



ATTACHMENT 1

AIRWORTHINESS GROUP FACTUAL REPORT

NTSB No. ERA21FA130

**Rolls-Royce Materials Evaluation Report No. 21FAE-025-PR
(111 pages)**

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 Rolls-Royce	Rolls-Royce Corporation 450 S. Meridian Street Indianapolis, Indiana 46225-1103, USA	REPORT NO. 21FAE-025-PR	REV. Initial	PAGES 1 of 111
TITLE METALLURGICAL INVESTIGATION OF COMPRESSOR COMPONENTS REMOVED FROM AN M250-C20B, ENGINE S/N CAE833459, OPERATED BY CARIBBEAN BUZZ HELICOPTER		PREPARED Signatures on File		
		APPROVED Signatures on File		

IDENTIFICATION

Report Request ID:	42575
Traceability ID Number:	EDNS04000134967
Part Name:	Stage 2-3 Compressor Wheel
Part Number:	23057112
Part Time:	3031.7 hours
Engine Model:	M250-C20B
Engine Serial Number:	CAE833459
User:	Caribbean Buzz Helicopters
Removal Station:	Not Applicable
Evaluations:	Failure Analysis

No Export Controlled Information

1 Foreword

The subject stage 2-3 compressor wheel, P/N 23057112, was installed on M250-C20B, engine S/N CAE833459, operated in St. Thomas, USVI by Caribbean Buzz Helicopters. From review of cell phone footage of the event, the aircraft was reportedly maneuvering slowly at 200 to 300 feet altitude when there was a puff of smoke from the engine accompanied by a sudden yaw to the right by the aircraft. The main rotor then slowed and the helicopter began descending at an accelerating rate. The aircraft then disappeared into jungle foliage, where it reportedly caught fire. All passengers and crew of the flight were fatally injured. Following the event, personnel from the Rolls-Royce Air Safety Investigation team examined the engine onsite, which reportedly revealed distress to the compressor section. The entire compressor section and select components from the gearbox were submitted to the Rolls-Royce Corporation Materials Laboratory in Indianapolis, IN for detailed metallurgical investigation under the oversight of the National Transportation Safety Board (NTSB).

2 Summary of Findings

- 2.1 One stage 3 compressor blade fractured in fatigue initiating from the trailing edge area near the pressure side, approximately 0.12 inch above the rim. The fatigue progressed approximately 0.31 inch toward the leading edge before the airfoil liberated in overload. Impact damage at the trailing edge obliterated the origin area.
- 2.2 The stage 3 blade following the primary fractured blade in the direction of engine rotation also exhibited a fatigue fracture on the pressure side surface near the trailing edge. This fatigue surface extended approximately 0.023 inch from the trailing edge.
- 2.3 Magnetic particle inspection of the stage 2-3 wheel did not reveal any other crack-like indications in the stage 3 blades; however, secondary impact damage at the trailing edge of the stage 3 blades obfuscated the original surface of most blades. No corrosion pitting was noted on the stage 2-3 wheel.
- 2.4 The microstructure, hardness, and chemistry of the stage 2-3 wheel were consistent with the component definition requirements.
- 2.5 The stage 4 and 5 compressor blades all liberated near the root in overload. No corrosion pitting was noted on the stage 4 and 5 wheels. The chemistry of the stage 4 and 5 compressor wheels was consistent with the component definition requirements.
- 2.6 The stage 6 compressor blades all liberated near the root. All the fracture surfaces exhibited fatigue progressing from the suction side crown root. Transverse cross sections through two blades revealed additional cracks on the pressure side. No corrosion pitting was noted on the stage 6 wheel.
- 2.7 The hardness and chemistry of the stage 6 wheel were consistent with the component definition requirements.

3 Results and Discussion

Figure 1 shows the as-received condition of the compressor section. The entire compressor rotor including the impeller, the compressor tie bolt, the No. 1 bearing and sump, compressor rear diffuser, No. 2 bearing and spanner nut, compressor splined adaptor, and the spur adaptor gearshaft were all assembled together when received by the lab. The No. 2 bearing spanner nut was fused to the impeller stub shaft and cutting was required to remove it. The rest of the assembled compressor was able to be disassembled via standard disassembly procedures, except for the stages 1 through 6 compressor rotors (see Figure 2 and Figure 3). All the blades on the stage 4 through 6 compressor wheels were liberated near the root. Two adjacent stage 3 compressor blades from the stage 2-3 compressor wheel were liberated near the root. The compressor rotor was subsequently cut through the gap between blades to separate all the wheels. Table 1 lists the components documented below.

Table 1: List of components documented in this report.

Part Name	Part Number	Part Serial Number
Stage 2-3 Compressor Wheel	23057112*	KR112489
Stage 4 Compressor Wheel	23057114*	KR72700
Stage 5 Compressor Wheel	23057115*	KR52387
Stage 6 Compressor Wheel	23060406*	KR22377*
Stage 1 Compressor Wheel	23057111*	KR115419*
Compressor Case	23057142	??30045

*: Indicates a part number or serial number not legible on the part but gathered from the packaging information

?: Refers to characters in a number that were not legible on the component

3.1 Stage 2-3 Compressor Wheel: P/N 23057112, S/N KR112489

3.1.1 Visual and Non-Destructive Examination

Figures 4 and 5 show the stage 2-3 compressor wheel prior to cutting it from the compressor rotor. Two adjacent stage 3 compressor blades were liberated from the wheel near the root (see Figure 4). For the purposes of this report, these two blades were labeled blades 1 and 2, and the rest of the blades were numbered counter to the direction of rotation. The trailing edge side of every stage 3 compressor blade was impact damaged. Five of the stage 3 blades also exhibited impact damage and deformation at the leading edge tip. The rest of the stage 3 compressor blade leading edges did not exhibit impact damage. None of the stage 2 compressor blades exhibited impact damage.

The compressor wheel exhibited generalized corrosion over the entire gas path surface. There were isolated areas on the inner diameter that also exhibited corrosion (see Figure 6). Figures 7 through 11 show detailed views of the trailing edge root areas of all the non-liberated stage 3 compressor blades. No corrosion pitting was noted on any of the blades. There was impact damage on every stage 3 blade trailing edge area, which obfuscated any visually detectable cracking on other blades; however, magnetic particle inspection (MPI) was performed by the Rolls-Royce Test Department to see if any other stage 3 blades exhibited crack-like indications. One blade (blade 16) had an MPI indication on the trailing edge, suction side radius; however, scanning electron microscope (SEM) examination of the area revealed that the indication was in an area of damage from the cutting process (see Figure 12). No other blades exhibited MPI indications.

3.1.2 Fractography / Scanning Electron Microscope Examination

Figure 13 shows the fracture surfaces from stage 3 compressor blades 1 and 2. Figure 14 shows detailed views of the trailing edge area of blade 1, which exhibited fatigue fracture initiating near the trailing edge, pressure side. The fatigue fracture surface extended approximately 0.31 inch from the trailing edge along the pressure side surface. The trailing edge area was impact damaged on both the radius and pressure side corner.

SEM examination of the fracture surface revealed fatigue progression from the impact damaged area on the trailing edge pressure side corner (see Figures 15 and 16). Figure 17 shows representative ductile fracture features from the overload region. Figure 18 shows the trailing edge of blade 1, which did not exhibit any geometric or material anomalies other than the aforementioned impact damage.

Figure 19 shows SEM images of the trailing edge of blade 2, which revealed two fatigue fractures initiating from multiple origins on the pressure side near the trailing edge. The total length of the fatigue crack was approximately 0.023 inch along the pressure side surface, extending from the trailing edge. Figures 20 and 21 show detailed SEM images of fatigue fracture features from multiple initiations on the pressure side surface of

blade 2. Figure 22 shows the trailing edge of blade 2, which also exhibited impact damage. No other geometric or material anomalies were noted.

3.1.3 *Metallographic Examination*

A single, circumferential-radial metallographic cross section was taken through the trailing edge of blade 1 along the plane shown in Figure 13. The cross section was mounted in slow set epoxy, polished to standard laboratory procedures, and examined in the unetched condition and after etching with Stainless No. 2. Following examination, an additional approximately 0.020 inch was removed from the surface to move the plane farther from the trailing edge and the mount was re-polished and examined in both the etched and unetched conditions.

Figure 23 shows the cross section on the first plane of polish. The fracture surface was approximately 0.12 inch above the rim at this plane of cross section. Figure 24 shows the trailing edge origin area at the first plane of cross section and Figure 25 shows the trailing edge origin area at the second plane of cross section. Both planes of cross section exhibited subsurface voids (see Figure 26). The second plane of cross section exhibited one area on the suction side of the blade in the impact damaged area where the voids appeared to have an intergranular morphology. An etched view of this area is shown in Figure 27. Energy dispersive x-ray spectroscopy (EDS) mapping of the area showed that there were elevated levels of oxygen in the area that appeared to have an intergranular morphology (Figure 28).

Figure 29 shows representative views of the aluminide coating from the cross section in Figure 23. The coating was present everywhere examined except for areas that exhibited impact damage. Near areas of impact damage, the coating was cracked. The microstructure of the base material, Figure 30, was consistent with material type required by the component definition.

3.1.4 *Hardness*

The average hardness of the stage 2-3 compressor wheel on the cross section in Figure 23 measured 37.7 HRC (averaged, converted value of 364, 373, 367, 373 HV500gf) which met the component definition requirement.

3.1.5 *Chemistry*

Semi-quantitative EDS analysis determined the stage 2-3 compressor wheel was consistent with the material type required by the component definition.

3.2 ***Stage 4 Compressor Wheel: P/N 23057114, S/N KR72700*** ***Stage 5 Compressor Wheel: P/N 23057115, S/N KR52387***

3.2.1 *Visual Examination*

Figures 31 and 32 show the stage 4 and 5 compressor wheels before they were cut from the rest of the rotor. All the compressor blades from both wheels were fractured near the root. Both rotors also exhibited generalized corrosion on both the outer and inner diameter (see Figures 33 and 34).

Figures 35 through 47 show the fracture surfaces from the stage 4 compressor wheel, which were all smeared. The portions of the fracture surfaces that were not smeared exhibited a rough surface texture. No corrosion pitting was noted on the airfoil and rim.

Figures 48 through 61 show the fracture surfaces from the stage 5 compressor wheel, which were all smeared. The portions of the fracture surfaces that were not smeared exhibited a rough surface texture. No corrosion pitting was noted on the airfoil and rim.

Outside of the cuts required to disassemble the rotor, no destructive analysis was performed on the stage 4 and 5 wheels.

3.2.2 Chemistry

Semi-quantitative x-ray fluorescence (XRF) analysis determined the stage 4 compressor wheel was consistent with the material type required by the component definition.

Semi-quantitative XRF analysis determined the stage 5 compressor wheel was consistent with the material type required by the component definition.

3.3 Stage 6 Compressor Wheel: P/N 23060406, S/N KR22377

3.3.1 Visual and Scanning Electron Microscope Examination

Figures 62 and 63 show the stage 6 compressor wheel before it was cut from the rest of the rotor. All the compressor blades were fractured near the root. The wheel also exhibited generalized corrosion on both the outer and inner diameter (see Figures 33 and 34).

Figures 64 through 88 show the fracture surfaces and suction side surfaces of the stage 3 blades. Every fracture surface, except for one, exhibited fatigue progression from multiple origins near the suction side crown root. Every airfoil suction side surface also exhibited parallel coating cracking. All the airfoils exhibited this cracking on the entirety of the suction side surface. The airfoil that did not exhibit fatigue fracture features did have a crack on the suction side surface when observed in the SEM (see Figure 89), and laboratory fracture of the crack revealed fatigue progression from multiple origins near the suction side crown root on this airfoil as well (see Figure 90). Detailed SEM examination of all the fracture surfaces revealed that the fine fatigue fracture features were obliterated by smearing damage.

3.3.2 Metallographic Examination

Two representative compressor blades were selected for transverse cross sections through the suction side crown root (see Figures 65 and 74). The cross sections were mounted in slow set epoxy, polished per standard laboratory procedures, and examined in the unetched condition.

The cross section through blade 2 is shown in Figures 91 through 93, and the cross section through blade 11 is shown in Figures 94 through 96. Both cross sections exhibited multiple cracks on both the pressure side and suction side surfaces.

No corrosion was noted on either cross section.

3.3.3 Hardness

The average hardness of the stage 6 compressor wheel on the cross section in Figure 94 measured 34 HRC (averaged, converted value of 341, 336, 330, 337 HV500gf) which met the component definition requirement.

3.3.4 Chemistry

Semi-quantitative EDS analysis determined the stage 6 compressor wheel was consistent with the material type required by the component definition.

3.4 Stage 1 Compressor Wheel: P/N 23057111, S/N KR115419

3.4.1 Visual Examination and Chemistry

The stage 1 compressor wheel did not exhibit any damage. No impact damage was noted on the leading edge of the stage 1 blades (see Figure 97).

Semi-quantitative XRF analysis determined the stage 1 compressor wheel was consistent with the material type required by the component definition.

3.5 Compressor Case Assembly: P/N 23057142, S/N ??30045

3.5.1 Visual Examination

Figures 98 and 99 show the as-received condition of the compressor case halves. The outer diameter of the compressor case was missing the corrosion resistant paint and exhibited discoloration. The forward stages of the compressor vanes were intact and the aft stages of the compressor vanes were damaged. There was no impact damage on the leading edges of the stage 1 vanes (see Figure 100). Figures 101 through 103 show detailed images of each stage of vanes. The stage 1 vanes did not exhibit any deformation, and the stage 2 vanes only exhibited impact damage on the trailing edge side of a portion of the airfoils. Sixteen (16) of the stage 3 vane airfoils were liberated near the root and the rest of the airfoils were bent flat in the direction of engine rotation. All the stage 4, 5, and 6 airfoils were liberated near the root. All the remaining airfoils exhibited generalized corrosion.

Figures 104 and 105 show detailed views of representative fracture surfaces from the stage 3 through 6 airfoils. The entirety of every fracture surface was completely obliterated by smearing damage.

3.6 Other Components

The No. 1 bearing could be turned freely by hand. The No. 2 bearing could not be freely turned by hand. The gearbox components exhibited corrosion and oxidation. No other damage was noted on the other components, and they were not documented in this report.

4 Revision History

Issue	Change Summary	Date
Initial	Not applicable	11 Jun 2021

5 Figures and Tables

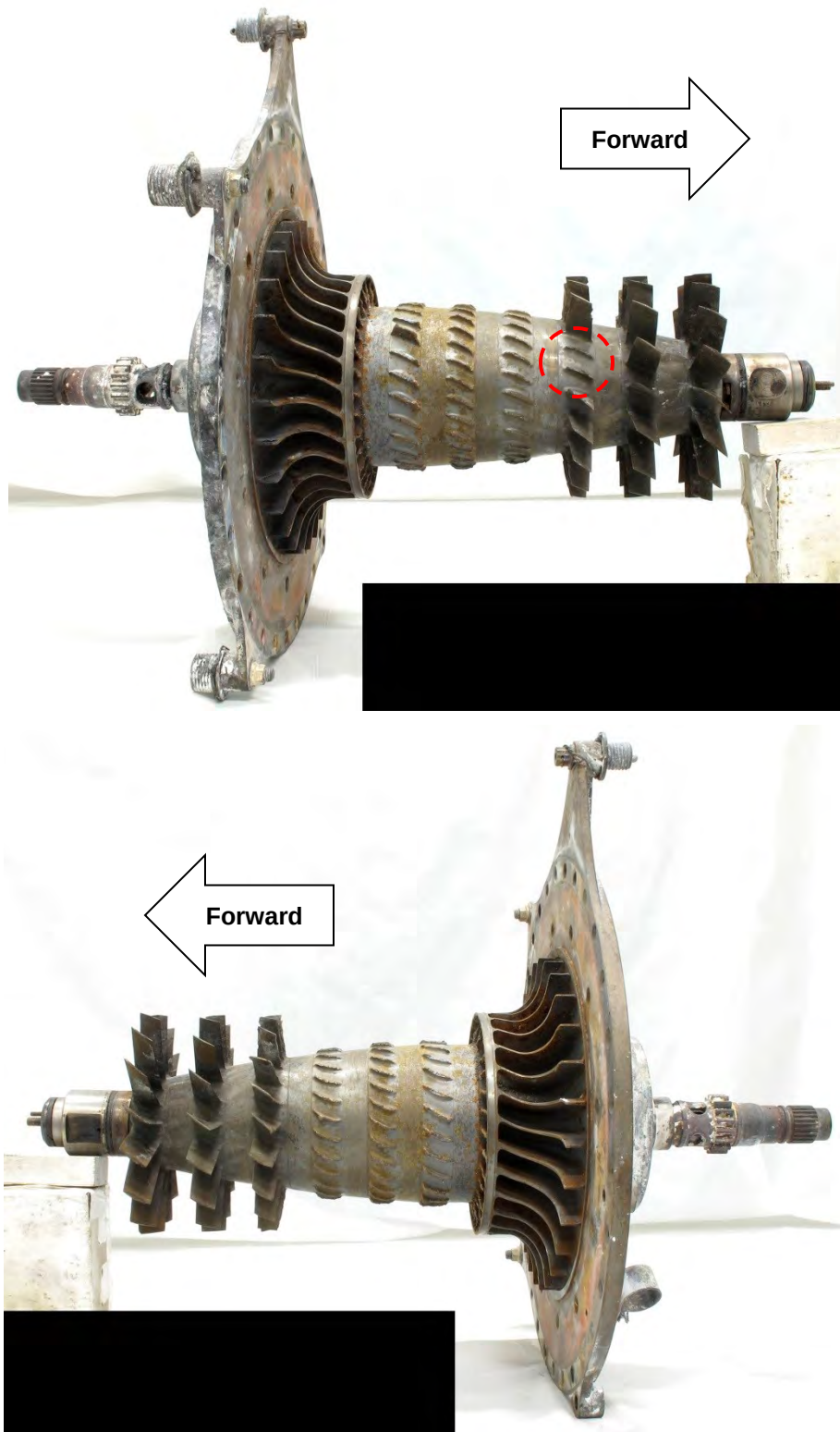


Figure 1. As-received condition of the compressor rotor. The red dashed circle indicates the two stage 3 blades that liberated near the root.



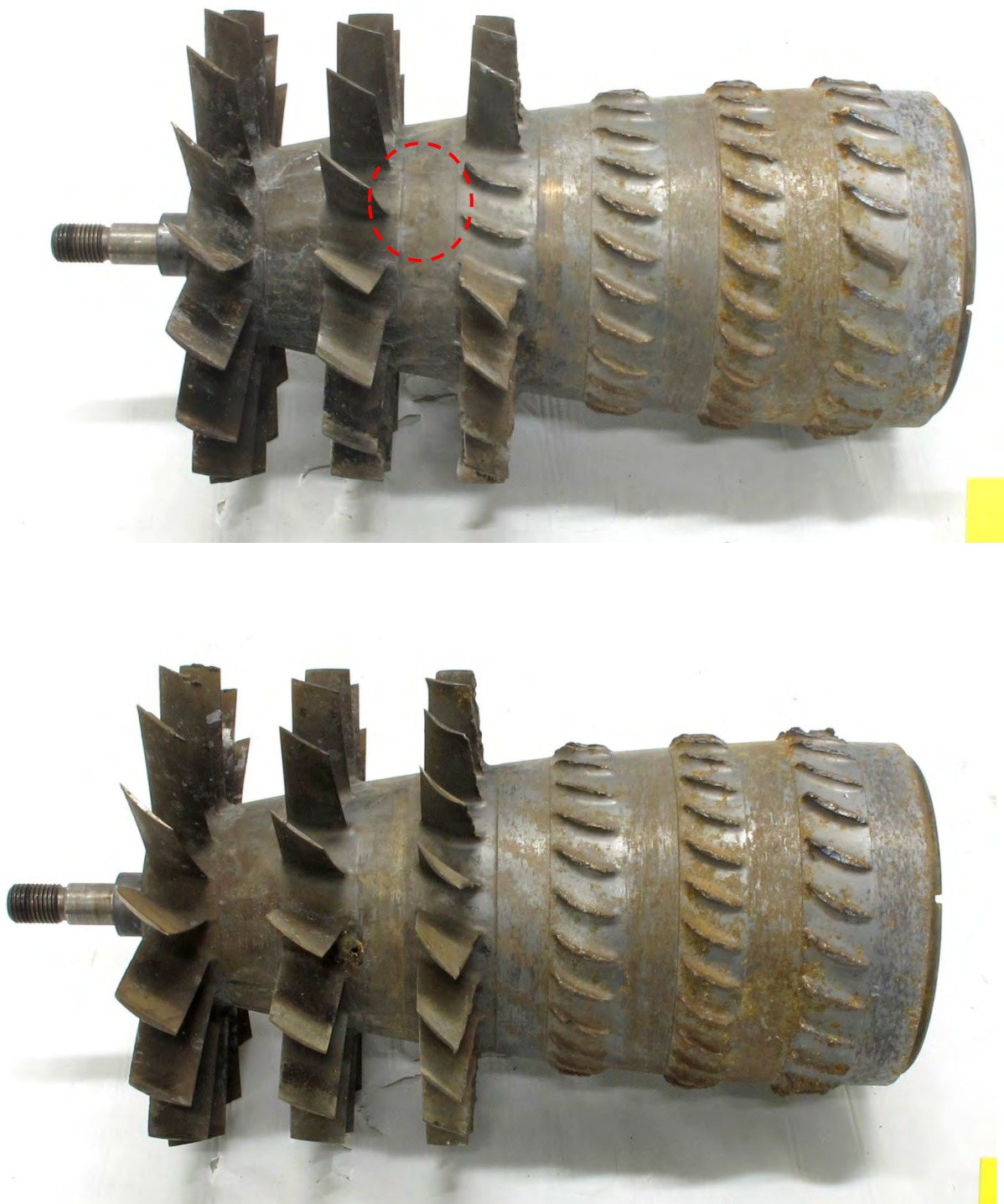


Figure 3. Stage 1 through stage 6 compressor wheels. The red dashed circle indicates the two stage 3 blades that liberated near the root. The bottom image shows the rotor rotated approximately 180° relative to the top image.



Figure 4. Detailed radial views of the stage 2-3 compressor wheel. Each image shows the wheel rotated approximately 90° from the previous. The black annotations indicate the blade numbering scheme used throughout this report.



Figure 5. Detailed radial views of the stage 2-3 compressor wheel. Each image shows the wheel rotated approximately 90° from the previous. The black annotations indicate the blade numbering scheme used throughout this report.

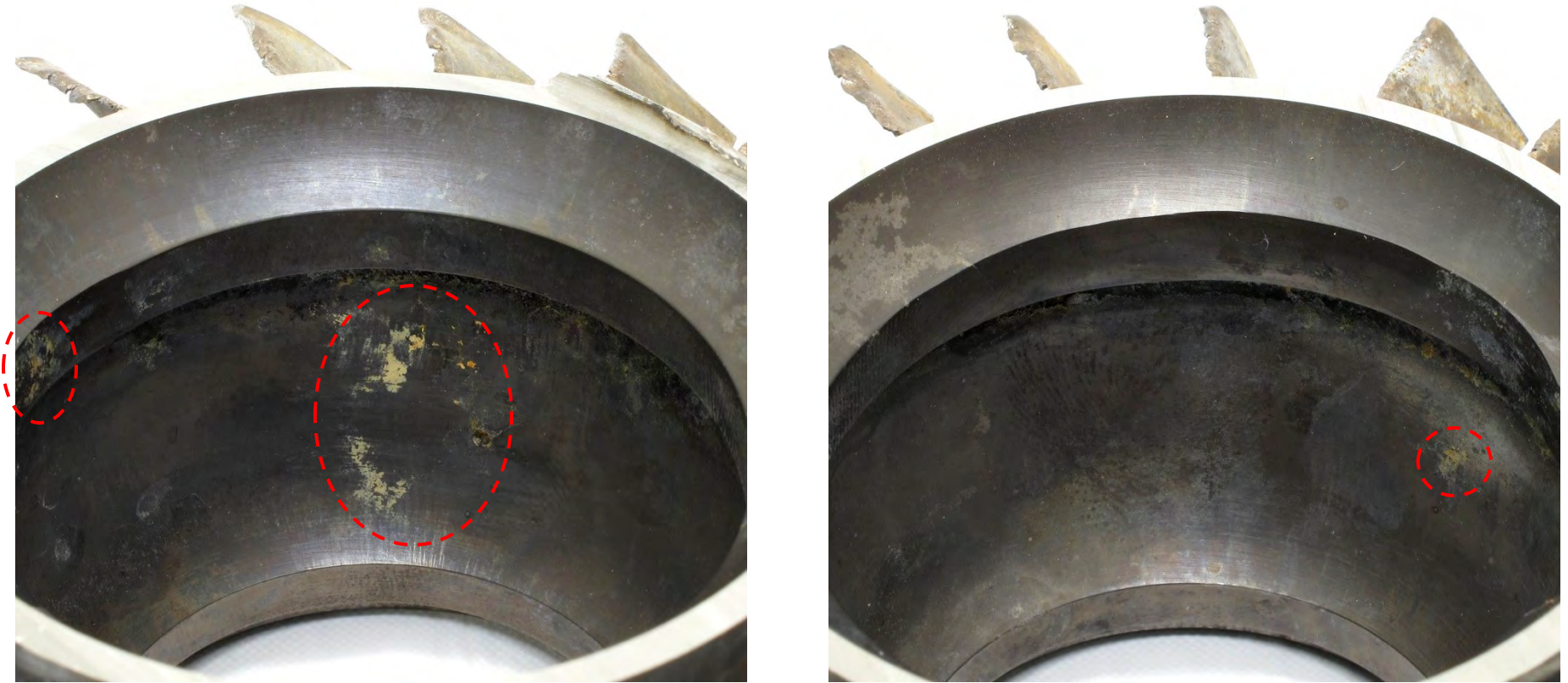


Figure 6. Inner diameter of the stage 2-3 compressor wheel. The red circles indicate areas of corrosion damage. Not all corrosion damage is indicated. Each image shows the component rotated approximately 180° from the previous.

