

NATIONAL TRANSPORTATION SAFETY BOARD

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



April 4, 2018

MATERIALS LABORATORY FACTUAL REPORT

Report No. 17-018

1. ACCIDENT INFORMATION

Place : Ft. Lauderdale, FL
Date : October 28, 2016
Vehicle : FedEx MD-10-10F, N370FE
NTSB No. : DCA17MA022
Investigator : Dan Bower, AS-10

2. COMPONENTS EXAMINED

Pieces of left main landing gear

3. DETAILS OF THE EXAMINATION

On October 28, 2016, at about 1751 eastern daylight time, FedEx flight 910, a McDonnell Douglas MD-10-10F, experienced a left main landing gear (MLG) collapse and subsequent fire in the left wing after landing at Ft. Lauderdale-Hollywood International Airport. The two flight crewmembers evacuated the airplane after it came to rest on the side of the runway. The crew were not injured, but the airplane was substantially damaged.

The left landing gear cylinder assembly (P/N ARG7002-505) had fractured during landing. Two small pieces from the landing gear cylinder (P/N ARG7002-13, S/N CPT0137HT) were found separated from the airplane and were sent to the NTSB Materials Laboratory for examination. The remainder of the landing gear cylinder was later disassembled and sent to the NTSB Materials Laboratory.

3.1 Examination of the Fractured Cylinder Fragments

The two fragments found separated from the rest of the cylinder are shown in Figure 1 and Figure 2, as received. Figure 1 shows the relative positions of the two fragments, which comprised the majority of the material surrounding the Schrader valve (or air filler valve) bore. Figure 2 illustrates the pieces with the flat fracture surfaces opened and facing the reader, also showing the bore of the valve.

The arrow in the upper left of Figure 2 denotes the location of a small thumbnail crack. This crack was located at the radius between the cylinder inner diameter surface and the Schrader valve bore surface. This region is highlighted in Figure 3. Most of the fracture surface area had been damaged by smearing, consistent with post-fracture impact damage. Surface contamination, such as rust and dirt, were also present on the fracture surfaces.

However, as also shown in Figure 4, a small portion adjacent the radius exhibited features, such as crack-arrest marks, consistent with progressive crack growth. This progressive crack growth was found to be mostly consistent with fatigue cracking, as exhibited by the fatigue striations found on microscopic examination of the thumbnail crack (see Figure 5). The farthest depth of fatigue striations that could be observed on this fracture surface were located about 0.083 inches (2.1 mm) from the radius apex. Due to the post-fracture damage, no discernible features were observed at the crack initiation site.

3.2 Examination of the Main Landing Gear Cylinder

The main fragments of the landing gear from the accident had fractured into three pieces, in addition to the two smaller fragments detailed in Section 3.1. Figure 6 shows these three largest fragments, as received. Figure 7 shows the three largest landing gear pieces arranged to show their relative positions at fracture.

Almost all of the fracture surfaces exhibited a dull luster with a rough surface, including radial lines and chevron marks. These features were consistent with overstress fracture in low ductility (hardened) metal alloys. These features were consistent with having emanated from the small thumbnail crack in the air valve bore on the landing gear, as shown in Figure 8 and Figure 9. At the bore location was a flat, thumbnail-shaped crack. This feature was consistent with pre-existing cracking prior to complete fracture of the landing gear during the final landing. This thumbnail crack was consistent with the mating crack face illustrated in Figure 4.

The thickness of the fractured landing gear was measured using calipers at several positions, as depicted in Figure 10 and Figure 11. The measurements were as follows.

- Thickness 1: 0.8215 inches
- Thickness 2: 0.8100 inches
- Thickness 3: 1.4240 inches
- Thickness 4: 0.8765 inches
- Thickness 5: 0.8200 inches (180° from Thickness 4, not pictured)

The inner diameter of the cylinder at the valve bore was measured using a tape measure, accurate to the 1/16-inch scale. The maximum recorded cylinder diameter was 12.531 inches. The drawing requirement for the diameter was 12.540 inches.

The inside bore of the Schrader valve was measured from a replicating rubber negative using an optical comparometer. The smooth portion of the bore had a diameter between 0.492 and 0.523 inches, with an average of 0.514 inches. The stated requirement for the bore diameter was 0.494 to 0.524 inches, up to a maximum of 0.550 inches after rework due to a hard landing.

The radius of the curved portion of the landing gear bore at the location of the thumbnail crack initiation site was measured between 0.105 and 0.154 inches, with an average of 0.128 inches. The stated requirement for the radius diameter in the Service

Bulletin and CMM was 0.015-0.030 inches. The recorded radius on the Hawker Aerospace Traveler was 0.090 inches.^{1,2}

The area around the bore was sectioned from the largest landing gear fragment using a plasma torch cutter, and then sectioned further using water-cooled abrasive saws. Figure 12 through Figure 15 show the initial point of fracture from several angles, after sectioning. All the overstress features observed were consistent with having emanated from the thumbnail crack near the bore.

Figure 16 shows a closer view of the thumbnail crack. The thumbnail crack exhibited arrest marks, consistent with progressive crack growth. The crack was asymmetric in shape, being about 0.111 inches (2.81 mm) on one side, and about 0.192 inches (4.87 mm) on the other.

Figure 17 shows a closer view of the thumbnail crack from Figure 16. The thumbnail crack exhibited a banded morphology, later found to be consistent with mixed alternating regions exhibiting fatigue, intergranular, and overstress features. Using Keyence digital microscope measurement software, several dimensions of the thumbnail crack were measured, as illustrated in Figure 18 and Figure 19. The crack initiation site was located at the radius apex: approximately 0.018 inches from the air valve bore surface and approximately 0.061 inches from the inside cylinder surface tangent. The radius of curvature at the thumbnail crack was measured as approximately 0.142 inches (compared to 0.128 using replicating rubber).

The thumbnail crack was examined using a scanning electron microscope (SEM). Figure 20 shows the location of the start of the crack, located inside the machined portion of the bore, which showed radial machine marks. Fatigue striations were present in the initial portion of the crack and the subsequent fatigue bands (Figure 21). Outside of the fatigue bands, dimple rupture consistent with overstress was observed. The fatigue features extended to a minimum of approximately 0.110 inches along the inner diameter (Figure 22) and a maximum of 0.192 inches (4.871 mm) along the air valve bore, as depicted in Figure 23.

Closer examination found that the thumbnail crack was not exclusively consistent with fatigue crack propagation, but rather contained bands of other failure modes. As shown in Figure 24, after the initial fatigue cracking from the initiation site, there was an intergranular fracture band surrounding the first 0.02 inches (0.5 mm) of fatigue, followed by a band of fatigue striations. After this there were three overstress bands (exhibiting dimple rupture features) alternating with fatigue, before a final mixed fatigue and overstress band. The distances of each of these bands from the crack initiation site were as follows:

¹ Hawker Pacific Aerospace Work Order Traveler L07793-077, Generated November 10, 2007.

² Hawker Pacific Aerospace is a maintenance, repair and overhaul provider located in Sun Valley, CA, specializing in landing gears and associated hydraulic components. Since 2002, they have been subsidiary of the Lufthansa Technik AG, Hamburg, Germany.

- Distance from fatigue crack to intergranular region: 0.019 in (0.47 mm)
- Distance from fatigue crack initiation site to 1st overstress band: 0.041 in (1.03 mm)
- Distance to overstress band 2: 0.052 in (1.32 mm)
- Distance to overstress band 3: 0.062 in (1.58 mm)
- Distance to overstress band 4: 0.080 in (2.03 mm)
- Distance to end of all fatigue features: 0.094 in (2.39 mm)

Figure 25 illustrates the faceted morphology of the intergranular band on the thumbnail crack. The width of the intergranular band was measured as 0.013 inches (0.33 mm), as illustrated in Figure 26. This region was inspected using energy dispersive x-ray spectroscopy (EDS). There were no elements unique to the intergranular fracture band or on the fractured facets that were not present on other regions of the fracture surface. As shown in Figure 17, the outer banded characteristics of the thumbnail crack could be observed visibly. After the intergranular band, the alternating bands were consistent with either fatigue (striations), overstress (dimple rupture), or both in the final band, shown in Figure 27.

Figure 28 shows the fatigue crack initiation site. The most prominent quality of the initiation site was a corrosion pit (Figure 29). The corrosion pit measured 0.004 inches wide (0.109 mm) with a depth of 0.002 inches (0.051 mm). EDS probes in the pit found detectable levels of oxygen, sodium, calcium, and phosphorus.

Figure 30 shows a view of the radius at the transition from the valve bore to the inner diameter surface of the landing gear. The area consistent with the valve bore surface exhibited corrosion pitting. Figure 31 illustrates a closer view of one of the corrosion pits. EDS spectra of this corrosion pit were consistent with that of probes taken at the corrosion pit at the fatigue crack initiation site. Measurement of these pits found that they averaged 0.0012 inches (0.032 mm) in diameter.

3.3 Examination of Cylinder Properties

The chemical composition of the cylinder was inspected using EDS and x-ray fluorescence (XRF). The composition was consistent with 300M, the prescribed material for the part.³ The bore was inspected to determine if there were any electrodeposits or remnants of other metallic coatings in the area. No indications of cadmium or cadmium compounds were found in the bore using EDS. Likewise, inspection of the fracture surface and bore using backscattered electron imaging found no evidence of any particles consistent with previous nickel, chromium, or cadmium plating.

Near the plasma torch cut portion of the landing gear section, a specimen was cross-sectioned and polished to facilitate hardness tests. Hardness tests were performed in accordance with ASTM E18.⁴ The hardness adjacent to the plasma torch section measured 54 HRC, and then dropped to a minimum of 45 HRC. The hardness measurements increased

³ Alloy 300M is a silicon-modified 4340 alloy steel that exhibits deep hardenability and improved resistance to quenching stresses.

⁴ ASTM E18 – *Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials*. ASTM International, West Conshohocken, PA.

farther away from the cut surface, and, at a depth of 0.565 inches, the hardness measurements stabilized and averaged 54 HRC.

According to published data, this hardness was consistent with 300M having a tensile strength of 297 ksi, which typically requires a tempering temperature of 500 °F (260 °C).⁵ The part drawing required a heat treatment to a tensile strength of 275 to 305 ksi. According to literature, the measured hardness values were consistent with the prescribed heat treatment requirements.⁵

One of the fragments of the landing gear about the air valve bore was sectioned, mounted, polished and etched with a 2% Nital solution. Figure 32 shows a cross section of the threads in the bore. The threads exhibited no indication of a metallic coating. In addition, the grain structure inside the thread was consistent with that of the bulk, indicative of cut threads. Figure 33 shows a closer view of the bulk microstructure. This region exhibited a tempered martensite microstructure, consistent with those typically observed for this alloy and heat treatment. No microstructural deformation or grain flow was present in the threaded portions, indicating they were machined (cut) rather than rolled.

A cross section through the valve bore, near the fracture surface shown in Figure 2, was mounted and polished. This surface was used to inspect the local hardness properties using microindentation hardness testing per ASTM E384.⁶ Figure 34 illustrates a false color image representing the hardness values obtained, from 52 HRC (580 HV₅₀₀), colored green, to 60 HRC (691 HV₅₀₀), colored red. The regions of highest hardness were located along and near the threads, consistent with strain hardening imparted by the cutting process. There were no indications of lower hardness regions near the bore.

3.4 Maintenance History of the Landing Gear Cylinder

A previous NTSB investigation involving a fracture of the same landing gear cylinder.⁷ This fracture also originated at a small fatigue crack inside the Schrader valve bore. The NTSB probable cause in that investigation stated that the left main landing gear had fractured from fatigue cracking in the air valve hole due to the presence of stray nickel electroplating in the air filler valve hole. The Board also stated that inadequate maintenance procedures preventing said excess nickel electroplating in the bore contributed to fatigue cracking.

Because of these preliminary investigation findings, Boeing issued Alert Service Bulletin DC10-32A259 on October 30, 2007. The Bulletin instructed the operator to perform inspections of the MLG cylinder air filler valve bore for stray nickel or chromium electroplating deposits, corrosion, or cracks. If any of these conditions were found, the service bulletin provided instructions for repair or replacement of the MLG shock strut cylinder assembly.

⁵ *Metals Handbook Desk Edition, 2nd ed.*, J.R. Davis, ed., ASM International: Materials Park, OH (1998) p. 261s

⁶ ASTM E384 – *Standard Test Method for Knoop and Vickers Hardness of Materials*. ASTM International, West Conshohocken, PA

⁷ J. Epperson. *Materials Laboratory Factual Report 06-076*. NTSB Investigation DCA06MA058 (Memphis, TN, July 28, 2006): Washington, DC, (September 13, 2006).

Prior to the release of the Service Bulletin, Boeing issued a revision to the applicable Component Maintenance Manual (CMM) on September 15, 2007.⁸ The revision added instructions for a video probe inspection of the air filler valve bore for corrosion, sulfamate nickel or chromium electroplating splatter, tool marks, or other defects followed by an eddy current inspection of the bore for cracks. Instructions for repair of allowable damage were also included.

