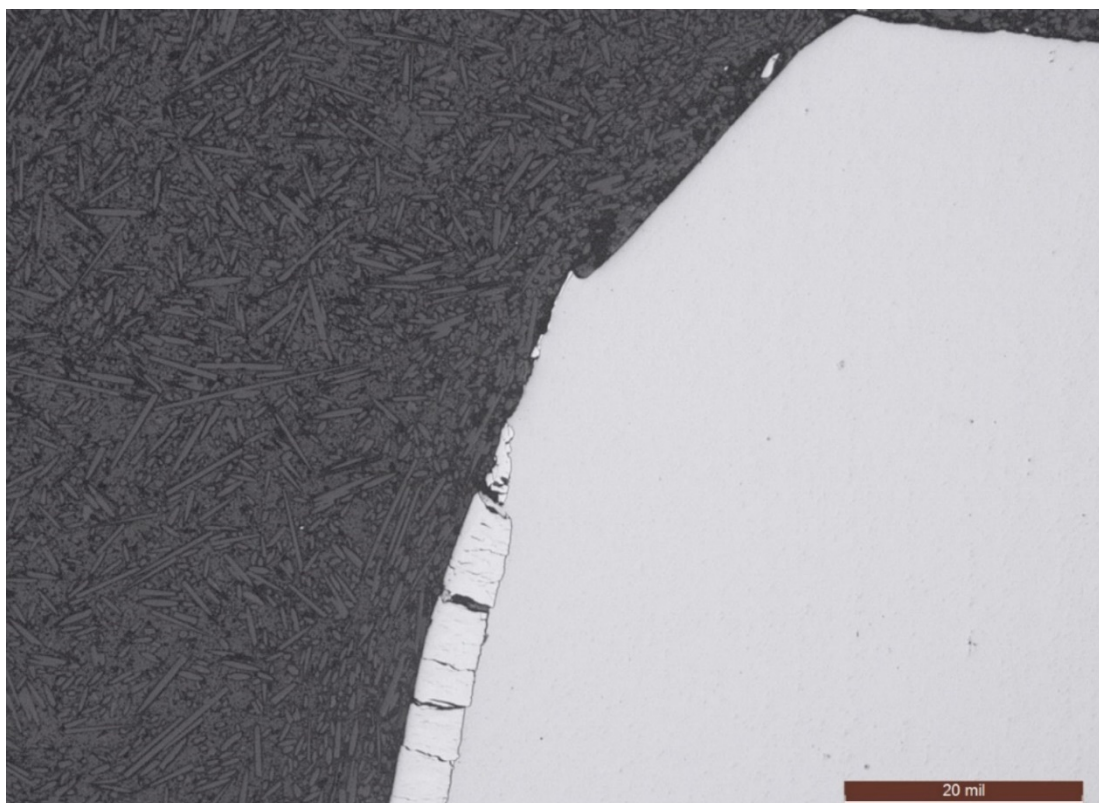


Figure 30 – Bright field (BF) optical micrograph of the cross section through the thumbnail crack on the aft fracture surface (~50X, as-polished).



Figure 31 – BF optical micrograph of the location in Figure 30, after etching (~50X, etched 2% Nital).



Figure 32 – BF optical micrograph of a closer view of the cracking in the chromium electroplated layer near the edge with the fracture surface (~100X, as-polished).

