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 Rolls-Royce	Rolls-Royce Corporation 450 S. Meridian Street Indianapolis, Indiana 46225-1103, USA	REPORT NO. 19FAE-061-PR	REV. Initial	PAGES 1 of 64
TITLE METALLURGICAL INVESTIGATION OF A THIRD STAGE TURBINE WHEEL, P/N 23065818, REMOVED FROM AN M250 C20B ENGINE, S/N CAE832565 OPERATED BY WILBUR ELLIS CO.		PREPARED Signatures on File		
		APPROVED Signatures on File		

IDENTIFICATION

Part Name:	Third Stage Turbine Wheel
Part Time:	1,661.9 hours, 1,030 cycles
Part Number:	23065818
Part Serial Number:	X637545
Part Time:	1,661.9 hours, 1,030 cycles
Engine Model:	M250-C20B
Engine Serial Number:	CAE832565
User:	Wilbur Ellis Co.
Removal Station:	Dallas Airmotive
Evaluations:	Failure Analysis

No Export Controlled Information

1 Foreword

The third stage turbine wheel, P/N 23065818 S/N X637545, was installed in an M250-C20B engine, S/N CAE832565, in a Bell 206B performing agricultural operations when the helicopter reportedly struck trees during a forced landing. The pilot reported hearing a faint buzzing sound lasting about one to two seconds, and did not report any annunciator light warnings or alert horns. The pilot reported the N_2 speed gauge was oscillating between approximately 50 and 65% when they decided to perform an auto-rotation. The engine was recovered and sent to an Air Transport (a salvage recovery and storage facility in Phoenix, AZ) where the engine was removed and then transferred to Dallas Airmotive for engine disassembly inspection. This inspection reportedly revealed one third stage turbine airfoil fractured near the root. The wheel was also identified as part of a post-CEB-1365, or “enhanced,” turbine assembly design. The third stage turbine wheel along with various other turbine hardware was sent to the Rolls-Royce Corporation Materials Laboratory in Indianapolis, IN for detailed metallurgical investigation.

2 Summary of Findings

- 2.1 A single packet trailing third stage turbine airfoil was fractured and liberated. The fracture initiated at the trailing edge tip approximately 0.025 inch outboard of the rim in fatigue and grew to a total length of 0.546 inch before the airfoil was liberated in overload.
- 2.2 All of the other packet trailing airfoils on the third stage turbine wheel as well as the airfoil immediately preceding the fractured and liberated airfoil exhibited crack-like FPI indications.
- 2.3 The crack-like FPI indication in the airfoil immediately preceding the fractured and liberated airfoil was fractured in the laboratory. The fracture initiated in fatigue at the trailing edge tip of the airfoil approximately 0.020 inch outboard of the rim and grew to a total length of 0.051 inch.
- 2.4 The pressure side wax weld adjacent to every airfoil intersected the airfoil root radius.
- 2.5 The hardness, chemistry, and microstructure of the third stage turbine wheel were consistent with the material required by the component definition.
- 2.6 FPI of the first and fourth stage turbine wheels did not reveal any crack-like indications.

3 Results and Discussion

Figure 1 shows the hardware returned to the laboratory in the as-received condition. The components submitted to the laboratory are listed in Table 1.

Table 1: Engine Components Submitted for Investigation

Part Name	Part Number	Serial Number
Third Stage Turbine Wheel	23065818	X637545
Fourth Stage Turbine Wheel	23055944 ⁺	X638996 ⁺
First Stage Turbine Wheel	M250-10223	X635160
Second Stage Turbine Wheel	23073854	X642985
First Stage Turbine Nozzle	23062753	508816
Second Stage Turbine Nozzle	6887194	BL9237
Third Stage Turbine Nozzle	23069744	X615844
Fourth Stage Turbine Nozzle	23055939	X615217
Power Turbine Support	6898731	D22331
Gas Producer Support	23038118	DW36563
Power Turbine Outer Shaft	EH23037416	SG81307
Power Turbine Inner Shaft	23005258 [*]	Unknown
Power Turbine Labyrinth Seal	23037444 [*]	
Turbine to Pinion Gear Coupling	PMA	SG35357
Turbine to Compressor Coupling	E6870832	QT1-251
Turbine Tie Bolt	23068265 [*]	
Exhaust Collector	6879879	32305
No. 6 Bearing	M250-10117 [*]	Unknown
No. 7 Bearing	23007302 [*]	Unknown
No. 8 Bearing	PMA	
No. 5 Bearing	PMA	
No. 5 Bearing Labyrinth Seal	6875491 [*]	Unknown
Exhaust Collector	6879879	32305

*: Retrieved from reference documentation

+: Retrieved from paperwork accompanying hardware

3.1 **Third Stage Turbine Wheel P/N 23065818 S/N X637545**

3.1.1 *Visual Examination*

The as-received condition of the third stage turbine wheel is shown in Figure 2 and Figure 3, and the part markings are shown in Figure 4. The part markings read: PNR 23065818 REV G AREA 11.32, MFR 63005, SER X637545. A single airfoil was liberated from the wheel. The leading edge side hub of the wheel exhibited dark discoloration. The airfoils on the wheel were numbered sequentially for the purposes of this report, starting with #1 for the liberated airfoil and increasing opposite the direction of engine rotation. The shroud slots were found adjacent to the pressure side of the airfoils numbered #1, #8, #15, #22, and #29, indicating the liberated airfoil (#1) was the last airfoil in its packet. The shroud slots appeared to be centered between the adjacent airfoils. Airfoil #1 was liberated just outboard of the rim as shown axially in Figure 5 and radially in Figure 6. Additionally, the shroud outboard of airfoils #34, #35, and #2 was fractured and liberated. Detailed views of the shroud fractures are shown in Figure 7 and Figure 8; The liberated material from airfoil #1 and the fractured shroud were not recovered.

Figure 9 shows 90° radial views of the third stage turbine wheel. The outboard surface of the shroud and knife seals, as well as the trailing edge side interstage knife seals, exhibited asymmetric rub damage. The thickness

of the shroud band on both the leading and trailing edge sides was measured adjacent to airfoils #2, #9, #18, and #27 and the results are shown in Table 2. The bore also exhibited rub damage, Figure 10, on a span from airfoil #2 to #7. The leading edge side of the bore also exhibited coked oil. Figure 11 shows the interstage curvic teeth on the third stage turbine wheel, which exhibited wear on both the drive and coast side flanks.

Table 2: Shroud Band Thickness Measurements

Location	Leading Edge Side Thickness	Trailing Edge Side Thickness
	(inch)	(inch)
Airfoil #2	0.084	0.063
Airfoil #8	0.075	0.060
Airfoil #18	0.071	0.057
Airfoil #27	0.081	0.050

3.1.2 Non-Destructive Examination

The third stage turbine wheel was subjected to fluorescent penetrant inspection (FPI) by the Rolls-Royce Corporation Test Department. Crack-like FPI indications were found in the trailing edge root radius of each of the packet trailing airfoils #8, #15, #22, and #29, as well as in airfoil #35, which immediately preceded the fractured and liberated airfoil #1. The indications in each packet trailing airfoil and in airfoil #35 are shown in Figure 12 through Figure 16, along with radial views showing the pressure side wax weld adjacent to each airfoil with an FPI indication in the trailing edge. The pressure side wax weld intersected the airfoil root radius of each airfoil. Figure 17 and Figure 18 show representative pressure side wax weld intersections on airfoils that did not exhibit crack-like FPI indications.

Airfoil #35 was laboratory fractured. Attempted laboratory fracture of the indications in airfoils #15, #22, and #29 were unsuccessful. Airfoil #15 was subjected to metallographic examination, as the FPI indication was not damaged during the attempted lab fracture process.

3.1.3 Fractography

Detailed visual inspection of the inboard portion of airfoil #1 showed that the airfoil fractured approximately 0.025 inch outboard of the rim at the trailing edge root radius as shown in Figure 19. From the trailing edge, the fracture progressed along the length of the airfoil and slightly inboard toward the rim for approximately 0.044 inch as measured on the pressure side and 0.069 inch as measured on the suction side. The fracture surface profile at the trailing edge is shown in Figure 20 and Figure 21. The fracture propagated toward the leading edge approximately parallel to the rim surface before turning outboard approximately halfway along the length of the fatigue fracture, shown in the confocal laser scanning microscope (CLSM) image in Figure 22. Detailed inspection of the remnant of airfoil #1 also revealed that the pressure side airfoil wax weld intersected the airfoil fillet on the pressure side of the airfoil. The wax weld also extended out of the fillet radius at the trailing edge tip of the airfoil as shown in Figure 23.

Detailed examination of the fracture surface on airfoil #1 revealed macroscopic fracture features consistent with fatigue progression from the trailing edge to approximately 0.546 inch from the trailing edge as shown in Figure 24. After this point, the fracture surface exhibited macroscopic fracture features with a dendritic appearance consistent with overload. The fracture surface also exhibited a change in reflectivity on an arc located approximately 0.072 inch from the trailing edge, shown in Figure 25. The fracture surface was examined using a scanning electron microscope (SEM), which revealed fracture features, Figure 26, consistent with a single fatigue origin at the trailing edge tip of the airfoil between where the wax weld extended out of the fillet radius and the airfoil parting line. The fatigue origin area is shown in Figure 27. Approximately 0.012 inch from the trailing edge, the fracture surface exhibited a transition in fracture features from cohesive crack fronts to multiple crack fronts on several planes as shown in Figure 28 and Figure 29. There was no obvious change in the degree of oxidation on the fracture surface. Representative fatigue fracture features are shown in Figure 30.

The crack-like FPI indication in the trailing edge root radius of airfoil #35 (Figure 16) was fractured in the laboratory; the revealed fracture surface, located approximately 0.020 inch outboard of the rim, is shown in Figure 31. The fracture surface exhibited beach marks radiating away from the trailing edge tip. Figure 32 shows a suction side view of the fracture, which propagated inboard and toward the leading edge for approximately

0.020 inch before turning to propagate towards the leading edge approximately parallel to the rim to a total length of approximately 0.051 inch. There was no obvious transition in fracture features or degree of oxidation of the fracture surface at the change in propagation direction. Figure 33 shows the origin area at the trailing edge tip of the airfoil, which was oxidized. Figure 34 shows representative fracture features near the trailing edge on the inboard plane of propagation and near the end of the fatigue fracture.

3.1.4 *Metallographic Examination*

A metallographic cross-section (Figure 26) was prepared through the origin of the fatigue fracture on airfoil #1 and is shown in Figure 35. In this plane of examination, the fracture propagated inboard for approximately 0.063 inch before turning to progress parallel to the rim surface.

An attempt at lab fracturing the crack-like FPI indication in airfoil #15 was unsuccessful, but the indication was undamaged from the lab fracture process. The airfoil was cut, mounted, and polished, which revealed a crack measuring approximately 0.051 inch long extending from the trailing edge root radius, shown in Figure 36.

The microstructure of the component was consistent with the material required by the component definition.

3.1.5 *Hardness*

The hardness of the third stage turbine wheel was consistent with the component definition requirement.

3.1.6 *Chemistry*

Semi-quantitative x-ray fluorescence (XRF) analysis determined the third stage turbine wheel was consistent with the material required by the component definition.

3.2 ***Fourth Stage Turbine Wheel P/N 23055944 S/N X638996***

The as-received condition of the fourth stage turbine wheel is shown in Figure 37. The airfoil leading edges exhibited impact damage. Figure 38 shows two diametrically opposed views of the shroud and knife seals on the wheel, which exhibited asymmetric rub damage with a fracture through the shroud band in one location. The fourth stage turbine wheel to stub shaft curvic teeth are shown in Figure 39; both the drive and coast side flanks exhibited patches of wear. Coked oil was found in the troughs between curvic teeth and on the inner diameter surfaces of the teeth. The interstage curvic teeth on the fourth stage wheel are shown in Figure 40 and exhibited wear patches on the drive side flanks of the teeth. The fourth stage wheel was subjected to FPI by the Rolls-Royce Corporation Test Department, which did not reveal any crack-like FPI indications.

3.3 ***Other Engine Components***

The as-received condition of the first stage turbine wheel is shown in Figure 41. The web of the wheel was heat tinted on the leading edge side and exhibited brownish discoloration on the trailing edge side. The suction side surfaces of the airfoils also exhibited brownish discoloration. The first stage turbine wheel was subjected to FPI, which did not reveal any crack-like FPI indications. The second stage turbine wheel is shown in Figure 42 and exhibited impact damage to the leading and trailing edges. The suction side surfaces near the root exhibited a reddish-brown coloration.

The first stage turbine nozzle is shown in Figure 43. The trailing edge side web exhibited oil deposits and there was debris on the airfoils. The second stage turbine nozzle is shown in Figure 44. The suction side surfaces of the vane airfoils exhibited impact damage. The third stage turbine nozzle is shown in Figure 45 and exhibited impact damage to the trailing edges and vane airfoil suction side surfaces. The fourth stage turbine nozzle is shown in Figure 46 and exhibited impact damage to the airfoil surfaces. Part of the third stage blade track was liberated from the nozzle.

Figure 47 through Figure 49 show the power turbine support assembly, the Nos. 6 and 7 bearing sump stationary labyrinth seal, and the Nos. 6 and 7 bearing sump. The bore was fractured at the forward end. Figure 50 shows the gas producer turbine support. The forward face of the bore exhibited coked oil on the surface.

Figure 51 shows the power turbine outer shaft (PTOS). The PTOS exhibited rub and coked oil deposits on the outer diameter surface. Figure 52 shows the power turbine inner shaft (PTIS) with the fractured-off portion of the PT support bore and the No. 6 bearing, Figure 53, retained on the aft end of the shaft. Figure 54 shows the PT

outer and inner shaft nuts. Figure 55 and Figure 56 show the third stage power turbine labyrinth seal, which exhibited rub that rubbed through the seal forward of the knives. Figure 57 shows the turbine to pinion gear coupling, which was a PMA component and was not examined in detail. Figure 58 shows the turbine to compressor coupling, which exhibited rub damage on the outer diameter at one end. Figure 59 shows the turbine tie bolt, which was not fractured. Figure 60 shows the No. 7 bearing. Figure 61 shows the No. 8 bearing, which was a PMA component and not examined in detail. Figure 62 shows the No. 5 bearing, which was a PMA component and not examined in detail.

4 Revision History

Issue	Change Summary	Date
Initial	Not applicable	17 Oct 2019

5 Figures and Tables



Figure 1. As-received condition of the components returned to the laboratory.

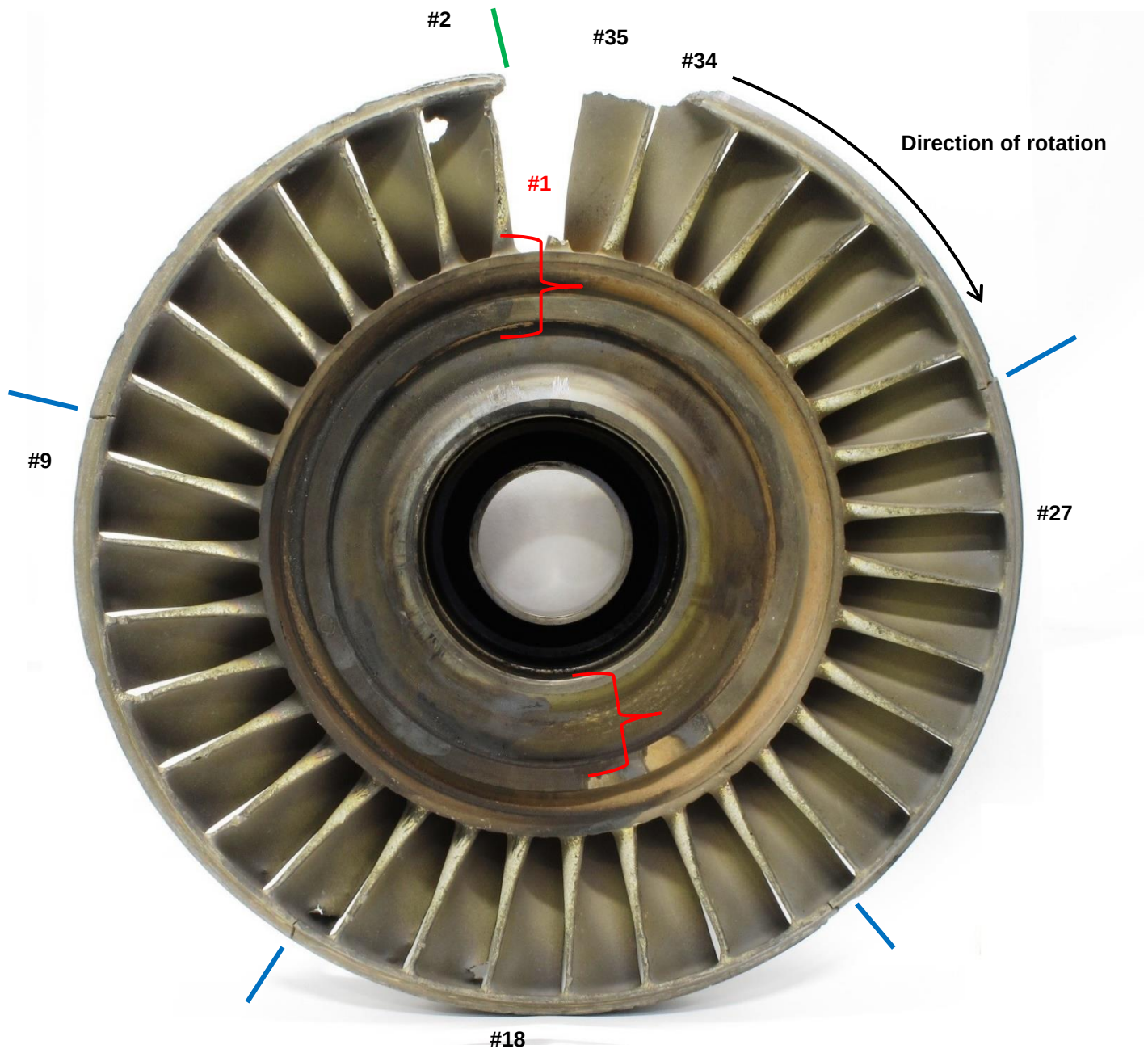


Figure 2. Leading edge side view of the third stage turbine wheel showing the fractured airfoils and shroud. The liberated airfoil was numbered #1 and the rest of the airfoils were numbered sequentially opposite the direction of engine rotation for the purposes of this report. The blue lines indicate the locations of the shroud slots; the nominal location of the fifth slot was immediately following the liberated airfoil and is indicated by the green line. The hub of the wheel was stained dark gray around approximately 180° (between red braces).

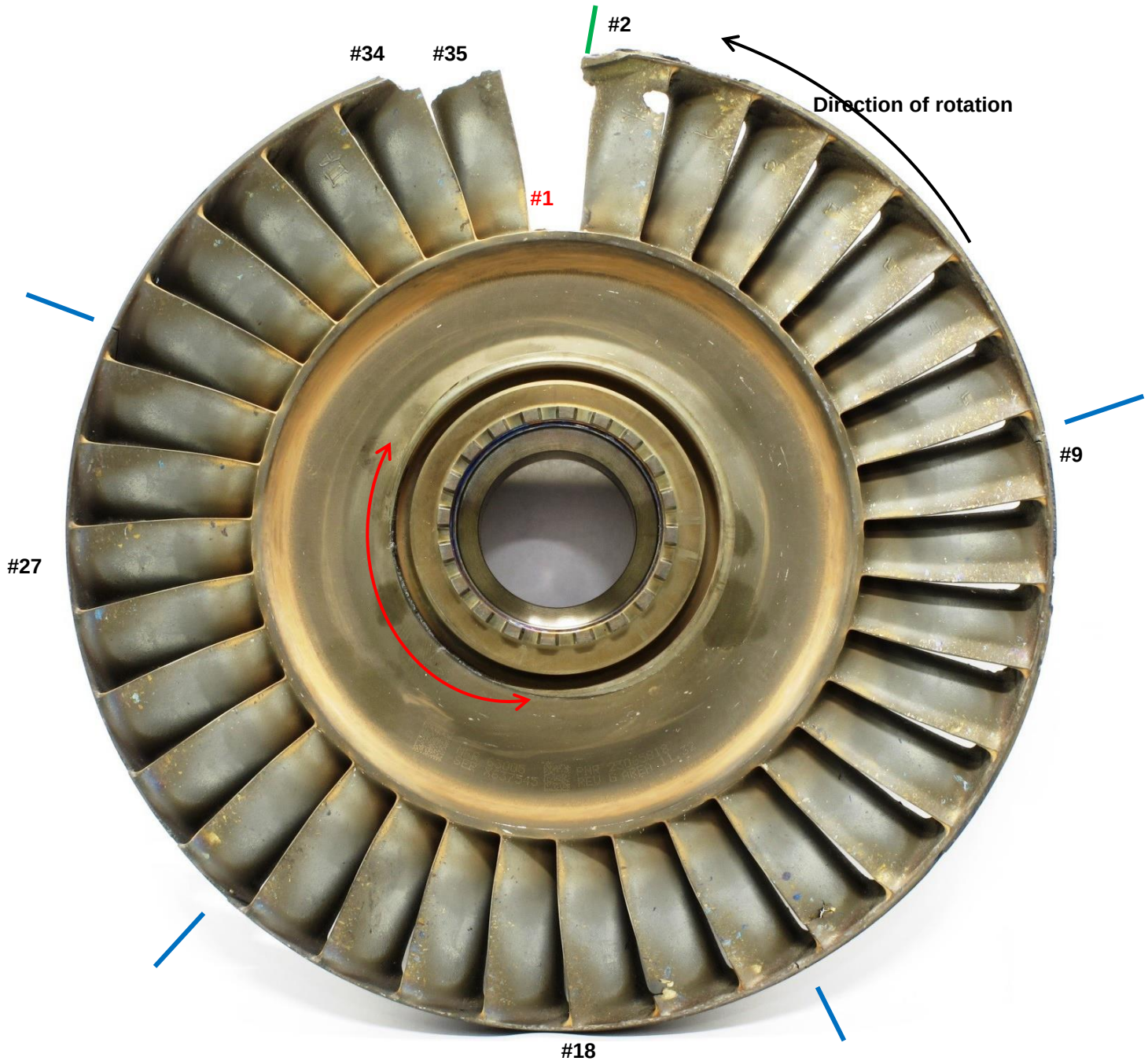


Figure 3. Trailing edge side view of the third stage turbine wheel showing the fractured airfoils and shroud. The liberated airfoil was numbered #1 and the rest of the airfoils were numbered sequentially opposite the direction of engine rotation for the purposes of this report. The blue lines indicate the locations of the shroud slots; the nominal location of the fifth slot was immediately following the liberated airfoil and is indicated by the green line. The red arrow indicates the fractured span of the inter-stage knife seal arm (see Figure 9).

