

NATIONAL TRANSPORTATION SAFETY BOARD

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



October 28, 2022

MATERIALS LABORATORY FACTUAL REPORT

Report No. 21-054

A. ACCIDENT INFORMATION

Place : Seiling, Oklahoma
Date : 07/12/2021
Vehicle : WSK PZL Mielec M-18A Dromader (N9310R)
NTSB No. : CEN21FA314
Investigator : Tim Sorenson

B. COMPONENTS EXAMINED

1. Portion of outboard left-wing main spar piece with fractured lower attachment fitting (also referred to as the main lower attachment fitting piece)
2. Separated left-wing outboard lower attachment fitting lug piece (also referred to as the separated lower attachment fitting piece)
3. Expansion mandrel assembly: split mandrel, tapered plug, retention bolt, castellated nut, and washer from the left-wing outboard lower attachment fitting

C. DOCUMENTS REVIEWED

1. Service Bulletin E/02.170/2000, Polskie Zakłady Lotnicze Co. Ltd. 08.03.2000. Procedure for dealing with corrosion, when reaming or replacing (centerwing-to-outboard wing) attachment joints
2. Federal Aviation Administration Airworthiness Directive AD 2000-18-12, ; Polskie Zakłady Lotnicze Sp. z o.o. Models PZL M18, PZL M18A, and PZL M18B Airplanes
3. Service Letter No. M18/034/2016, Polskie Zakłady Lotnicze Sp. z o.o. 02.22.2016: Paying attention during the inspection of joints attaching the outer wing with the centerwing according to the Service Bulletin No. E/02.170/2000

D. DETAILS OF THE EXAMINATION

Documentation of the As-Received Outboard Left-Wing Main Spar and Fractured Outboard Lower Attachment Fitting Pieces and Expansion Mandrel Assembly

The as-received evidence is shown in Figures 1 and 2. Figure 1 shows the approximate mechanical arrangement of the as-received pieces and the nomenclature of the pieces of interest. Figure 2 shows a forward-facing side view of the as-received outboard left-wing main spar piece with fractured main lower attachment fitting. An aft-facing view of the spar piece is shown in Figure 3. Sketches showing the location of the lower attachment fitting (based on the right wing) are shown in Figures 4 and 5.

An oblique view of the outboard left-wing main spar piece with fractured lower attachment fitting is shown in Figure 6 with all hardware in place. Inboard views of the spar piece showing details of the fractured main lower attachment fitting are shown in Figure 7. Sealant, paint, and accumulated dirt deposits around the fractured portion of the main lower attachment fitting are consistent with original OEM installation of the lower attachment fitting. A closer view of the fracture faces on the main lower attachment fitting are shown in Figure 8 with the lower and upper lugs identified.

As-received, the main lower attachment fitting piece was inspected under UV light using an UltraLite ALS inspection system with UV head at 400 nm/250 mW to identify the presence of any deposits from a fluorescent magnetic particle inspection. No positive indications of fluorescent deposits were observed on the lug area of the main lower attachment fitting piece and surrounding areas.

Detailed images of the separated left-wing outboard lower attachment fitting lug piece are shown in Figure 9 in the as-received condition and after cleaning in acetone with ultrasonic agitation. In Figure 10, the separated lower attachment fitting piece was placed next to the main lower attachment fitting piece to approximate the mechanical deformation at the time of separation. Annotations have been made to identify key features of the attachment fitting pieces.

A side-by-side comparison of the fracture surfaces from the main lower attachment fitting piece and the separated lug piece is shown in Figure 11 in the as-received condition. The upper and lower attachment fitting lug fractures are identified in the figure.

The fractured main lower attachment fitting piece was removed from the spar piece by disassembling all necessary pieces and removal of mounting bolts. The outboard left-wing main spar piece with the main lower attachment fitting removed is shown in Figures 12 and 13. As annotated in Figure 12, the bolt closest to the attachment fitting lug was pressed out with a hydraulic press. About 15,000 lbf was required to press out this bolt. All the other bolts on the lower attachment fitting were removed by pushing out or with slight tapping with a mallet and punch. The bolt shanks and inner bores of the mounting holes were clean and did not exhibit corrosion deposits. The fractured lower attachment fitting piece is shown in Figure 14 with the separated piece placed in proximity to its position at the point of separation. Key features are annotated. All paint deposits on the lower attachment fitting piece (Figure 14) and the faying surfaces on the spar piece (Figures 12 and 13) are consistent with the lower attachment fitting being original to the airplane. According to the engineering drawing number D.22.200.36.1, the attachment fitting is specified to be made from PN 30HGSA low alloy high strength steel, heat treated to a tensile strength between 110 and 130 kg/mm² (156,456 and 184,903 psi)¹.

¹ PN is the designation for PKN - National Standards Body in Poland.

Fractography of the As-Received Main and Separated Lower Attachment Fitting Pieces

Figure 15 shows both halves of the lug bore and lower lug fracture faces imaged using a Keyence VHX-7000 digital microscope. Numerous circumferential scratches are present of varying length and depth on the bore surface of the main lower attachment fitting piece. No scratches or marks were observed across the width of the bore on either lower attachment fitting piece. The bore surface on the separated lower attachment fitting piece exhibited a dark and rough surface consistent with corrosion product deposits. A higher magnification image is shown in Figure 16. Macrofractographs of the fracture surfaces on both halves of the lower lug are shown in Figures 17-20. Using a digital microscope with HDR imaging and oblique lighting, the macrofractographs in Figure 17 were taken². Key fracture features are annotated in Figure 18a on the same images as Figure 17a. Fractographic features such as crack progression marks and ratchet marks reveal that a fatigue crack developed at an origin on the bore surface centered about 0.12 inch from the forward side of the lower lug. At its longest length, the fatigue crack propagated about 0.80 inch (see Figure 36) before the remaining ligament fractured in ductile overstress. The ratchet marks at the origin region were associated with corrosion pits on the bore surface.

Using a digital microscope in the normal imaging mode, the macrofractographs in Figure 19 were acquired on both halves of the lower lug fractures. The images reveal stains on the fracture surfaces immediately below and parallel to the surface of the bore (see Figure 20 for annotations on the image in Figure 19). An area within the stain was evaluated on the separated lower attachment fitting piece (after acetone cleaning) using a scanning electron microscope (SEM) with an energy dispersive spectrometer (EDS). Features associated with the stain on the fracture surface are documented in Figures 20b through 23. The stain comprises continuous and flake-like deposits that occlude the fracture features. Exemplar flakes or clumps are identified in Figure 23 and the associated EDS spectra are shown in Figure 24. The composition of the clump deposits is consistent with ferrous corrosion product. In Figure 25, an SEM fractograph just outside the stained area (see Figure 20b for location) reveals fractographic features covered with a thin, continuous deposit consistent with ferrous corrosion products.

Macrofractographs of the fatigue fracture origin region on the lower lugs are shown in Figures 26 and 27 (the separated lower attachment fitting piece has been acetone-cleaned). As indicated in the figure, ratchet marks at pits in the bore surface are in the origin region. An SEM image of the fatigue crack origin region on the separated lower attachment fitting piece is shown in Figure 28. Three observed pits near the origin region are identified as Pit 1, Pit 2, and Pit 3. As will be documented later in the report, the fracture origin is at Pit 1. Higher magnification SEM images of the pits are shown in Figures 29-31. Pit 1 was examined using EDS and its elemental composition was compared with the elemental composition of an exemplar spot on the main fracture

² HDR is an acronym for high dynamic range. The digital microscope used is a Keyence VHX 7000, which renders images with 16-bit or 65,536 levels of color gradation. Such microscopy enables the imaging of fine surface features with sharp contrast and true color with fine variations.

surface. The spectra are shown in Figure 32 and summarized in Table 1. The composition of deposits in the pit and on the fracture surface are consistent with steel corrosion products. The observed iron, manganese, silicon, and chromium are constituents in the attachment fitting base metal and cadmium is used as an external protective coating. The sulfur, chlorine, potassium, calcium, and aluminum in the pit are from exogenous sources but are consistent with salts or compounds encountered in crop dusting environments. The elevated oxygen and iron concentrations in the pit and on the fracture surface are consistent with iron corrosion product. Carbon may be present in both sample areas as it is present in the base metal and may be present due to its adventitious nature.

Table 1 Summary of Energy Dispersive Spectrum Peak Intensity

Element	Line	Pit 1 (intensity)	Fracture surface (intensity)
C	K _α	9476	4563
O	K _α	69911	26449
Fe	L _α	18142	31473
Al	K _α	Trace	Trace
Si	K _α	4987	4367
S	K _α	Trace	None detected
Cl	K _α	Trace	None detected
Cd	L _α	Trace	3038
K	K _α	Trace	None detected
Ca	K _α	Trace	None detected
Cr	K _α	2868	1843
Mn	K _α	2116	1660
Fe	K _α	58322	44592
Fe	K _β	7694*	5989*

*Total counts (net counts + background)

Figure 33 documents the as-received surface of the bore on the lower lug of the separated lower attachment fitting piece, just adjacent to the fracture origin pit, Pit 1. As revealed in the SEM micrographs, the bore has a deposit on the surface consistent with corrosion product. A void in the deposit reveals an underlying pit (View b in Figure 33).

Fractography of the Evapo-Rust®-Cleaned Fracture Surface on the Separated Lower Attachment Fitting Piece—Lower Lug

A sample with the lower lug fracture surface on the separated lower attachment fitting piece was sectioned from the piece using a narrow-kerf diamond saw as indicated in Figure 34. Two thin slices were also cut from the piece for hardness testing and compositional analysis as indicated in the figure. The fracture sample was progressively

cleaned in Evapo-Rust, to remove corrosion product deposits on the fracture face as well as the bore surface³. Images of the fracture surface after cleaning in Evapo-Rust for 15, 60, and 120 minutes are shown in Figure 35. As revealed in the images, after 15 minutes in Evapo-Rust, a superficial deposit of corrosion product was removed (Figure 35b), revealing a thicker, more persistent corrosion product deposit that appears to be due to corrodent entering the crack where it intersected with free surfaces. After 15 minutes and subsequently after 60 and 120 minutes in Evapo-Rust, distinct semicircular crack progression marks appear, centered about Pit 1 (also called a “thumbnail” feature in fractography vernacular). After 120 minutes and 240 minutes, a persistent band of corrosion product remained just below the lower lug bore as seen in Figure 35d. On the as-received fracture surface, this dark band was observed as documented in Figures 19-25. After cleaning in Evapo-Rust for 60 minutes, the dimensions of the pit, its location relative to the edge of the lug, and the overall length of the fatigue crack were documented as shown in Figures 36 and 37.

The corrosion product layer on the bore surface was quite persistent. The fracture sample was cleaned in Evapo-Rust for a total of 240 minutes and then the bore surface was cleaned with Alconox® and a fine, but stiff bristle brush⁴. Images of the bore surface before cleaning and after 240 minutes of cleaning (with subsequent brushing) are shown in Figure 38. The bore surface of the sample is almost entirely pitted due to material loss associated with corrosion. Figures 39-42 document the corrosion pits on the bore surface near the Pit 1 origin area with progressively higher digital microscope magnification.

Close SEM micrographs of Pit 1 are shown in Figure 43 after the fracture sample was cleaned in Evapo-Rust for a total of 240 minutes and then the bore surface was cleaned with Alconox and a fine, but stiff bristle brush. The higher magnification micrograph in Figure 43b shows some remaining corrosion product within Pit 1. The depth of Pit 1 was measured on an SEM micrograph as shown in Figure 44, consistent with digital microscope measurements. Figures 45-47 show SEM fractographs of the fracture surface at various locations. In areas with more significant corrosion (see Figure 35b) corrosion product and corrosion damage affected the ability to observe fatigue striation features.

Fractography of the Separated Lower Attachment Fitting Piece—Upper Lug

Close views of the upper lug fracture surfaces on the main and separated lower attachment fitting pieces are shown in Figure 11 (see also Figure 10 for reference). These fractures occurred under Mode 1 (with minor levels of Mode 2) due to upward bending of the inboard portion of the lug after the fatigue crack in the lower lug grew to a critical size and the remaining ligament fractured via ductile overstress (see Figure 10 for annotation

³ Evaporust is a chelating rust remover manufactured by CRC Industries. A study validates its use on fracture surfaces: A. Strifas, et. al., *The Efficacy of a Chelating Agent-Based Oxide Remover to Clean Corrosion Products from Ferrous Fracture Surfaces*, Journal of Failure Analysis and Prevention, 2019, 1860-1865.

⁴ Alconox is an anionic detergent for manual and ultrasonic precision cleaning. It is manufactured by Alconox, Inc.

of the bending moment on the lug after the lower fracture occurs)⁵. Fractographs by HDR digital microscopy of the fracture surfaces in the upper lug pieces are shown in Figures 48 and 49. The upper lug fracture surfaces exhibited shear lips at the perimeter of the section and rougher fracture surfaces in the core with river patterns. Based on the river pattern fracture features, the direction of crack propagation is shown using the white arrow annotations in Figure 49. The attributes in the figure are indicative of overstress fracture associated with gross plastic deformation as evidenced by the lateral contraction along the lug width at the internal bore.

Infrared Spectroscopy of Deposits on the Main Lower Attachment Fitting and Expansion Mandrel Components

Cotton swabs were used to remove samples from the surfaces of the as-received split mandrel components and the surfaces of the lugs on the main portion of the left wing lower main attachment fitting piece. In accordance with Service Bulletin No. E/02.170/2000, the wing fittings and associated split mandrel hardware are to be coated with DINITROL AV-30 for corrosion protection after inspection and other maintenance. The NTSB requested a reference sample of DINITROL AV-30 from the manufacturer (in order to acquire a reference infrared spectra), but none was available. An equivalent corrosion protectant was procured as a reference: ARDROX AV 30 (BASF Chemtall, Frankfurt, Germany). Deposits on the swabs were evaluated using a Fourier transform infrared (FTIR) spectrometer with a diamond attenuated total reflectance (ATR) accessory in accordance with ASTM E1252 and the spectra were compared with a spectrum for the exemplar ARDROX AV 30. The infrared spectra are shown in Figure 50 including a reference spectrum for ARDROX AV 30. The samples from the tapered retention bolt, tapered plug and the split mandrel revealed spectra consistent with degraded or oxidized ARDROX AV 30. The samples from the lugs and bore of the main attachment fitting piece revealed spectra that was not a comparative match to the ARDROX AV 30 spectrum.

Dimensional Analysis of the Main Lower Attachment Fitting Piece

A model of the main attachment fitting piece was generated using a Keyence VL-500 3D Scanning System. Profile sections parallel to the lug faces were viewed at five locations through the thickness of the lug and a best-fit arc was constructed approximately 65° around the remaining bore surface and 5 mm from the fracture surface (see Table 2). The arc radius was measured and was used to calculate an average diameter for the lug bore of about 36.064 mm. Figure 51 shows an example of one of the arc measurements. The engineering drawing for the lower attachment fitting required a bore diameter of 36.000 mm to 36.039 mm. Service Bulletin E/02.170/2000 allows the bore diameter to be machined to 36.3 mm to remove corrosion pits.

⁵ Loading directions (or modes) for fracture are categorized as: Mode 1—tension; Mode 2—in-plane shear; Mode 3—out-of-plane shear.

Table 2 Arc Radii Measured on the Main Piece of Left-Wing
Lower Attachment Fitting Lug Bore

Profile Section [a]	Measured radius (mm)	Calculated diameter (mm)
Arc 1	18.020	36.040
Arc 2	17.939	35.878
Arc 3	17.928	35.856
Arc 4	18.036	36.072
Arc 5	18.237	36.474
Average	18.032	36.064
SD [b]	0.124	0.248
CV [c]	0.69 %	

[a] Arc locations were taken at approximately equal intervals beginning near the fatigue crack origin and continuing through the lug thickness.

[b] Standard deviation of the sample set

[c] Coefficient of variation, $CV = SD \div \text{Average}$

Expansion Mandrel Assembly

The expansion mandrel assembly (see Figure 52) comprising a split mandrel, tapered plug, retention bolt, castellated nut, and washer was examined for indications of wear and corrosion. The components were documented in the as-received condition and cleaned condition after ultrasonic agitation in acetone.

Detailed images of the split mandrel at 90° intervals about the main axis are shown in Figure 53. Some areas on the outside diameter (OD) of the mandrel exhibited corrosion deposits as indicated in the figure. Corrosion deposits were prevalent on the portion of the mandrel OD that contacted the outboard lower main attachment fitting bore. A closer view of the mandrel surface exhibiting corrosion deposits is shown in Figure 54.

Detailed images of the retaining bolt at 90° intervals about the main axis are shown in Figure 55. Closer images of the surface of the tapered portion of the retaining bolt are shown in Figure 56. Annotations in the figure reveal the presence of two longitudinal marks consistent with marks that were created at the slot along the inside diameter (ID) of the split mandrel. A vibro-engraved mark present on the large end of the tapered portion of the retaining bolt is shown in Figure 57.

Detailed images of the tapered plug at 90° intervals about the main axis are shown in Figure 58. Closer images of the surface of the tapered portion of the plug are shown in Figure 59. Annotation in the figure reveals the presence of a longitudinal mark consistent with a mark created at the slot along the inside diameter (ID) of the split mandrel. A vibro-engraved mark present on the large end of the tapered portion of the retaining bolt is

shown in Figure 60a. Small circular impressions were observed at the small end of the tapered plug as indicated in Figure 60b.

Close images of the castellated nut and the washer are shown in Figures 61 and 62. The expansion mandrel diameter was measured in accordance with Figure 63 and Table 3.

Table 3—Expansion Mandrel Diameter Measurements

Length location	Diameter location	Diameter (mm)
1	A	35.97
1	B	35.95
2	A	35.94
2	B	35.96
3	A	35.96
3	B	35.97

Composition, Microstructure, and Hardness of the Lower Attachment Fitting

A cross sectional sample piece was cut from the separated piece of the lower attachment fitting lug. The sample was metallurgically mounted for microstructural examination and hardness. The cross section revealed numerous pits in the bore surface and the forward side of the lower lug, consistent with corrosion. Typical pits with corrosion product are shown in Figure 64. The side of the lower lug exhibited corrosion pitting and corrosion product scale as demonstrated in Figure 65. The microstructure was uniformly tempered martensite as shown in Figure 66.

The composition of the steel was determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) and combustion-infrared absorbance carbon-sulfur analysis for all elements greater than 0.01 weight% in accordance with ASTM A751 and E1019, respectively. The results are summarized in Table 4.

Table 4—Composition of the Lower Attachment Fitting

Element	30HGSA composition (weight %)	Accident attachment fitting (weight %)
C	0.28-0.34	0.30
Cr	0.8-1.1	0.82
Mn	0.8-1.1	0.96
Ni	0.3 max	0.22
P	0.025 max	0.018
S	0.025 max	0.011
Si	0.9-1.2	1.06
Cu	0.03 max	0.11*
Al	—	0.03
Ca	—	0.01
Co	—	0.01
Mo	—	0.03
Ti	—	0.04
V	—	0.01
W	—	0.01
Fe	Balance	Balance

*Copper content exceeds specification limits.

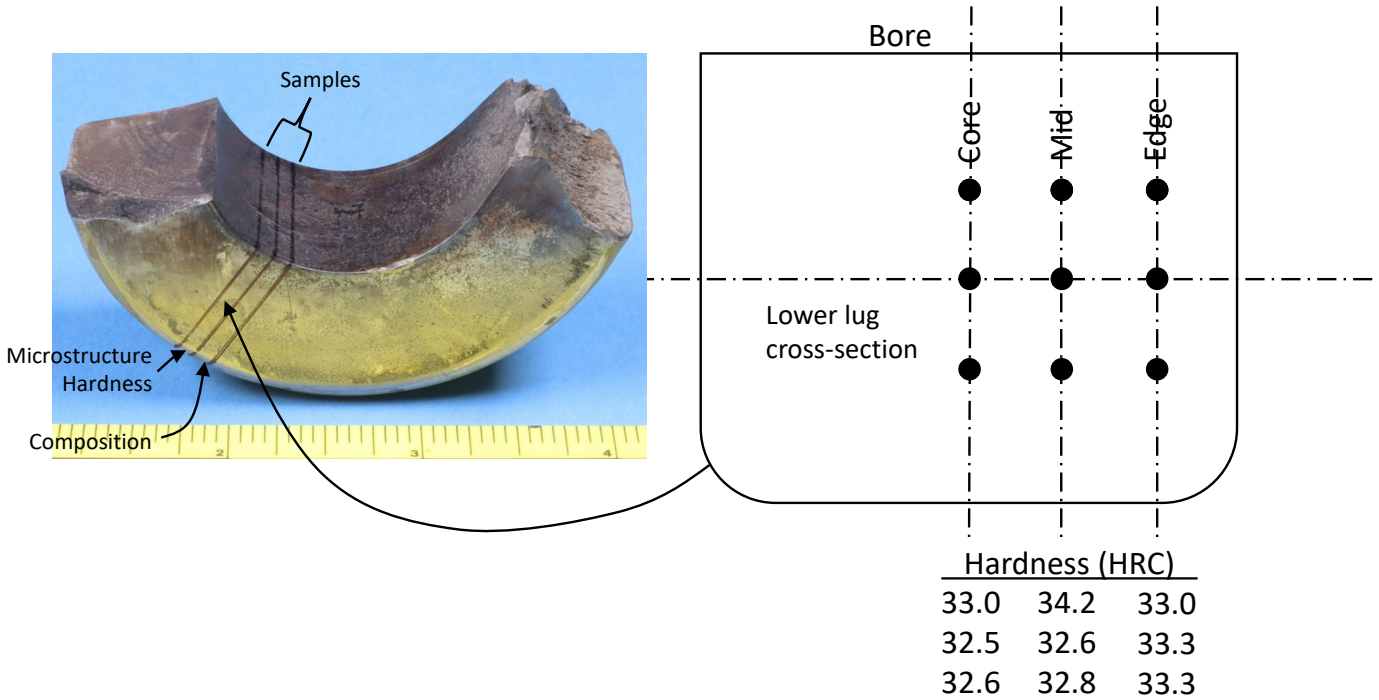
According to the engineering drawing number D.22.200.36.1, the attachment fitting is specified to be made from PN 30HGSA low alloy high strength steel, heat treated to a tensile strength between 110 and 130 kg/mm² (156,456 and 184,903 psi). In accordance with guidance in ASTM A370 table 2, the tensile strength to hardness conversion is shown in Table 5

Table 5—Tensile Strength to Hardness Conversion

Tensile strength (psi)	Hardness (HRC)
156456	35.0
184903	40.5

The hardness of the lower attachment fitting was measured on a cross sectional sample cut from the lower lug portion of the separated lower attachment fitting piece in accordance with ASMT E18 and A370. Three replicate hardness measurements were made at three locations as indicated in Table 6. The average hardness was 33.0 HRC, which is below the 35.0 HRC minimum required hardness.

Table 6—Hardness Measurements



Michael Budinski
Chief, Materials Laboratory Division

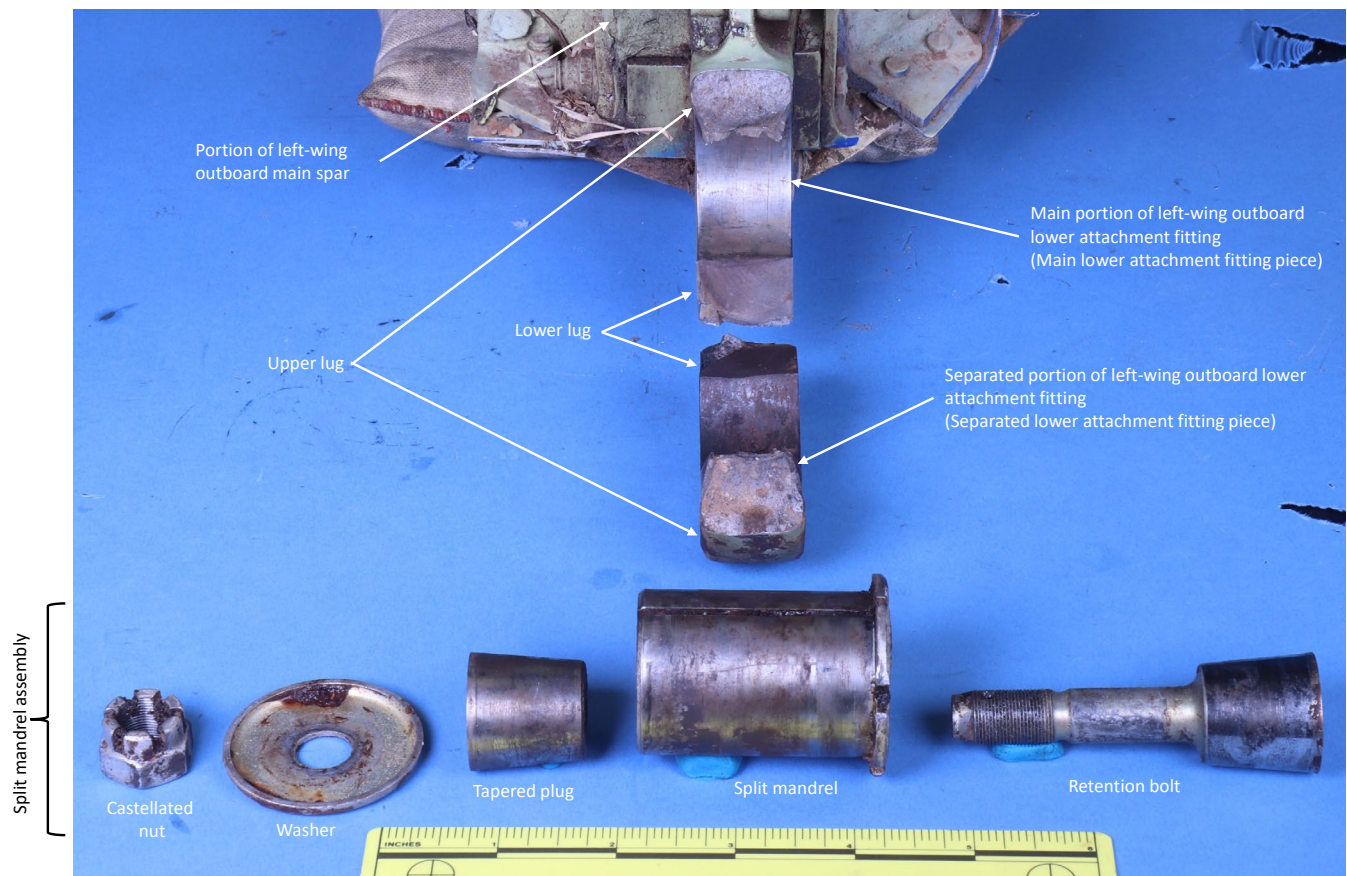


Figure 1 Close view of the as-received evidence with the name of key components annotated in the image.

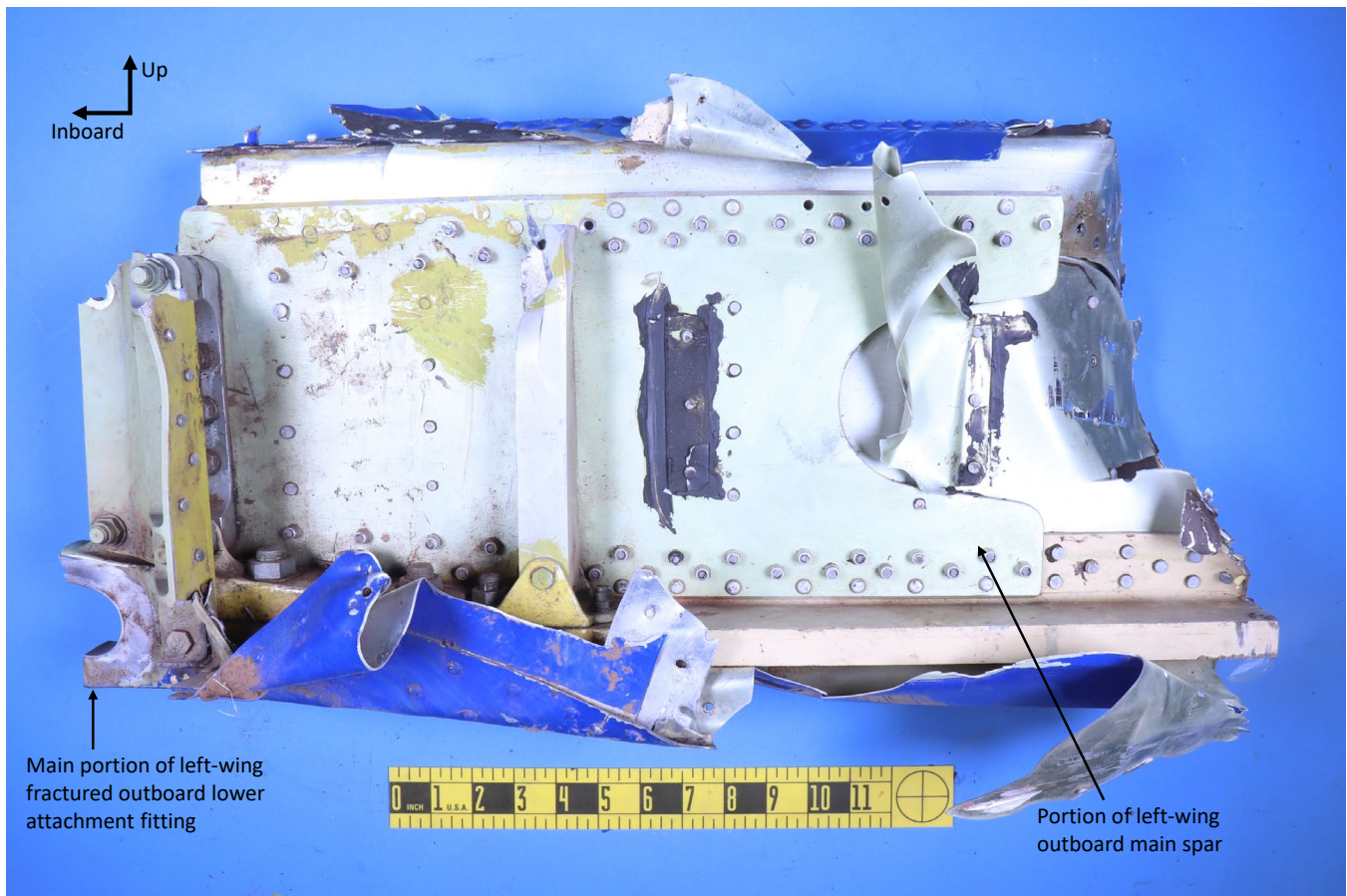


Figure 2 View of the forward-facing side of the as-received outboard left-wing main spar piece with fractured main lower attachment fitting piece.