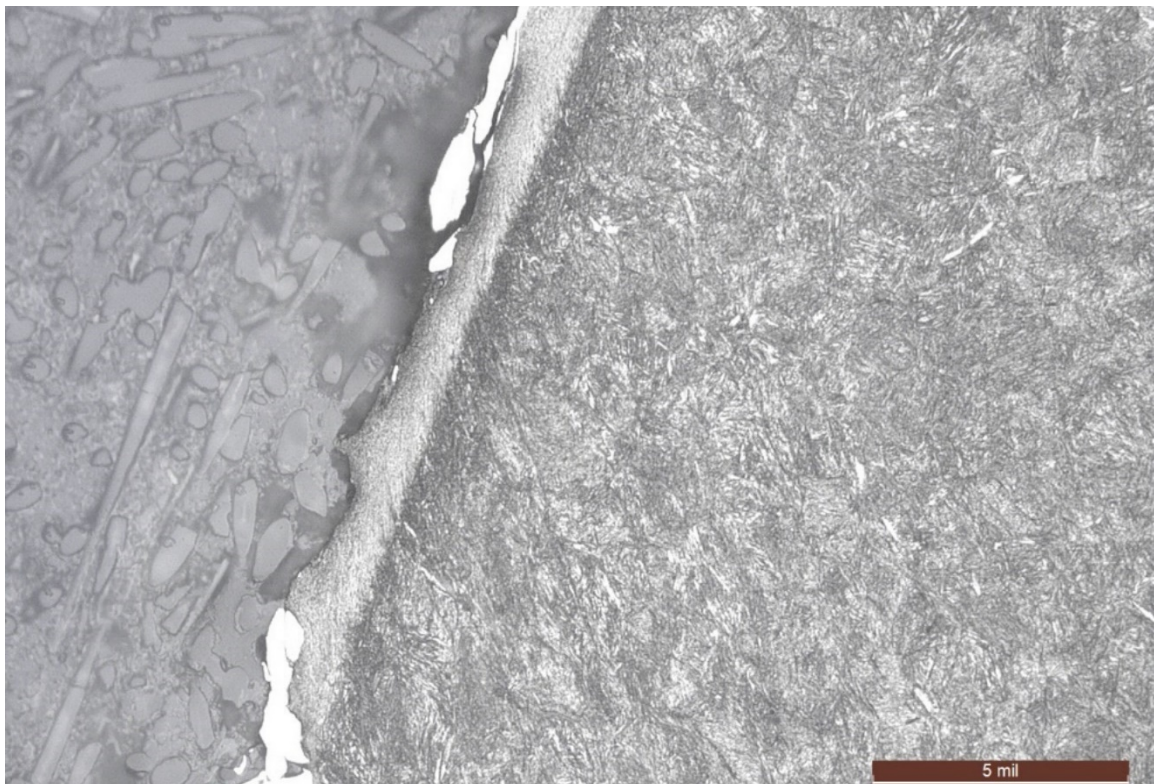


Figure 33 – BF optical micrograph of an area adjacent the impacted fracture surface edge, showing a lack of chromium electroplated layer and a distressed surface region (~200X, etched 2% Nital).



Figure 34 – The mating cross section to Figure 30, after chromium electroplated layer stripping.



Figure 35 – BF optical micrograph of a closer view of the pin surface, showing the relative depth of the darker subsurface area (~500X, etched 2% Nital).