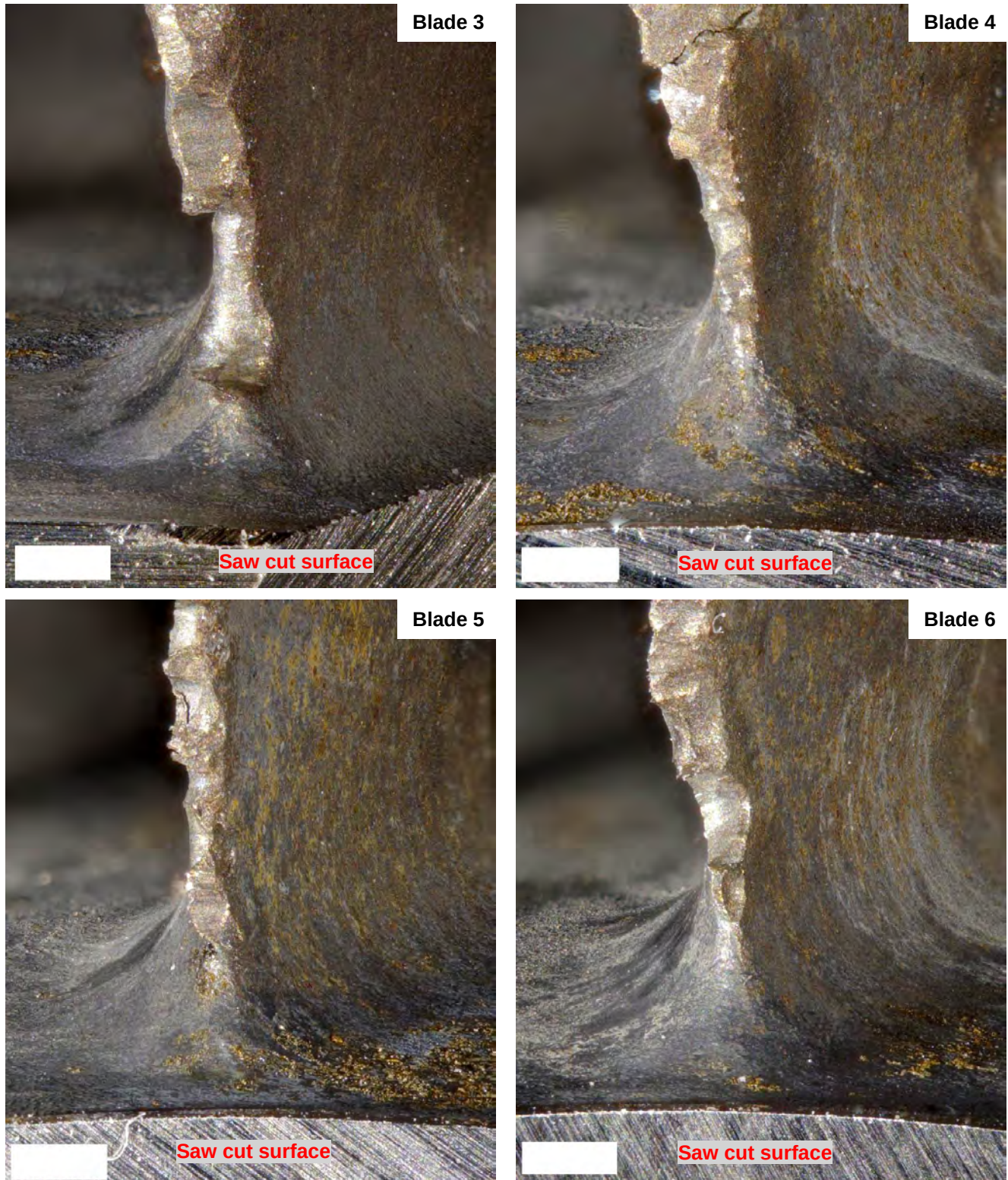


Figure 7. Detailed images of the trailing edge root area of stage 3 compressor blades 3 through 6.

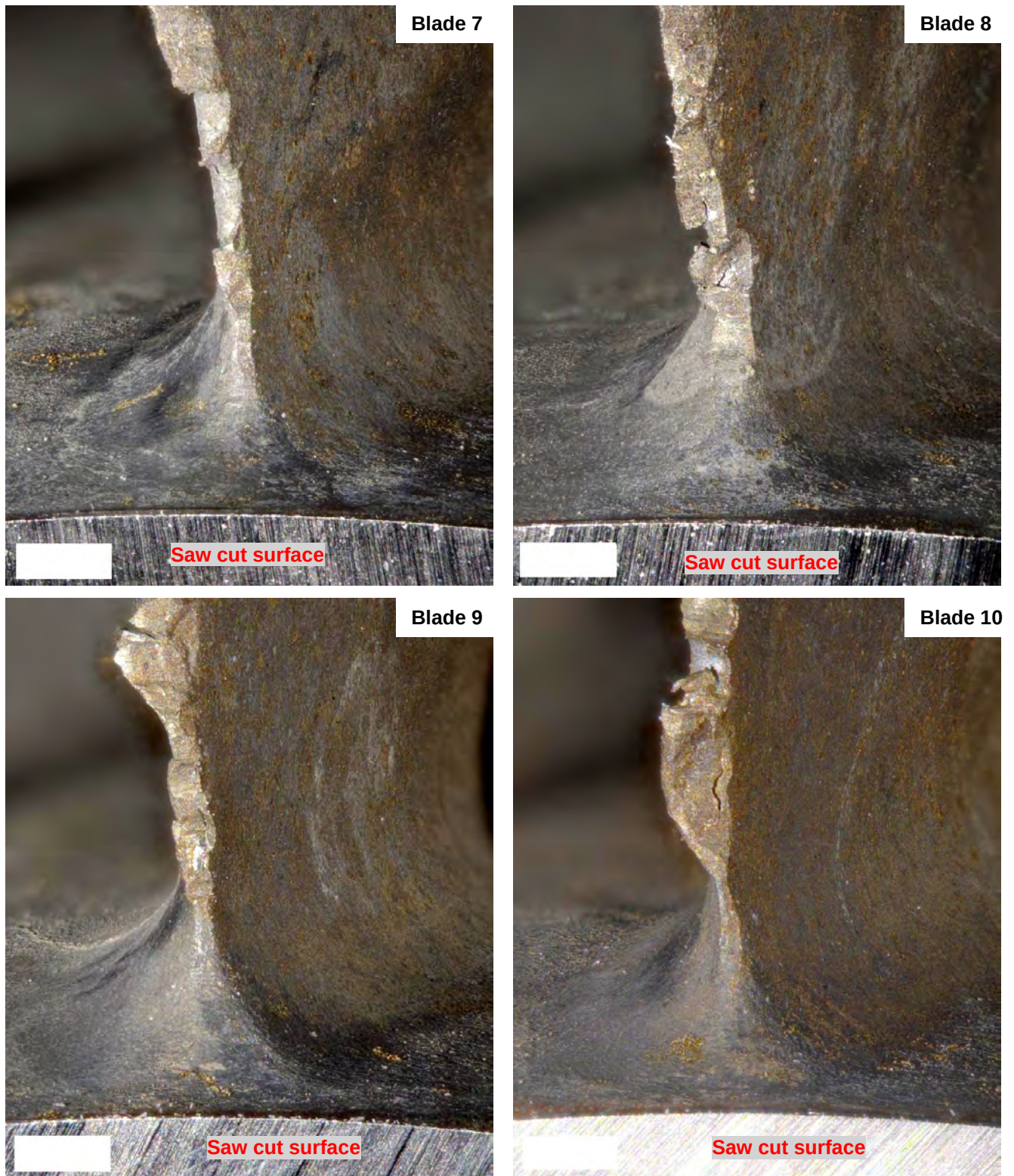


Figure 8. Detailed images of the trailing edge root area of stage 3 compressor blades 7 through 10.

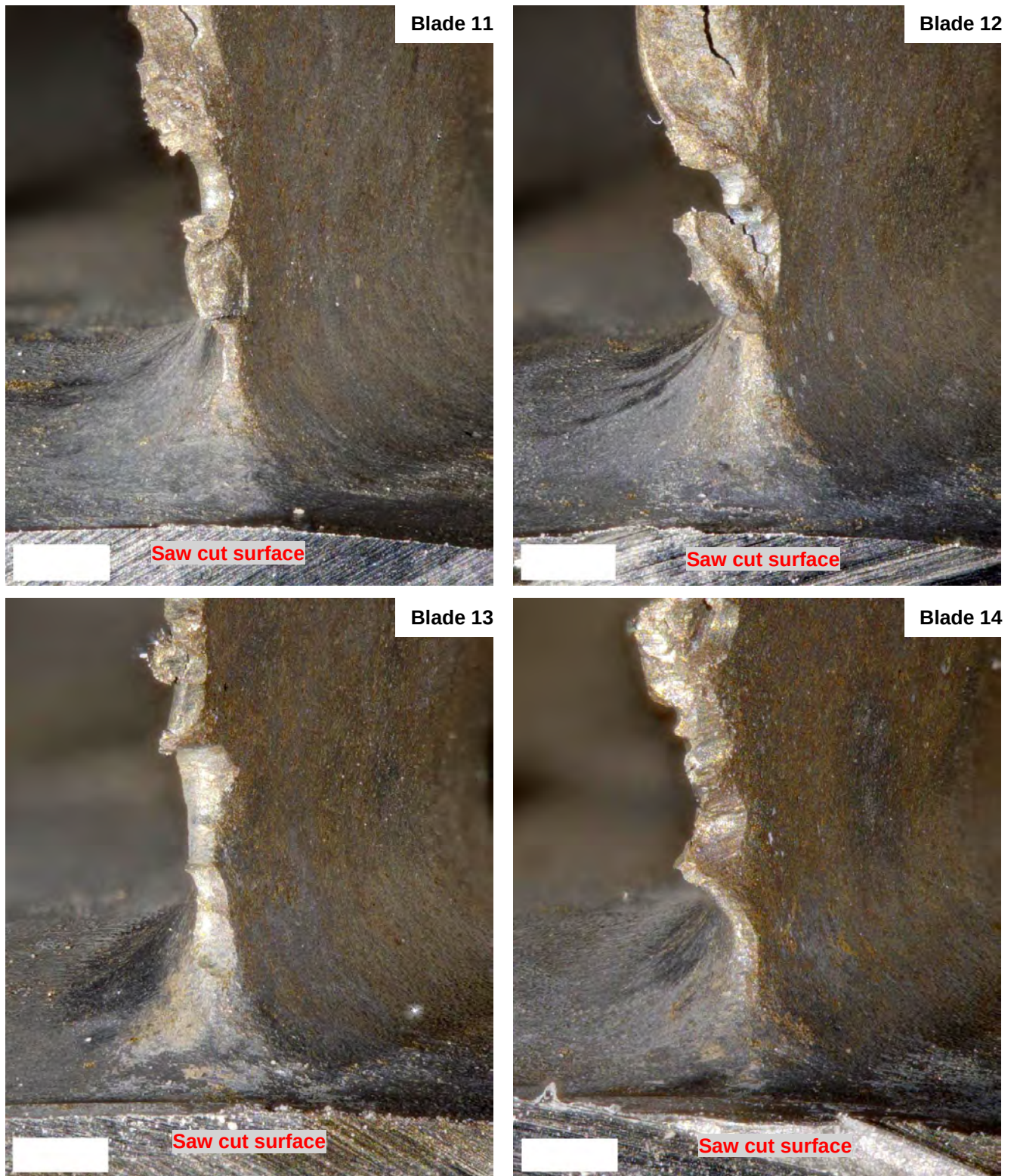


Figure 9. Detailed images of the trailing edge root area of stage 3 compressor blades 11 through 14.

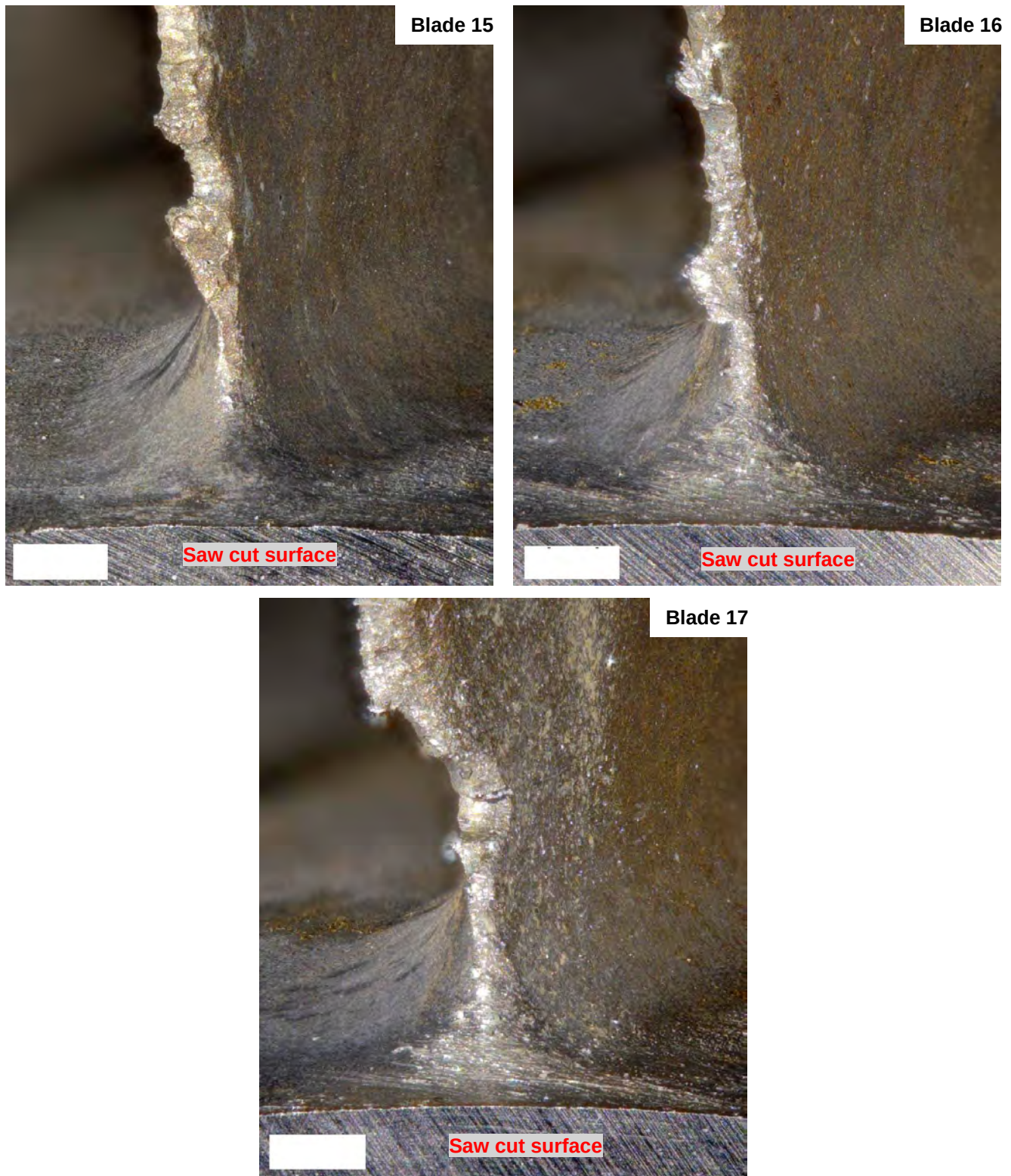


Figure 10. Detailed images of the trailing edge root area of stage 3 compressor blades 15 through 17.

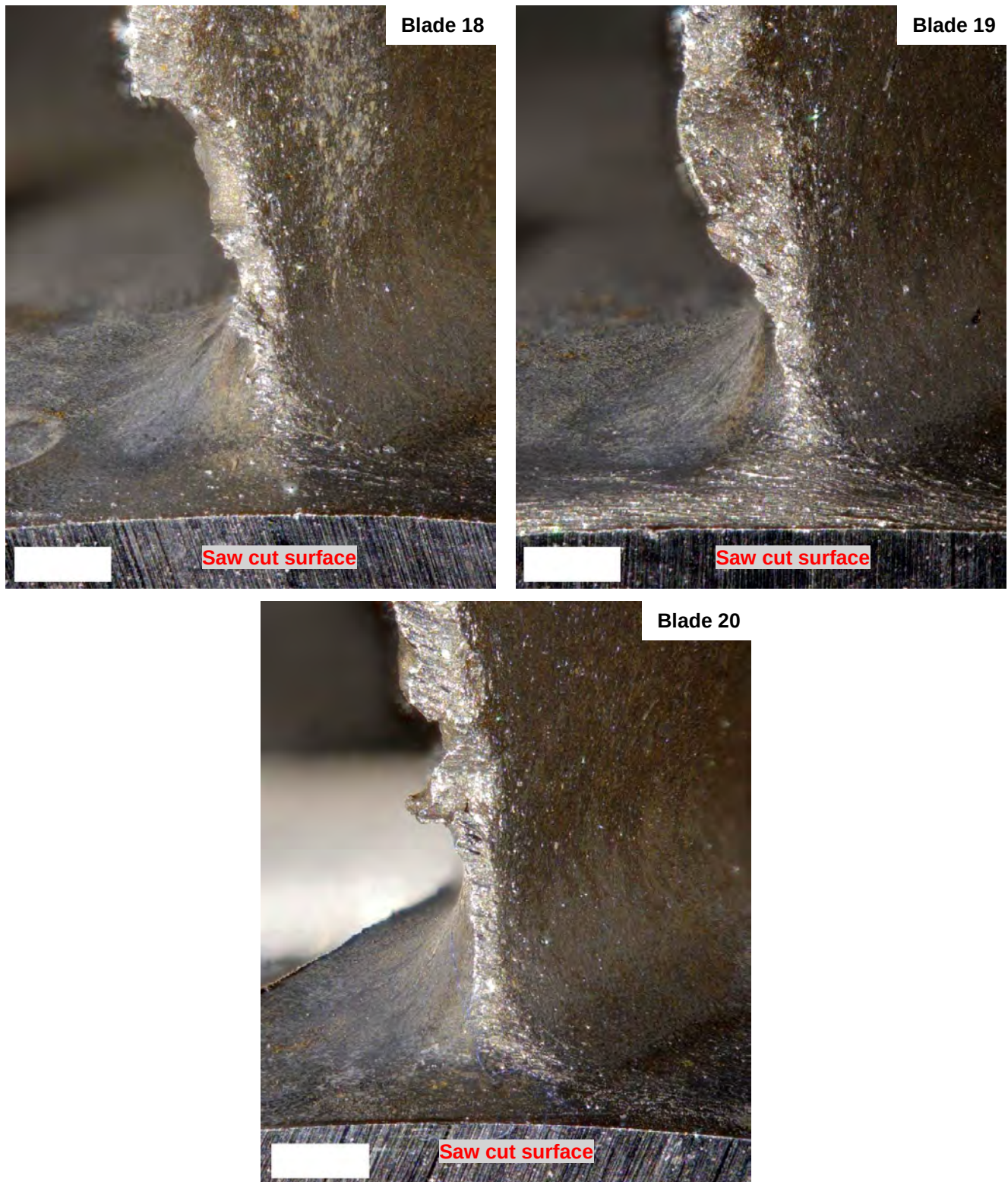


Figure 11. Detailed images of the trailing edge root area of stage 3 compressor blades 18 through 20.

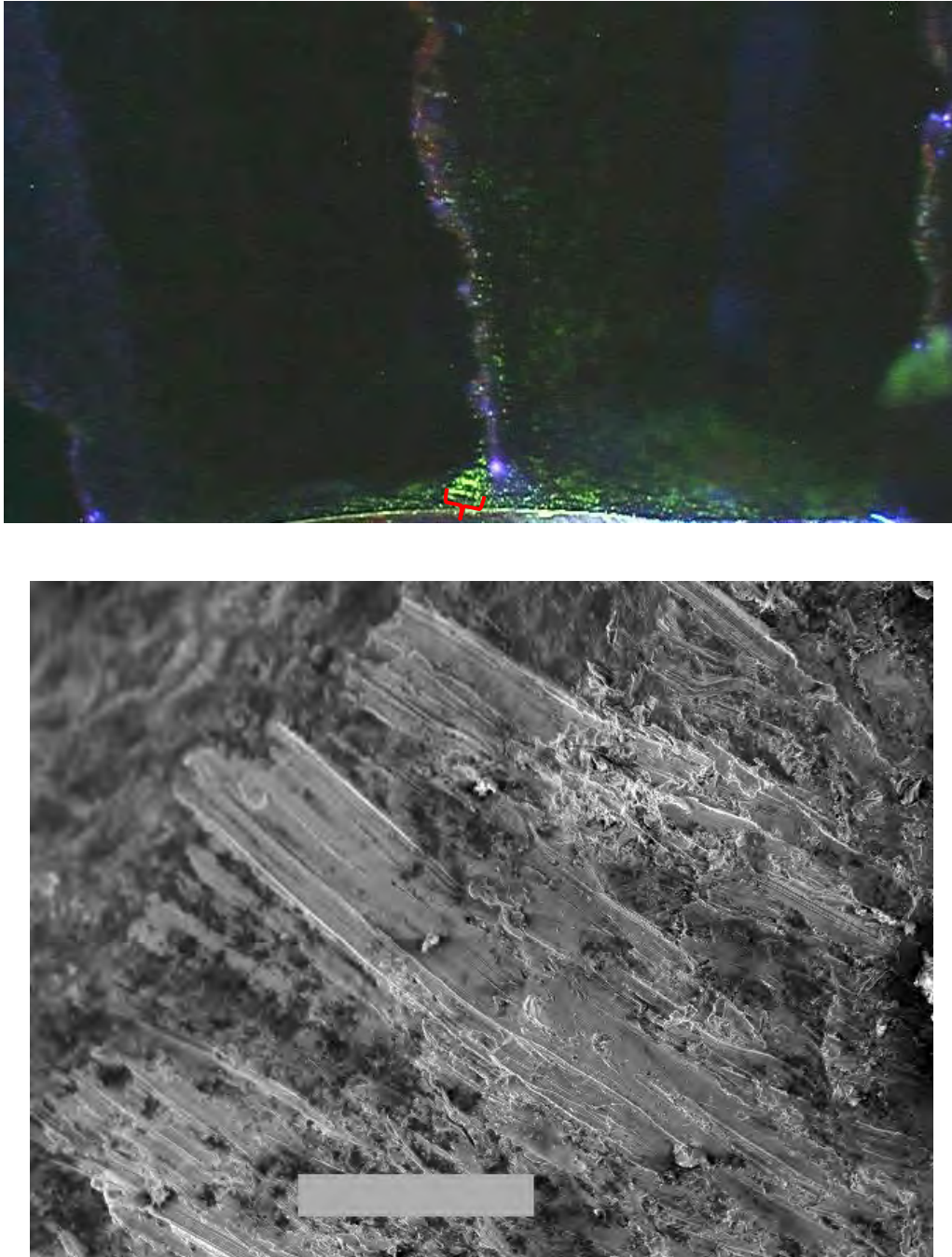


Figure 12. Top: Blacklight MPI photo of the trailing edge of blade 16. The red brace indicates an MPI indication. Image provided by the Rolls-Royce Test Department.
Bottom: Secondary electron SEM image of the area of the MPI indication, which exhibited cutting damage.



Figure 13. Detailed radial views of the fracture surfaces of the two liberated stage 3 compressor blades. The blue dashed line shows the approximate plane of metallographic cross section shown in Figure 23.