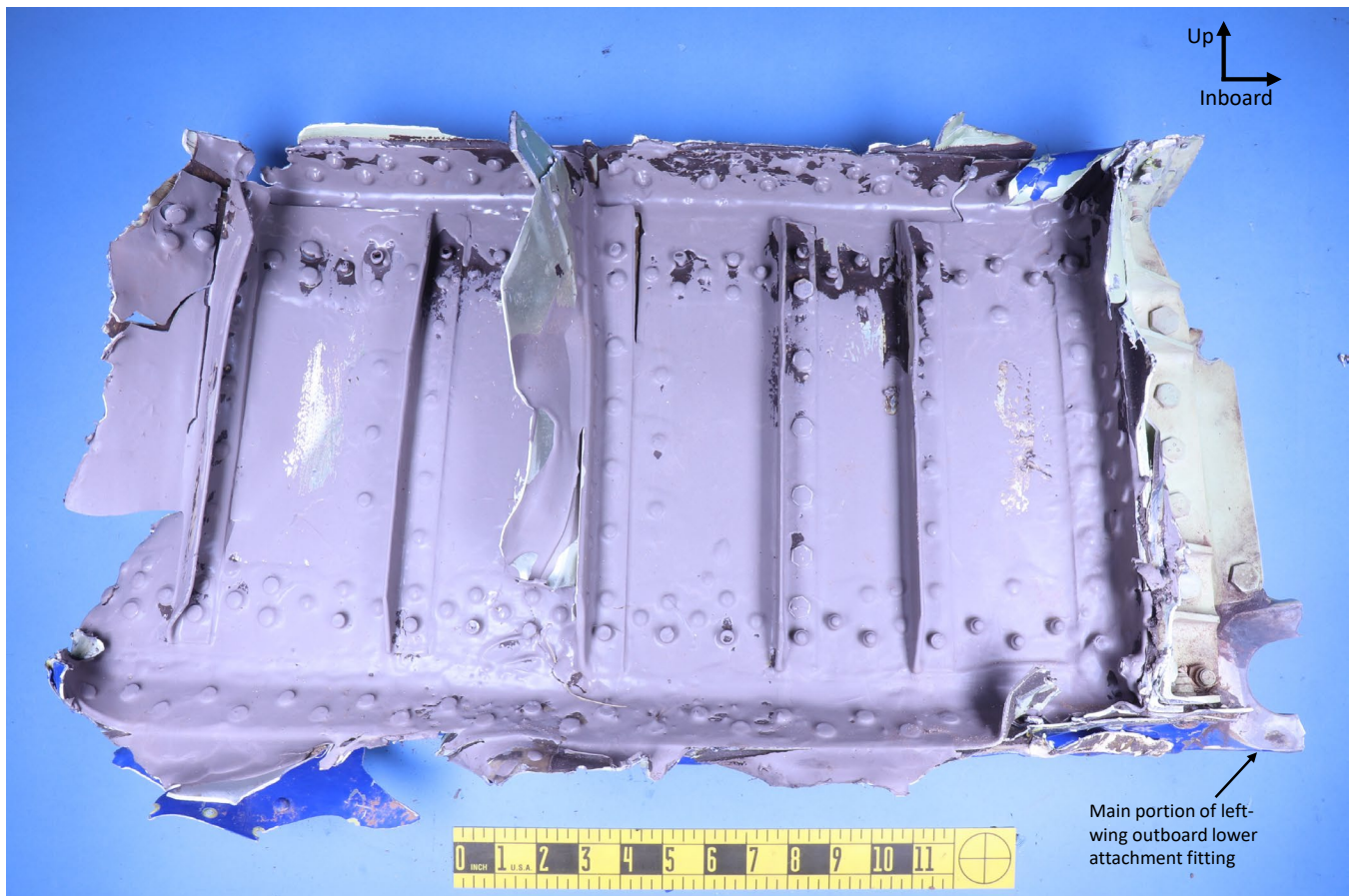


Figure 3 View of the aft-facing side of the as-received outboard left-wing main spar piece with fractured main lower attachment fitting piece.

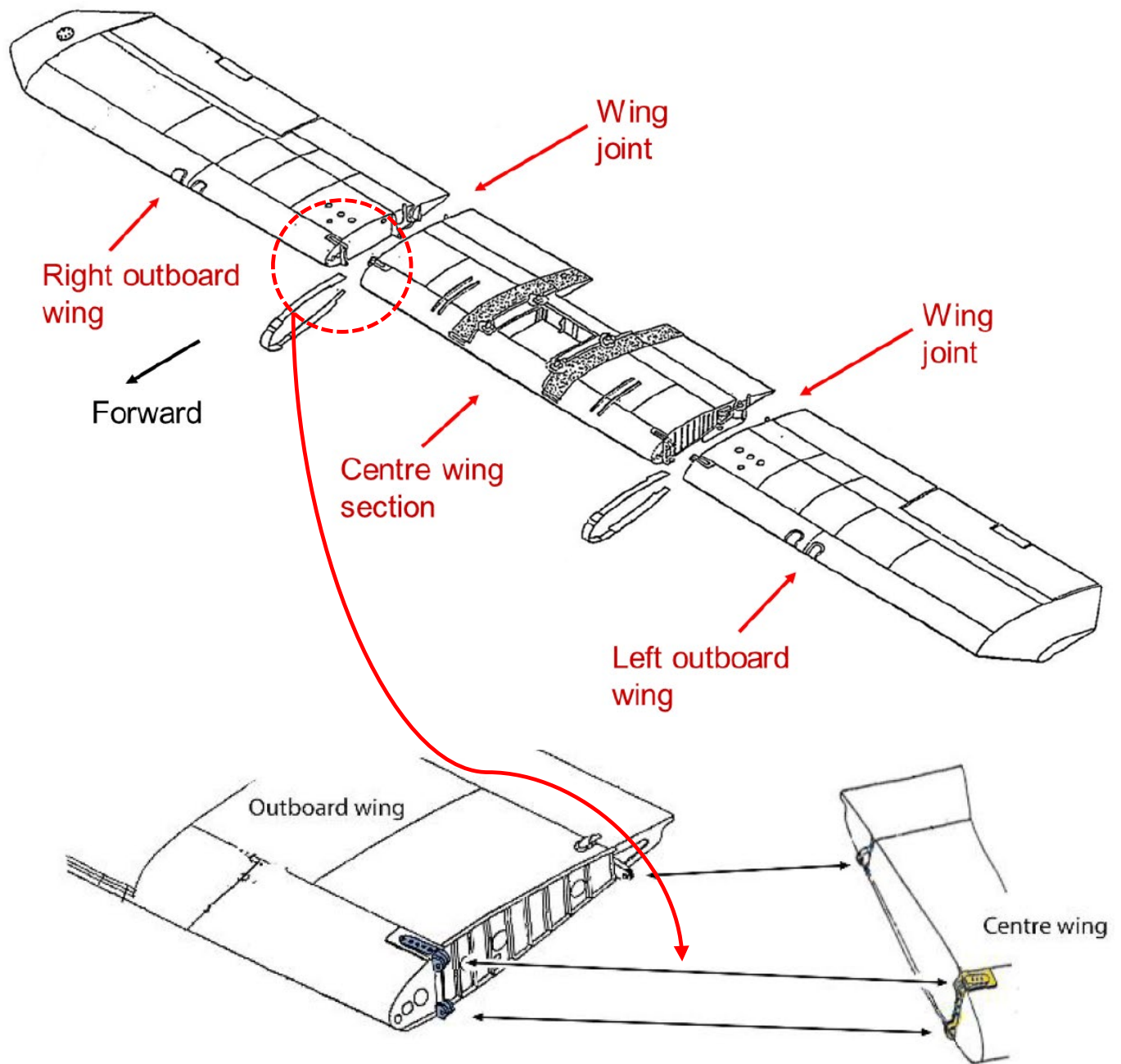


Figure 4 Sketch of the wing assembly and the location of the forward wing attachment fittings (example from the right wing). (Adapted from ATSB Transport Safety Report AO-2013-187 Final 15Feb2016)

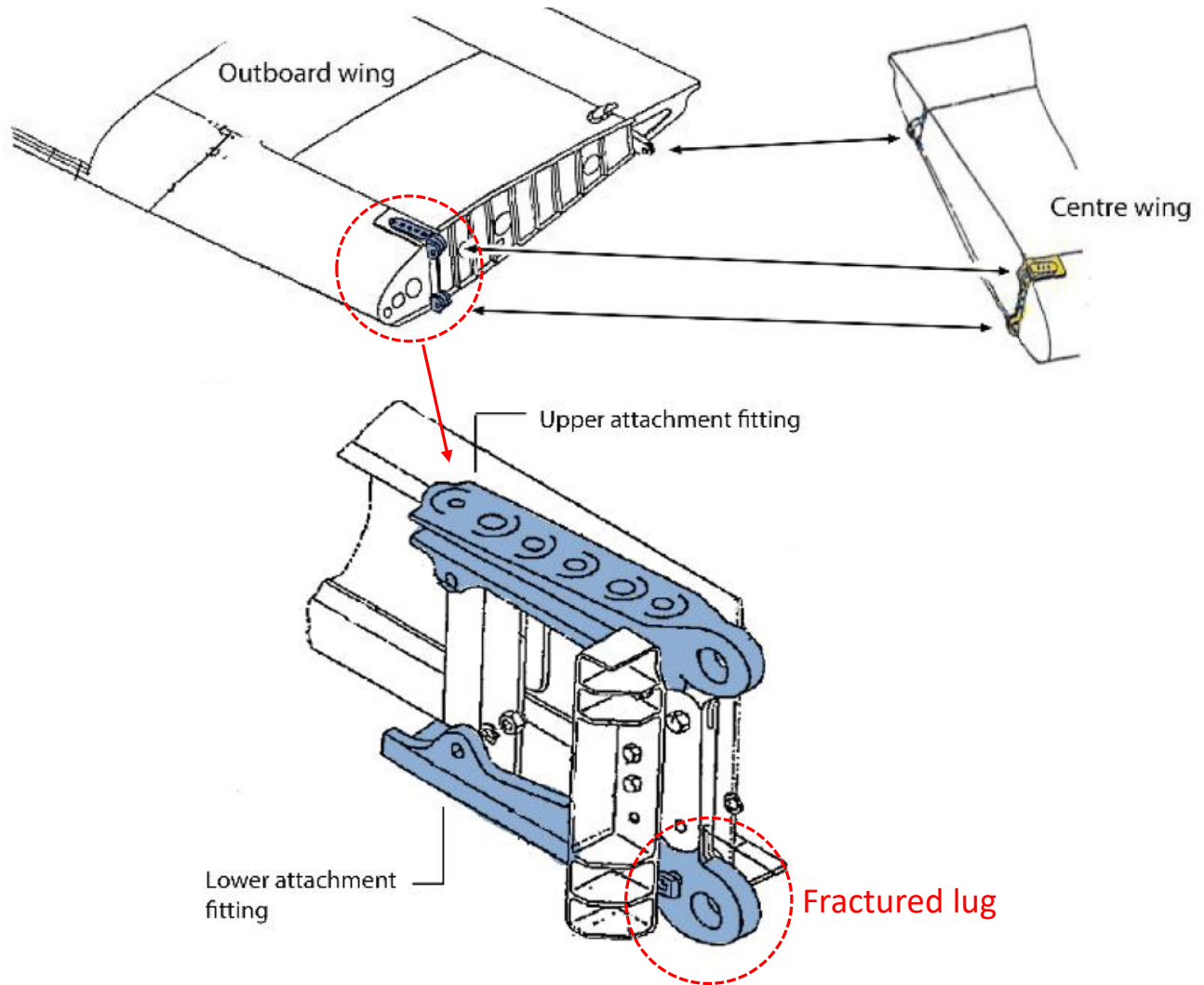


Figure 5 Sketch of the right wing assembly and the location of the right forward lower wing attachment fitting. (Adapted from ATSB Transport Safety Report AO-2013-187 Interim 23Dec2013)

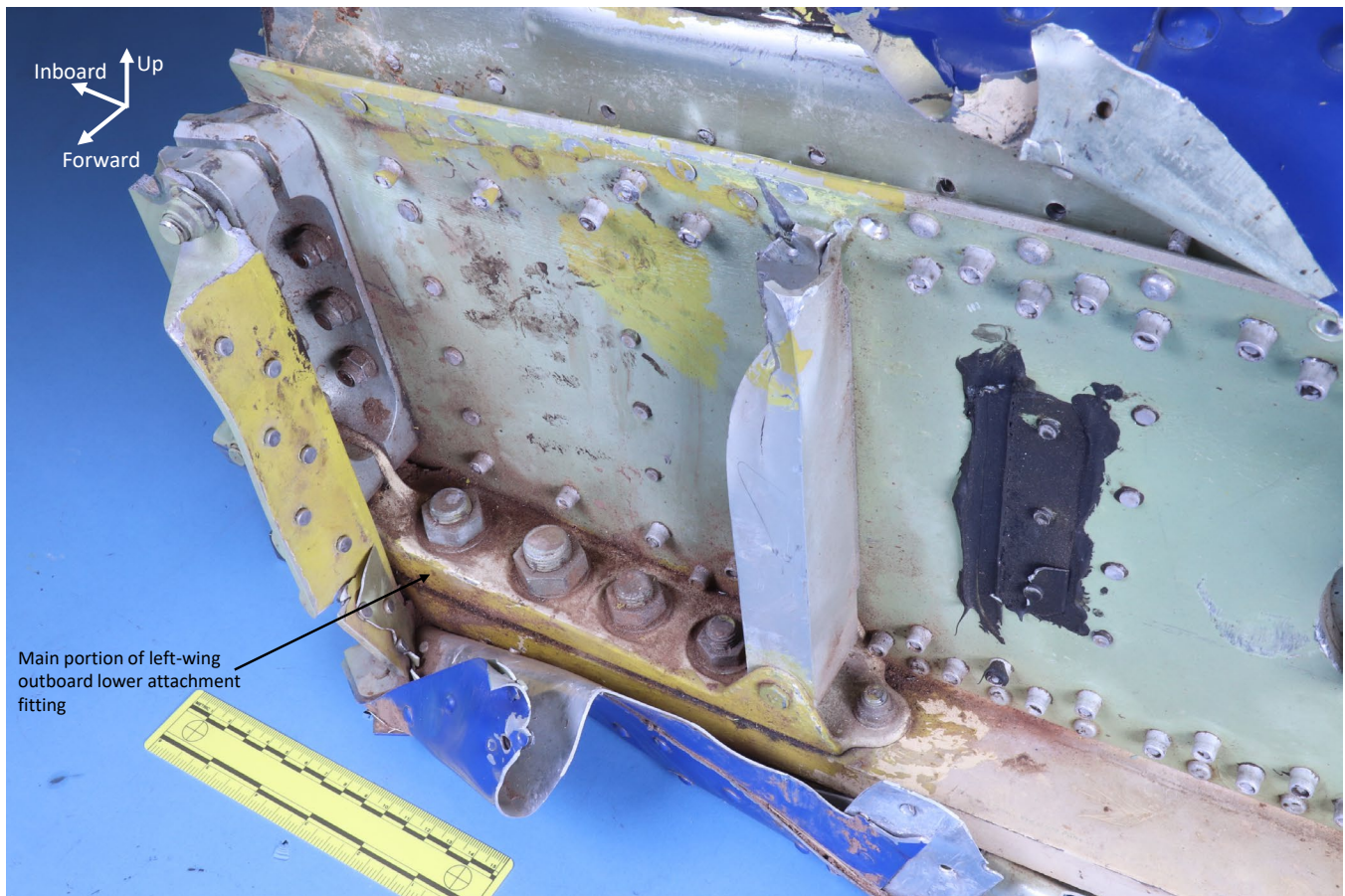


Figure 6 Oblique view of the as-received left-wing spar piece with the outboard main lower attachment fitting piece as installed.

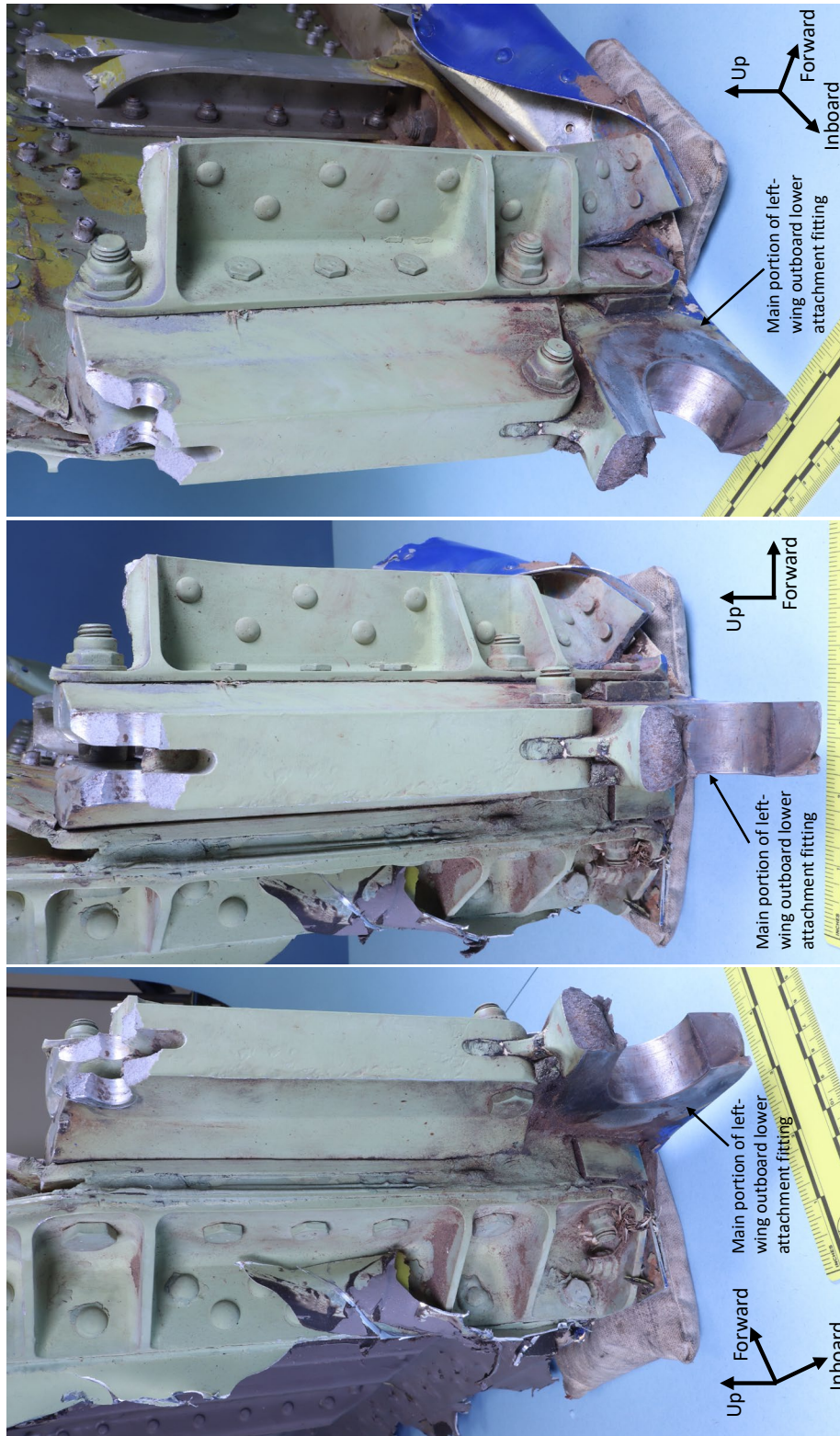


Figure 7 Images of inboard face of the as-received spar piece with the fractured end of the main lower attachment fitting piece.

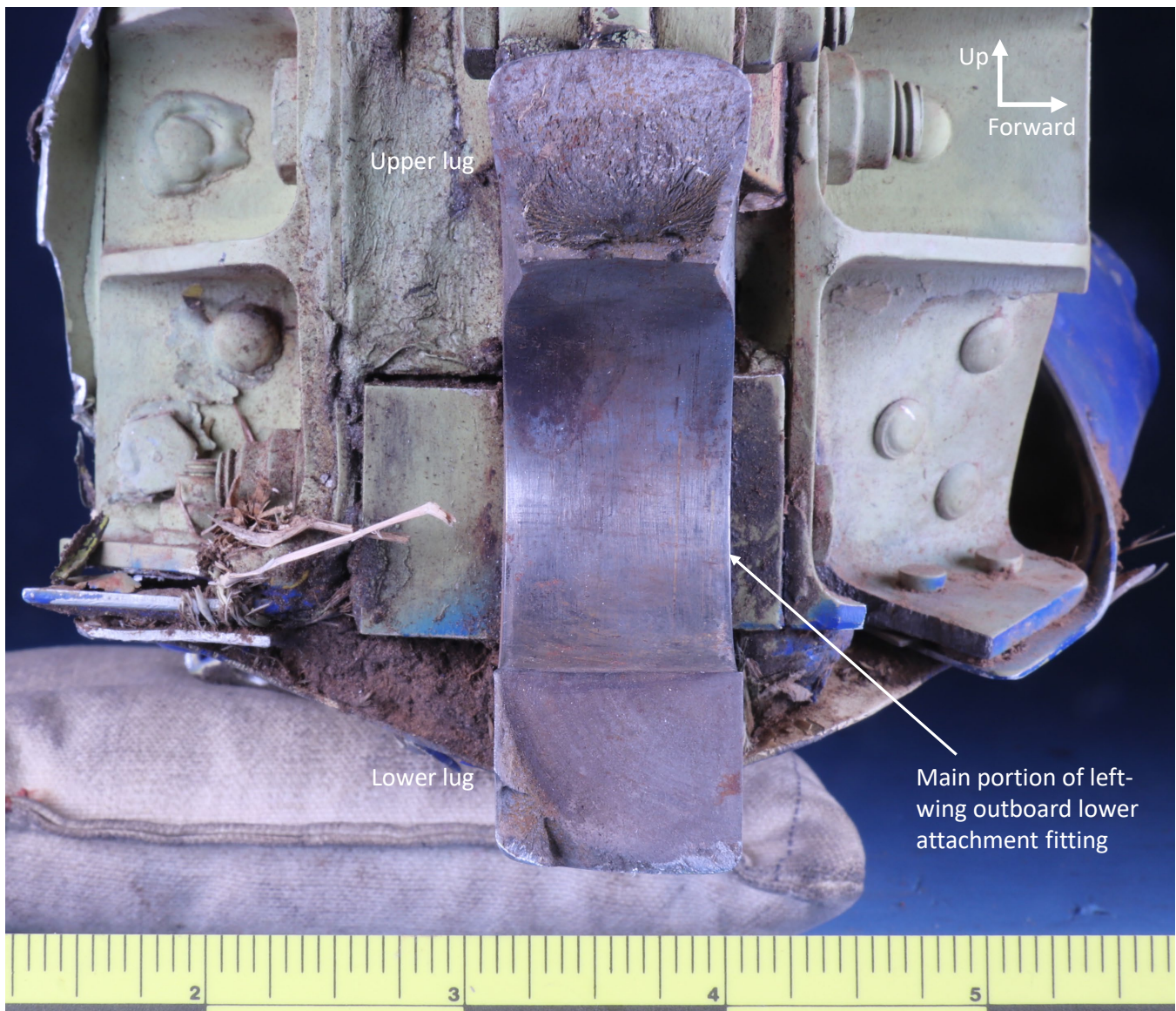


Figure 8 Closer view of the as-received left spar piece and the fractured end of the lower attachment fitting. The upper and lower lug fracture surfaces are identified.

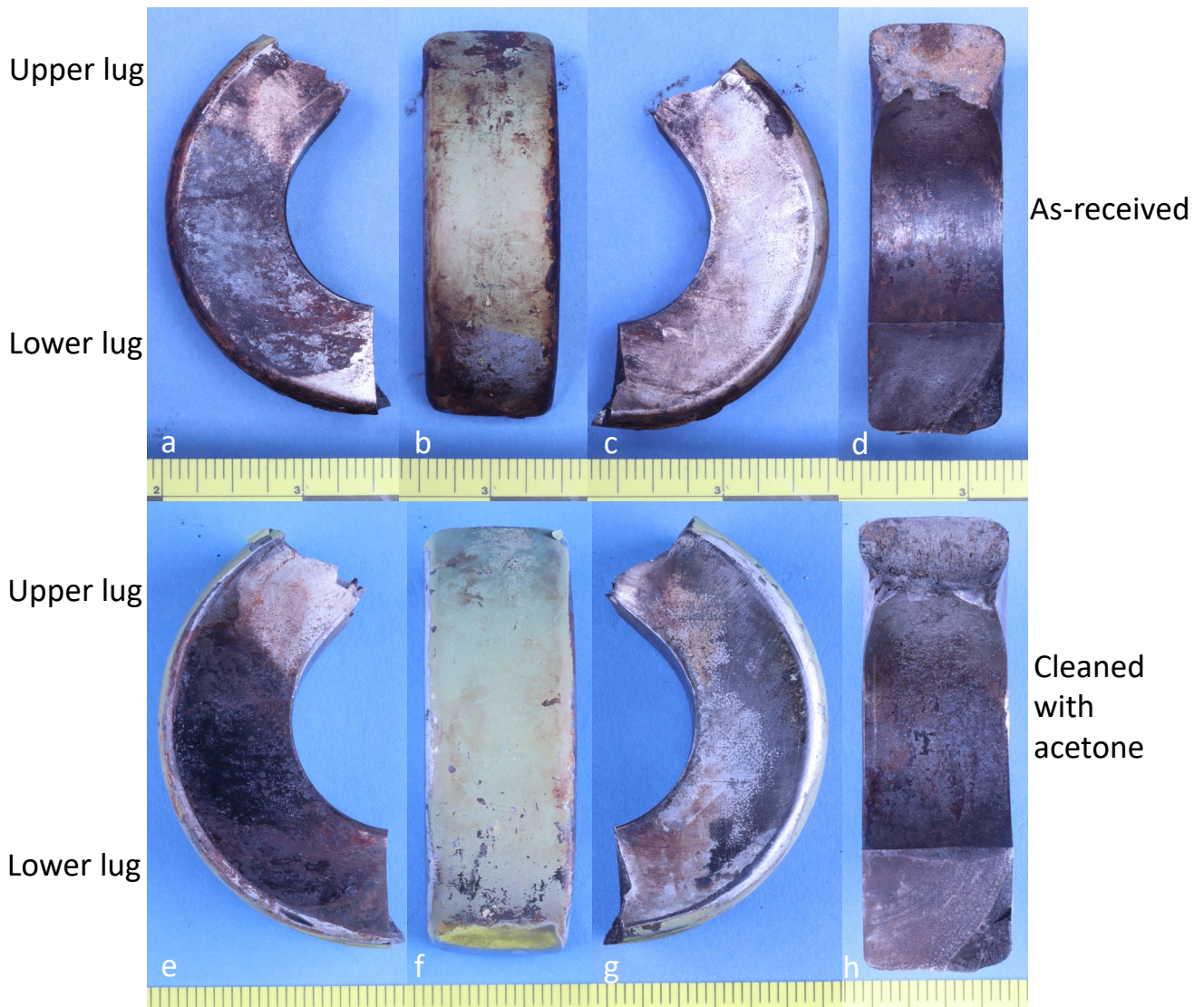


Figure 9 Views of the separated piece of the lower attachment fitting. The upper and lower fracture surfaces are identified.

