NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

September 7, 2018

MATERIALS LABORATORY FACTUAL REPORT

Report No. 18-028

A. ACCIDENT INFORMATION

Place	:	Oldenburg, Indiana
Date	:	December 16, 2017
Vehicle	:	Cessna T210M, N761YZ
NTSB No.	:	CEN18FA053
Investigator	:	Timothy Sorensen, ASI-CEN

B. COMPONENTS EXAMINED

Components from a Continental Motors TSIO-520-R9B engine (S/N: 269562):

1) Superior Air Parts cylinder at number 4 position – P/N: SAC52006-A1 F, S/N: 526-B07-4506;
2) Fractured Superior Air Parts piston at number 4 position – P/N: SA648044;
3) Superior Air Parts pistons at numbers 1-3, 5, and 6 positions – P/N: SA648044;
4) Upper spark plugs from numbers 1- 6 cylinders;
5) Lower spark plug from number 4 cylinder;
6) Piston pins from numbers 1-6 cylinders;
7) Multiple fractured piston pieces from number 4 piston;
8) Multiple fractured pieces of number 4 piston top compression ring;
9) Multiple fractured pieces of number 4 piston compression ring insert.

C. DETAILS OF THE EXAMINATION

The numbers 1 through 6 cylinder pistons, along with their corresponding upper spark plugs and pins, are shown in figures 1a through f, respectively, as they were received by the lab. A photo of the number 4 cylinder, as received, is shown in figure 2. A schematic cross section of the piston is shown in figure 3. Initial examination indicated that pieces of the number 4 piston, including the top land, top ring groove, top compression ring, and outer portion of the piston crown had separated from the piston body. This report details the findings from the examination of the piston and other cylinder assembly components. Before presenting the findings, background information is given on the fabrication of the piston.

1. Piston fabrication information

According to information provided by Superior Air Parts, the pistons were made by KS Pistões, a division of KS Kolbenschmidt GMBH, located in Nova Odessa, Brazil. The pistons were made from a cast aluminum alloy designated as KS 1275 (see below for chemical and mechanical properties of the accident piston material). KS 1275 is an aluminum/silicon eutectic casting alloy with additions of copper and magnesium, the composition of which is given in table 1.

The top compression ring sits in a groove that is made from an austenitic cast iron insert (Ni-Resist), as indicated in figure 3. According to information provided by Superior Air Parts, the insert is first cast as an oversized blank. The blank is machined into an intermediate shape, cleaned, dipped in molten aluminum, and placed in a mold. The molten aluminum is then cast around the insert. The insert (as well as the rest of the piston) is subsequently machined to form the groove for the top compression ring, as shown in figure 3.

According to the casting drawing, the pistons were to be labelled with the vendor identification (KS P), the part number (SA 648044), the word “SUPERIOR”, piston casting number (132701+R1), type of alloy (1275), and week/year of production. There were no week/year labels on the pistons at the location indicated by the drawing. Opposite of the location indicated on the drawing, the pistons were labelled 25 S 16, 25 S 16, 24 S 16, 25 S 16, 25 S 16, and 26 S 16 for pistons 1 through 6, respectively. Superior Air Parts stated that these labels were unlikely to be week/year production marks because KS Pistões did not produce any pistons for Superior Air Parts after 2005.

The corresponding number 4 cylinder was serialized with the number 526-B07-4506. Engine overhaul documentation from PennYan Aero in 2007 confirmed the installation of a Superior Air Parts cylinder kit (which includes a piston) with the same serial number. Superior Air Parts stated that the cylinder kit with that serial number would have included a piston from a lot produced in 2005.

2. Visual examination

As seen in figure 1d, figure 4a and figures 5a-d, the top land, outer region of the piston crown, top compression ring, and the Ni-Resist insert had separated from the rest of the piston around the entire perimeter. The fracture through the top of the piston was oriented at an approximately 53° angle to the crown, as indicated by the red dashed line on the schematic in figure 3 and as visible in the 90° rotating views in figures 5a-d. The piston top land region, insert, and top compression ring were all fractured into multiple pieces. The size and shape of the fragments were used to sort the pieces by component. The sorted insert fragments, piston fragments, and ring fragments are shown in figures 6a-c, respectively. An estimated 80% to 90% of the insert and piston material was recovered while approximately 70% of the ring was recovered.

The piston pieces exhibited features consistent with extensive impact damage after separation, as seen in figure 6b, to the point where few discernable features remained (machining marks, fractures surfaces, etc.). The few fracture surfaces that were identifiable were either smeared, covered with debris, or exhibited features consistent with overstress fractures. The crown region was visible on one piece, shown in figure 7, and exhibited discernable machining lines on the surface up to the beveled edge.

The insert and compression ring pieces were also fractured into multiple pieces, as seen in figures 6a and 6c, but did not exhibit the same extent of impact damage. The fracture surfaces of the insert and ring pieces were visually examined and all surfaces exhibited features consistent with overstress fractures.

The inclined fracture surface around the top of the piston was examined visually. Much of the surface was mechanically damaged or covered with deposits as seen in figure 8a. Occasional ratchet marks were observed around the perimeter of the piston fracture adjacent to the insert support material (back face) and a material lip was observed along the intersection of the inclined fracture with the crown, as seen in figure 8b. The features were consistent with the fracture originating at the insert recess upper transition radius from multiple origins and progressing toward the crown.

The piston skirt exhibited an approximately 2-inch wide by 1.3-inch high scuff mark on one side, as seen in figure 5b. There was a corresponding scuff mark on the interior cylinder wall, as seen in figure 9. For reference purposes, the piston and cylinder were assigned clock orientations as if viewing the assembled engine outboard looking inboard. In that orientation, the scuff marks were located between the 6:00 and 7:00 positions.

The region of the piston containing the scuff mark was sectioned from the rest of the piston and examined using a scanning electron microscope (SEM) equipped with an electron backscatter detector and an energy dispersive x-ray spectrometer (EDS). Images taken using the backscatter detector exhibit elemental contrast. Regions containing low atomic weight elements (such as aluminum) appear comparatively dark relative to regions containing high atomic weight elements (such as iron). A SEM backscatter image taken near the center of the scuff mark is shown in figure 10a. Light colored regions were observed that were smeared and elongated along the axial direction of the piston. One of the more discreet regions, indicated in the figure, was examined using EDS. The resulting spectrum is shown in figure 10b. The spectrum indicated the presence of an iron-based material transferred onto the surface of the piston.

Additional regions were examined in a similar manner. Iron-based material transfer marks were seen throughout the scuff mark. However, toward the top of the scuff mark, an additional copper peak was observed in many of the EDS spectra. Figure 11a shows a SEM backscatter image taken just below the oil control ring groove. An EDS spectrum from the area indicated in the figure is shown in figure 11b. The spectrum contained similar elements as the spectrum shown in figure 10b with the addition of a copper (Cu) peak at an X-ray energy of 8.04 keV.

Reference spectra of the insert material, cylinder wall, and top compression ring were collected using EDS and are shown in figures 12a-c, respectively. All three materials were iron-based. However, of the three, only the insert material exhibited a Cu peak and only the insert and cylinder wall materials exhibited a chromium (Cr) peak.

For reference purposes, the regions of the insert were referred to as the upper arm, vertical segment, and lower arm, as indicated in figure 3. The cast aluminum that was bonded to the insert was referred to as the support material. Along the perimeter of the piston, where the insert lower arm support material met the second (intermediate) land, the aluminum either exhibited a step along the edge or the outer edge was fractured, as shown in figures 13 and 14, respectively. The step was observed along two segments, one from approximately 11:00 to 1:00, and the other from approximately 6:00 to 7:00. The fractured edges were covered with lead deposits from approximately the 5:00 to 6:00 and 7:00 to 11:00 positions. Elsewhere, the fractures exhibited a rough appearance and multiple ratchet marks that were consistent with overstress fractures starting on the face of the lower support material, approximately 0.02 inch to 0.04 inch from the outer face of the piston and progressing radially outward and down (toward the piston skirt).

One area near the 7:00 position, near the transition from stepped to fractured edge, exhibited a region where the step became discontinuous as shown in figure 15. In the figure, the stepped regions are indicated by shading in the top photograph while the same image without the shading is shown in the bottom photograph. One region, at the edge of a stepped region exhibited a crack along the support material face as indicated in the top photograph.

The insert vertical segment support material was covered by lead deposits from approximately the 4:30 position proceeding clockwise to the 11:00 position. See figure 8a (6:00 position) and 8b (3:00 position) for regions with and without lead deposits on the vertical support material and the fractures along the lower support edge, respectively. The lead deposits had been rubbed away exposing discreet regions of the underlying support material. Those discreet regions exhibited a rubbed appearance, as seen in figure 16.

3. Examination of the other pistons

The crowns for the five remaining pistons are shown in figures 17a – e for cylinders 1, 2, 3, 5, and 6, respectively. The piston crowns were comparatively clean. The crowns on pistons 1, 2, 5, and 6 exhibited a thin intermittent layer of residue with a cream-colored appearance in spots. Piston 3 opposite of piston 4 exhibited a pitted appearance similar to that observed on the piston 4 crown, consistent with impact damage.

The top compression ring inserts and the aluminum material cast around them were examined by sectioning the pistons in two in the radial/circumferential plane through the ring groove using a band saw. The sectioned crown and top land regions are shown in figure 18 after removal of the insert pieces. The insert pieces were removed using a hammer and chisel. The chisel was placed along the insert/aluminum interface and the two materials were mechanically separated by striking the chisel with a hammer, moving the chisel along the interface as it separated. The first insert piece removed, on piston 2, was done so without cutting the insert but due to the difficulty, subsequent insert pieces were removed by first radially cutting through the insert in two or three places and starting the chisel at one of the cuts.

Visual examination of the aluminum backing material indicated that none of the other pistons exhibited the step that was observed along the edge of the lower insert support material, as shown in figure 19 for a typical region on piston 3. Nor did any of the pistons exhibit any deposits on the support material. A notable feature was observed on the upper insert support material for piston 5 as shown in figure 20. Two regions were observed where aluminum had separated with the insert piece revealing regions of dark particles embedded in the aluminum. Scanning electron microscopy (SEM) and energy dispersive spectroscopy indicated the presence of molybdenum (Mo). However, none of the other pistons, including piston 4 exhibited any similar features.

The exposed aluminum support material for pistons 1, 2, 3, 5, and 6 were cleaned and then examined for cracks using a fluorescent penetrant dye using standard laboratory procedures. One region on the piston 3 upper support material exhibited visible fluorescence along a radially aligned feature, which is shown in figure 21. The piston top was sent to an external laboratory and the feature examined using X-ray computed tomography but there were no sub-surface findings.

4. Material properties and microstructure

The hardness of the number 4 piston was evaluated using a Brinell hardness tester equipped with a 10 mm diameter tungsten carbide ball, a 3,000 kgf force, and a 30 s dwell time. The piston was prepared for the test by sectioning the top of the piston through the third ring groove using an abrasive cutting saw, which separated the top of the piston from the skirt. The cut face was lightly ground by hand using abrasive silicon carbide papers in order to remove the abrasive saw cutting marks. The cut face was placed face-up in the hardness tester and three indentation tests were performed. The diameters of the residual impressions were measured using a calibrated digital optical microscope. Three points along the perimeter of the impression were used to fit a circle to the impression and the diameter of each circle was recorded. The circle diameters were 0.230 inch, 0.240 inch, and 0.231 inch, corresponding to Brinell hardness values of 101 HBW 10/3000, 92 HBW 10/3000, and 100 HBW 10/3000, respectively. The hardness values were in conformance with the material requirement for KS 1275.

The chemical composition of the piston material was evaluated by an external laboratory using inductively coupled plasma optical emission spectrometry (ICP-OES). A slice of the piston top, taken between the second and third ring grooves near the 12:00 position was sectioned from the rest of the piston top using an abrasive cutting wheel and sent to the test lab. The silicon concentration was 10.16% and was below the minimum concentration requirement of 11.0%.

A second sample was cut from the crown region of the piston near the 12:00 position and sent to the same laboratory for a second check of the chemical composition. For the second sample, all elements, including silicon, met the chemical composition requirements.

The material microstructure for the number 4 and number 3 pistons were evaluated on metallurgical cross sections through the lower insert support material. Pieces of the numbers 4 and 3 pistons were sectioned in the radial/axial plane using a water-cooled abrasive cutting saw. The cut faces were placed face down in a mounting press and mounted in a diallyl phthalate resin. The mounted samples were ground and polished through a series of silicon carbide papers, diamond suspensions, and colloidal silica suspension in accordance with standard laboratory procedures. A mosaic image of the number 4 piston cross section is shown in figure 22 for reference. The insert support material for the insert lower face and back face are indicated in the figure. Also indicated is the location of a higher magnification image at the intersection of the lower support material and the outer face of the piston that is shown in figure 23a.

Figures 23a and b show the morphology and microstructure of the cast aluminum material at the edge where the lower support material met the outer face of the piston for the numbers 4 and 3 pistons respectively. The step near the edge for the number 4 piston is viewed in cross section in figure 23a. The step height was approximately 100 µm (0.004 inch). Both pistons exhibited a typical cast microstructure with interspersed segregated aluminum and silicon regions. Near the aluminum/insert interface, the cast aluminum alloy exhibited multiple crack-like/porosity features on both cross sections. For the number 4 piston, this band extended approximately 150 µm (0.006 inch) and for the number 3 piston, this band extended approximately 200 µm (0.008 inch) from the interface.