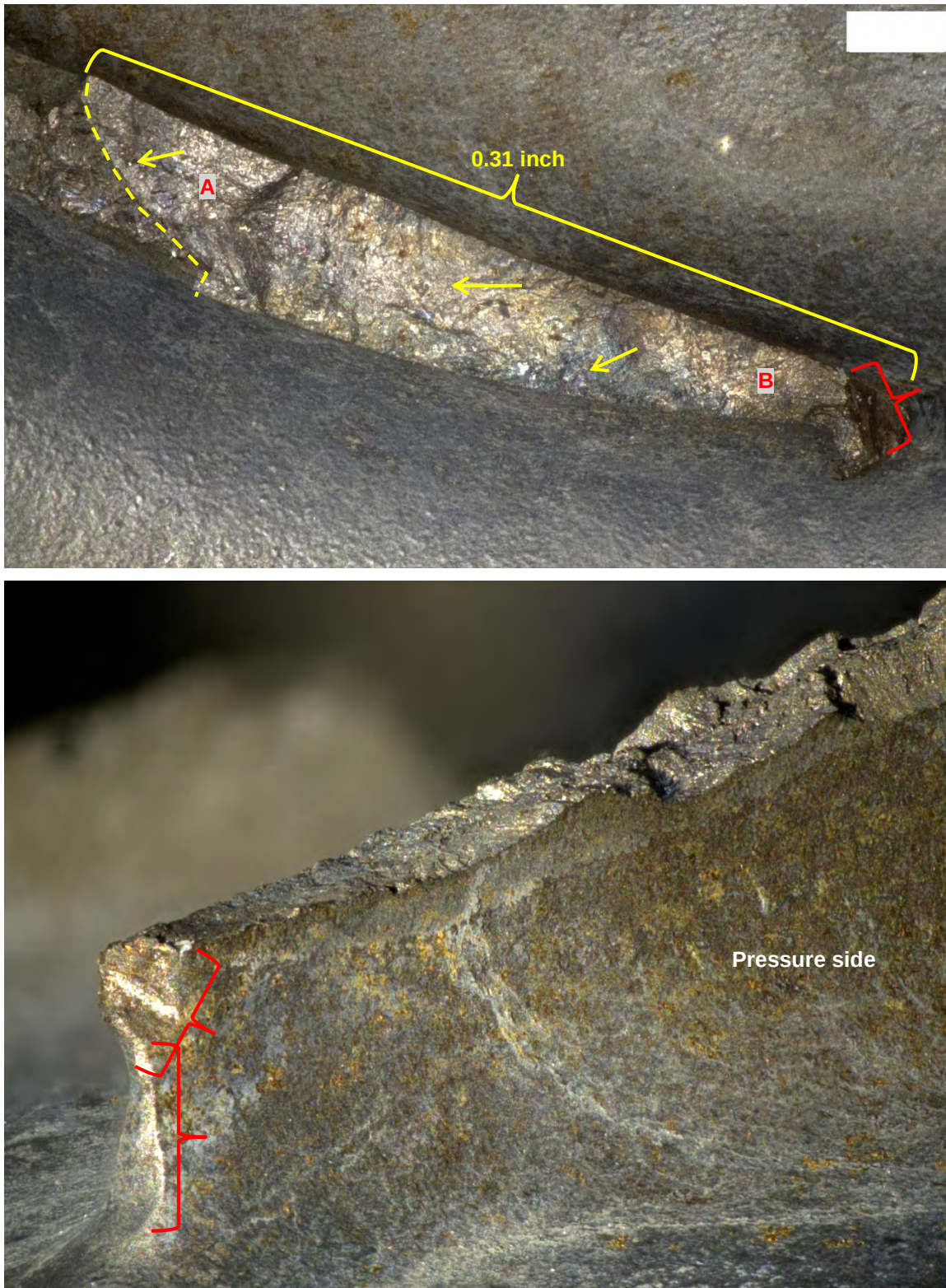


Figure 14. Detailed views of the trailing edge area of blade 1. The yellow dashed line indicates the approximate transition from fatigue to overload. The yellow arrows indicate the local direction of fatigue progression. The red braces indicate impact damage at the trailing edge. Areas A and B are shown in the following figure.

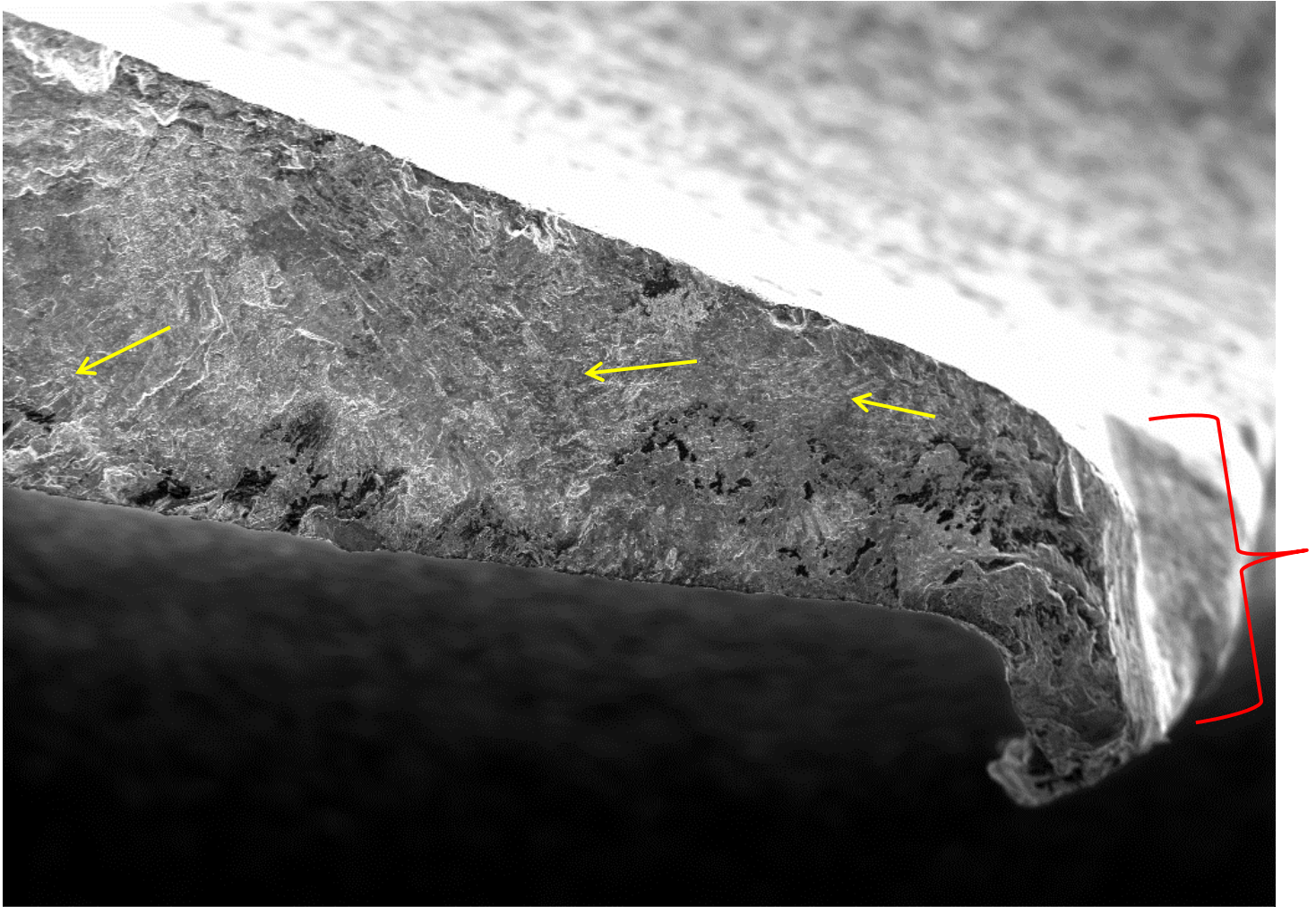


Figure 15. Detailed SEM image of the trailing edge of blade 1. The red brace indicates the impact damage. The yellow arrows indicate the direction of fatigue progression.

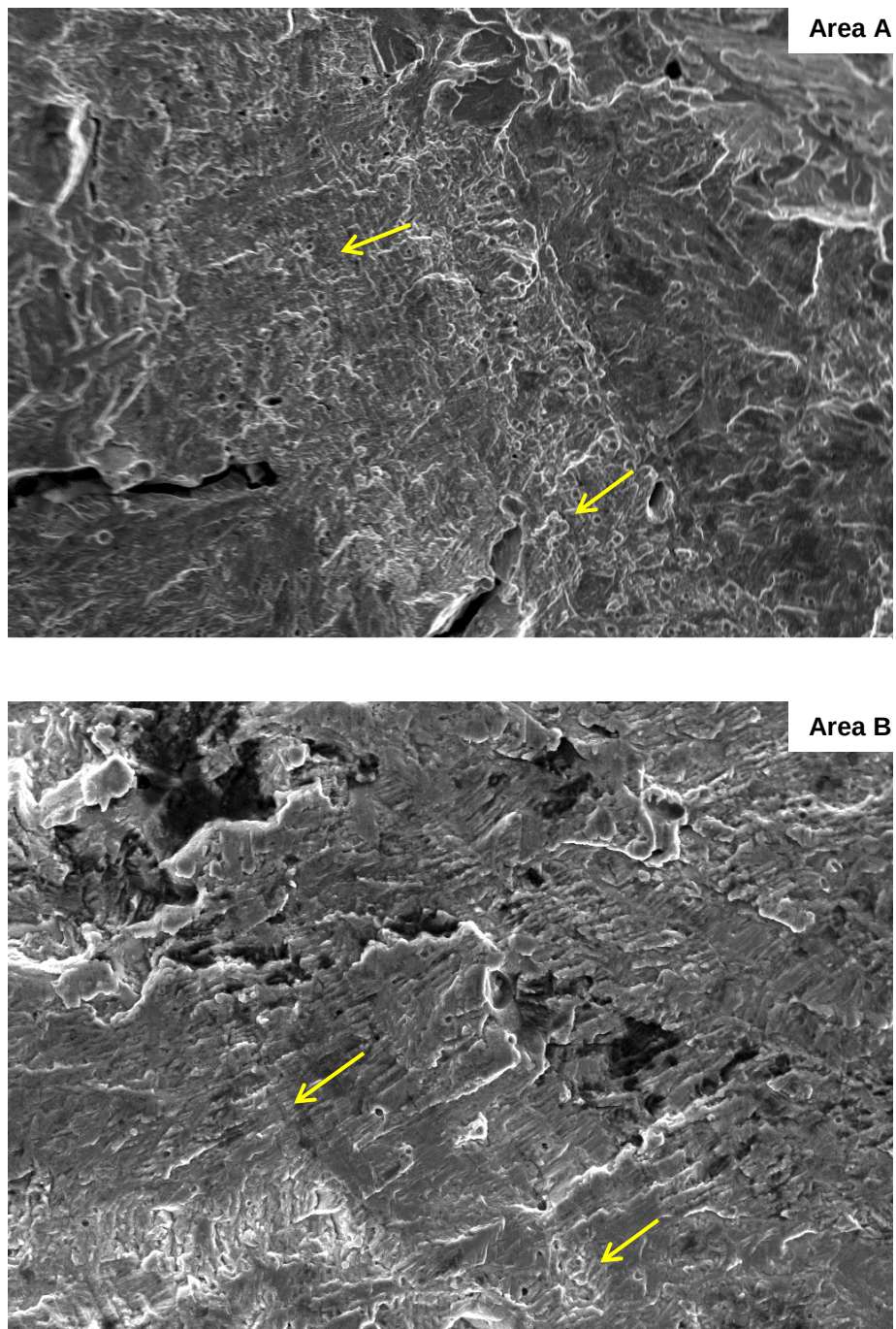


Figure 16. Detailed secondary electron SEM images of fatigue fracture features from blade 1 (see Figure 14).

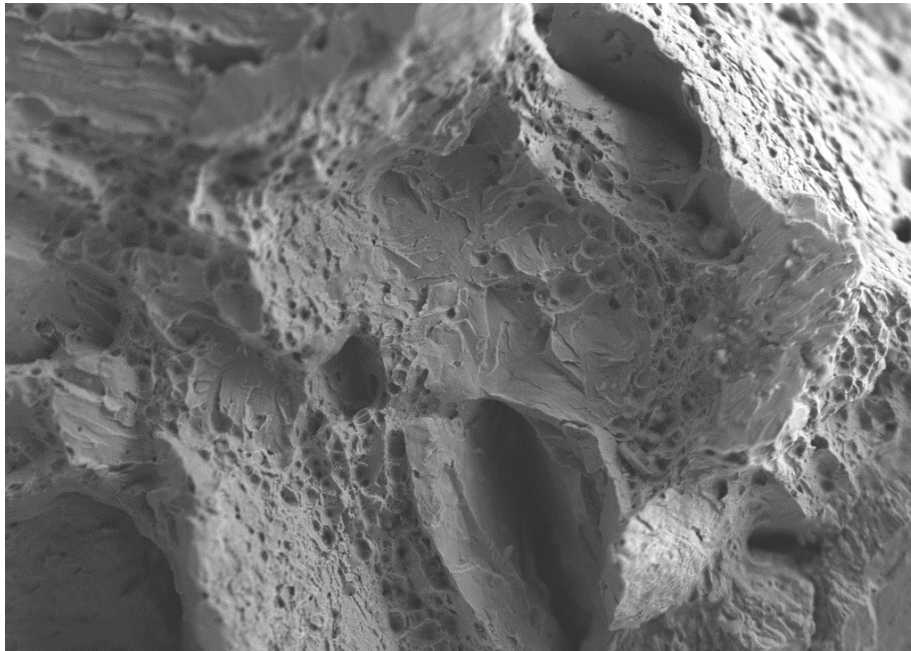


Figure 17. Detailed secondary electron SEM image of representative ductile dimple fracture features from the overload region of blade 1.

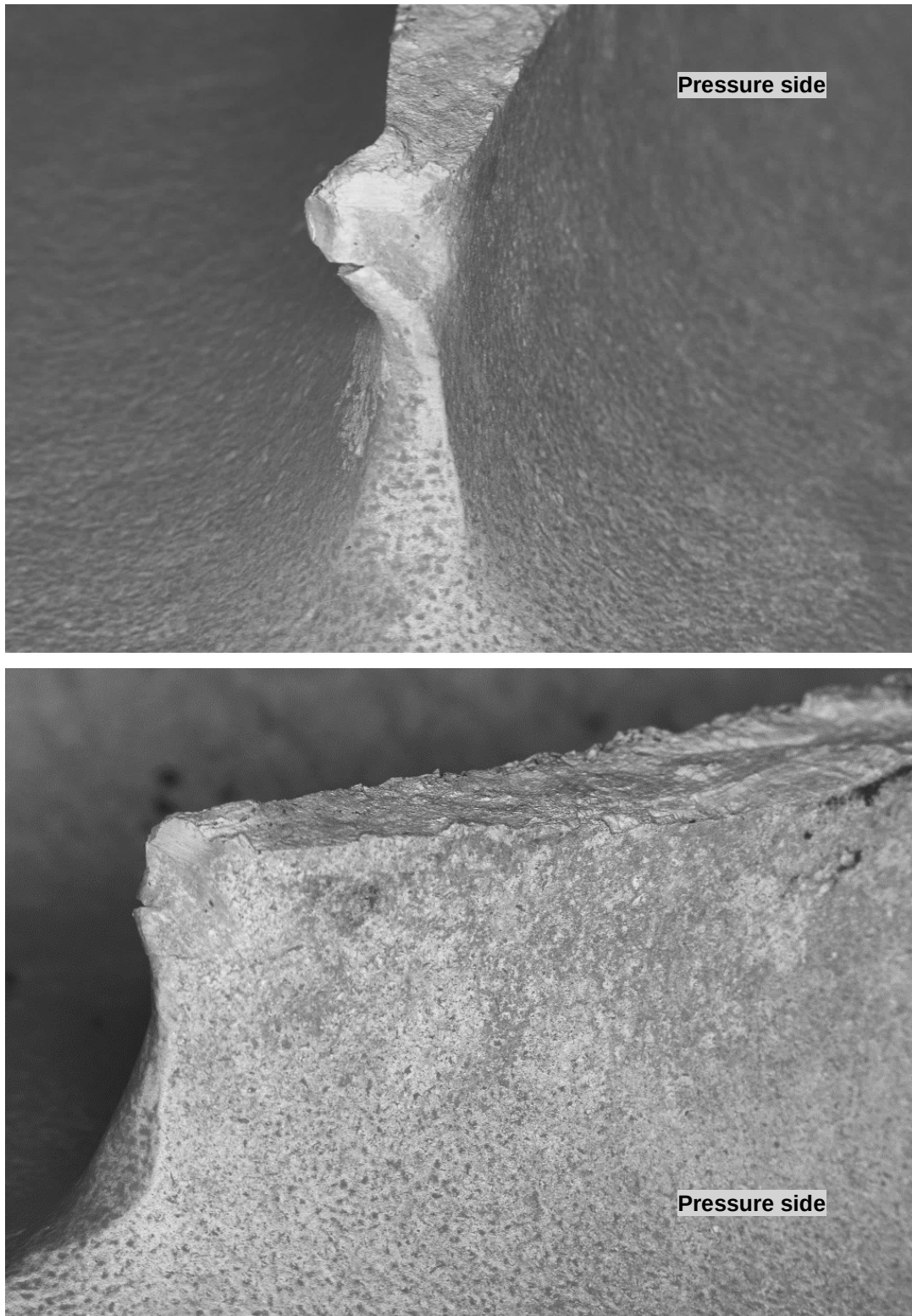


Figure 18. Detailed backscattered electron SEM images of the trailing edge area of blade 1.

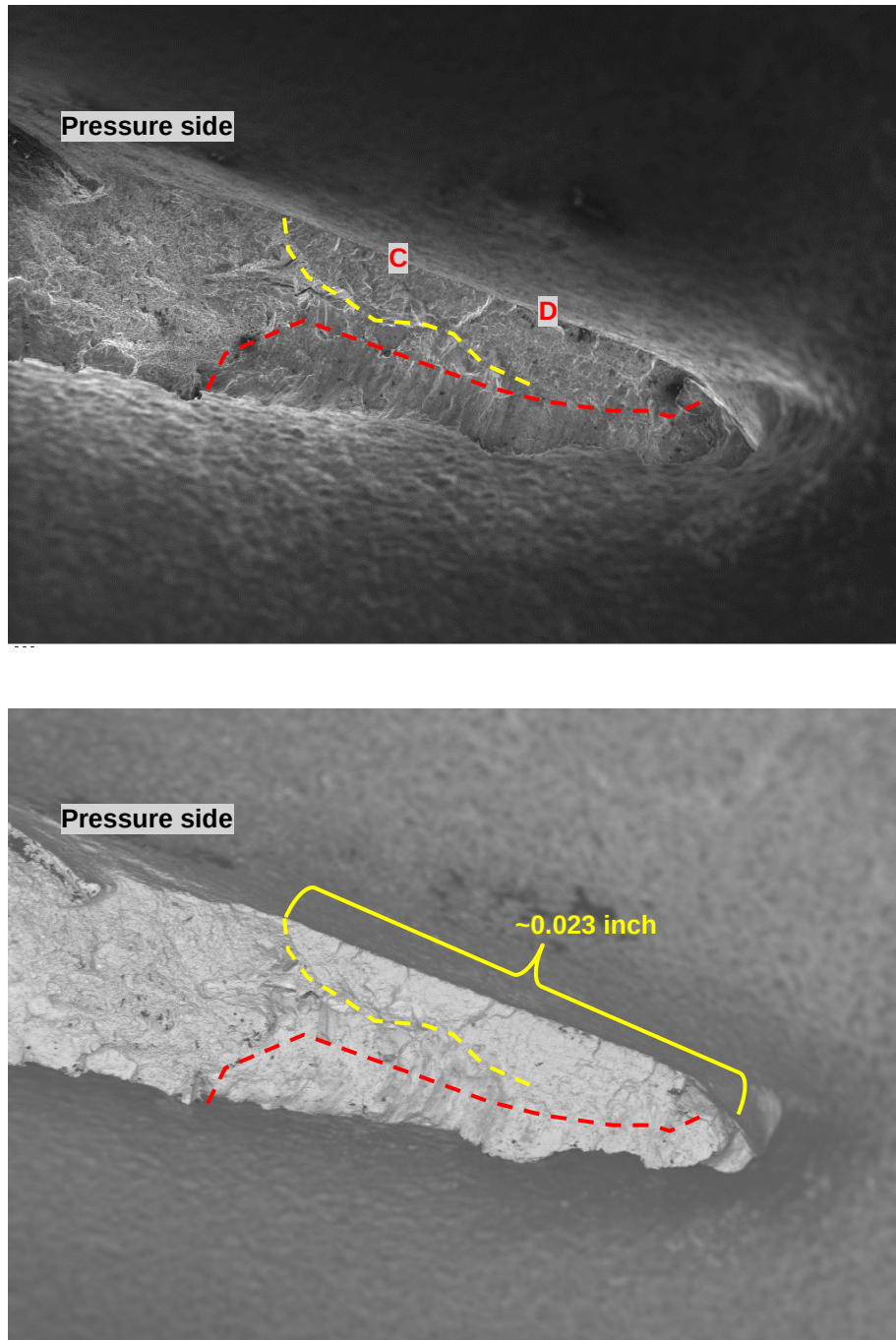


Figure 19. Secondary (top) and backscattered (bottom) electron SEM images of the trailing edge area of the blade 2 fracture surface. The red dashed line outlines an area of smearing consistent with secondary impact damage. The yellow dashed line indicates the approximate boundary of the fatigue region at the pressure side. Areas C and D are shown in greater detail in Figures 20 and 21, respectively.

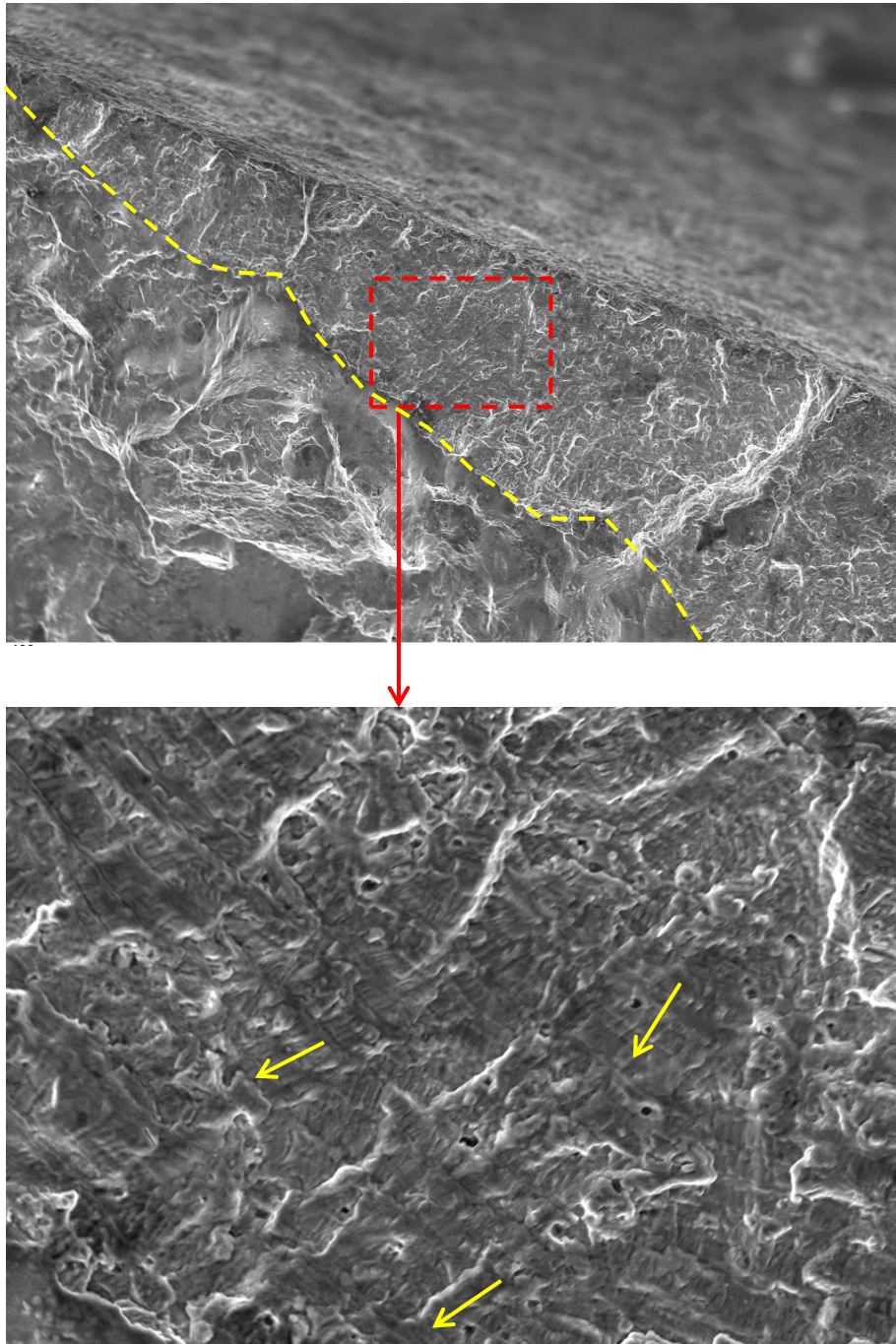


Figure 20. Secondary electron SEM images of area C from Figure 19. The yellow dashed line indicates the approximate boundary of the fatigue region. The yellow arrows indicate the local direction of fatigue progression.