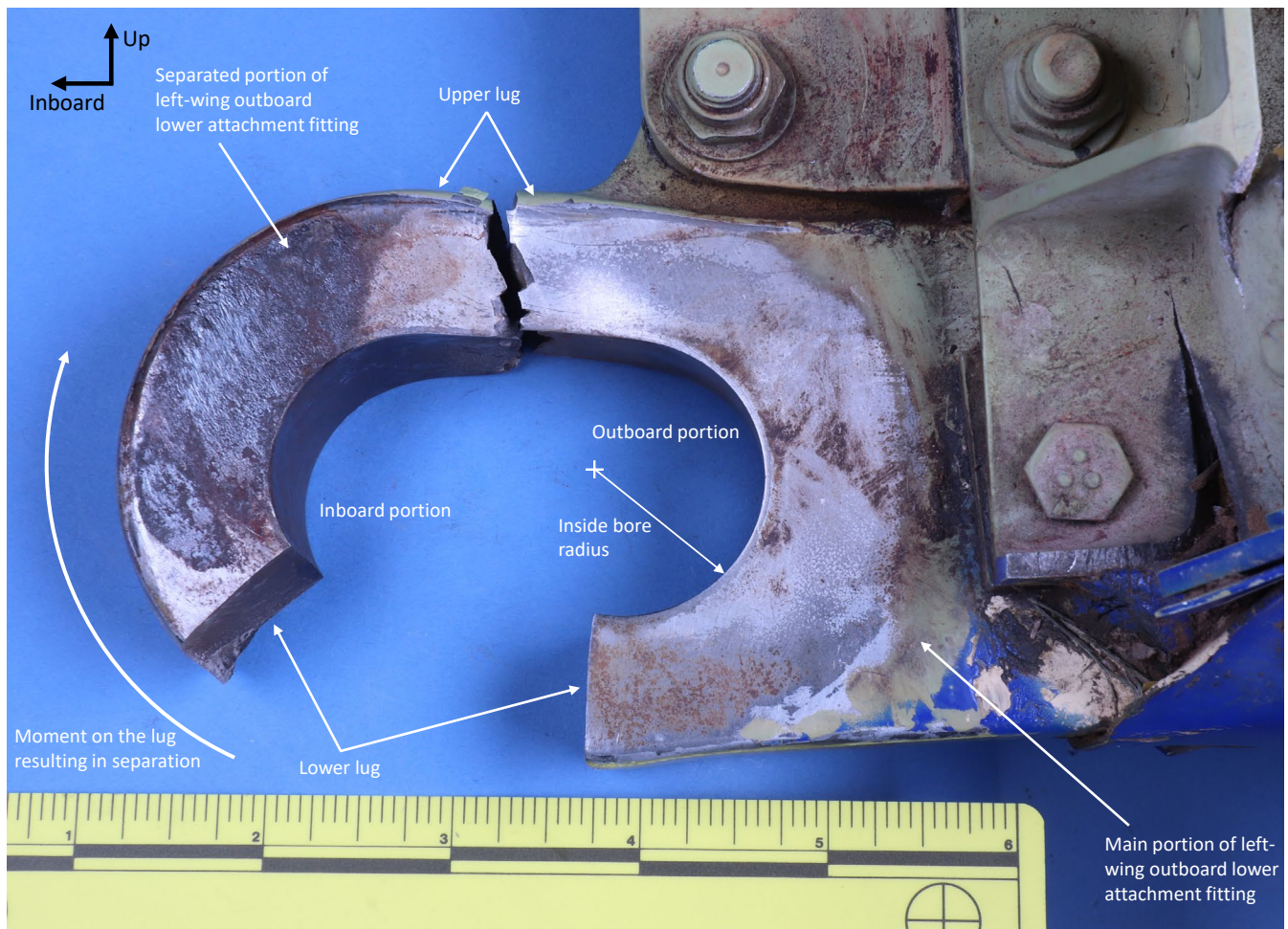


Figure 10 Close side view of the as-received fractured end of the lower attachment fitting with the separated piece of the fitting placed in the approximate location at the point of separation.

Upper lug

Lower lug



Figure 11 Close views of the as-received fracture faces and bore surfaces on the lower attachment fitting and the separated lug piece. Corrosion product deposits are evident on the bore surface of the separated lower fitting piece.

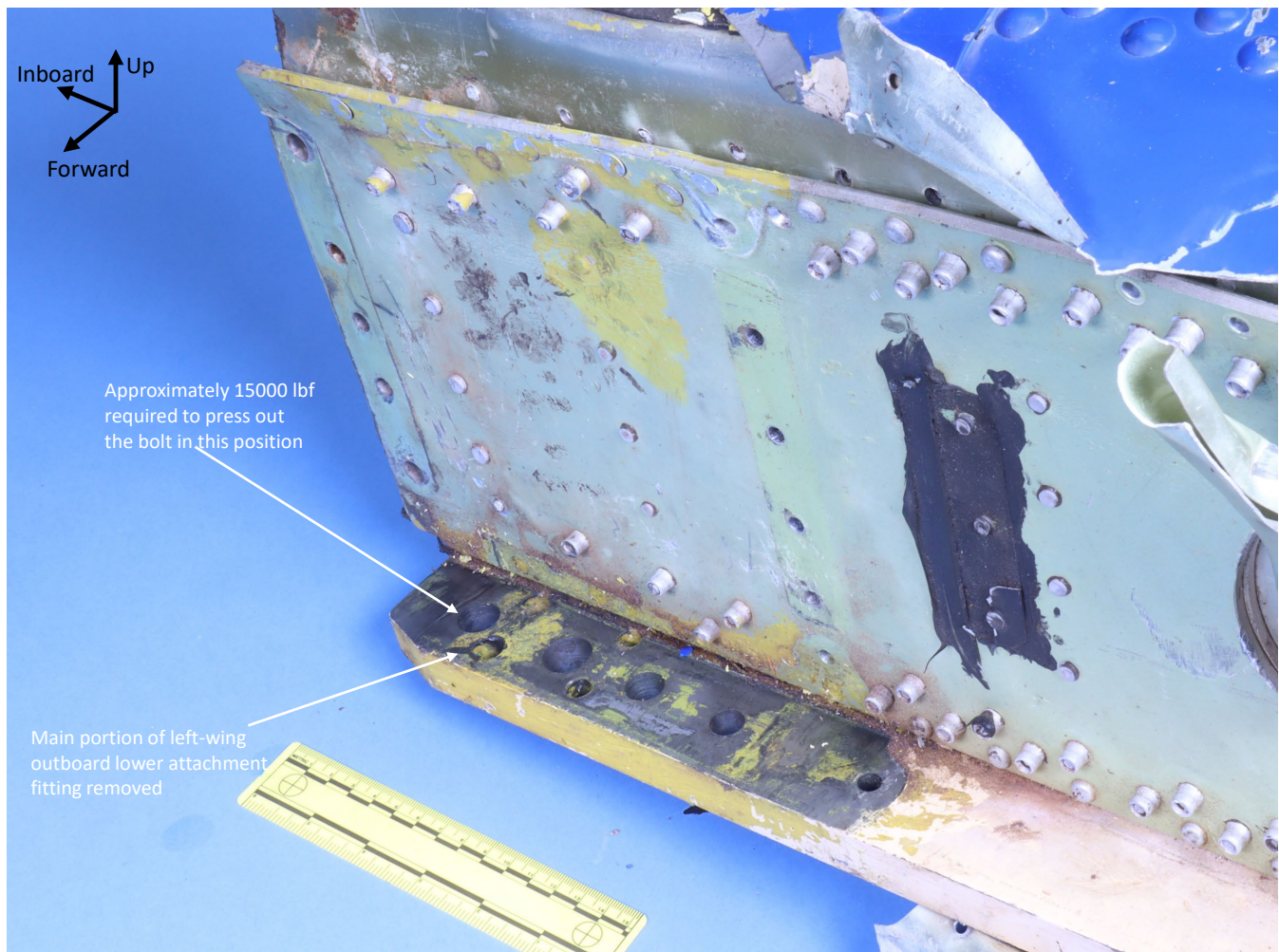


Figure 12 Oblique view of the spar piece after removal of the main lower attachment fitting piece.

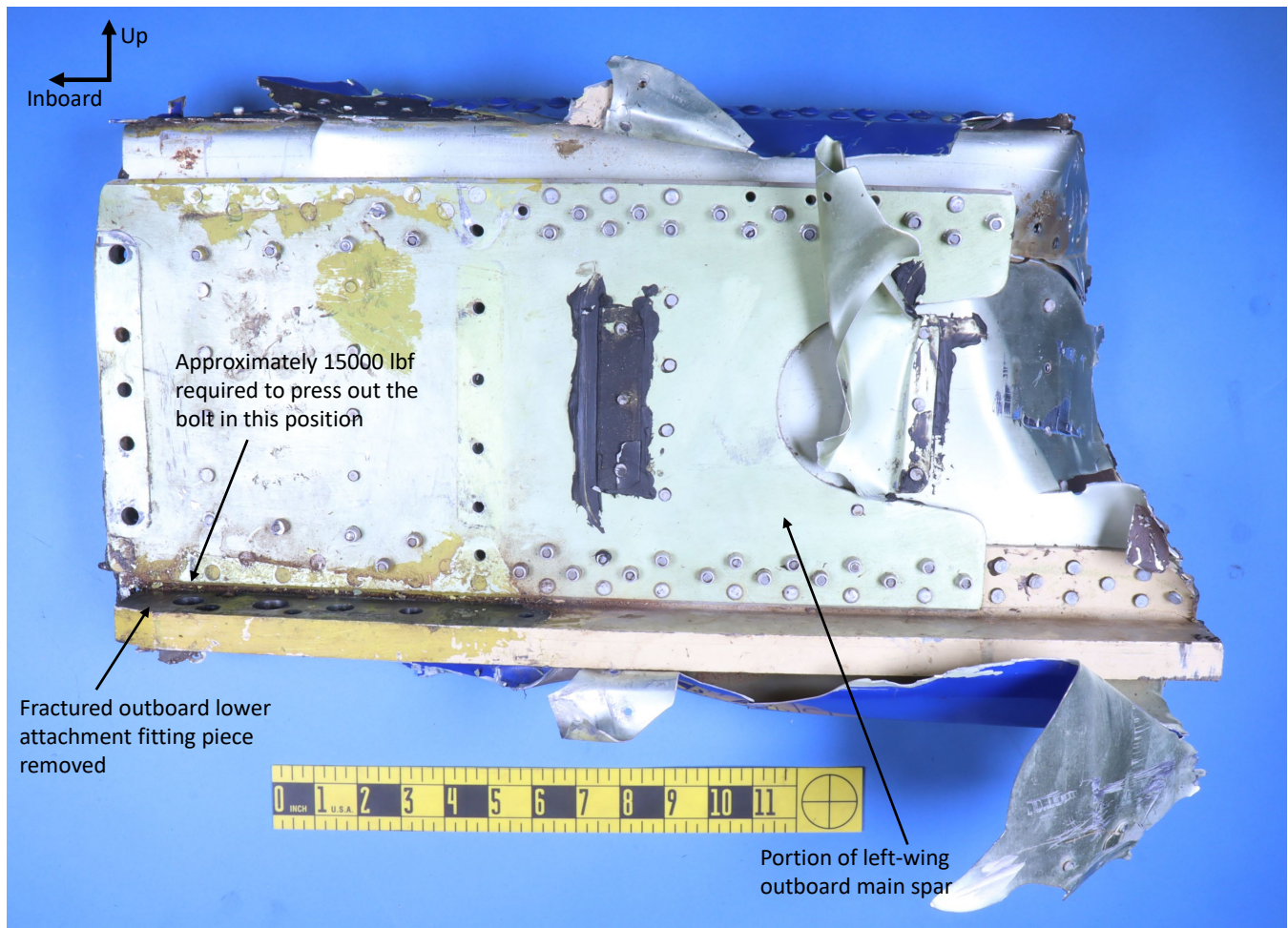


Figure 13 Side view of the spar piece after removal of the main lower attachment fitting piece.



Figure 14 Side views of the lower attachment fitting pieces with the separated piece arranged to approximate its position at the point of separation.

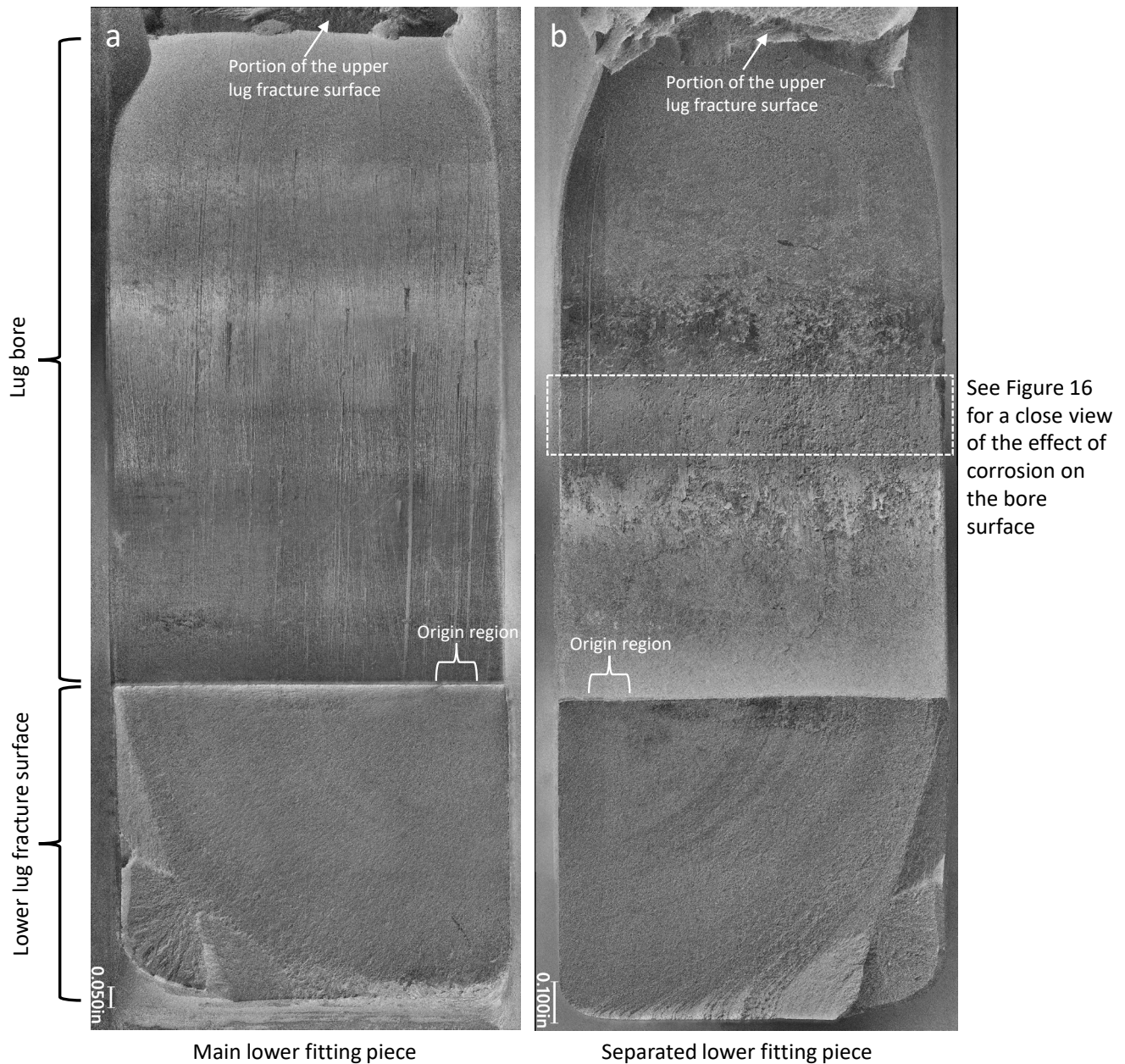


Figure 15 Digital microscope monochromatic images of the lug bore and lower lug fracture surfaces for both halves of the fractured lower attachment fitting. The lower lug fracture surfaces exhibit crack progression marks and a fine thumbnail region at the fracture origin. The surface of the bore on the separated lower fitting piece exhibited corrosion product scale and pits (a higher magnification view is shown in Figure 16).



Figure 16 Digital microscope view across with width of the lug bore for the separated lower fitting piece (see Figure 15 for location) revealing corrosion product scale and pits. A circumferential score mark is also present.

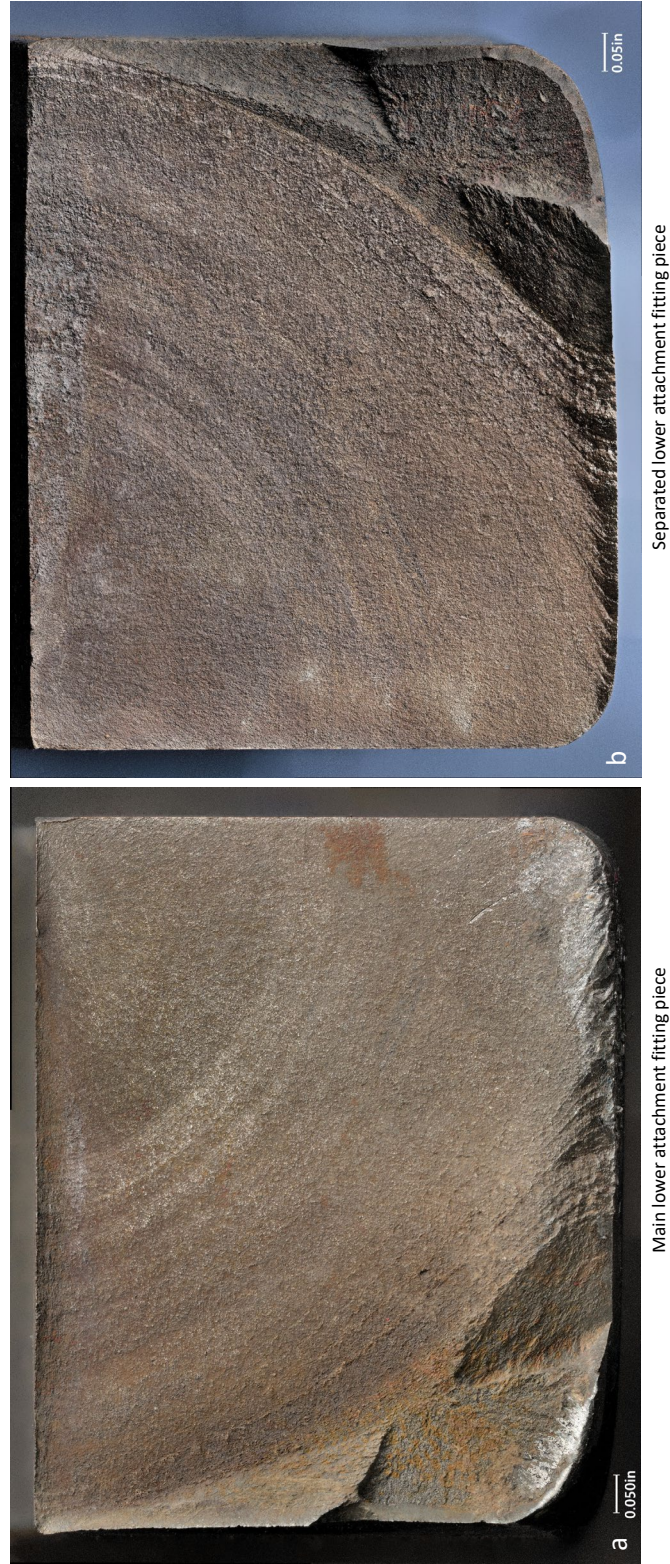


Figure 17 Digital microscope images of both halves of the lower lug fracture surfaces (see Figure 18 for the same images with annotations). The images were acquired under HDR imaging conditions with oblique lighting.

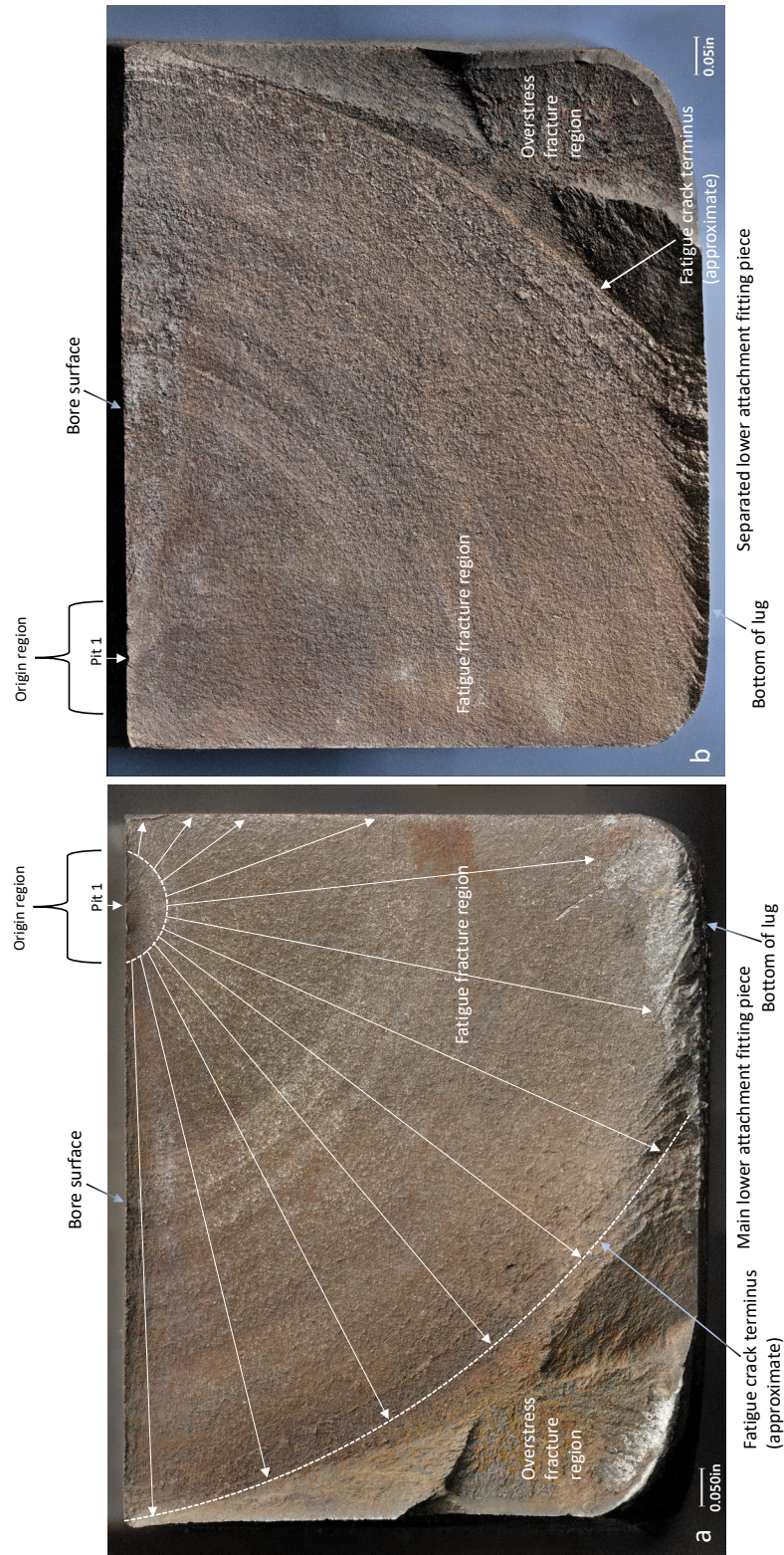


Figure 18 Digital microscope images of both halves of the lower lug fracture surfaces with annotations to identify key features on the fracture surfaces (same images as Figure 17 but with annotations). The images were acquired under HDR imaging conditions with oblique lighting.



just below the bore surface

Figure 19 Digital microscope images of both halves of the lower lug fracture surfaces showing a stained region just below the bore (see Figure 20 for the same images with annotations). The images were acquired under normal imaging conditions with oblique lighting.

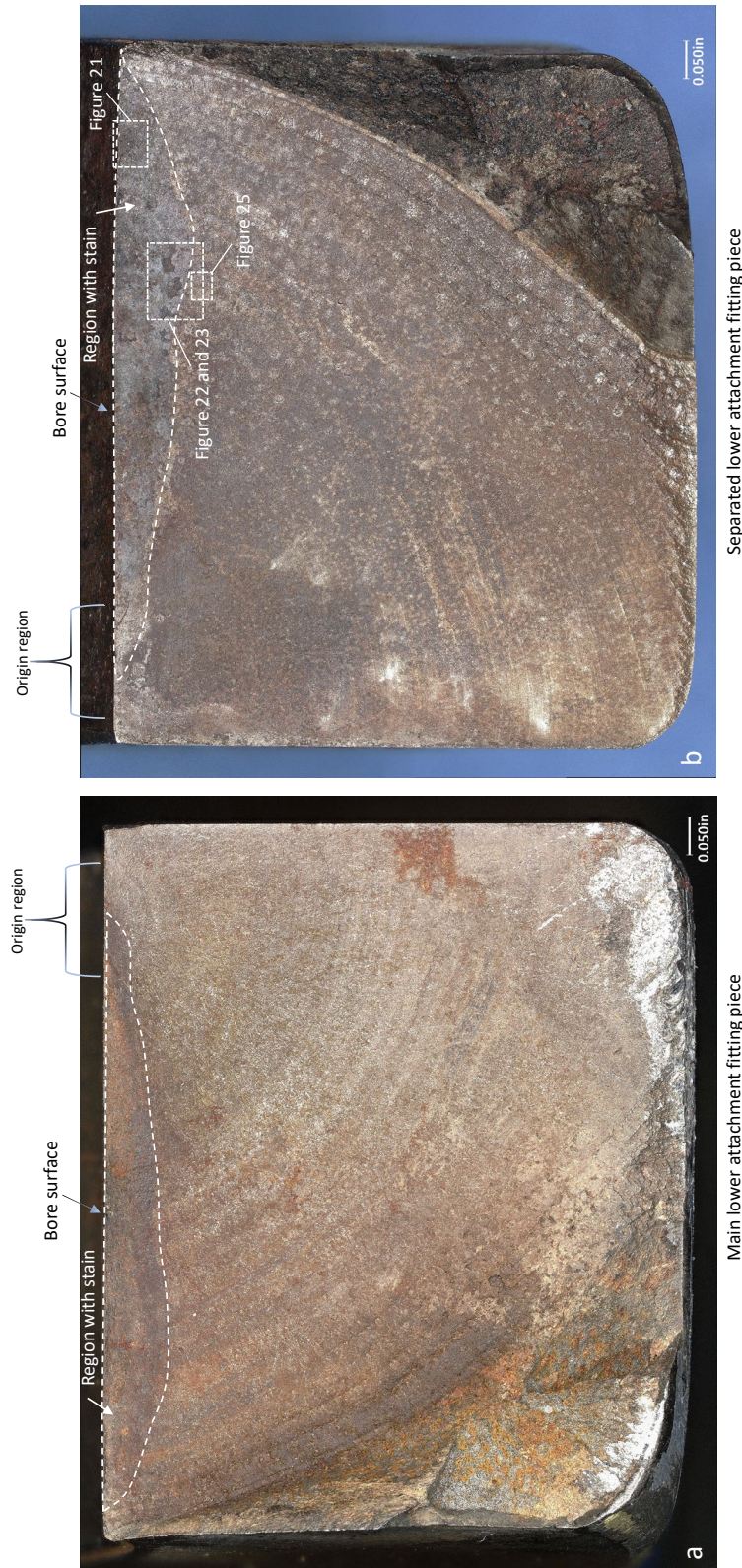


Figure 20 Digital microscope images of both halves of the lower lug fracture surfaces showing a stained region just below the bore with annotations (same images as Figure 19 but with annotations). The images were acquired under normal imaging conditions with oblique lighting.

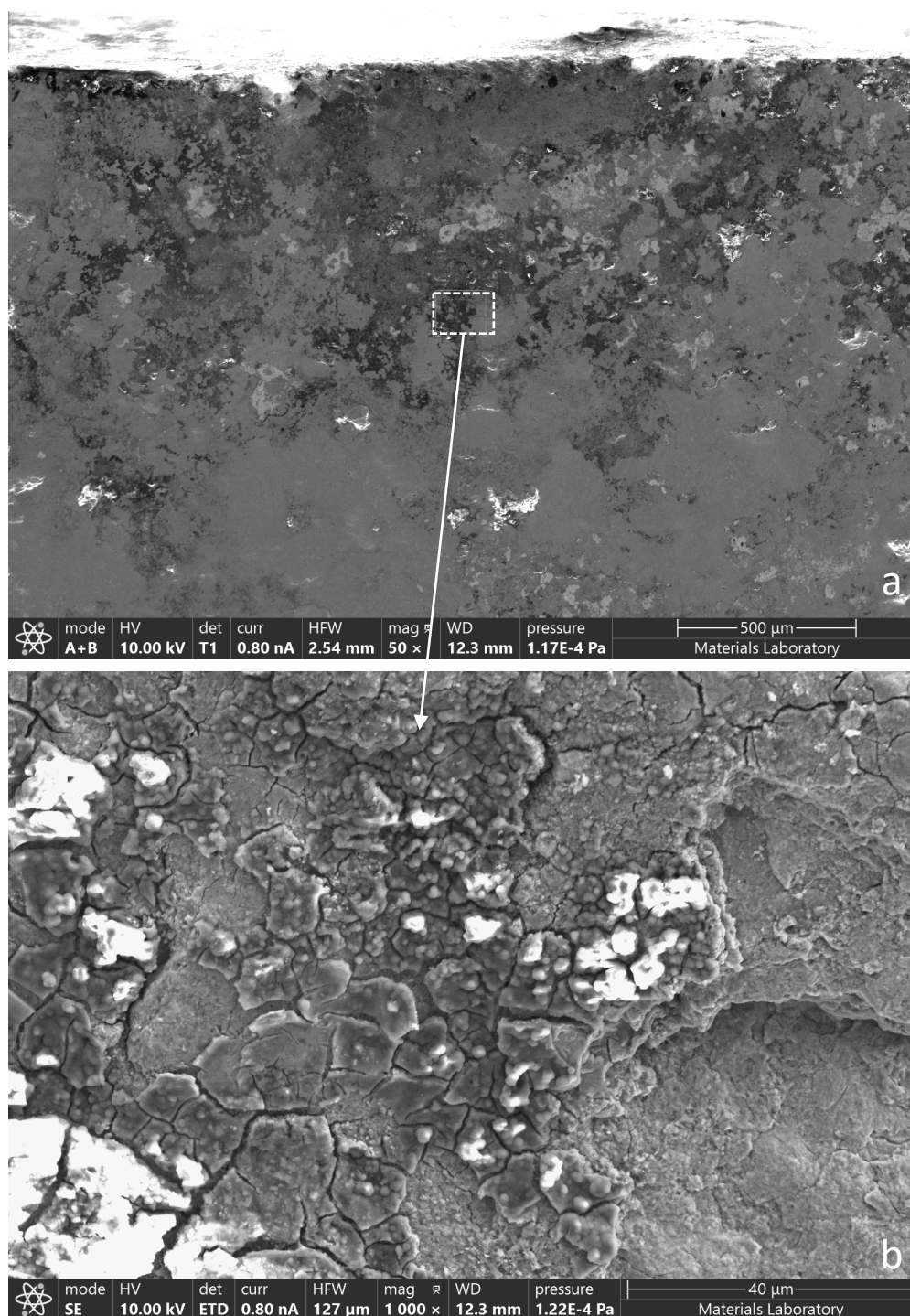


Figure 21 SEM images of the stained region on the fracture surface (see Figure 20 for location). View a is a lower magnification image showing the general morphology of the corrosion product scale. View b is a higher magnification image that shows the corrosion product scale morphology. The thickness of the scale occludes the fine fractographic features on the fracture surface.