5. Dimensional measurements

The piston pin hole position on the number 4 piston, relative to the center of the piston, was measured using a metrology table and a digital height gauge (prior to any destructive testing). The piston pin was inserted through the pin hole. The piston was then set on its side, supported to prevent movement, and then lightly clamped against the table. The digital height gauge was used to measure the piston pin height (on the cylindrical section, relative to the table top) on each end of the pin and the piston was adjusted until the pin heights were within 0.04 mm or less of one another. The average pin height position was recorded. The height gage was then used to measure the skirt height. The piston was unclamped, rotated 180 degrees, and the procedure repeated. In this way the piston pin heights and skirt heights at the 12:00 and 6:00 positions were measured. On one side the pin height and skirt height measurements were 21.65 mm and 30.64 mm (arbitrary to the zero point of the height gauge) for a difference of 8.99 mm. On the other side, the pin height and skirt height measurements were 21.73 mm and 30.69 mm for a difference of 8.96 mm. The height differences differed by 0.03 mm (0.001 inch) indicating that the pin hole was less than 0.001 inch from the mid-plane of the piston, in accordance with the engineering drawing requirements.

The ring gap in the number 4 cylinder was checked using the top ring from the number 2 piston.[1] The ring was compressed, placed inside the cylinder barrel, and pushed approximately 6 inch into the barrel using a piston as a guide so that the plane of the ring was nominally perpendicular to the axis of the cylinder bore. A set of feeler gauges was then used to estimate the ring gap. A 0.025-inch gauge passed through the

[1] The cylinder bore was wiped with a towel but otherwise not cleaned and exhibited scrape marks between the 6:00 and 7:00 positions due to contact with piston skirt. Therefore, the ring gap measurement is an approximate measurement and is for information purposes only.

ring gap while a 0.028-inch gauge did not. The allowable ring gap range was 0.028 inch to 0.044 inch according to the manufacturer.

6. Spark plugs examination and measurements

The spark plugs from the top position on the numbers 1 through 6 cylinders and the spark plug from the bottom position on the number 4 cylinder were examined visually and the continuity of the spark plug electrodes was examined with the assistance of an ohmmeter. The tips of the top spark plugs are shown in figure 24 and are labelled 1T through 6T for the numbers 1 through 6 cylinders, respectively. The bottom position spark plug from the number 4 cylinder is shown in figures 25a and b. None of the tips exhibited any pitting or erosion. None of the insulators exhibited cracking. However, the 4T and 4B spark plug ground and center electrodes were deformed.

The electrical continuity of the electrodes was measured using an ohmmeter set to a range of 20 kΩ. One lead was placed in contact with the center electrode from the terminal end. The other lead was placed in contact with either the center electrode or ground electrode at the spark end. The resistance readings for all of the center electrodes ranged from 0.98 Ω to 1.07 Ω. The resistance reading for the 1T, 2T, 3T, 5T, and 6T ground electrodes was infinity (∞), while the resistance reading was 1.05 Ω the 4T ground electrode and 2.28 Ω for the 4B ground electrode, consistent with the mechanical damage to those electrodes.

Donald Kramer, Ph.D.
Sr. Materials Engineer

Table 1: Chemical composition requirements for the KS 1275 aluminum alloy used to cast the aluminum pistons.

Element	Composition (weight percent)
Silicon (Si)	11.0 – 13.0
Copper (Cu)	0.8 – 1.5
Magnesium (Mg)	0.8 – 1.3
Nickel (Ni)	< 1.3
Iron (Fe)	< 0.7
Titanium (Ti)	< 0.2
Manganese (Mn)	< 0.3
Zinc (Zn)	< 0.3
Aluminum (Al)	Rest

a)

b)

Figure 1: a) Image of the number 1 cylinder piston, piston pin, and upper spark plug; b) image of the number 2 cylinder piston, piston pin, and upper spark plug;

c)

d)

Figure 1 (cont.): c) image of the number 3 cylinder piston, piston pin, and upper spark plug; d) image of the number 4 cylinder piston, piston pin, upper spark plug, and bag containing piston, insert, and ring fragments;

e)
f)

Figure 1 (cont.): e) image of the number 5 cylinder piston, piston pin, and upper spark plug; and f) image of the number 6 cylinder piston, piston pin, and upper spark plug.

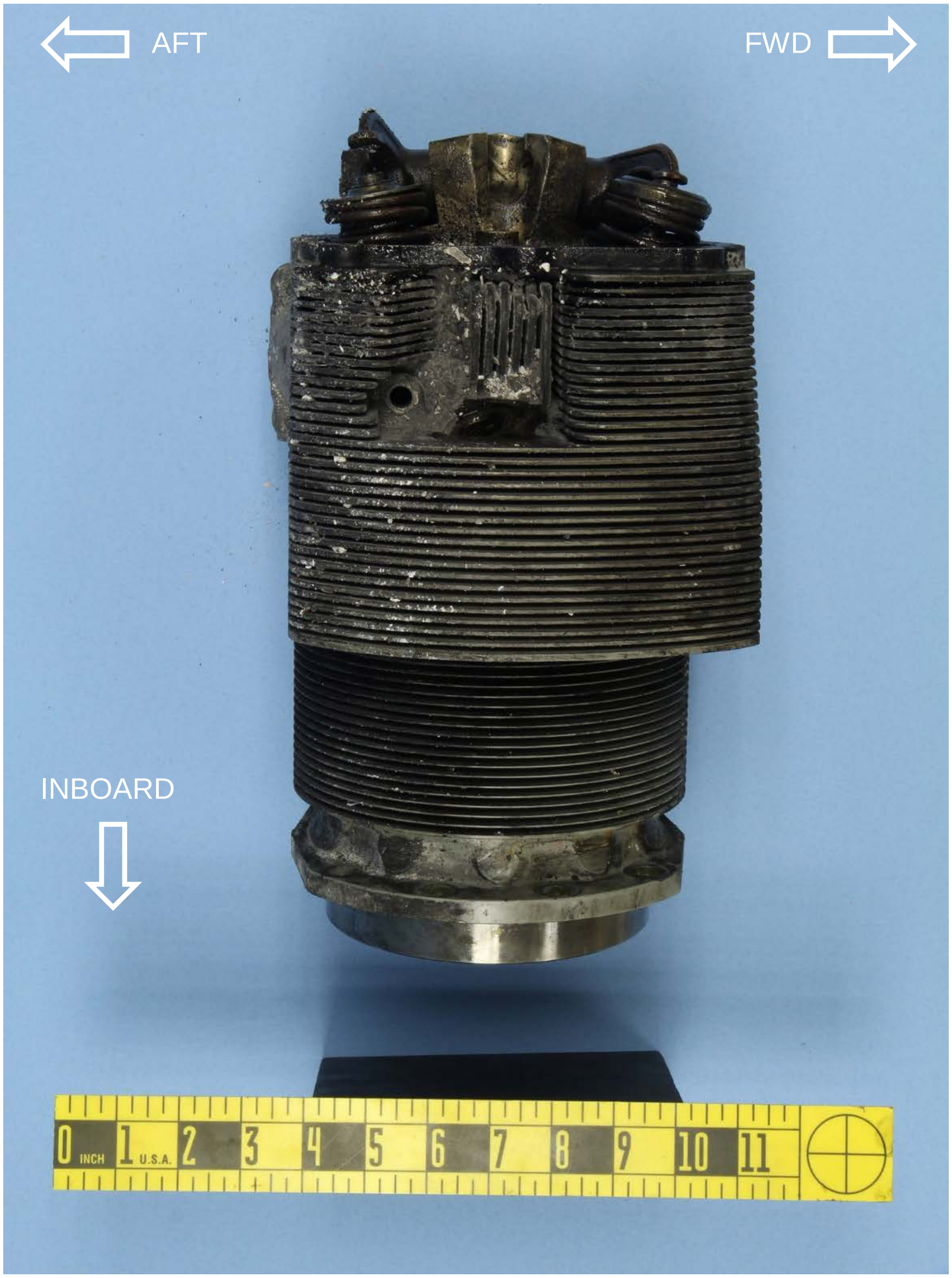


Figure 2: Image of the number 4 cylinder viewed from the top down as installed on the engine.

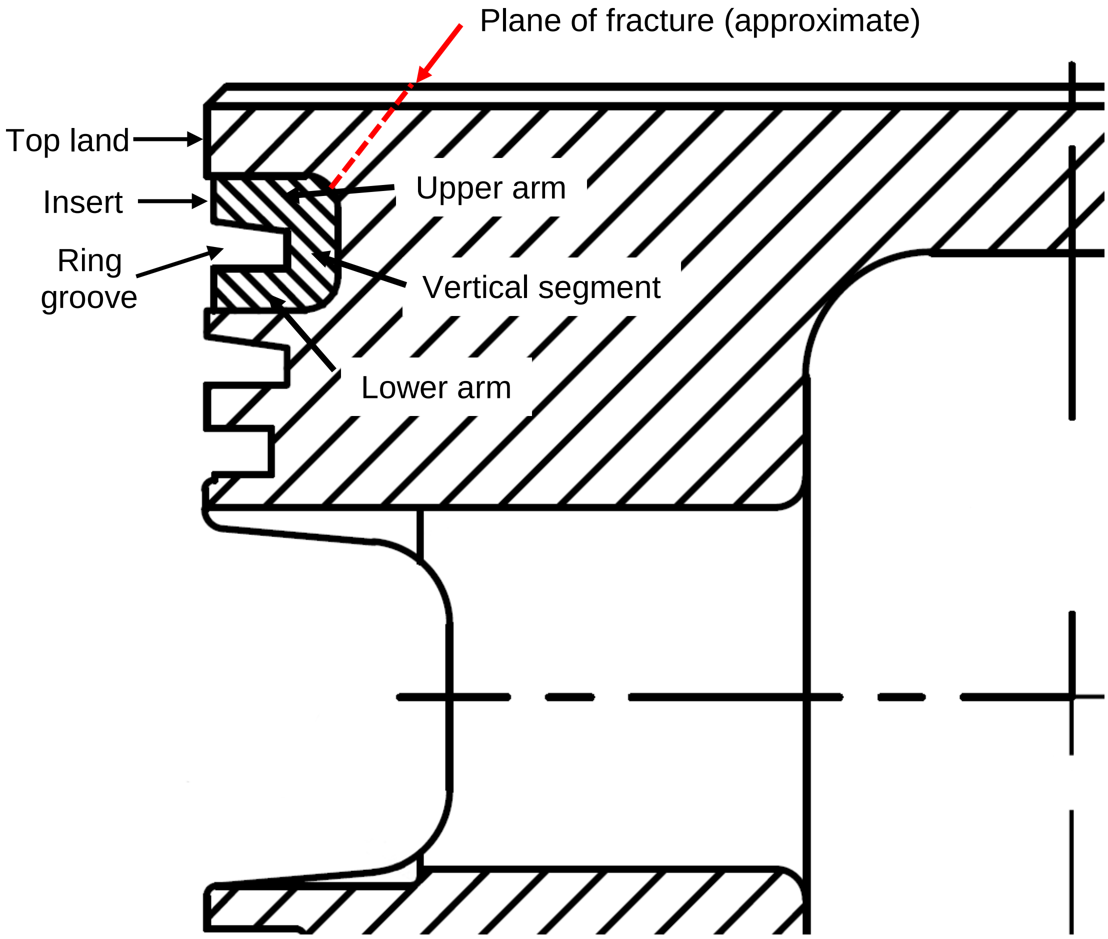
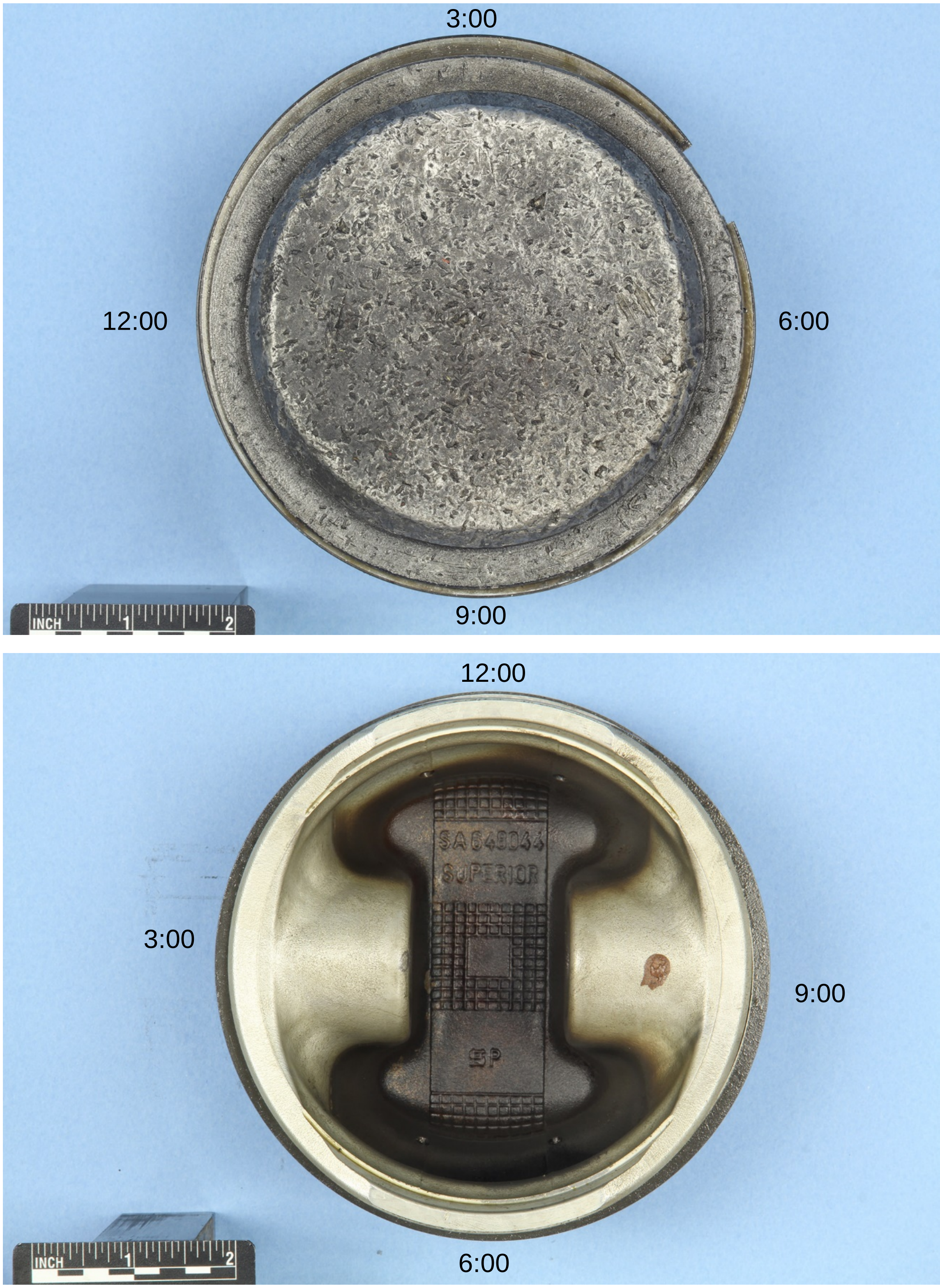