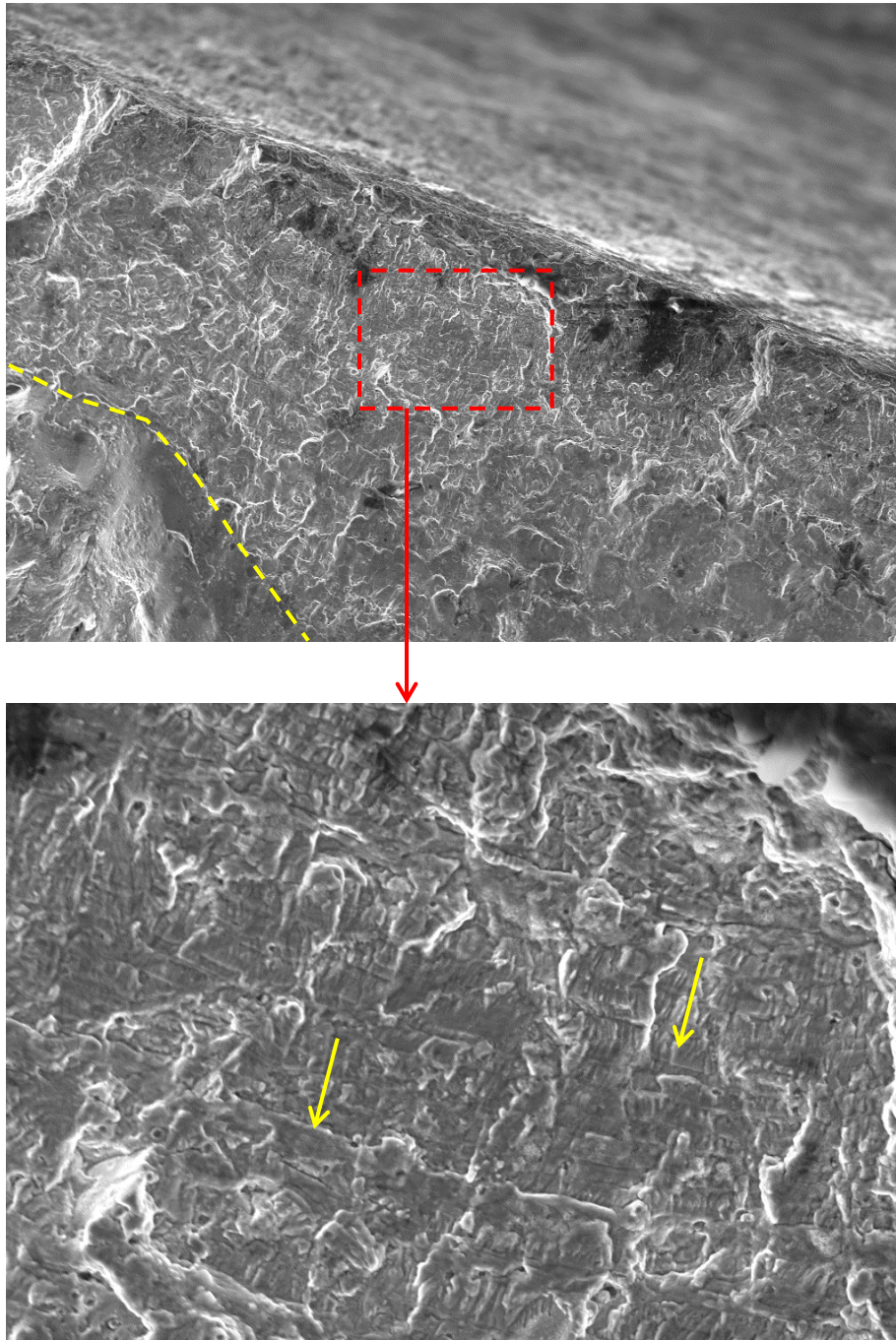


Figure 21. Secondary SEM images of area D from Figure 19. The yellow dashed line indicates the boundary of the fatigue region. The yellow arrows indicate the local direction of fatigue progression.

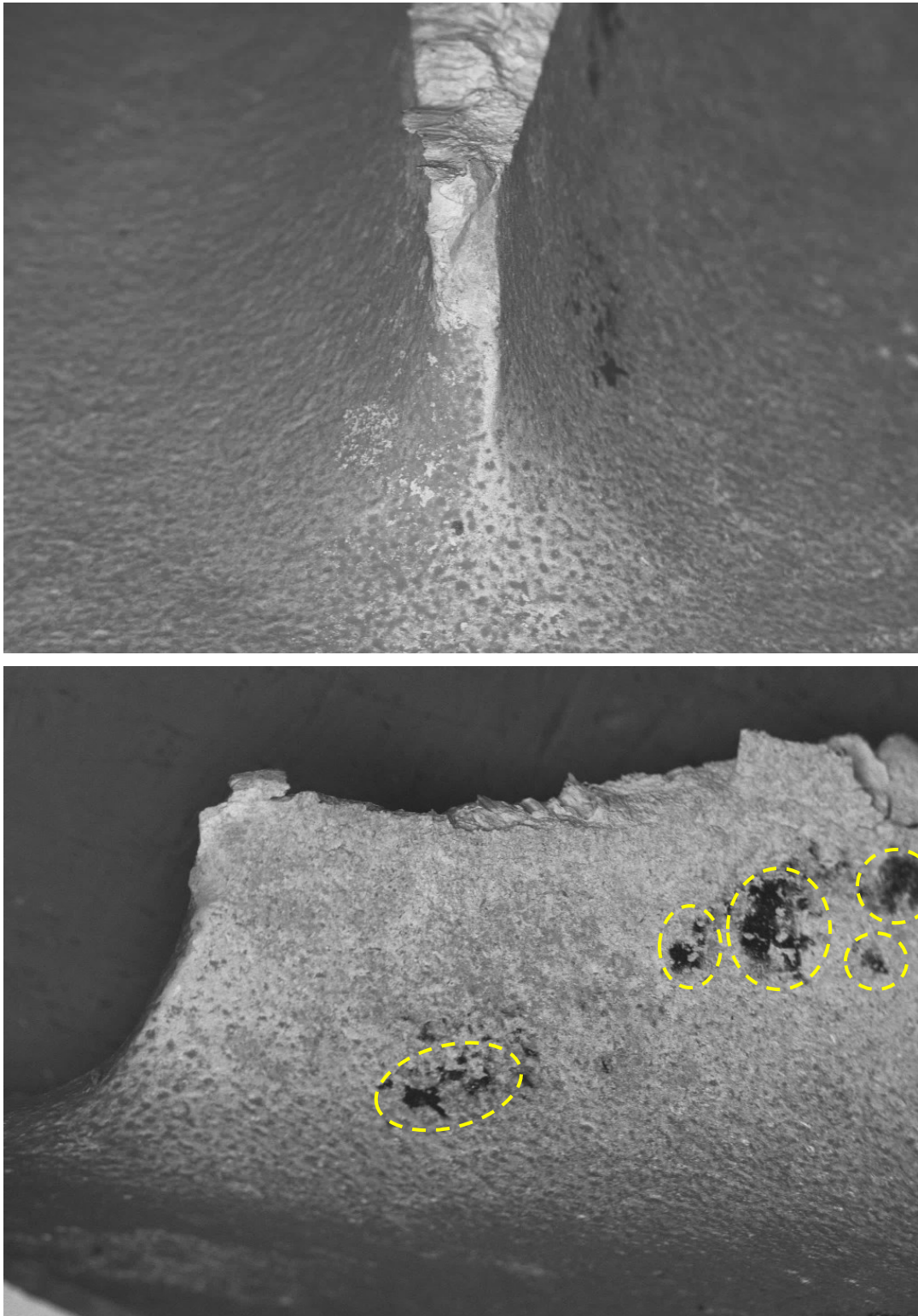


Figure 22. Backscattered electron SEM images of the trailing edge area of blade 2. The yellow dashed circles indicate residual adhesive on the surface from masking tape applied during cutting.



Figure 23. Circumferential-radial metallographic cross section through the fatigue origin area on blade 1 (see Figure 13). Unetched

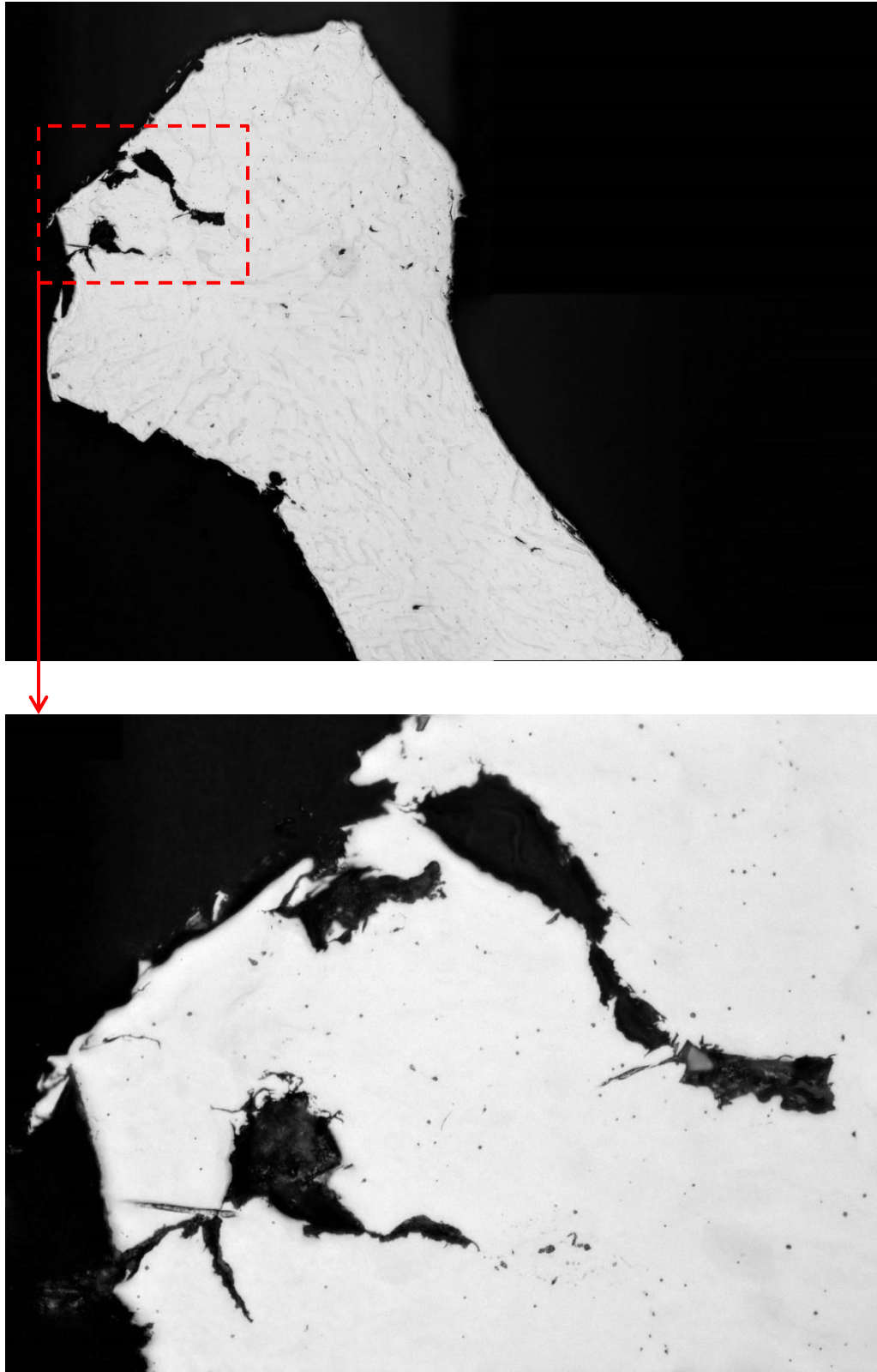


Figure 24. Detailed views of the area near the fracture surface from the cross section in Figure 23. Unetched.

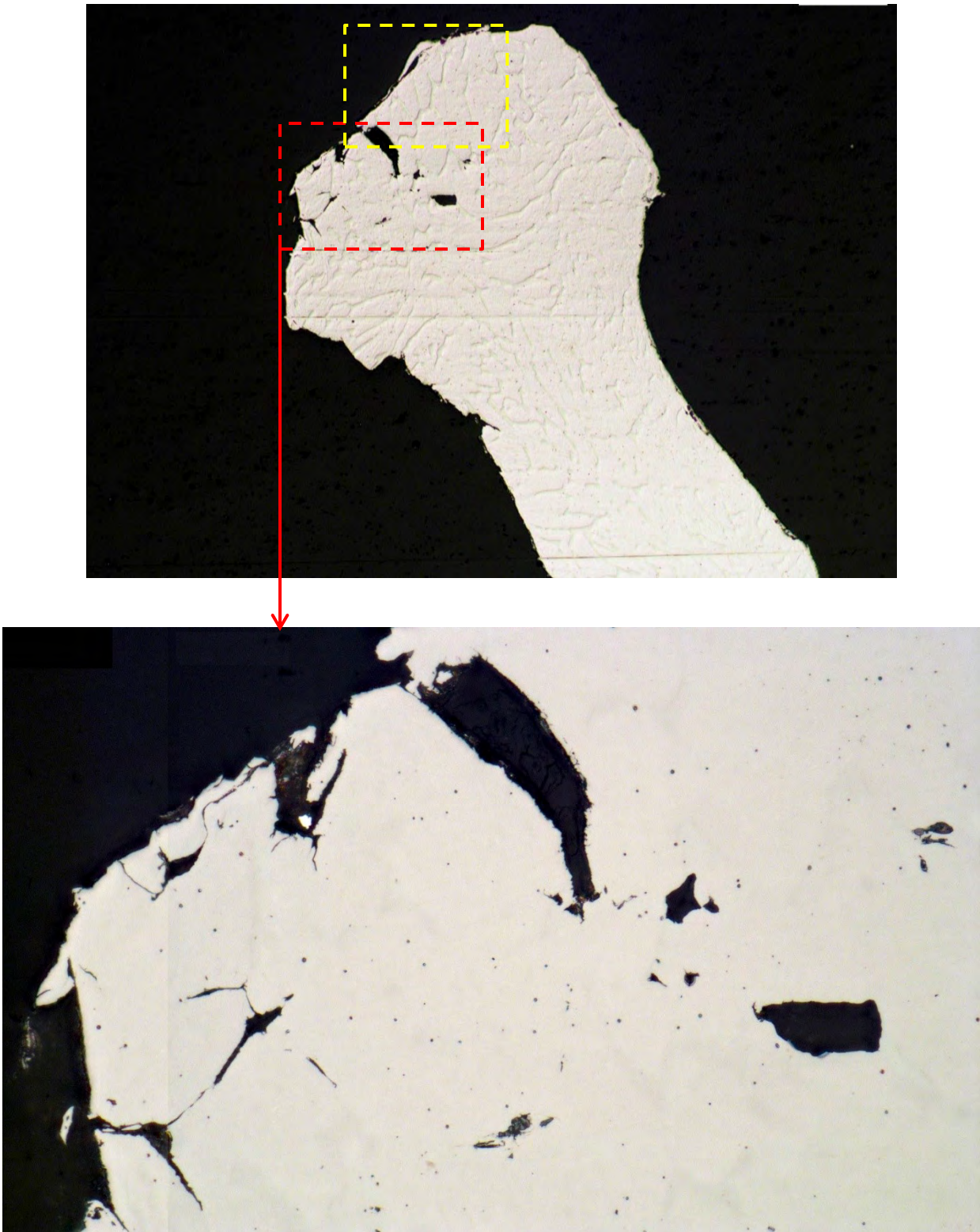


Figure 25. Detailed views of the origin area from the cross section in Figure 23 after removing approximately 0.02 inch of material to move the plane farther from the trailing edge. The area in the yellow dashed box is shown in greater detail in the following figure. Unetched.

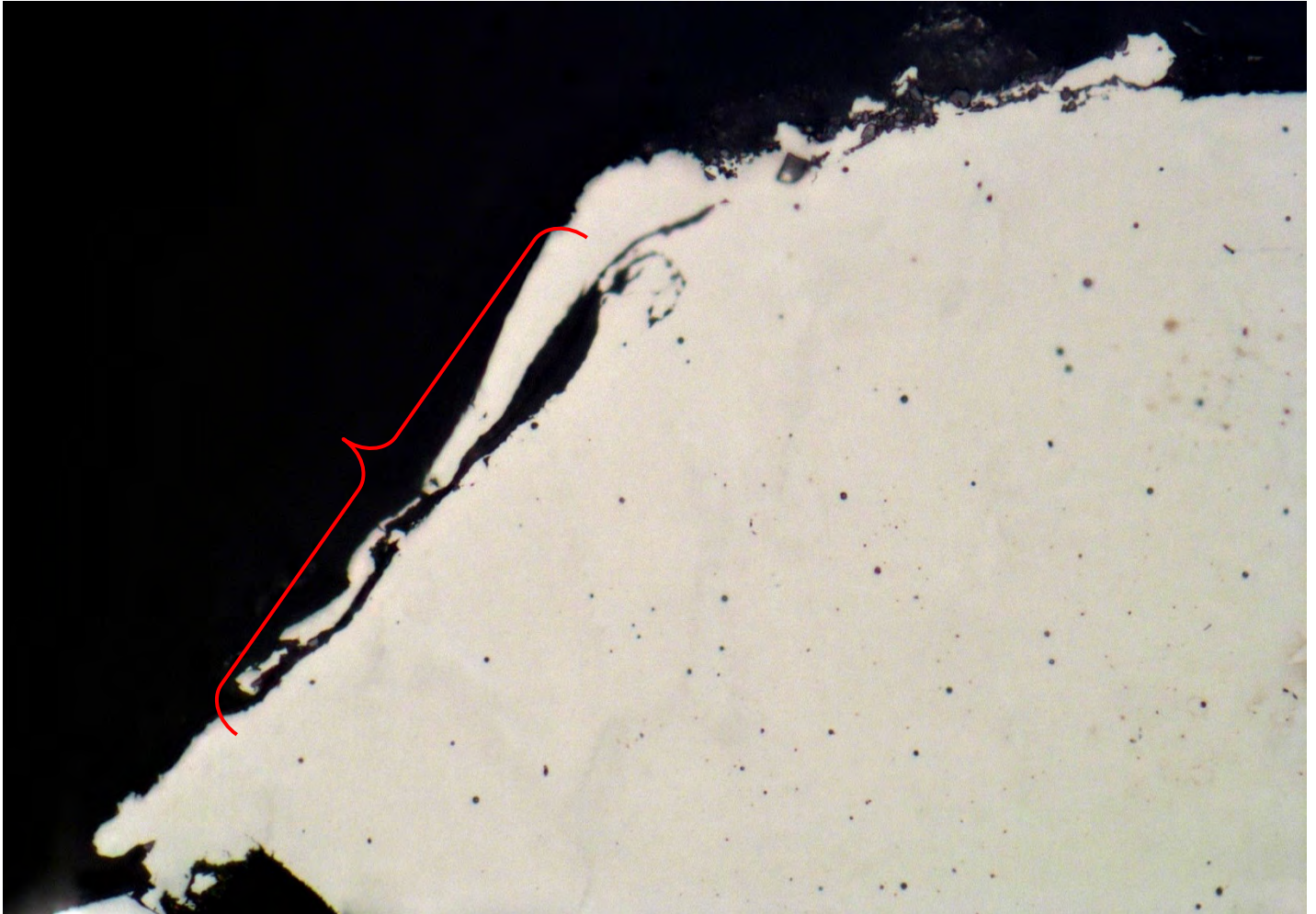


Figure 26. Deformed and folded over material (red brace) near the origin area consistent with secondary impact damage (see Figure 25). Unetched.

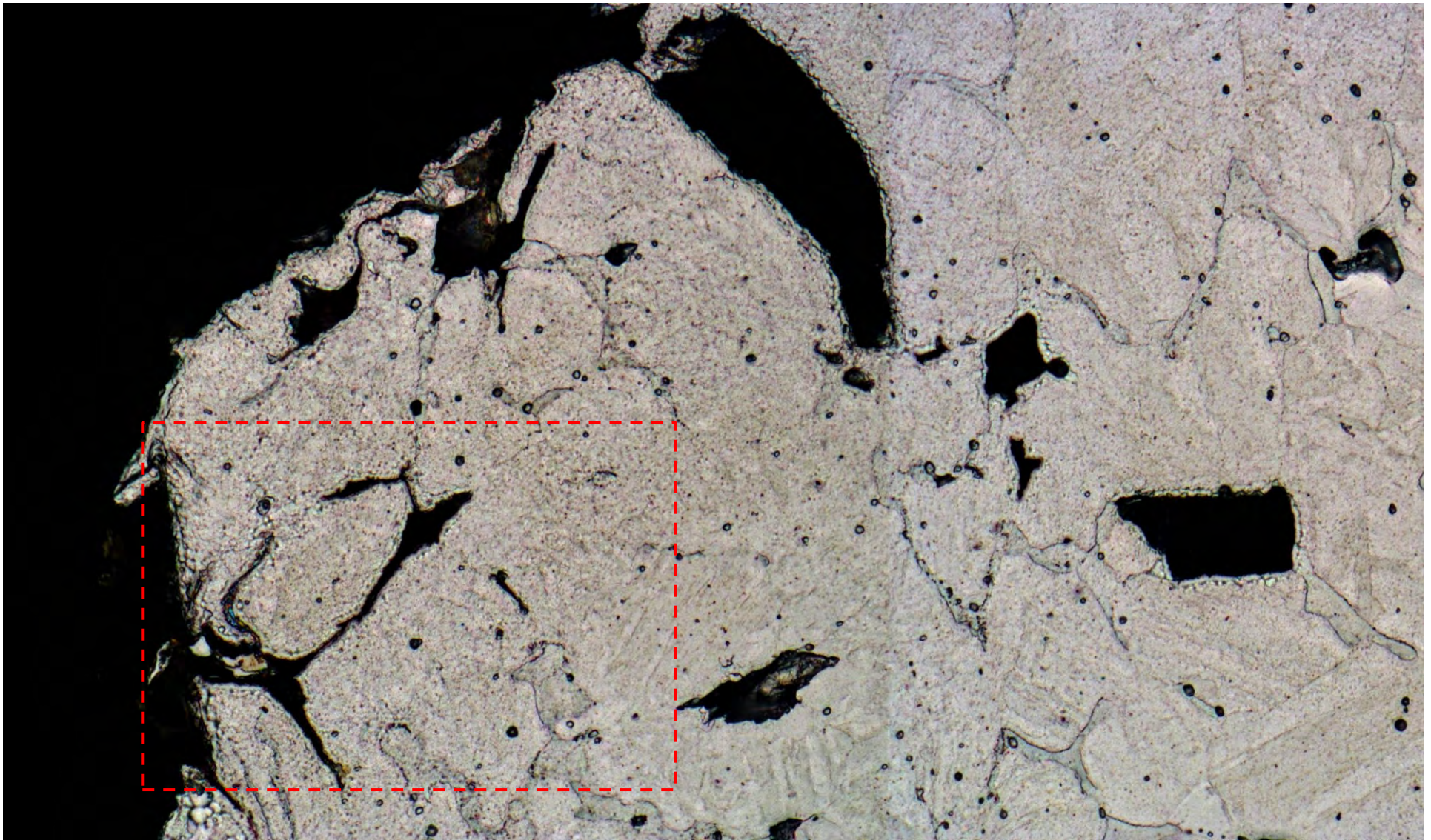
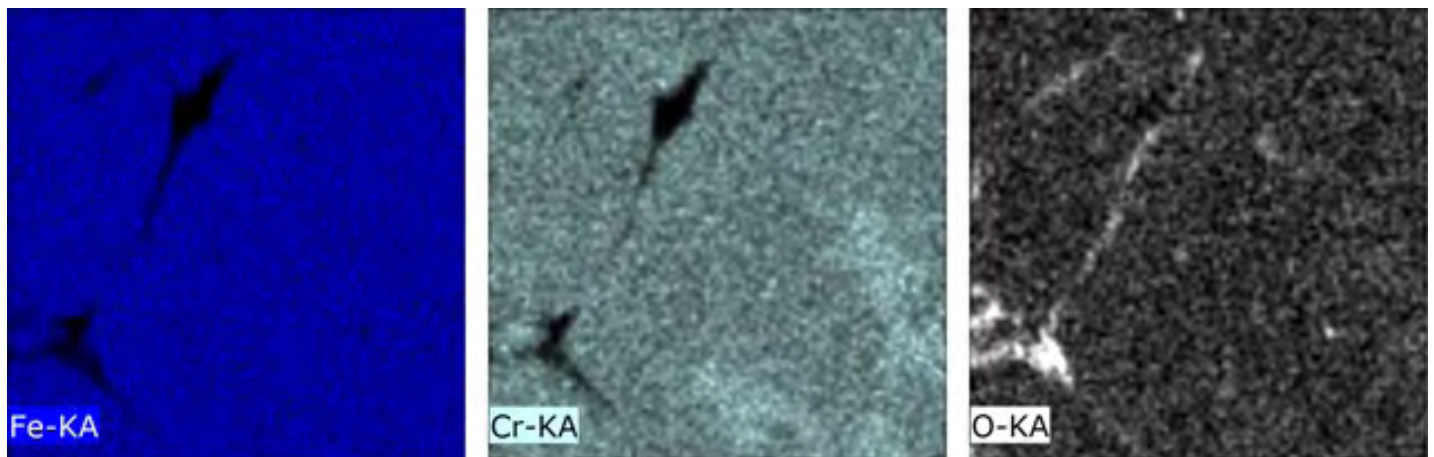
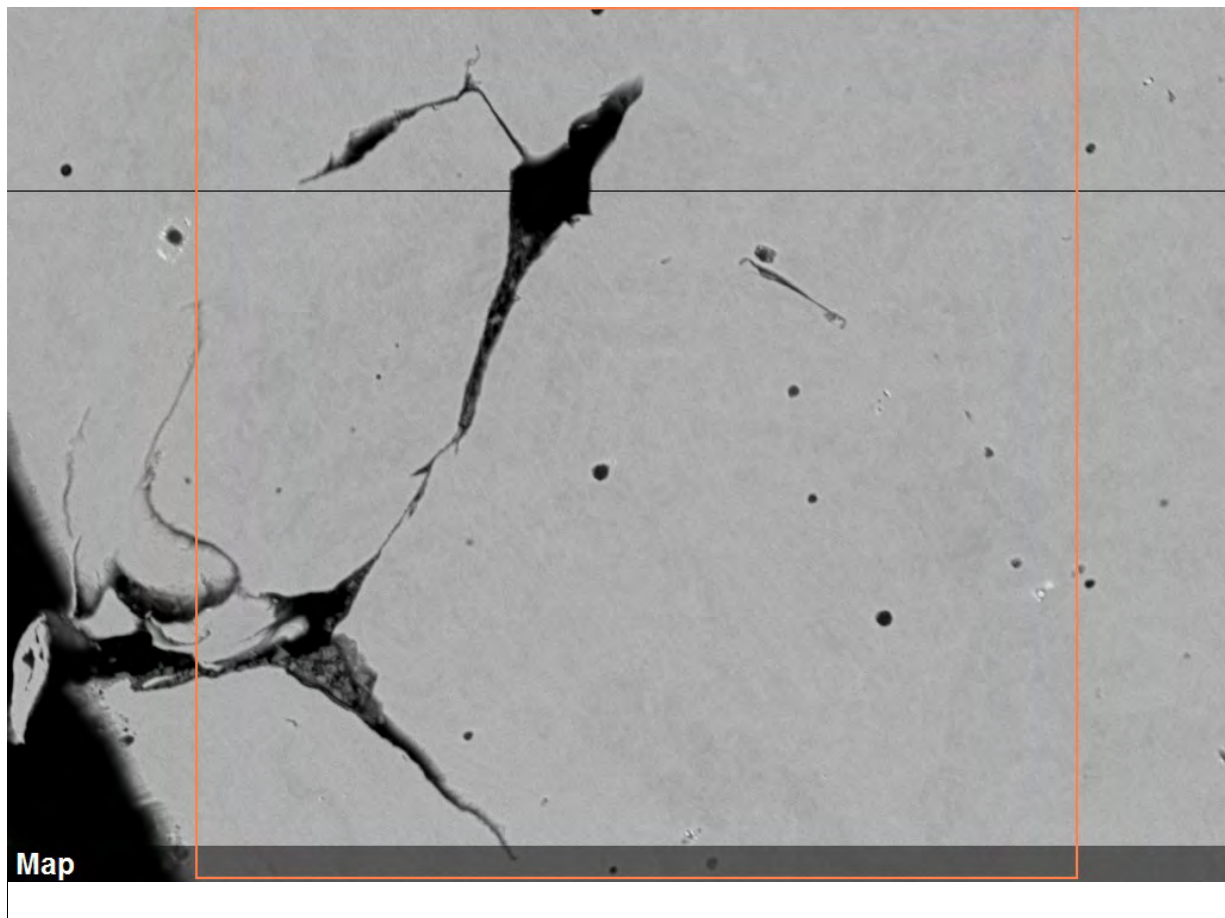


Figure 27. Montage of etched metallographic images of the area of the cross section in Figure 25 that exhibited subsurface voids. The area in the red dashed box is shown in Figure 28.