On May 2, 2008 the FAA issued AD 2008-09-17 requiring operators to perform a video scope inspection of the air filler valve bore for the presence of stray nickel or chromium electroplating deposits, and then requiring performing the corrective actions per the Boeing Alert Service Bulletin. The AD became effective on June 6, 2008.⁹

The main landing gear assembly in this accident was overhauled by Hawker Pacific Aerospace. The landing gear overhaul was completed on February 28, 2008.¹ The MLG assembly at time of overhaul had been in service for 33422 cycles since new. The outer cylinder had 26867 cycles since new. The piston (inner cylinder) had 33422 cycles since new. After installation on this aircraft, the cylinder operated an additional 5653 cycles for 3133 days (or 8 years and 7 months).

A review of the work order traveler paperwork for this MLG cylinder indicated that during initial inspection, no nickel or chromium was found in the valve bore, but corrosion was noted. The corrosion was removed, and the fill valve bore was oversized within manufacture limits. After eddy current and magnetic particle inspection, the valve bores were isolated and masked, to prevent excess deposits from later plating processes.

According to the work order, the cylinder was chromium electroplated followed by a bake relief, and then electroless nickel-plated. The next plating step of the cylinder was cadmium electroplating, followed by a post-process bake relief. After the tank electroplating, the masking was removed from the bores, which were then stylus (brush) cadmium electroplated. Once completed, these bores were borescope inspected, followed by a magnetic particle inspection. The applicable 2007 CMM for the cylinder directed the stylus cadmium electroplating after the cylinder had been tank plated and baked. The current CMM revision directs brush cadmium electroplating prior to tank plating and baking.¹⁰

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⁸ Boeing Component Maintenance Manual 32-11-04, Revision No. 25 Main Landing Gear Shock Strut Assembly (September 15, 2007)

⁹ NTSB Investigation DCA06MA058 Full Narrative.

https://www.nts.gov/ layouts/ntsb.aviation/brief2.aspx?ev_id=20060808X01115&ntsbno=DCA06FA058&akey=1

¹⁰ Boeing Component Maintenance Manual 32-11-04, Revision No. 43 Main Landing Gear Shock Strut Assembly (March 1, 2016)



Figure 1 – The landing gear cylinder fragments, as received. The arrow denotes the location of the flat fracture surface.



Figure 2 – The fracture surface along the Schrader valve bore of the cylinder fragment. The progressive fracture is located on the fragment on the left, denoted by the arrow.

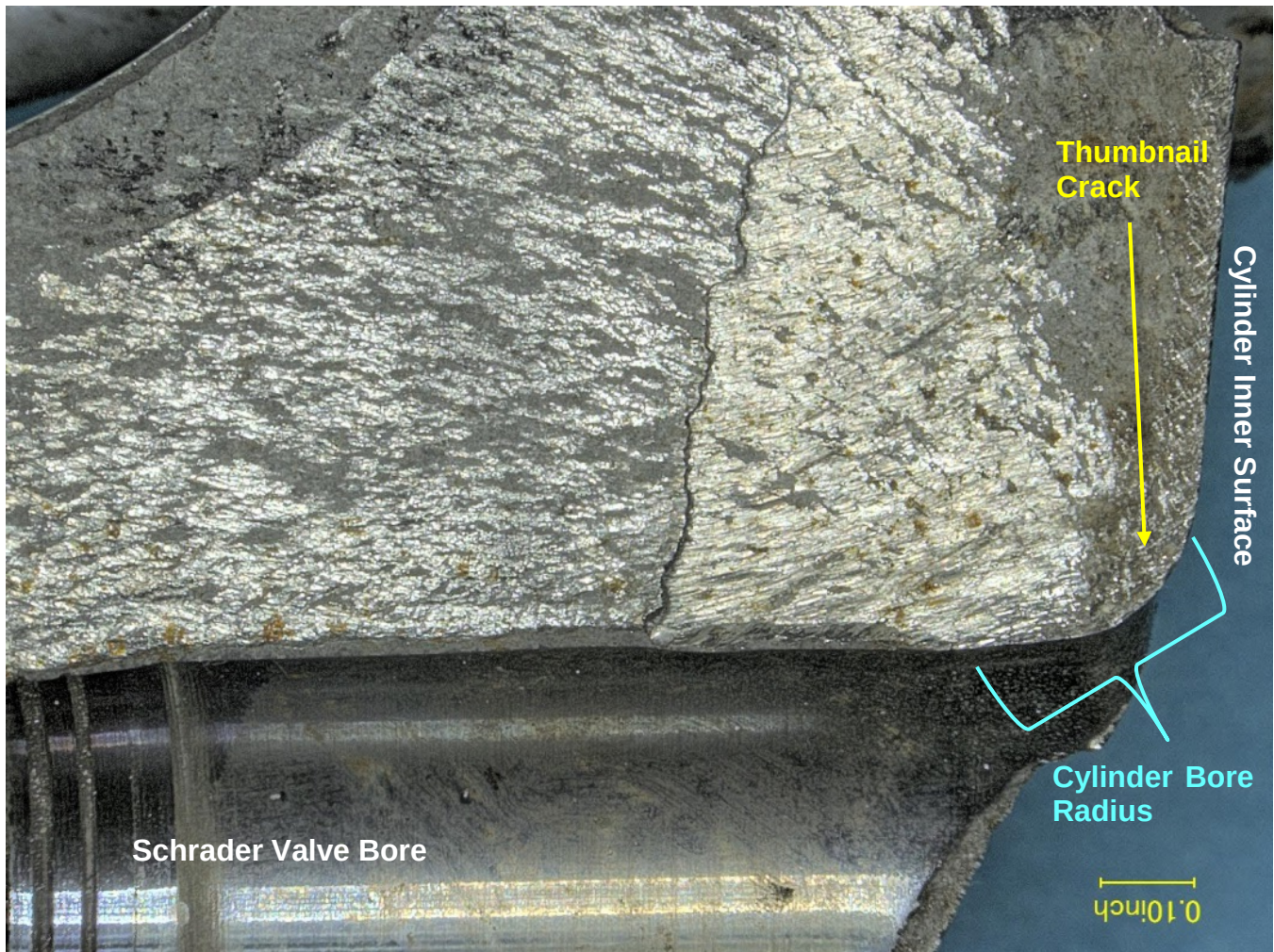


Figure 3 – A closer view of the progressive fracture on the cylinder fragments, showing the crack emanating from the radius inside of the valve bore.

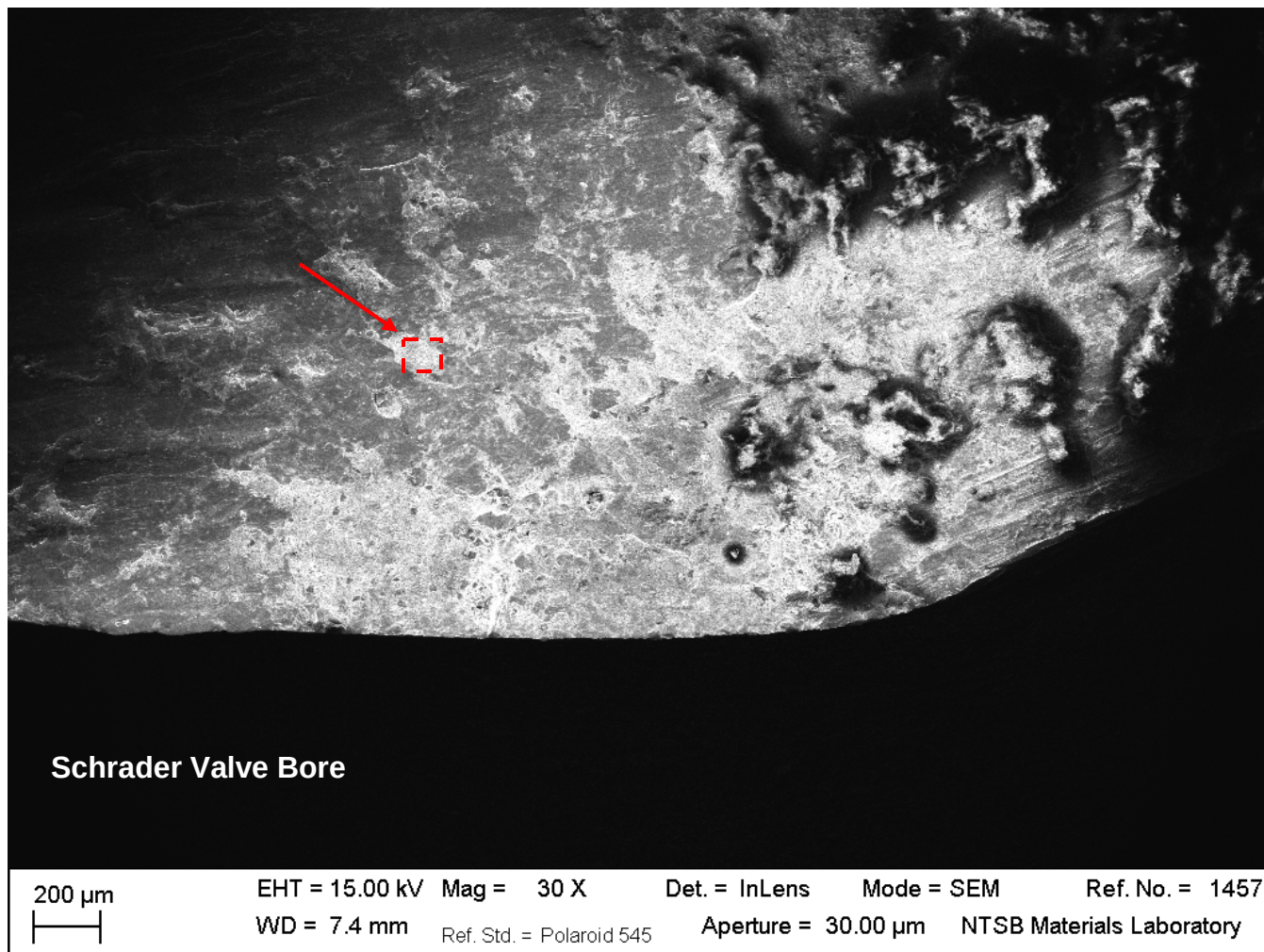


Figure 4 – Secondary electron (SE) micrograph showing a closer view of the fatigue crack in Figure 3. The boxed area (arrow) is shown in Figure 5.

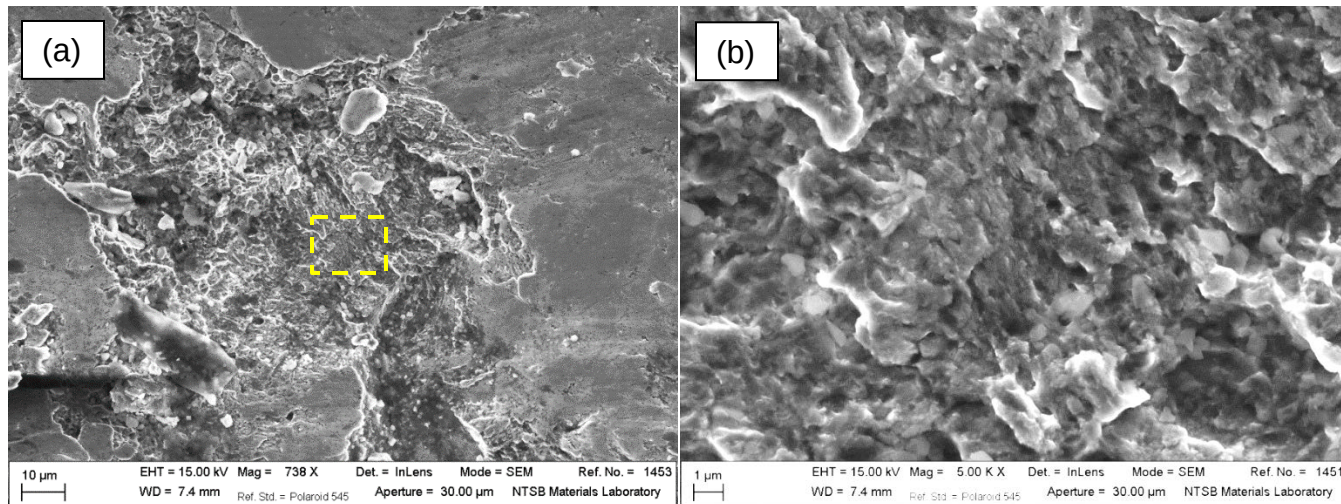


Figure 5 – SE micrographs showing a closer view of (a) the boxed area in Figure 4, showing fatigue striations highlighted in the boxed area, magnified in (b).



Figure 6 – The large pieces of the landing gear, as received in the NTSB Materials Lab.



Figure 7 – The large landing gear pieces, after rearranging to show their positions at fracture, viewed forward looking aft. The fill valve bore is located on the aft side of the cylinder (not pictured).