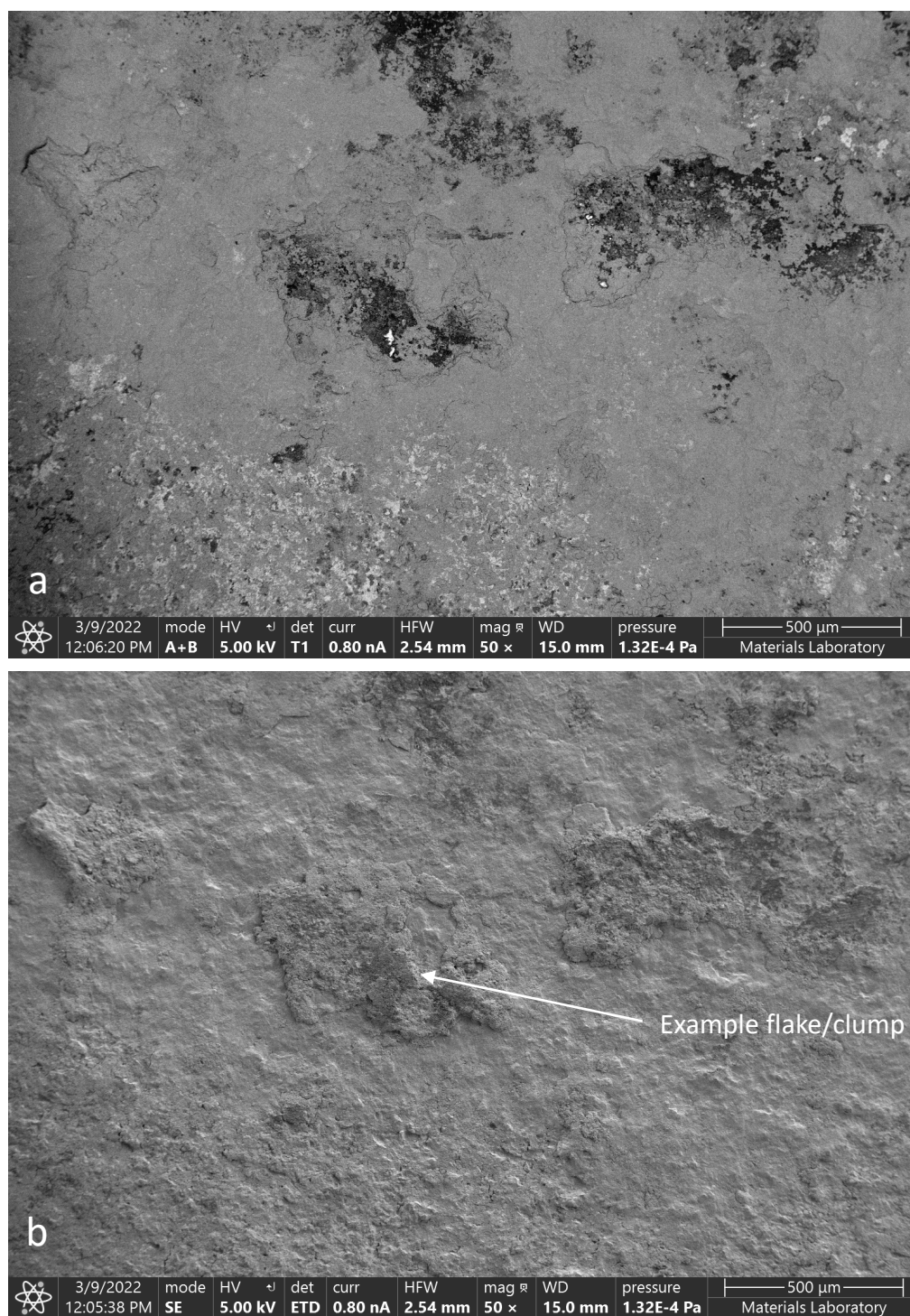


Figure 22 General SEM image of corrosion product with a thick clump or flake morphology. EDS analysis was performed on the central clump as documented in Figures 23 and 24.

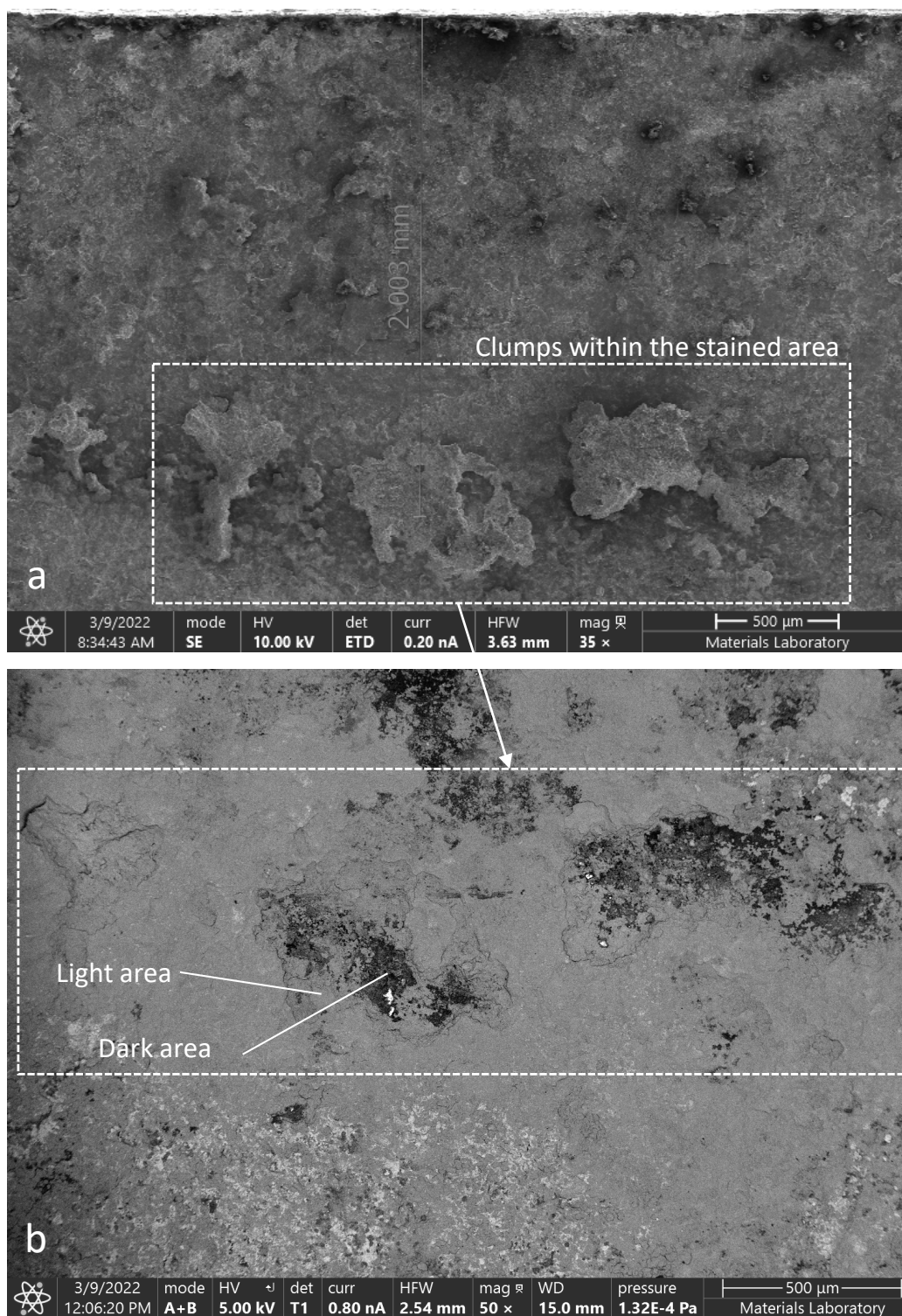


Figure 23 SEM images of the exemplar flakes or clump corrosion product deposits identified in Figure 22. View a is a secondary electron image and view b a mixed backscattered electron image. EDS spectra for the areas identified in view b are shown in Figure 24.

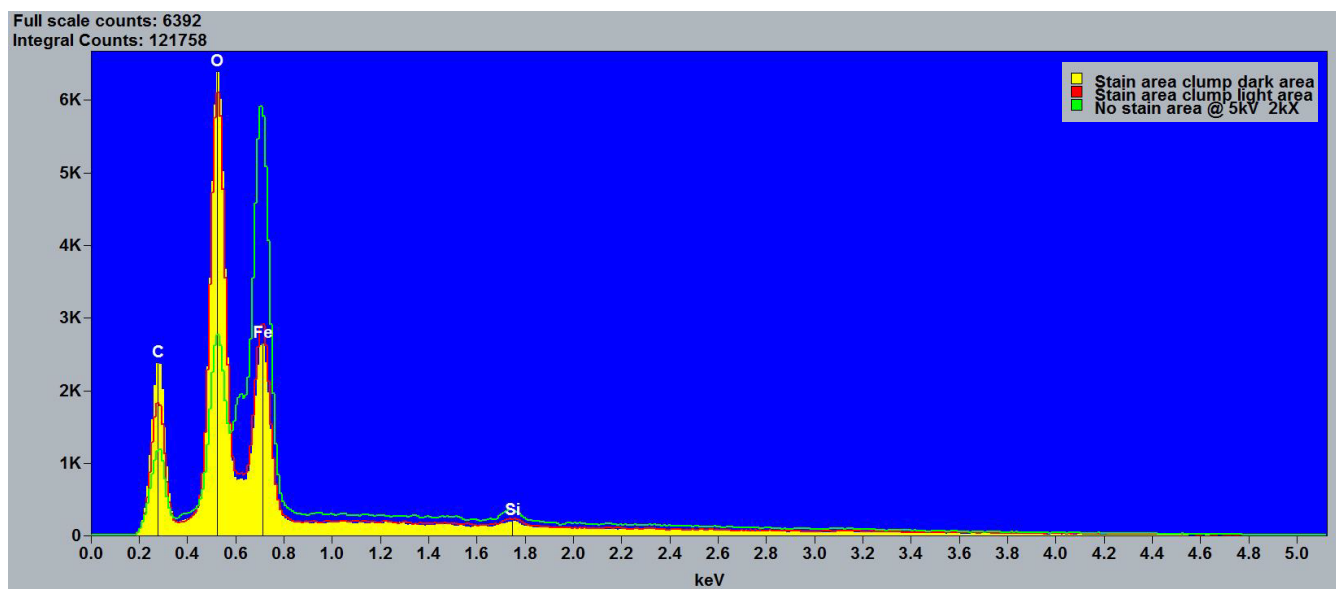


Figure 24 EDS spectra for the features identified in Figure 23b.

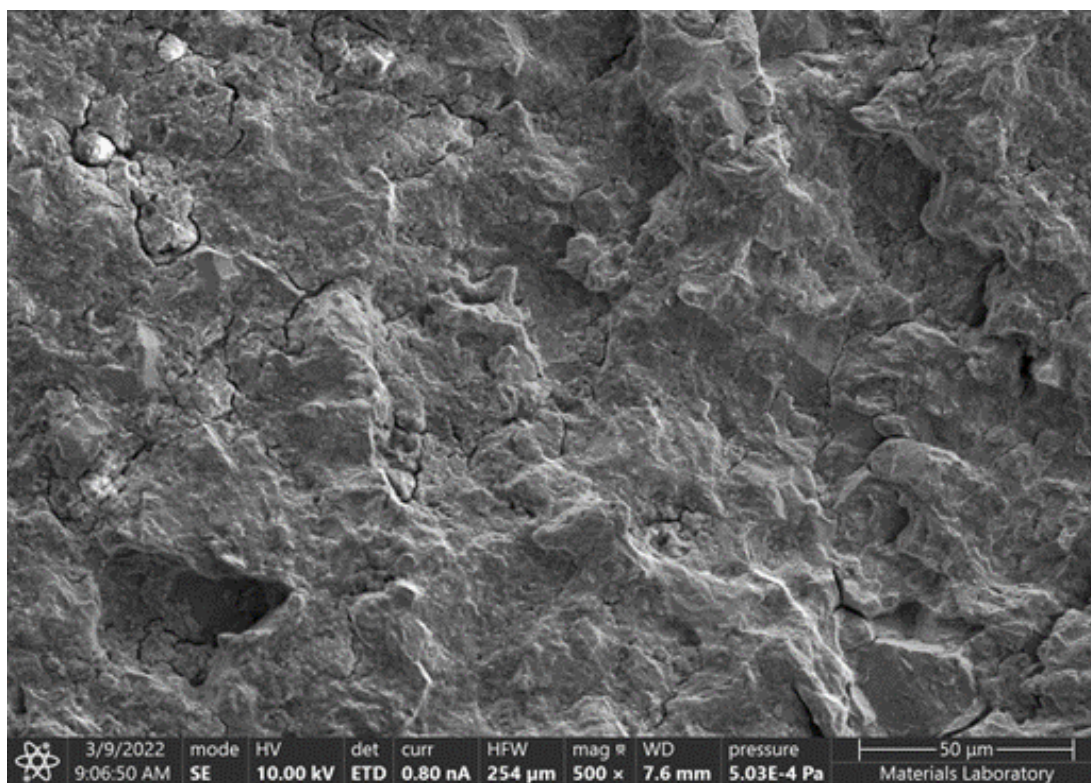
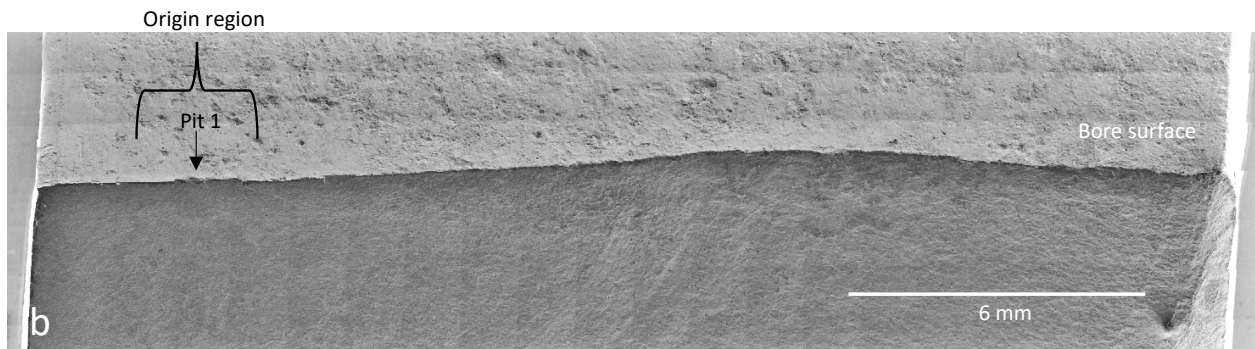


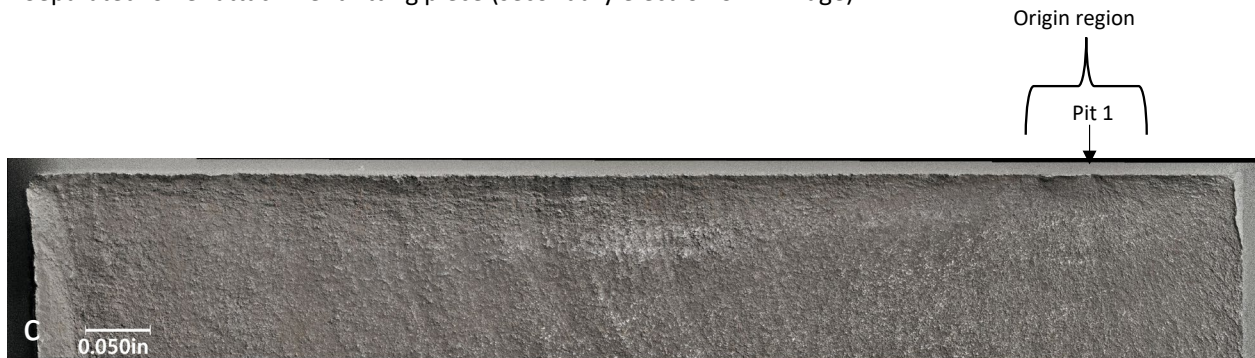
Figure 25 Close SEM view of the as-received fracture surface (after cleaning in acetone) for the area identified in Figure 20b. This fractograph, which is immediately below the stained region identified in Figure 20b, reveals a thin layer or deposit that occludes fine fractographic features.



Separated lower attachment fitting piece (digital microscope HDR image)



Separated lower attachment fitting piece (secondary electron SEM image)



Main lower attachment fitting piece (digital microscope HDR image)

Figure 26 Close images of both halves of the fracture surfaces just below the lug bore (full width of the lug in the as-received acetone-cleaned condition). Observations of pits and ratchet marks at the fatigue crack origin region are identified in the images. Crack progression marks are present in the images. Closer images of the origin region for the separated lower fitting piece are shown in Figure 27.

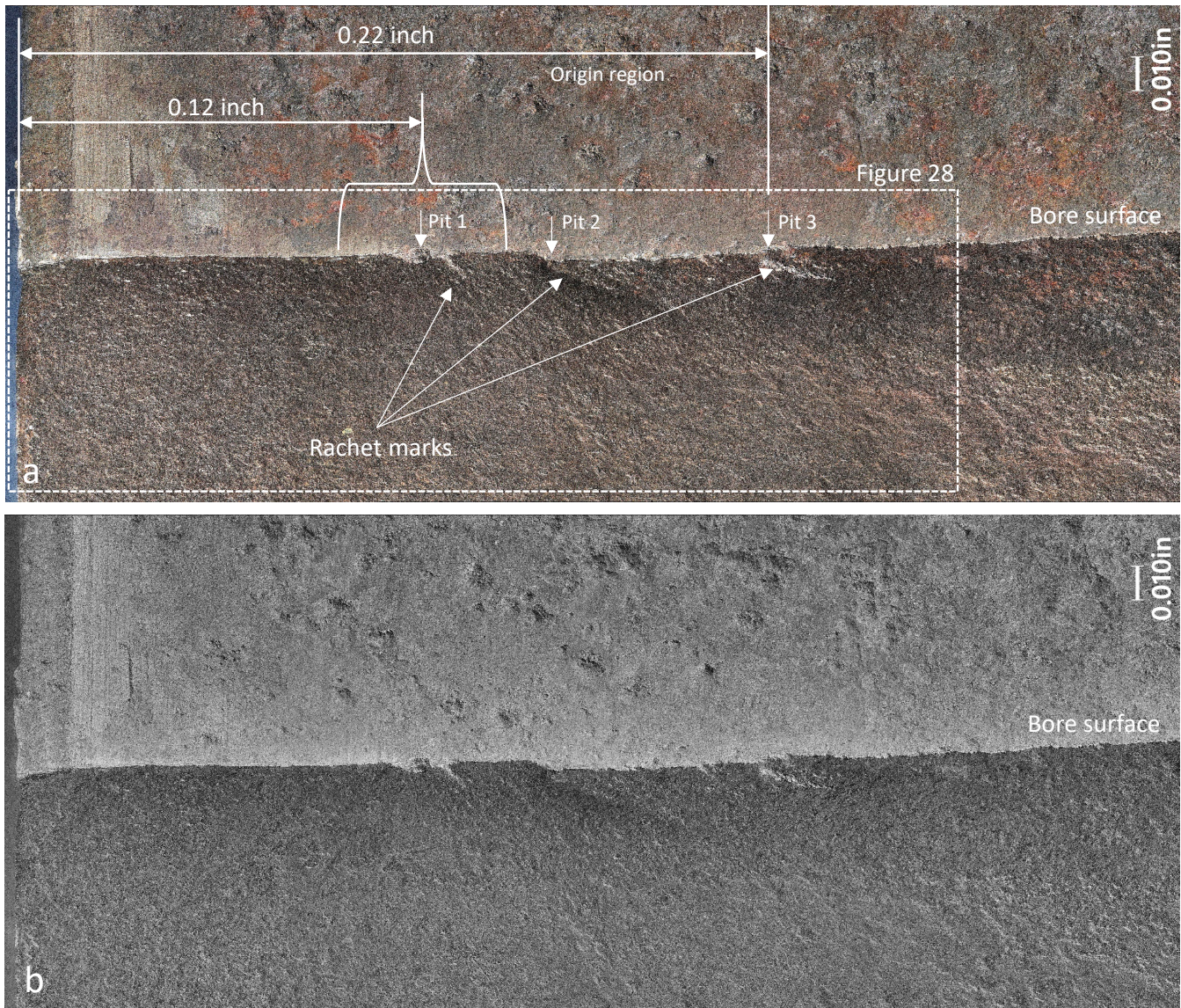


Figure 27 Higher magnification digital microscope images of the of the fatigue crack origin region on the separated lower attachment fitting piece (as-received acetone-cleaned condition). In view a, the location of several pits and associated ratchet marks are indicated (image taken under HDR with oblique lighting). View b is the same image as view a but under monochromatic conditions.

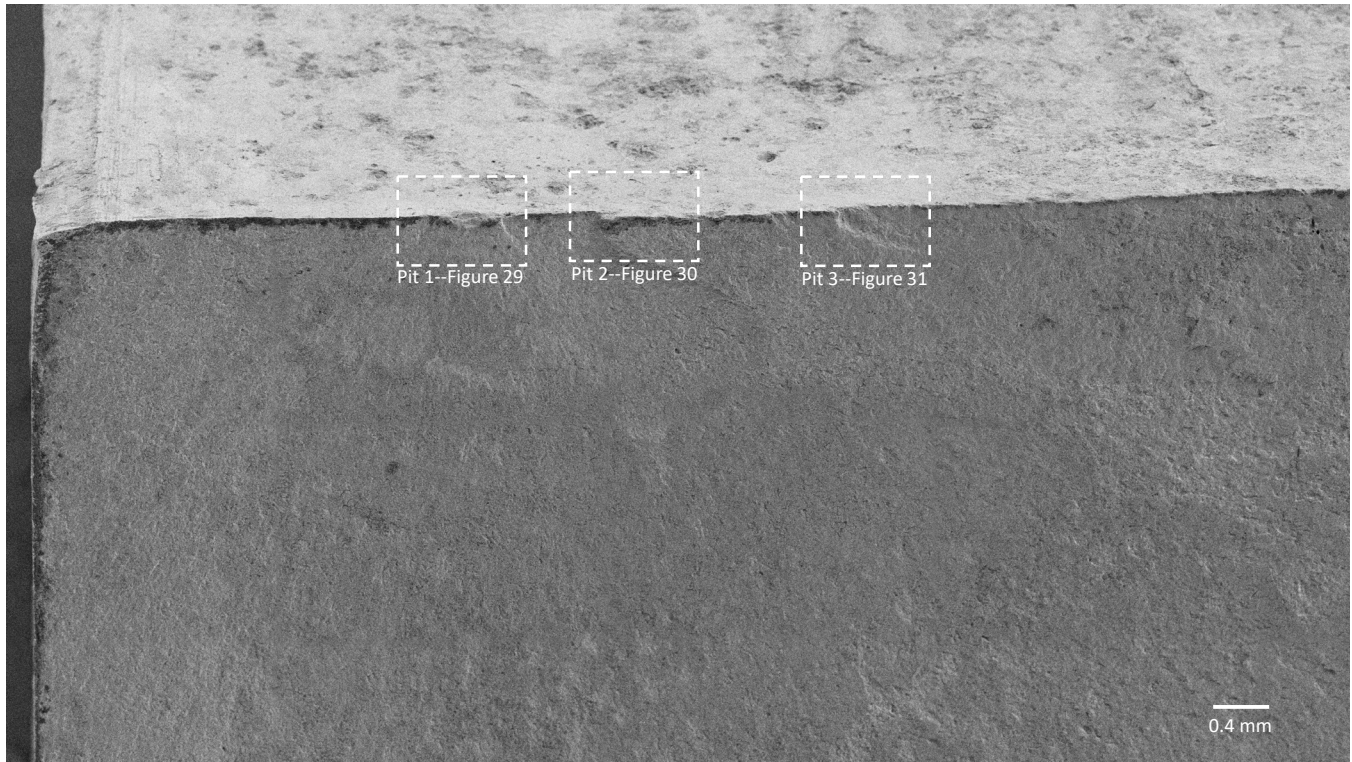


Figure 28 Secondary electron SEM fractograph of the fatigue crack origin region on the separated lower attachment fitting piece (in the acetone-cleaned condition).

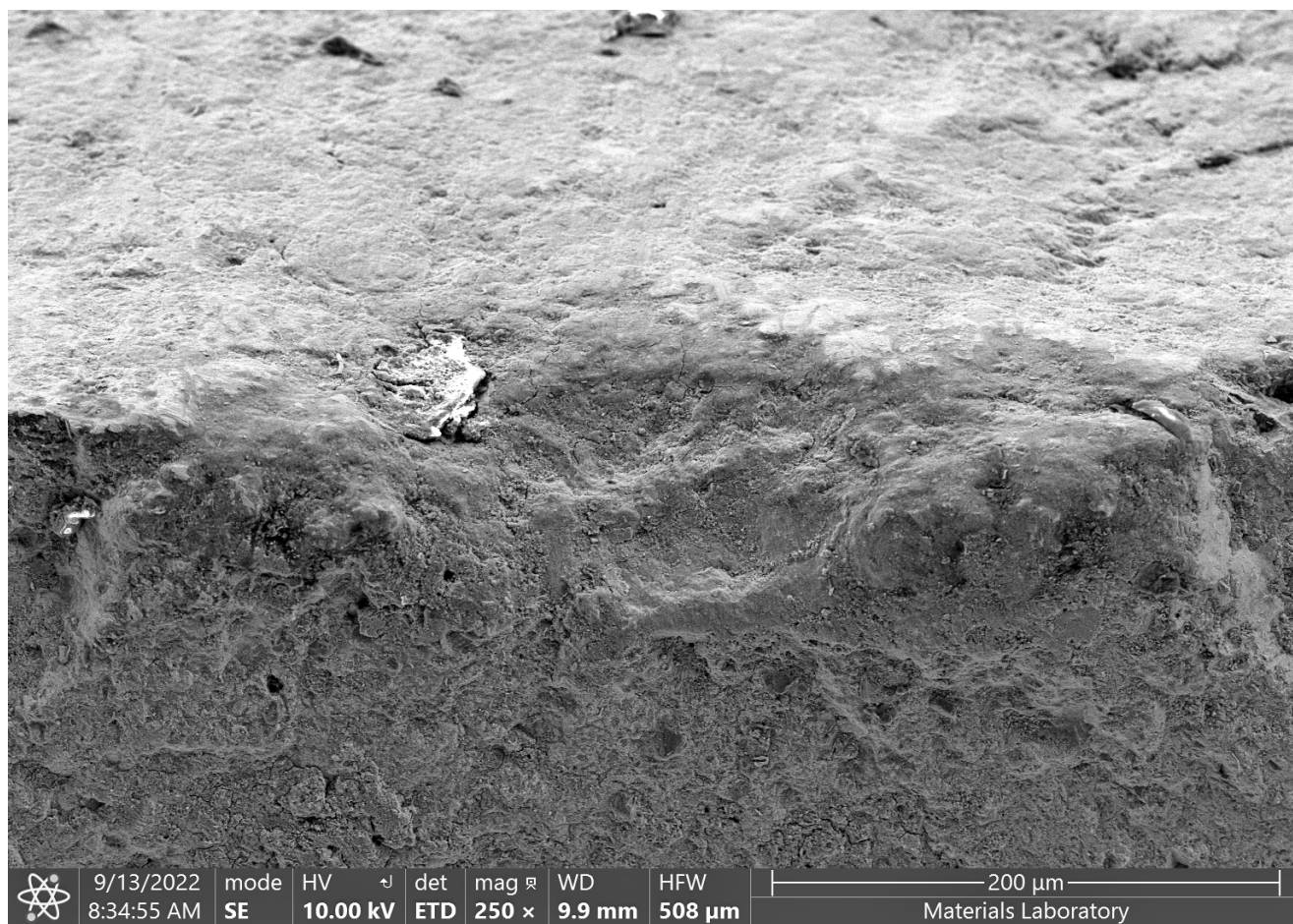


Figure 29 Secondary electron SEM micrograph of Pit 1 (see Figure 28) after cleaning in acetone. Corrosion product is present on all the surfaces, occluding the underlying surface features.