Etchant: Oxalic electrolytic, approximately 2 Volts, approximately 2 seconds



**Figure 28. Top: Backscattered electron SEM image of the area of voids annotated in Figure 27. The area in the orange box is shown in the EDS maps.
Bottom: EDS maps showing the spatial concentration variations of iron, chromium, and oxygen.**

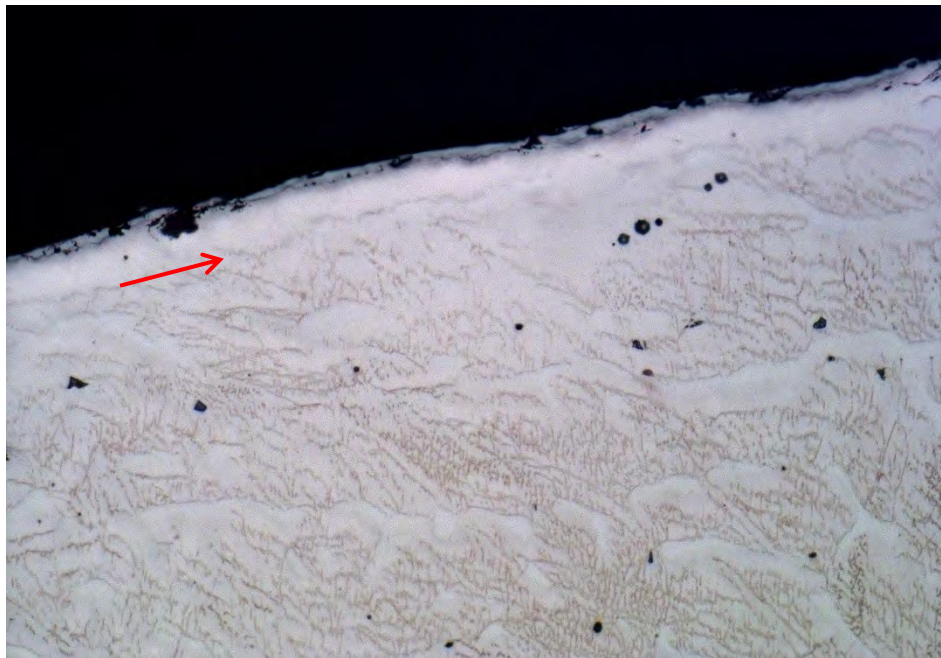
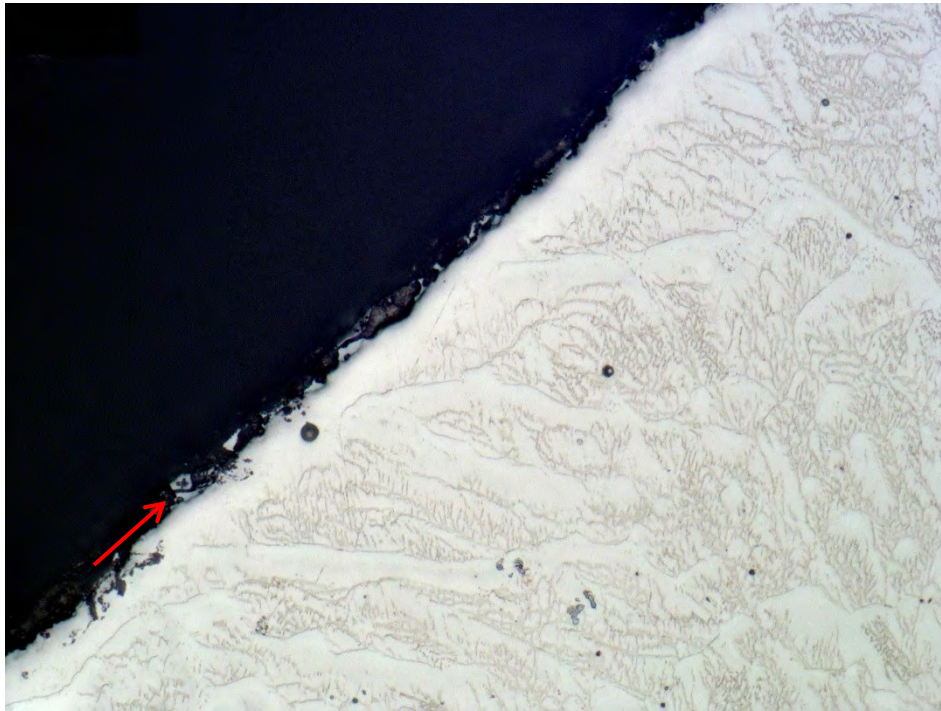
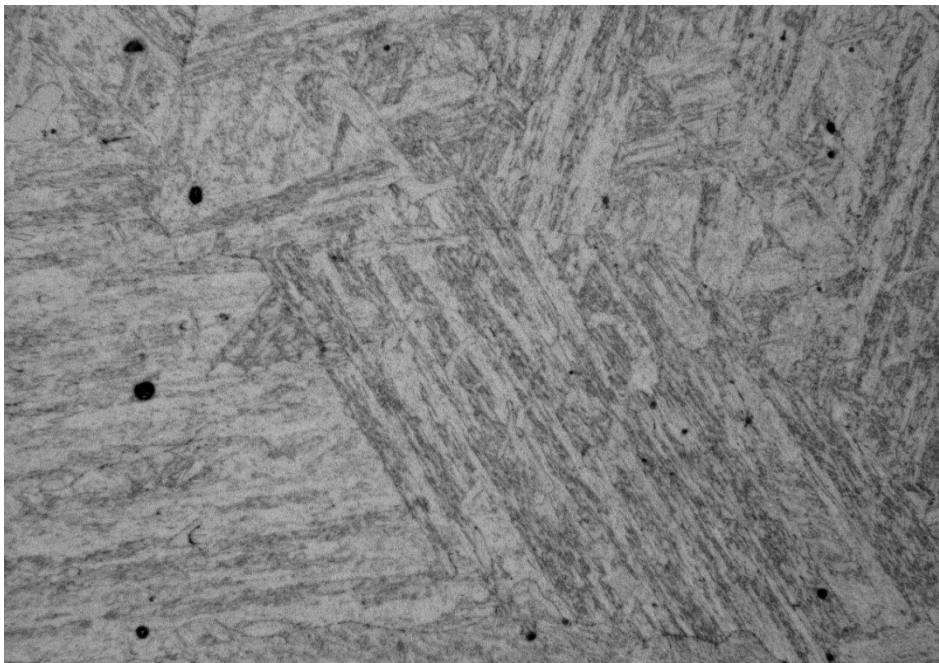
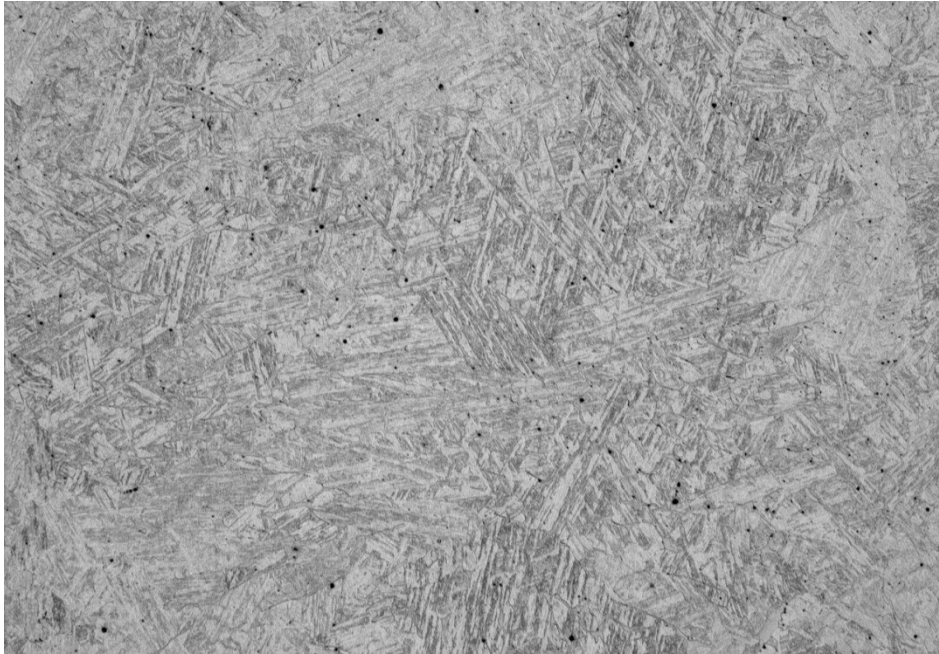


Figure 29. Detailed views of the aluminide coating (red arrows) in two locations on the cross section in Figure 23 showing representative damaged coating near an area of impact damage (top) and undamaged coating away from the impact damage (bottom). Etchant: Stainless No. 2



**Figure 30. Representative microstructure of the stage 2-3 wheel from the cross section in Figure 23.
Etchant: Stainless No. 2**

Stage 4



Stage 5



Stage 4



Stage 5



Figure 31. Detailed radial views of the stage 4 and 5 compressor wheels, while still in the rotor stack. Each image shows the rotor rotated approximately 90° from the previous.

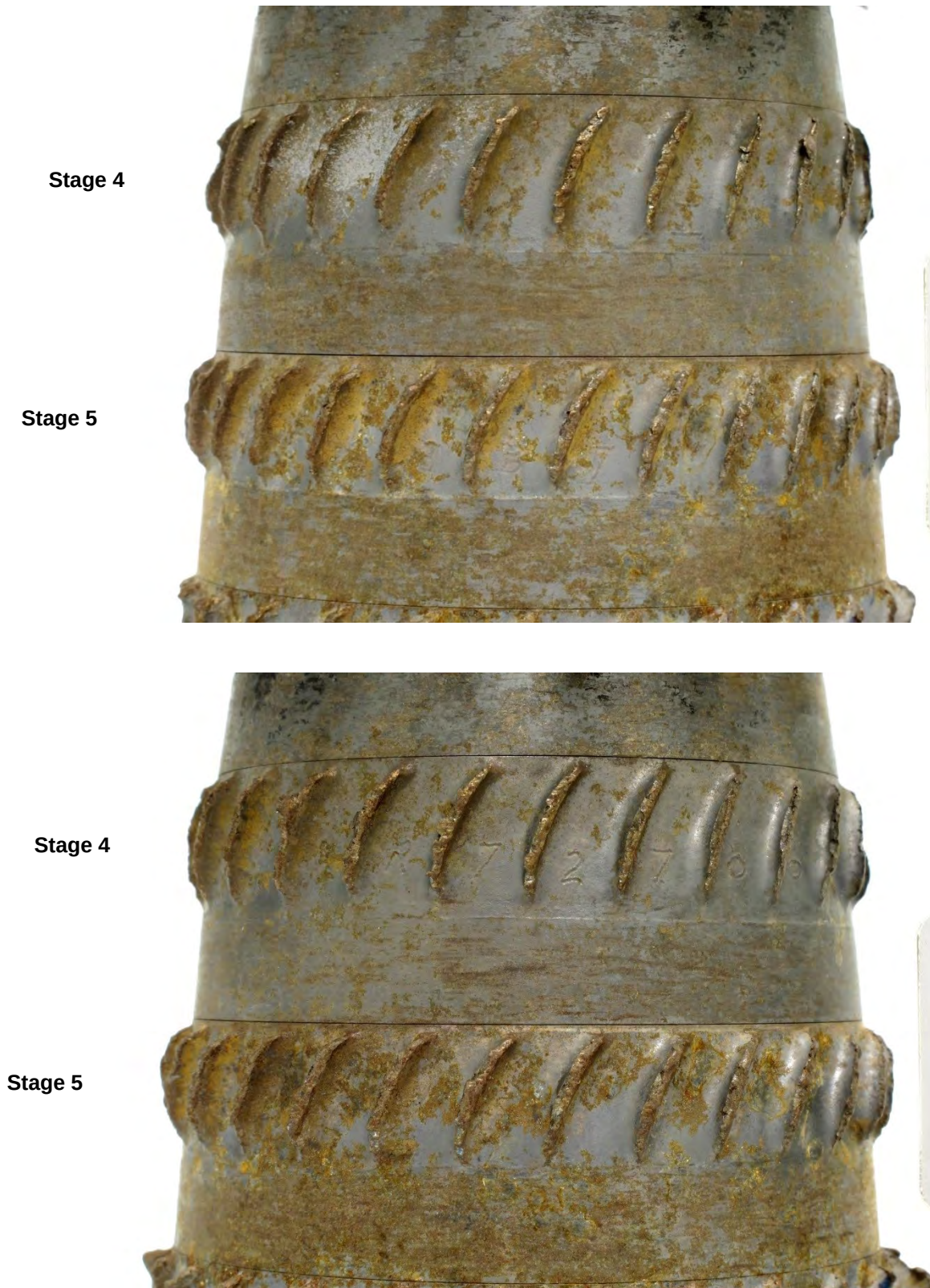


Figure 32. Detailed radial views of the stage 4 compressor wheel and stage 5 compressor wheel, while still in the rotor stack. Each image shows the rotor rotated approximately 90° from the previous.



Figure 33. Axial views of the stages 4 through 6 compressor wheels after separation from the stage 1 through 3 compressor wheels.



Figure 34. Inner diameter of the stage 4 through 6 compressor wheels after separation from the stage 1 through 3 compressor wheels. Each image shows the component rotated approximately 180° from the previous. Generalized corrosion was present on the majority of the inner diameter.



Figure 35. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 36. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 37. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 38. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 39. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 40. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 41. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 42. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.

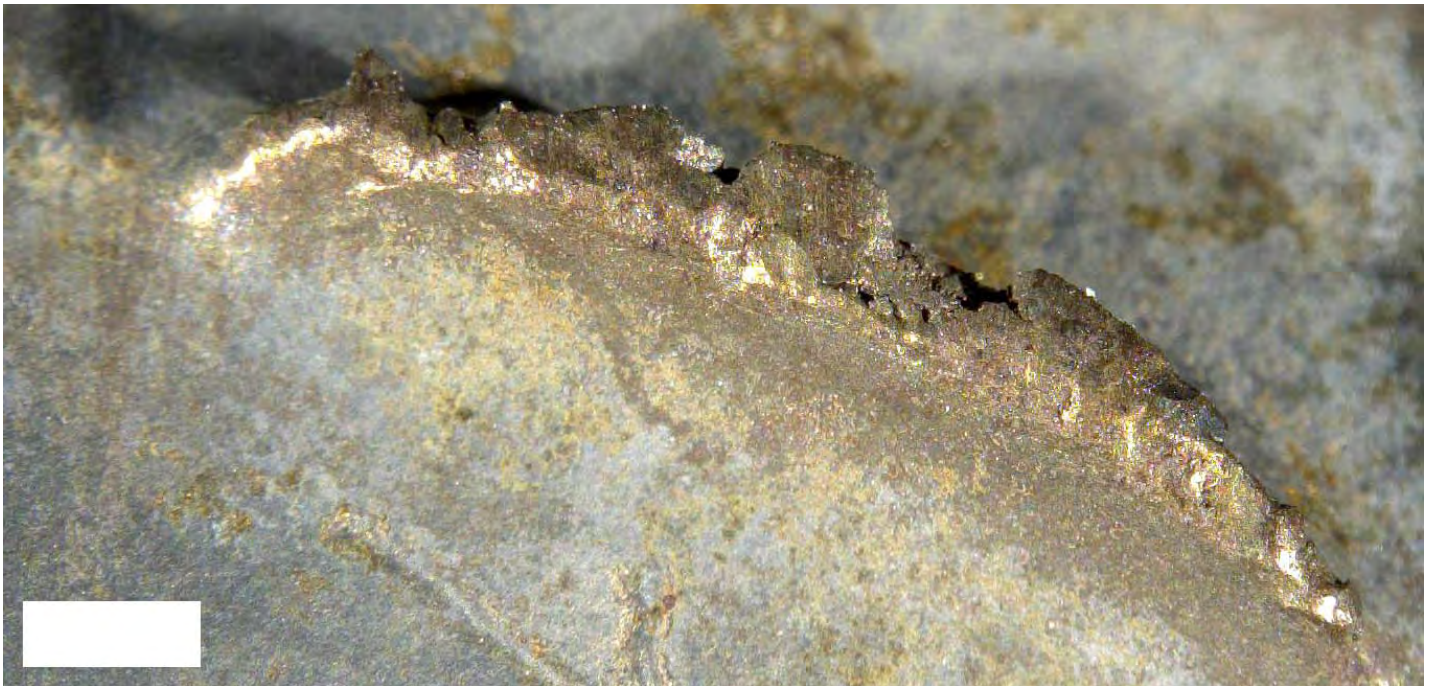


Figure 43. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.

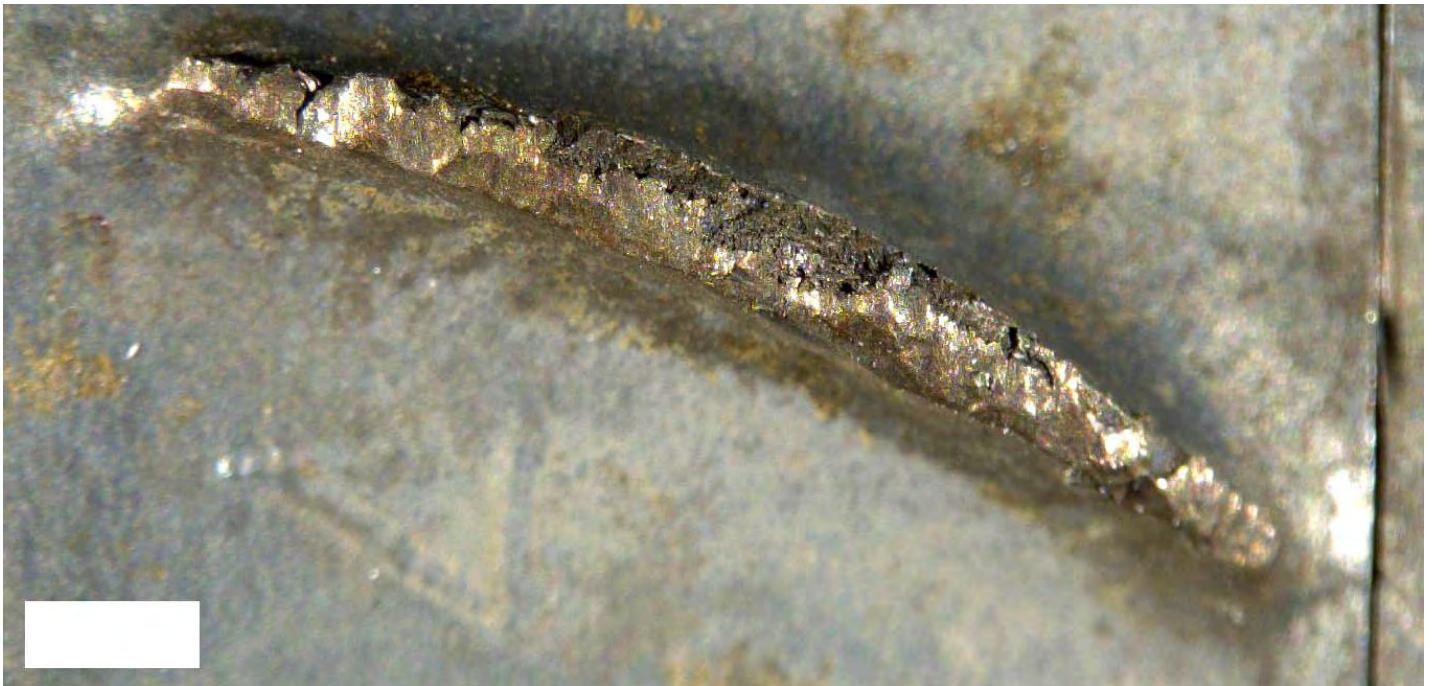


Figure 44. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 45. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 46. Detailed views of two stage 4 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 47. Detailed views of one stage 4 blade fracture surface. No fatigue fracture features were present on either of the fracture surfaces.

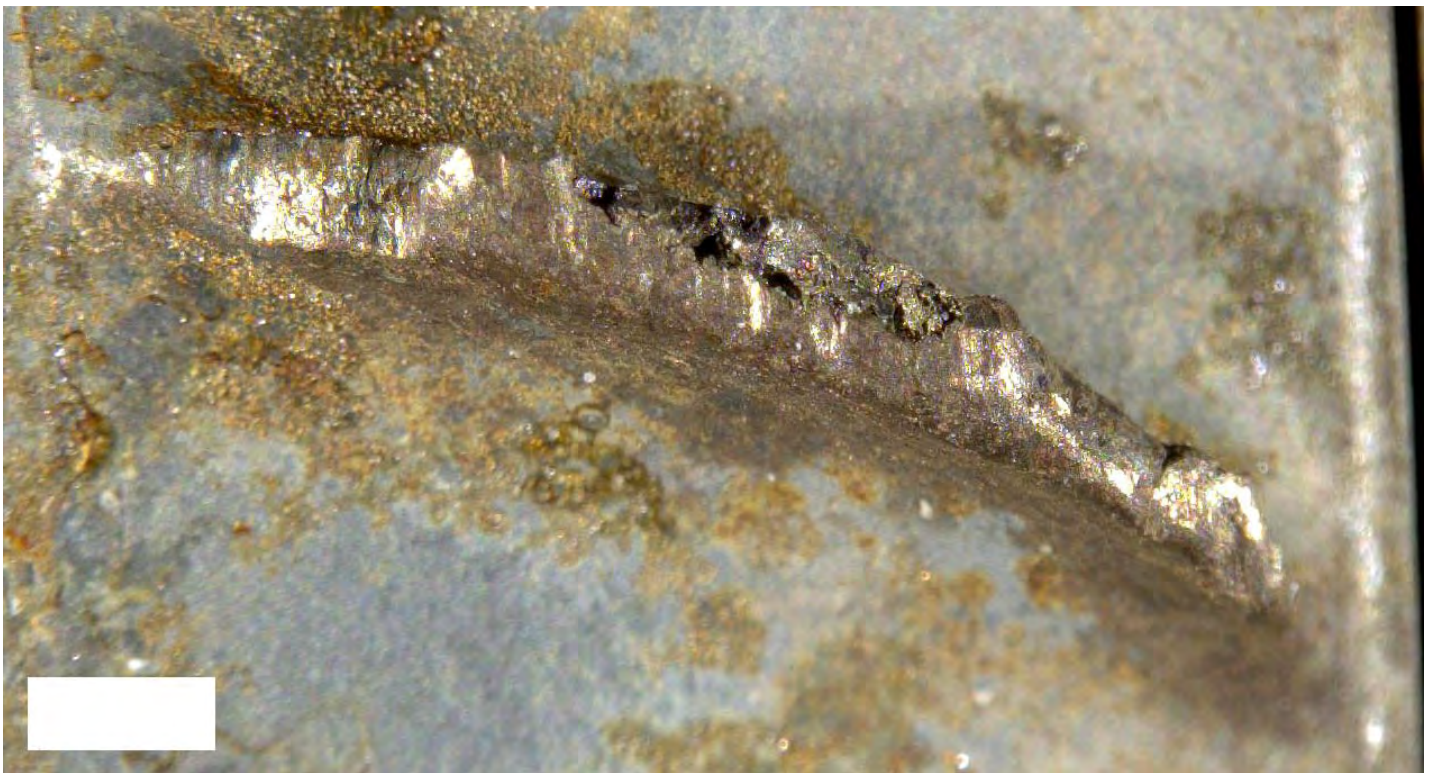


Figure 48. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 49. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 50. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 51. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.