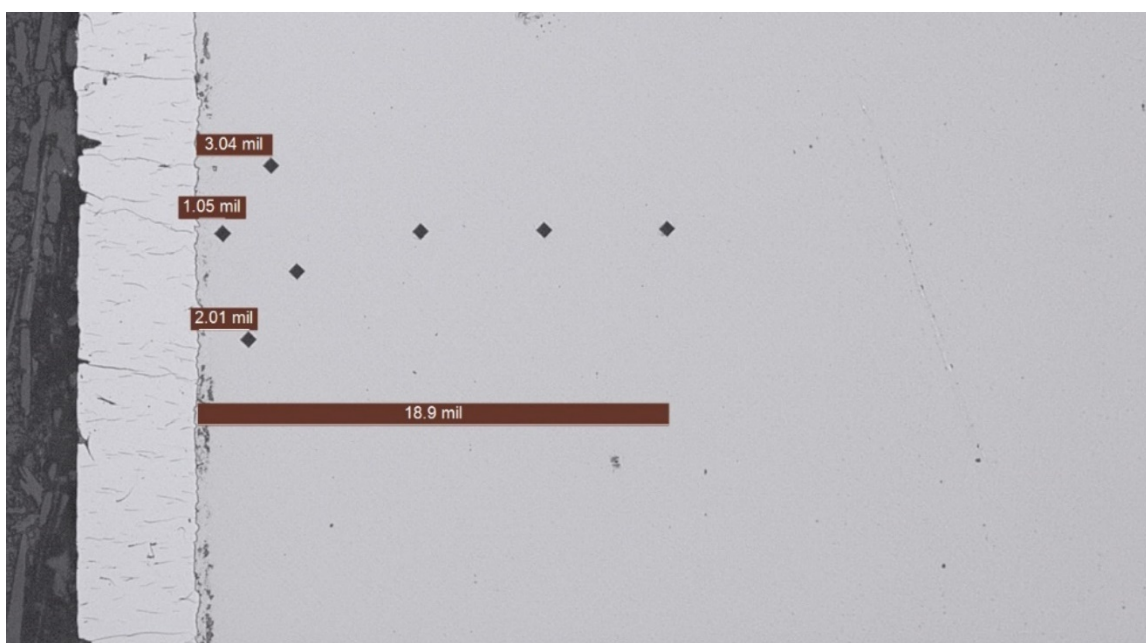


Figure 36 – BF optical micrograph of a closer view of the pin surface, showing the location of microindentation hardness indents (~200X, as-polished).

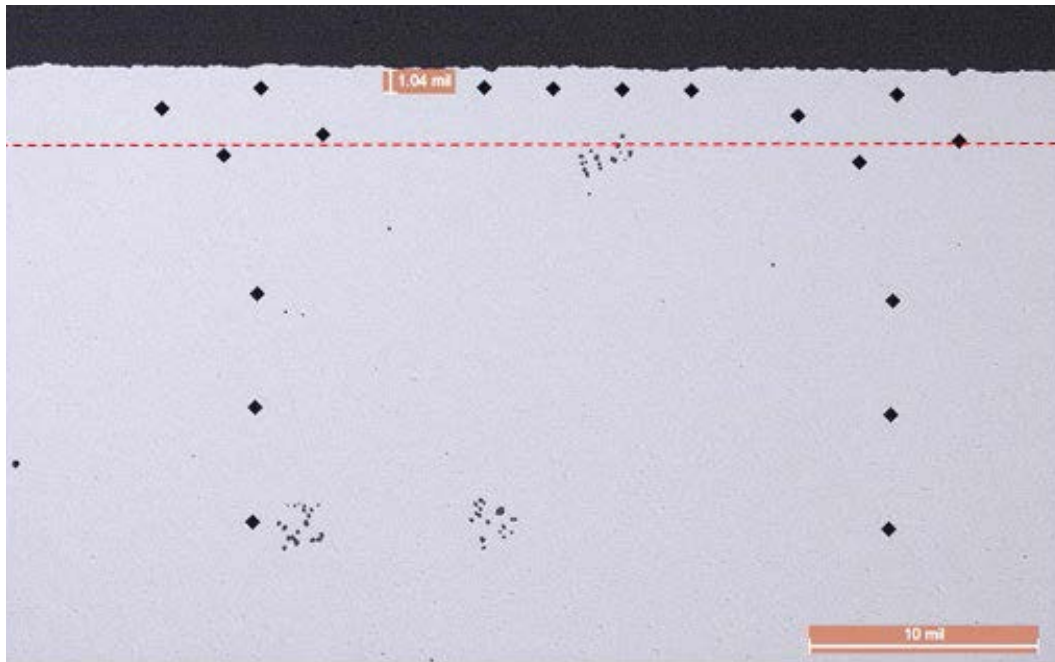


Figure 37 – BF optical micrograph of a cross section through the darker area in Figure 26, showing the series of microindentation hardness indents approaching and along the surface (~200X, as-polished).