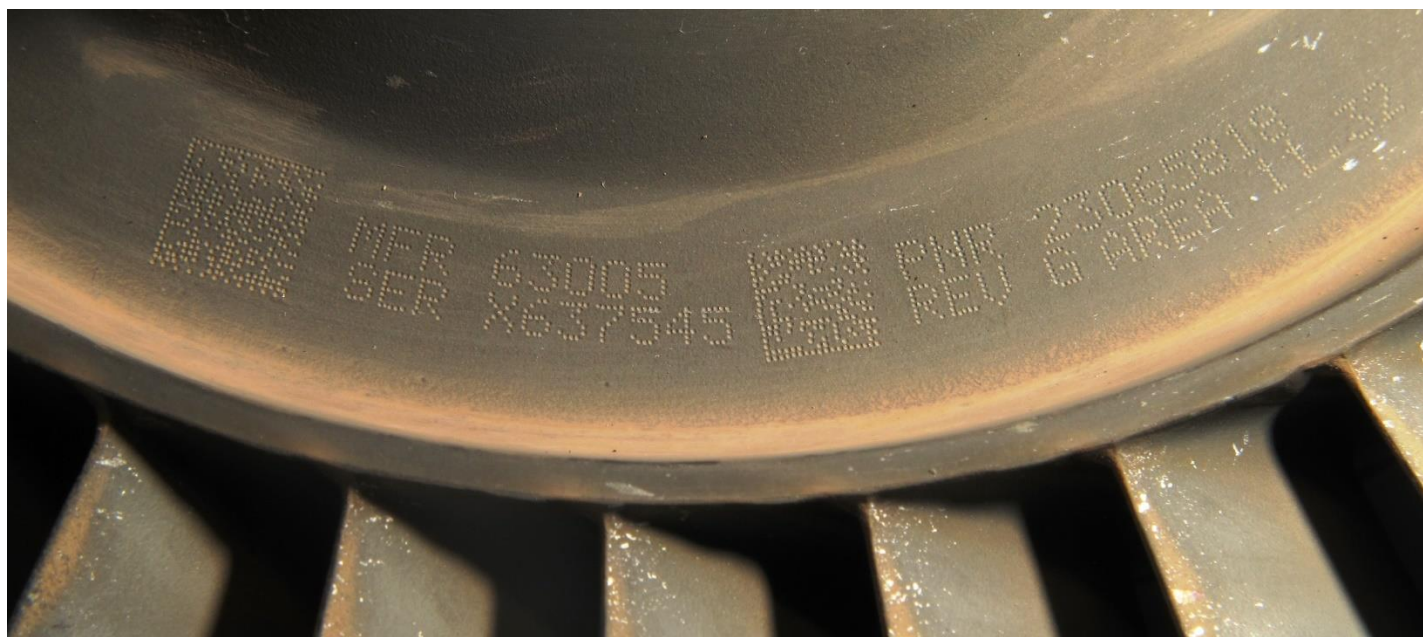


Figure 4. Detailed view showing the part markings on the third stage turbine wheel.



Figure 5. Detailed trailing edge view showing the fractured airfoils and shroud adjacent to the liberated airfoil on the third stage turbine wheel.

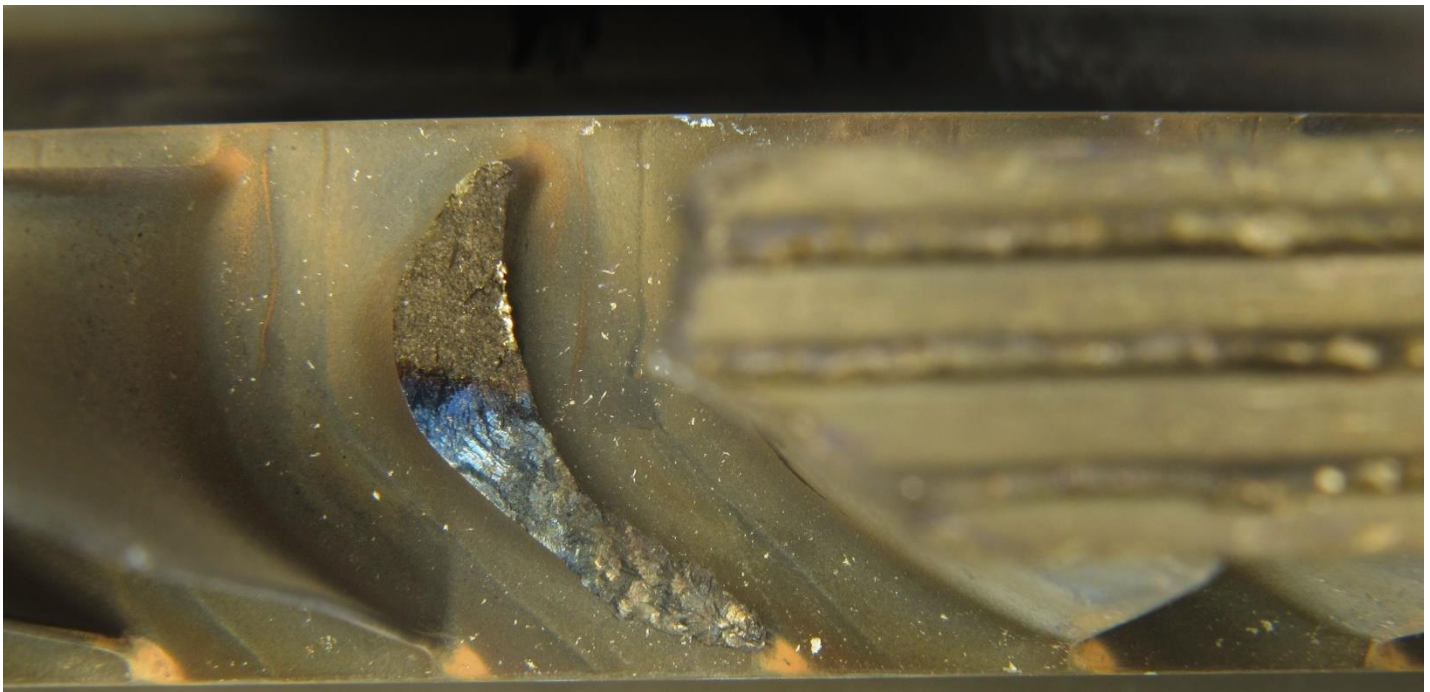


Figure 6. Fracture surface on airfoil #1 near the root.

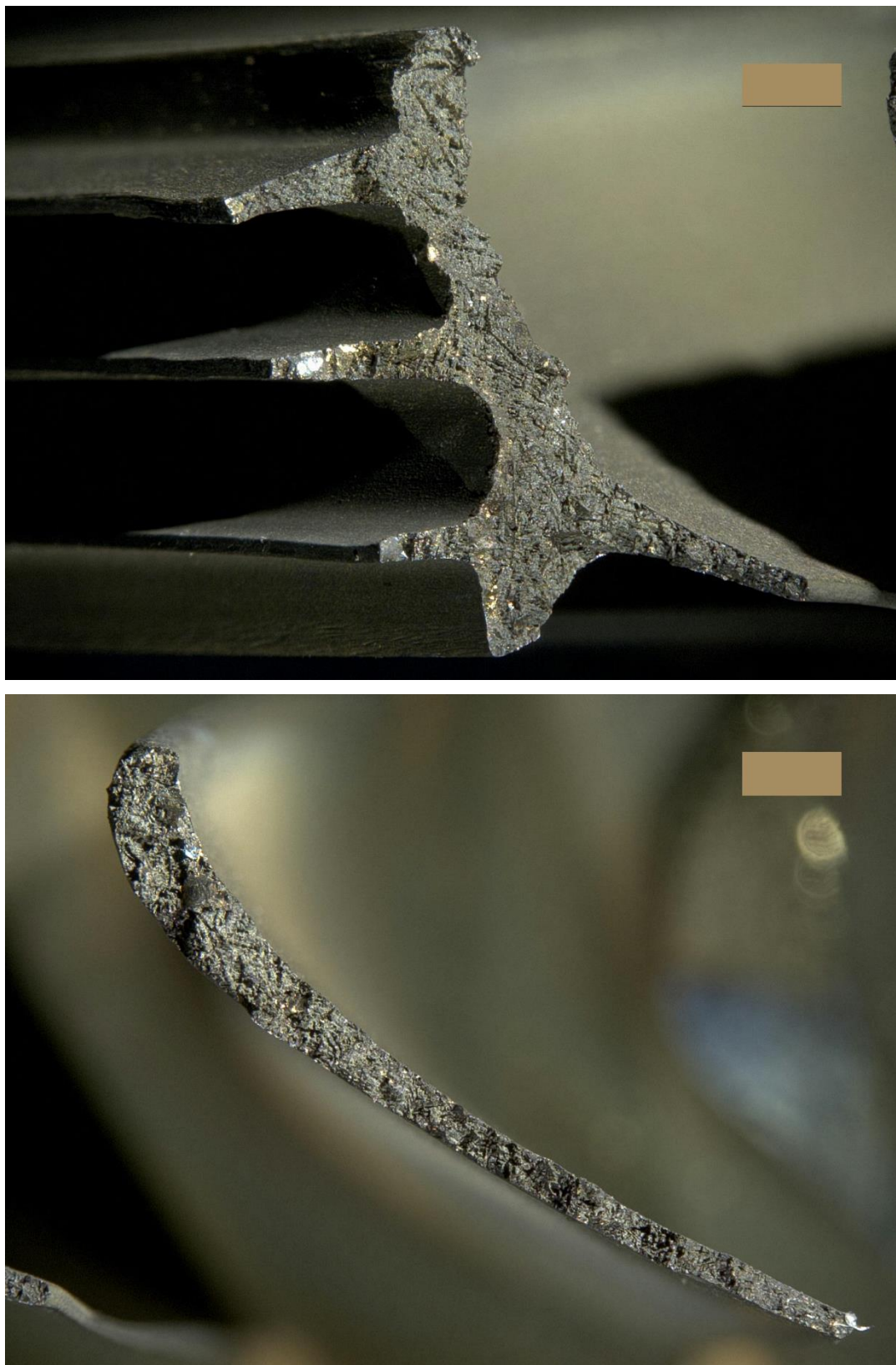


Figure 7. Detailed views of the fracture surfaces on airfoils #34 (top) and #35 (bottom).

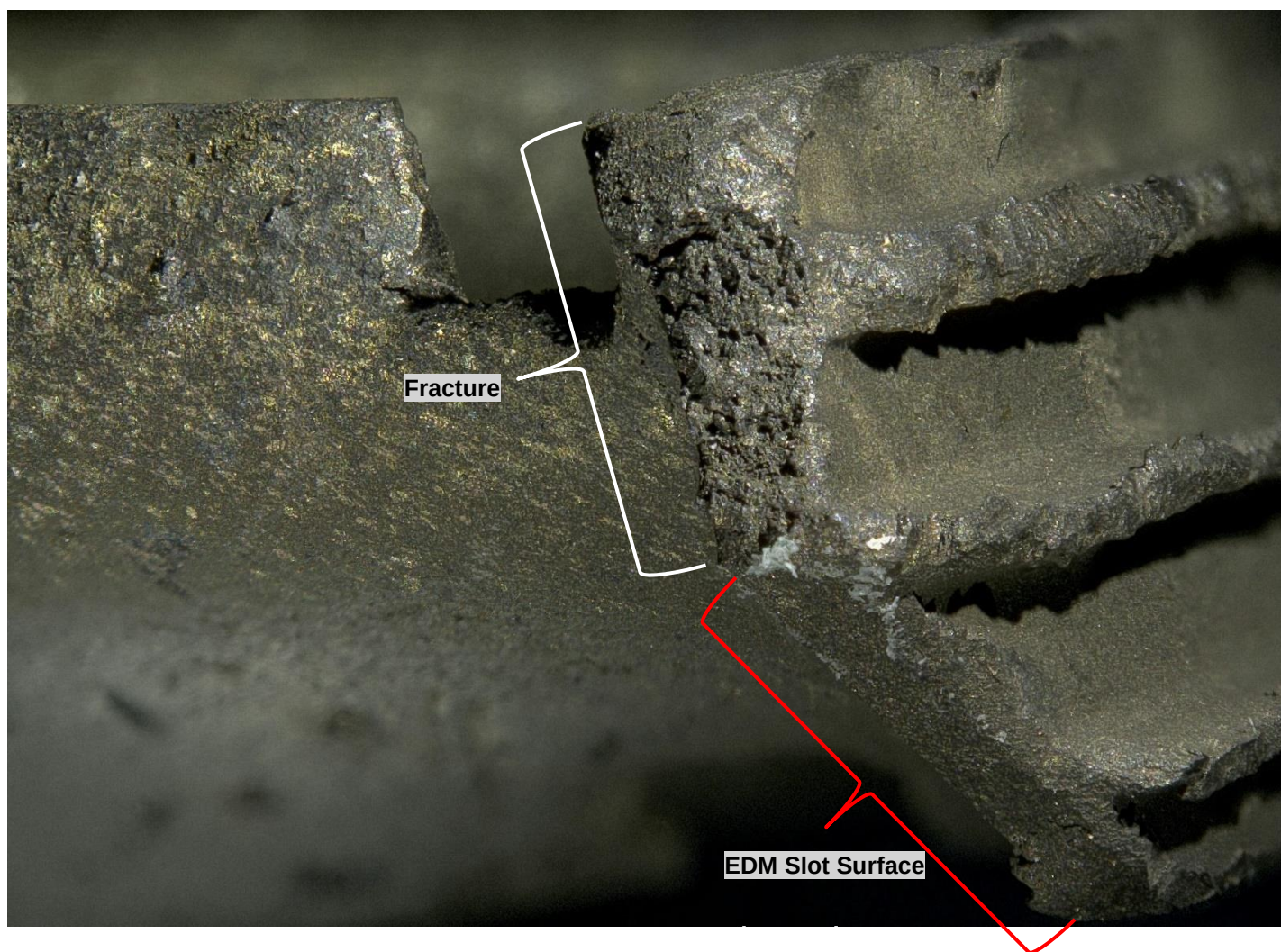


Figure 8. Detailed view showing the fracture through the shroud adjacent to the EDM slot outboard of airfoil #2.



Figure 9. Four views of the third stage turbine wheel showing the extent of the rub damage to the knife seals and shroud. Each image is rotated ~90° from previous in the direction of turbine rotation.

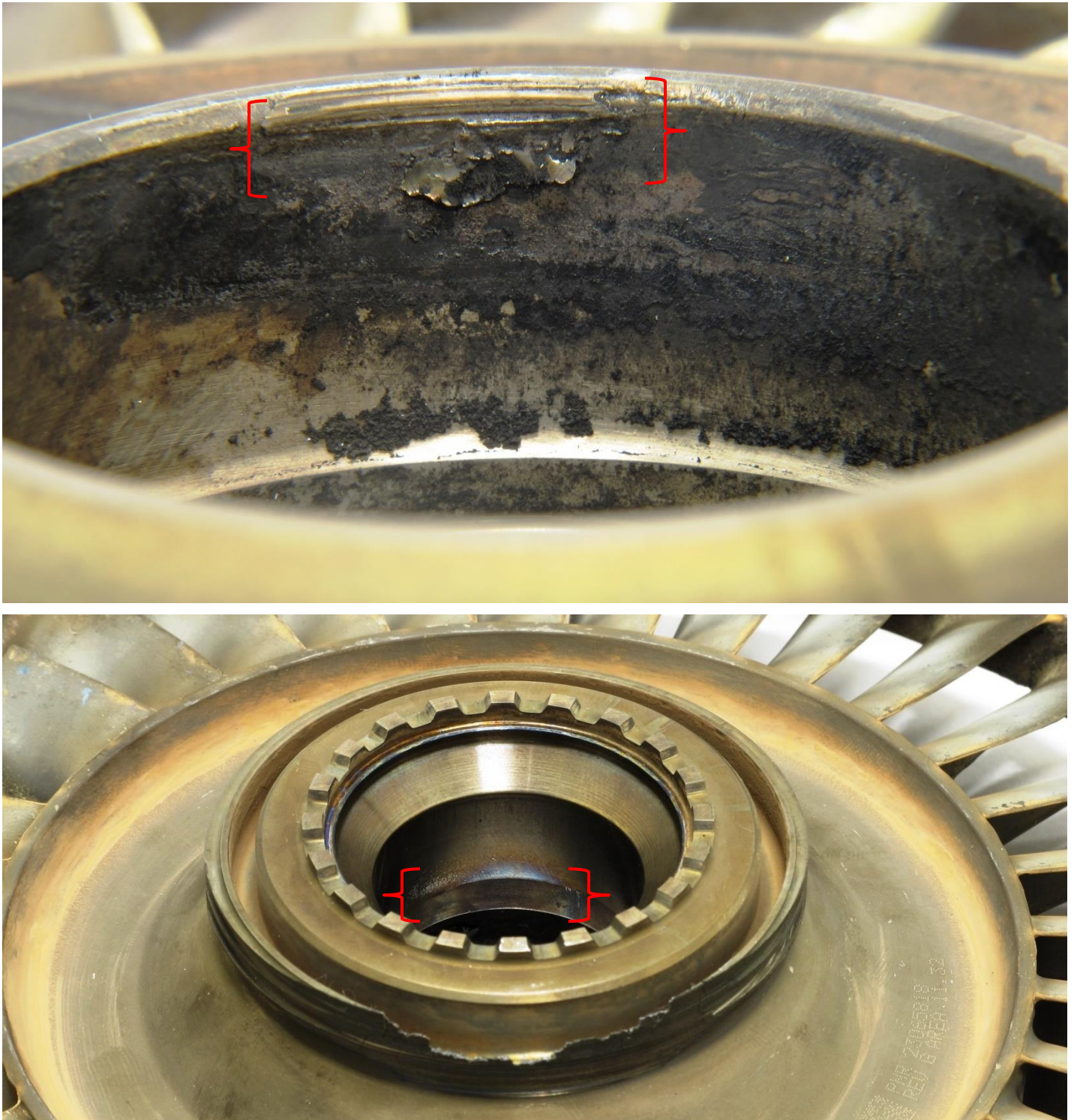


Figure 10. Detailed views showing rub damage (red braces) on the leading edge (top) and trailing edge (bottom) sides of the bore. The leading edge side of the bore also exhibited coked oil.