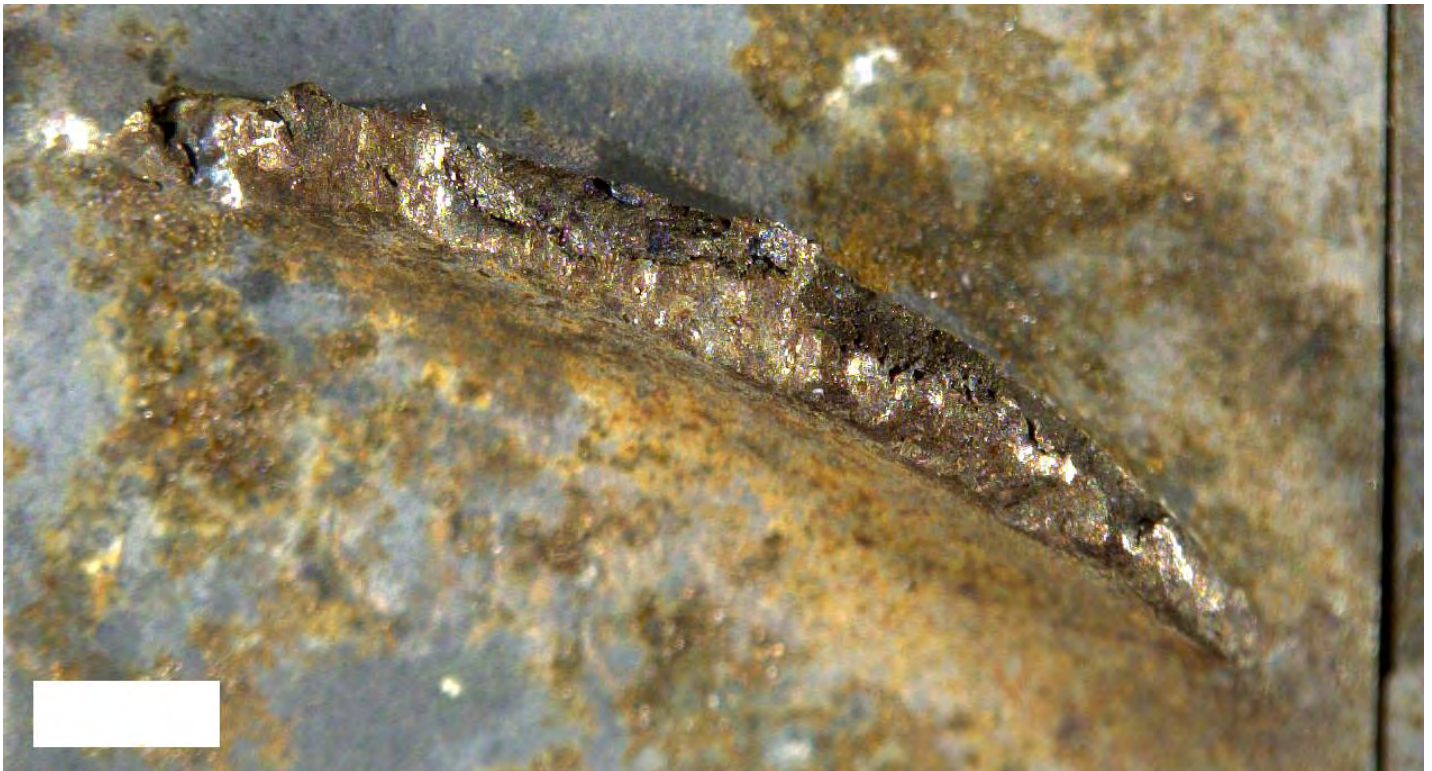


Figure 52. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 53. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 54. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.

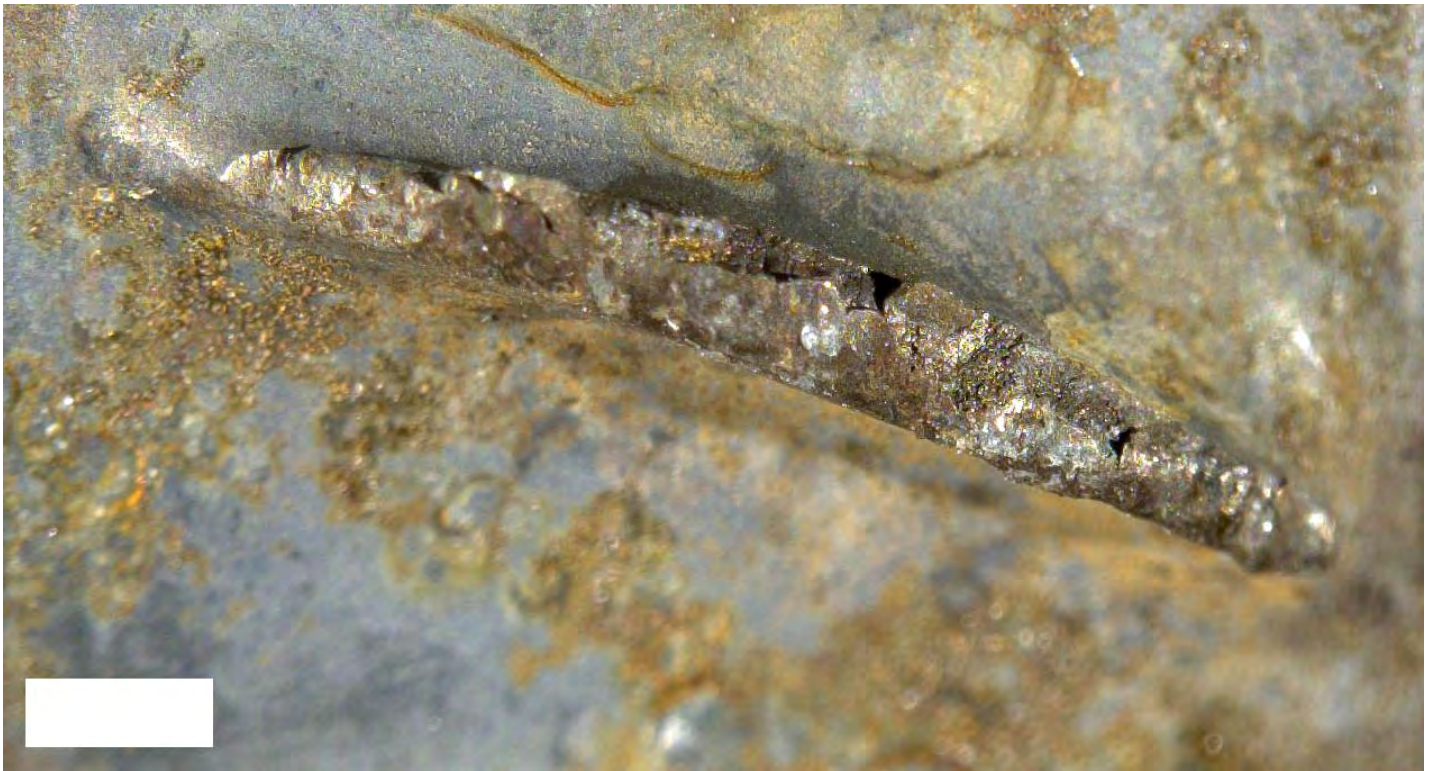


Figure 55. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.

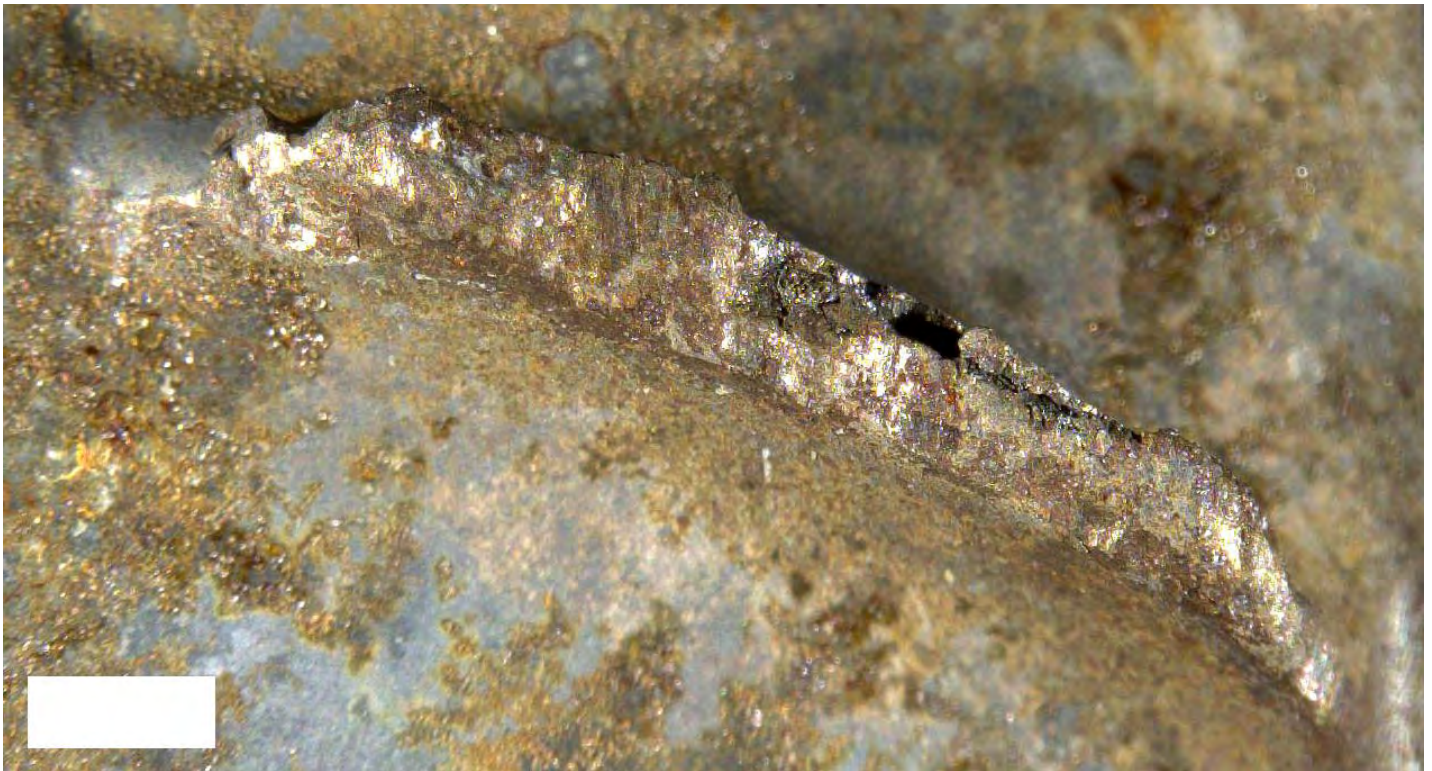


Figure 56. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 57. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 58. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 59. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 60. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 61. Detailed views of two stage 5 blade fracture surfaces. No fatigue fracture features were present on either of the fracture surfaces.



Figure 62. Detailed radial views of the stage 6 compressor wheel while still in the rotor stack. Each image shows the rotor rotated approximately 90° from the previous.



Figure 63. Detailed radial views of the stage 6 compressor wheel while still in the rotor stack. Each image shows the rotor rotated approximately 90° from the previous.



Figure 64. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 1 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression.

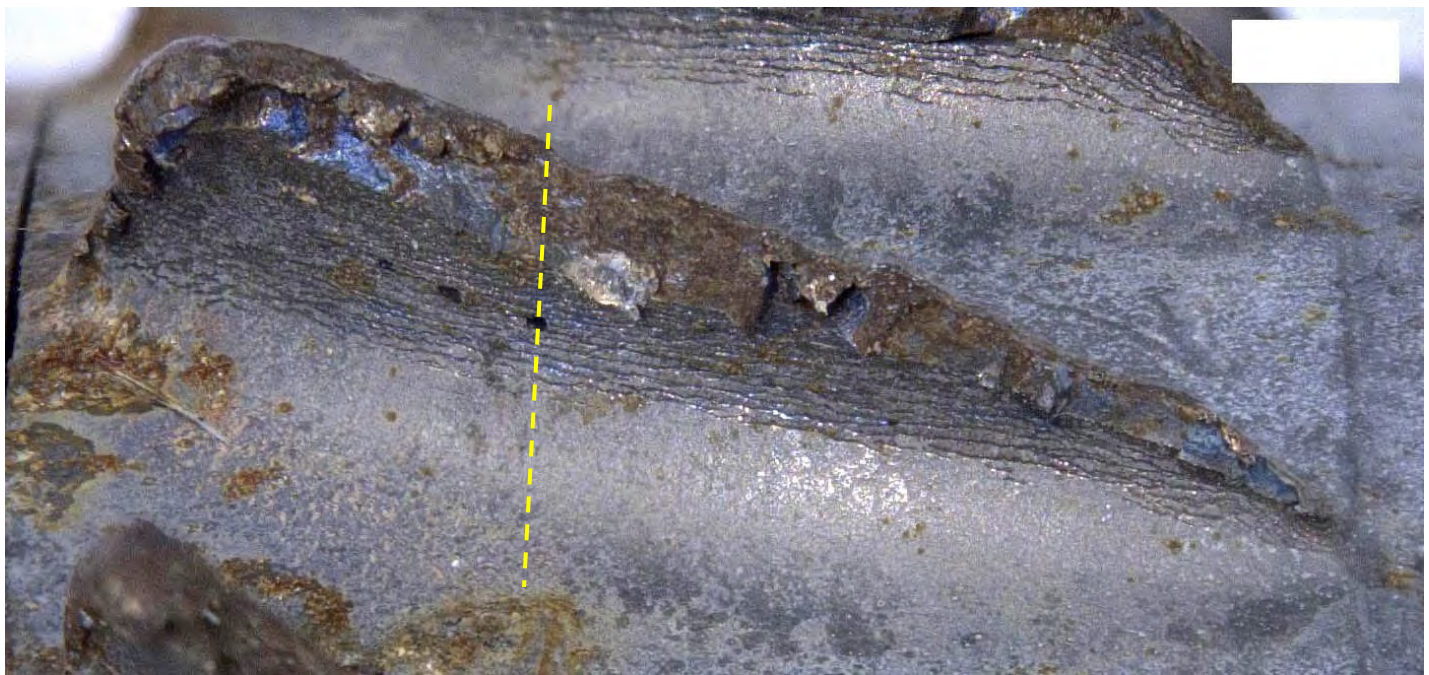


Figure 65. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 2 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow line indicates the plane of metallographic cross section in Figure 91.



Figure 66. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 3 (see Figures 62 and 63). The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 67. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 4 (see Figures 62 and 63). The red arrow indicates the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 68. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 5 (see Figures 62 and 63). The red arrows indicate the direction of fatigue progression.



Figure 69. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 6 (see Figures 62 and 63). The red arrow indicates the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 70. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 7 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 71. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 8 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 72. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 9 (see Figures 62 and 63). The red arrows indicate the direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 73. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 10 (see Figures 62 and 63). The red arrows indicate the direction of fatigue progression. The yellow arrow indicates a ratchet mark consistent with fatigue initiation on the suction side surface.

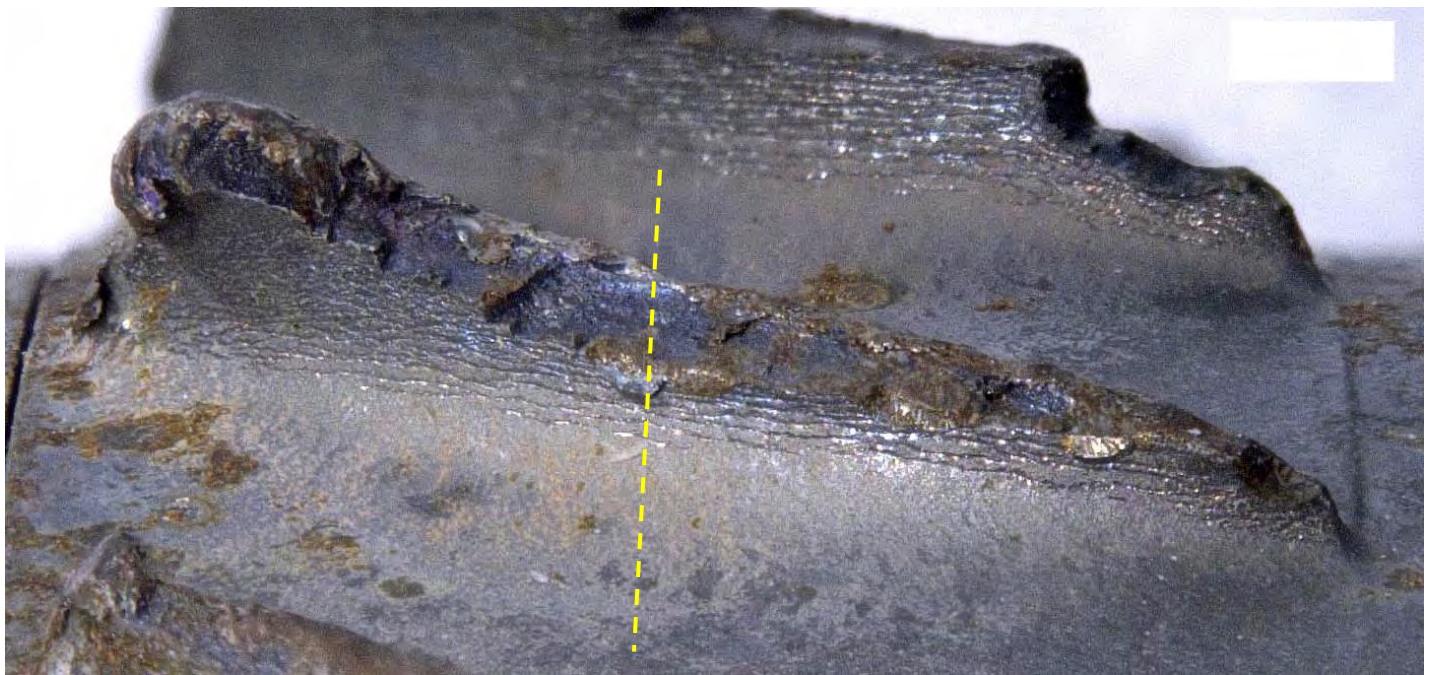


Figure 74. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 11 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface. The yellow line indicates the plane of metallographic cross section in Figure 94.



Figure 75. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 12 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 76. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 13 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 77. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 14 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.

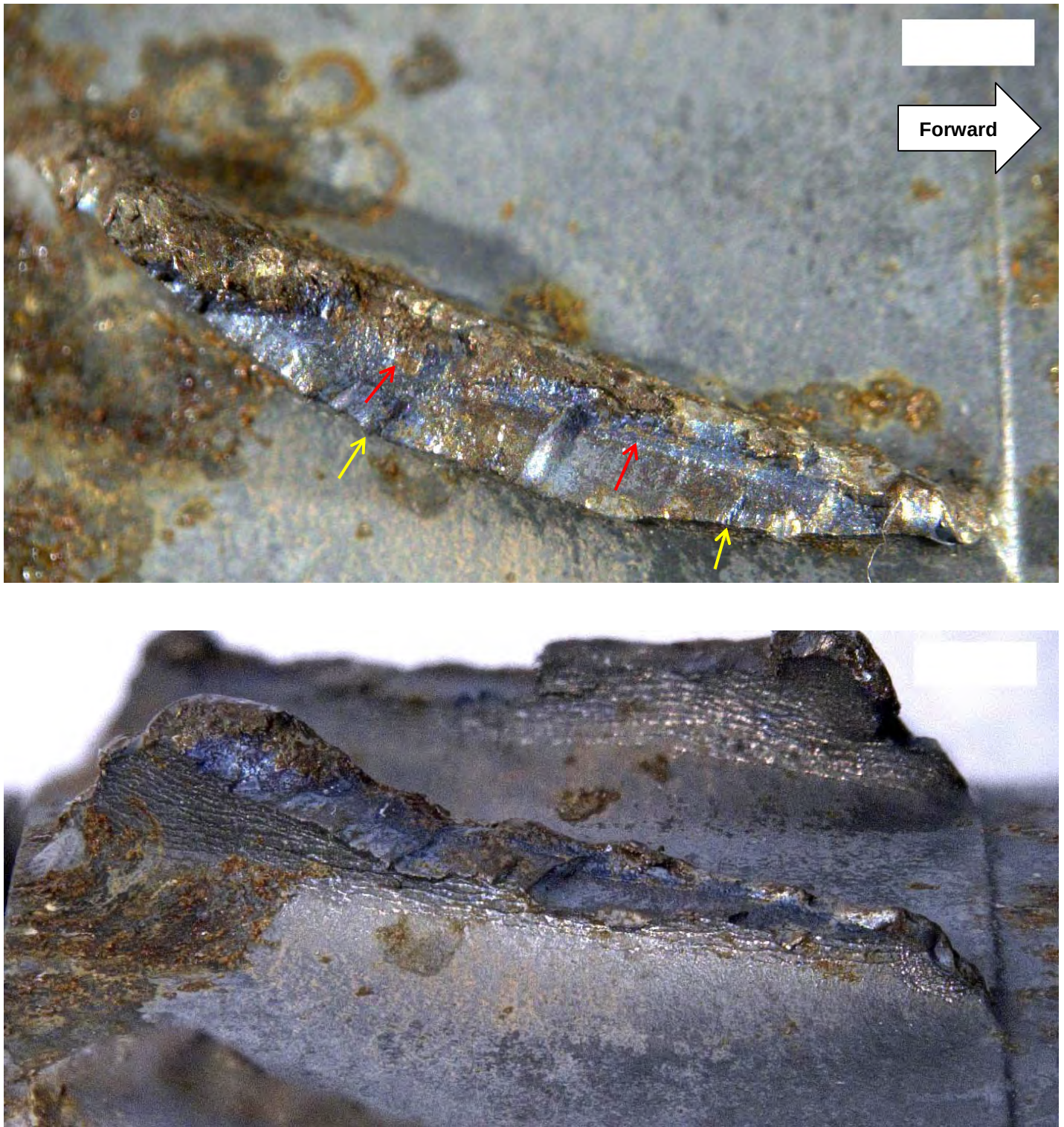


Figure 78. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 15 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 79. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 16 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 80. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 17 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.

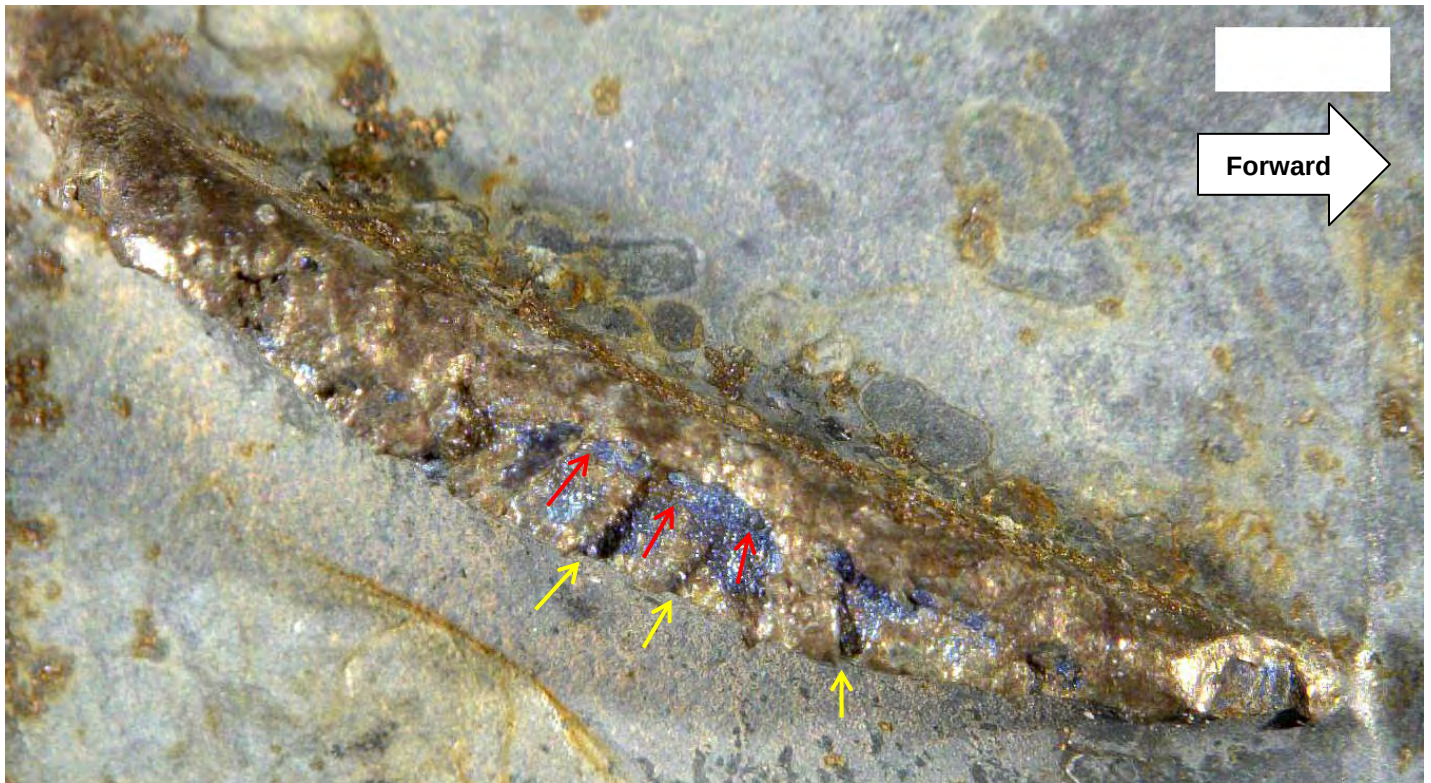


Figure 81. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 18 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 82. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 19 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 83. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 20 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 84. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 21 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrow indicates a ratchet mark consistent with fatigue initiation on the suction side surface.