Figure 3: Schematic cross section of the Superior Air Parts SA648044 piston (not to scale).



a)

b)

Figure 4: a) Crown side of the number 4 piston and b) underside of the number 4 piston.

a)

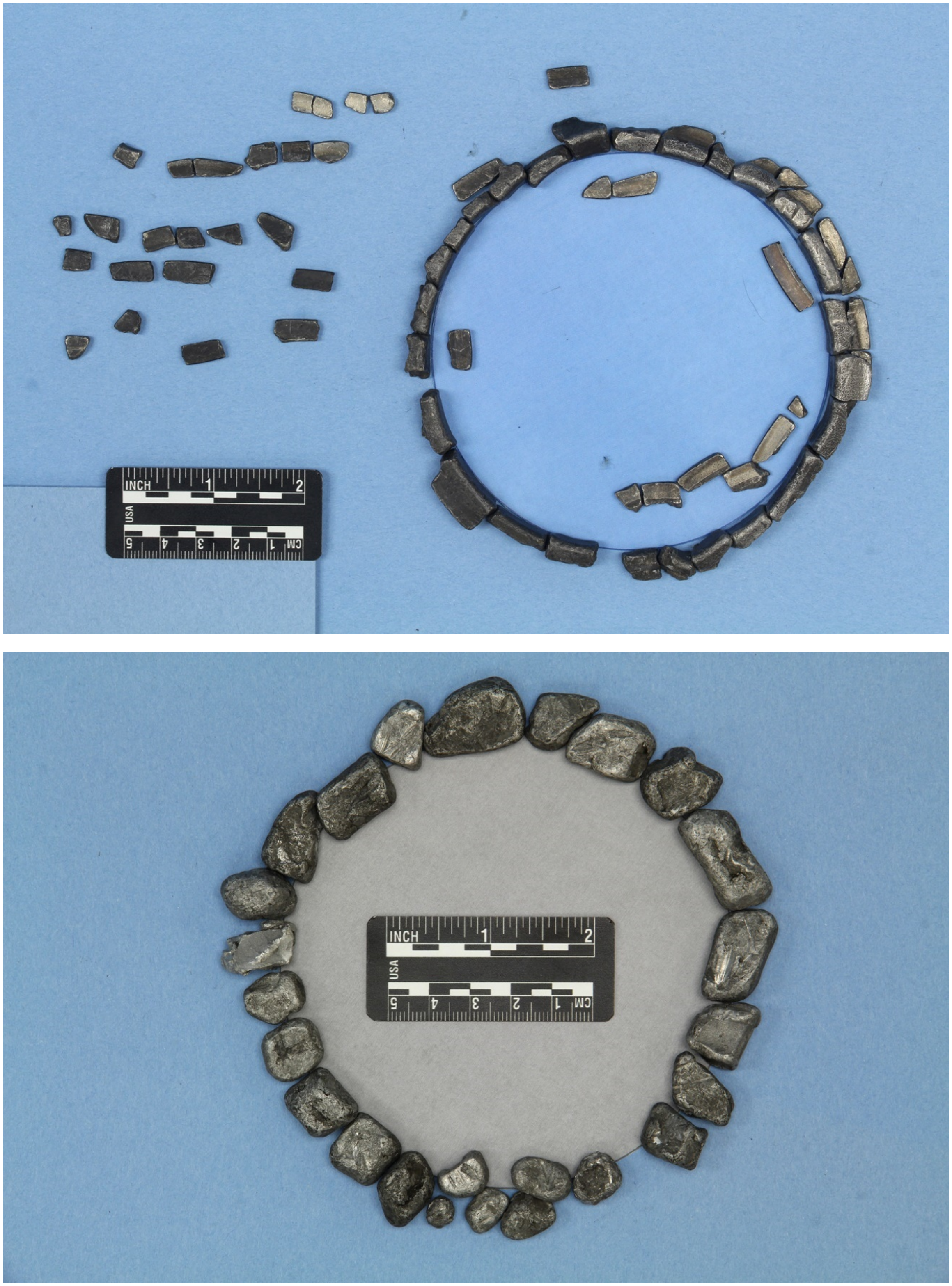
b)

Figure 5: Side view images of the number 4 piston: a) 9:00 position; b) 6:00 position;

c) 

d) 

Figure 5 (cont.): c) 3:00 position; and d) 12:00 position.



a)

b)

Figure 6: a) Pieces of the top ring insert. An estimated 80% to 90% of the insert was recovered; b) pieces of the piston from the top land/crown region. An estimated 80% to 90% of the top land/crown material was recovered.

c) 

Figure 6 (cont.): c) Recovered pieces of the top compression ring. Approximately 70% of the ring was recovered.

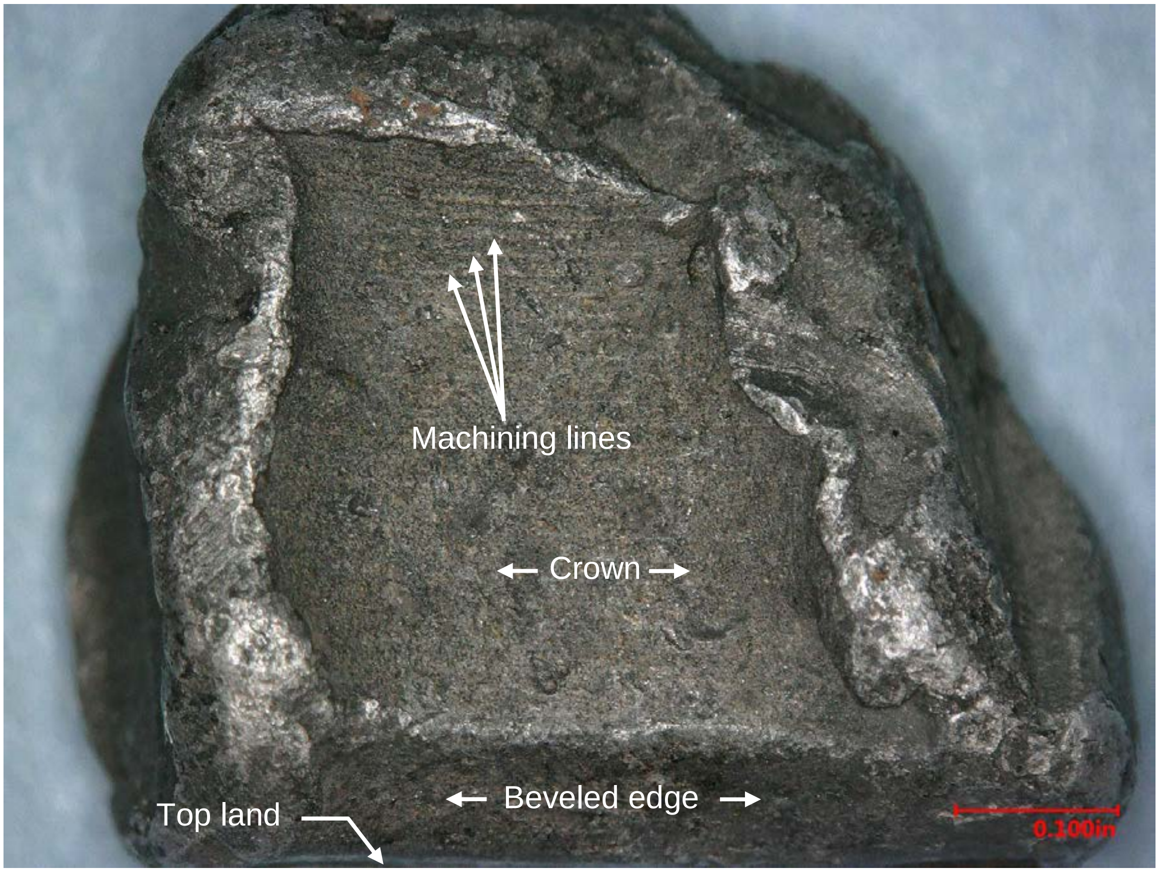
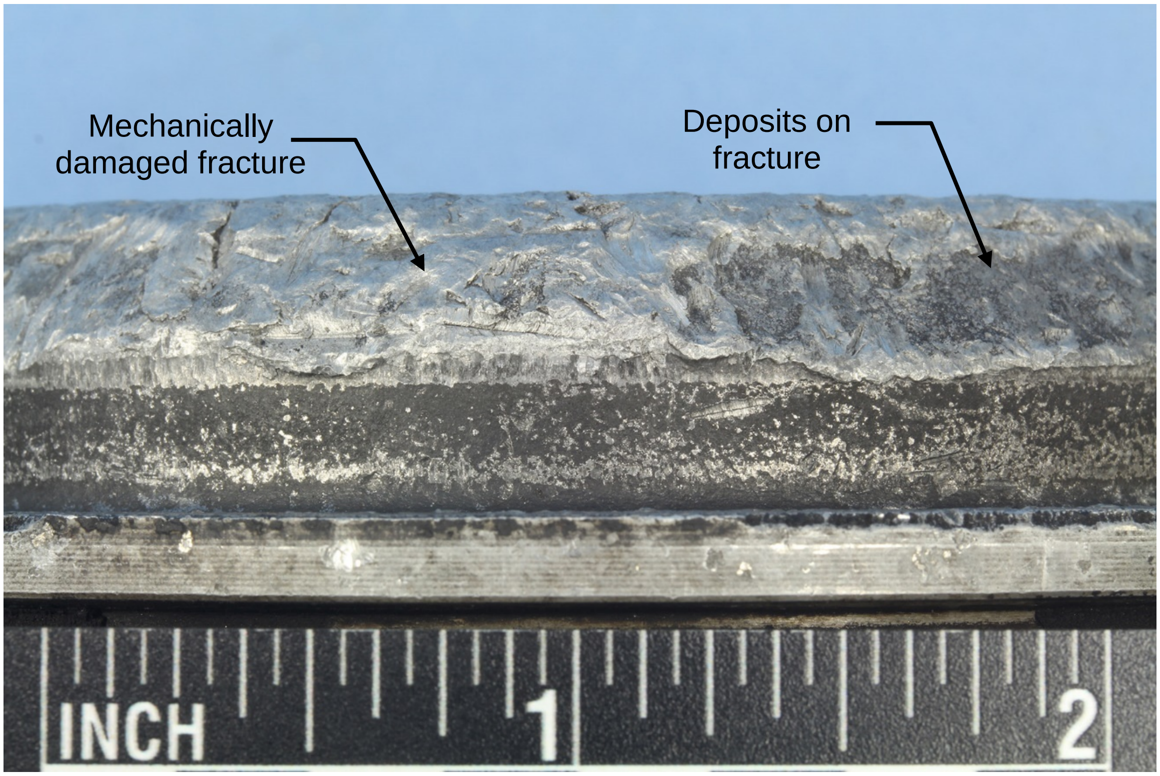
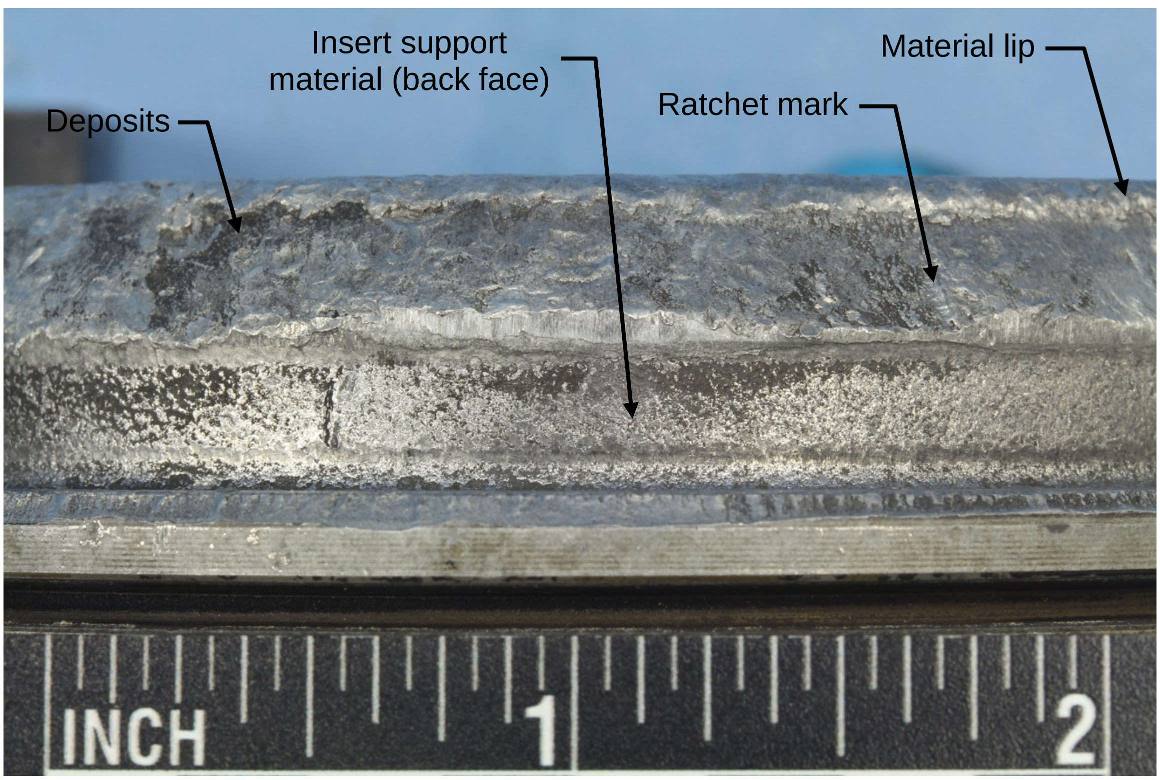