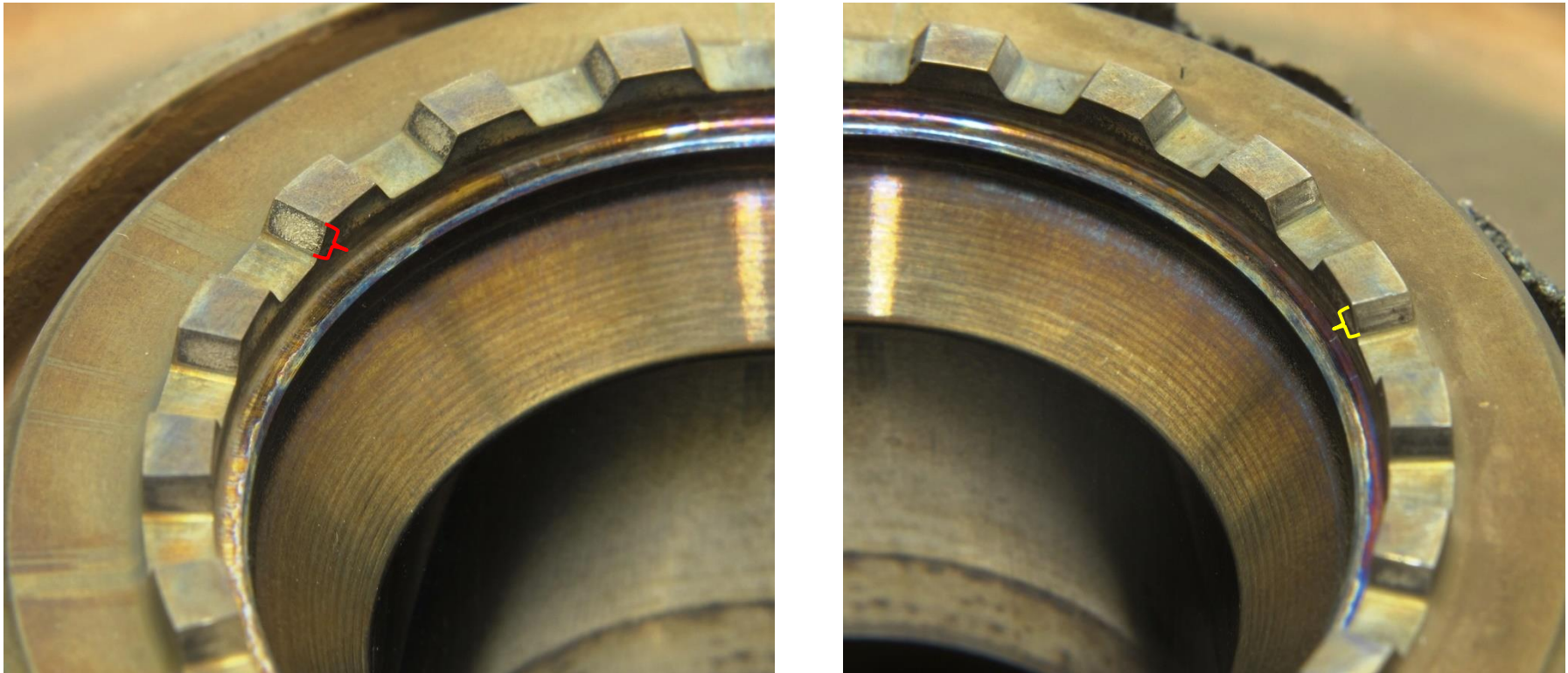


Figure 11. Representative condition of the drive (left, red brace) and coast (right, yellow brace) side flanks of the interstage curvic teeth.

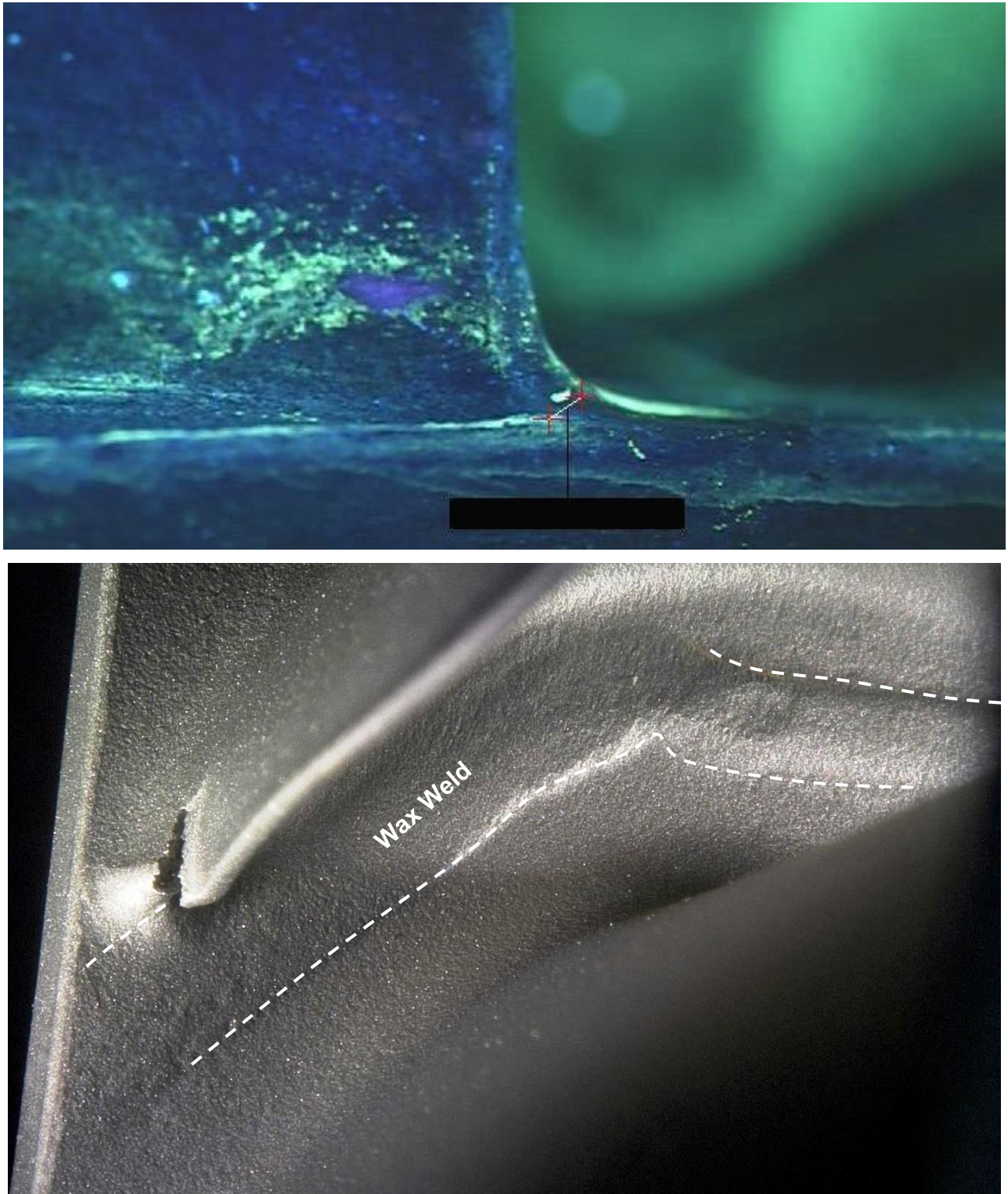


Figure 12. Top: Black light image showing the crack-like FPI indication in the trailing edge root radius of airfoil #8.
Bottom: White light image showing the wax weld on the pressure side of airfoil #8. The wax weld intersected the airfoil root radius.

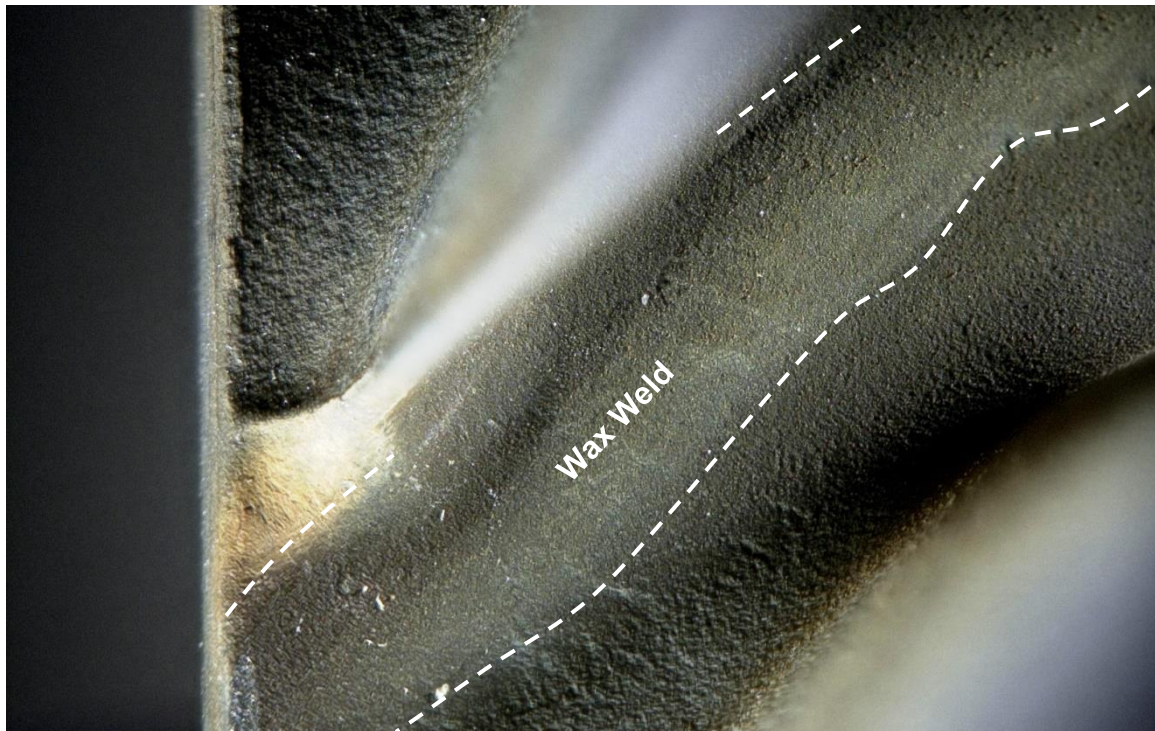
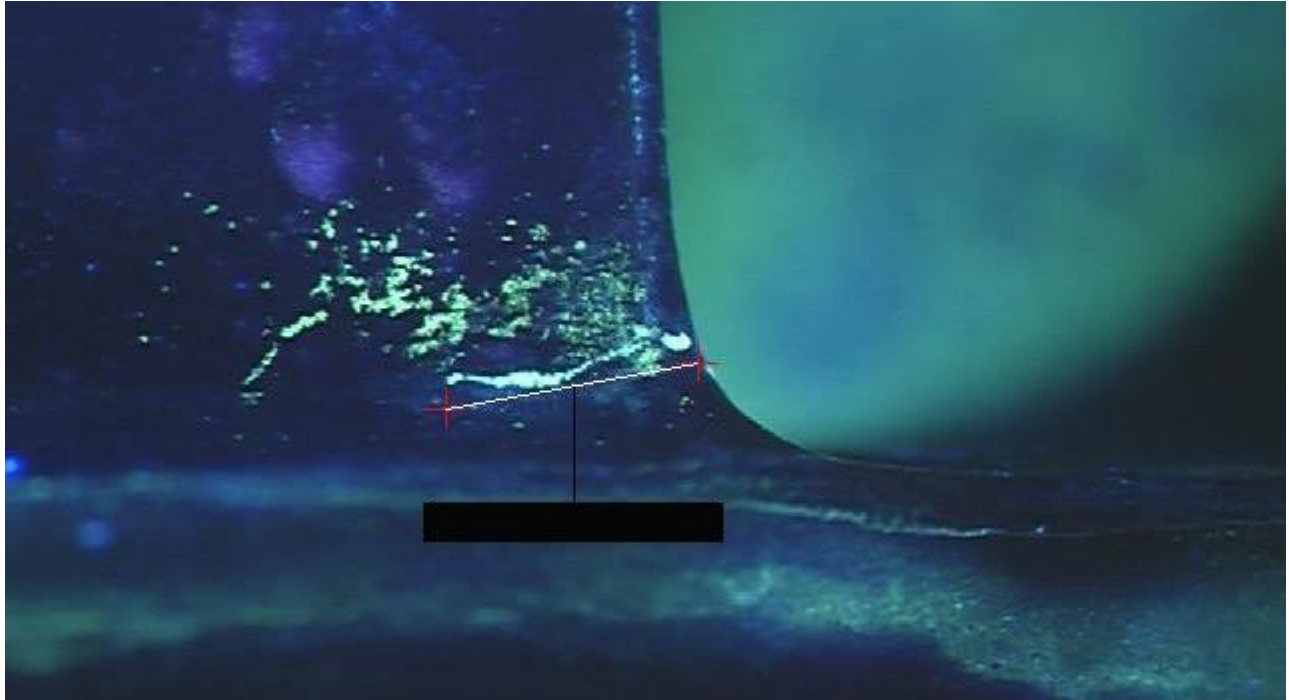


Figure 13. Top: Black light image showing the crack-like FPI indication in the trailing edge root radius of airfoil #15.
Bottom: White light image showing the wax weld on the pressure side of airfoil #15. The wax weld intersected the airfoil root radius.

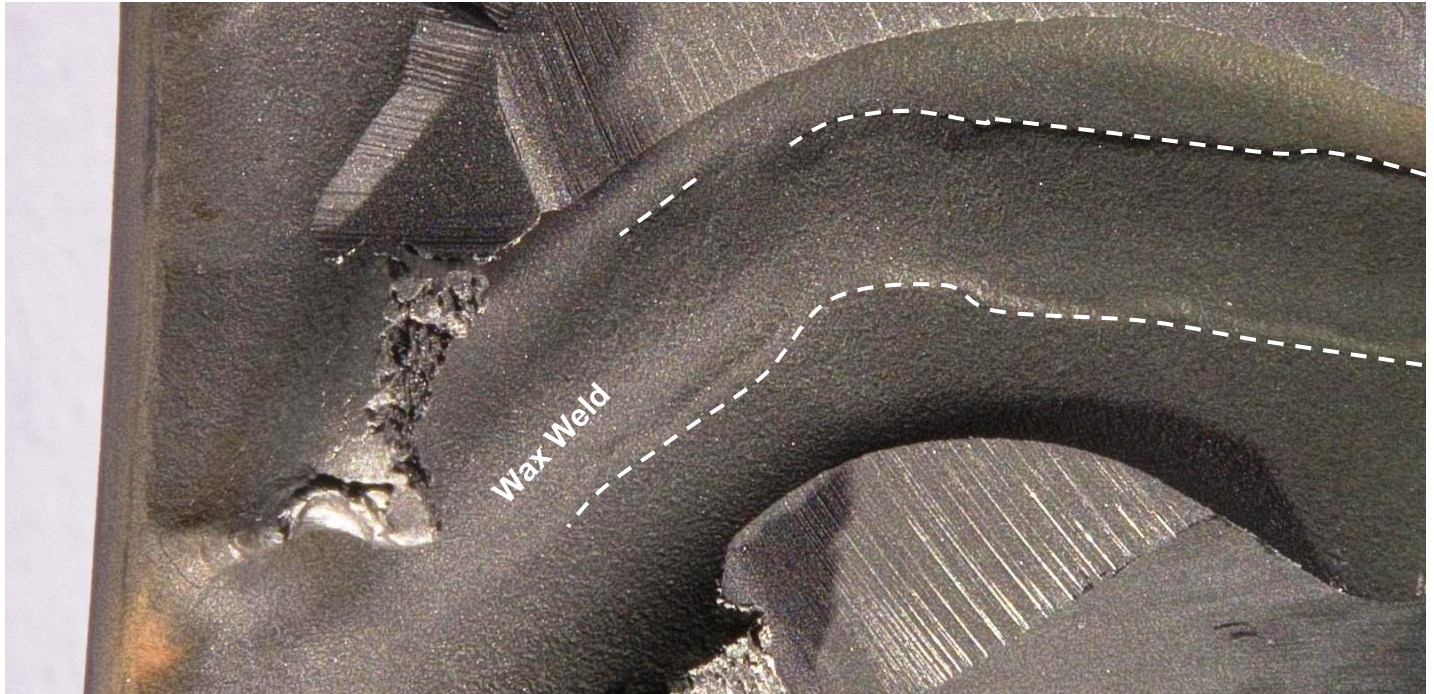
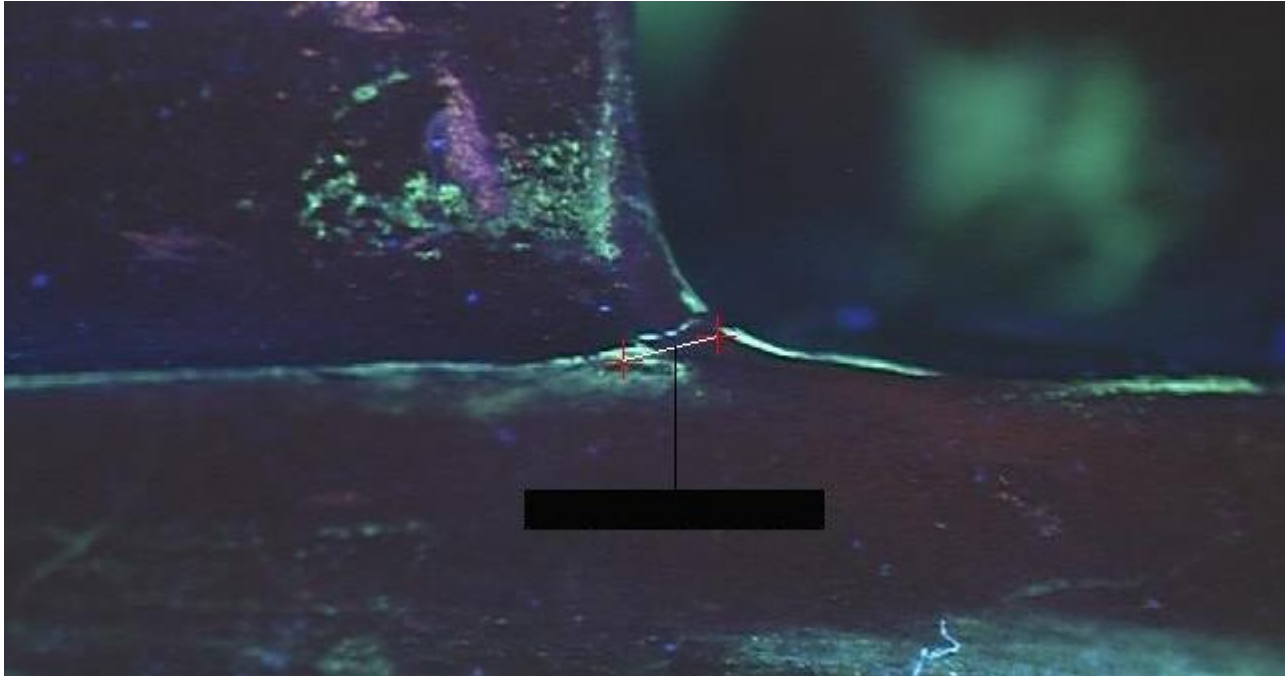


Figure 14. Top: Black light image showing the crack-like FPI indication in the trailing edge root radius of airfoil #22.
Bottom: White light image showing the wax weld on the pressure side of airfoil #22. The wax weld intersected the airfoil root radius.