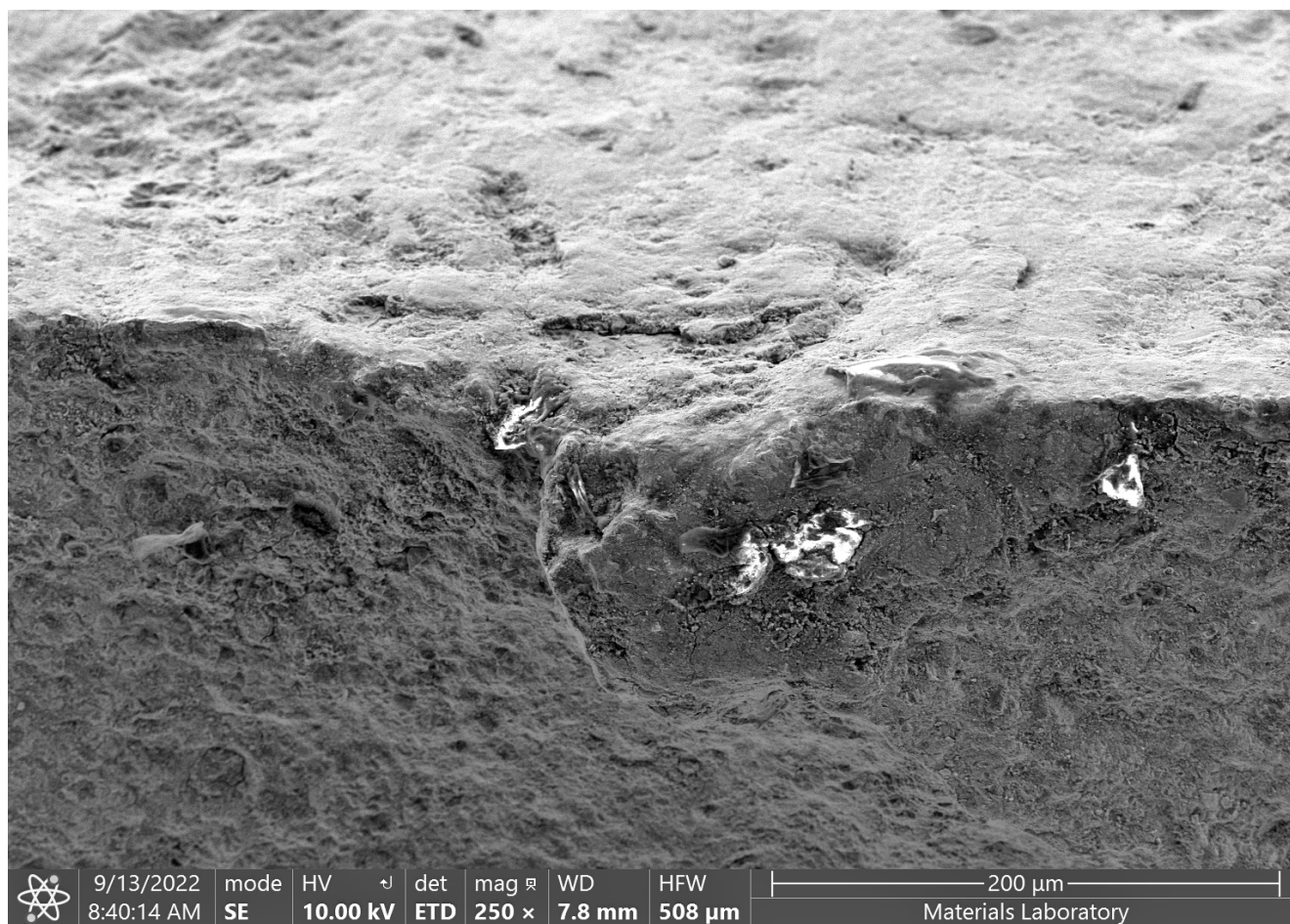


Figure 30 Secondary electron SEM micrograph of Pit 2 (see Figure 28) after cleaning in acetone. Corrosion product is present on all the surfaces, occluding the underlying surface features.

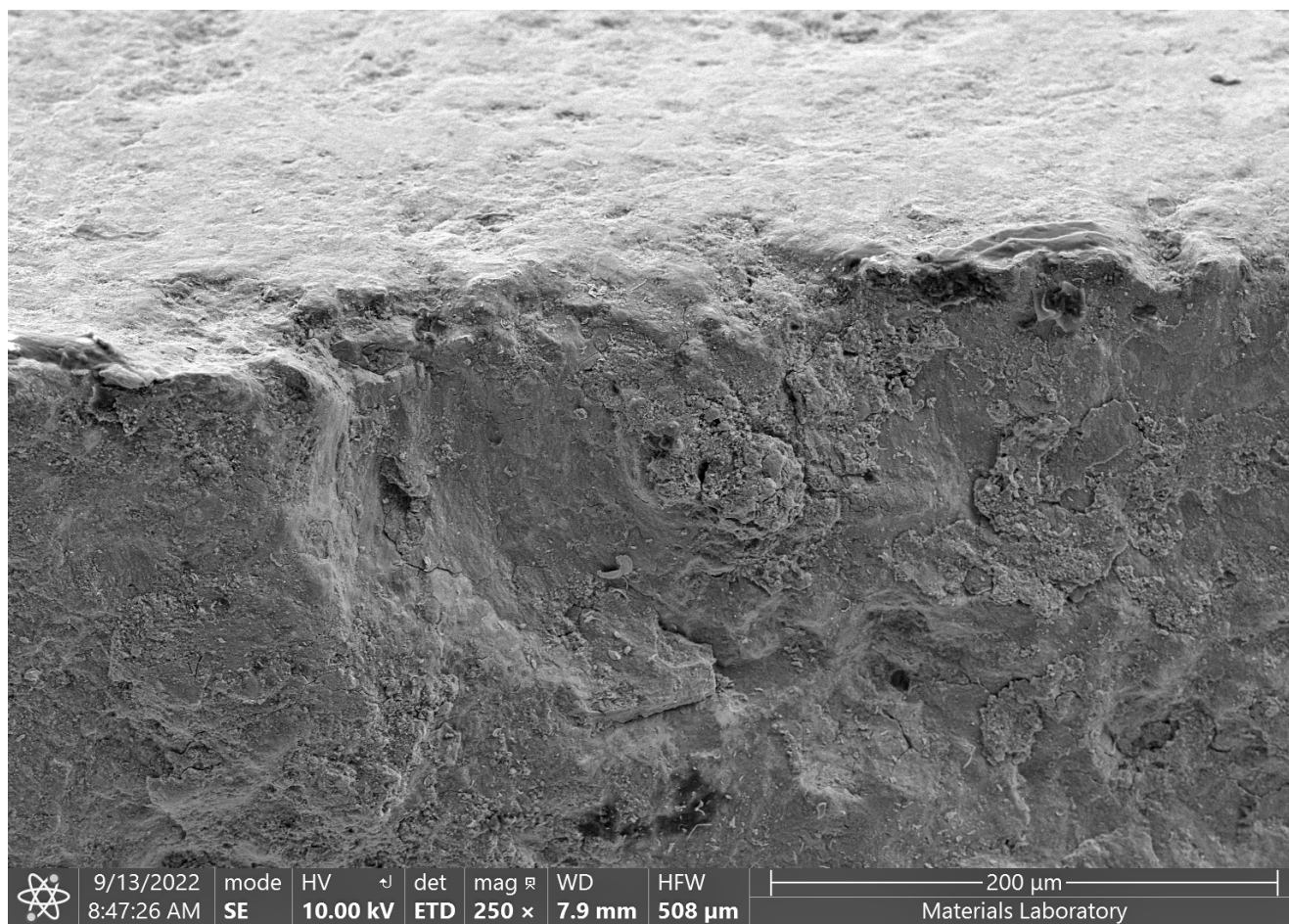


Figure 31 Secondary electron SEM micrograph of Pit 3 (see Figure 28) after cleaning in acetone. Corrosion product is present on all the surfaces, occluding the underlying surface features.

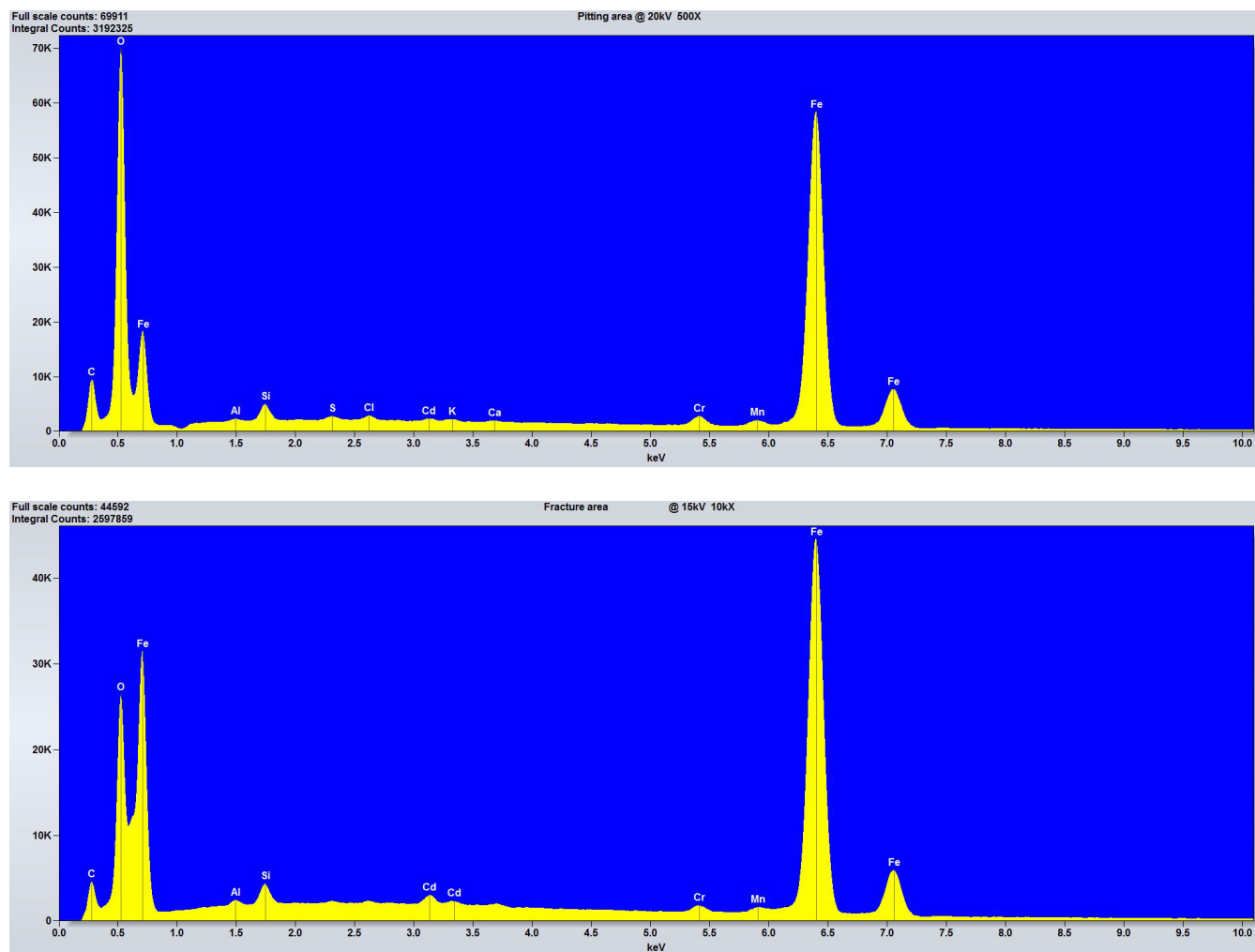


Figure 32 EDS spectra acquired from a sample area within Pit 1 and on the fracture surface of the as-received separated lower attachment fitting piece.

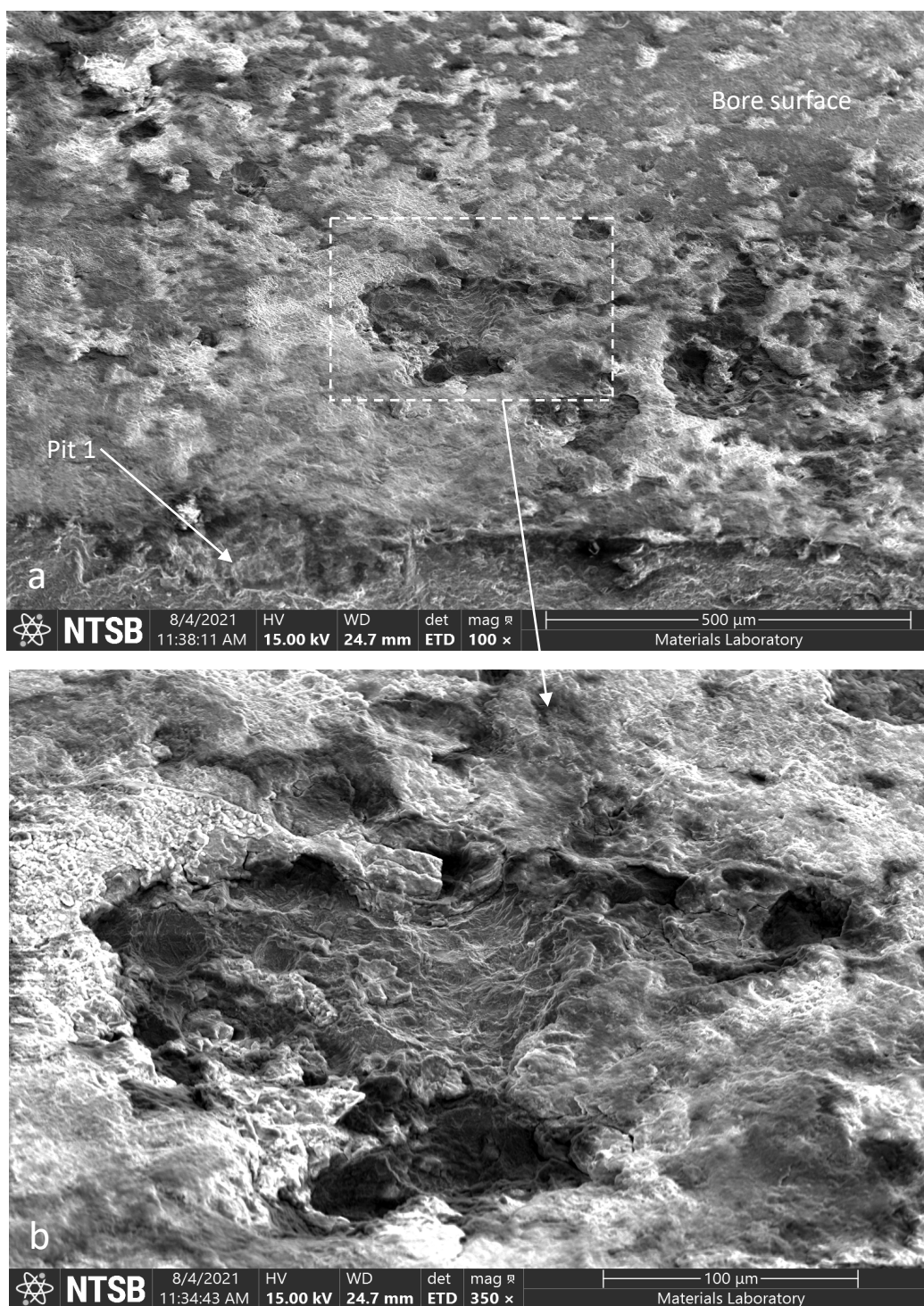
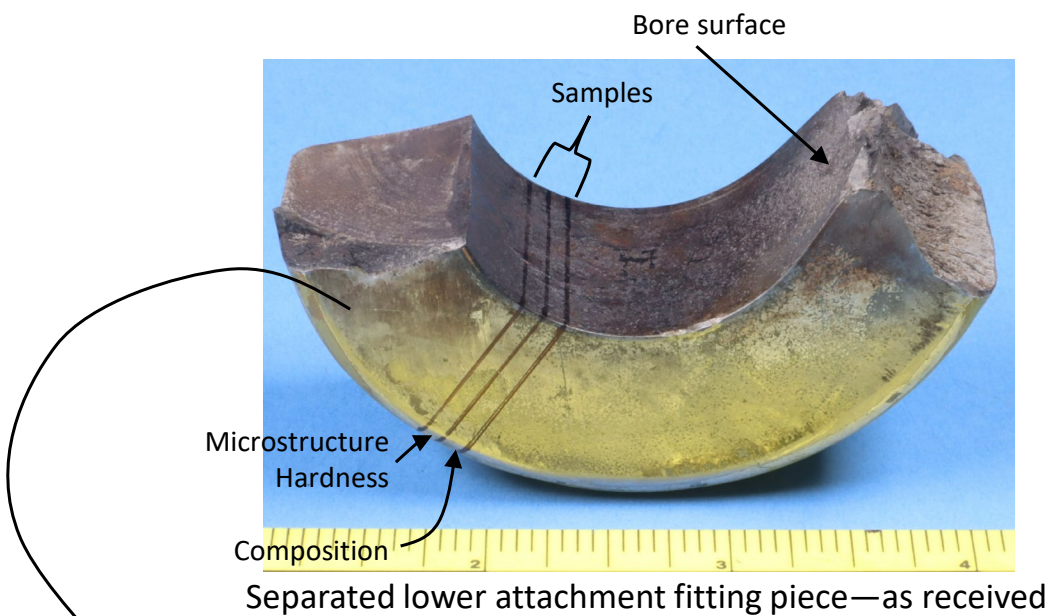


Figure 33 Secondary electron SEM micrographs of the bore surface adjacent to the fracture origin region on the separated lower attachment fitting piece (as-received condition, acetone cleaned). View a shows corrosion product and pits in the general region. Views b shows an example pit at higher magnification.



Sample with fracture to be progressively cleaned in Evapo-Rust®

Figure 34 Images showing the sections taken from the separated lower attachment fitting piece. Two thin slices were taken for hardness, microstructure, and compositional analysis. The larger fracture sample was cleaned in Evapo-Rust to remove corrosion product deposits.

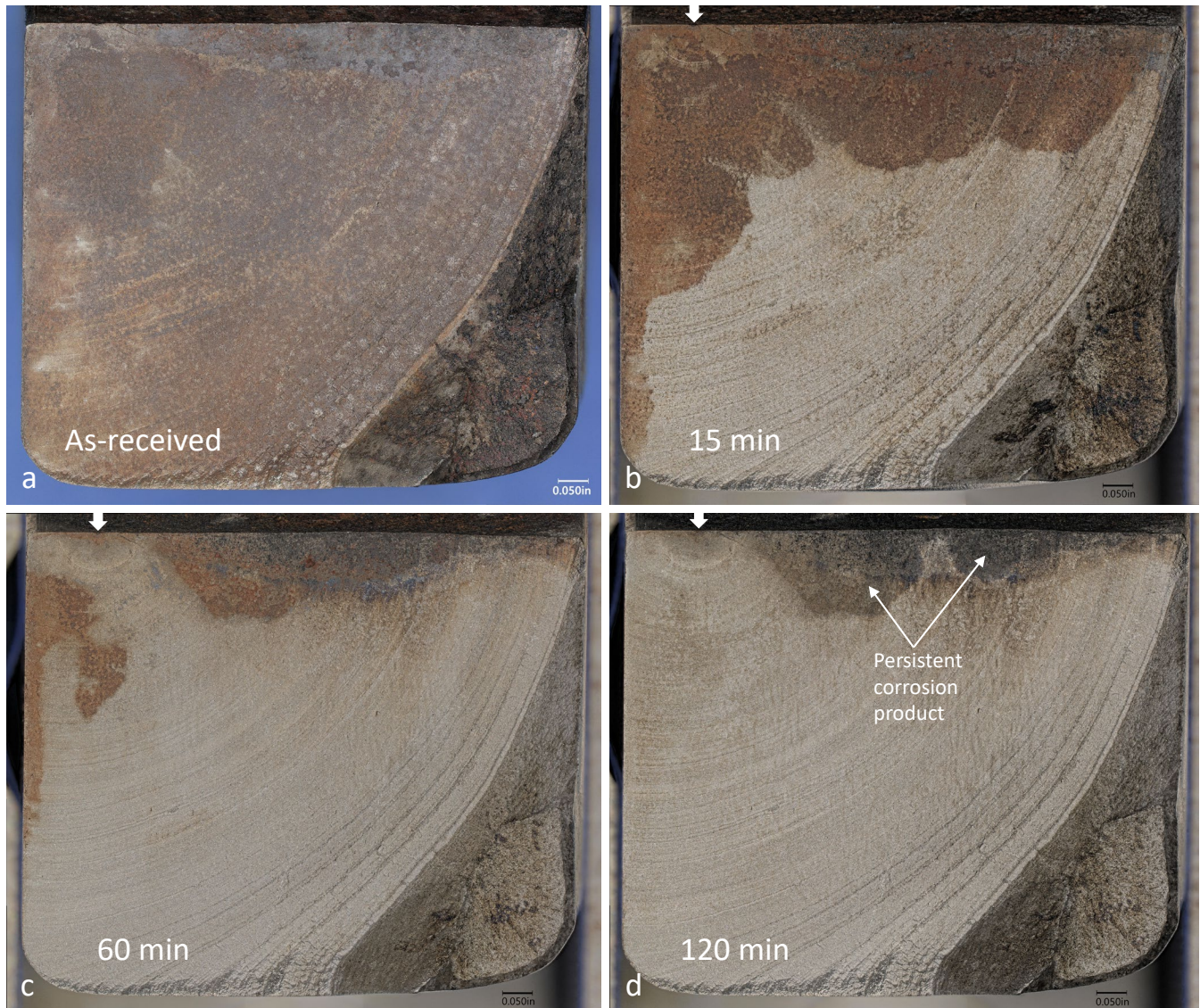


Figure 35 Digital microscope images in HDR revealing the temporal effects of cleaning in Evapo-Rust at different time intervals. View d shows that after 120 minutes of immersion in Evapo-Rust, a persistent corrosion product deposit remained on the fracture surface just below the bore surface.



Figure 36 Digital microscope image (HDR) showing the location of the initiating pit feature relative to the edge of the lug. The overall length of the fatigue crack was also measured from the origin (Pit 1) to the approximate terminus. Image taken after 60 minutes immersion in Evapo-Rust.

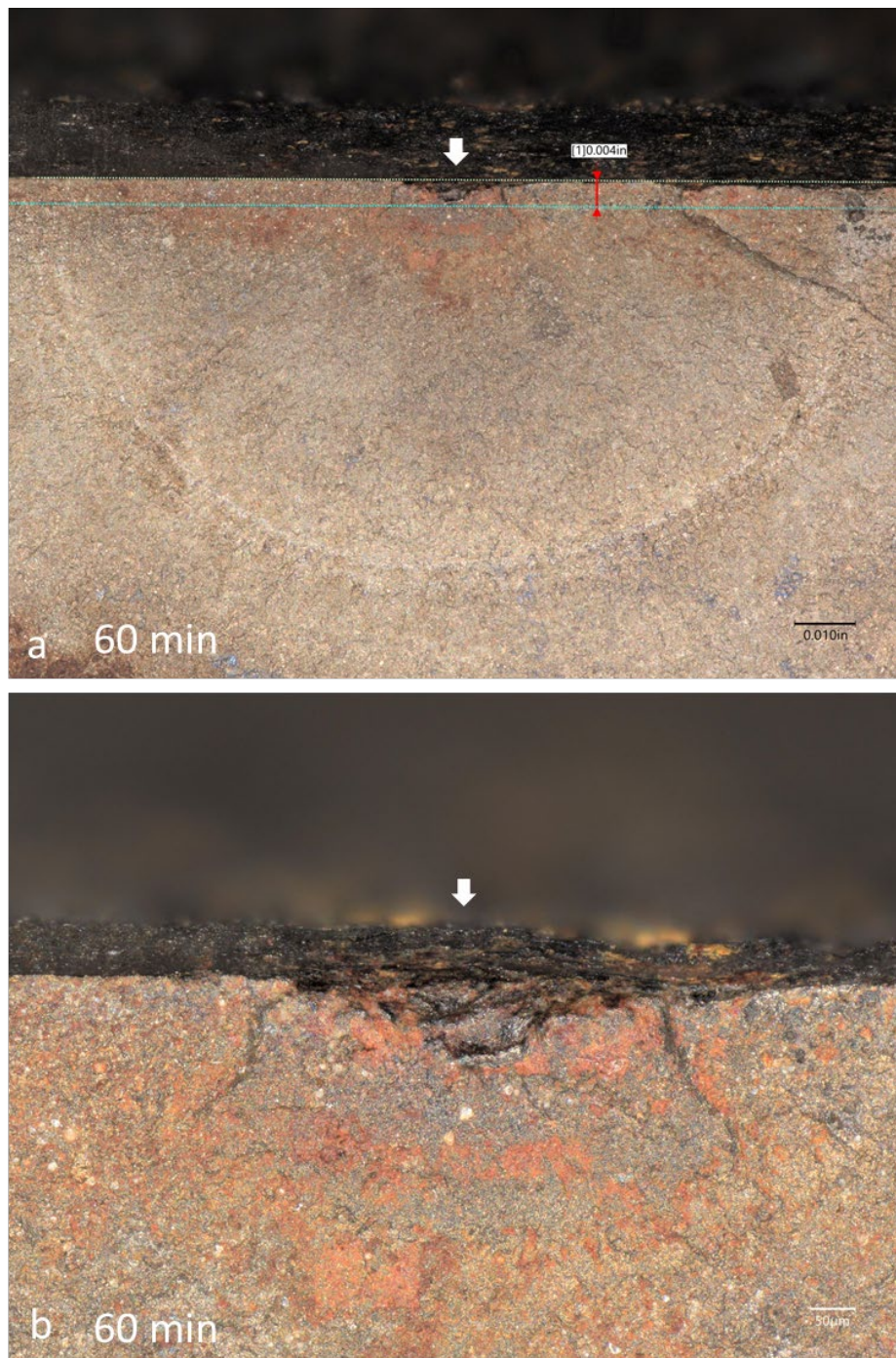


Figure 37 Close digital microscope images (HDR) of the origin region at Pit 1 (unmarked white arrow) after cleaning the fracture in Evapo-Rust for 60 minutes. View a shows the depth of the pit as well as the first semicircular crack progression mark (or thumbnail feature). In view b, ratchet marks are revealed on both sides of Pit 1.



Figure 38 Top down digital microscope images (HDR) of the surface of the lug bore in the vicinity of the fracture face. The unmarked white arrow in the images is the location of Pit 1. View a is in the as-received acetone-cleaned condition. View b is the surface after 240 minutes of Evapo-Rust immersion followed by brush cleaning to remove corrosion product deposits on the surface.

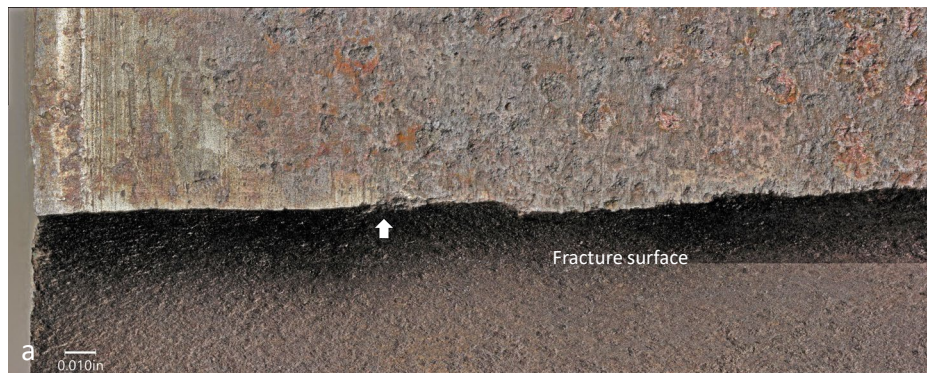


Figure 39 Closer digital microscope images (HDR) of those in Figure 38. View a is in the as-received acetone-cleaned condition. View b is the surface after 240 minutes of Evapo-Rust immersion followed by brush cleaning to remove corrosion product deposits on the surface. Under the corrosion product layer, material loss by corrosion is evident. Pit 1 is marked with an unlabeled white arrow.



Figure 40 Closer digital microscope images (HDR) of the bore surface in Figure 39b after 240 minutes of Evapo-Rust immersion followed by brush cleaning to remove corrosion product deposits on the surface. Under the corrosion product layer, material loss by corrosion is evident and pits cover the surface. Pit 1 is marked with an unlabeled white arrow.