Figure 7: Fractured piece of number 4 piston from the crown/top land region. Machining lines were visible on the crown up to the beveled edge.



a)



b)

Figure 8: Side view of the piston showing the fracture and separated insert region: a) 6:00 orientation and b) 3:00 orientation.

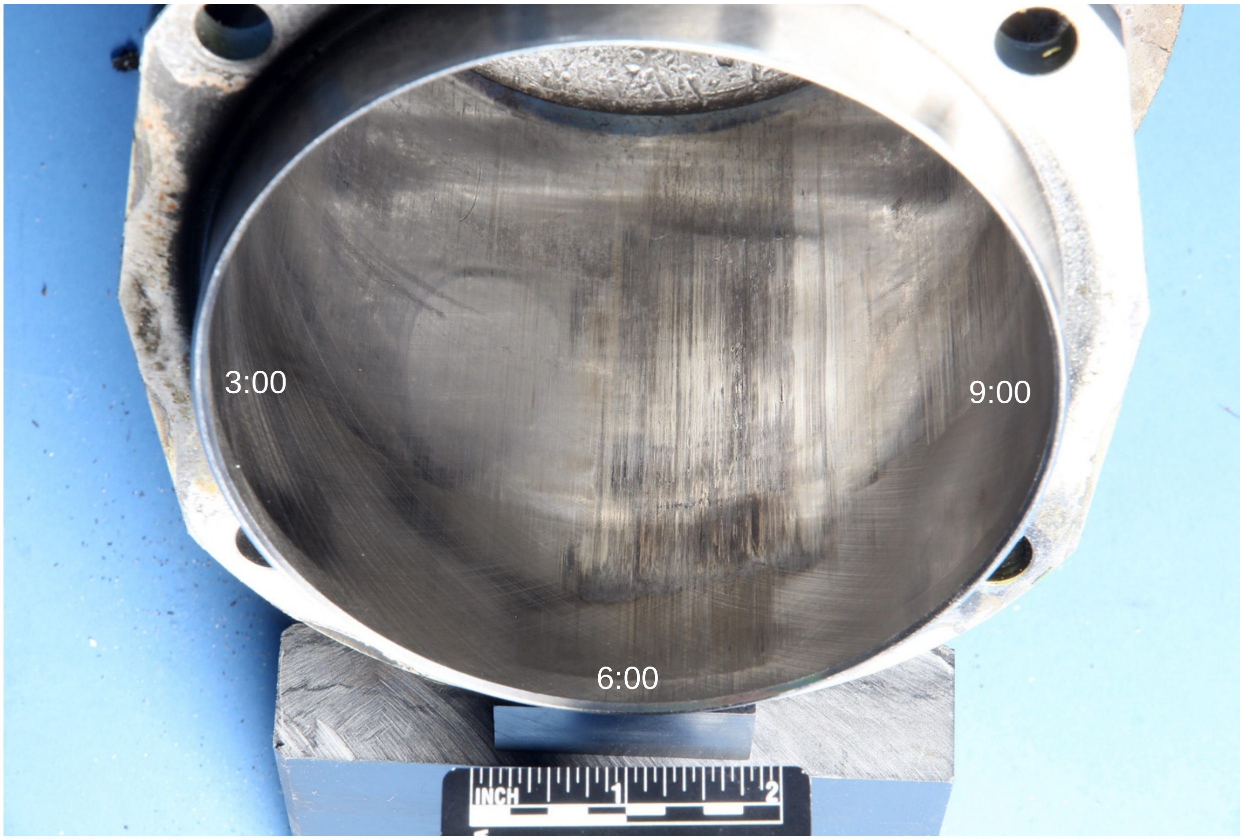
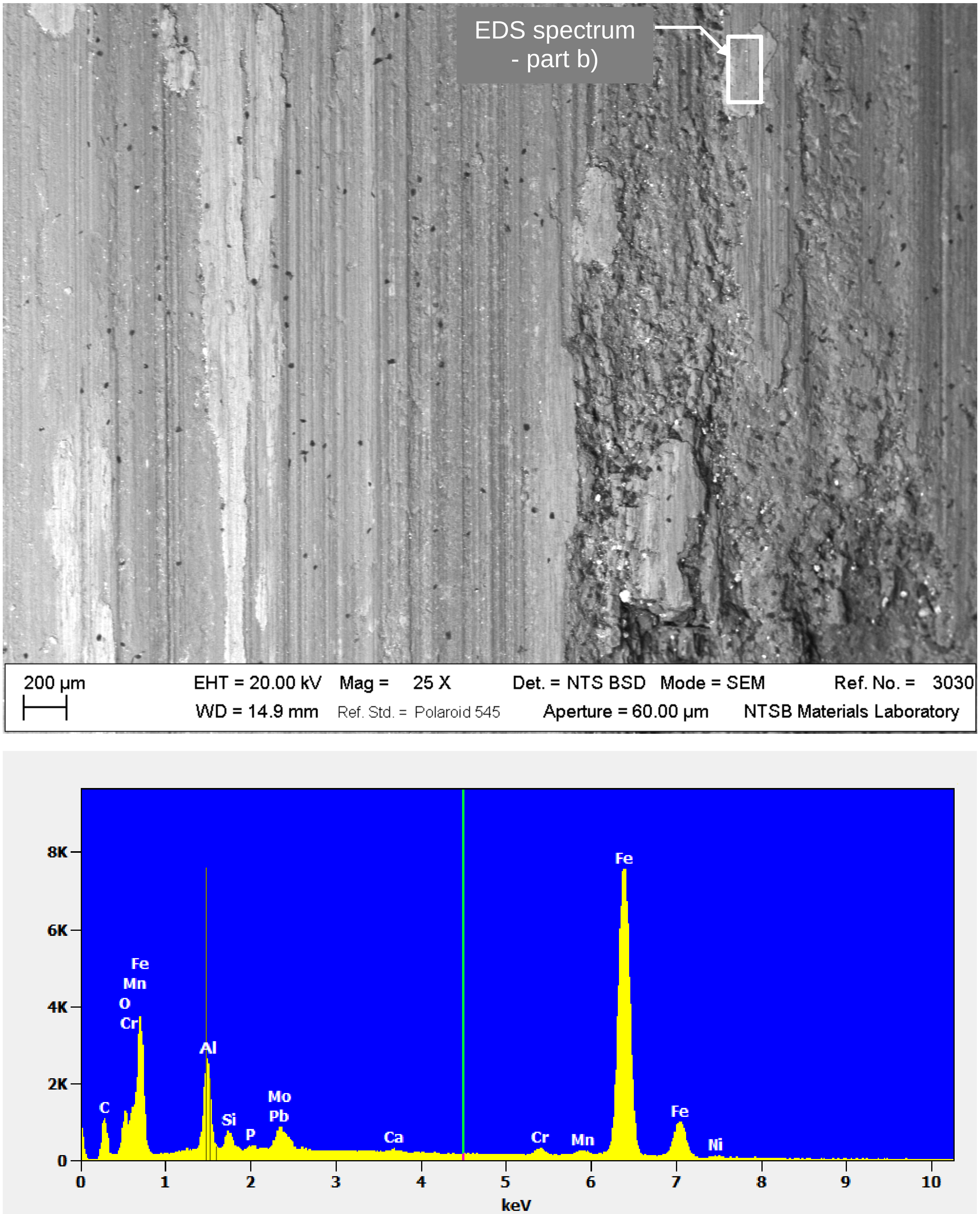
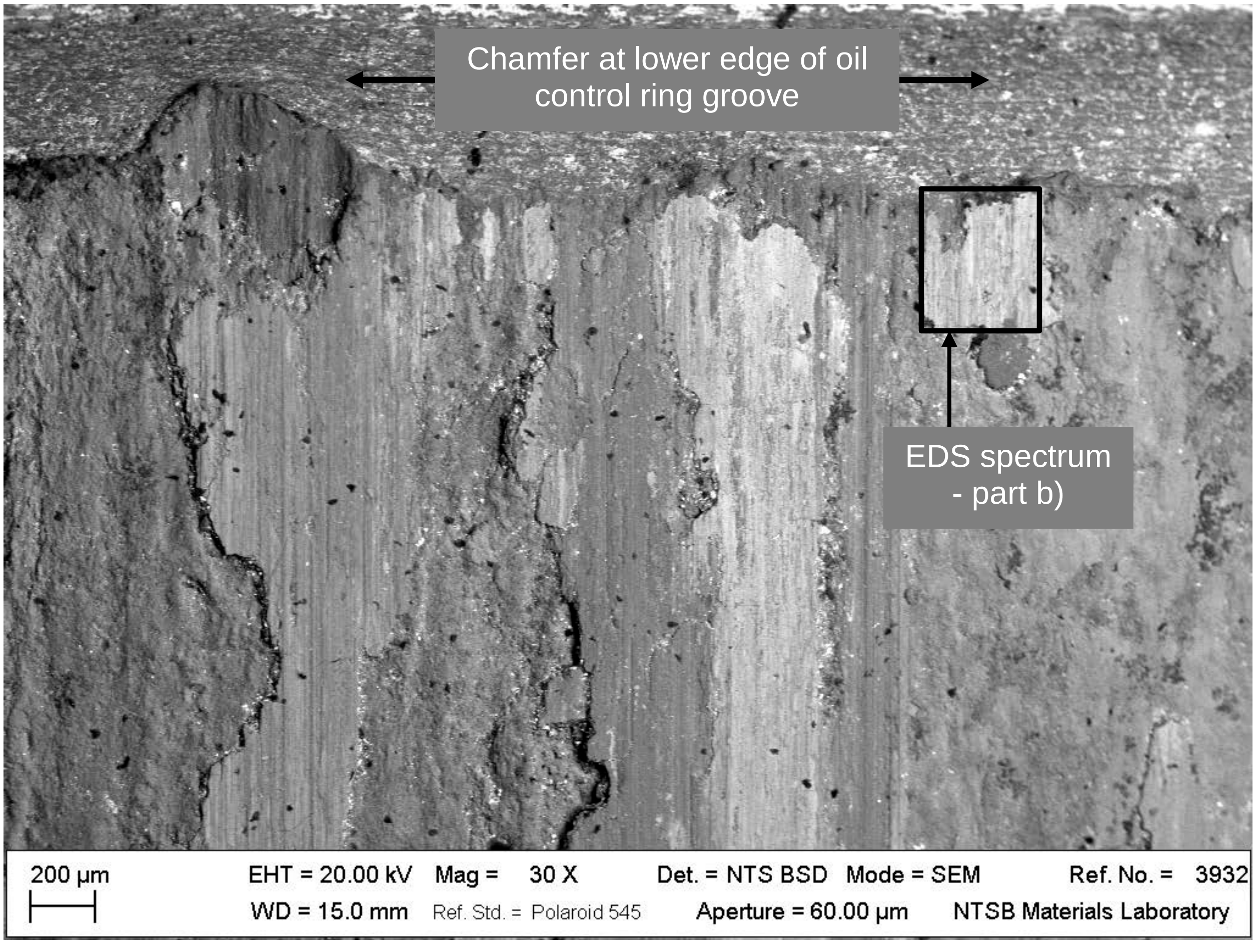


Figure 9: Image of the number 4 cylinder showing a scrape mark between the 6 o'clock and 7 o'clock positions. There was a corresponding scrape mark on the piston skirt.