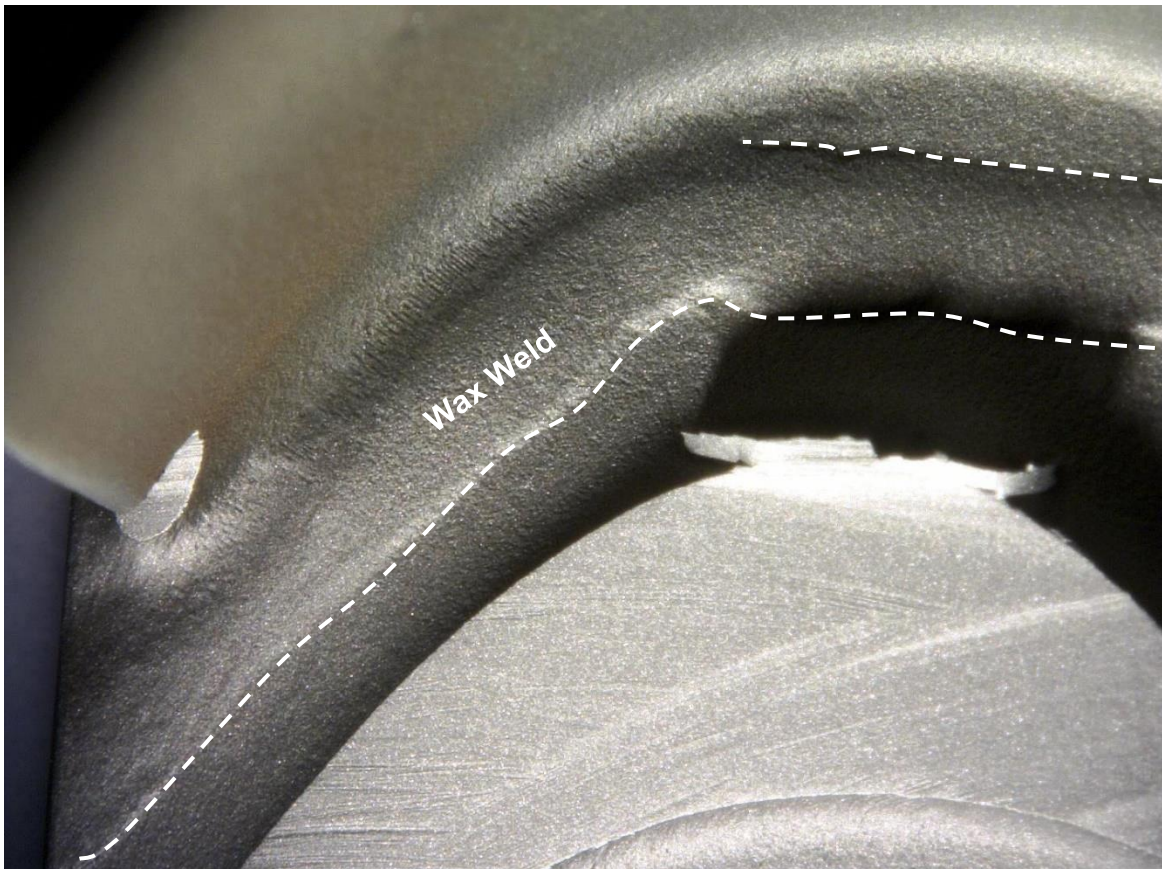
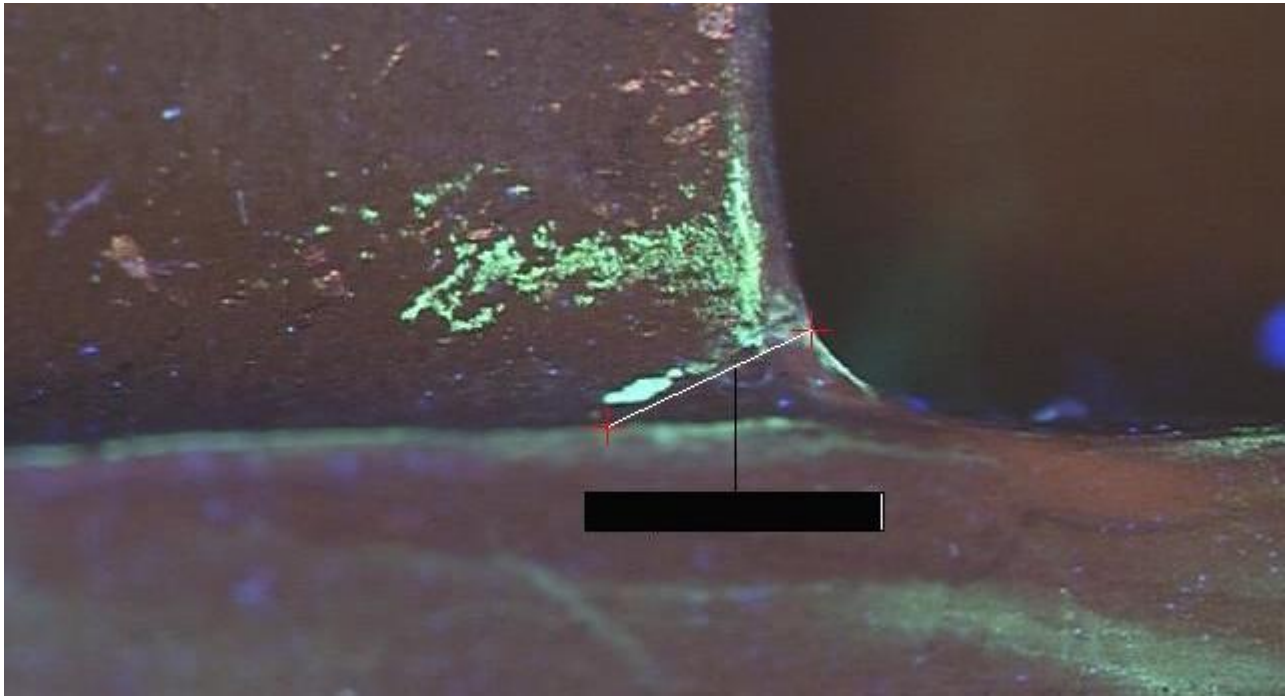


Figure 15. Top: Black light image showing the crack-like FPI indication in the trailing edge root radius of airfoil #29.
Bottom: White light image showing the wax weld on the pressure side of airfoil #29. The wax weld intersected the airfoil root radius.

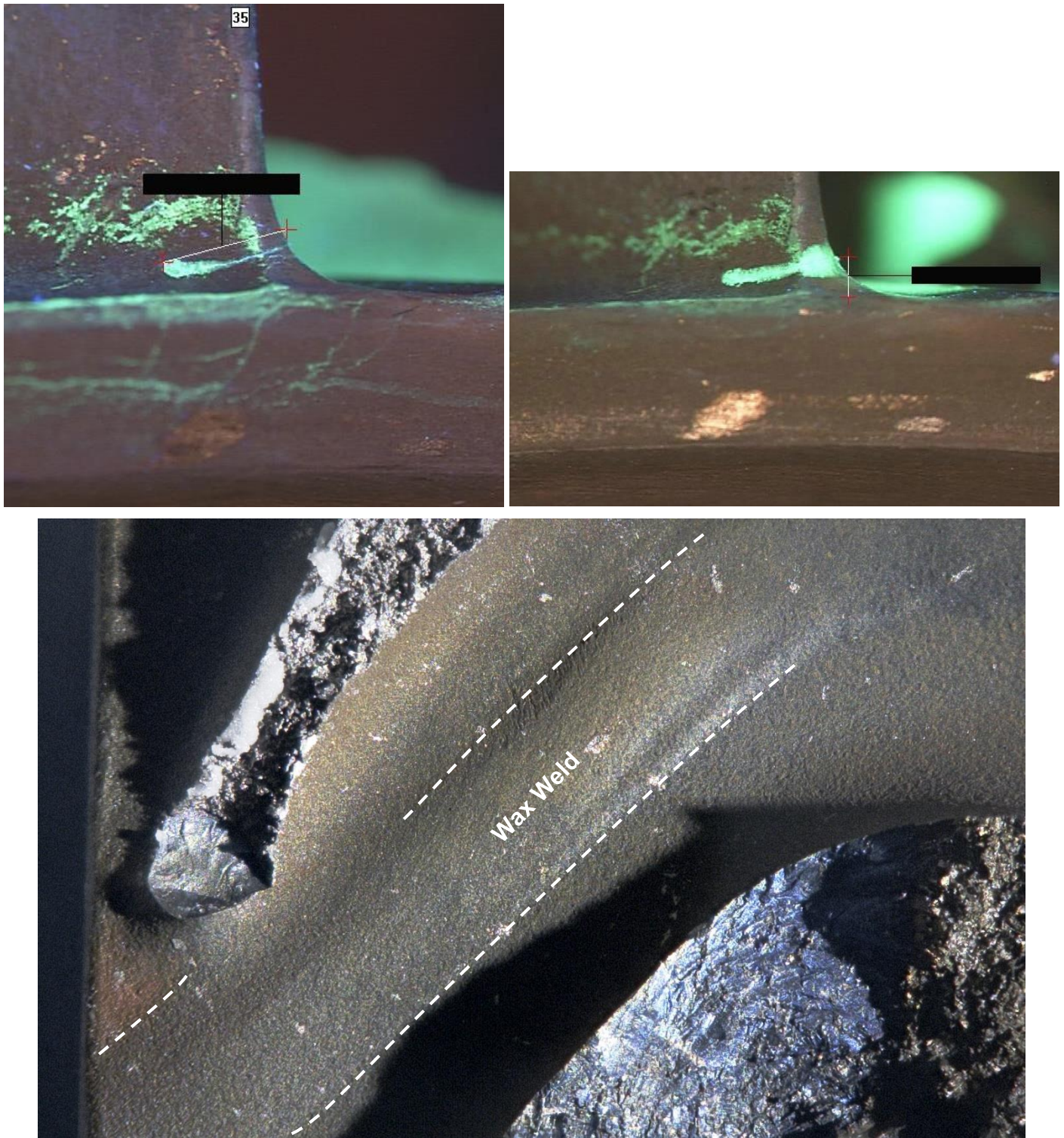


Figure 16. Top: Black light images showing the crack-like FPI indication in the trailing edge root radius of airfoil #35.
Bottom: White light image showing the wax weld on the pressure side of airfoil #35. The wax weld intersected the airfoil root radius.

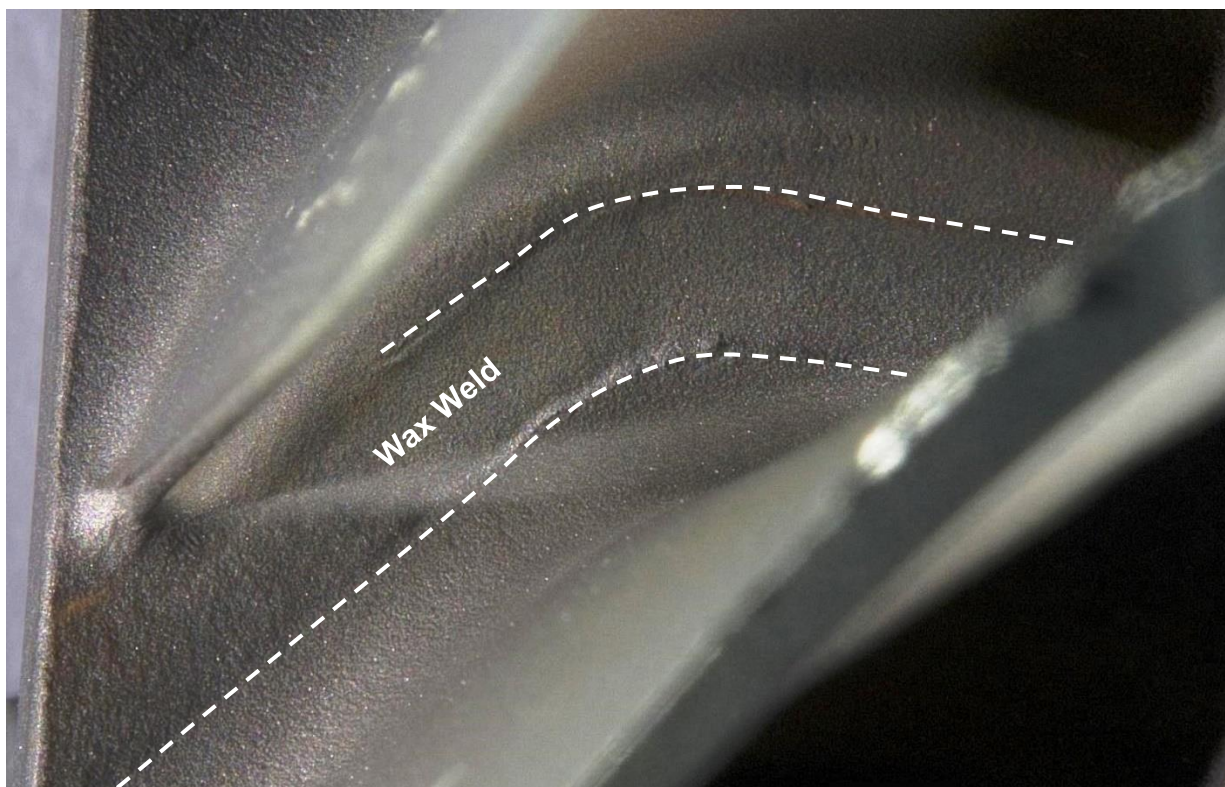
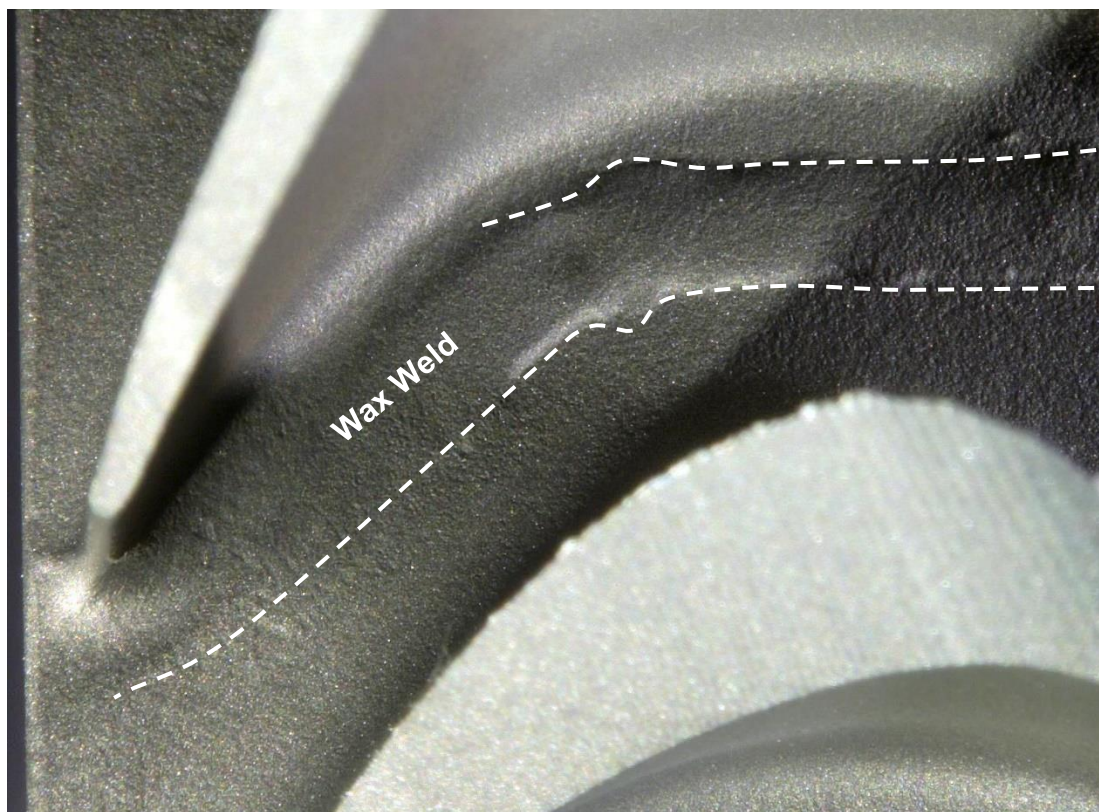


Figure 17. Detailed views showing the wax weld on the pressure side of airfoils #11 (top) and #24 (bottom). The wax weld intersected the airfoil root radius of both airfoils.

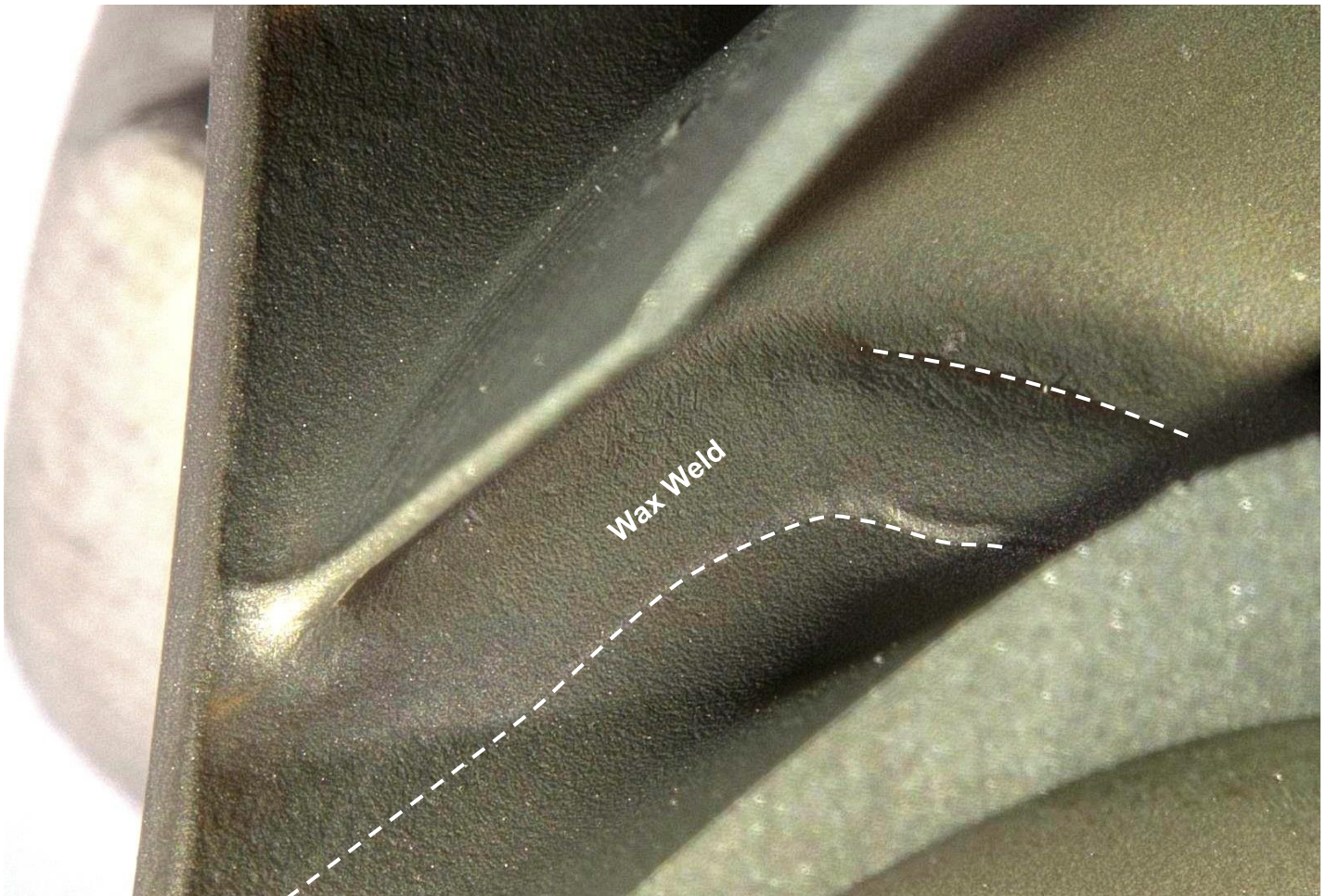


Figure 18. Detailed view showing the wax weld on the pressure side of airfoil #25. The wax weld intersected the airfoil root radius.



Figure 19. Detailed trailing edge view of airfoil #1 showing the geometry of the fillet and the profile of the fracture surface. The fracture initiated approximately 0.025 inch outboard of the rim.

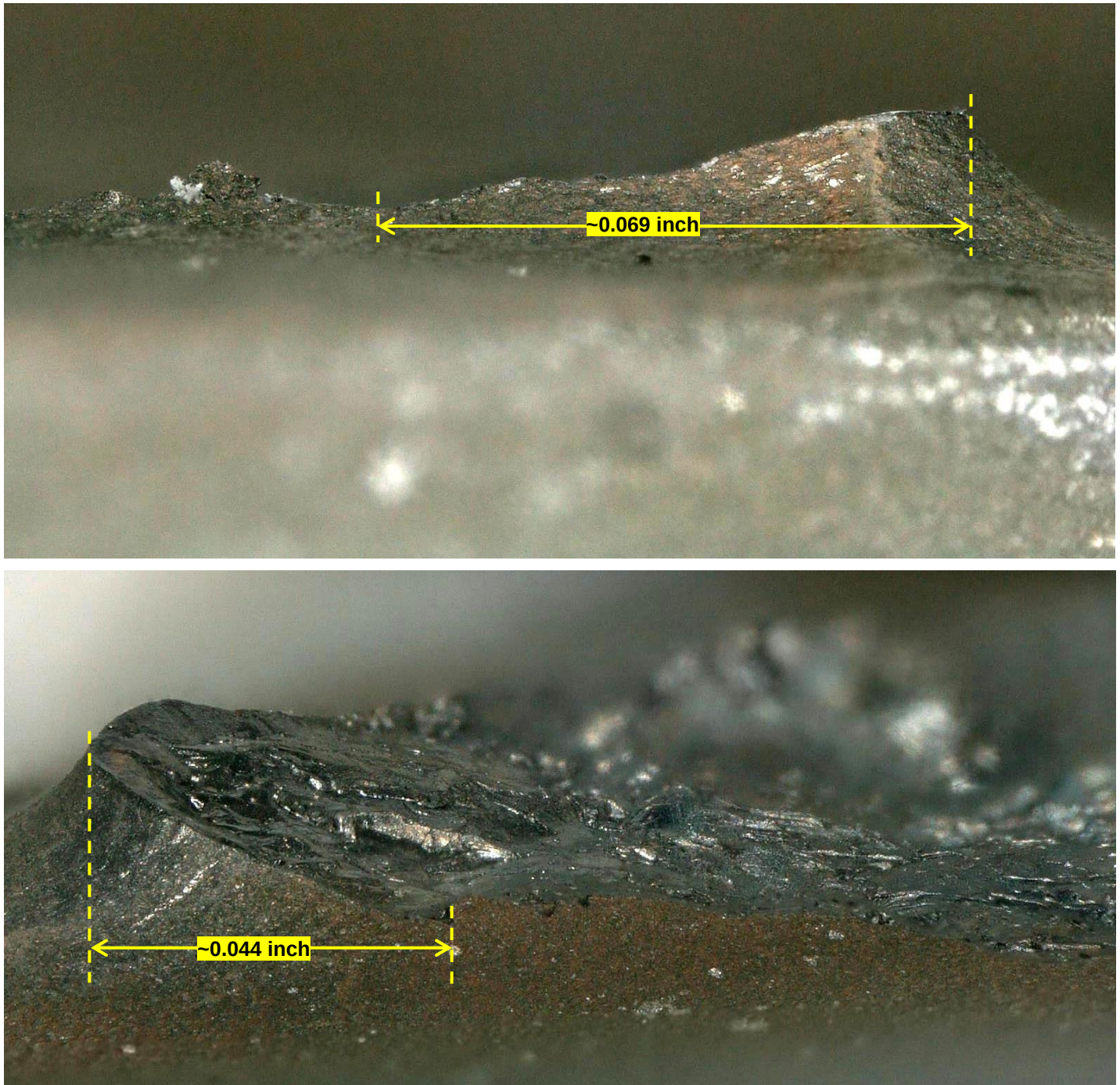


Figure 20. Suction (top) and pressure (bottom) side views of the trailing edge area of the fracture. The fracture progressed inboard from the trailing edge before turning to propagate approximately parallel to the rim surface.

