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 Rolls-Royce	Rolls-Royce Corporation 450 S. Meridian Street Indianapolis, Indiana 46225-1103, USA	REPORT NO. 21FAE-055	REV. Initial	PAGES 1 of 108
TITLE METALLURGICAL INVESTIGATION OF A THIRD STAGE TURBINE WHEEL, P/N 23065818, REMOVED FROM AN M250, ENGINE S/N CAE835942, OPERATED BY SIGNATURE UTILITY SERVICES		PREPARED Digitally signed by Alexander Sheridan_9782(Bldentity) Date: 2022.05.03 10:26:22 -04'00'		
		APPROVED Digitally signed by: Matthew Johnson_8679(Bldentity) Date: 2022.05.02 16:55:54 -05'00'		

IDENTIFICATION

Report Request ID:	44068
Traceability ID Number:	EDNS04000139392
Part Name:	Third Stage Turbine Wheel
Part Number:	23065818
Part Serial Number:	X637652
Material:	IN-713
Processes:	Not Applicable
Specifications:	EMS73648-3
Part Time:	528.9 hours, 540 cycles
Engine Model:	M250-C20B
Engine Serial Number:	CAE835942
FPA Number:	Not Applicable
FPD Number:	Not Applicable
Supplier:	Not Applicable
Vendor Code:	Not Applicable
User:	Signature Utility Services
Removal Station:	Arrow Aviation
Evaluations:	Failure Analysis
References:	AI-2020-086

1 Foreword

The subject M250-C20B, engine S/N CAE835942, was installed in a helicopter that was reportedly conducting tree trimming operations when the pilot reported to a ground crewmember their intention to make an emergency landing. Subsequently, the helicopter reportedly impacted wooded terrain and caught fire. The aircraft was damaged by the post-crash fire and the pilot was fatally injured. No other details about the event were provided to Rolls-Royce Corporation representatives. Following examination of the wreckage at the recovery location attended by representatives from Rolls-Royce, the FAA, and the NTSB, it could not be conclusively determined if the event was engine-involved.

The engine was removed at the wreckage examination site and sent to a Rolls-Royce approved facility for disassembly and inspection. The third stage turbine wheel was found to have several fractured airfoils, but it was not determined whether the damage was causal to the event or secondary damage from the reported terrain impact. Most of the turbine components as well as various shafting and structures from the compressor, combustion, turbine, and exhaust modules were sent to the Rolls-Royce Corporation Materials Laboratory in Indianapolis, IN for detailed metallurgical investigation.

2 Summary of Findings

- 2.1 Seven airfoils comprising a single packet of third stage turbine wheel airfoils between shroud slots were fractured in overload near the shroud. The outboard portions of the airfoils and the shroud segment were not recovered. All of the airfoil fractures were consistent with overload. There was no evidence of progressive fracture on any of the third stage turbine blades.
- 2.2 The intact portion of the shroud on the third stage turbine wheel exhibited asymmetric rub damage, with the most severe rub damage located approximately 90° in the direction of engine rotation from the center of the packet of missing airfoils.
- 2.3 The third stage turbine blades exhibited re-solutioned gamma prime near midspan consistent with thermal distress. The thermally distressed area spanned approximately 60% of the airfoil span, centered around midspan on a longitudinal cross-section through an unfractured blade.
- 2.4 The third stage turbine blades exhibited a re-crystallization layer on the airfoil surfaces in the thermally distressed area.
- 2.5 There was no evidence of any impact damage on the third stage turbine nozzle or the other turbine components in the gas path upstream of the third stage turbine wheel.
- 2.6 No evidence of stress rupture void formation was found on cross-sections through any of the turbine components.
- 2.7 The fourth stage turbine blades did not exhibit any impact damage. Deposited material was found on the fourth stage blades.
- 2.8 The fourth stage turbine blades exhibited coarsened gamma prime and rafting of the gamma prime at midspan.
- 2.9 The shroud on the fourth stage turbine wheel exhibited asymmetric rub damage and was cracked, with at least one through crack. The most severe rub damage was located approximately 90° in the direction of engine rotation from the center of the packet of missing third stage airfoils.
- 2.10 Two of the mounting tabs on the third stage turbine nozzle diaphragm were fractured and missing. Two fourth stage nozzle airfoils were fractured in overload. The hub castellations on the fourth stage nozzle assembly were partially fractured.
- 2.11 The first and second stage turbine airfoils exhibited tip rub.
- 2.12 The first stage turbine blades exhibited coarsened gamma prime and rafting of the gamma prime at midspan.