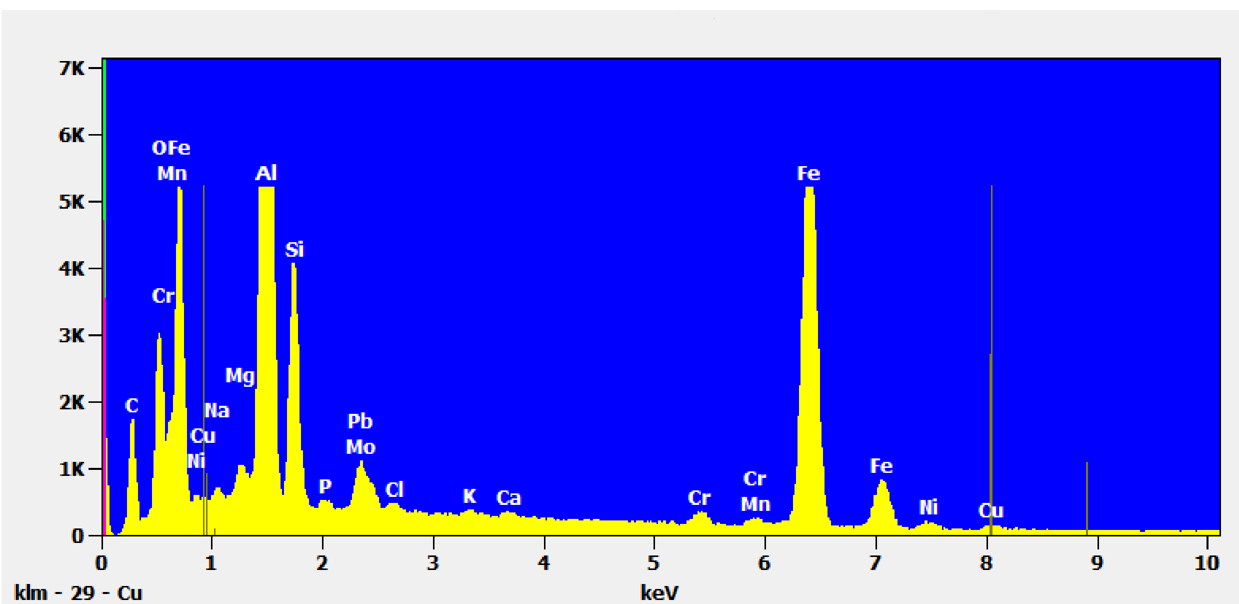


a) b)

Figure 10: a) SEM image near the center of the scuff mark on the number 4 piston skirt and b) EDS spectrum of transferred material at the location indicated in part a.

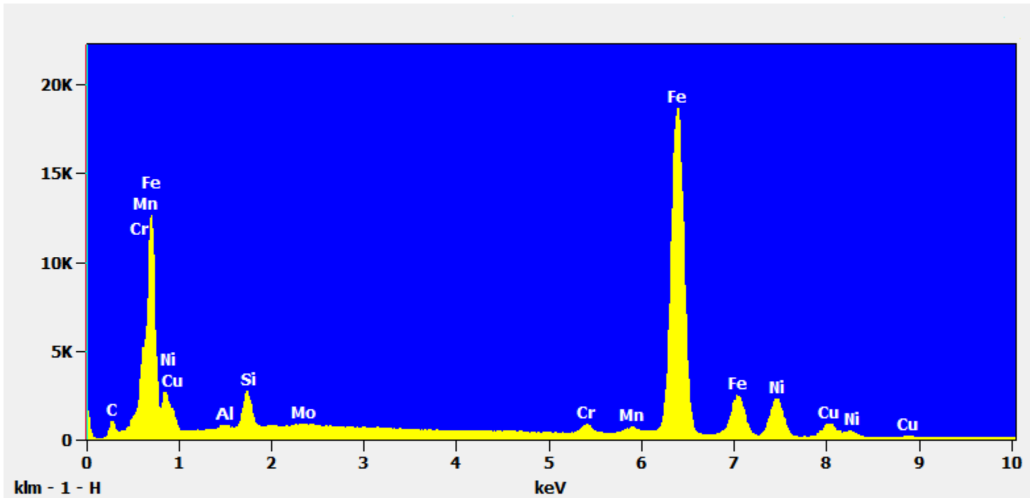


a)

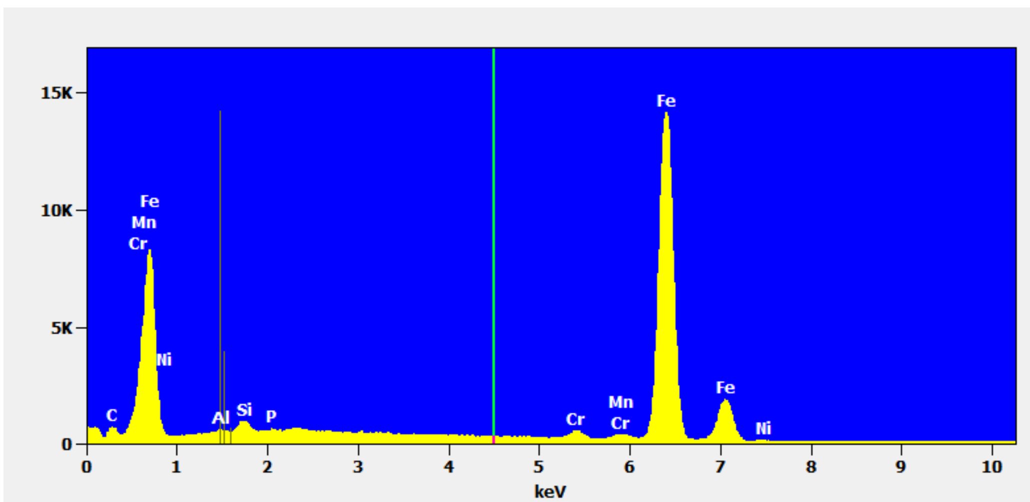


b)

Figure 11: a) SEM image near the top of the scuff mark on the number 4 piston skirt near the oil control ring groove and b) EDS spectrum of transferred material at the location indicated in part a.



a)



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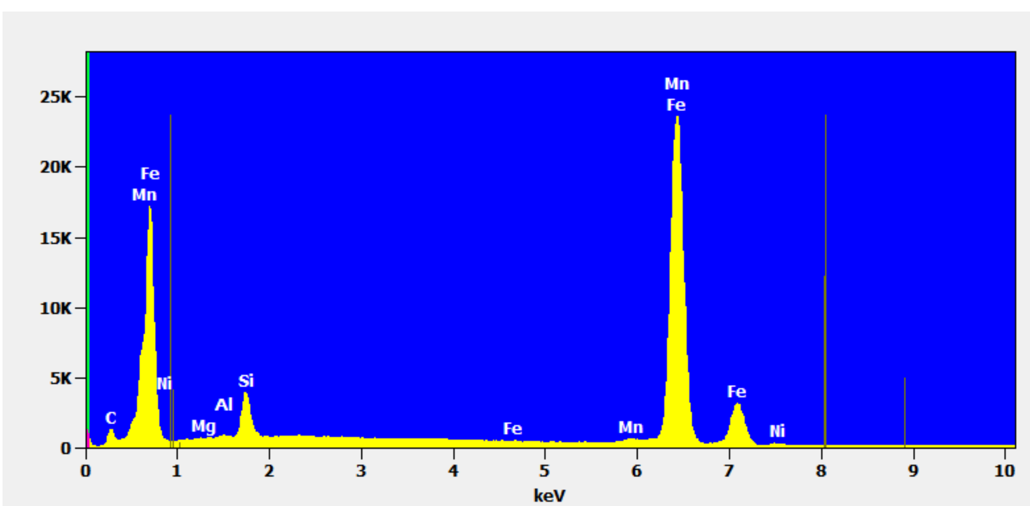
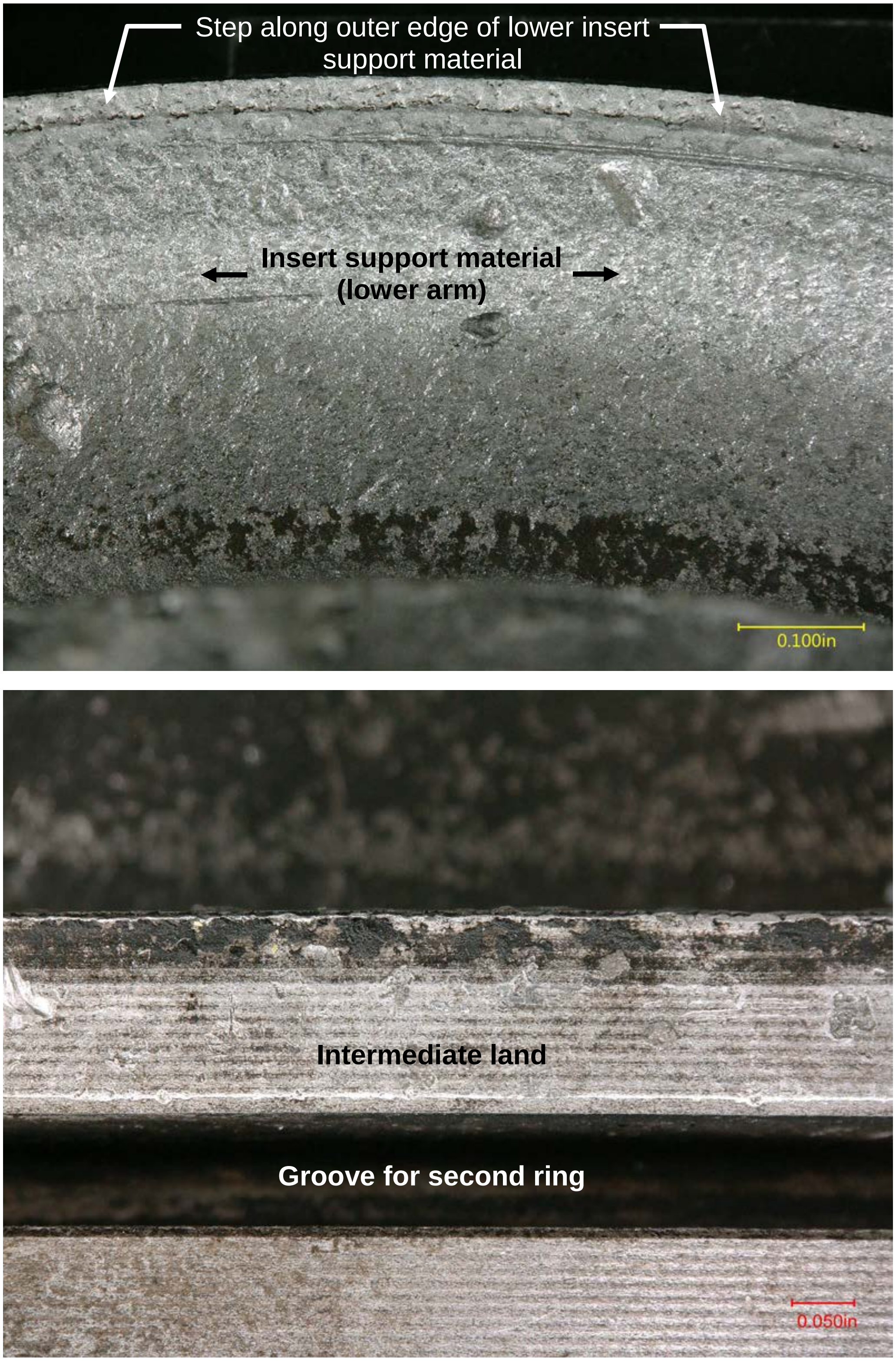


c)