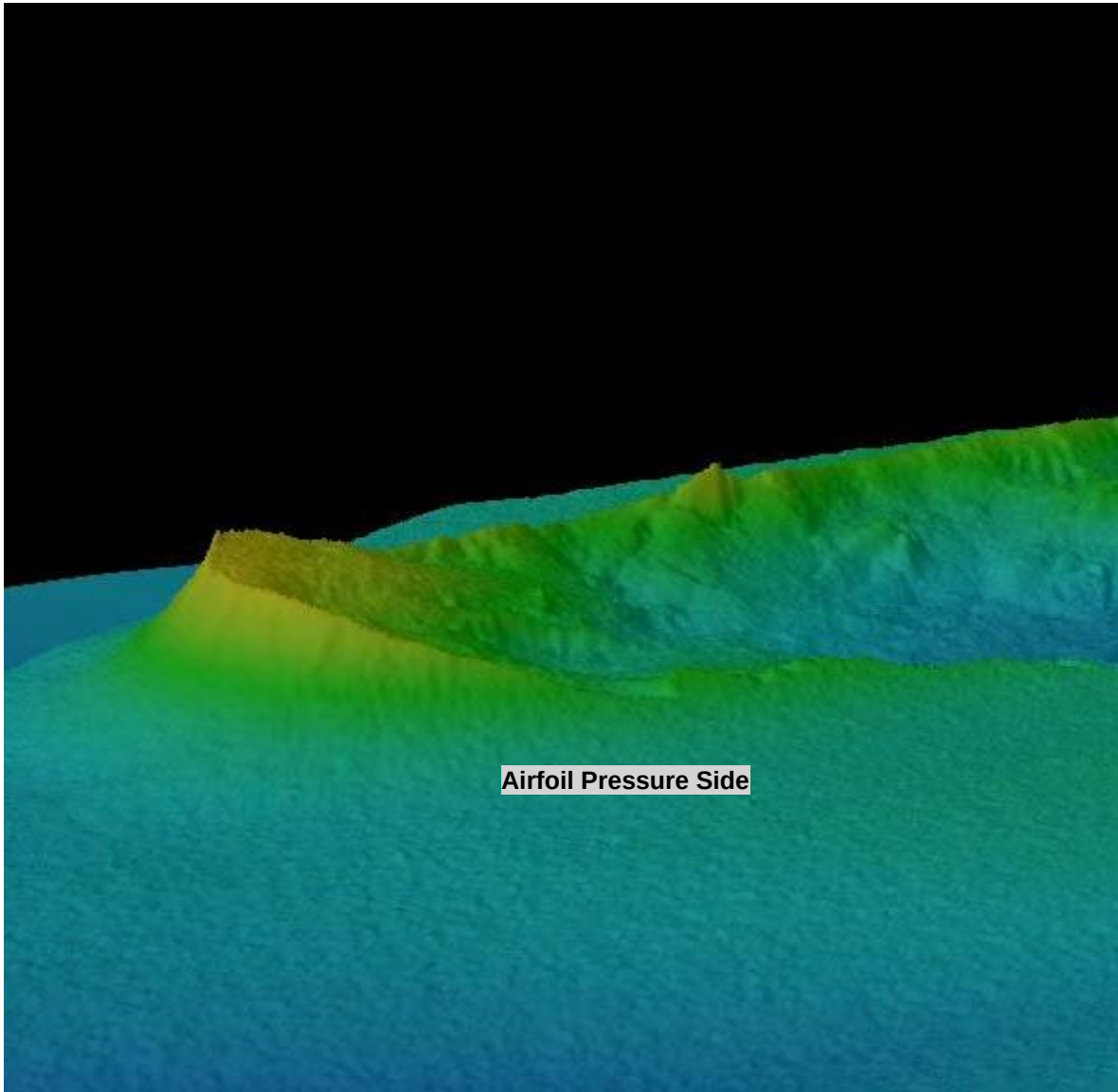


Figure 21. Confocal laser scanning microscope (CLSM) scan of the trailing edge of airfoil #1 showing the profile of the fracture surface.

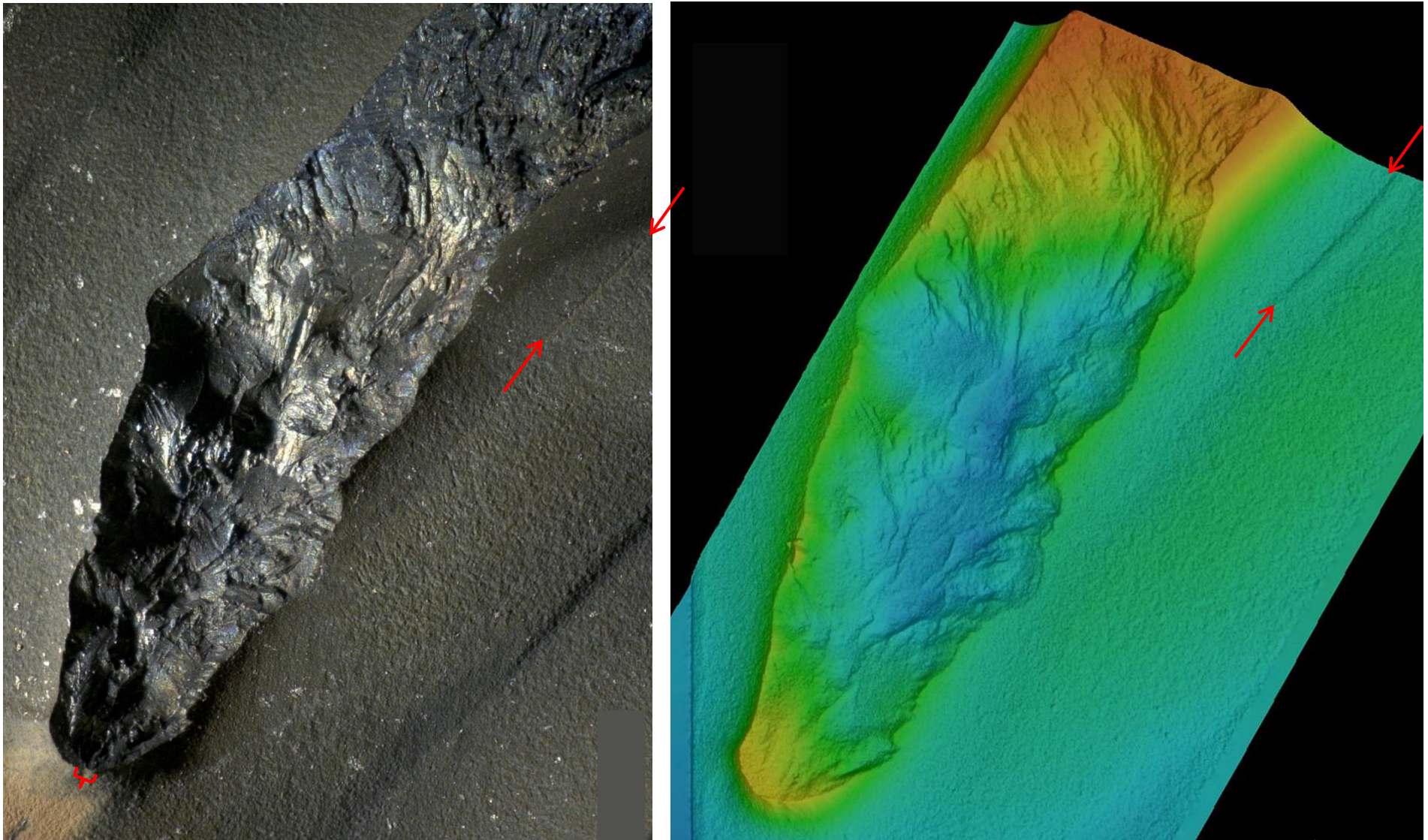


Figure 22. Optical image (left) and confocal laser scanning microscope (CLSM) topographical scan (right) of the trailing edge of airfoil #1 showing the location of the pressure side airfoil wax weld (between red arrows) adjacent to airfoil #1. The red brace shows the approximate location of the fatigue origin area shown in Figure 27.

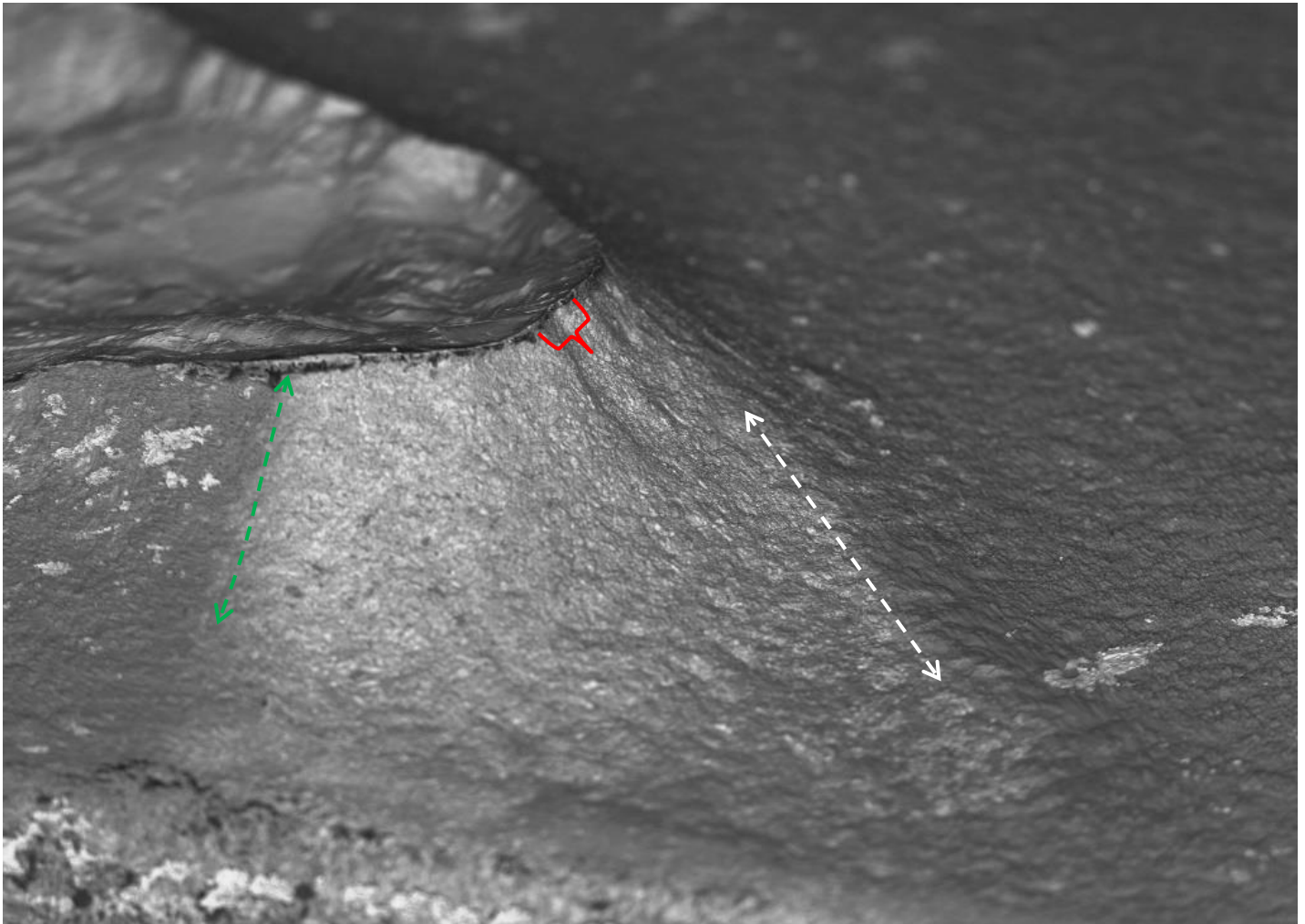


Figure 23. Backscattered electron SEM image showing the airfoil parting line (green dashed line) and the pressure side wax weld (white dashed line) extending out of the fillet radius at the trailing edge tip of the airfoil. The fatigue origin (red brace) was located between the wax weld and parting line.

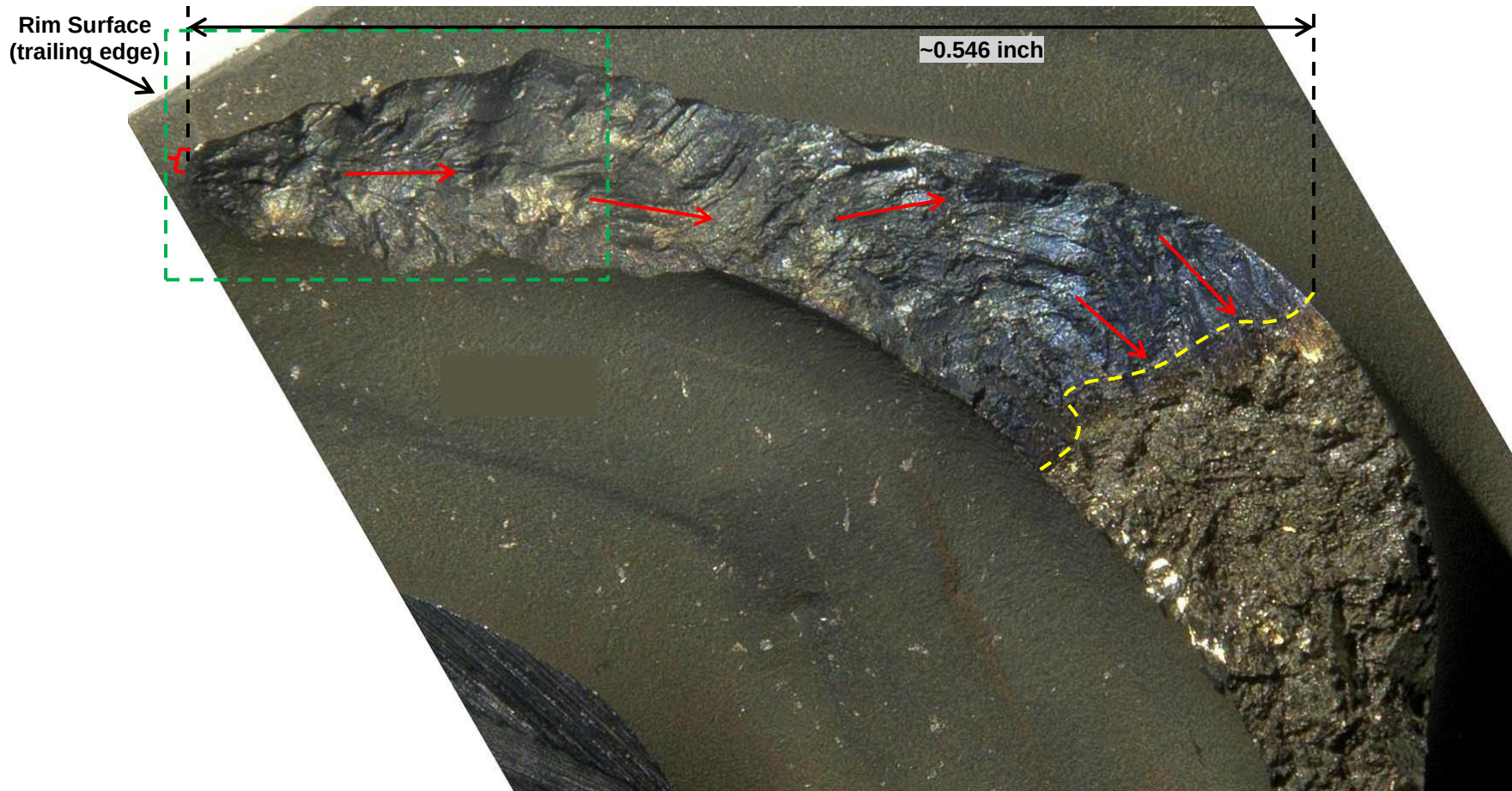


Figure 24. Detailed view of the fracture surface on airfoil #1 showing macroscopic fracture features consistent with fatigue progression (red arrows). The red brace indicates the origin area, shown in more detail in Figure 27. The crack progressed approximately 0.546 inch toward the leading edge before transitioning to overload (yellow dashed line). The green dashed boxed area is shown in more detail in the following figure.

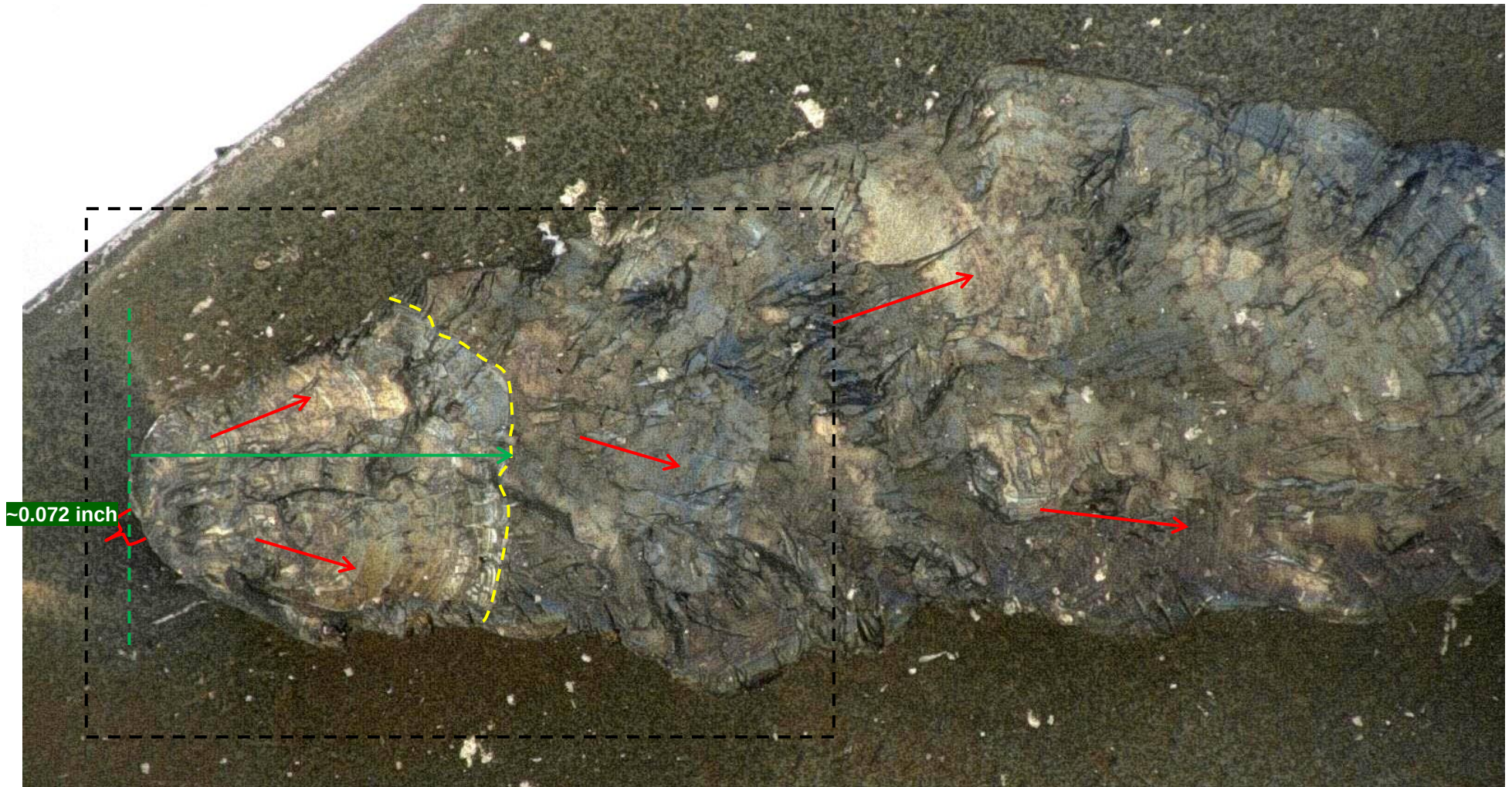


Figure 25. Detailed view showing macroscopic fracture features consistent with fatigue progression (red arrows). The red brace indicates the origin area at the trailing edge. The fracture surface exhibited a change in reflectivity from shiny (left of yellow dashed line) to dull (right of dashed line). The black dashed boxed area is shown in more detail in the following figure.