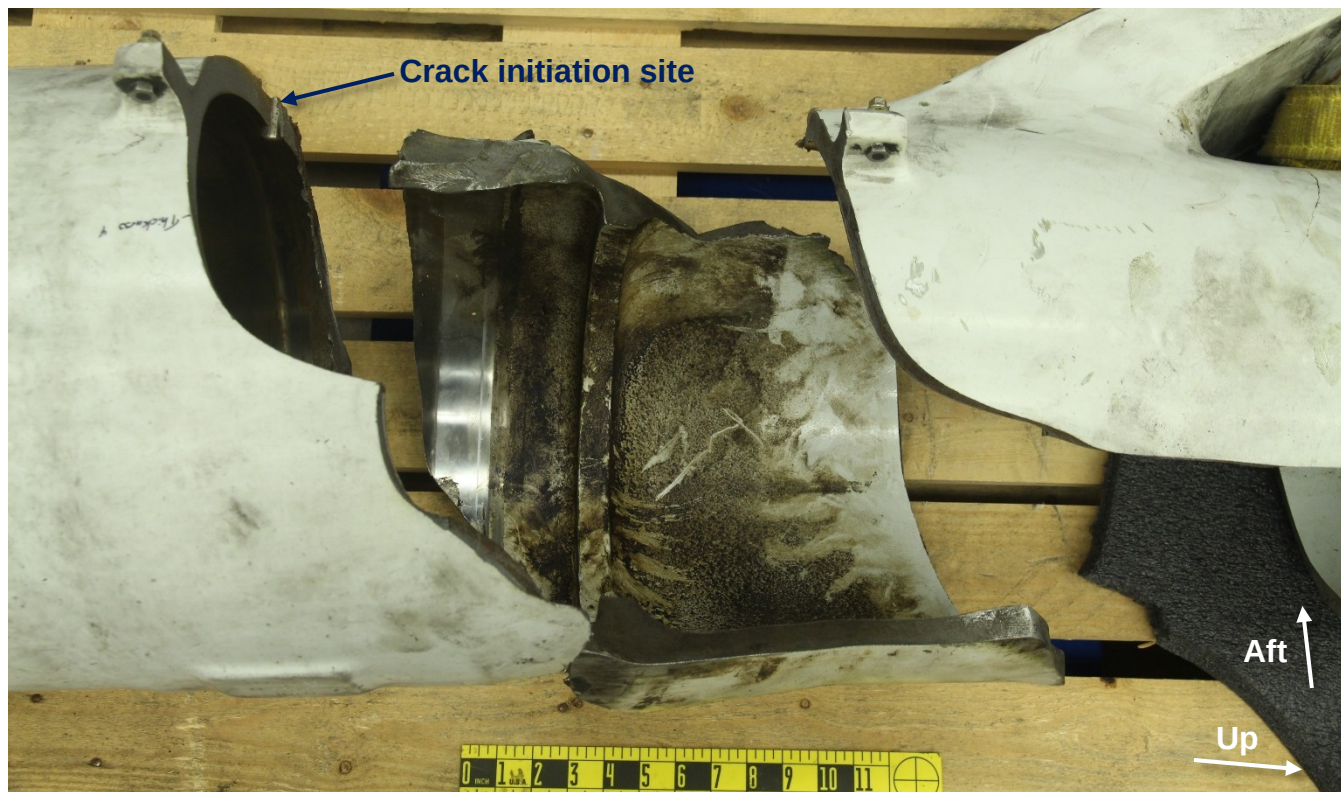


Figure 8 – The main fracture region of the landing gear, with the initial fracture region shown.

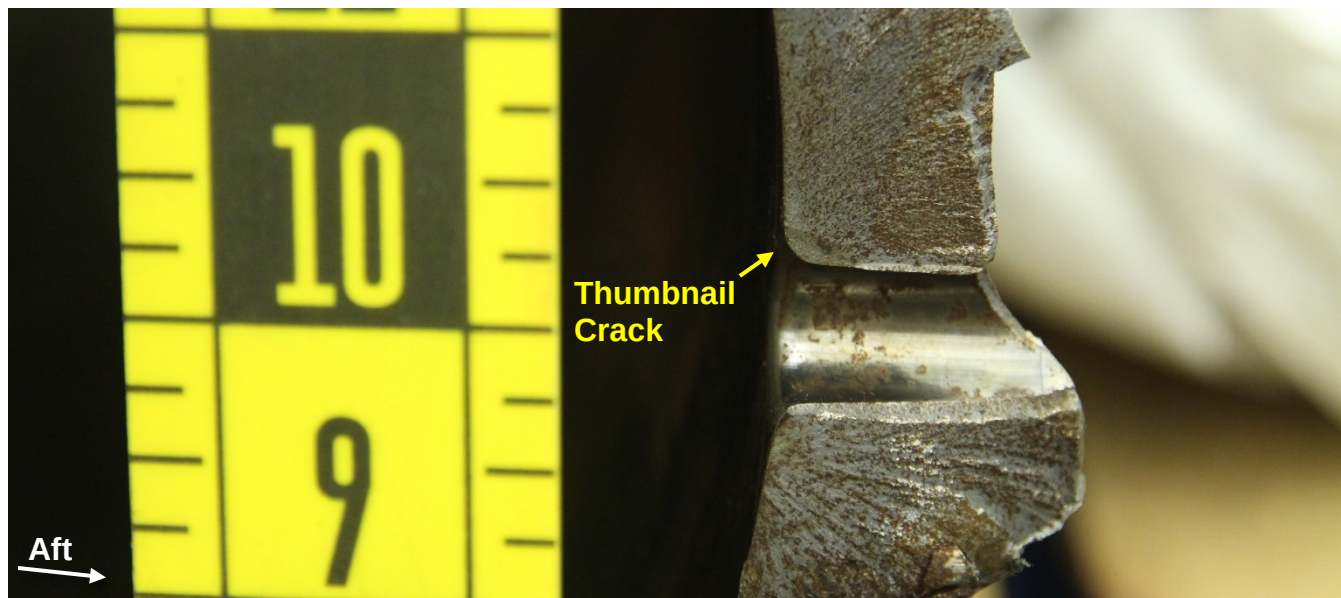


Figure 9 – The thumbnail crack at the bore.

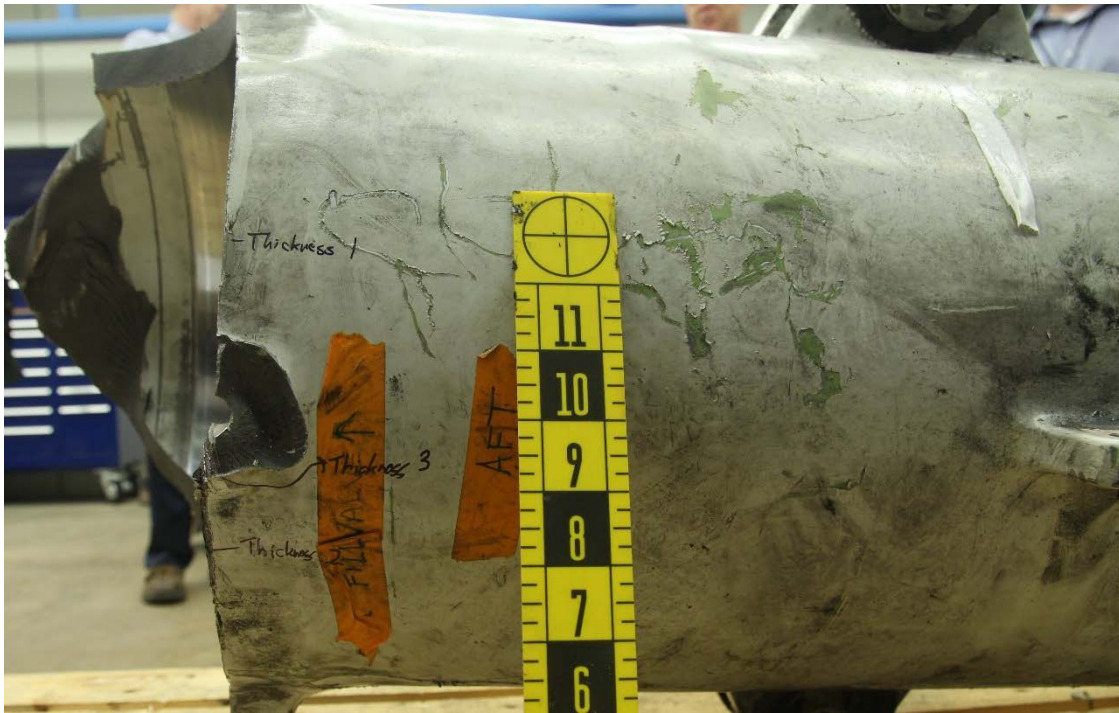


Figure 10 – The side of the largest landing gear fragment, showing thickness measurement locations 1 through 3.

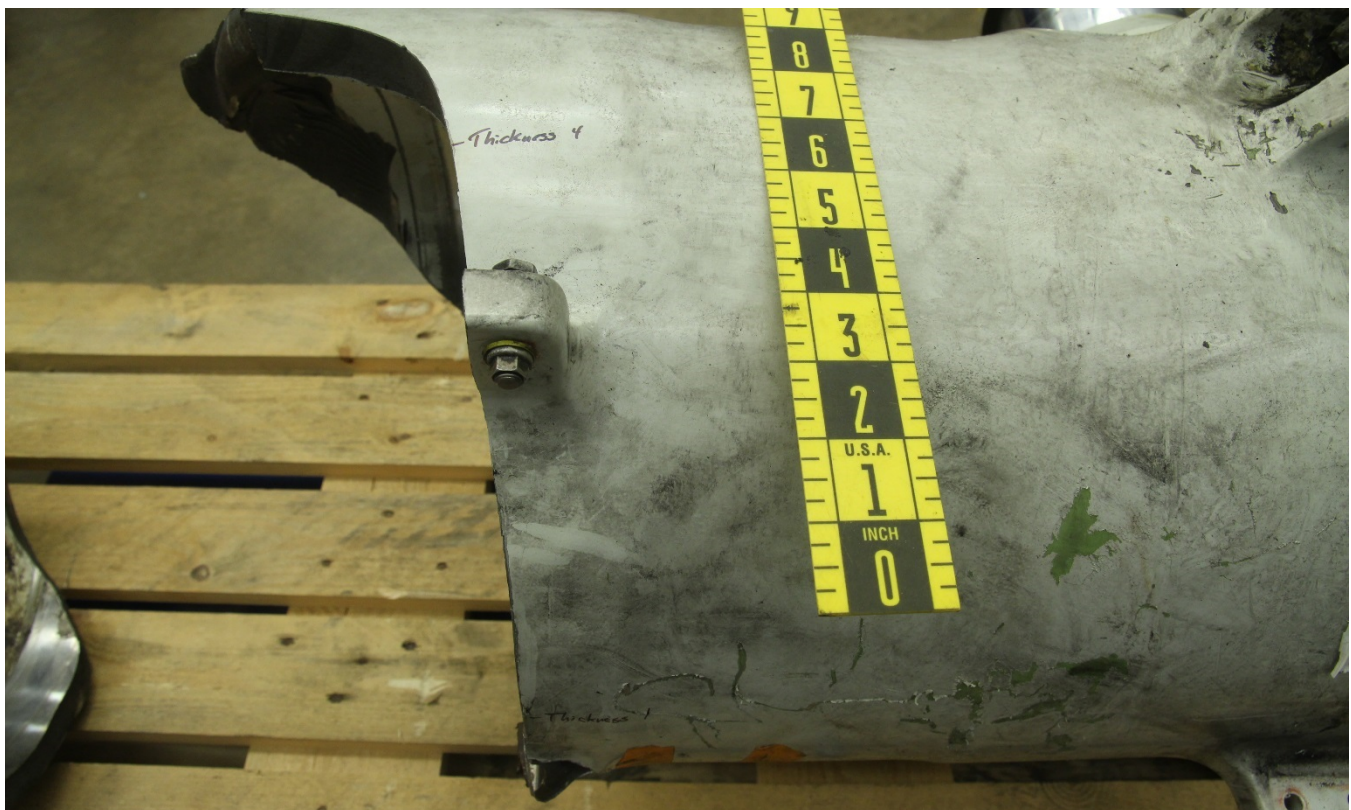


Figure 11 – The landing gear 90° from Figure 10, showing thickness measurement location 4.



Figure 12 – The landing gear fracture about the bore, after sectioning from the landing gear.



Figure 13 – Closer view of the thumbnail crack in Figure 12.



Figure 14 – The initial point of the fracture at the bore, viewed from the outside surface.



Figure 15 – A view of the thumbnail crack, angled from the inside surface.



Figure 16 – The thumbnail crack at the initial point of fracture, showing crack arrest marks.