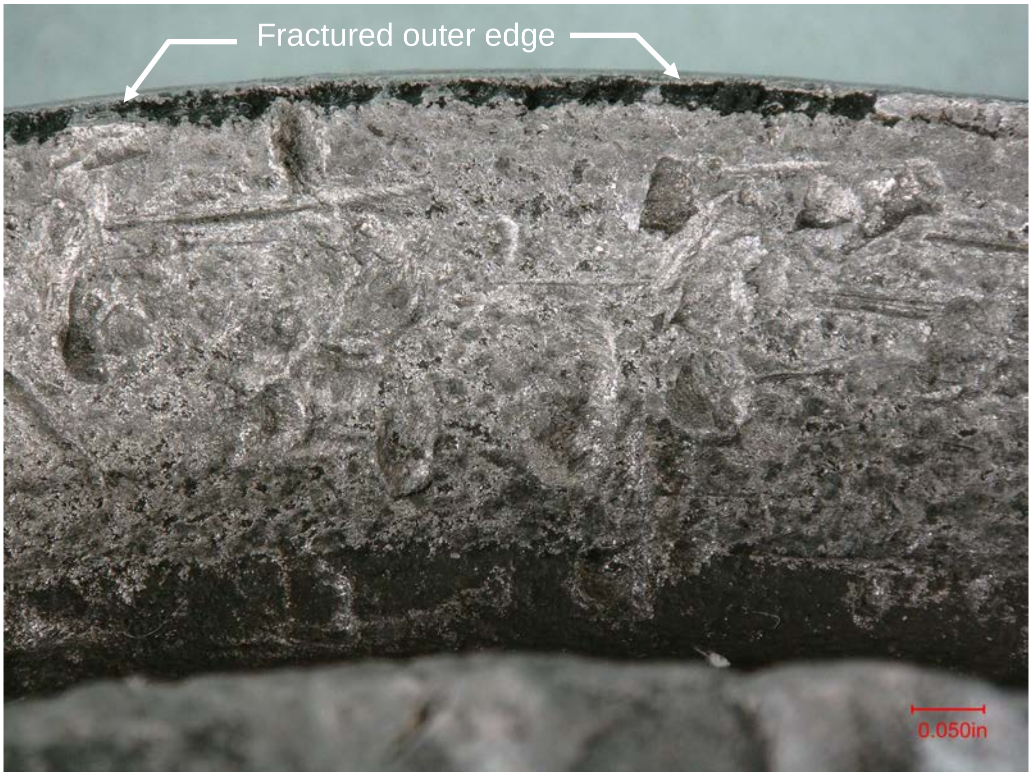
Figure 12: Reference EDS spectra of: a) a piece of insert material; b) a piece of the number 4 cylinder wall; and c) a piece of the top compression ring.



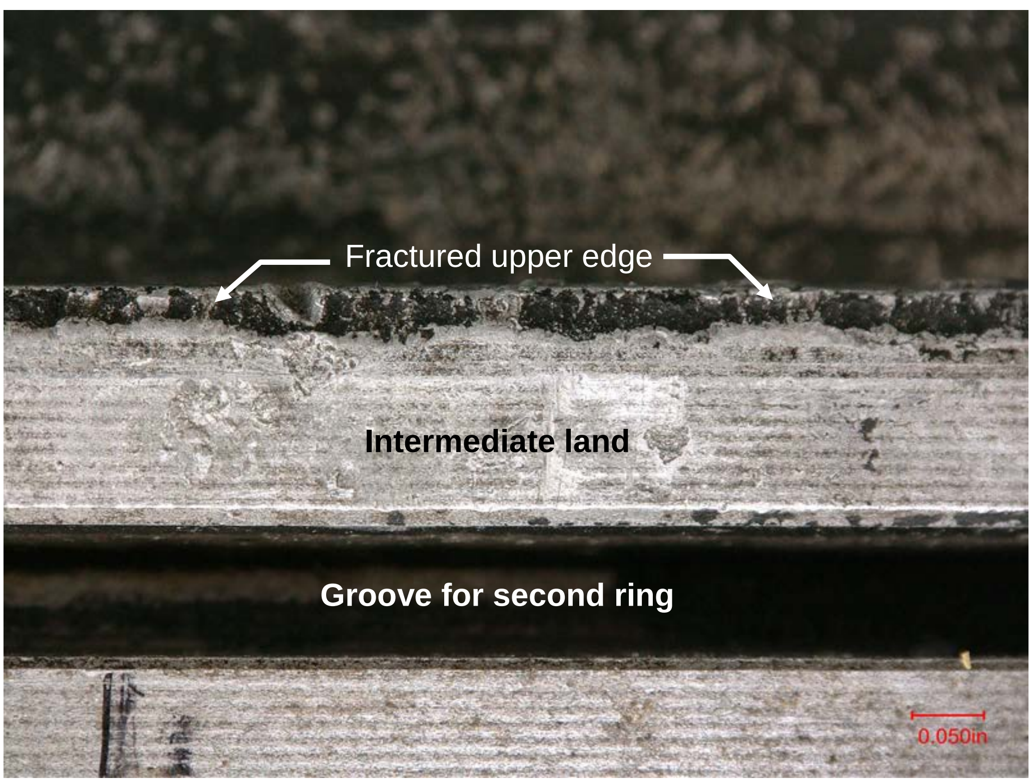
a)

b)

Figure 13: a) Image of the insert lower arm support material at the 12:00 position. A step was observed along the outer edge of the support material and b) side view showing the intact intermediate land.

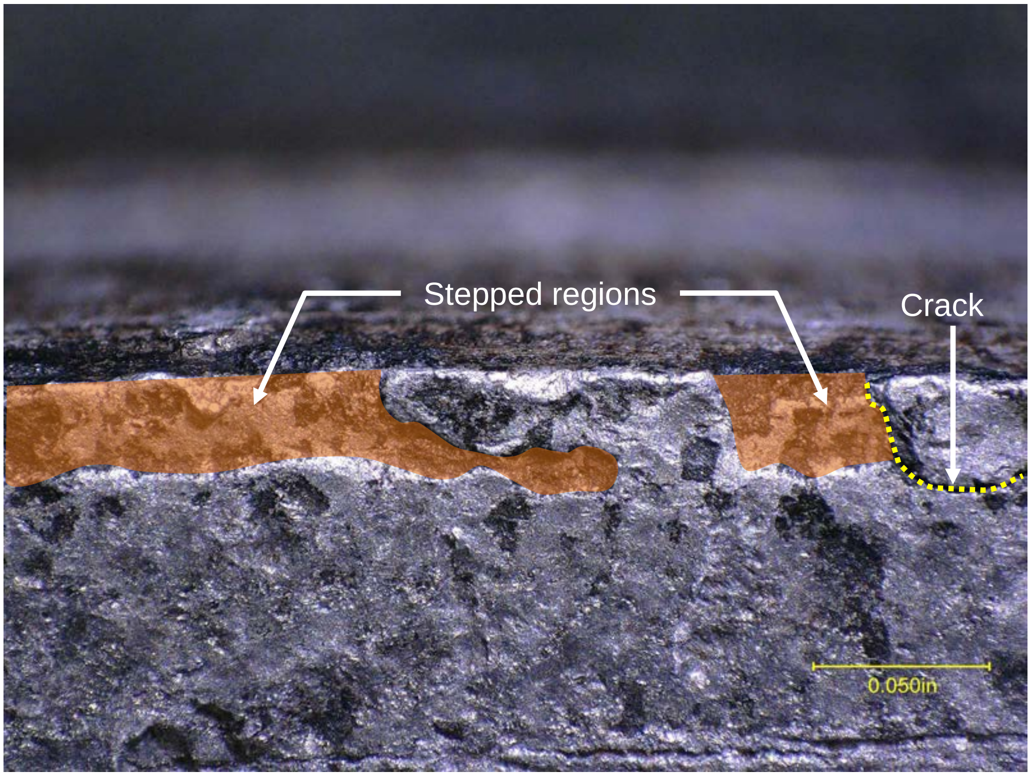


a)



b)

Figure 14: a) Image of the insert lower arm support material between the 5:00 and 6:00 positions. The outer edge of the lower arm support material was fractured and b) side view showing the fractured upper edge of the intermediate land.

a)


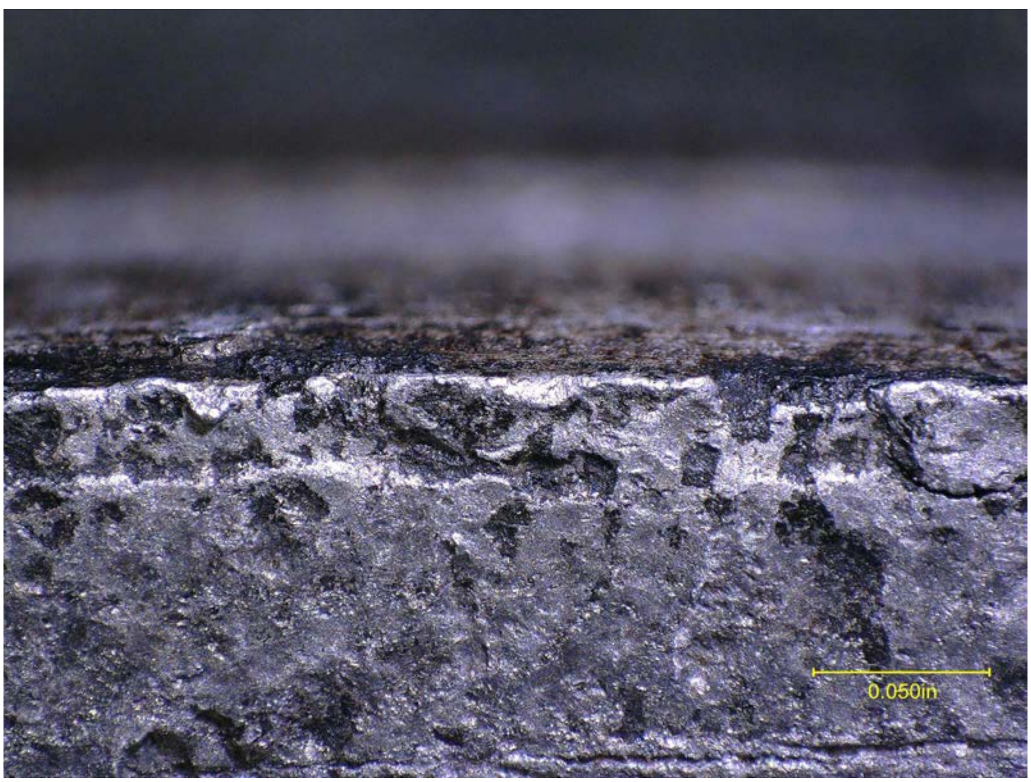
b)


Figure 15: Images near the 7:00 position at the transition from intact to fractured edge. At the location, the stepped edge was interrupted by a region without the step: a) Image with stepped regions shaded and a crack annotated and b) same image as part a) without annotations.

Figure 16: Image of the insert back face support material near the 5:00 position showing the presence of engine exhaust deposits and discreet regions of aluminum material with a rubbed appearance.

a) b) c)

Figure 17: Images of piston crowns for: a) number 1 piston; b) number 2 piston; and c) number 3 piston;

d) 

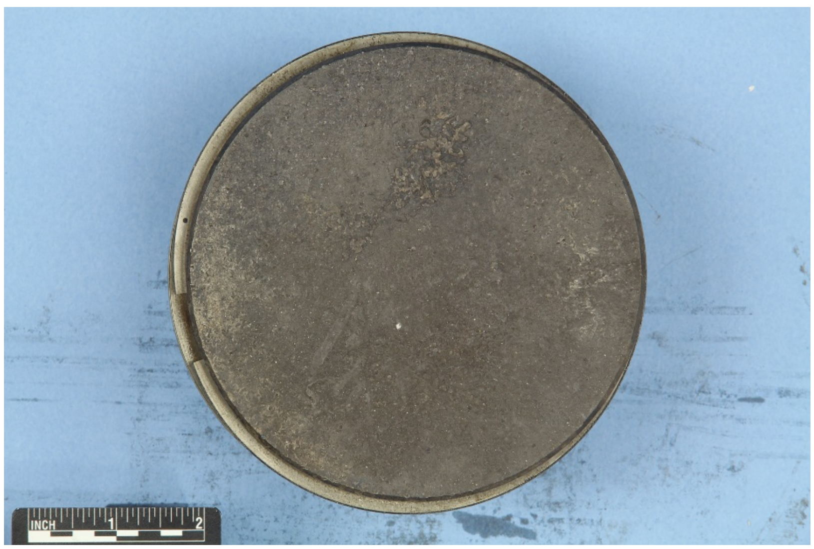
e) 

Figure 17 (cont.): d) number 5 piston; and e) number 6 piston.