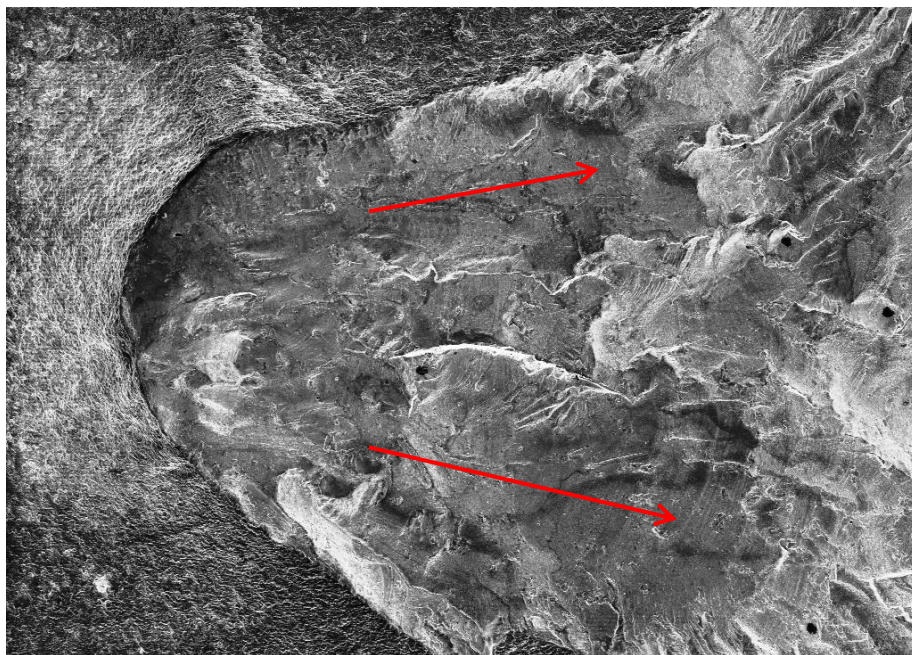
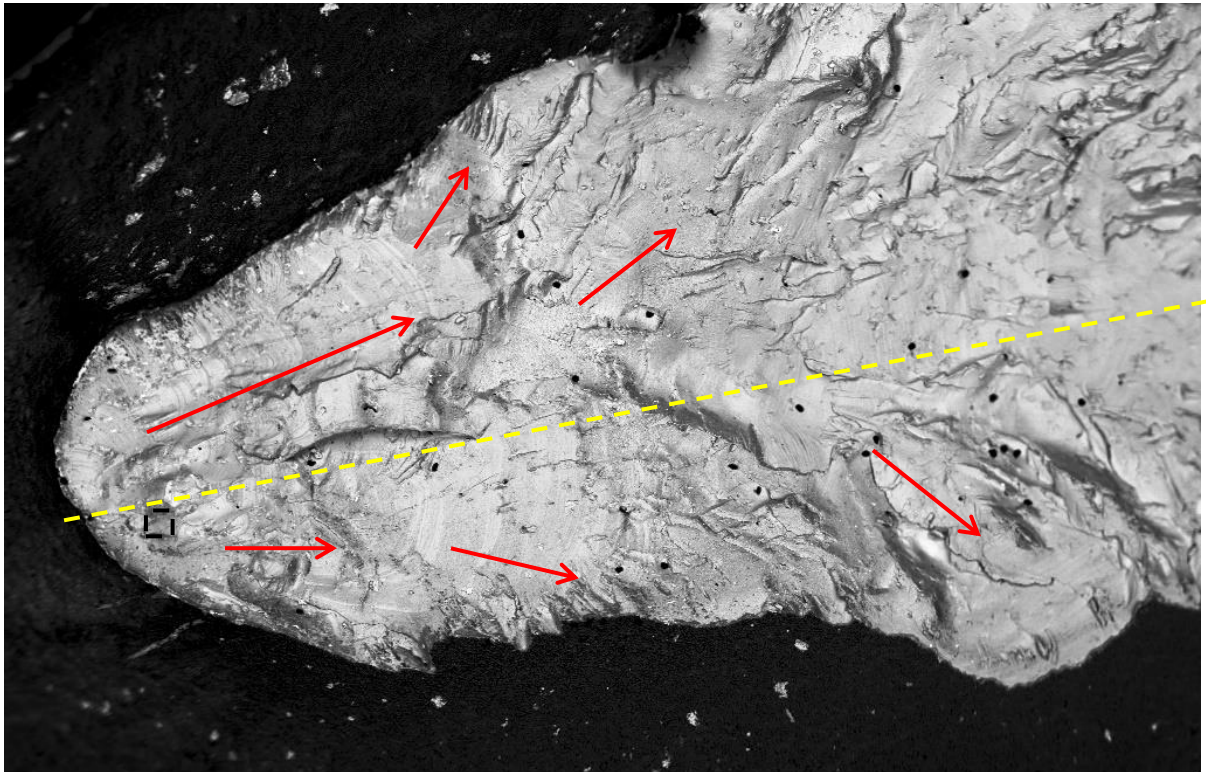


Figure 26. Backscattered (top) and secondary (bottom) electron SEM images of the fracture surface at the trailing edge of airfoil #1 showing fracture features consistent with fatigue progression (red arrows). The yellow dashed line indicates the plane of metallographic examination. The black dashed boxed area is shown in more detail in Figure 29.

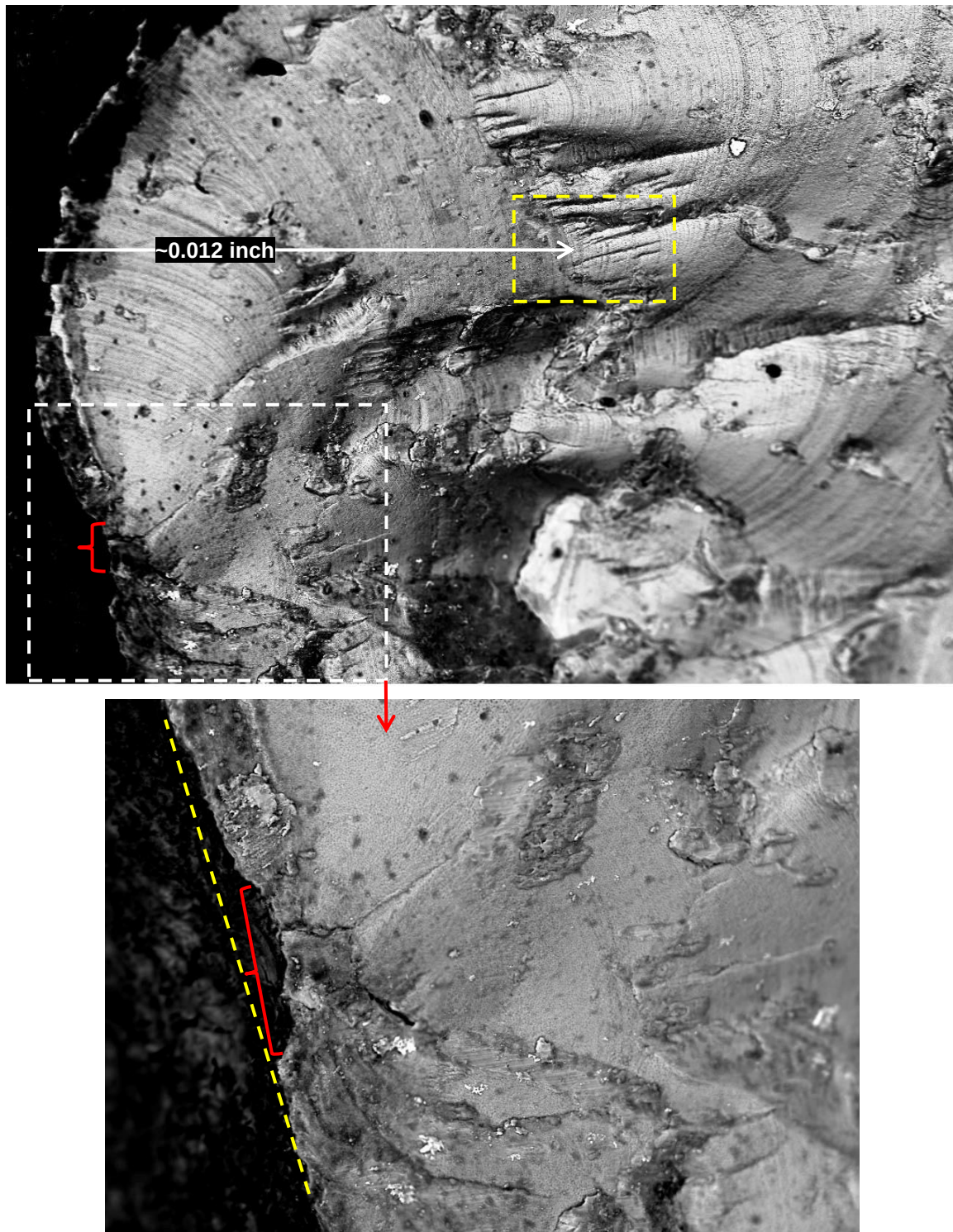


Figure 27. Detailed backscattered electron SEM images of the fracture surface at the trailing edge (top) and the fatigue origin area (bottom, red brace). The trailing edge surface was puckered inward at the origin (yellow dashed line on trailing edge profile for emphasis). The yellow dashed boxed area is shown in more detail in Figure 28.

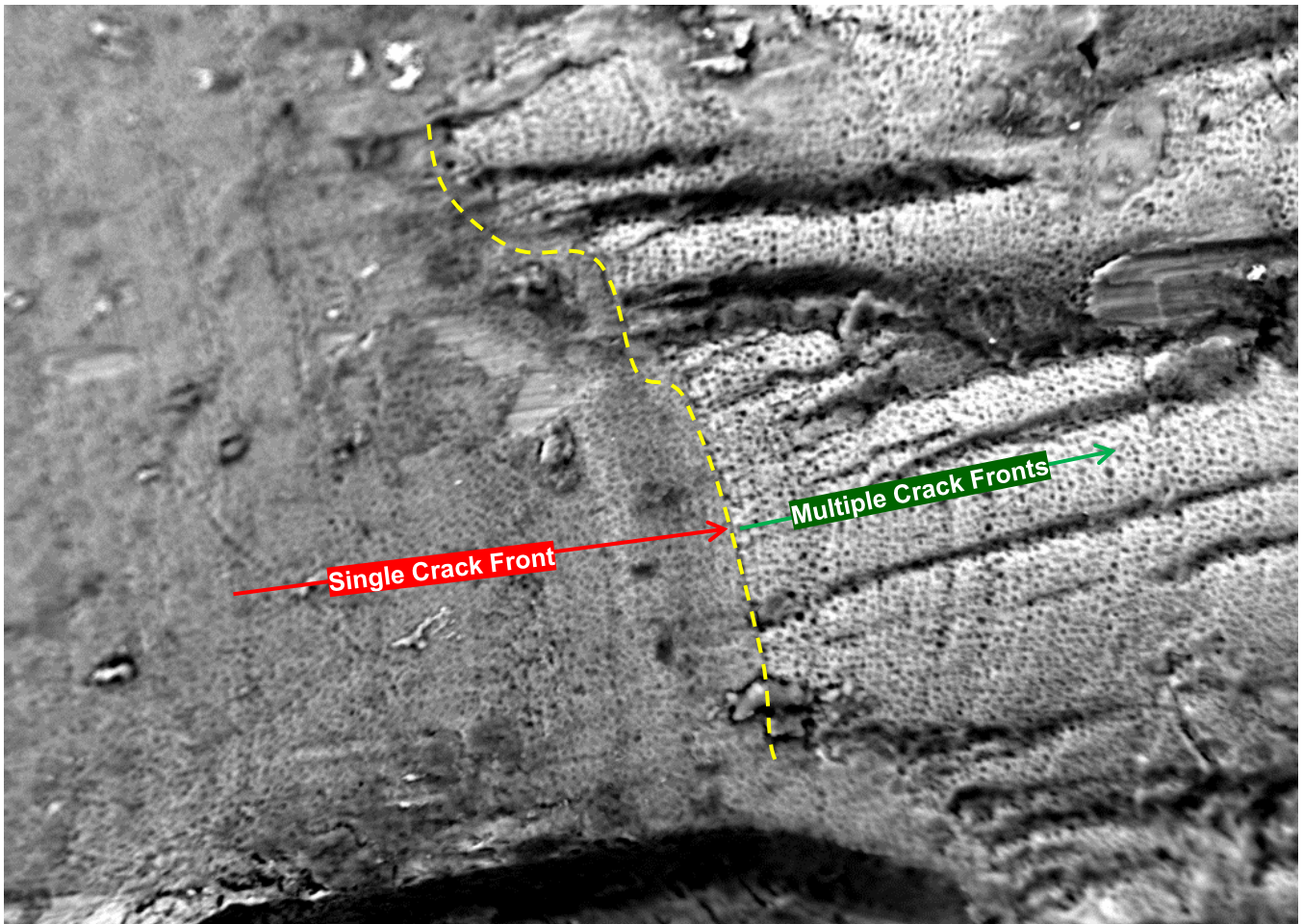


Figure 28. Detailed view showing one location where the fracture transitioned from a single crack front (left of yellow dashed line) to multiple crack fronts (right of line).

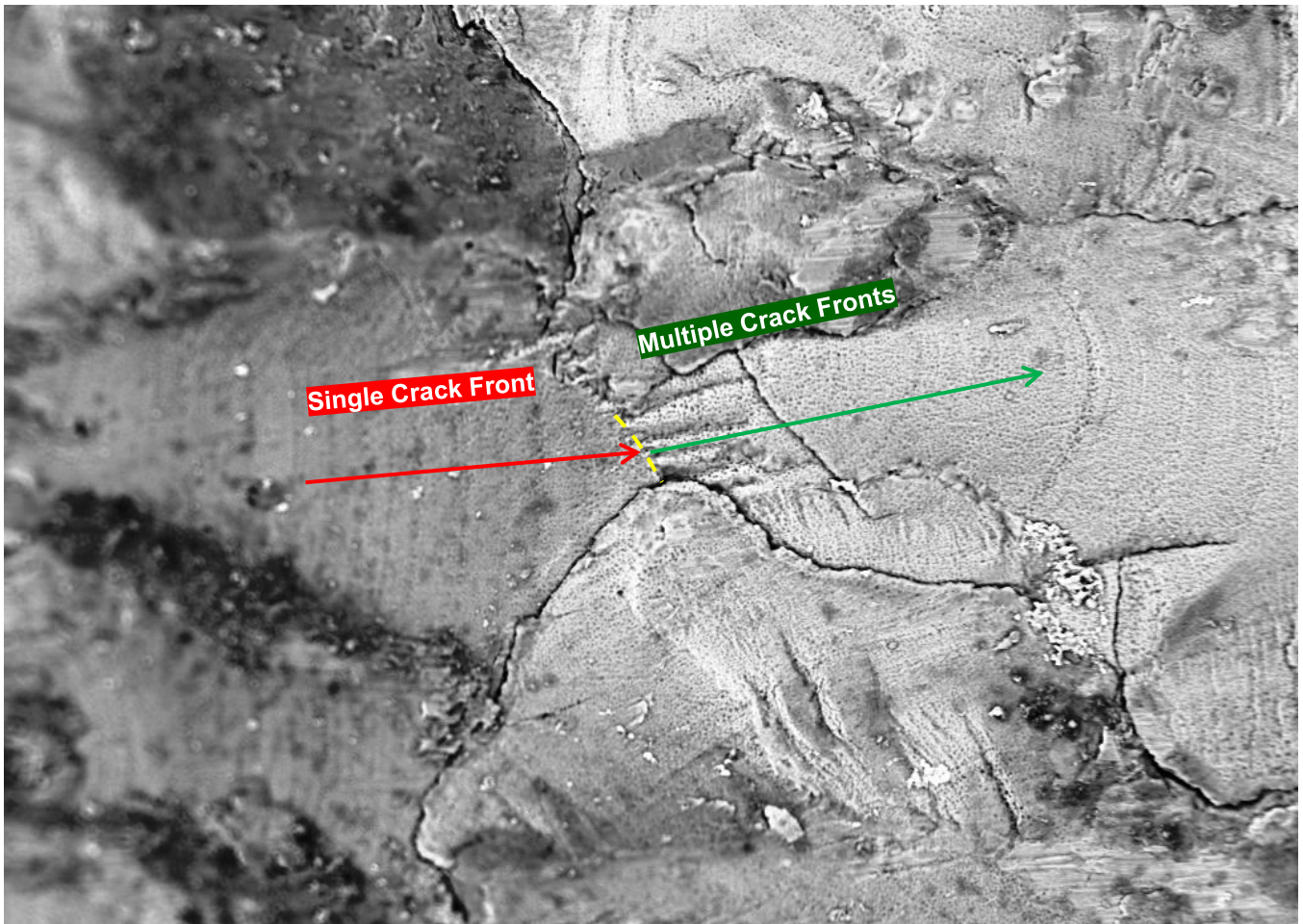


Figure 29. Detailed view showing another location where the fracture transitioned (yellow dashed lines) from a single crack front (red arrow) to multiple crack fronts (green arrow).

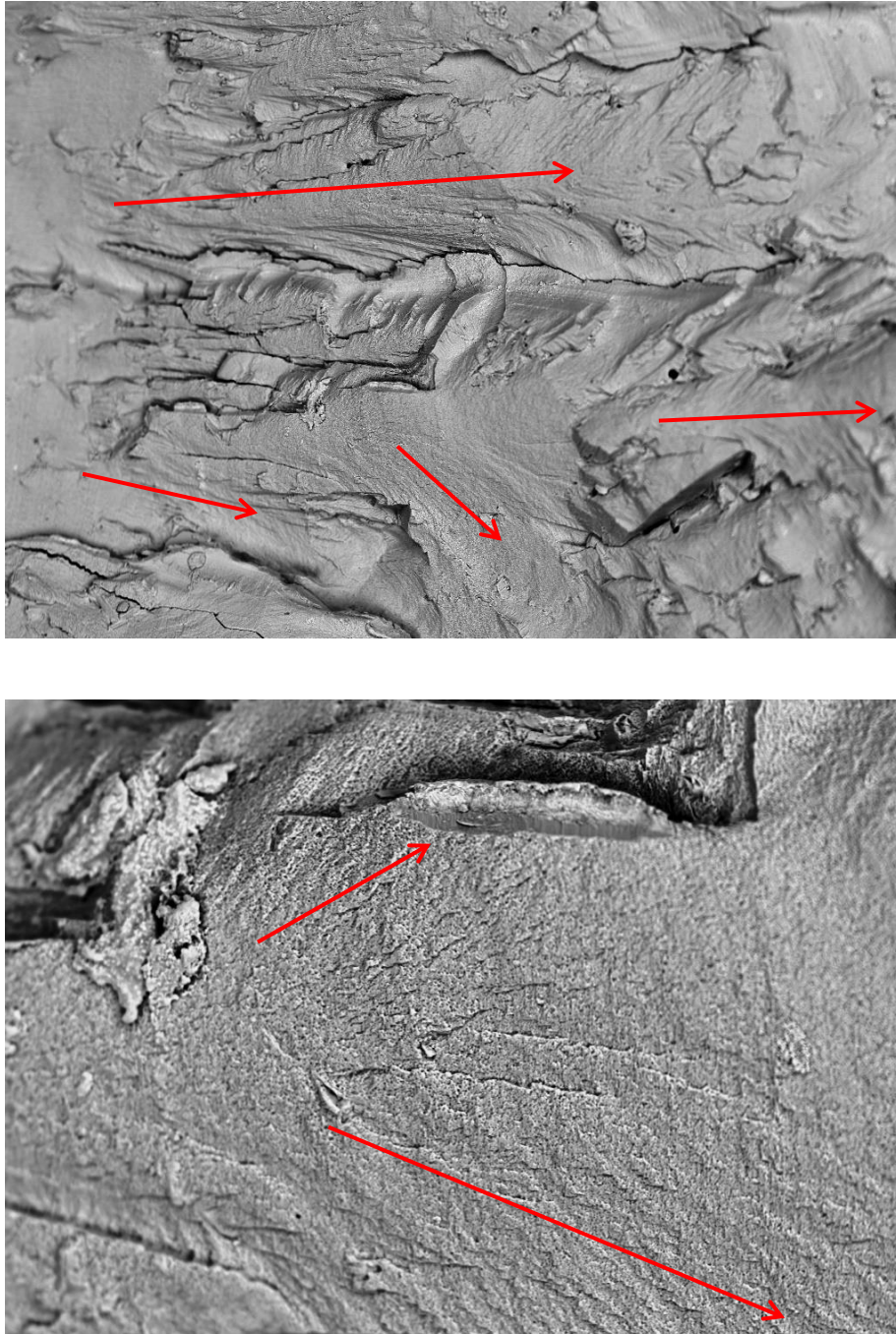


Figure 30. Backscattered electron SEM images showing representative fatigue fracture features (red arrows) remote from the trailing edge area.