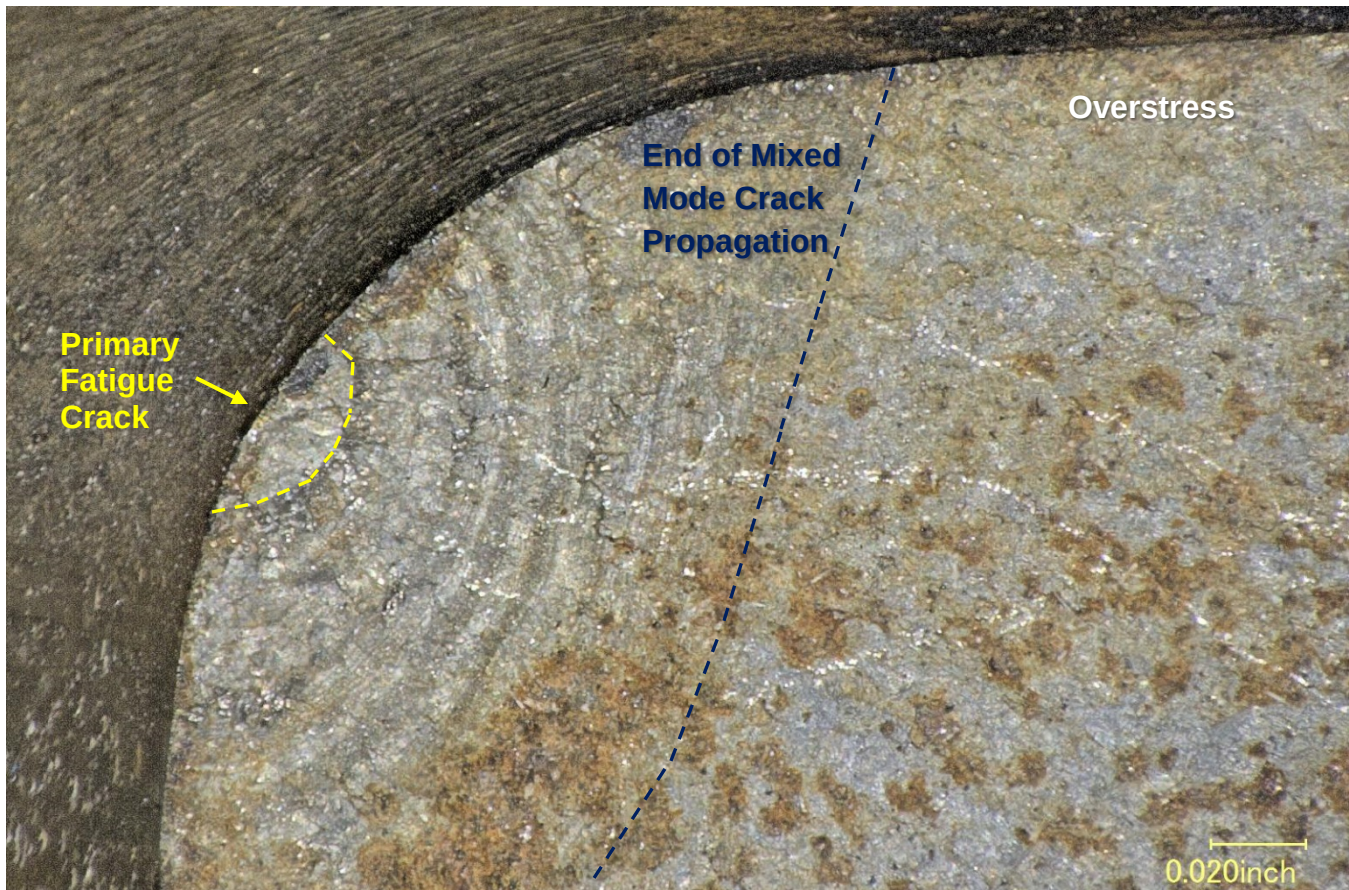


Figure 17 – Closer view of the thumbnail crack from Figure 16. The primary fatigue crack region (before the intergranular region) is highlighted by dashed yellow lines. The end of the all fatigue and mixed mode cracking is highlighted by the dashed green lines.



Figure 18 – Key measurements of the thumbnail crack relative to other surfaces. The radial depth of the crack initiation site to the valve bore was 0.018 inches, and the distance of the initiation site to the cylinder diameter was 0.061 inches.

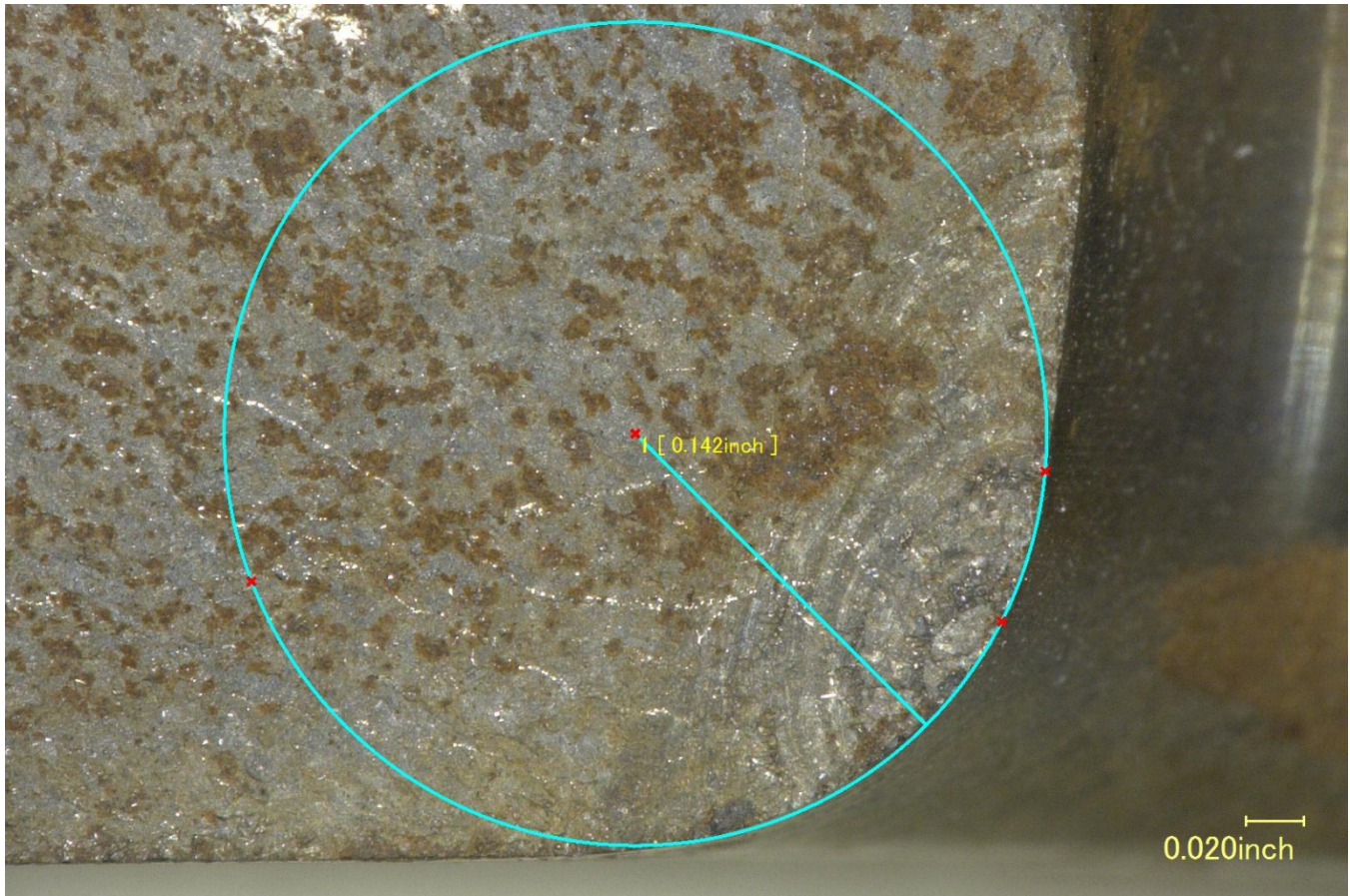


Figure 19 – Radius of curvature measurement at the thumbnail crack location.

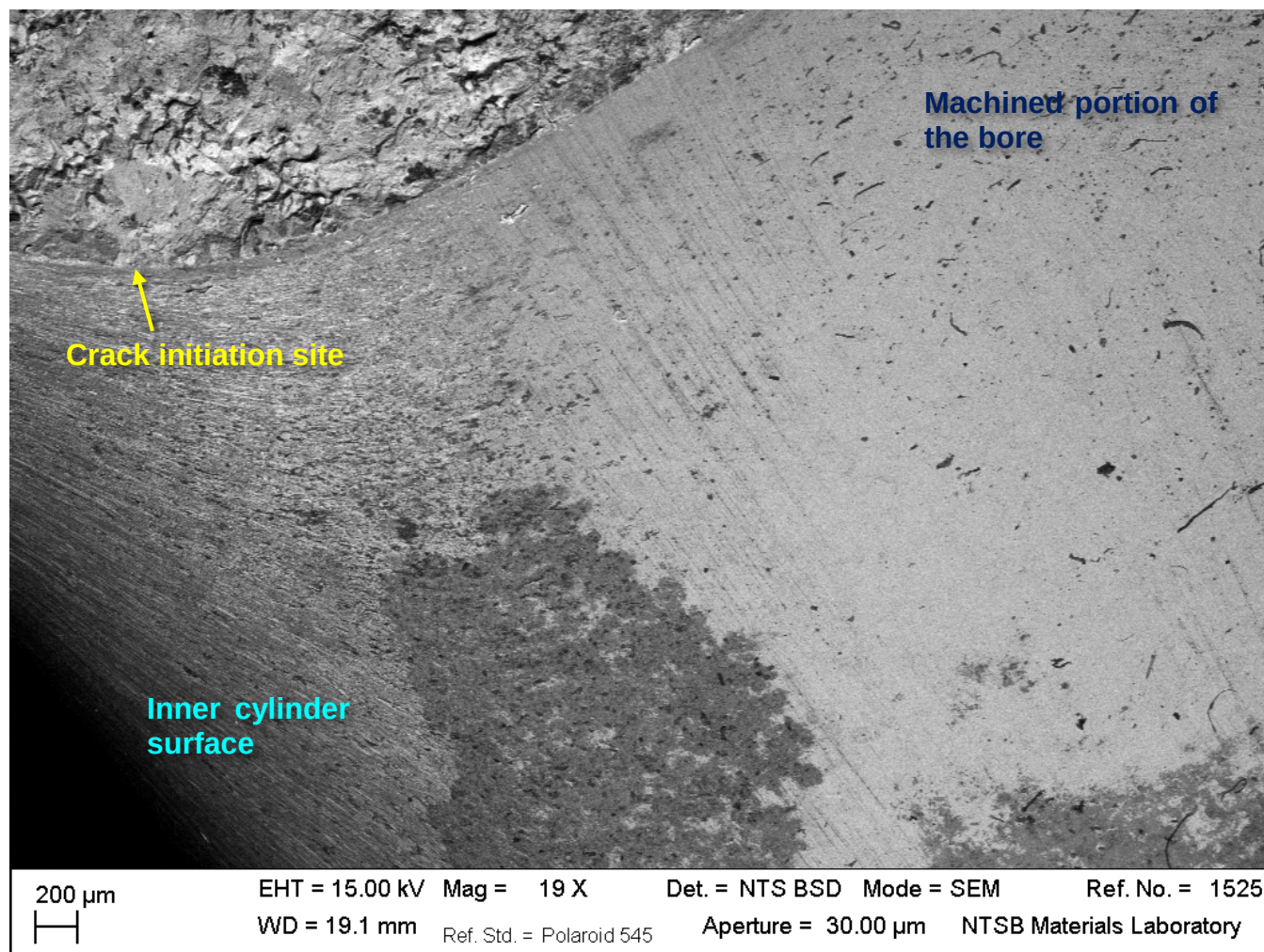


Figure 20 – Backscattered electron (BE) micrograph of the fracture surface initiation area, viewed tilted with the inner bore and inner surface shown.