Figure 85. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 22 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 86. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 23 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.



Figure 87. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 24 (see Figures 62 and 63). There were no fatigue progression features on this fracture surface. This blade is shown in more detail in Figures 89 and 90.



Figure 88. Detailed views of the fracture surface (top) and suction side surface (bottom) of stage 6 compressor blade 25 (see Figures 62 and 63). The red arrows indicate the local direction of fatigue progression. The yellow arrows indicate ratchet marks consistent with fatigue initiation on the suction side surface.

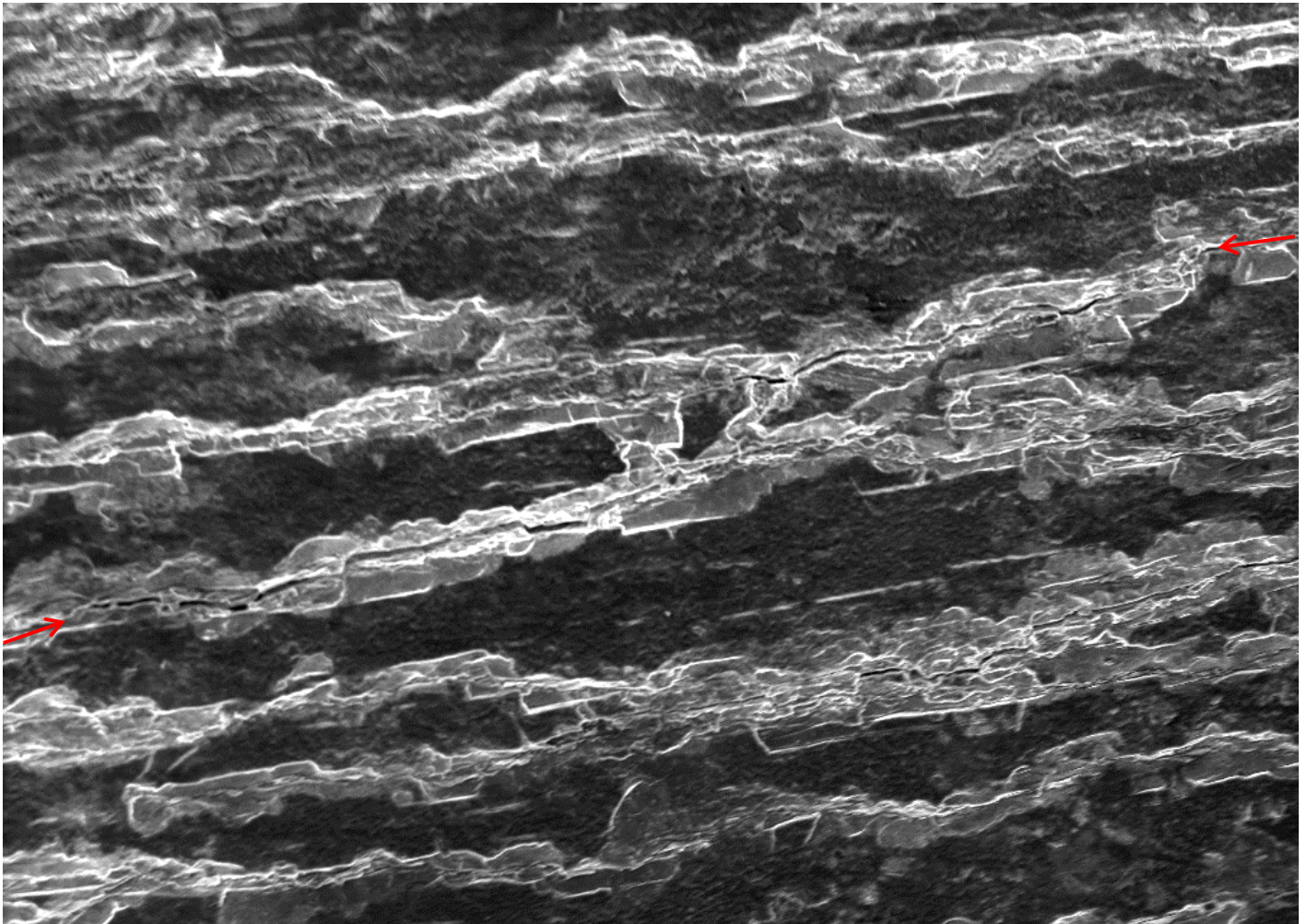


Figure 89. Secondary SEM image of the suction side crown root of blade 24 (see Figure 87). The red arrows indicate a crack in the surface.

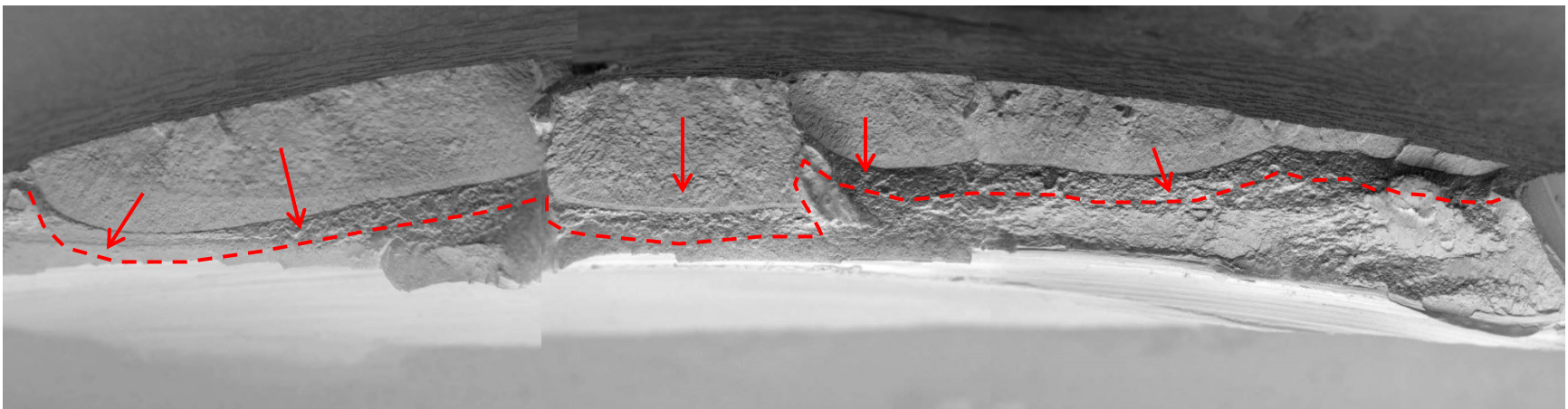
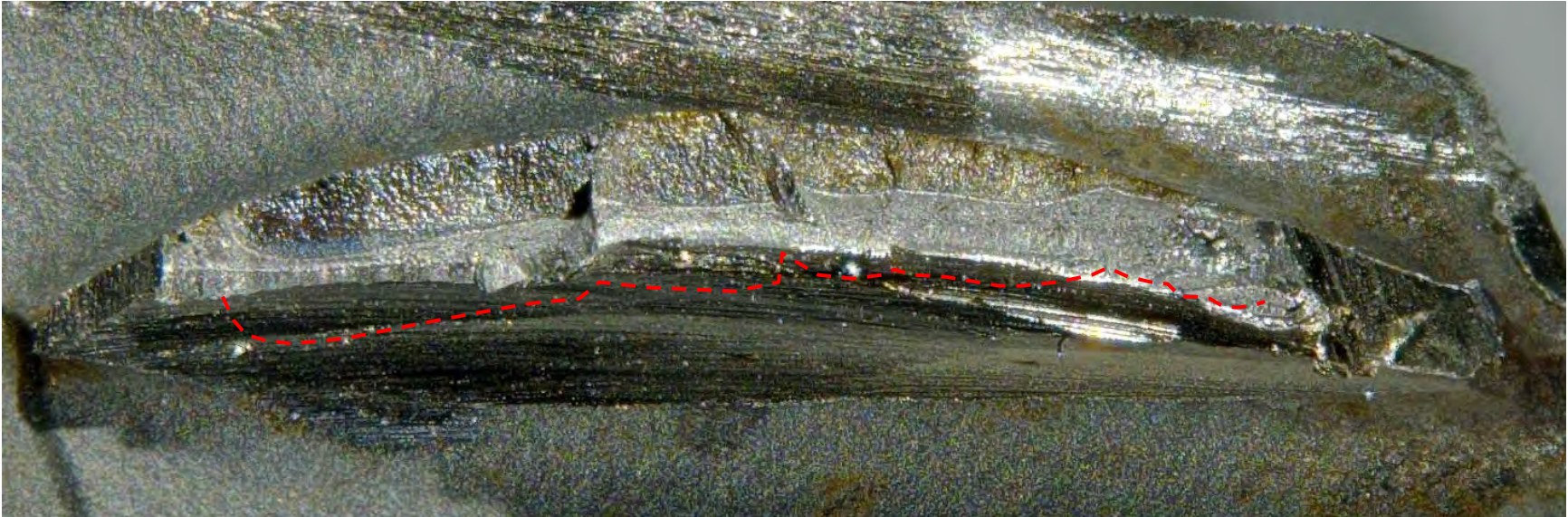


Figure 90. Optical (top) and backscattered electron SEM (bottom) images of the fatigue fracture surface from blade 24 after laboratory fracture. The red dashed lines show the transition from fatigue to laboratory overload. The red arrows indicate the local direction of fatigue progression.

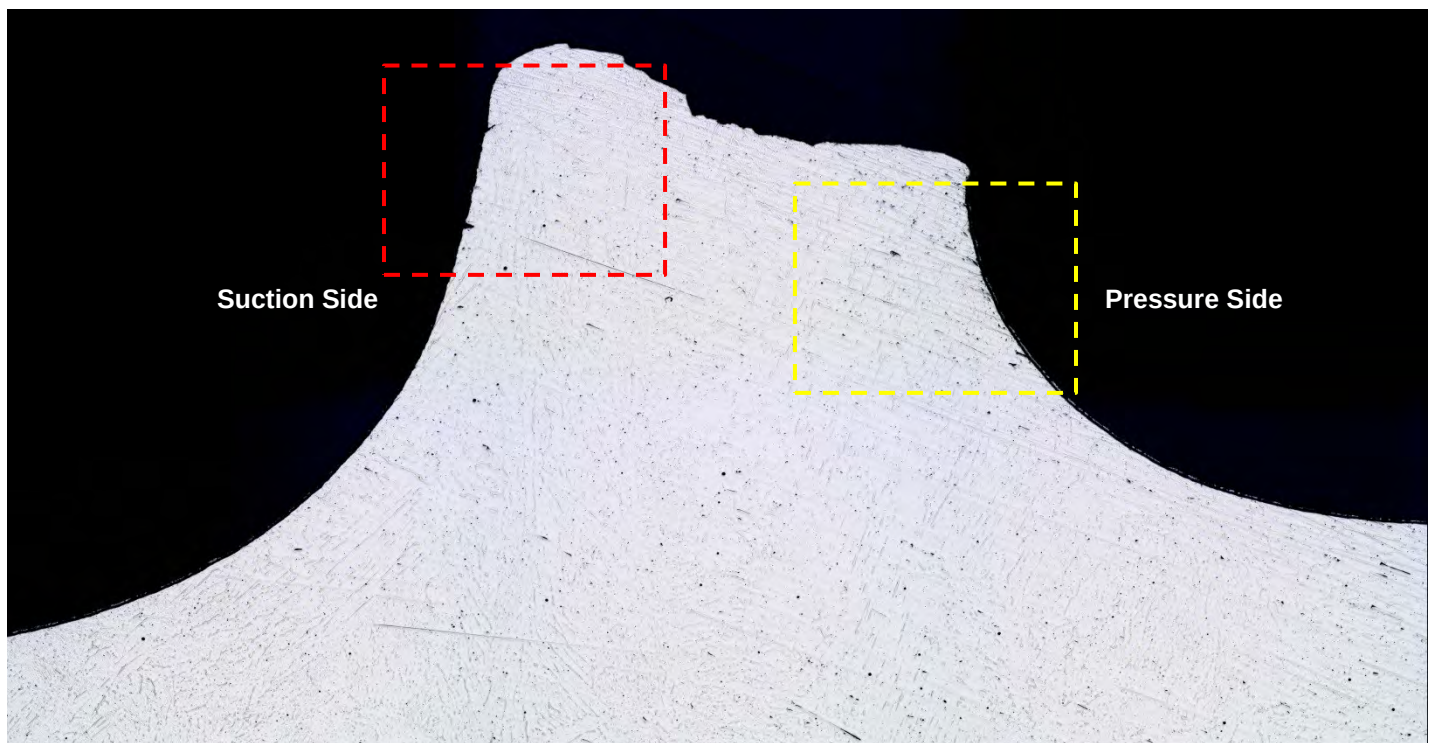


Figure 91. Overall view of the section through the first representative stage 6 blade, blade 2 (see Figure 65). The areas in the red and yellow dashed boxes are shown in greater detail in Figures 92 and 93, respectively. Unetched.

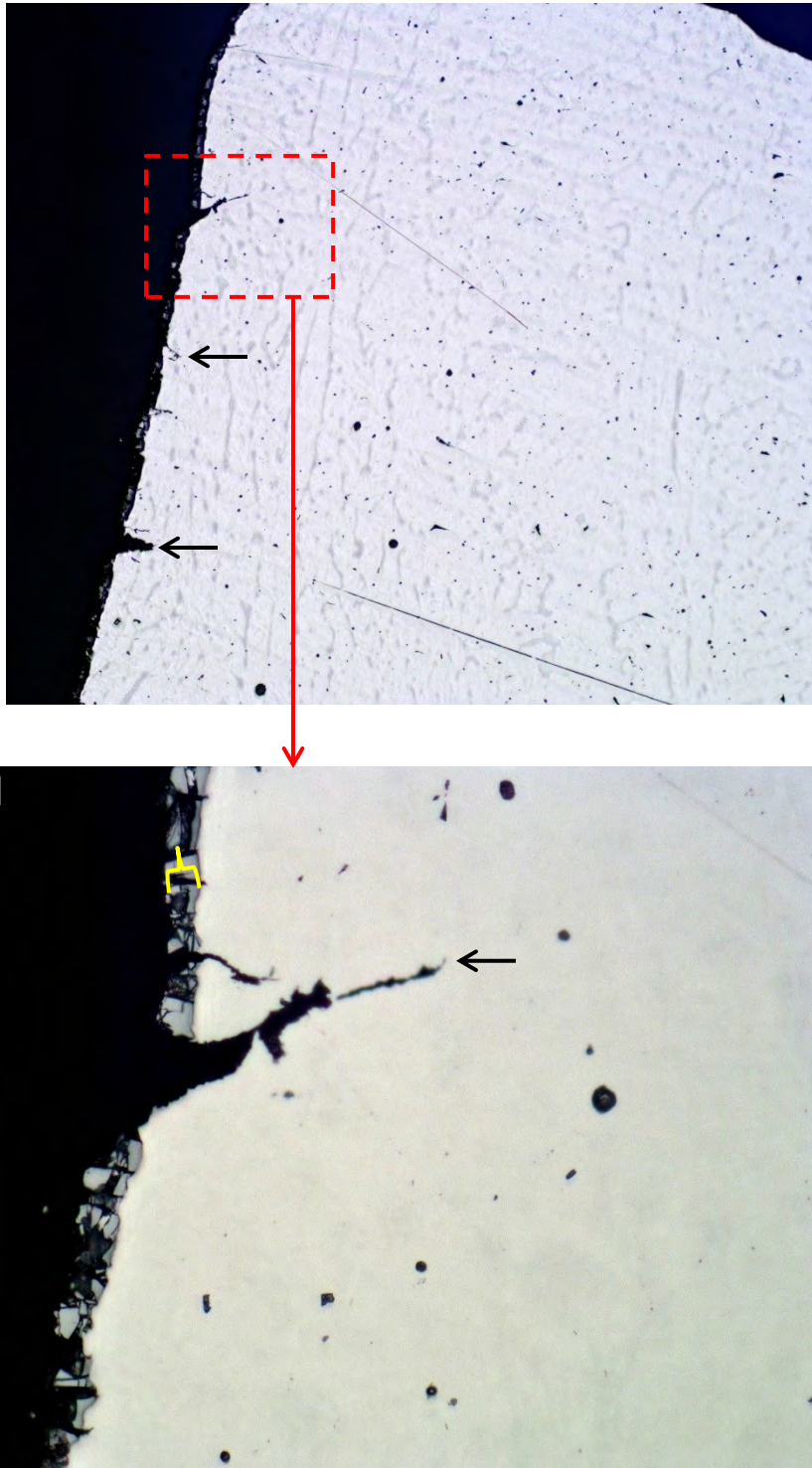


Figure 92. Cracks (black arrows) in the suction side crown of blade 2 (see Figure 91). The aluminide coating in indicated by the yellow brace. Unetched

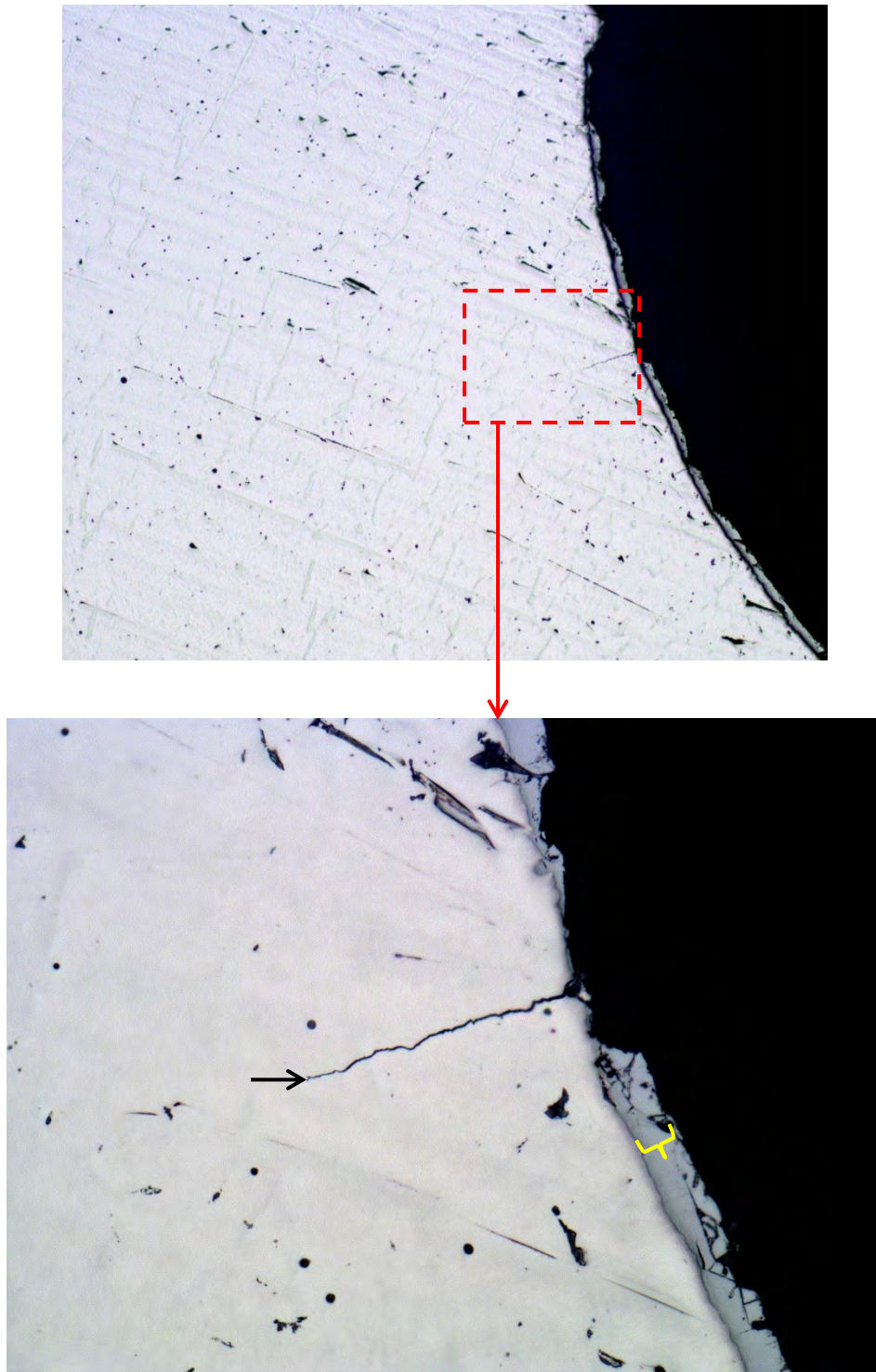


Figure 93. Crack (black arrow) in the pressure side, mid-chord of blade 2 (see Figure 94). The aluminide coating is indicated by the yellow brace. Unetched.

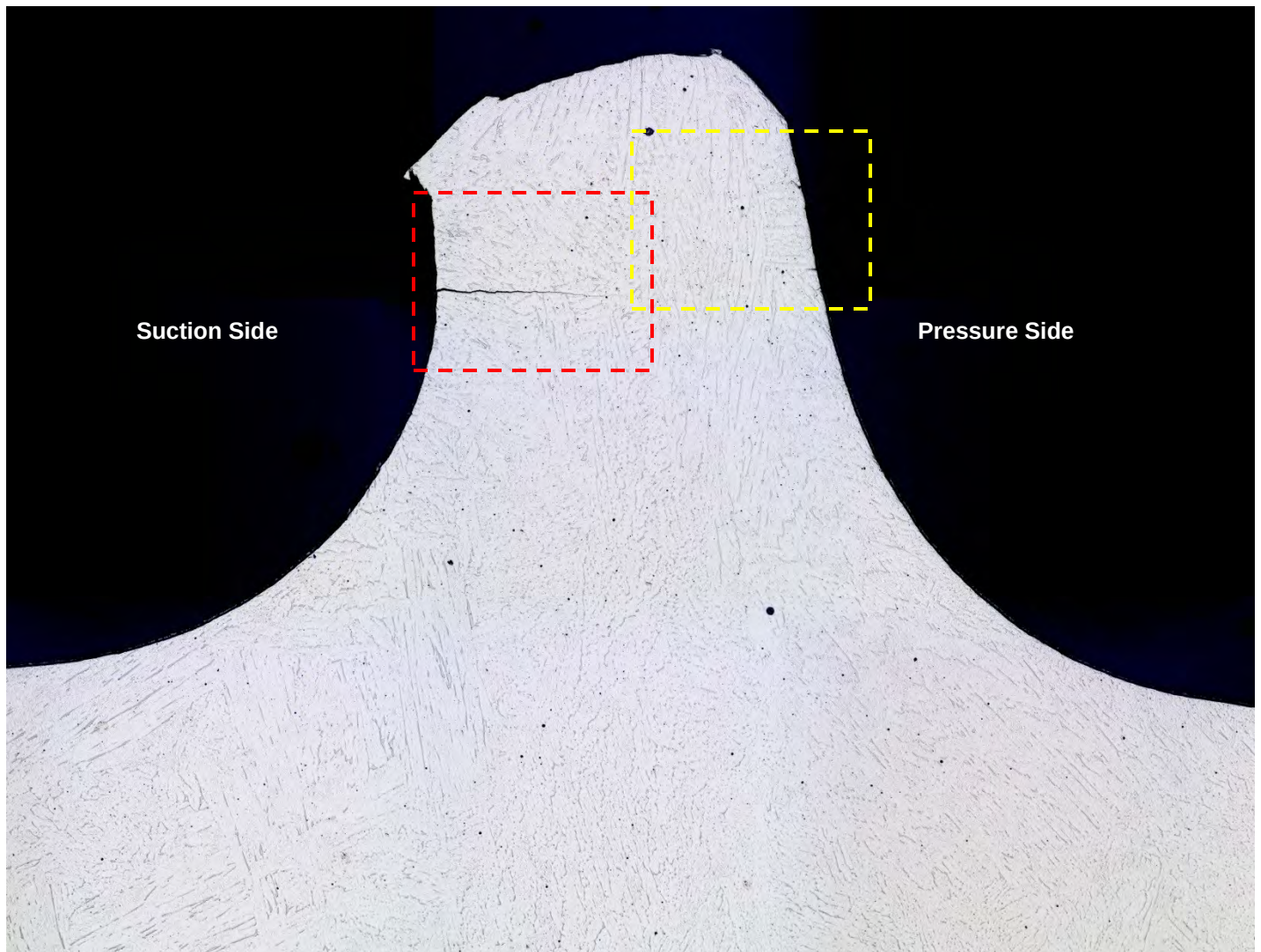


Figure 94. Overall view of the section through the second representative stage 6 blade, blade 11 (see Figure 74). The areas in the red and yellow dashed boxes are shown in greater detail in Figures 95 and 96, respectively. Unetched.