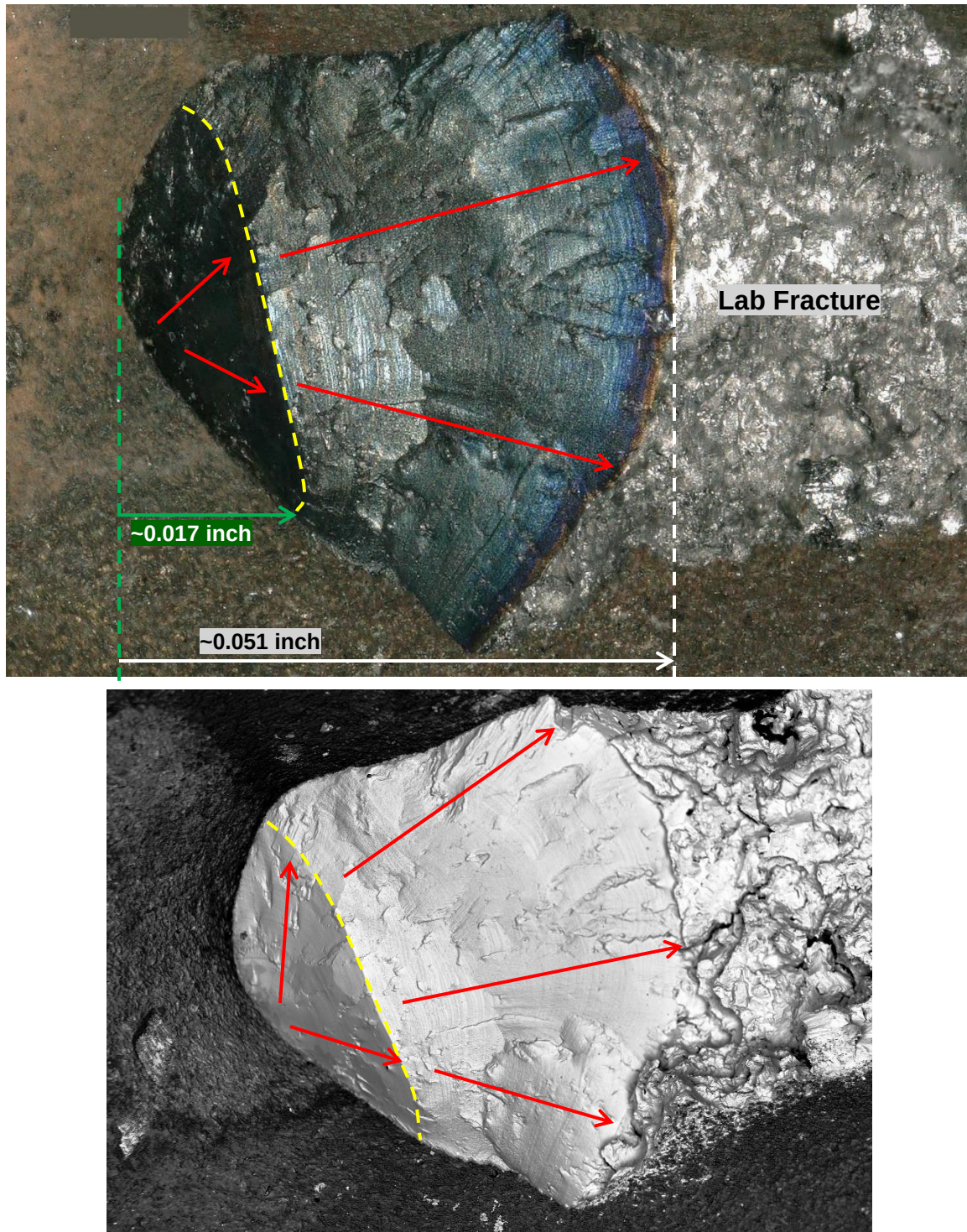


Figure 31. Optical (top) and backscattered electron SEM (bottom) images showing fracture features consistent with fatigue progression (red arrows) at the trailing edge of airfoil #35. The fracture progressed inboard from the trailing edge tip before turning to propagate approximately parallel to the rim surface. The darker appearance of the fracture surface (left of yellow dashed line) on the inboard plane of propagation was a geometric effect and did not indicate any gradient in oxidation on the fracture surface.

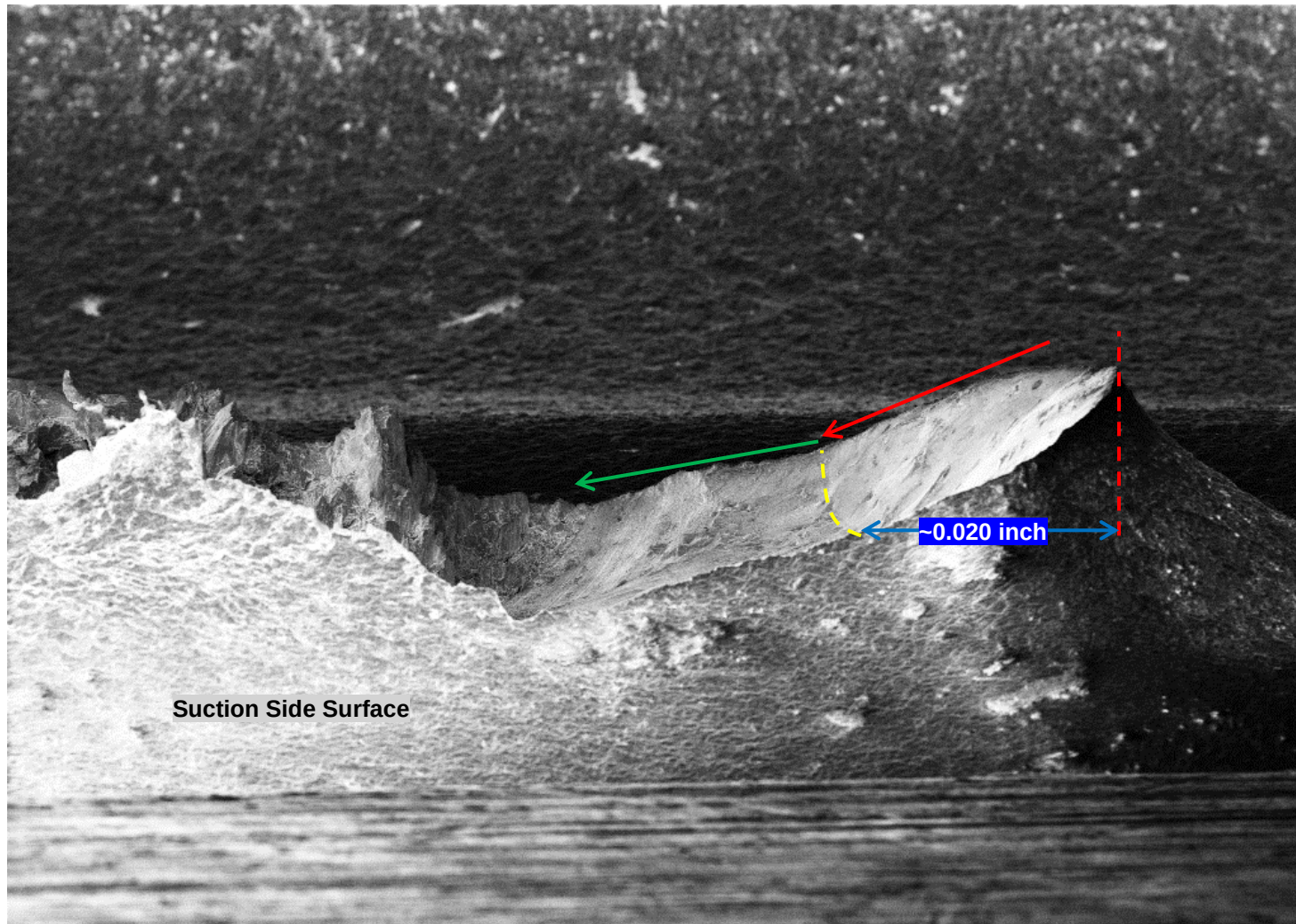


Figure 32. SEM image showing a suction side view of the fracture surface in airfoil #35. The yellow dashed line indicates where the fracture turned from propagating inboard and toward the leading edge (right of dashed line, red arrow) to propagate toward the leading edge approximately parallel to the rim (left of dashed line, green arrow). The change in propagation direction was coincident with the change in fracture surface appearance denoted by the yellow dashed line in Figure 31.

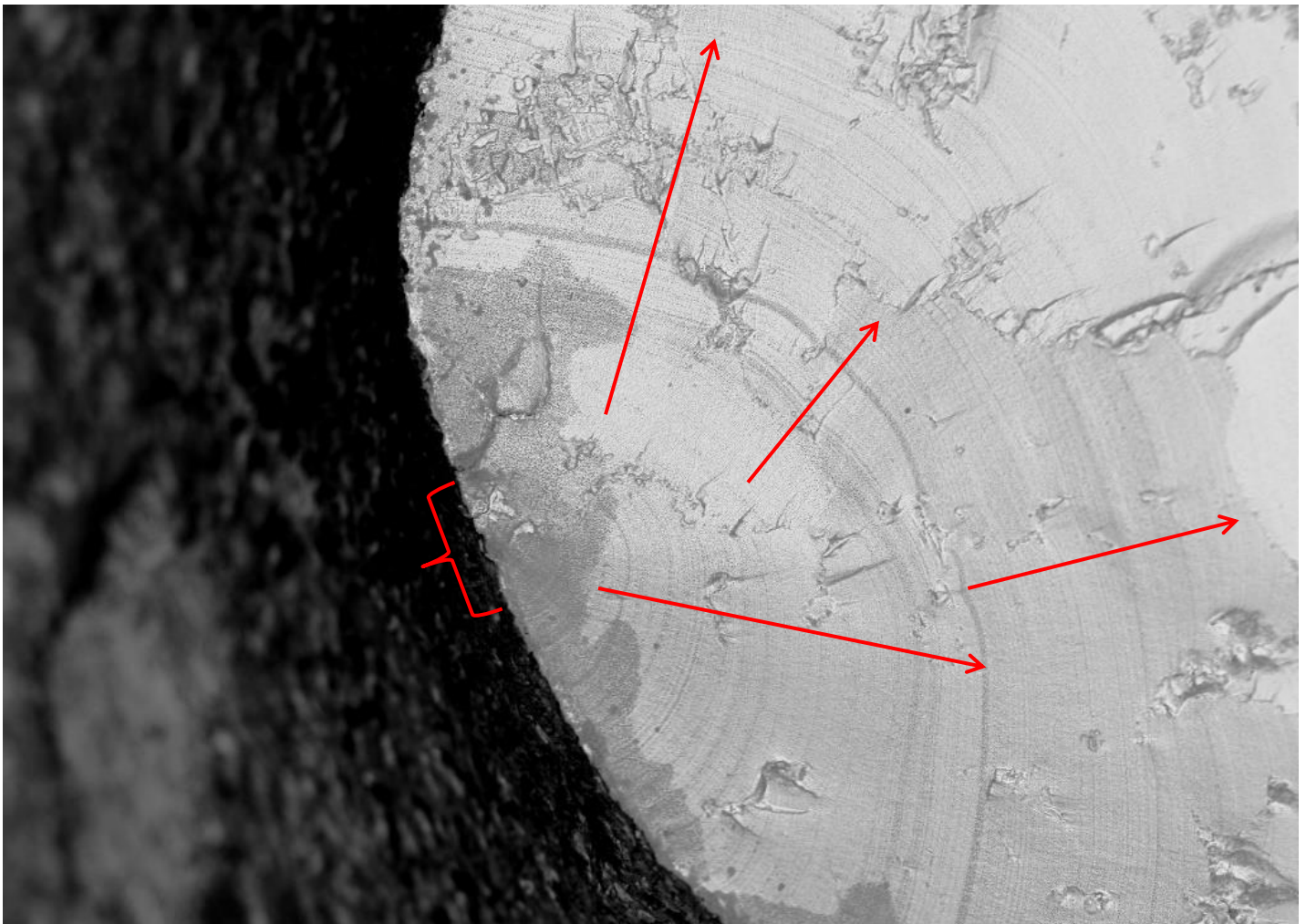


Figure 33. Backscattered electron SEM image showing the origin area (red brace) of the fatigue fracture on airfoil #35.

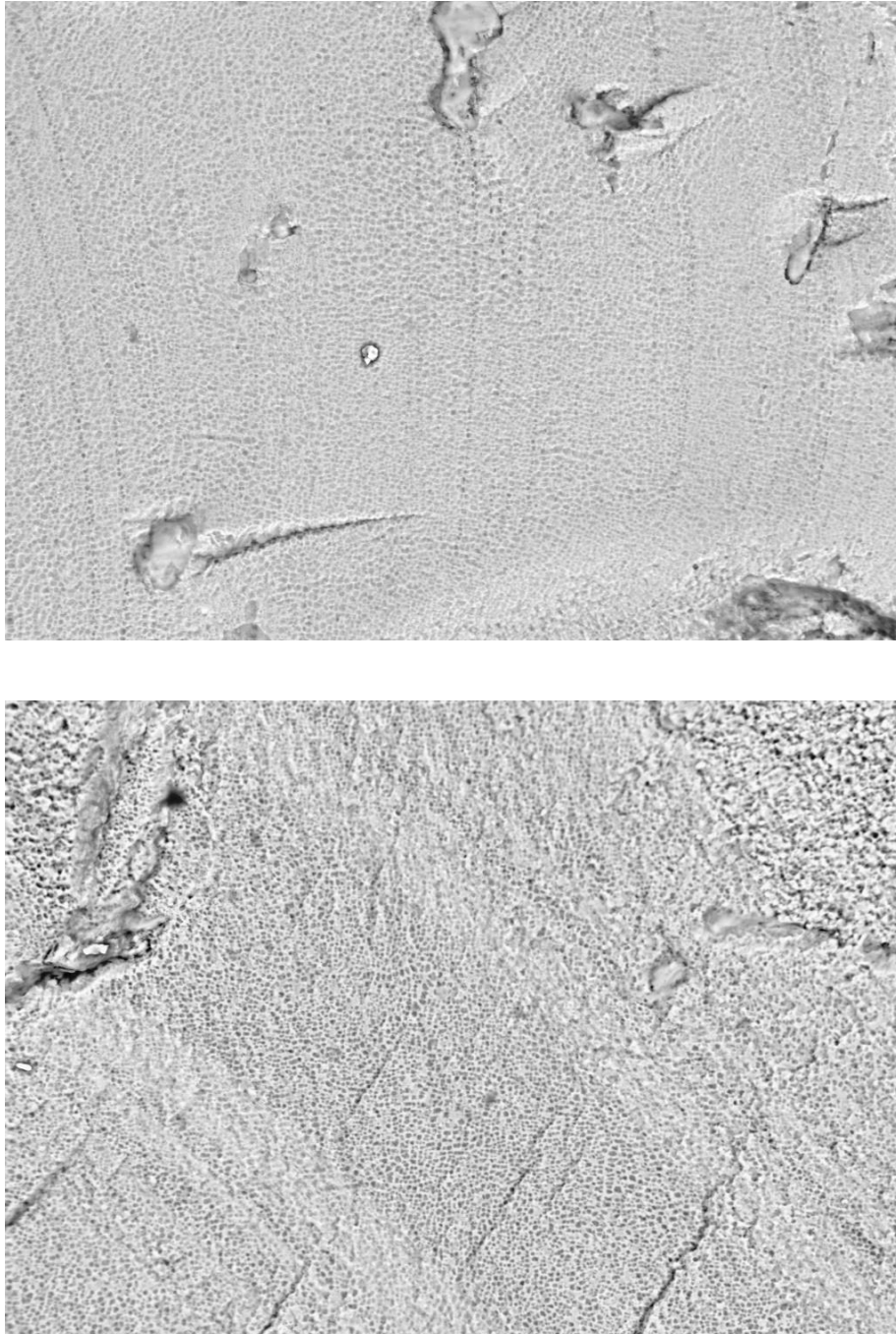


Figure 34. Backscattered electron SEM images showing representative fracture features near the trailing edge on the inboard plane of propagation (top) and near the end of the fatigue fracture (bottom). The fracture surface was equally oxidized in both areas.

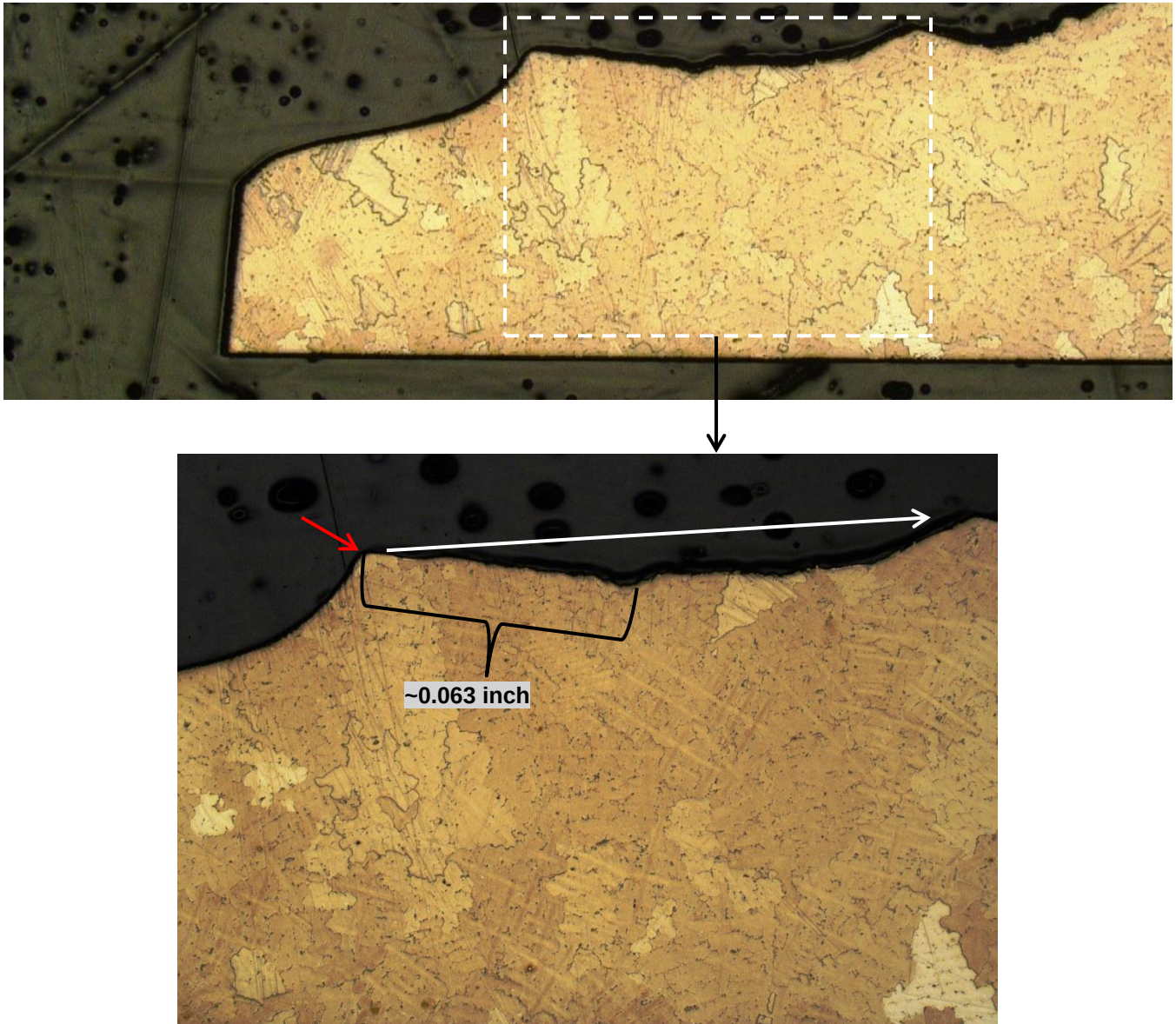


Figure 35. Cross-section through the fatigue origin (red arrow) on airfoil #35. There were no metallurgical anomalies at the origin. The white arrow shows the direction of fatigue propagation. In this plane of examination, the fracture propagated inboard for approximately 0.063 inch before turning outboard. Etchant: MT