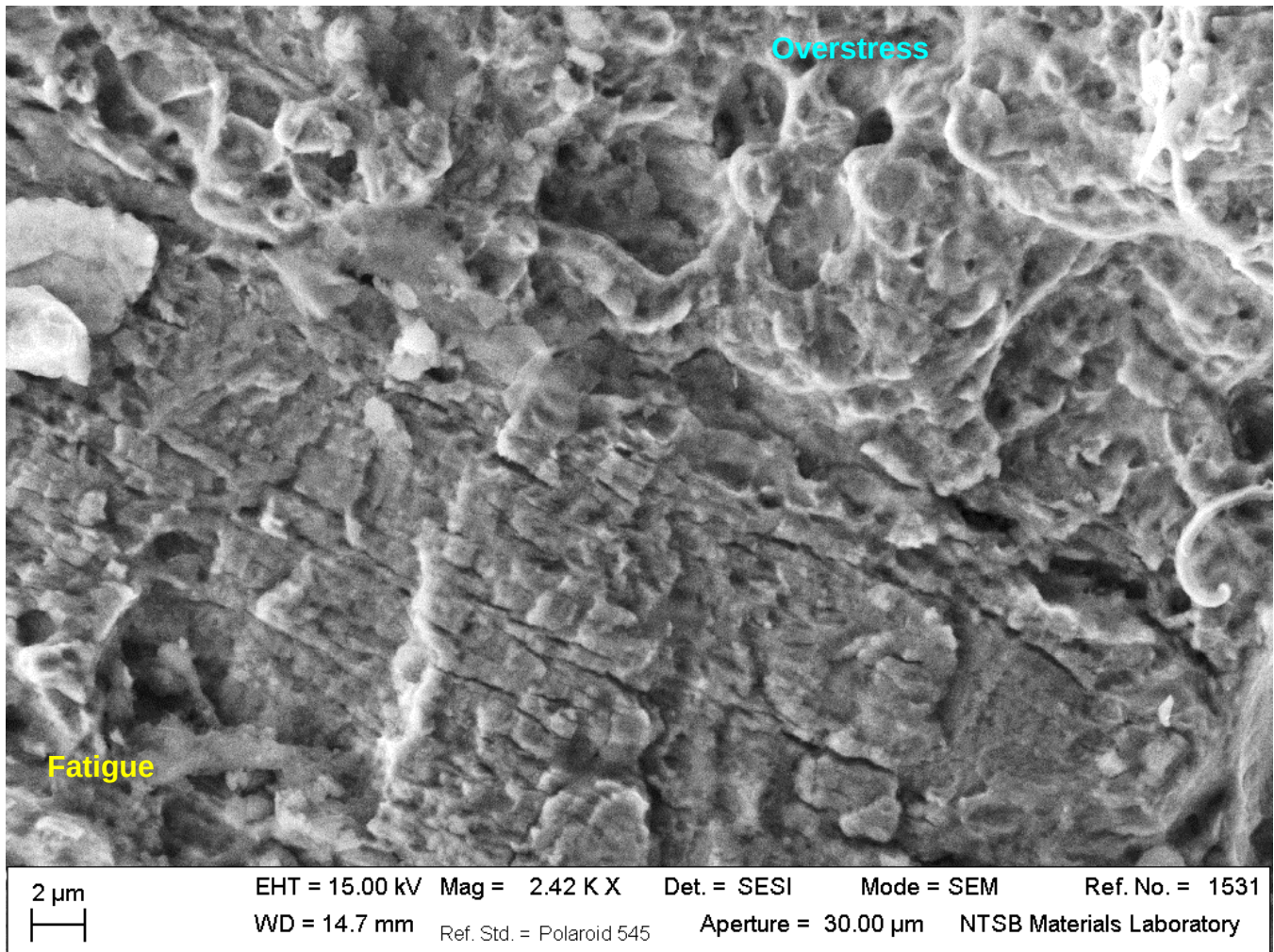


Figure 21 – SE micrograph of the end of the fatigue crack, showing striations.

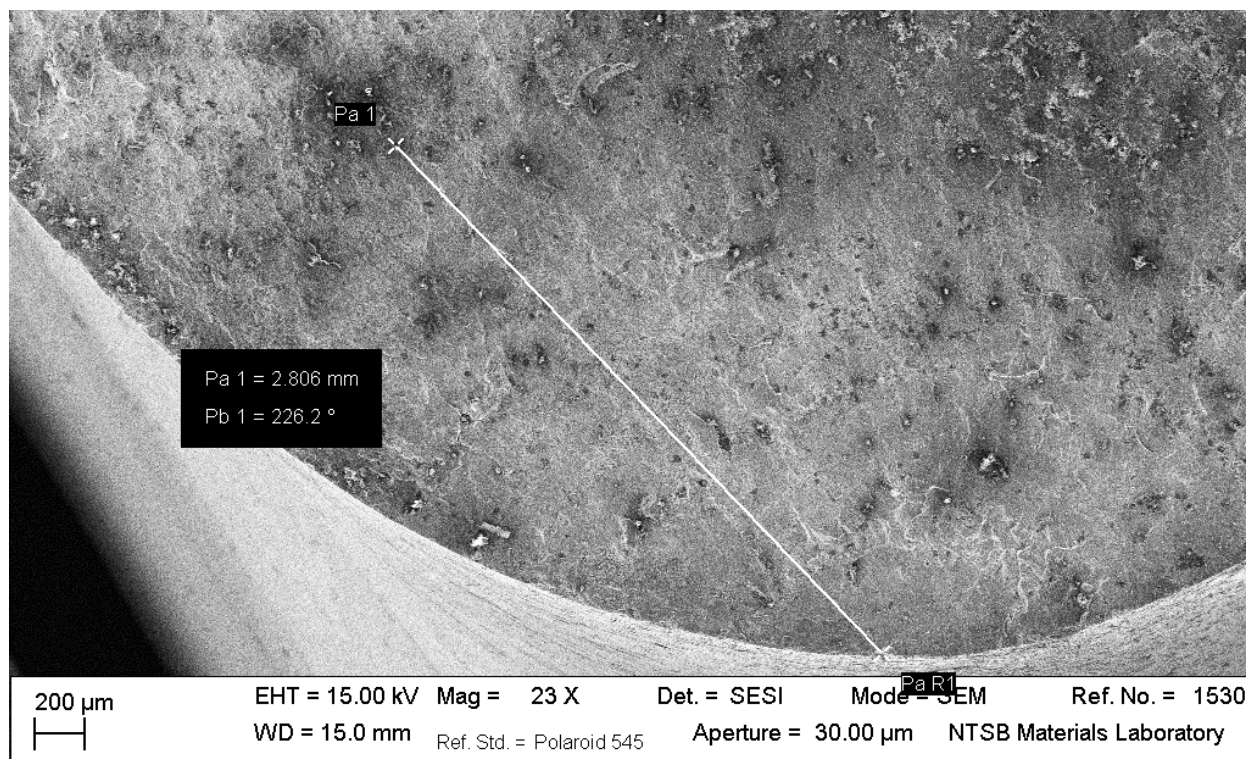


Figure 22 – SE micrograph showing the measured distance of the shorter side of the fatigue thumbnail crack.

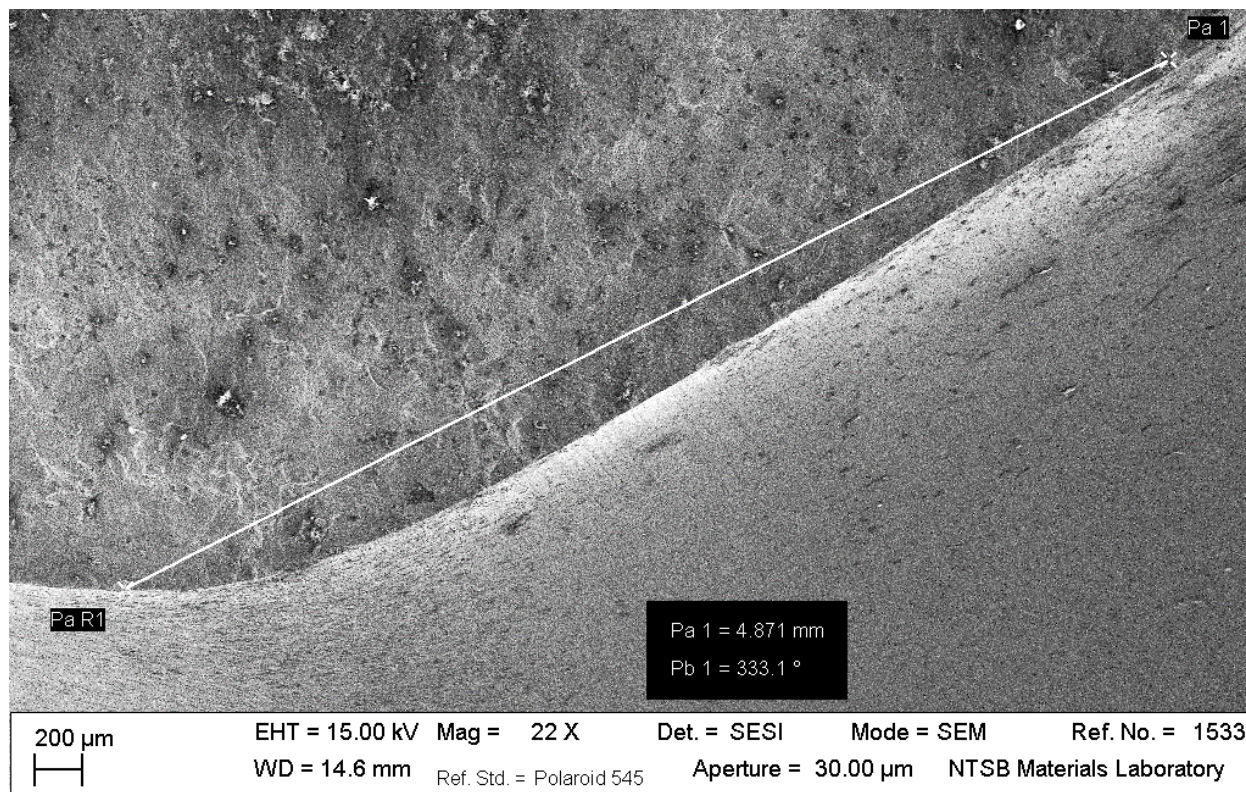


Figure 23 – SE micrograph of the thumbnail showing the extent of the fatigue cracking.

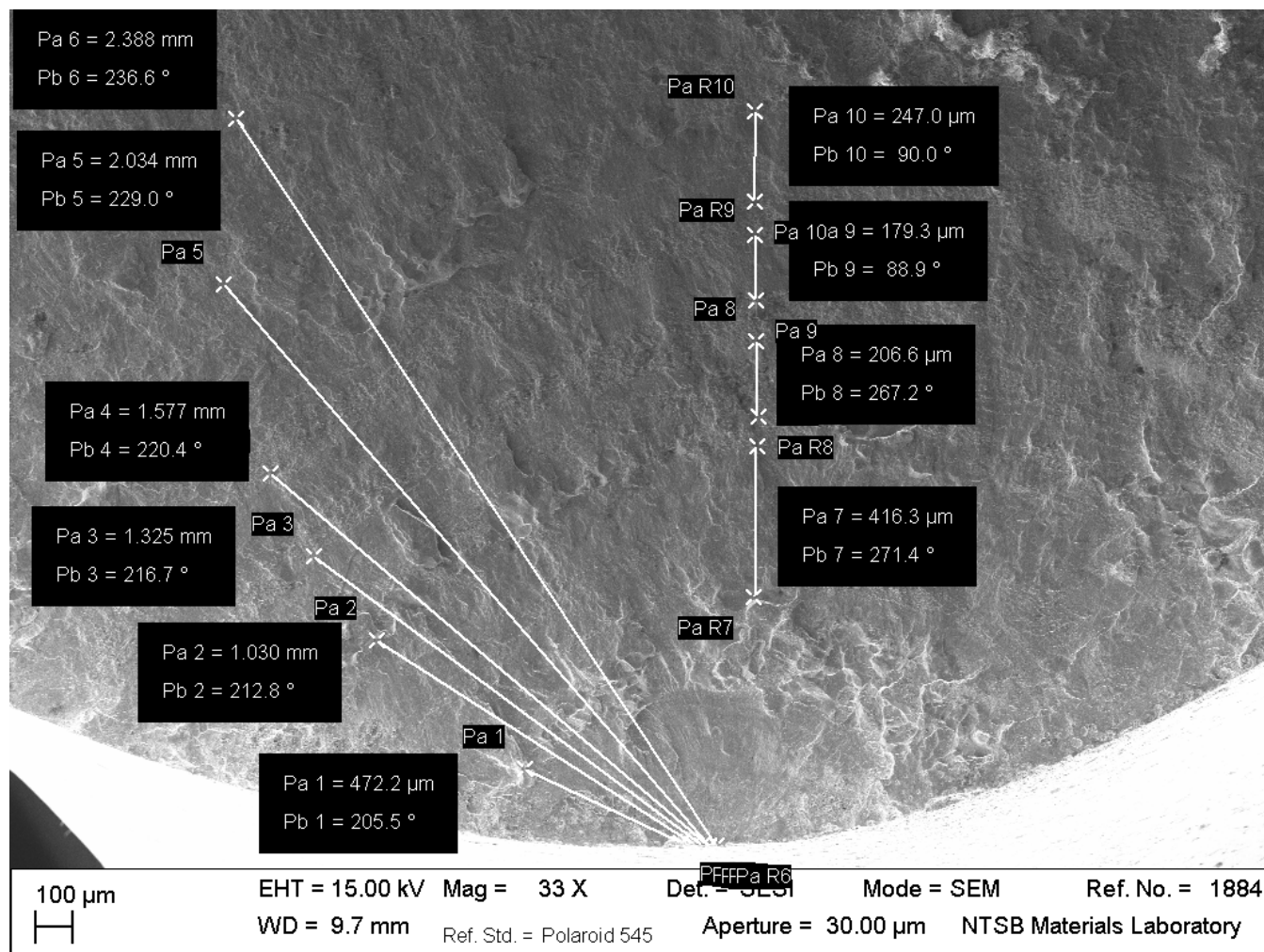
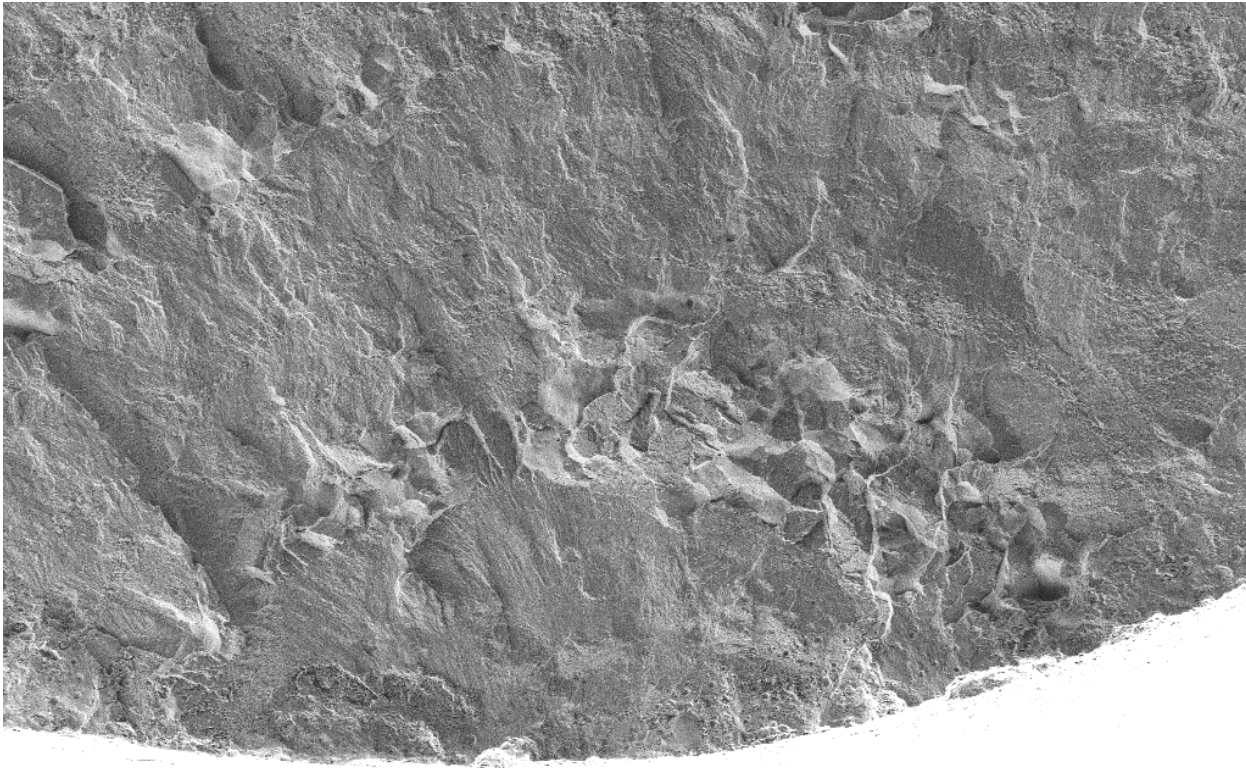