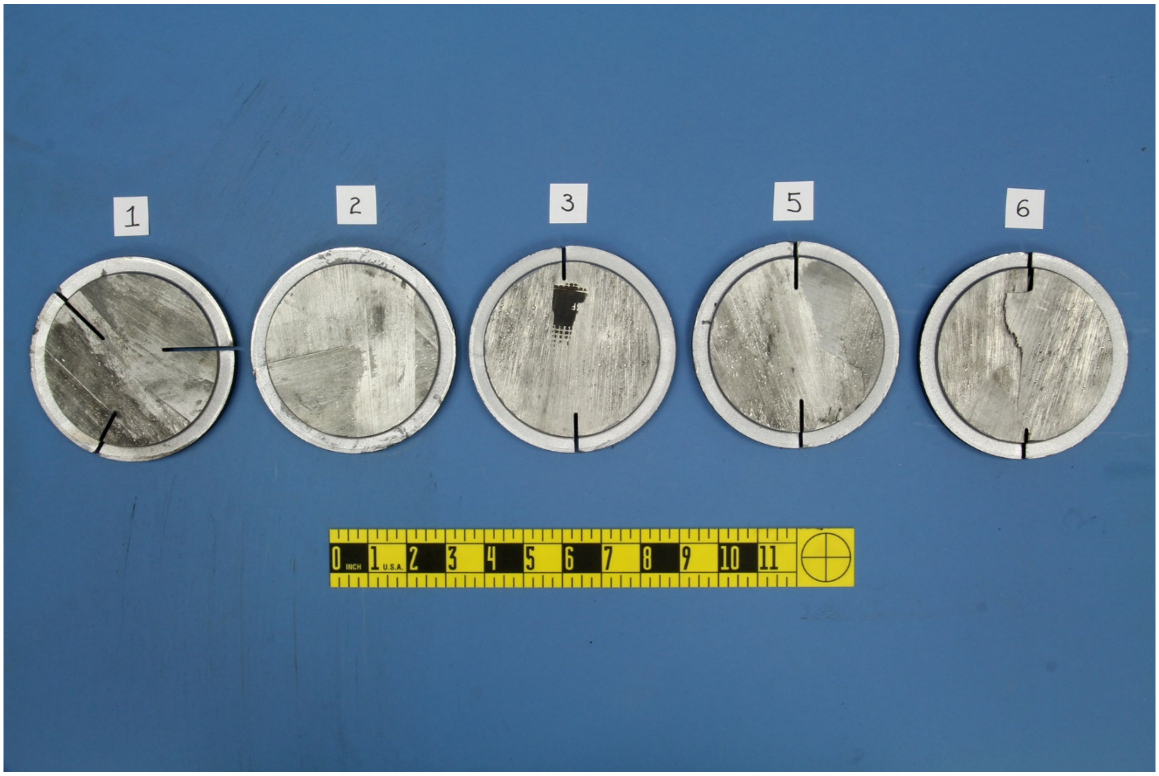


Figure 18: Image of the sectioned piston crowns after removal of the inserts for pistons 1, 2, 3, 5, and 6.

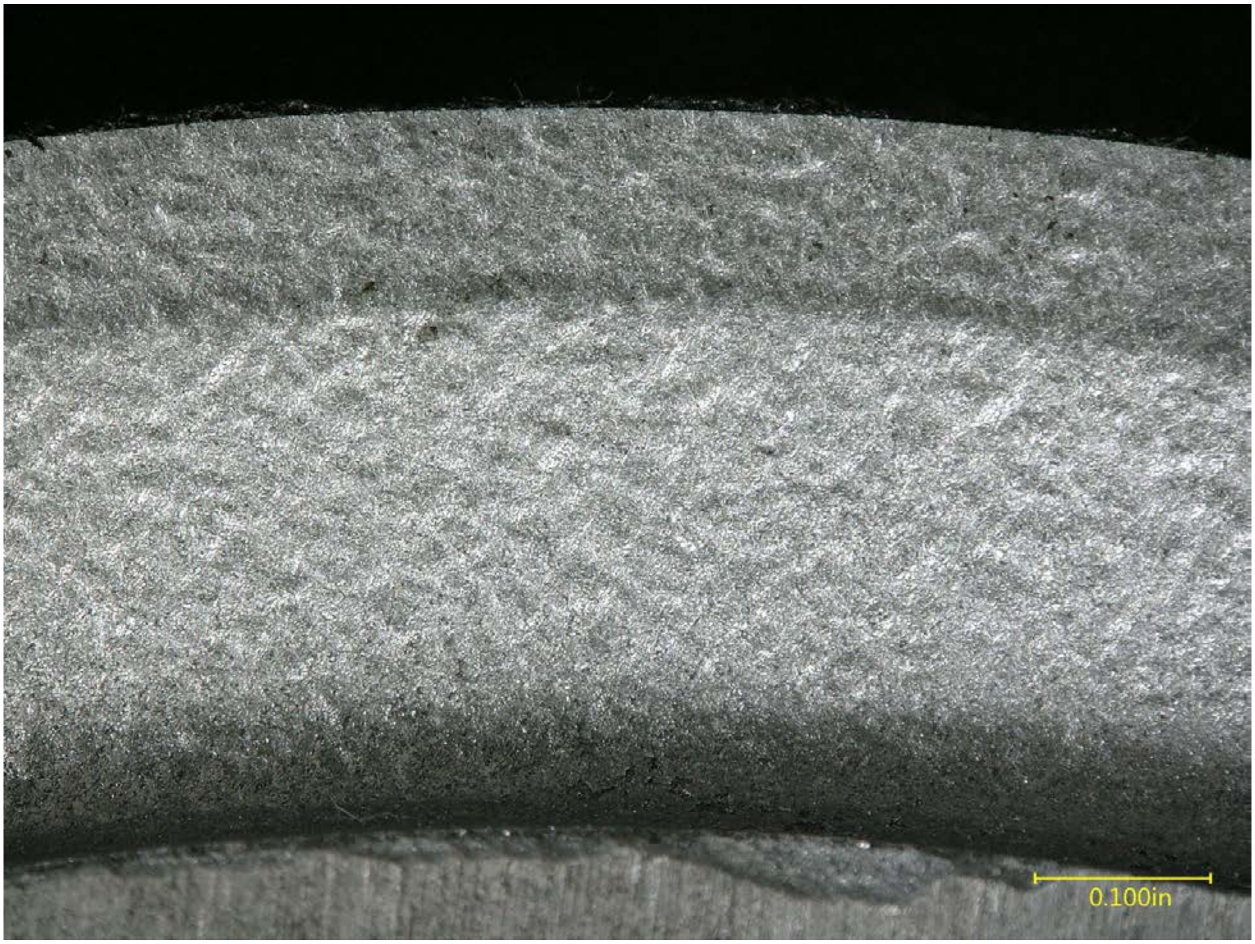


Figure 19: Image of the insert lower arm support material for the number 3 piston. No stepped region was observed along the outer edge of the support material.

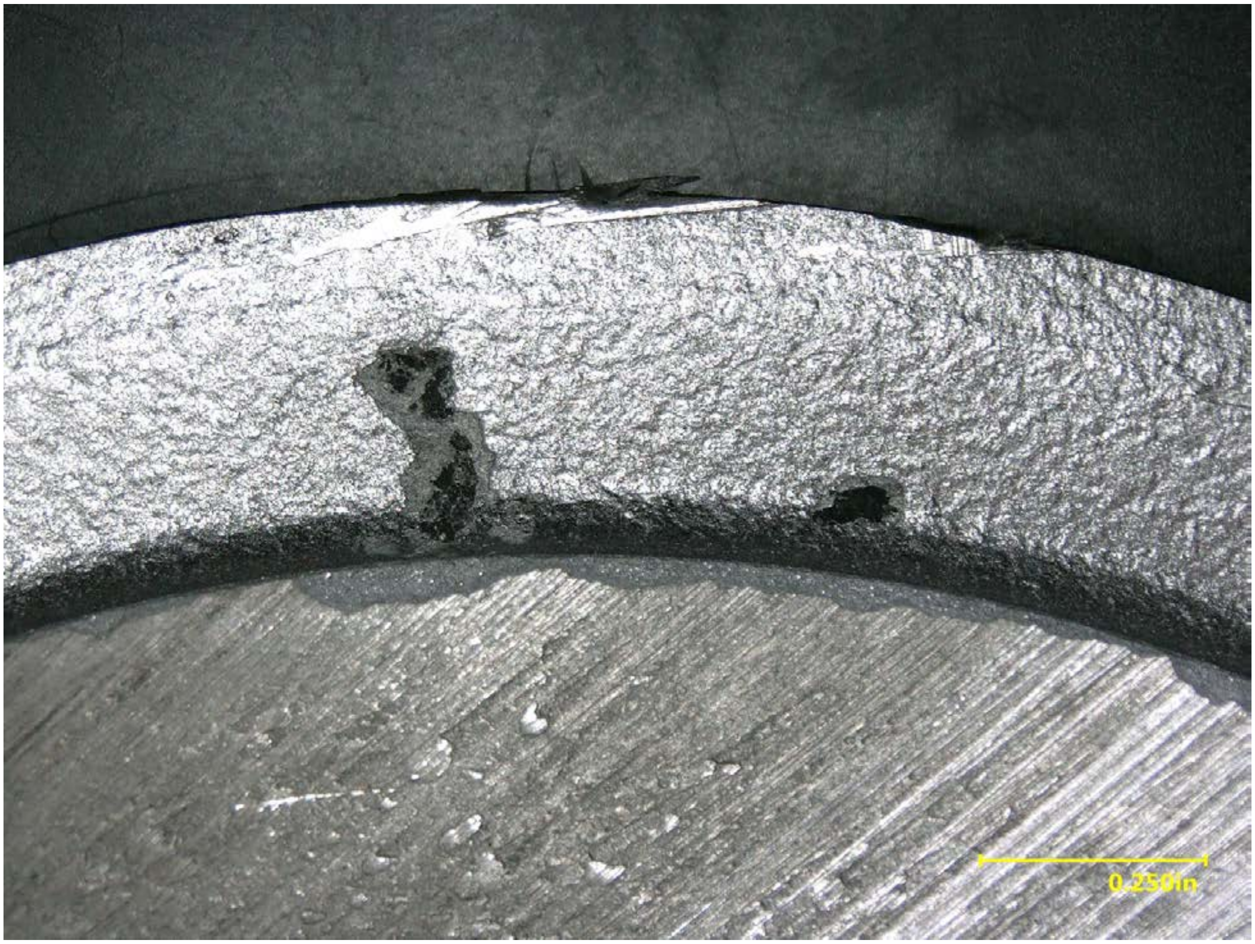


Figure 20: Dark particulates exposed after separation of the insert upper arm from the piston support material for piston number 5.

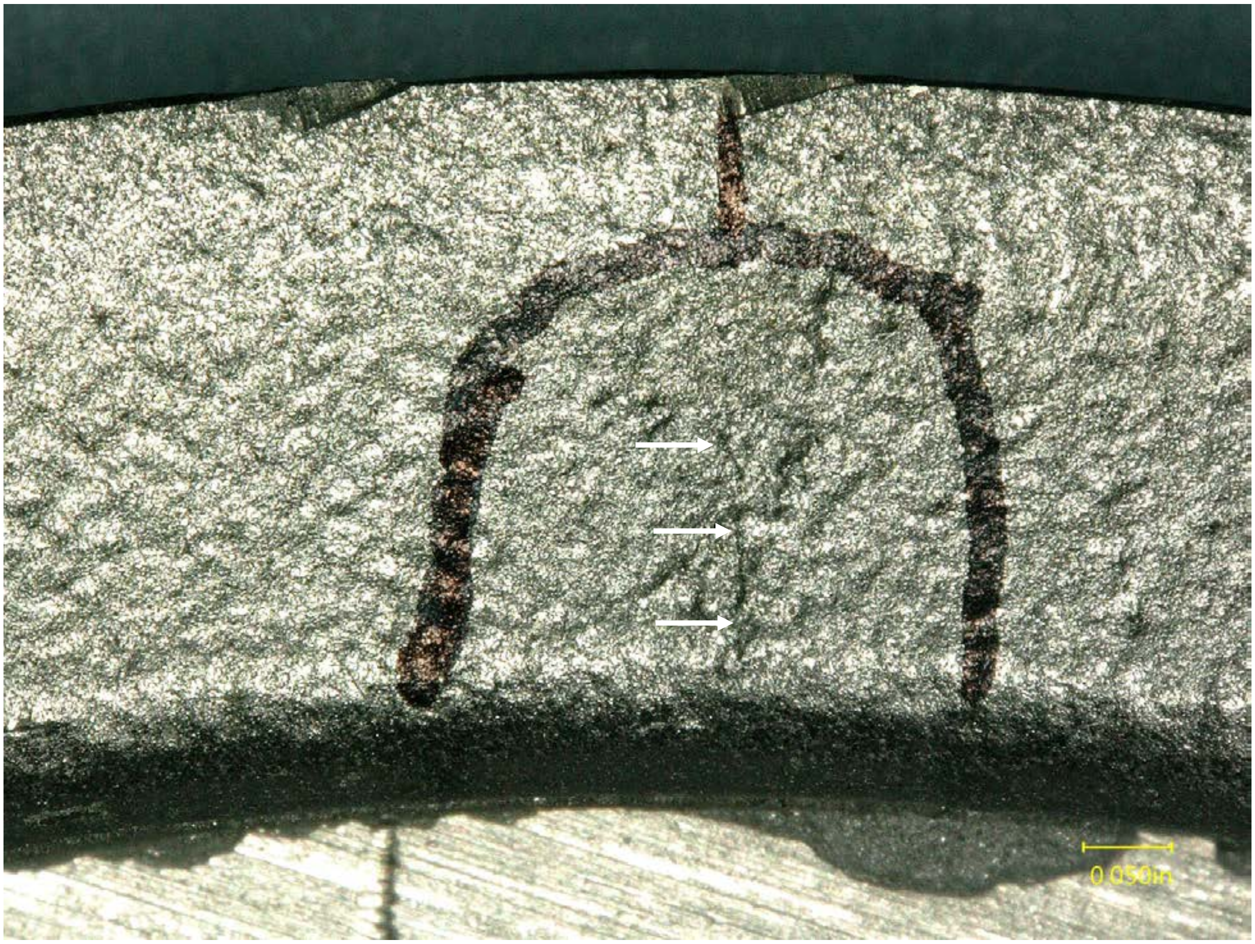


Figure 21: A linear feature detected by a fluorescent penetrant inspection of the number 3 piston insert upper arm support material. The edge of the feature is indicated by the white arrows.