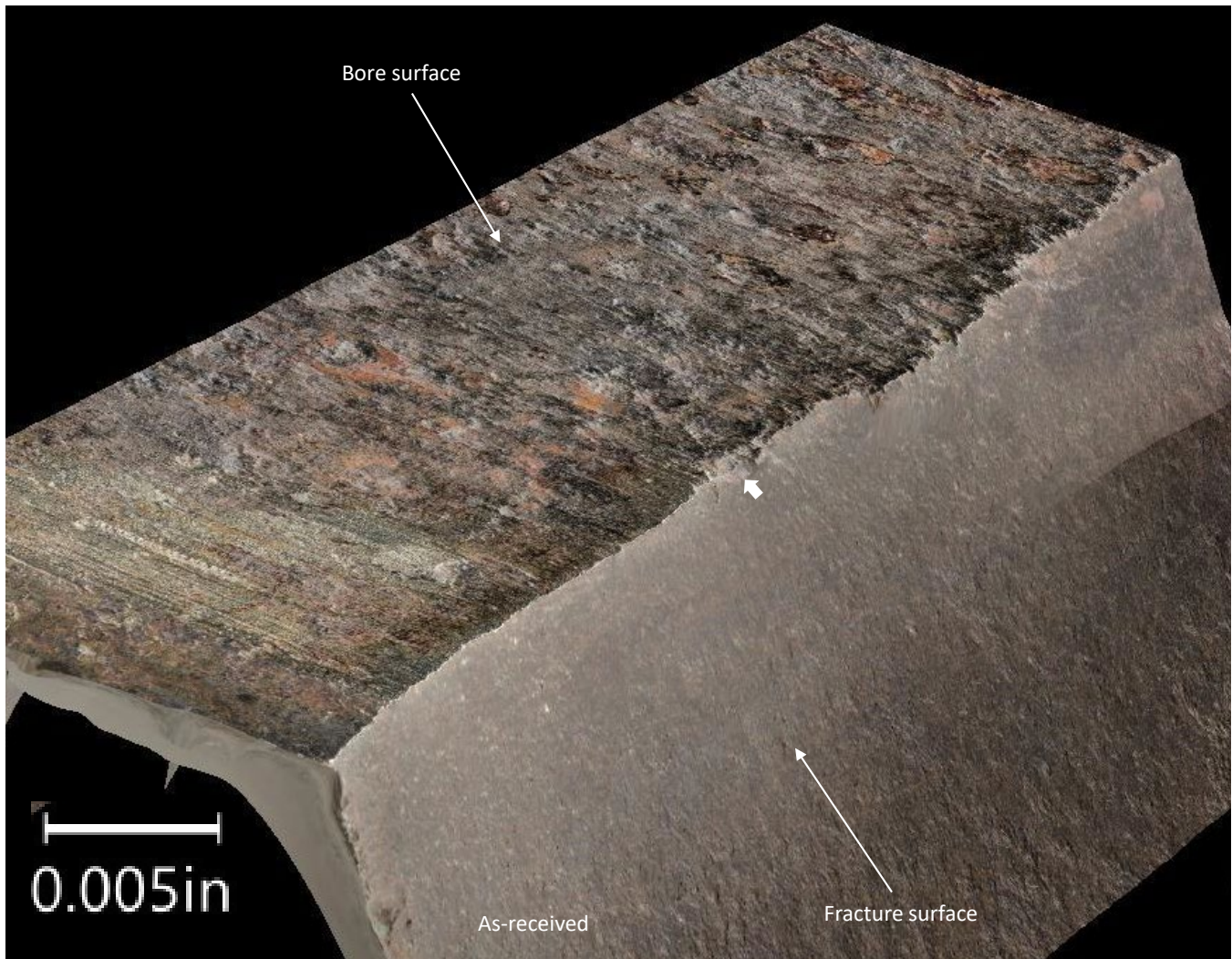


Figure 41 Oblique view of the bore surface in the as-received acetone-cleaned condition. Corrosion product deposits obscure the underlying features in the bore surface. Image taken with a digital microscope under HDR conditions. Pit 1 is marked with an unlabeled white arrow.

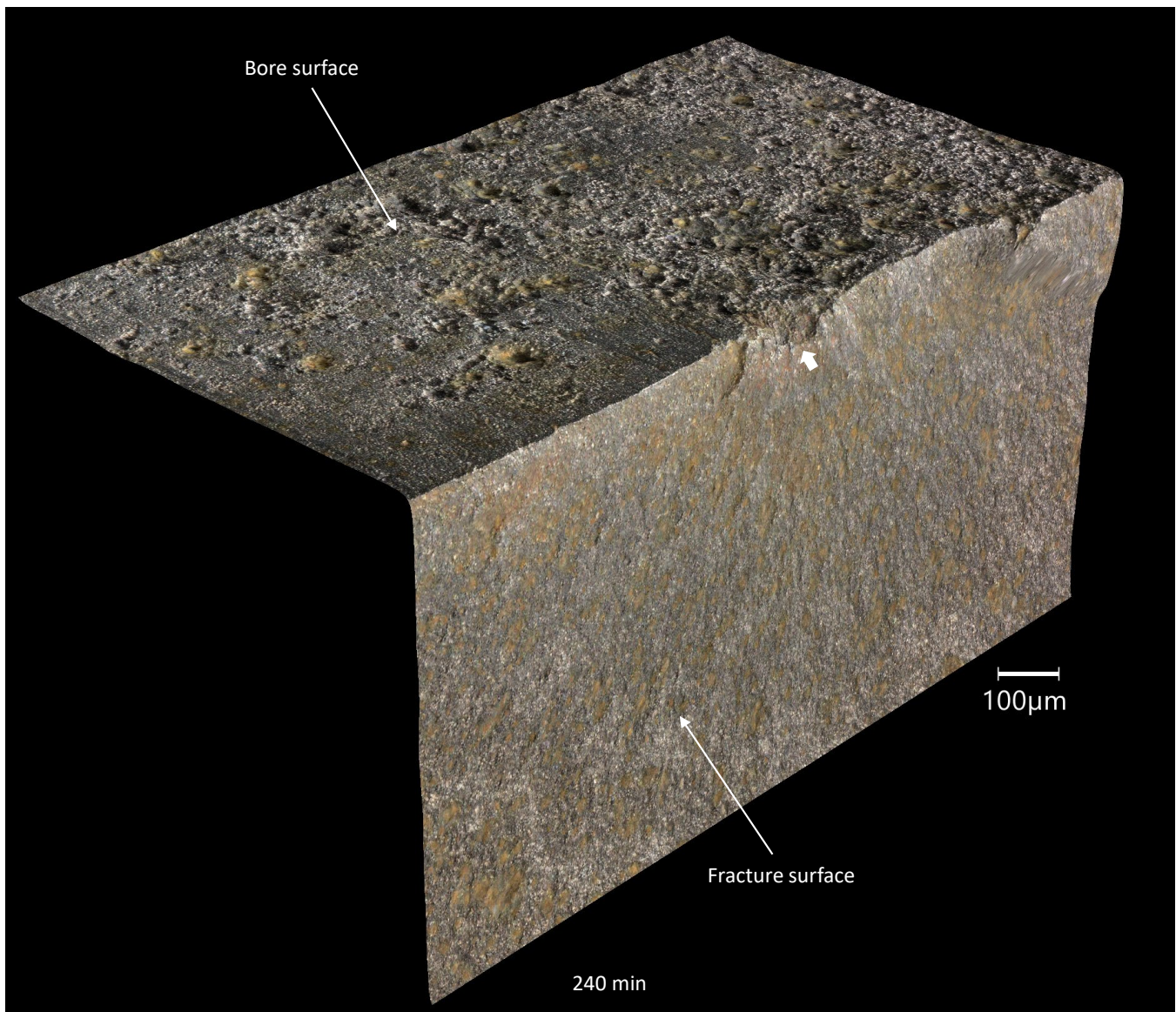


Figure 42 Oblique view of the bore surface after 240 minutes of Evapo-Rust immersion followed by brush cleaning to remove corrosion product deposits on the surface. Pitting on the surface reveals material loss due to corrosion. Image taken with a digital microscope under HDR conditions. Pit 1 is marked with an unlabeled white arrow.

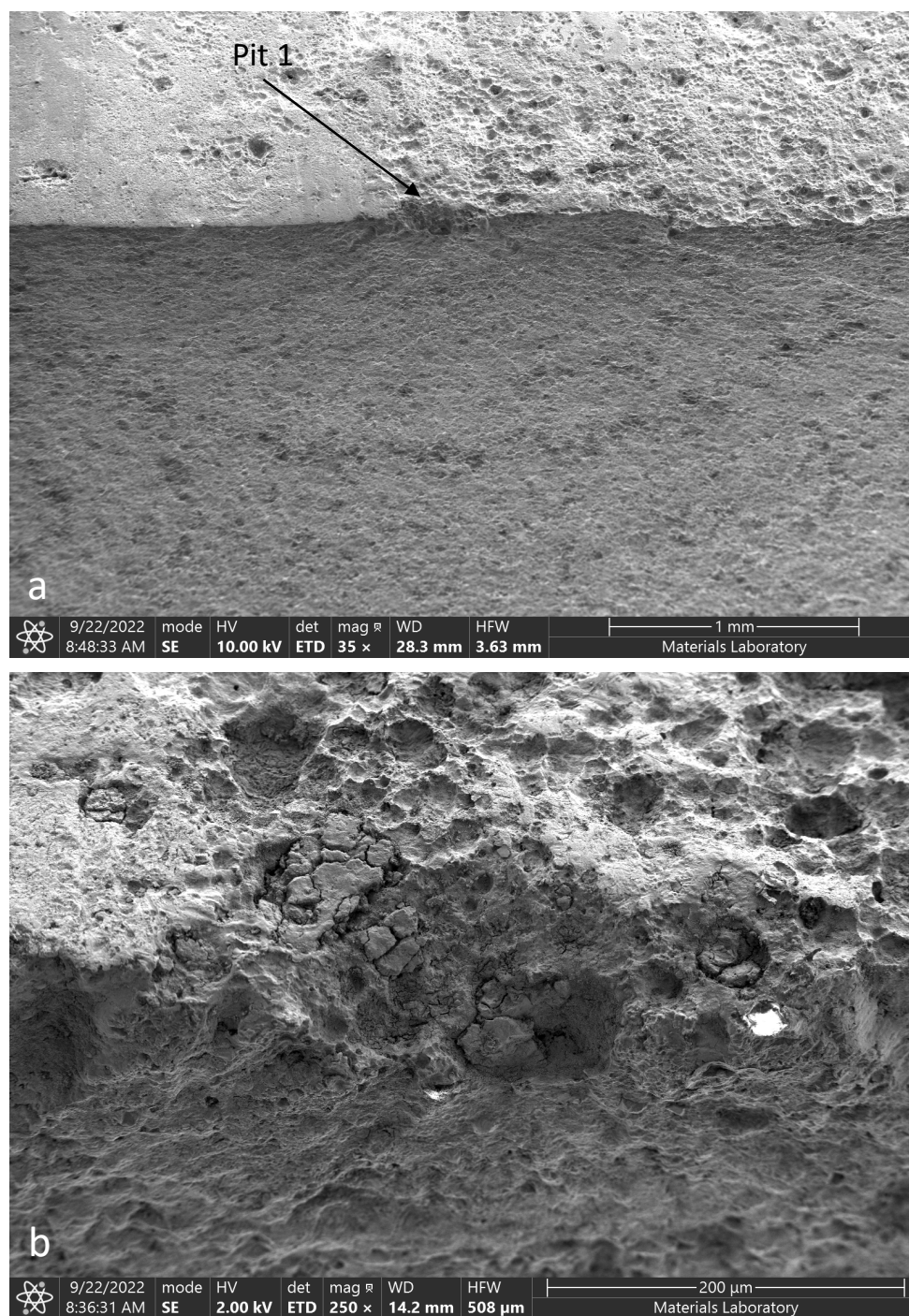


Figure 43 Secondary electron SEM micrographs of Pit 1 after 240 minutes of Evapo-Rust immersion (oblique view). View a shows Pit 1 flanked on both sides by ratchet marks as well as the first observable semicircular crack progression mark (or thumb nail feature) View b is a closer micrograph revealing vestiges of corrosion product deposits.

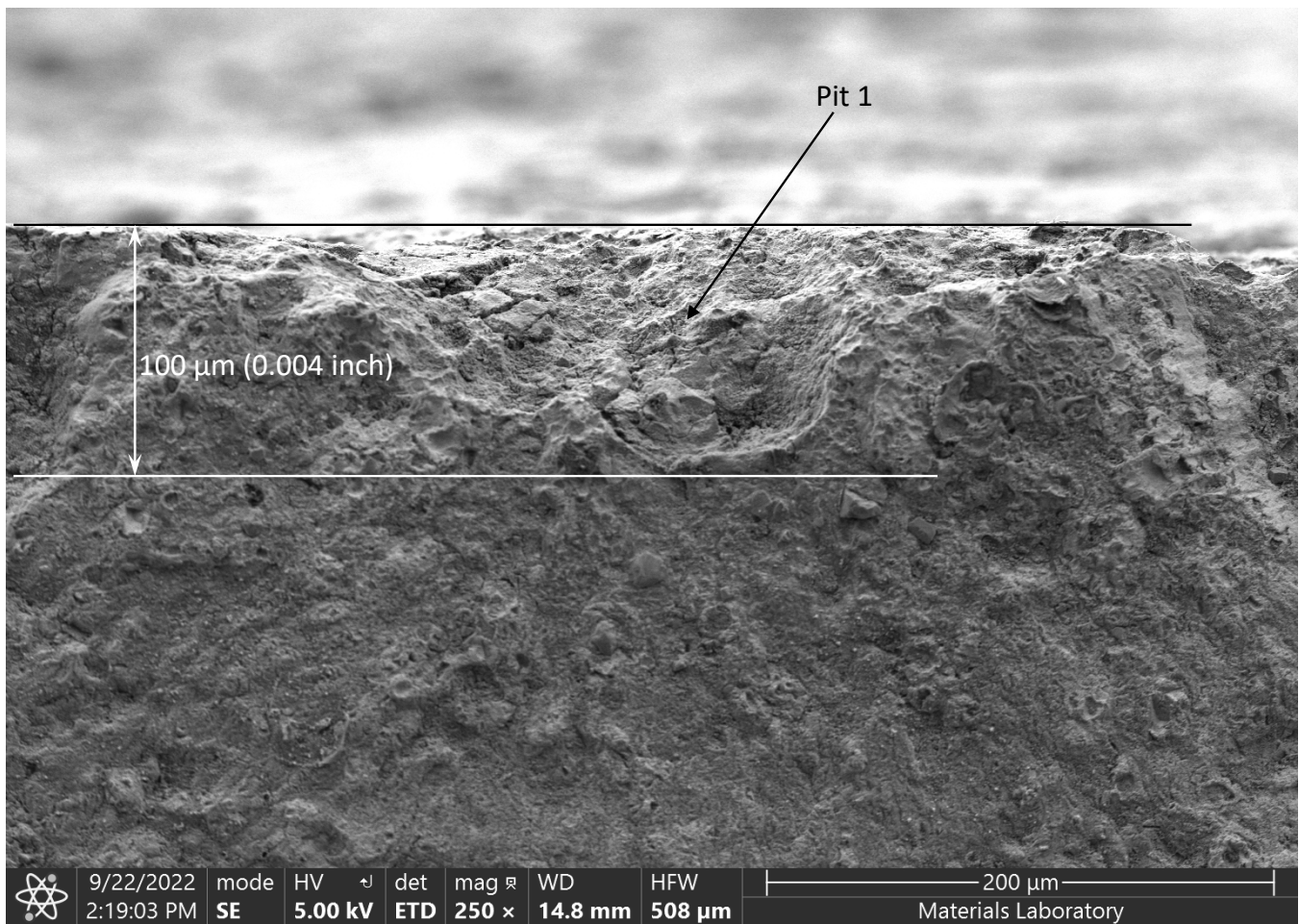


Figure 44 Secondary electron SEM images of Pit 1 after 240 minutes of Evapo-Rust immersion. Pit 1 depth is approximately 0.004 inch.

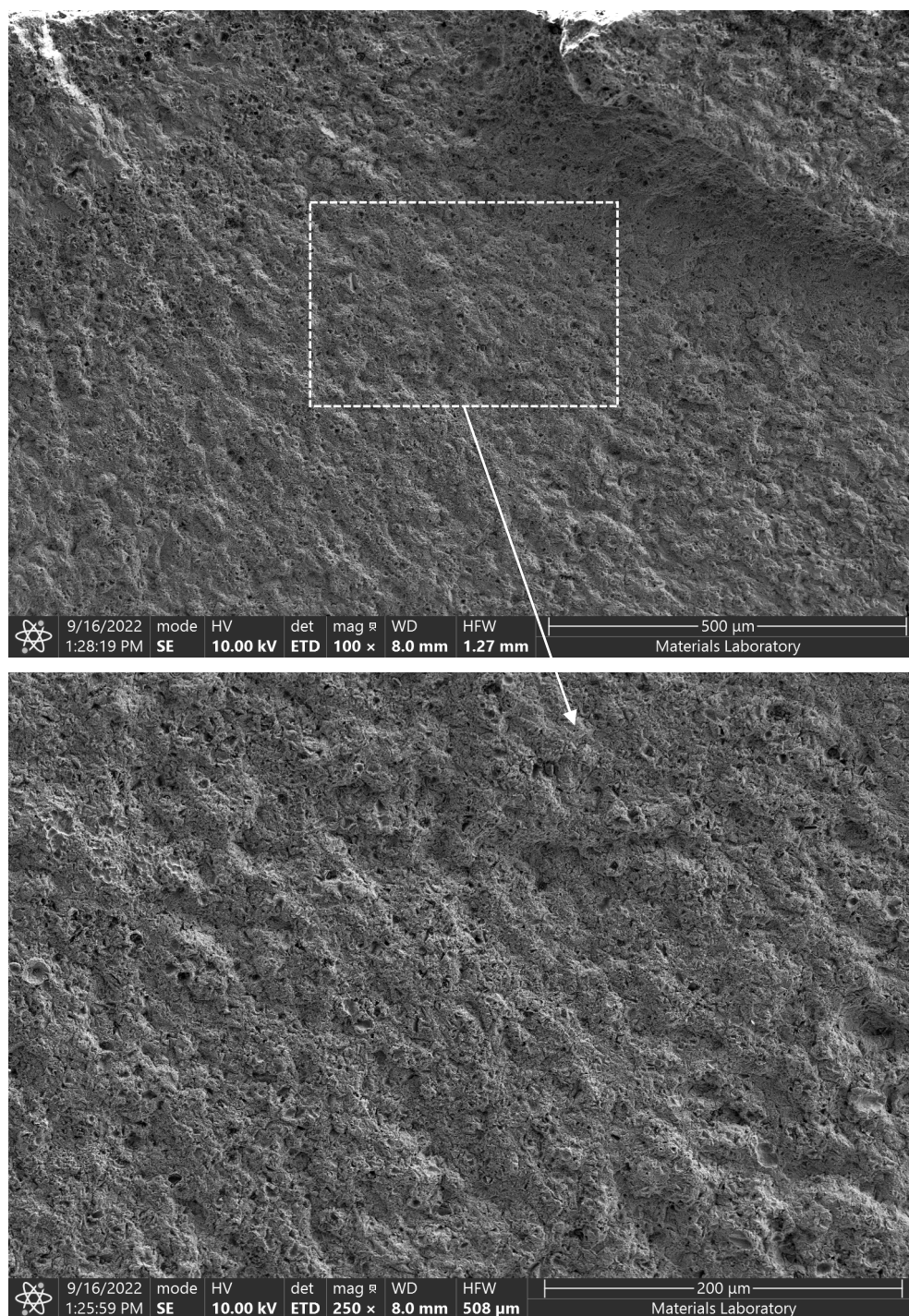


Figure 45 Secondary electron SEM fractographs of the fracture surface adjacent to the origin pit and within the first crack progression mark at the origin (see Figure 37a) after immersion for 120 minutes in Evapo-Rust. Fatigue striation features are not discernable due to corrosion and persistent corrosion product deposits.

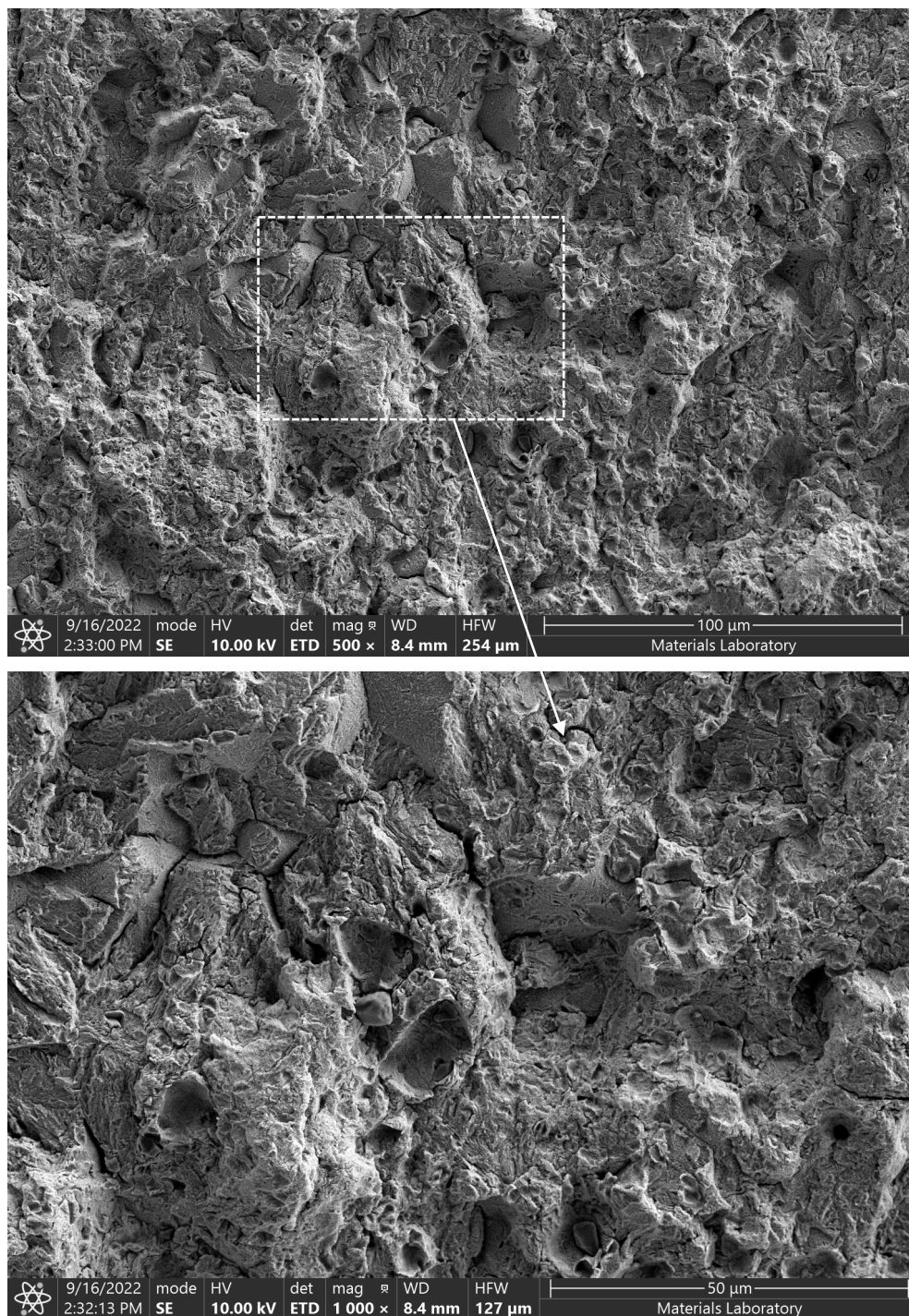


Figure 46 Secondary electron SEM fractographs of the fracture surface near the first crack progression mark at the origin (see Figure 37a) after immersion for 120 minutes in Evapo-Rust. Fatigue striation features are not discernable due to material loss by corrosion and persistent corrosion product deposits.

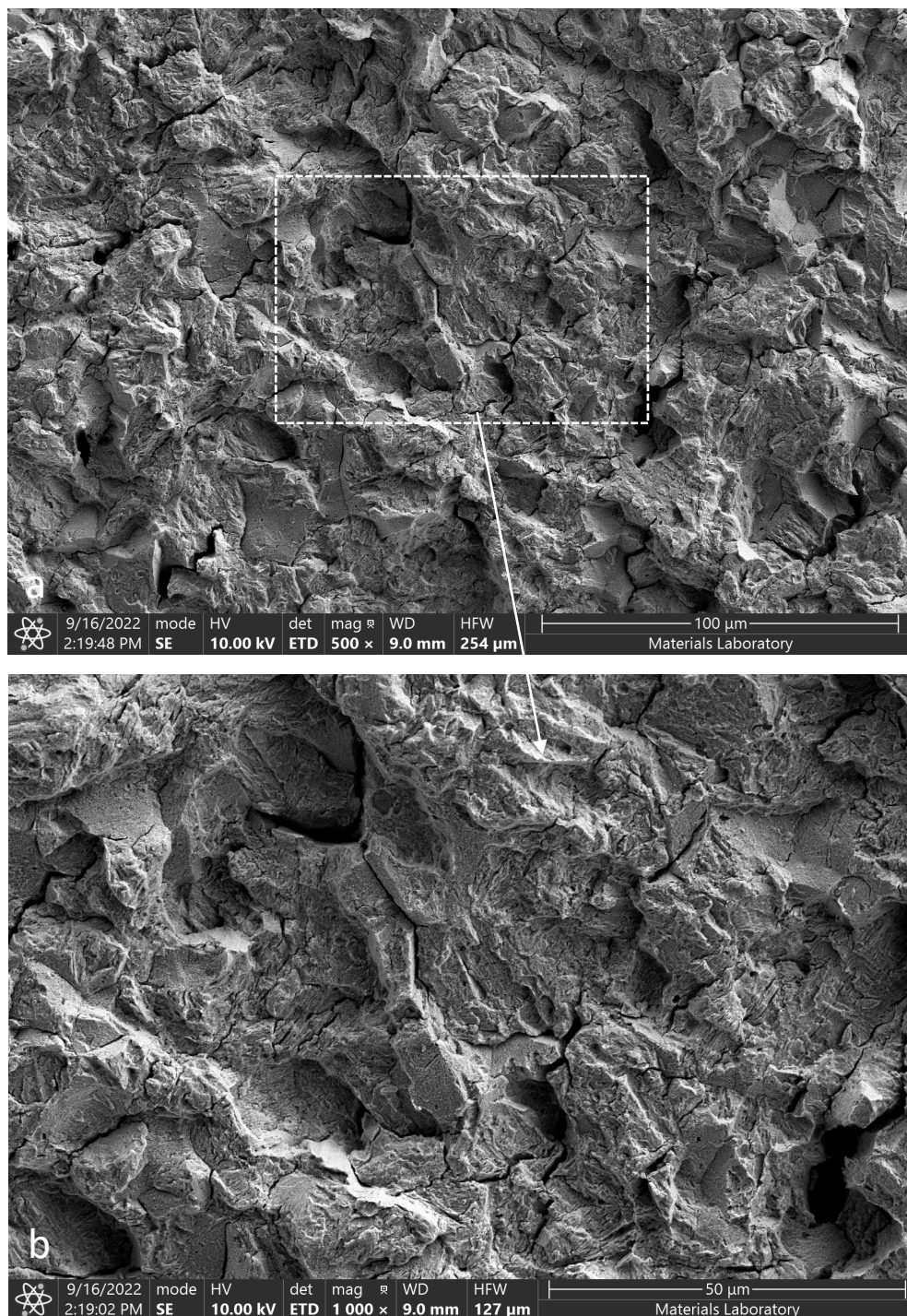


Figure 47 Secondary electron SEM fractographs of the fracture surface in the geometric middle of the lug fracture face after immersion for 120 minutes in Evapo-Rust. Fatigue striation features are discernable as well is evidence of intergranular fracture.



Figure 48 Fractographs by HDR digital microscopy of the fracture surfaces on the upper lug of the lower attachment fitting pieces (as-received condition). Key fractographic features are annotated in Figure 49.