Figure 24 – SE micrograph showing the distances from the fatigue crack initiation site to the different failure mode bands (left side), and the depths of the secondary fatigue bands (right).



100 μ m	EHT = 15.00 kV	Mag = 59 X	Det. = SEI	Mode = SEM	Ref. No. = 1841
	WD = 5.1 mm	Ref. Std. = Polaroid 545	Aperture = 30.00 μ m	NTSB Materials Laboratory	

Figure 25 – SE micrograph highlighting the intergranular band on the fatigue fracture surface.

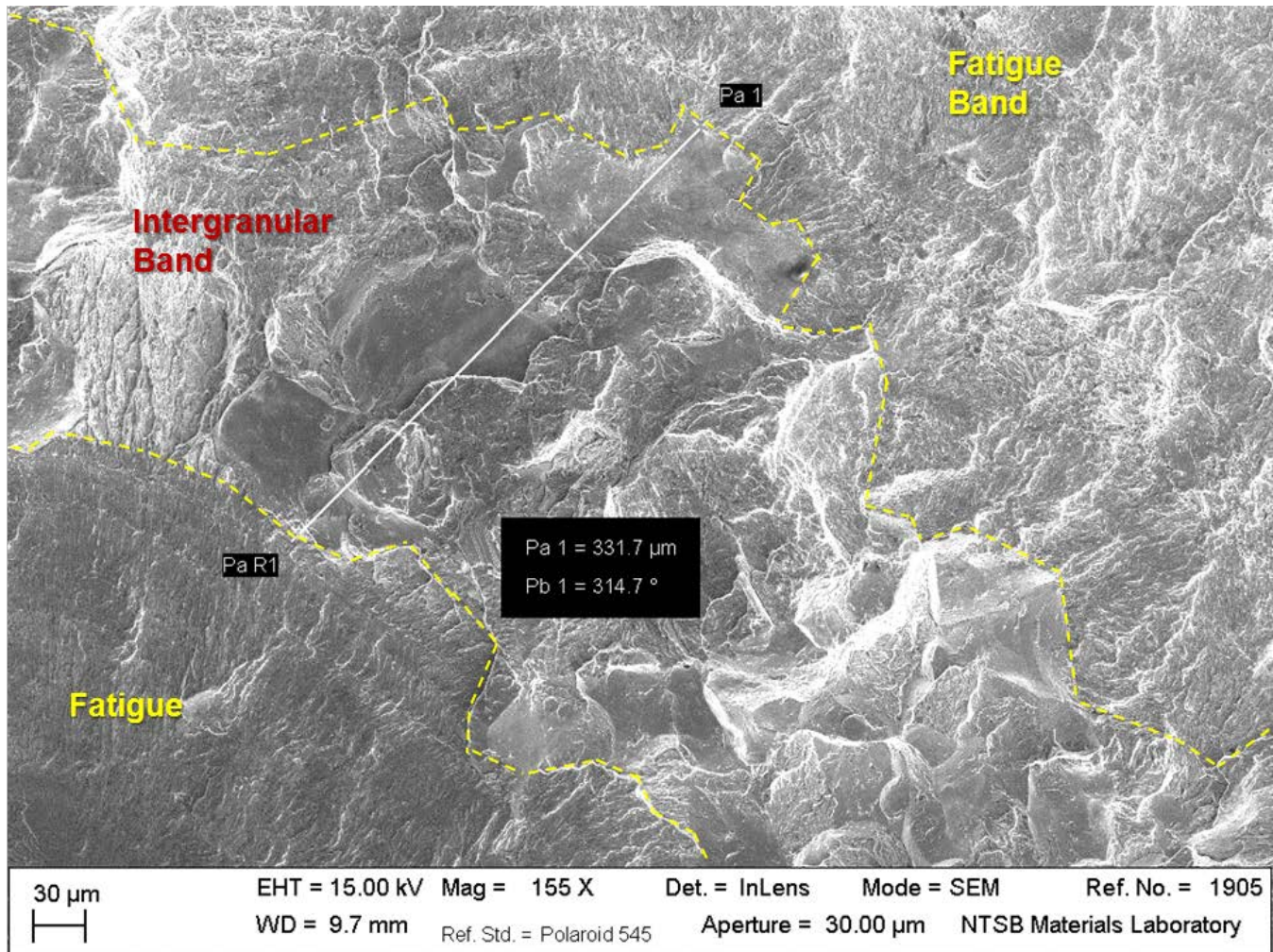


Figure 26 – SE micrograph showing the intergranular band on the landing gear fracture surface.

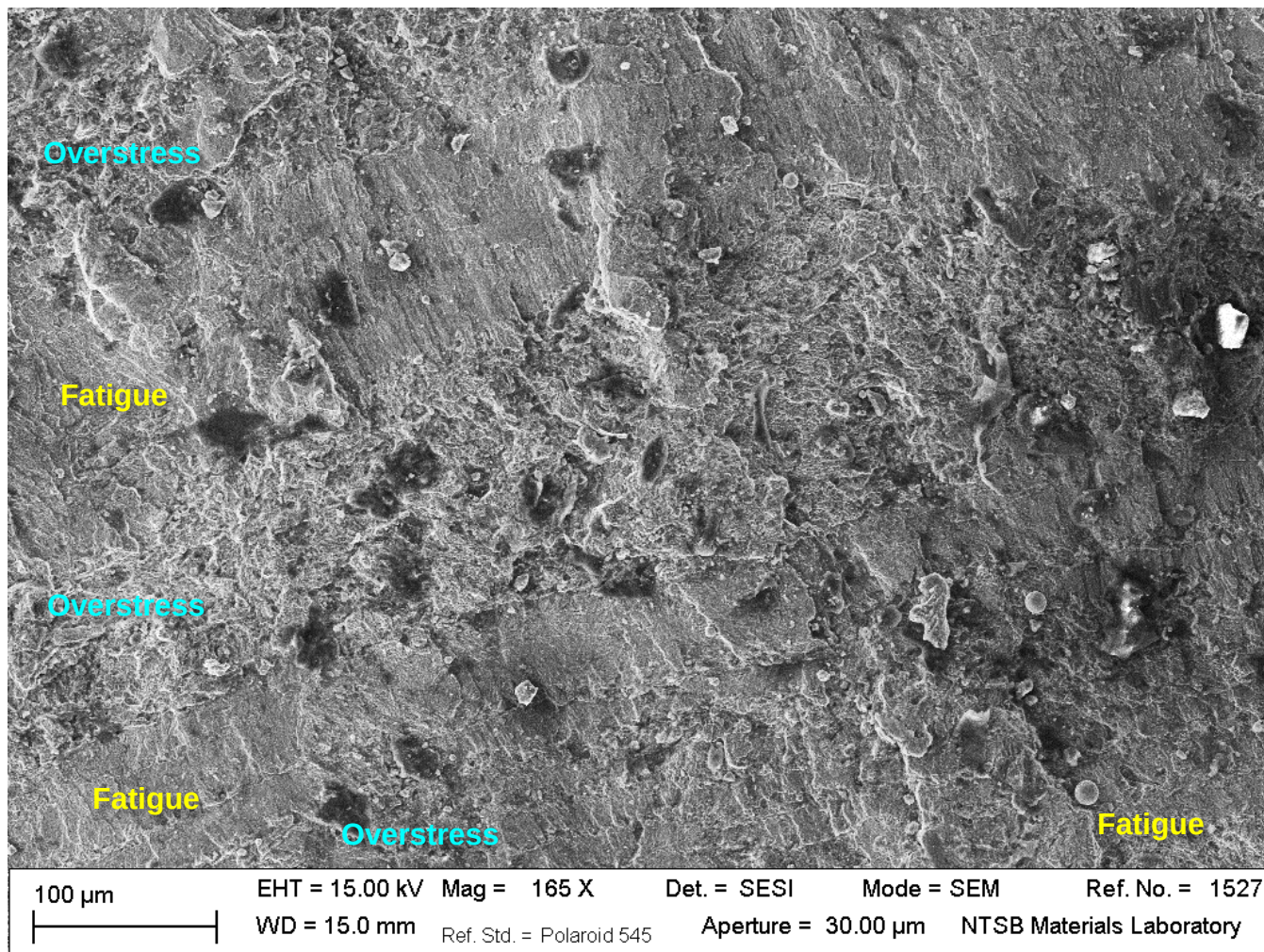


Figure 27 – SE micrograph showing intermittent overstress (dimple rupture) regions among fatigue crack growth.