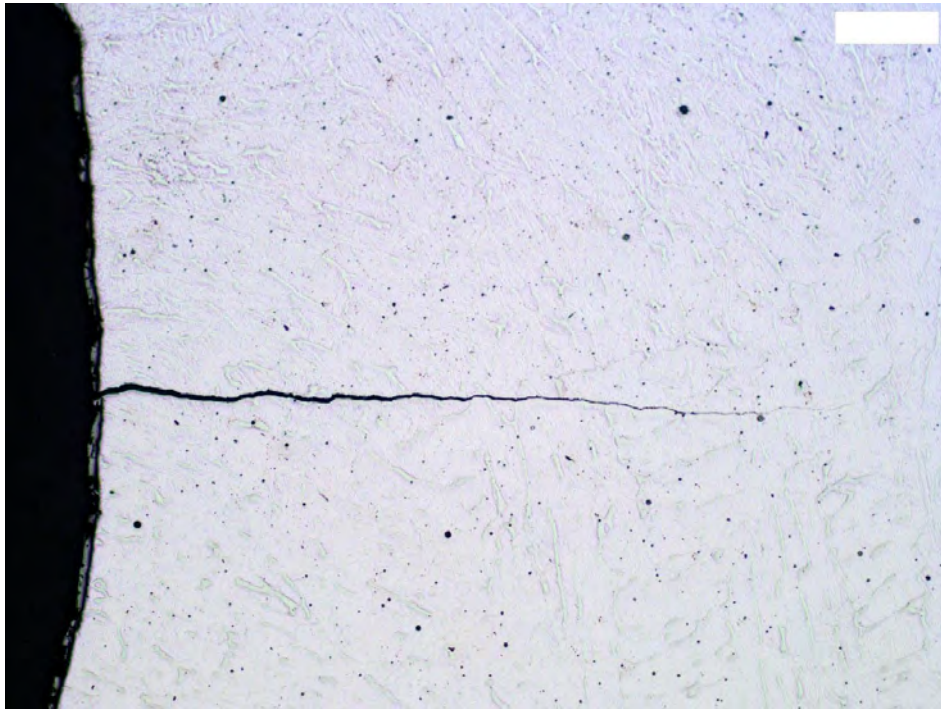


Figure 95. Crack in the suction side crown of blade 11 (see Figure 94). Unetched

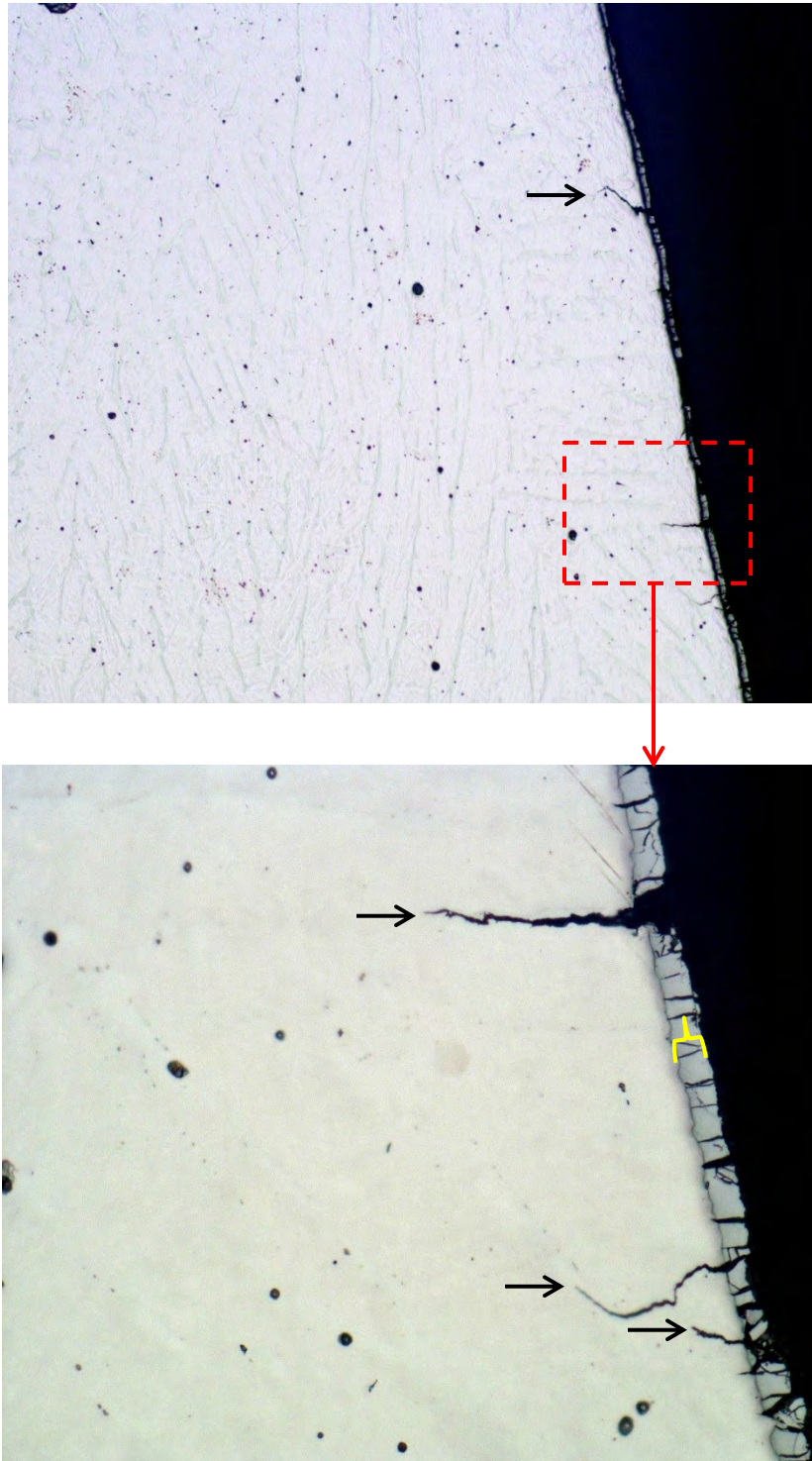


Figure 96. Cracks (black arrows) in the pressure side, mid-chord of blade 11 (see Figure 94). The aluminide coating is indicated by the yellow brace. Unetched.



Figure 97. Leading edges of representative stage 1 blades.



Figure 98. Outer diameter of the two compressor case halves.

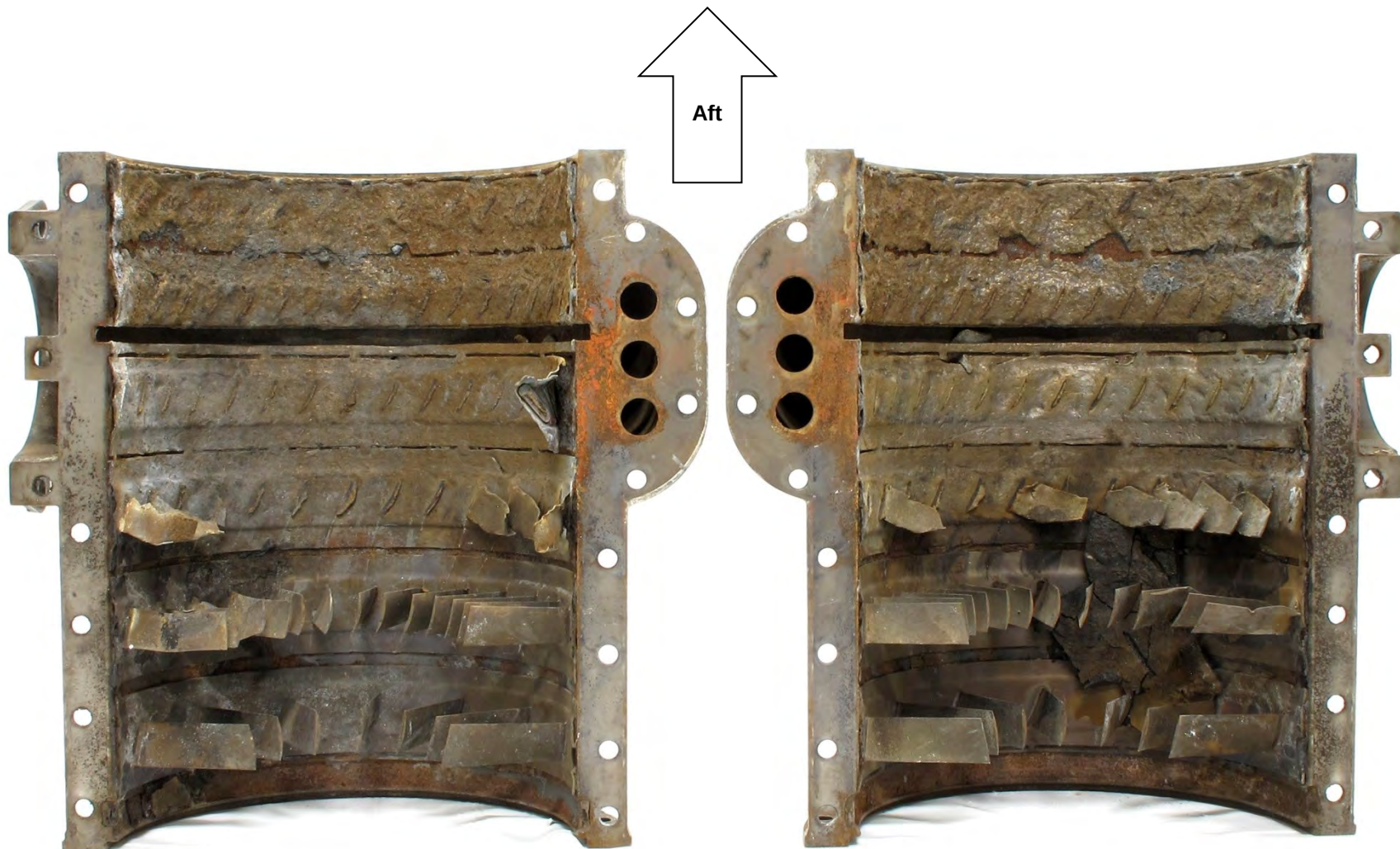


Figure 99. Inner diameter of both compressor case halves.



Figure 100. Forward looking aft axial view of the compressor case halves.

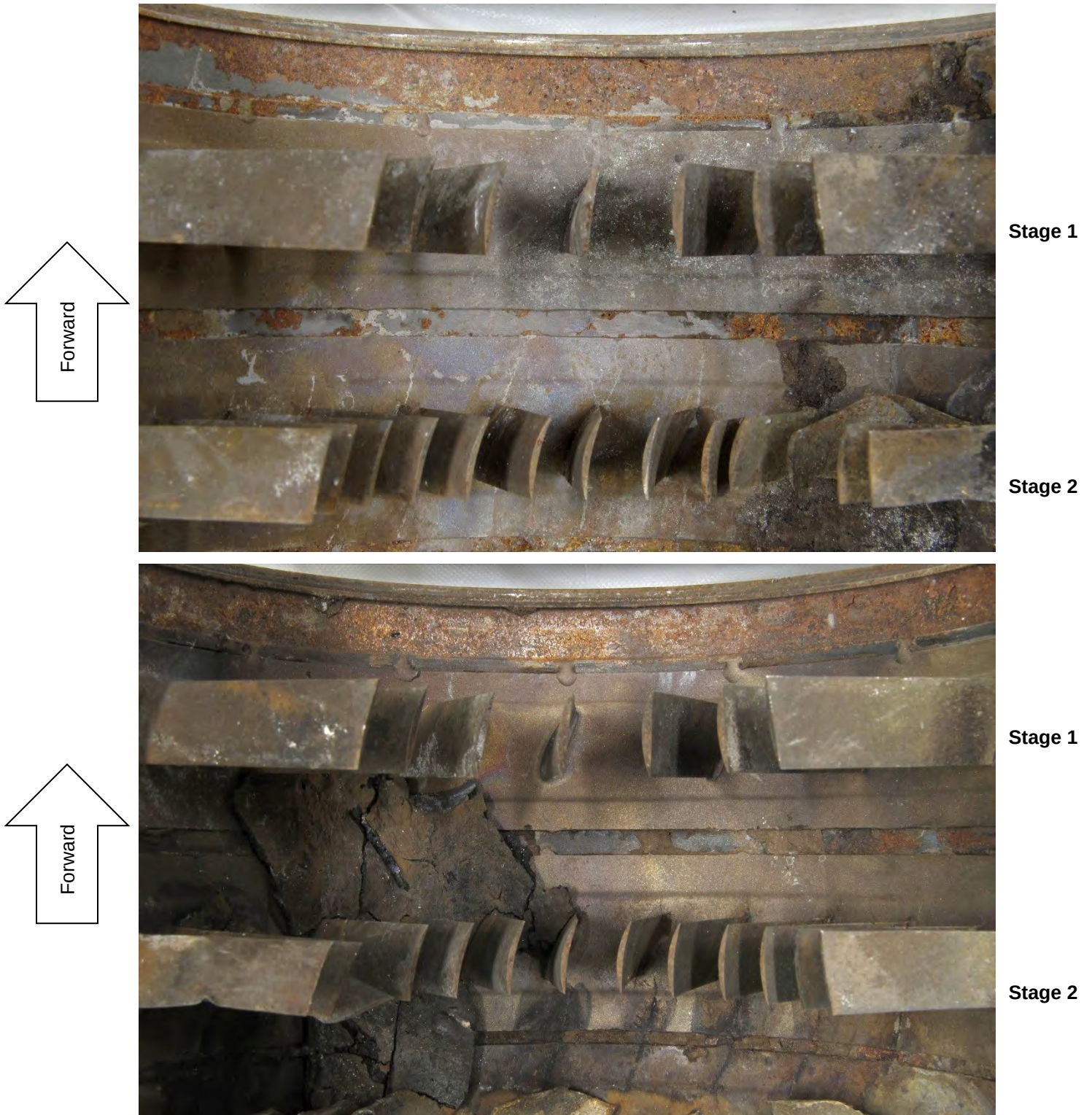


Figure 101. Detailed views of the stages 1 and 2 compressor vanes in both compressor case halves.

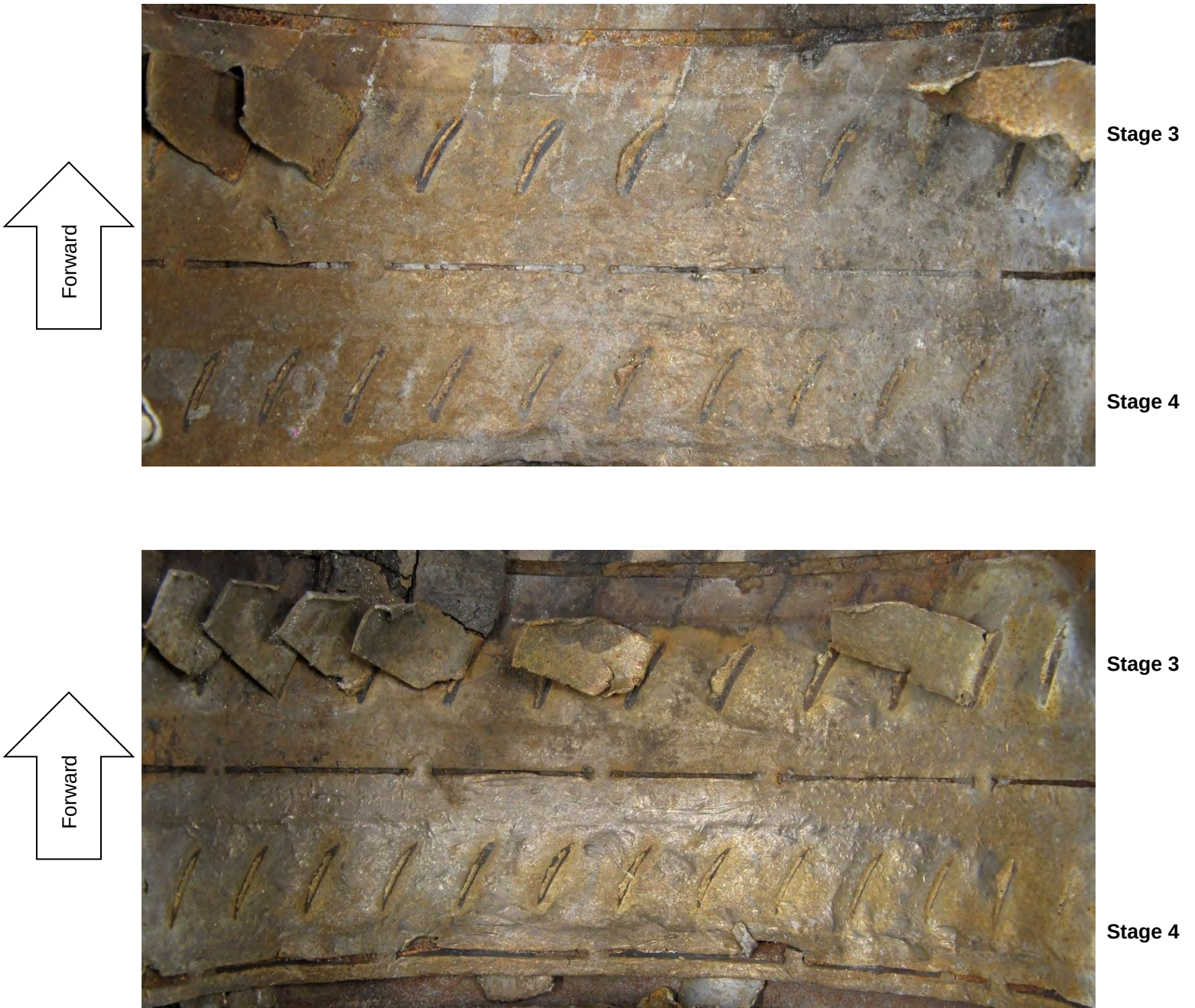


Figure 102. Detailed views of the stages 1 and 2 compressor vanes in both compressor case halves.

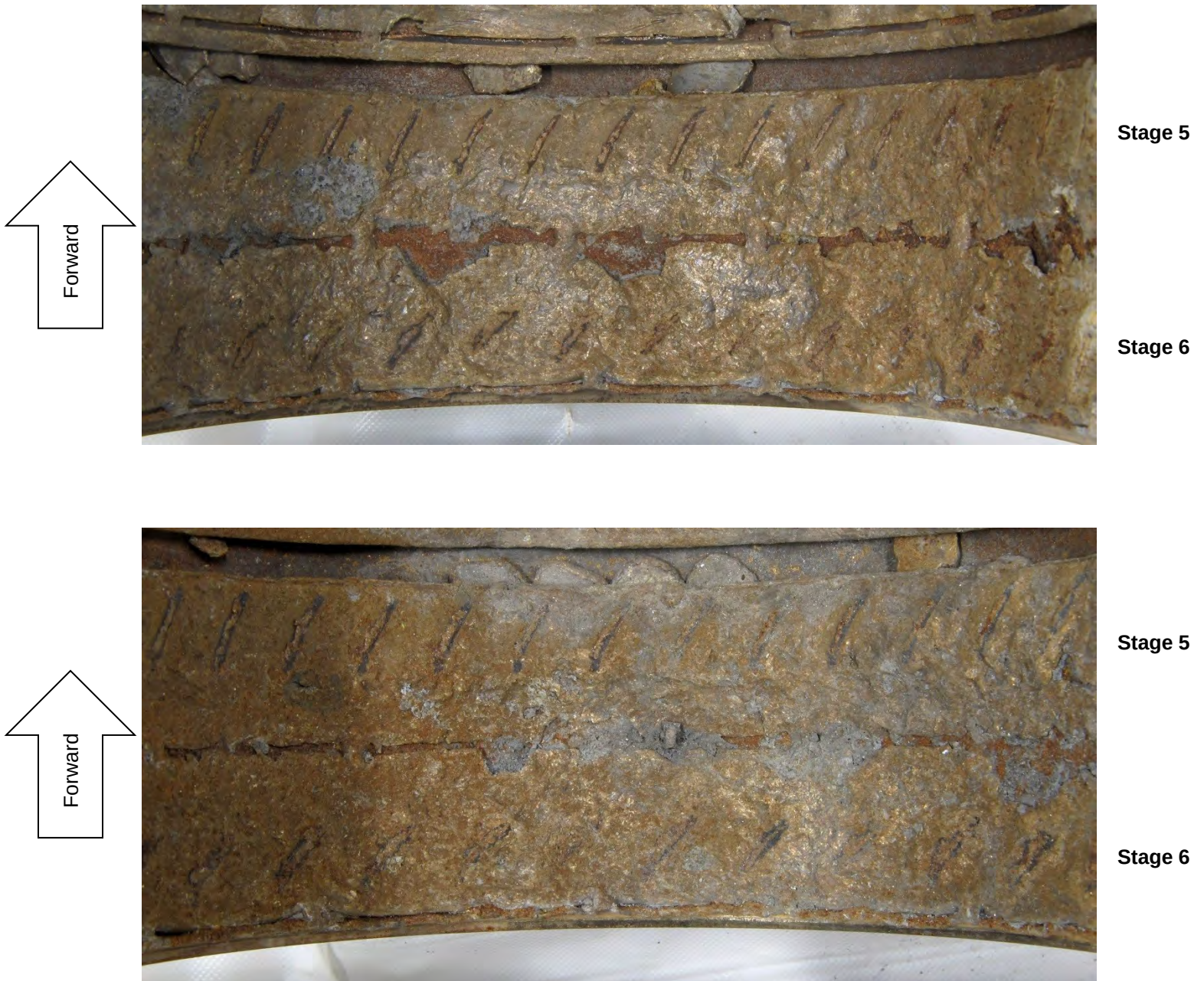


Figure 103. Detailed views of the stages 1 and 2 compressor vanes in both compressor case halves.



Figure 104. Detailed views of three representative stage 3 (top) and stage 4 (bottom) compressor vane fracture surfaces (red braces), which were completely smeared.

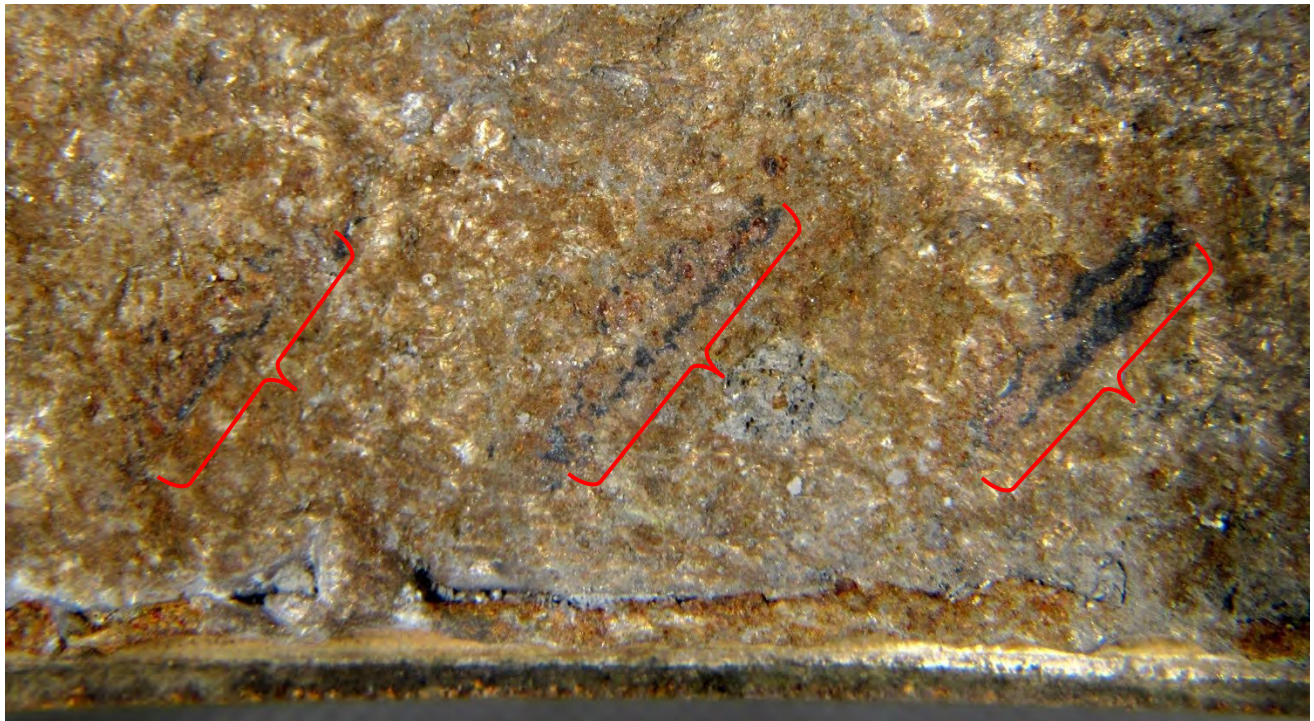


Figure 105. Detailed views of several representative stage 5 (top) and stage 6 (bottom) compressor vane fracture surfaces (red braces), which were completely smeared.