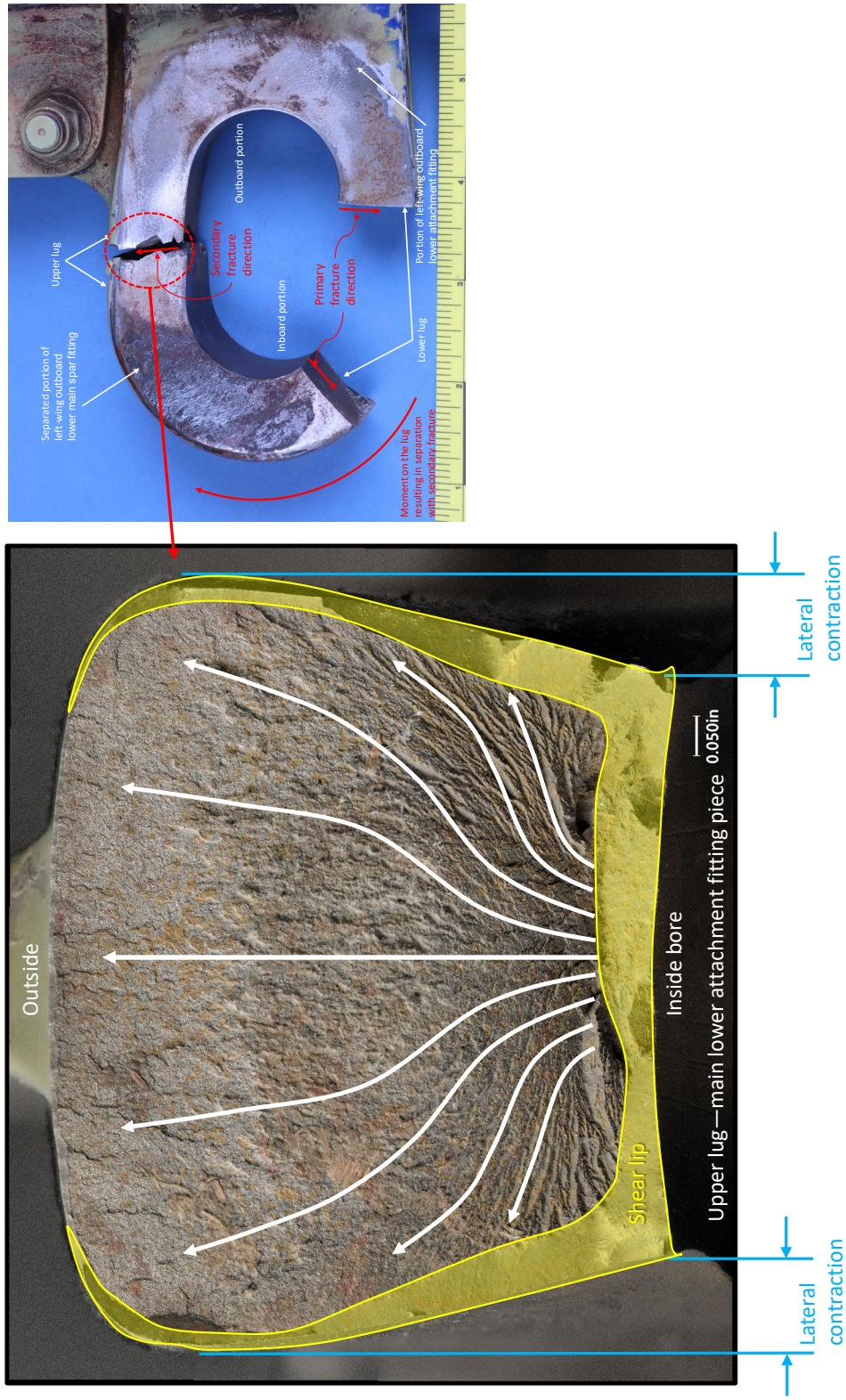


Figure 49 Fractograph by HDR digital microscopy of view a in Figure 48. The upper lug fracture surfaces exhibited shear lips (in yellow) at the perimeter of the section and rougher fracture surfaces in the core with river pattern features. The width at the inner bore exhibits lateral contraction. The direction of crack propagation is shown via the white arrow annotations. Such attributes are indicative of overstress fracture with gross plastic deformation.

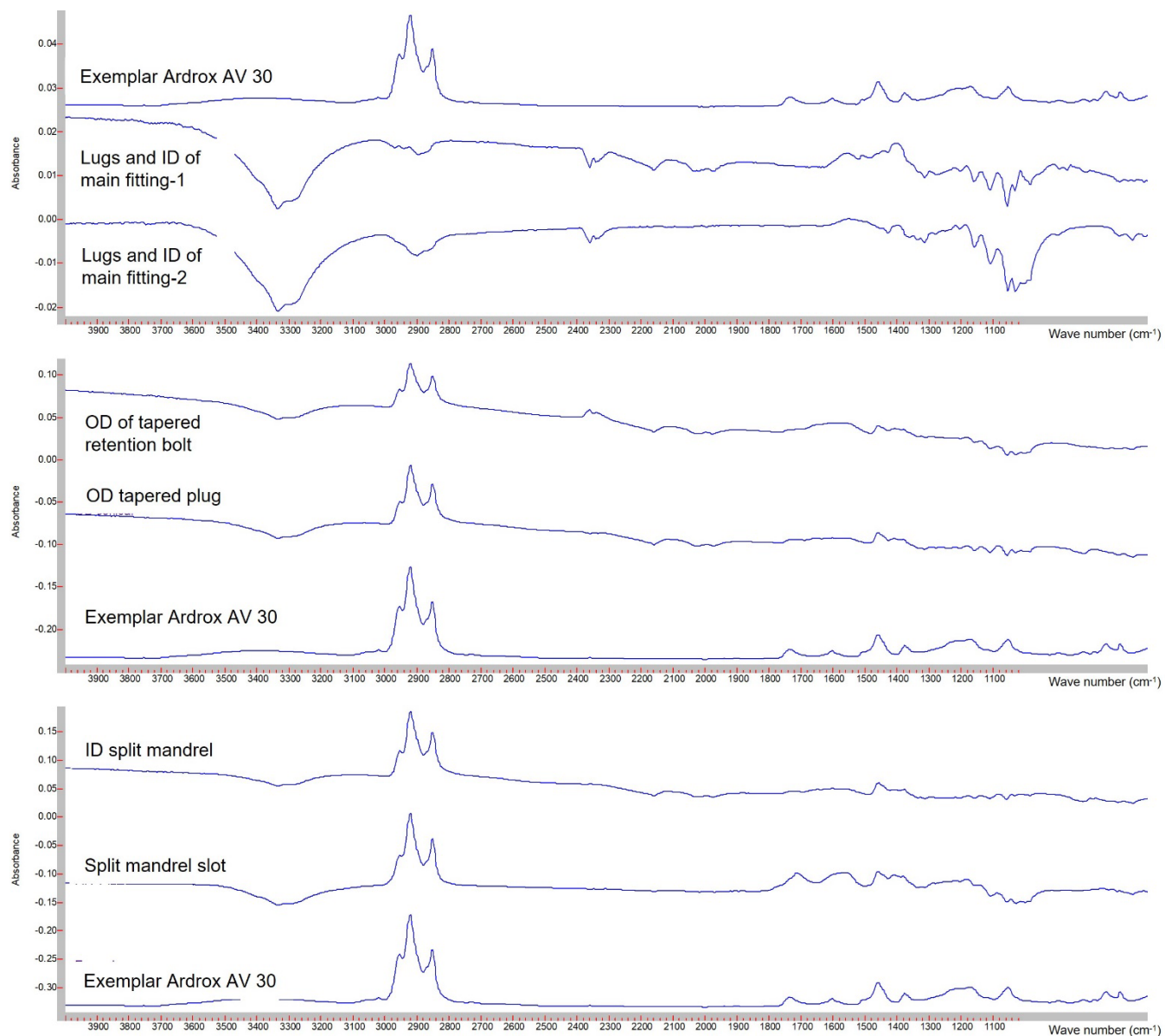
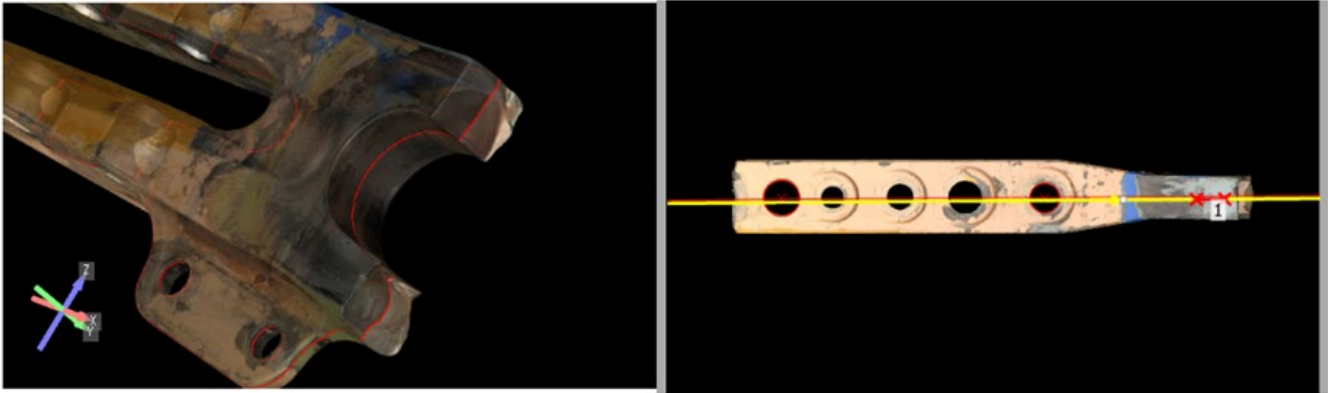


Figure 50 Fourier transform infrared spectra of surface deposits on components from the expansion mandrel assembly and the lug surfaces from the main lower attachment fitting piece. A reference spectrum for Ardrex AV 30 is included.



Profile



Figure 51 3D scanned image of the main portion of the lower attachment fitting showing the location of the arc radius measured within the lug bore. This image is for Arc 3 in Table 1.

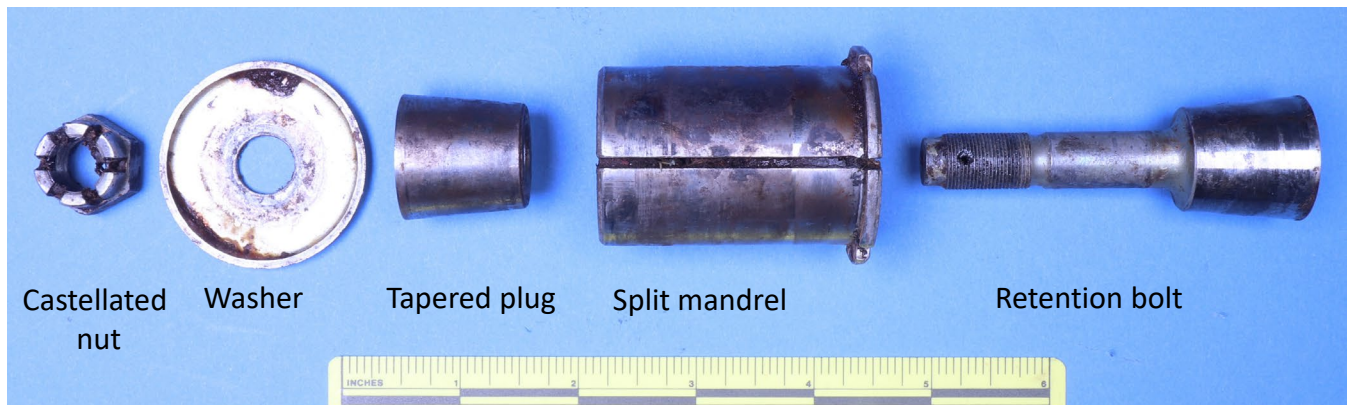


Figure 52 Image of the as-received expansion mandrel components.

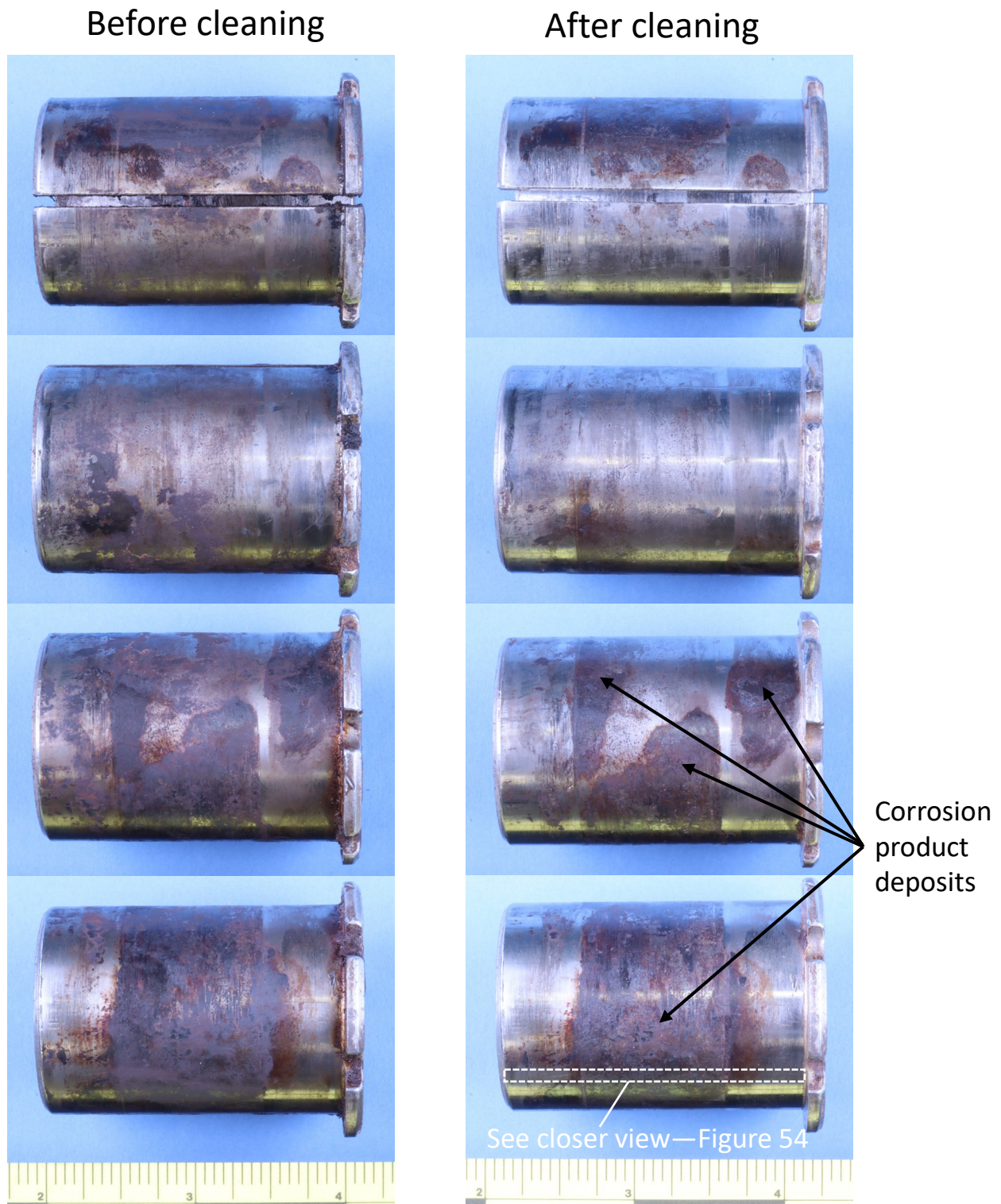


Figure 53 Views of the split mandrel in the as-received and after cleaning in acetone with ultrasonic agitation.

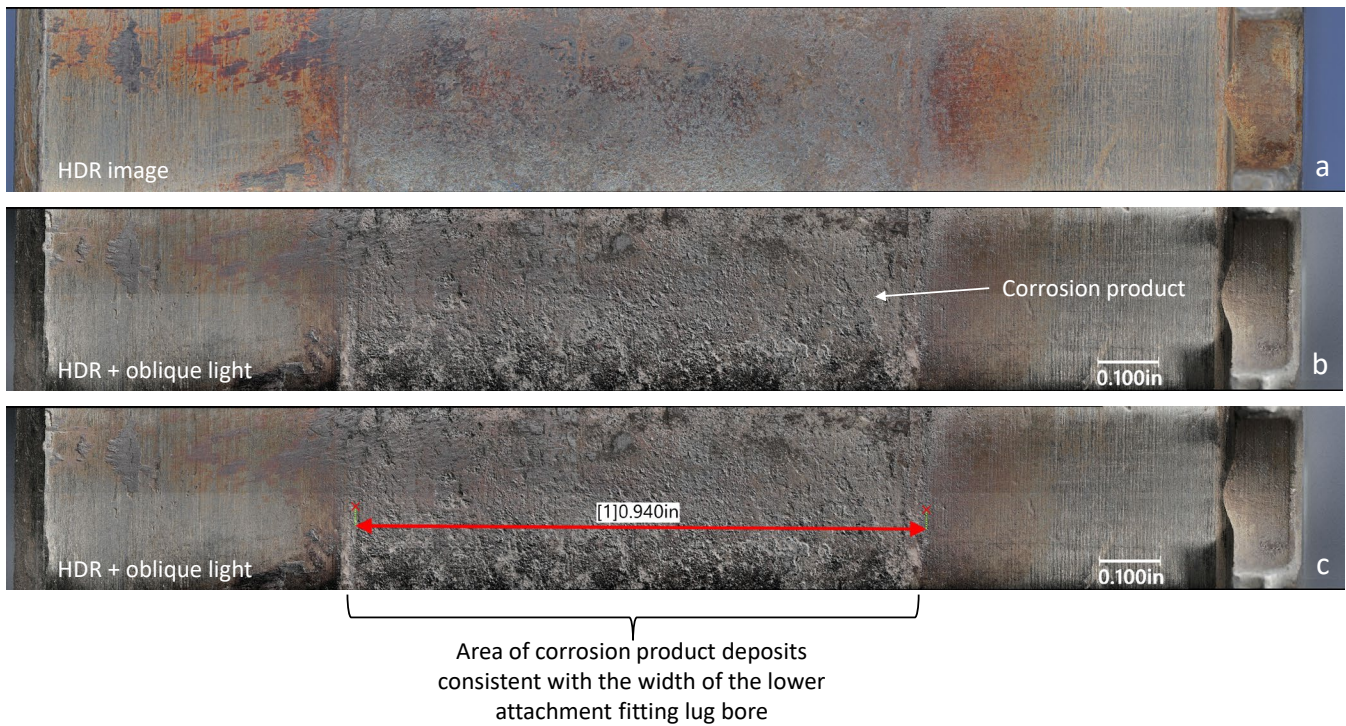


Figure 54 Digital microscope images of the surface of the split mandrel (see Figure 53 for the location). Under oblique lighting conditions corrosion deposits revealed by a rougher surface texture correspond to the location of the outboard lower attachment fitting.

Before cleaning



After cleaning



Figure 55 Views of the retention bolt from the expansion mandrel assembly in the as-received condition and after cleaning in acetone with ultrasonic agitation.

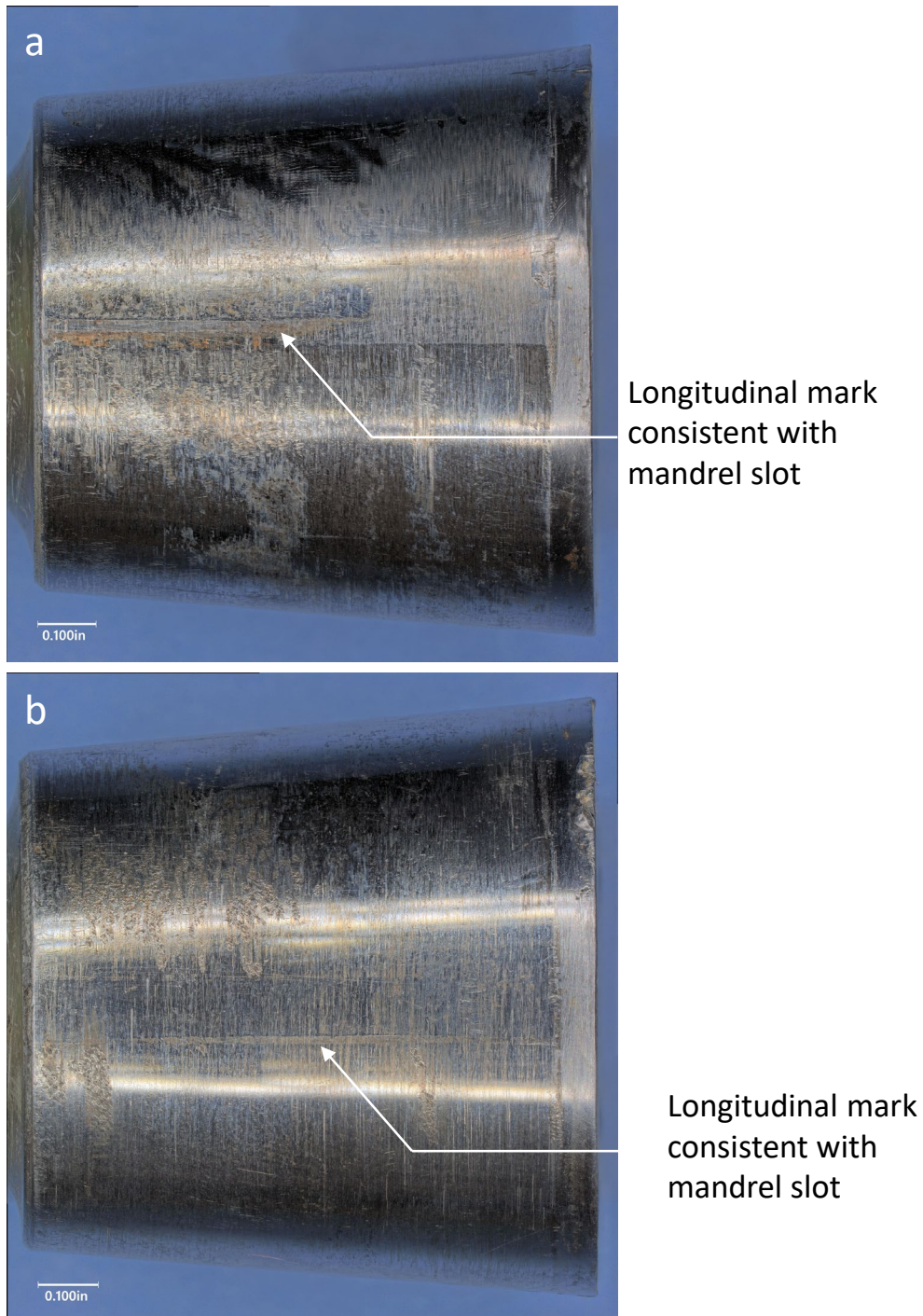


Figure 56 Close digital microscope images of the surface of the tapered portion of the retention bolt. The annotations indicate two longitudinal marks on the surface consistent with contact with the edge of the slot in the split mandrel.

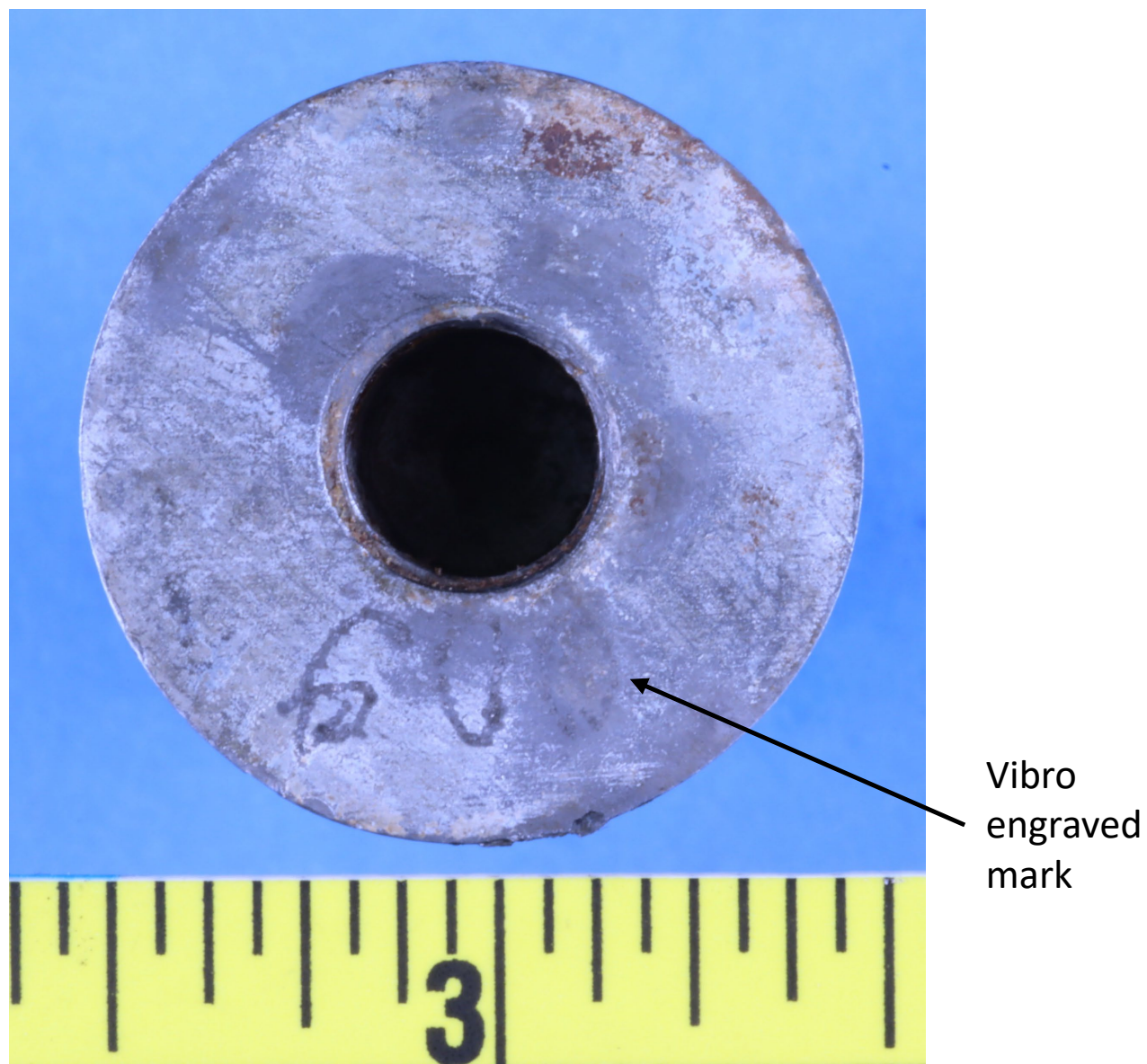


Figure 57 The large end of the retention bolt showing a vibro engraved mark.

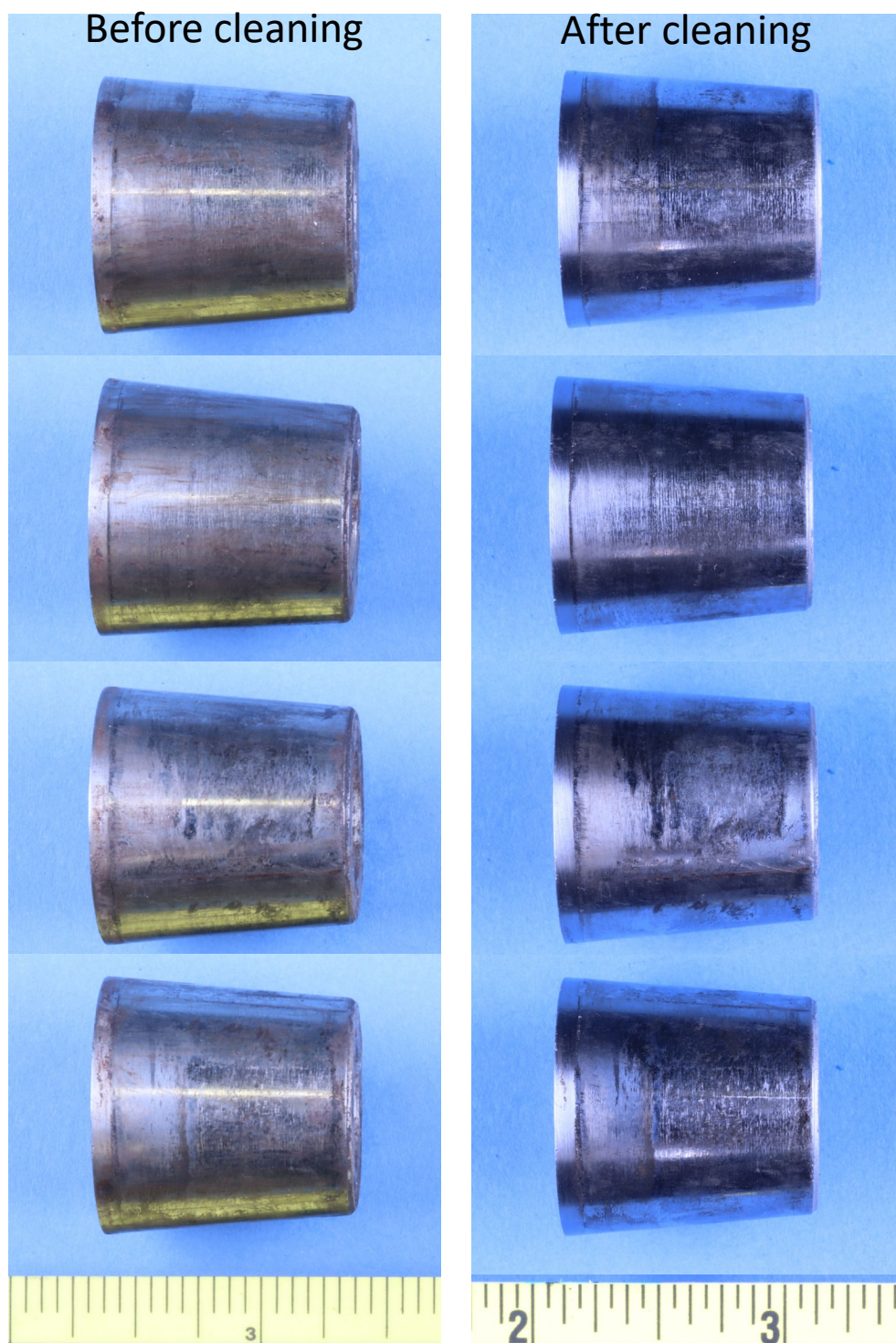
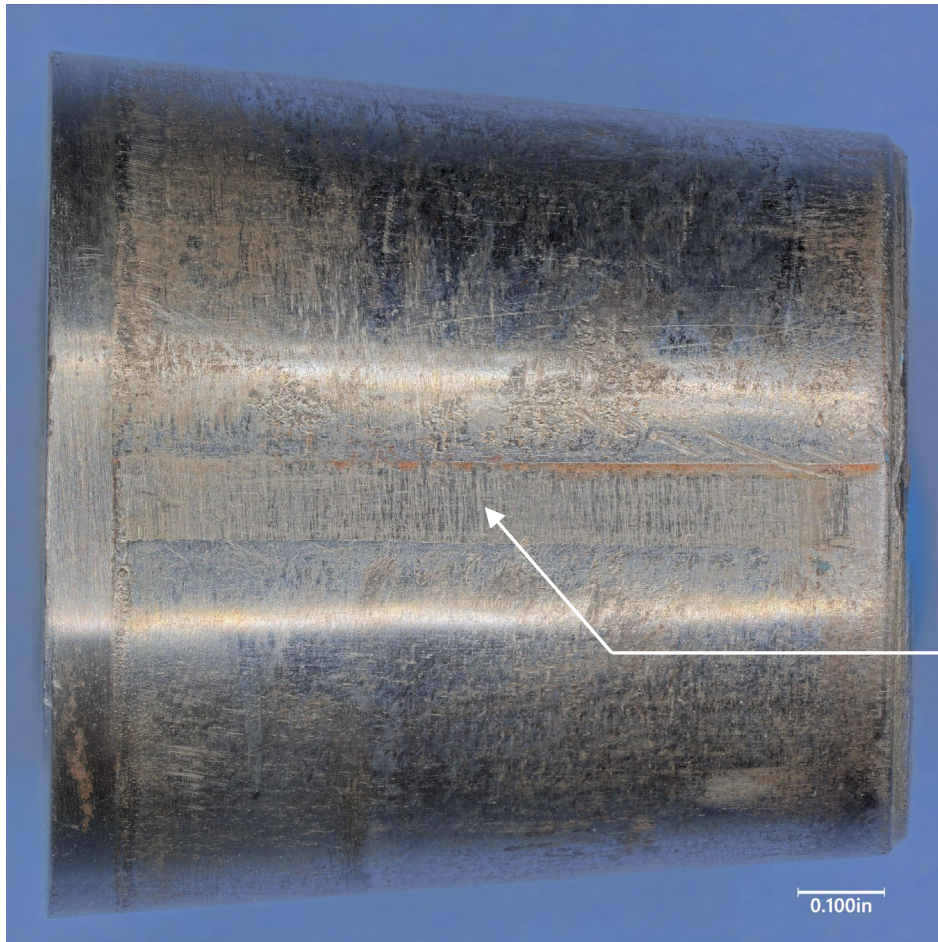


Figure 58 Views of the tapered plug in the as-received condition and after cleaning in acetone with ultrasonic agitation.