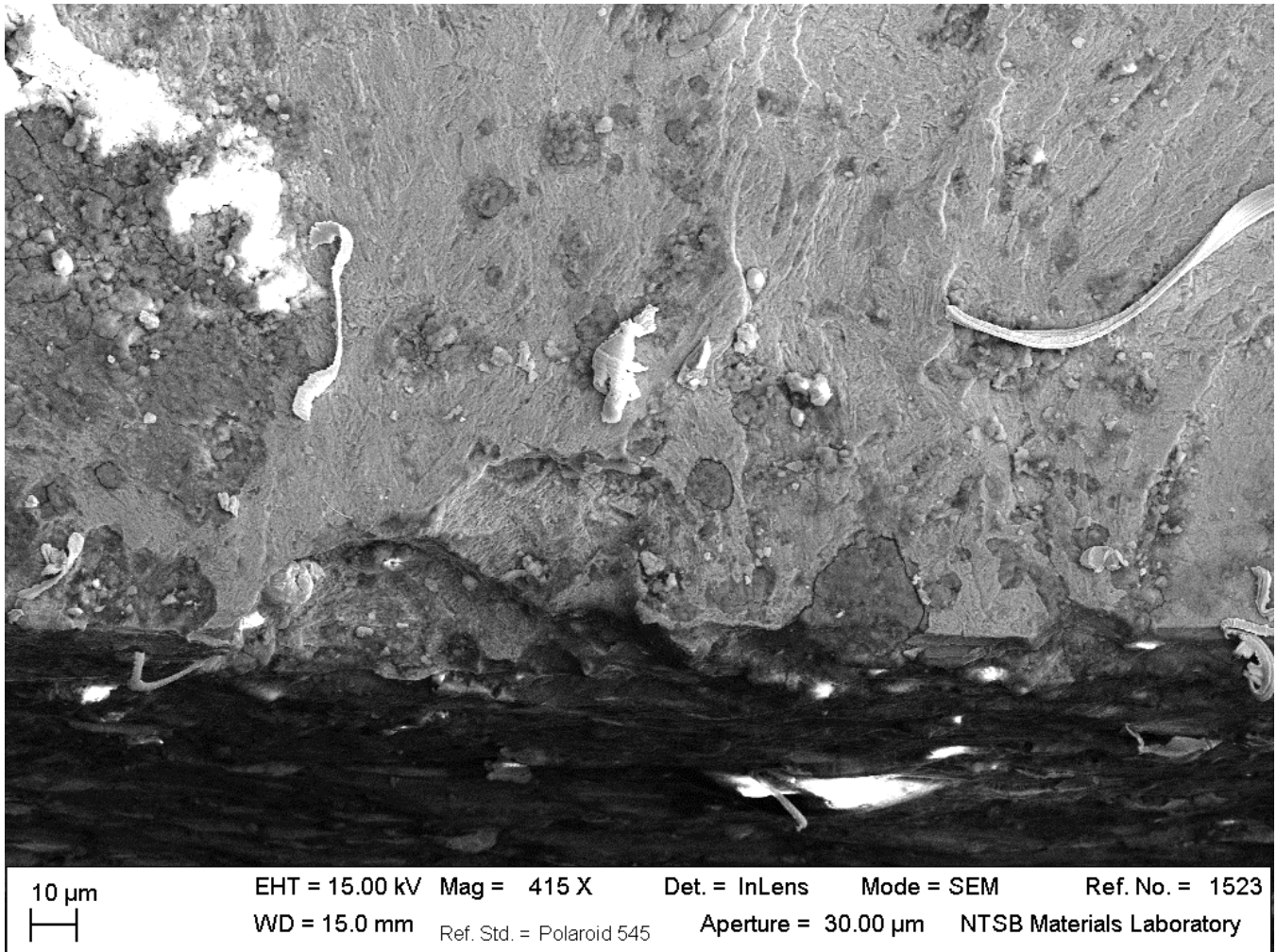


Figure 28 – Backscattered electron (BE) micrograph of the fatigue crack initiation site, showing a corrosion pit.

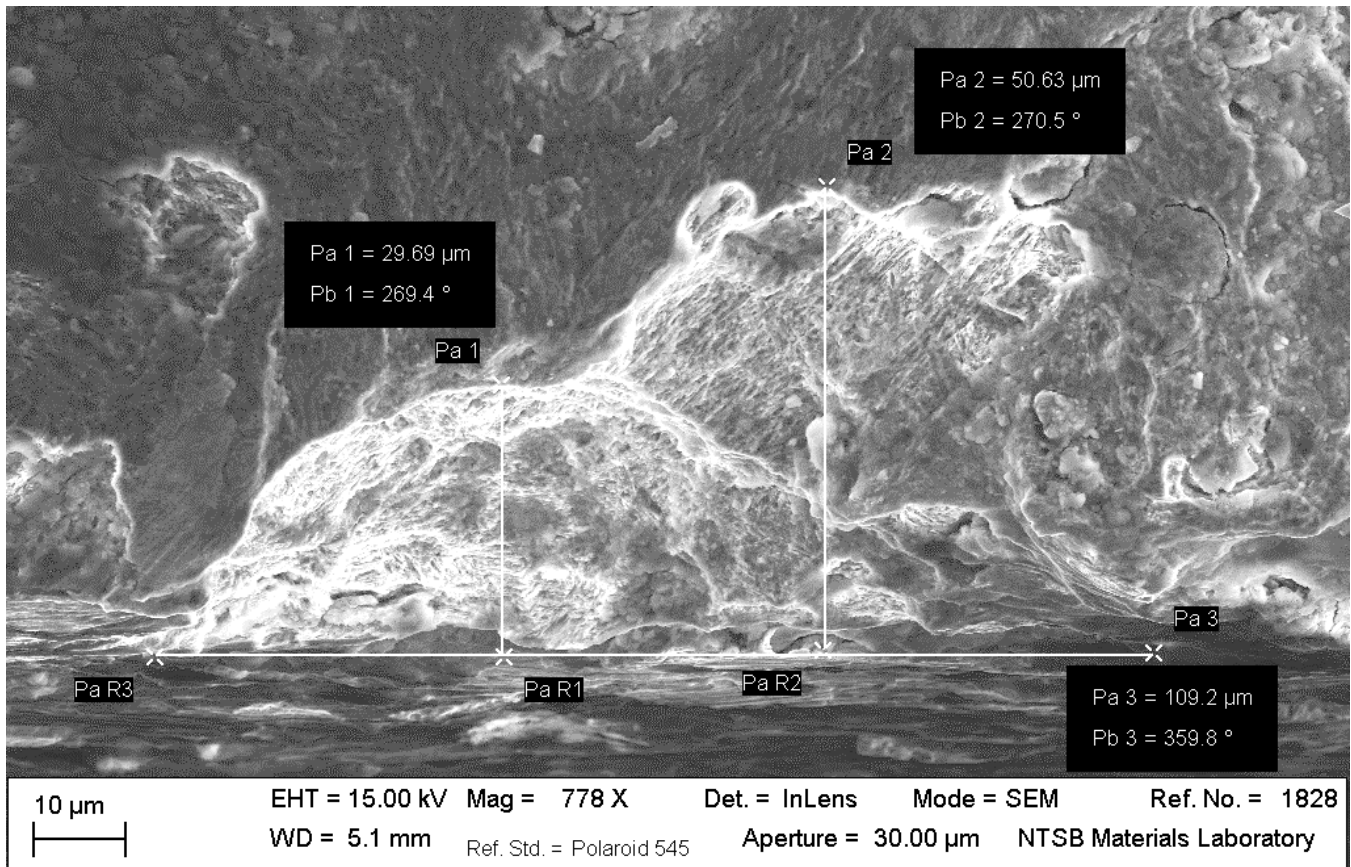


Figure 29 – SE micrograph of showing measurements of the corrosion pit in Figure 28.

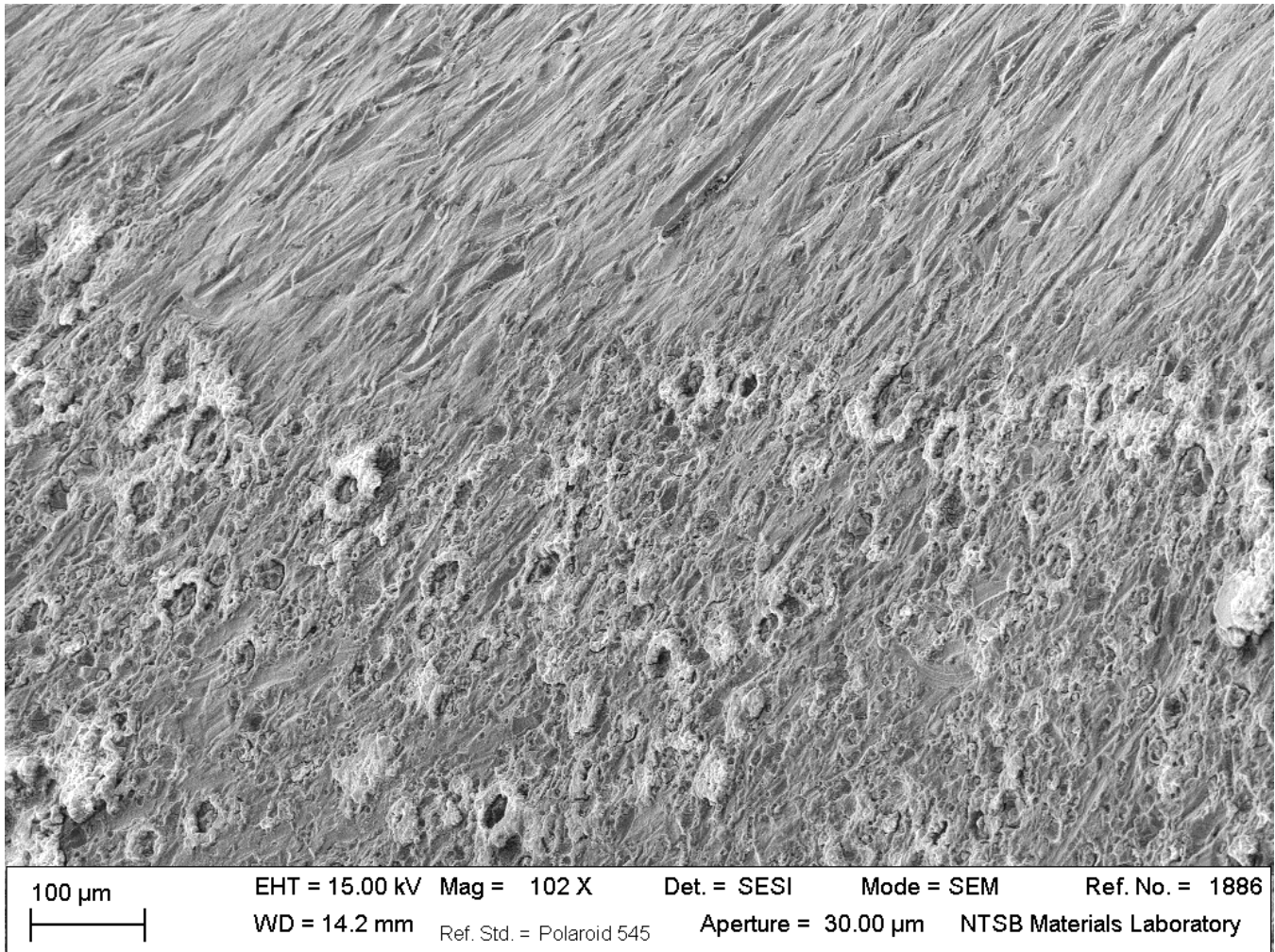


Figure 30 – SE micrographs showing colonies of corrosion pits at the radius of the bore.

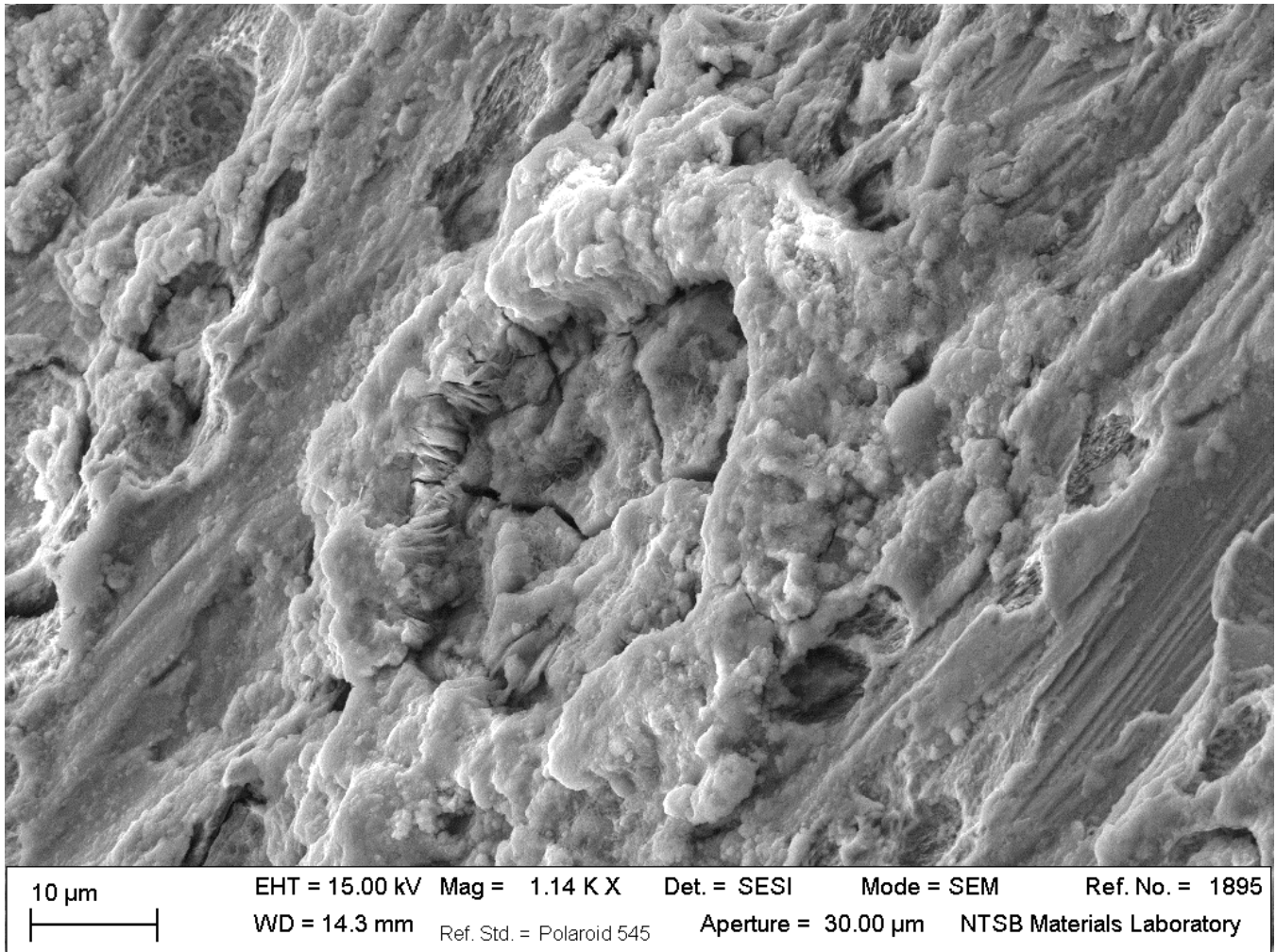


Figure 31 – SE micrograph showing a closer view of a corrosion pit on the valve bore.