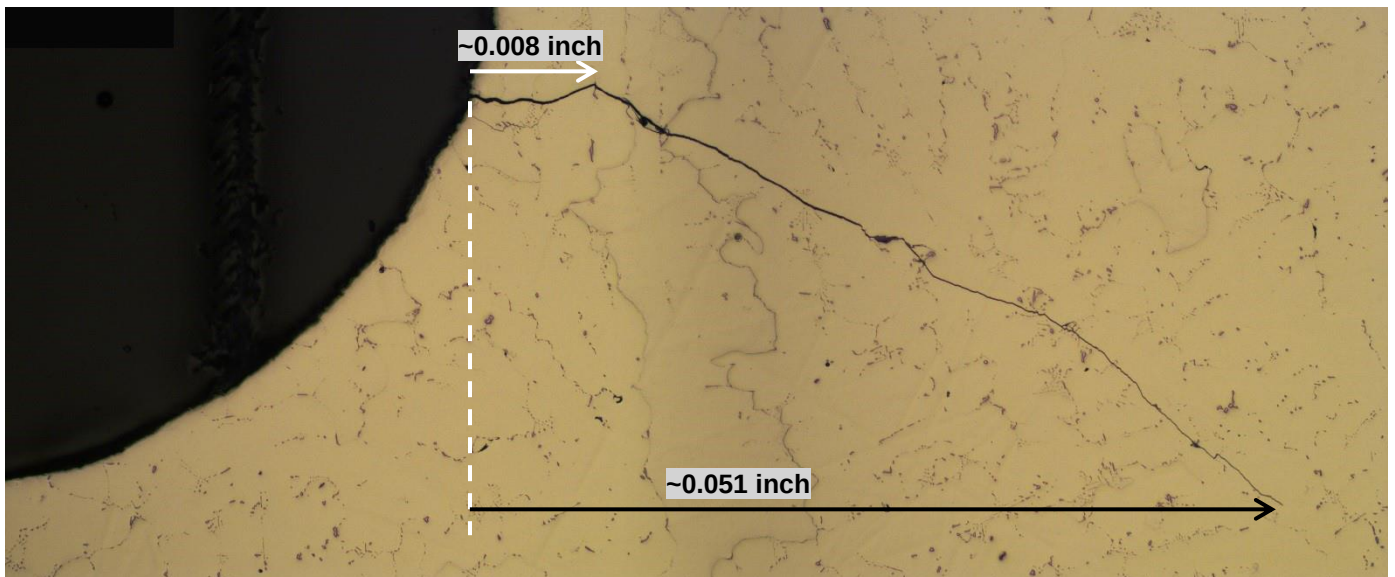
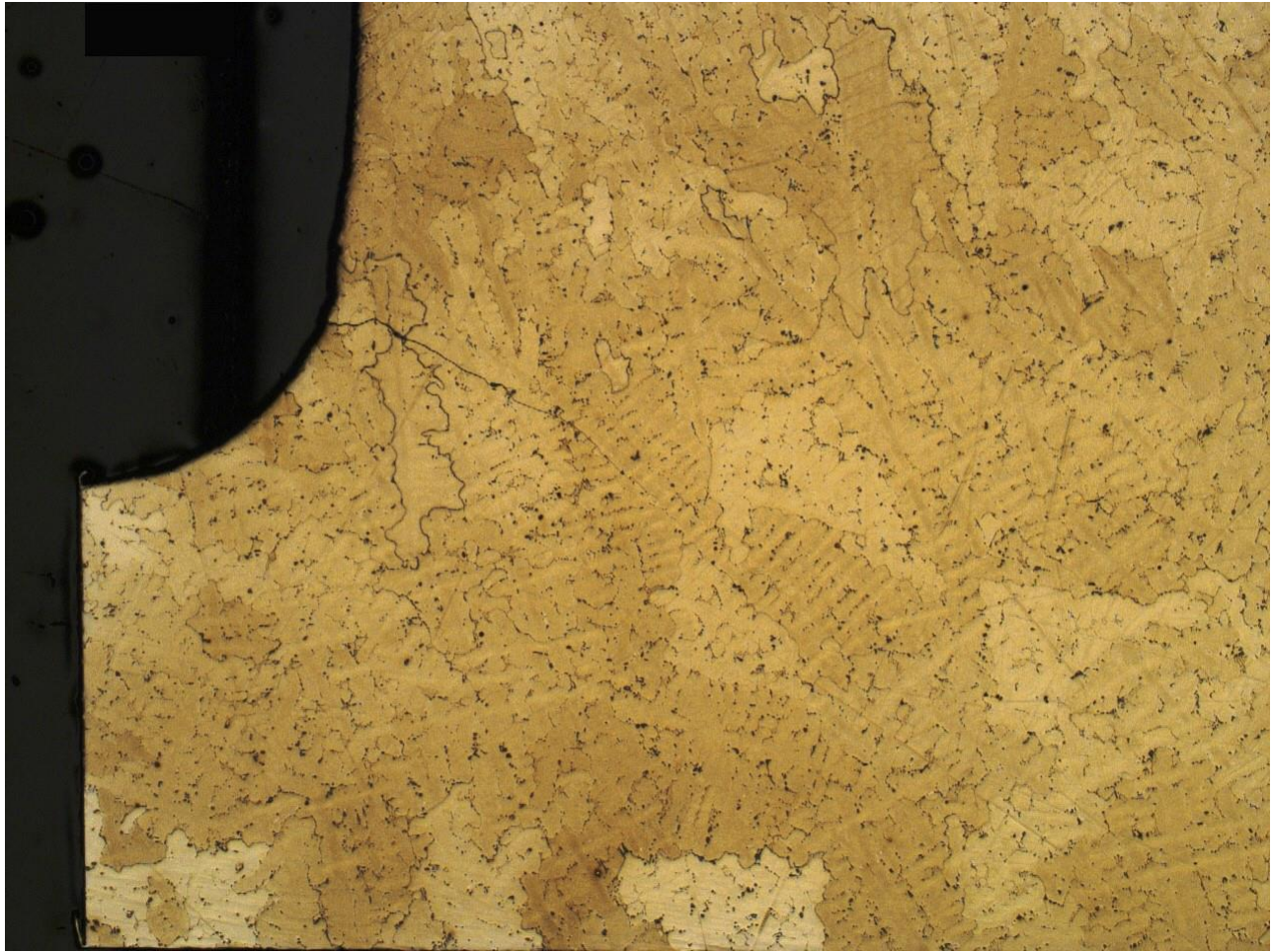


Figure 36. Cross-section through the crack in the trailing edge of airfoil #15. The crack propagated approximately parallel to the rim surface and slightly outboard for approximately 0.008 inch before turning inboard to propagate to a total length of approximately 0.051 inch. Top etchant: MT; Bottom: Unetched



Figure 37. Leading (top) and trailing (bottom) edge side views showing the as-received condition of the fourth stage turbine wheel.



Figure 38. Radial views showing the rub damage to the shroud and knife seals. The shroud band was cracked (red arrow).

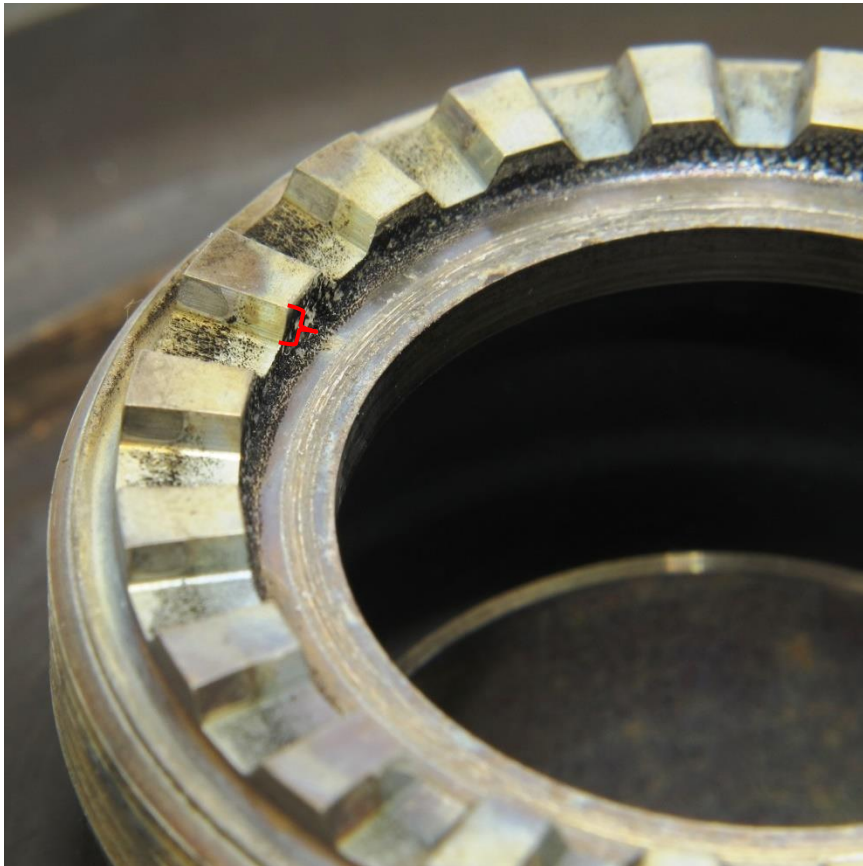


Figure 39. Detailed views showing the representative condition of the drive (left, red brace) and coast (right, yellow brace) side flanks of the turbine wheel to stub shaft curvic teeth of the fourth stage turbine wheel. The teeth exhibited patches of wear on both flanks. Coked oil was present on the curvic teeth and adjacent surfaces.

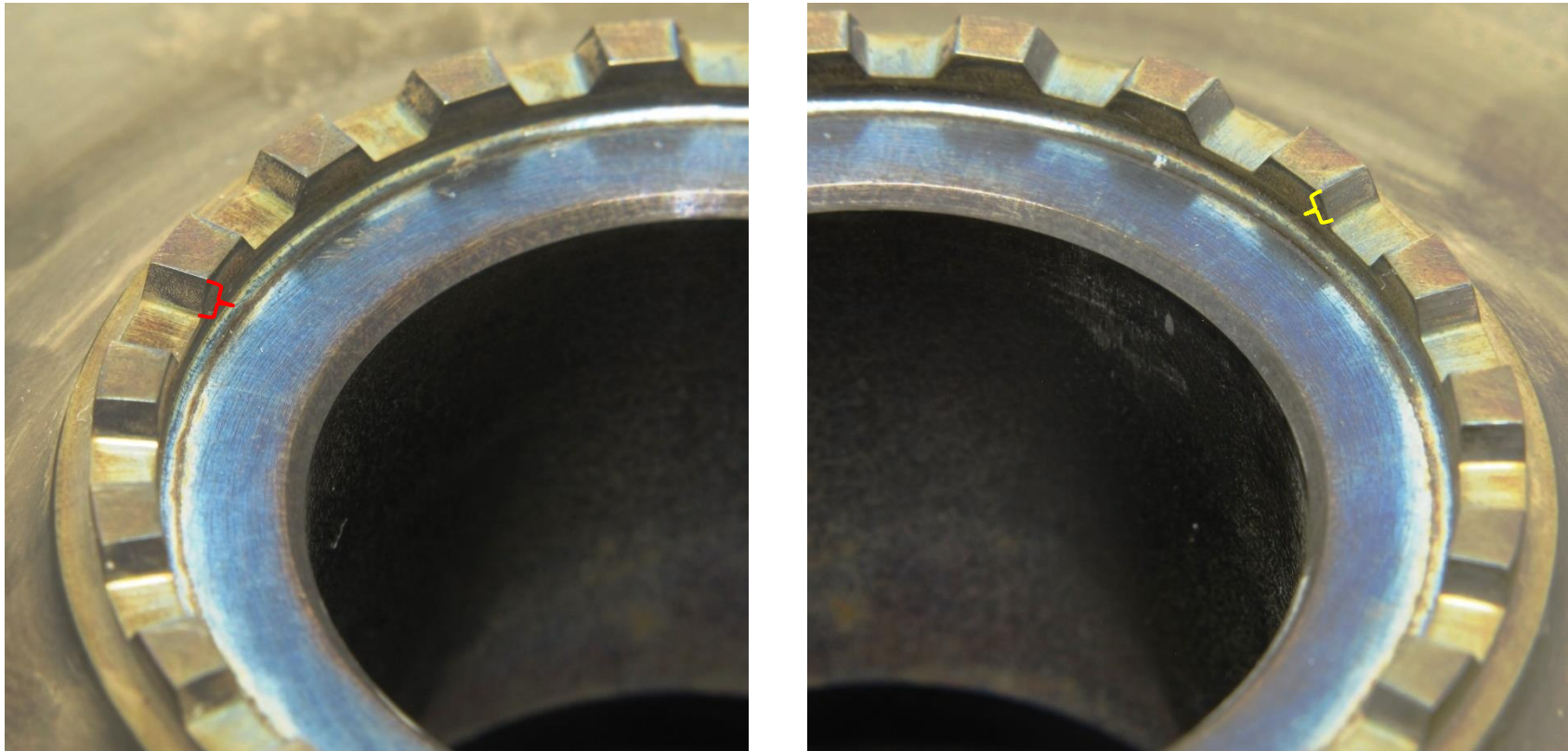


Figure 40. Representative condition of the drive (left, red brace) and coast (right, yellow brace) side flanks of the interstage curvic teeth on the fourth stage turbine wheel. The drive side flanks exhibited wear patches.

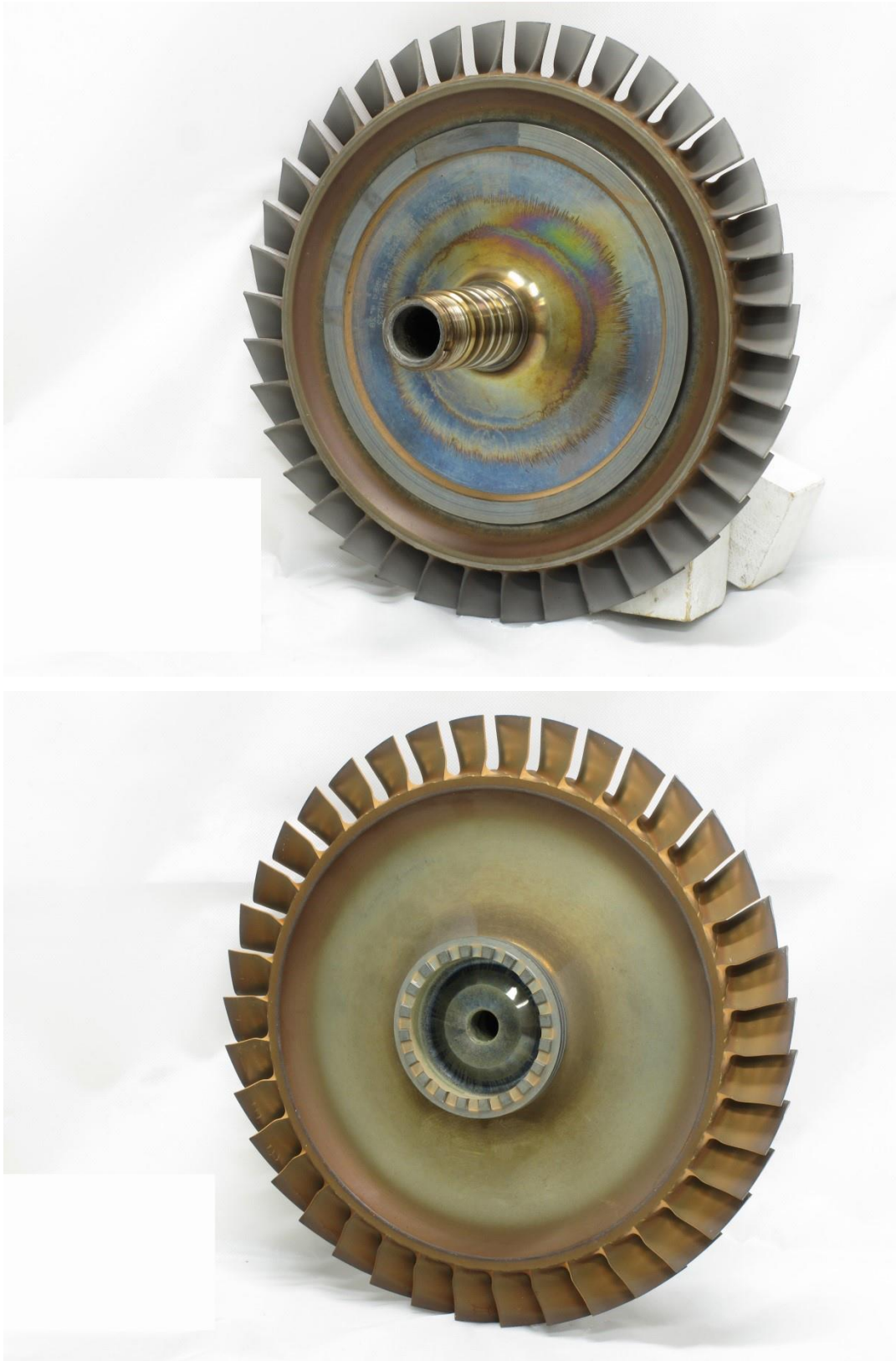


Figure 41. Leading (top) and trailing (bottom) edge side views showing the as-received condition of the first stage turbine wheel.



Figure 42. Leading (top) and trailing (bottom) edge side views showing the as-received condition of the second stage turbine wheel. The airfoil trailing edges exhibited impact damage.



Figure 43. Leading edge (top) and trailing edge (bottom) side views of the first stage turbine nozzle. The trailing edge side web exhibited oil deposits and there was debris on the airfoils.



Figure 44. Leading edge (top) and trailing edge (bottom) side views of the first stage turbine nozzle. The vane airfoil suction side surfaces exhibited impact damage.



Figure 45. Leading (top) and trailing (bottom) edge side views of the third stage turbine nozzle. The suction side surfaces and trailing edges of the vane airfoils exhibited impact damage.



Figure 46. Leading (top) and trailing (bottom) edge side views of the fourth stage turbine nozzle. Part of the third stage blade track was liberated (red arrow), and the airfoils exhibited impact damage.



Figure 47. Forward (top) and aft (bottom) side views showing the power turbine support.

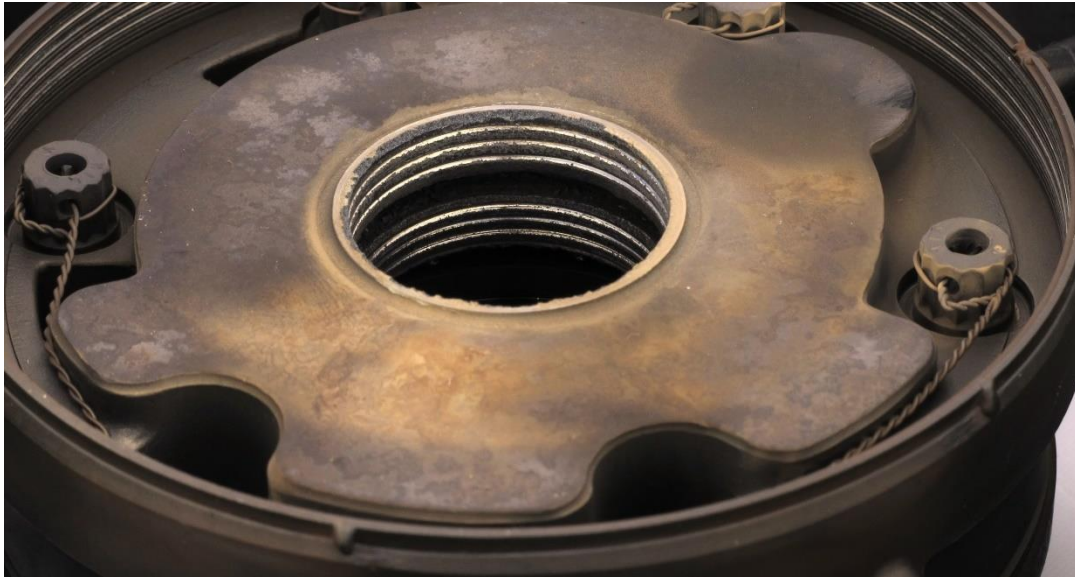


Figure 48. Detailed view showing the Nos. 6 and 7 bearing sump stationary labyrinth seal in the power turbine support assembly bore.



Figure 49. Forward looking aft view of the Nos. 6 and 7 bearing sump in the power turbine support. The bore of the sump was fractured circumferentially at the forward end (red brace).



Figure 50. Forward (top) and aft (bottom) side views showing the gas producer turbine support.



Figure 51. 90° rotated views of the power turbine outer shaft. The shaft exhibited asymmetric rub, with the most severe rub shown at far left. The shaft also had coked oil deposits on the surface.



Figure 52. 90° rotated views of the power turbine inner shaft with the No. 6 bearing stuck on the integral inner race. The fractured portion of the PT support bore was retained on the shaft.



Figure 53. Aft looking forward view showing the No. 6 bearing stuck on the inner race, which is integral to the power turbine inner shaft.



Figure 54. Power turbine outer (left) and inner (right) shaft nuts.



Figure 55. 90° rotated views of the third stage power turbine labyrinth seal. The seal exhibited asymmetric rub, with the most severe rub damage shown at top.



Figure 56. Detailed view showing the rubbed-through area on the third stage power turbine labyrinth seal.



Figure 57. Photographs of the turbine to pinion gear coupling, which was a PMA component and not examined in detail.



Figure 58. As-received condition of the turbine to compressor coupling. Orientation was not maintained.



Figure 59. As-received condition of the turbine tie bolt.



Figure 60. As-received condition of the No. 7 bearing.



Figure 61. Forward looking aft view (top) showing the as-received condition of the No. 8 bearing, which was a PMA component (bottom).



Figure 62. Forward (top) and aft (bottom) side views of the No. 5 bearing.



Figure 63. PMA marking (red dashed outlined area) on the No. 5 bearing.