Longitudinal mark
consistent with
mandrel slot
location

Figure 59 Close digital microscope view of the surface of the tapered plug, the annotation reveals a mark that is consistent with the location of the slot in the split mandrel.

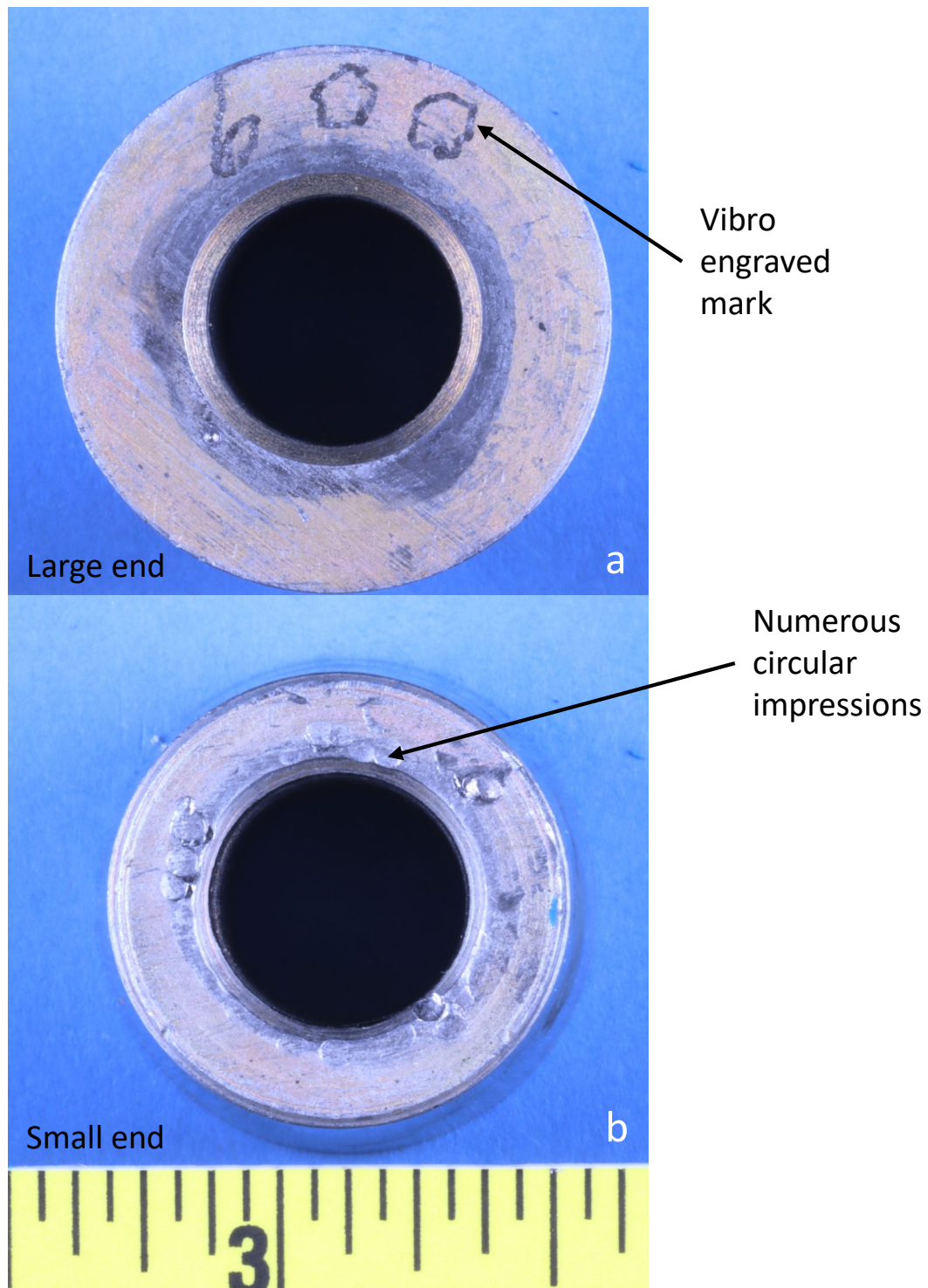


Figure 60 Image showing the small end of the tapered plug. Numerous circular impressions are present, consistent with contact marks from a drift pin.

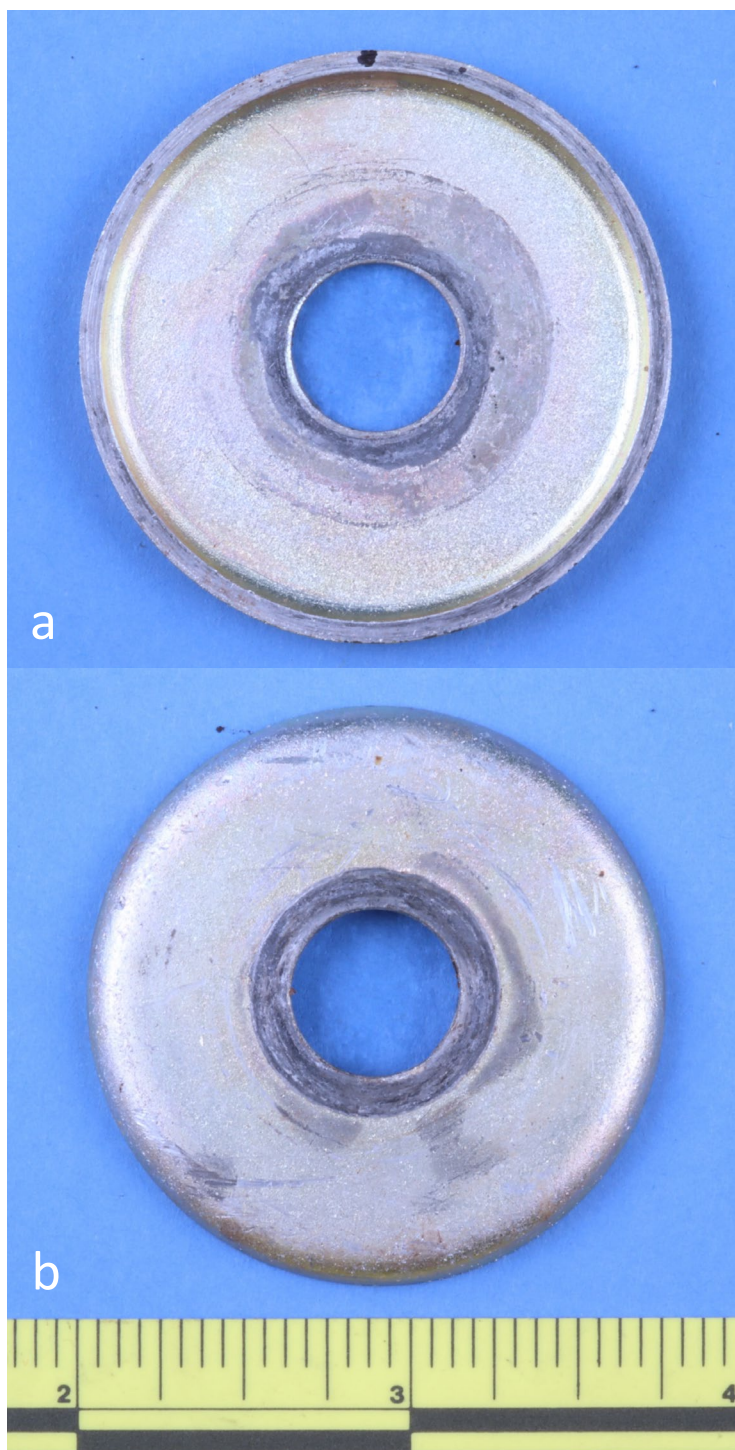


Figure 61 View of the obverse and reverse sides of the washer.

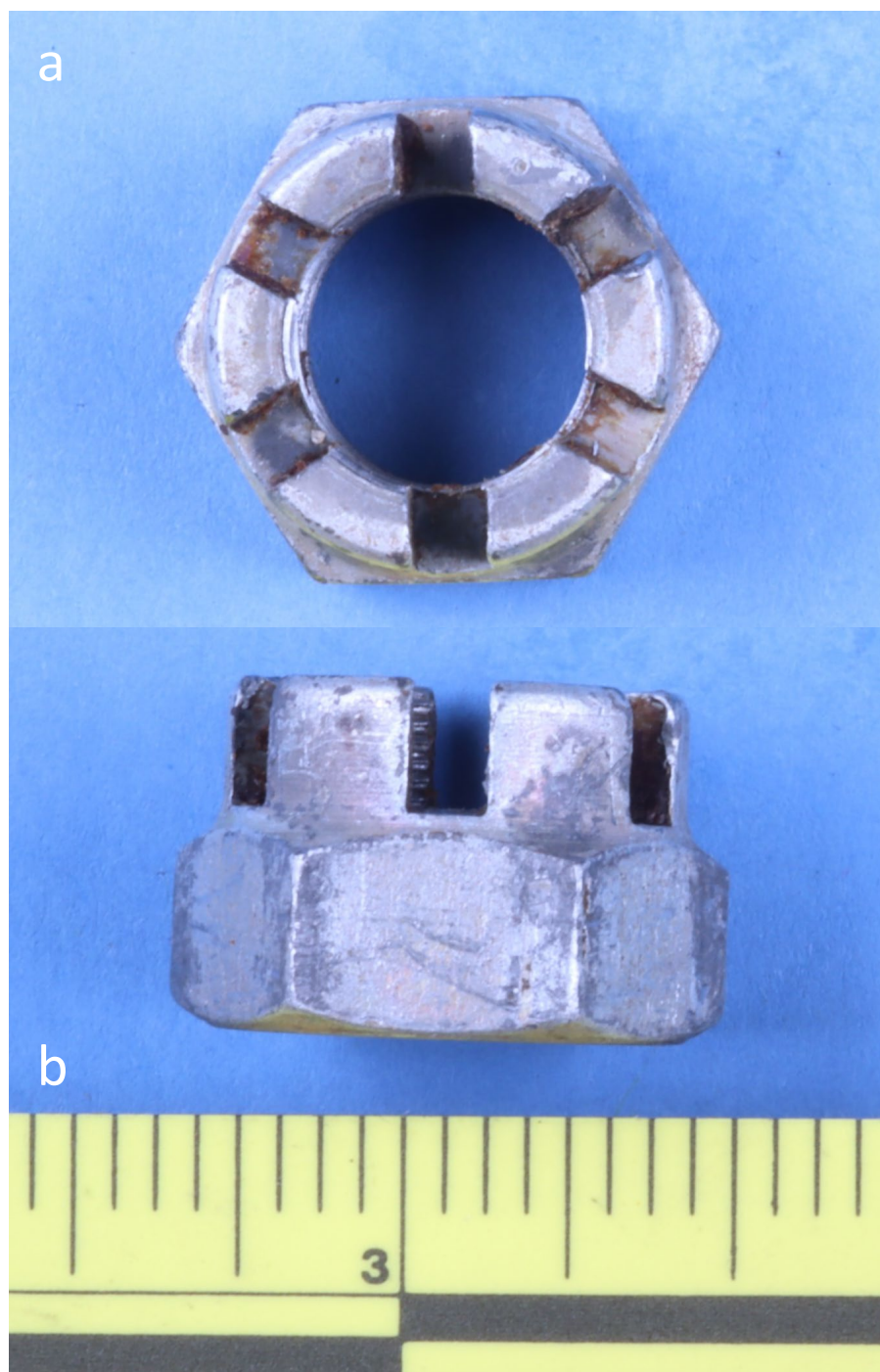


Figure 62 Top and side views of the castellated nut.

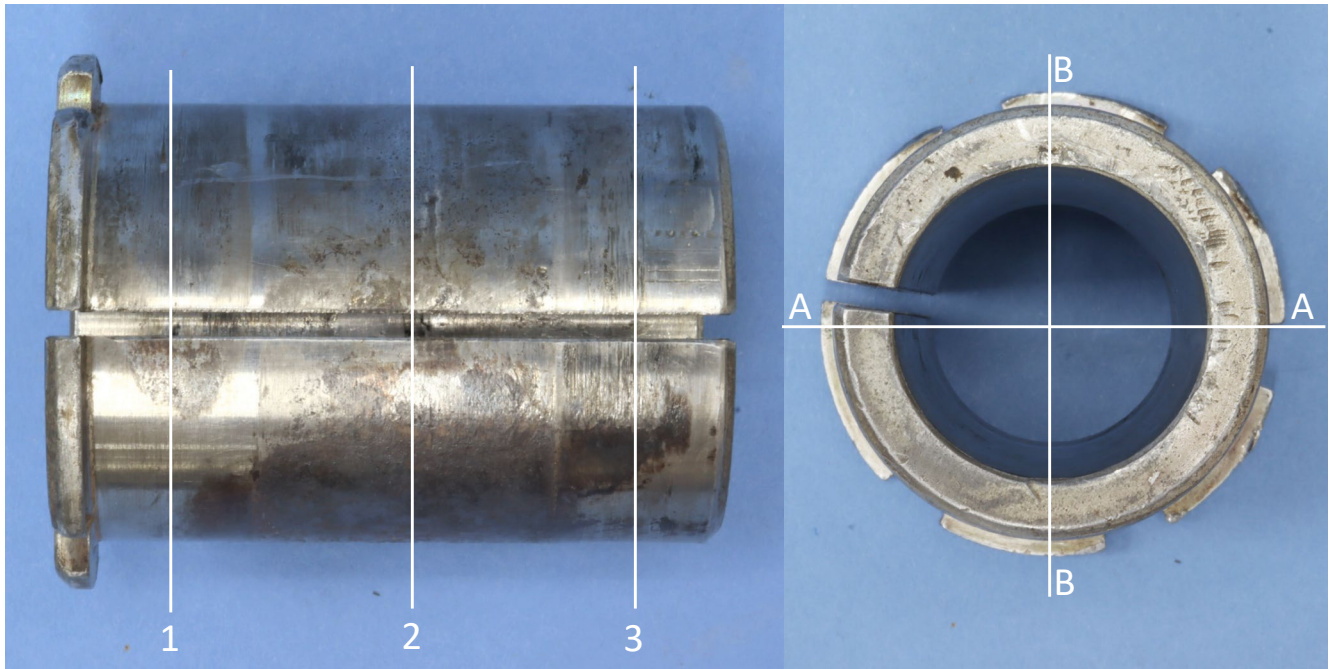


Figure 63 View of the split mandrel showing the locations where the outside diameters were measured (see Table 3).

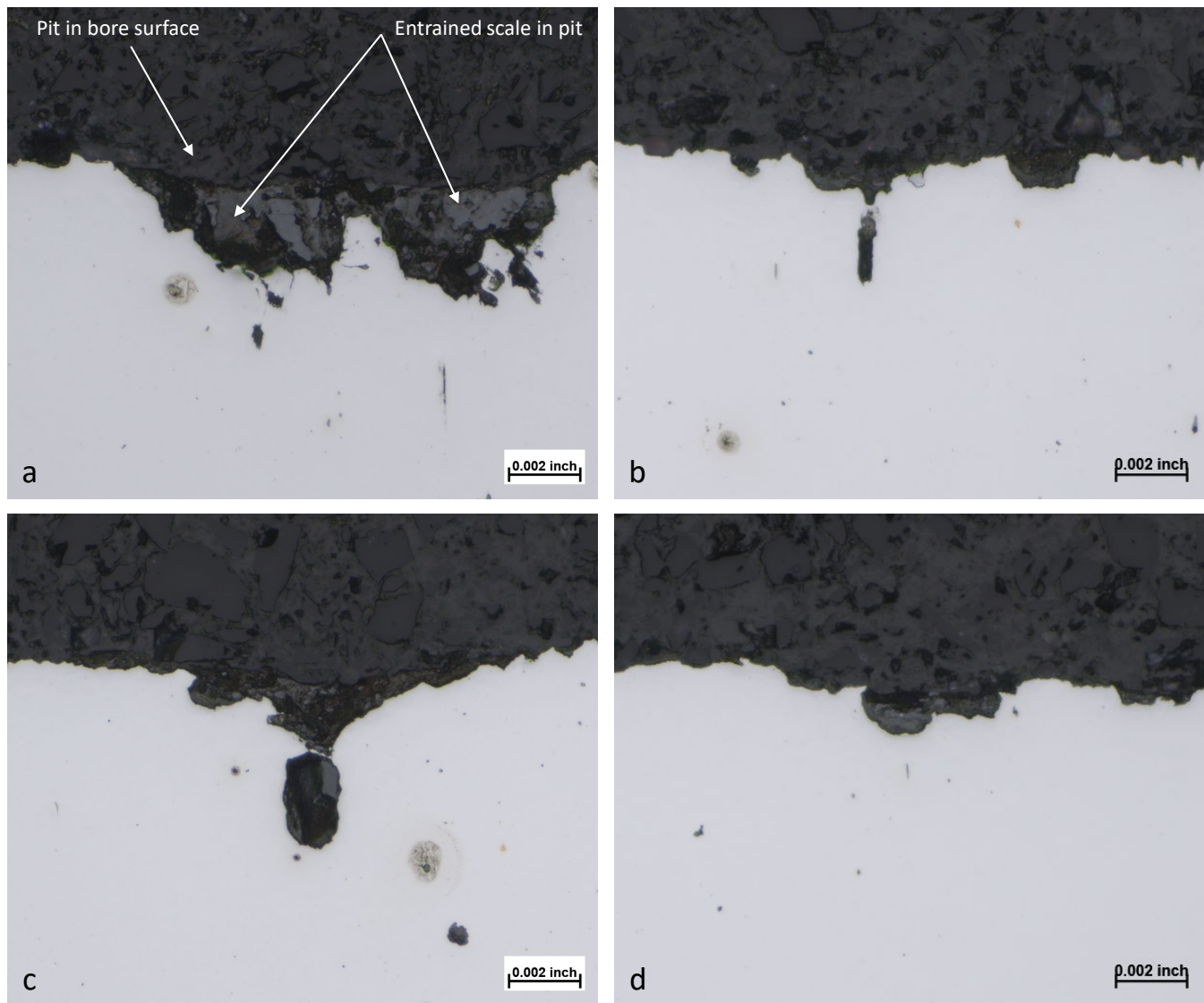


Figure 64 Bright-field optical micrographs of a cross section through the lower lug bore surface (See Figure 34 for sample location) revealing pit features in the surface of the bore as well as corrosion product scale entrained within the pits. (Unetched, 500X original magnification.)

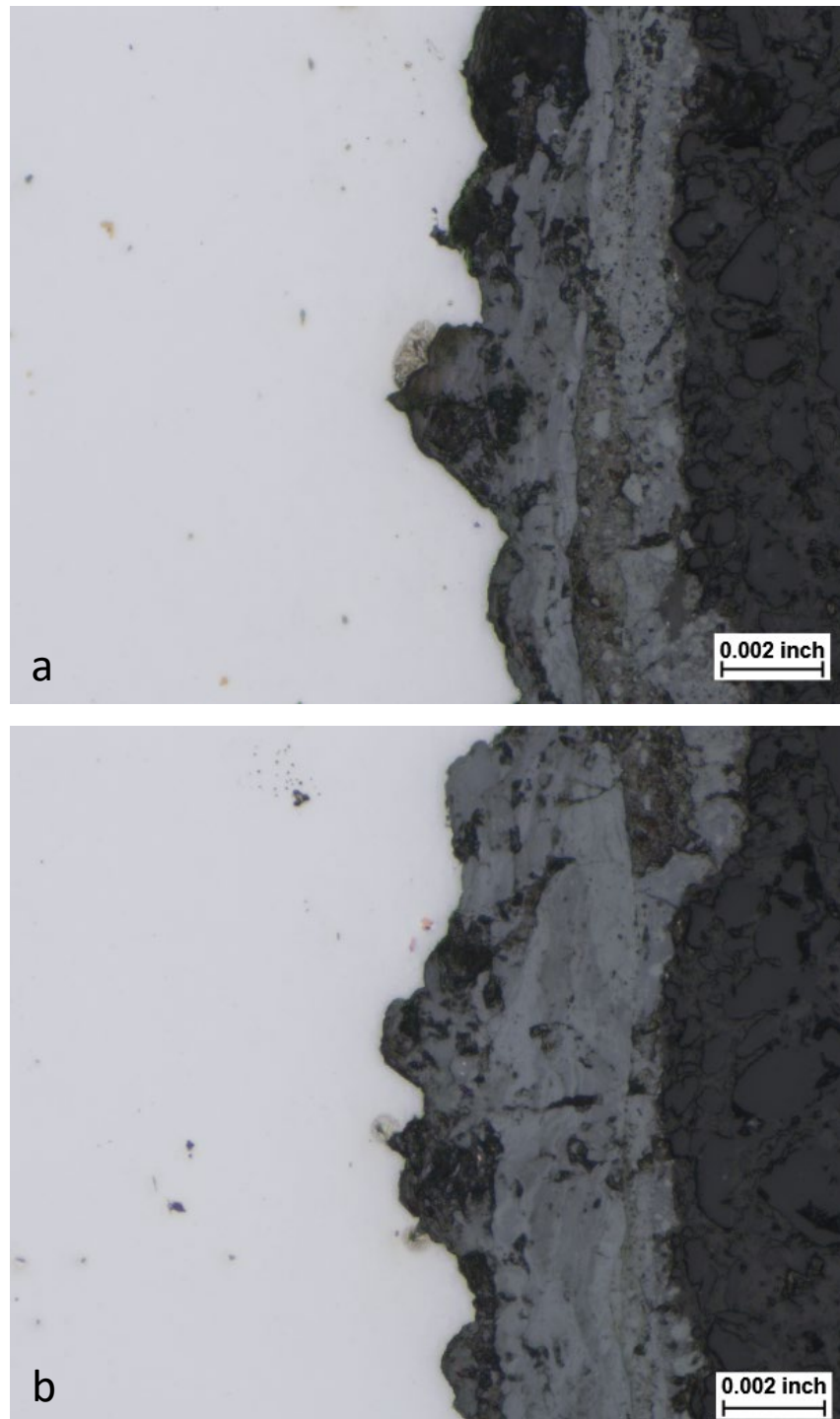


Figure 65 Bright-field optical micrographs of a cross section through the lower lug forward side surface (See Figure 34 for sample location) revealing pit features in the surface as well as corrosion product scale entrained within the pits. (Unetched, 500X original magnification)

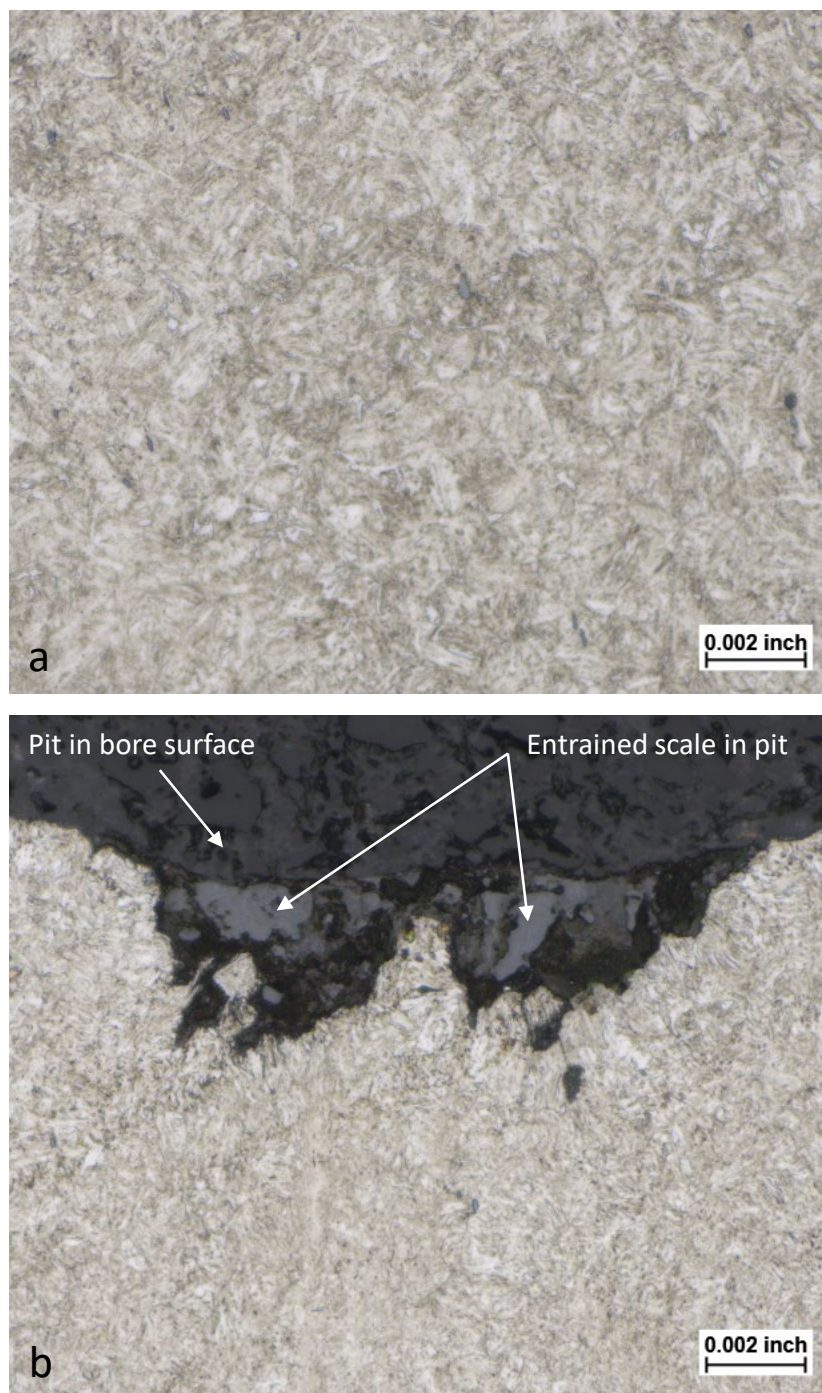


Figure 66 Bright-field optical photomicrographs of the microstructure of the lower attachment fitting taken from the lower lug portion of the separated fitting piece. View a shows a tempered martensitic core. View b shows a martensitic surface at a pit in the bore surface. (2% nital etched, 500X original magnification)