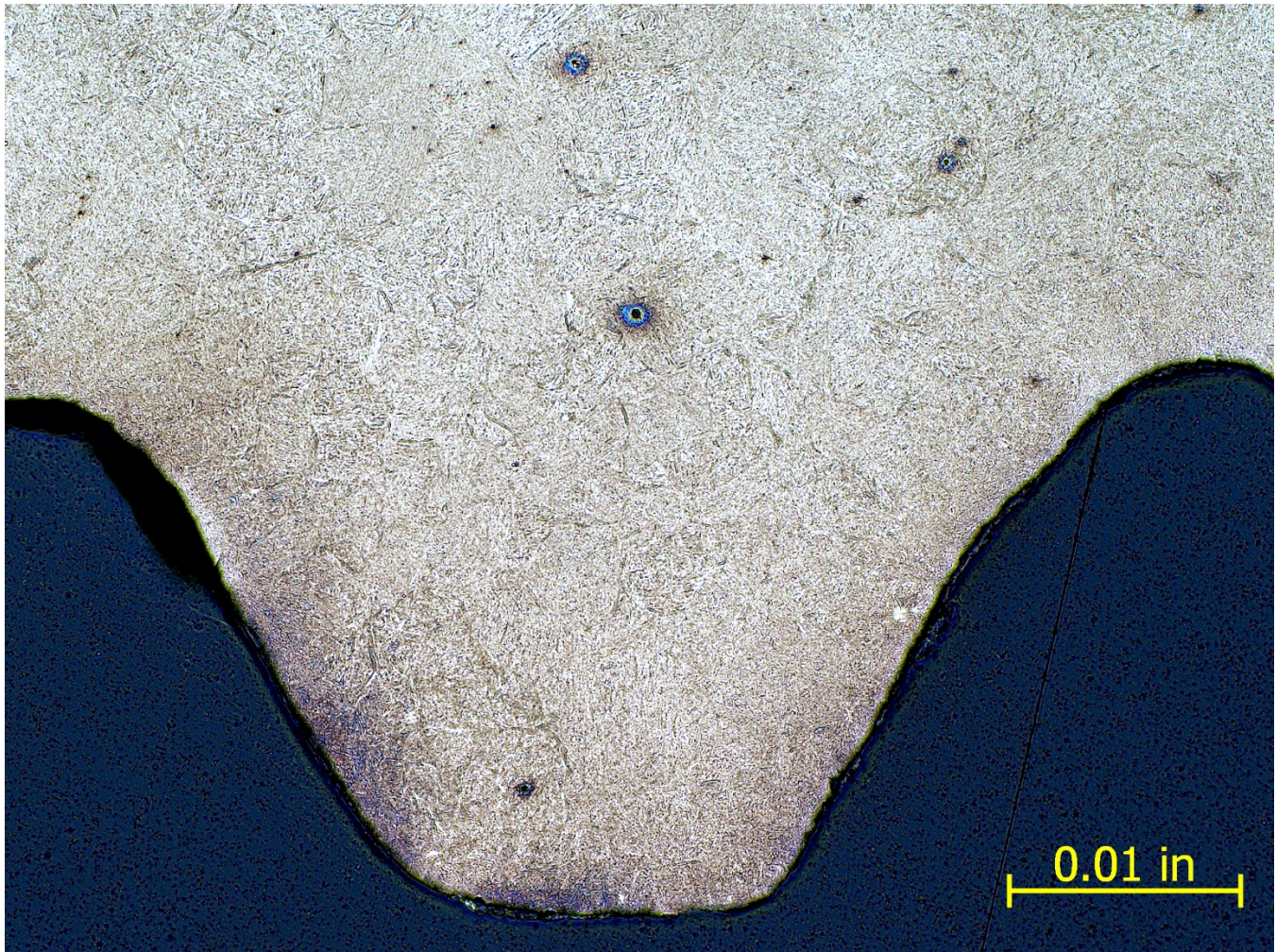


Figure 32 – Bright field micrograph of a cross-section of a thread root in the bore (~100X, etched 2% Nital).

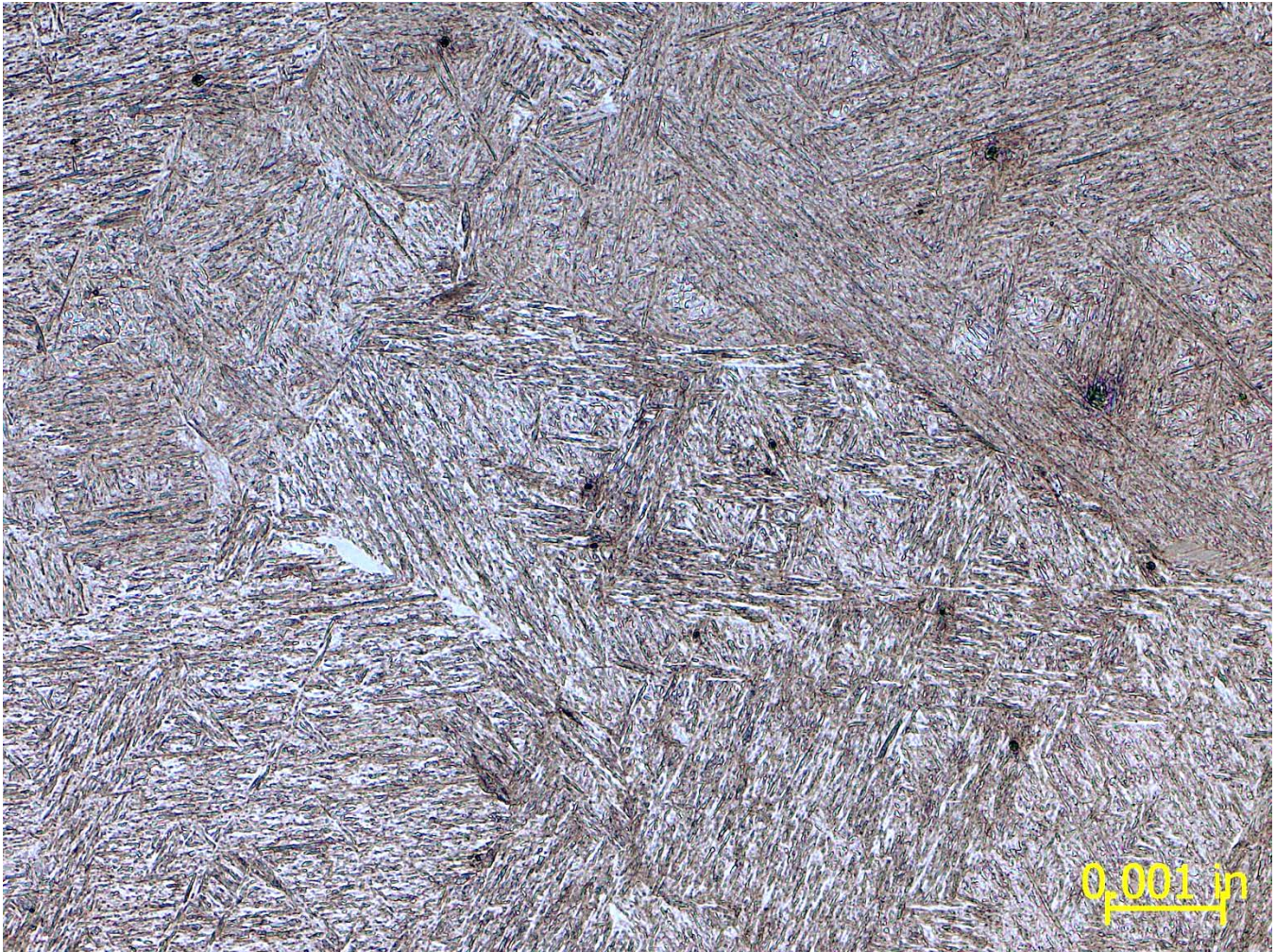


Figure 33 – Bright field micrograph showing the etched microstructure of the landing gear cross section, consistent with tempered martensite features (~500X, etched 2% Nital).

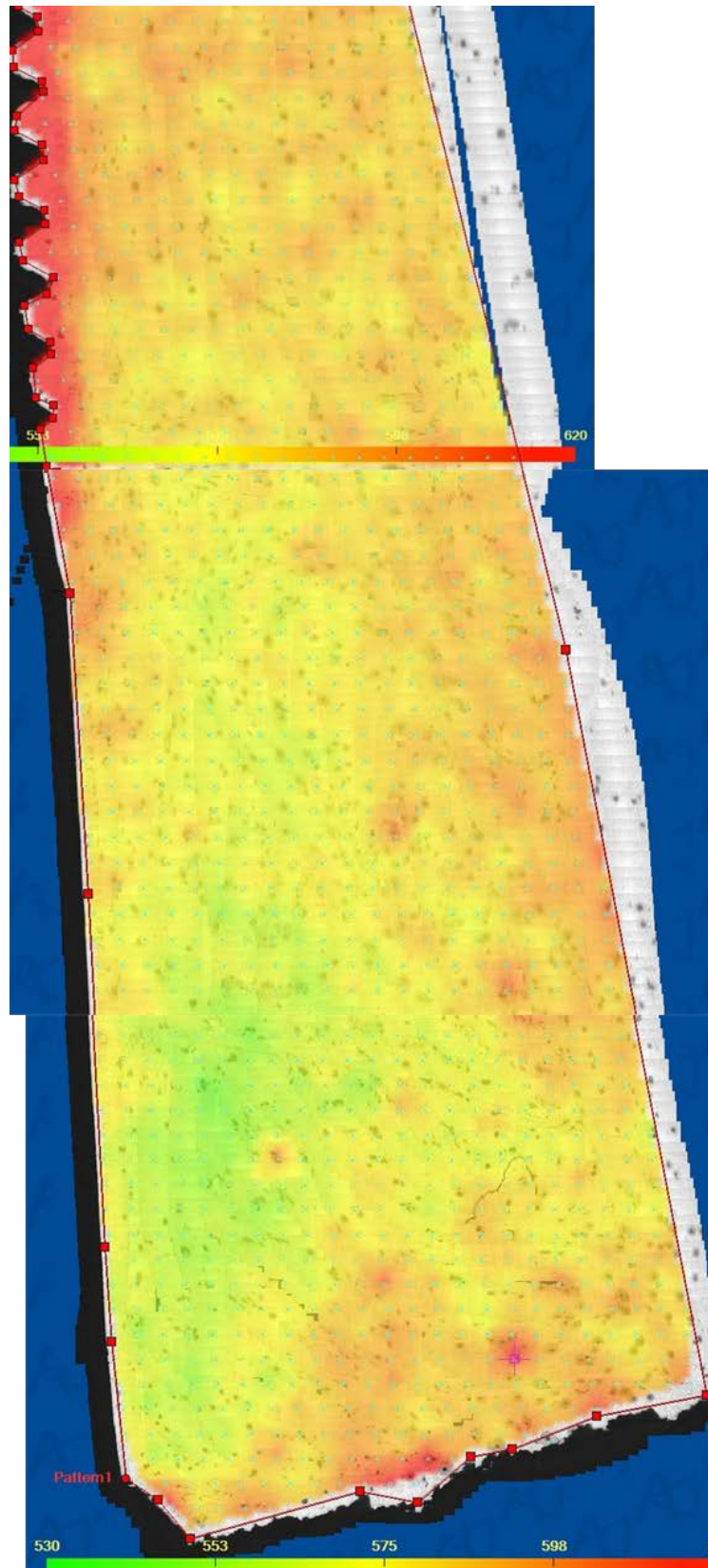


Figure 34 – False color microindentation hardness map of a cross-section of the material near the bore fracture surface. The hardness ranges from green, representing 52 HRC (530 HV₅₀₀), to red, 56 HRC (620 HV₅₀₀).