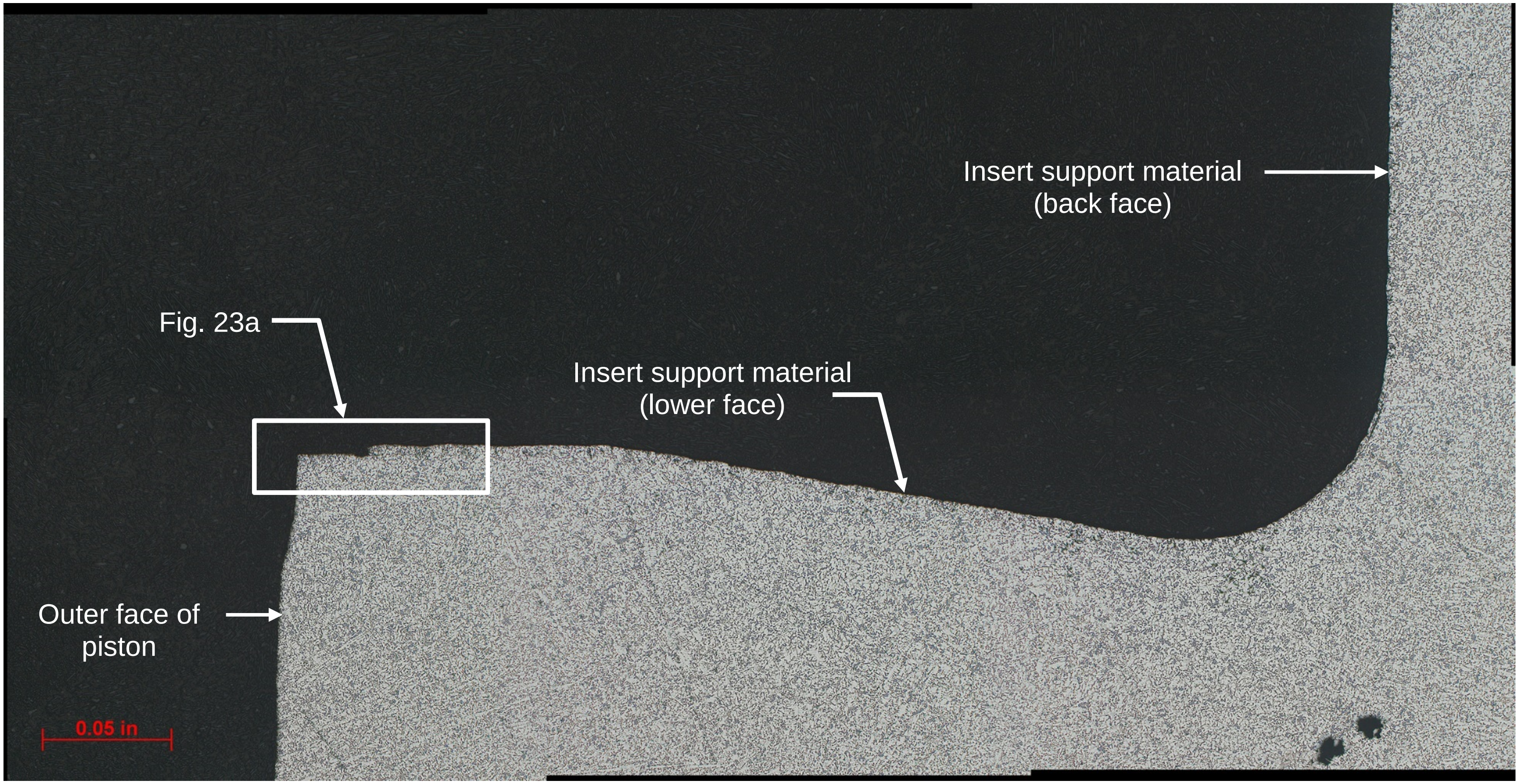
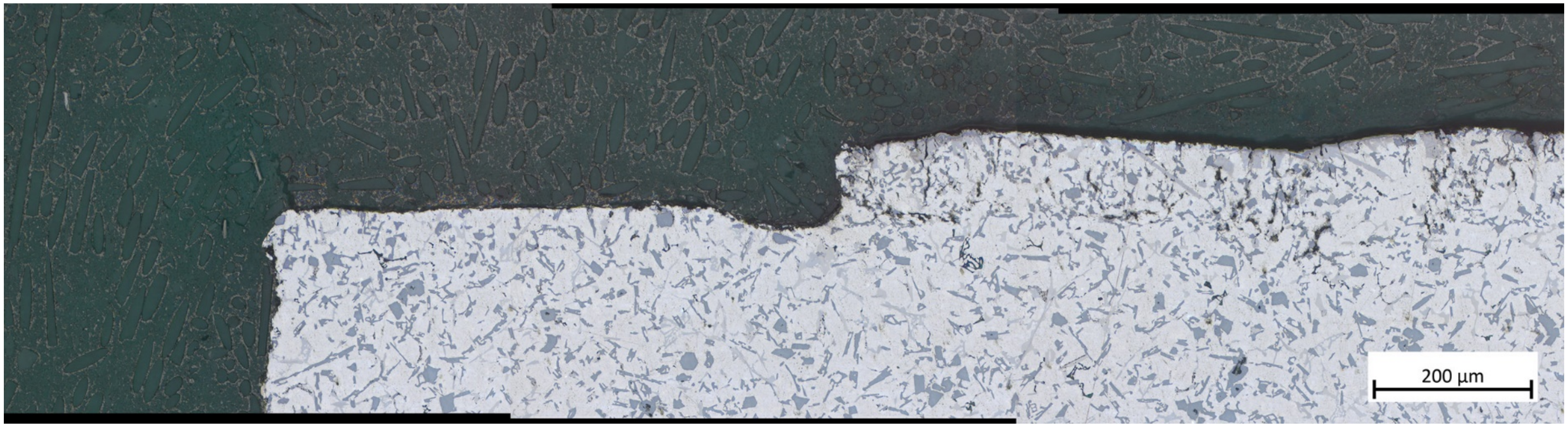
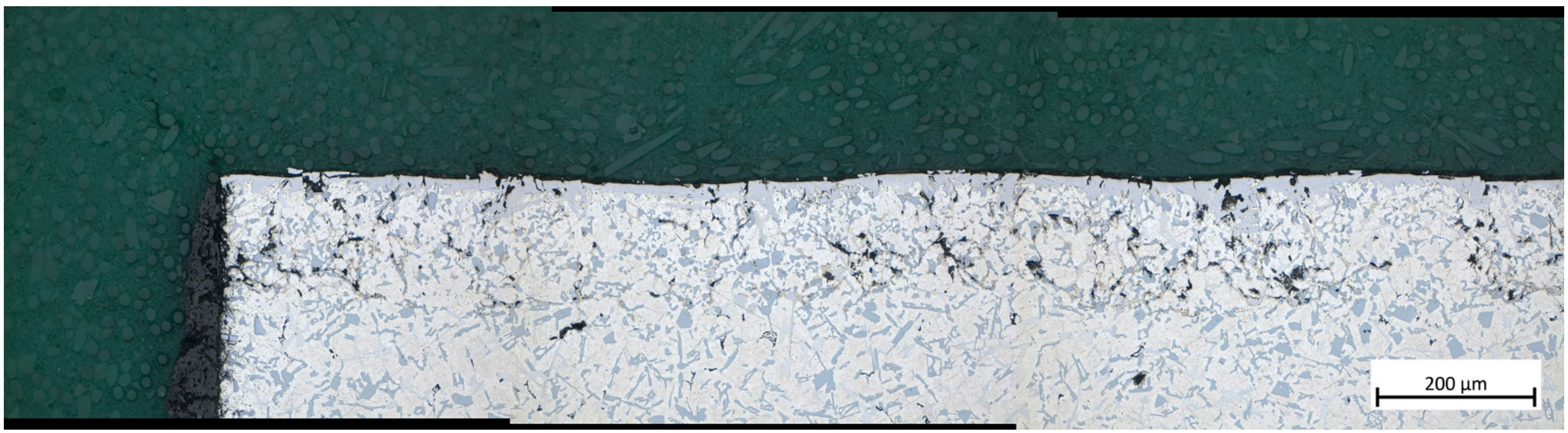


Figure 22: Mosaic image of a metallographic cross section through the number 4 piston insert support material including the lower arm and back face. The cross section was taken near the 12:00 position.



a)



b)

Figure 23: Metallographic cross sections at the intersection of the lower support material with the outer face of the piston (intermediate land): a) number 4 piston showing the stepped edge in cross section and b) number 3 piston showing no stepped edge.

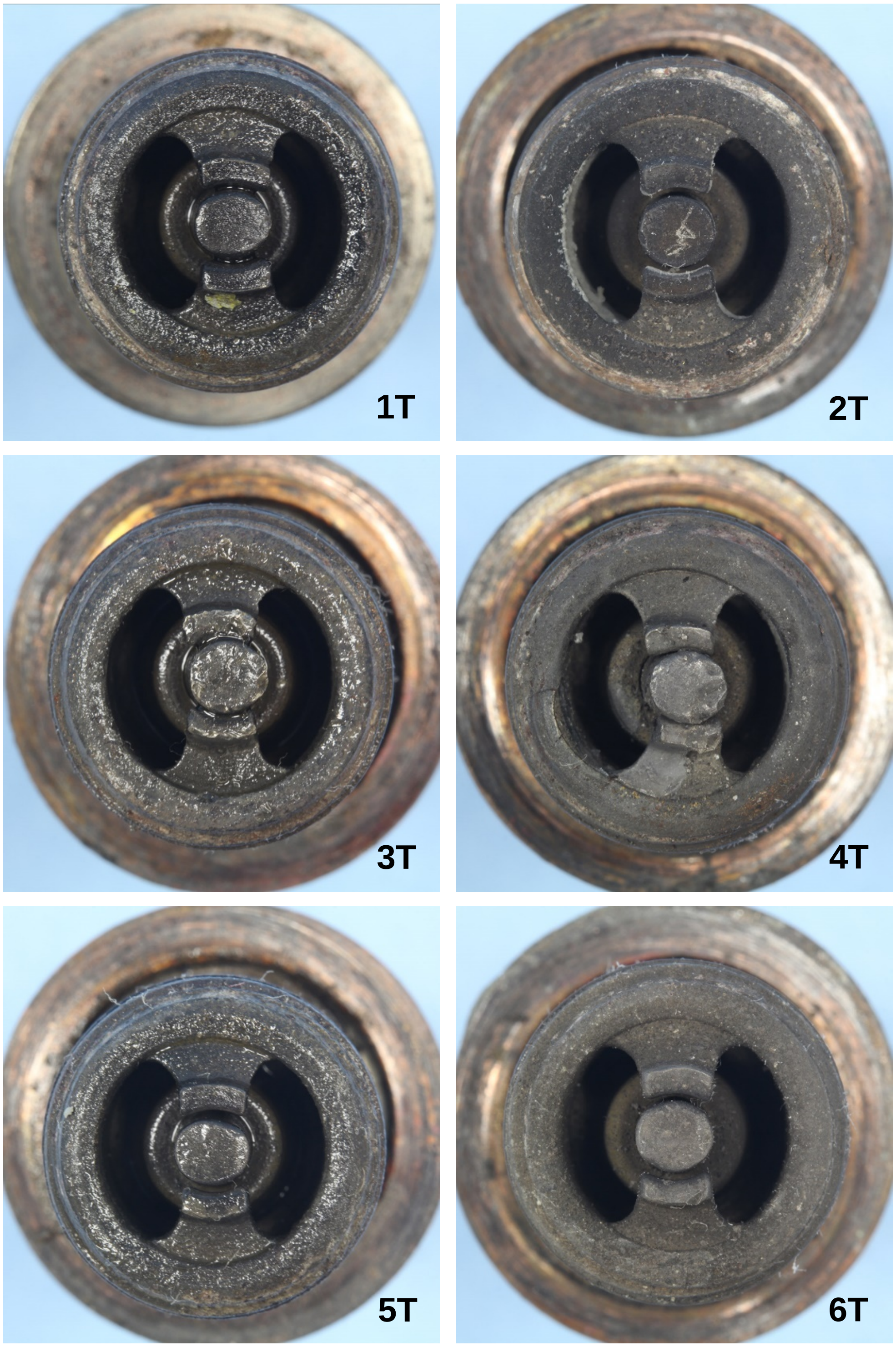


Figure 24: Top spark plug tips for the numbers 1 through 6 cylinders, labelled 1T through 6T, respectively.

a) b)

Figure 25: Images of the number 4 cylinder bottom spark plug: a) overview image of the plug and the terminal connector and b) image of the spark plug tip.