2.13 The power turbine labyrinth seal, second stage turbine nozzle, and Nos. 6 and 7 bearings were FAA PMA components and were not examined in detail.

3 Results and Discussion

Components from the compressor, combustor, turbine, and exhaust modules were sent to the Materials Laboratory but not all were documented as part of the investigation. Most of the power turbine components and some gas producer turbine components, listed in Table 1, were selected for detailed metallurgical investigation.

Table 1: Components Documented During Investigation

Part Name	Part Number	Serial Number
Third Stage Turbine Wheel	23065818	X637652
Fourth Stage Turbine Wheel	M250-10445	X651648
Third Stage Turbine Nozzle	23069744	X584067
Fourth Stage Turbine Nozzle	23055939	X591526
Power Turbine Labyrinth Seal	PMA	
Power Turbine Inner Shaft	23071309	GK535997
Power Turbine Outer Shaft	Illegible	
First Stage Turbine Wheel	M250-10223	X653697
Second Stage Turbine Wheel	23073854	X670623
No. 6 Bearing	PMA	
Power Turbine Support	Illegible	
No. 7 Bearing	PMA	
No. 8 Bearing	M250-10107	NWL150903
Second Stage Turbine Nozzle	PMA	

3.1 Power Turbine Module

Figure 1 and Figure 2 show the as-received condition of the power turbine (PT) module, which had the third and fourth stage wheels assembled with the power turbine outer and inner shafts and the fourth stage turbine nozzle. Seven consecutive airfoils in a single shroud packet on the third stage turbine wheel were fractured near the tip, liberating the shroud outboard of all the airfoils as shown in Figure 3. The missing portion of the shroud spanned the entire packet between two consecutive as-manufactured slots on the third stage turbine wheel. For reference, the third stage turbine wheel airfoils were numbered starting with #1 for the preceding blade in the packet and increasing opposite the direction of engine rotation.

Match markings were made on the rotating components where possible, corresponding to the approximate center of the missing shroud packet on the third stage wheel. To separate the power turbine wheels, shafting, and fourth stage turbine nozzle, a partial cut on a radial plane was made on the trailing edge side of the fourth stage turbine wheel. The cut separated the power turbine inner shaft into two halves, which freed the rest of the power turbine rotor to be further disassembled.

3.2 Third Stage Turbine Wheel P/N 23065818 S/N X637652

3.2.1 Visual Examination

Figure 4 shows the condition of the third stage turbine wheel on the leading and trailing edge sides after the PT rotor was disassembled. Detailed examination of the wheel revealed asymmetric rub damage to the shroud and trailing edge side knife seals as shown in Figure 5. The most severe rub damage to both seals spanned between blades #22 and #30, which was centered on a location approximately 90° in the direction of engine rotation from

the center of the packet of missing airfoils. However, the shroud also exhibited rub damage that was not continuous with the gradient of rub damage surrounding blades #22 and #30. Immediately adjacent to the EDM slot on the trailing side of the missing shroud segment (between blades #7 and #8), the knife seals exhibited rub damage that flattened the knife tips as shown in Figure 6. The knife seals immediately adjacent to the EDM slot on the leading side of the missing shroud segment were relatively undamaged.

The wheel was cleaned with soapy water prior to fluorescent penetrant inspection (FPI, discussed later), and the cleaned condition of several representative unfractured third stage turbine airfoils is shown in Figure 7 and Figure 8. The leading and trailing edges of the airfoils did not exhibit any deformation or impact damage. The pressure side surfaces exhibited intermittent deposited material consistent with re-deposited material from the rub damage to the shrouds and blade tracks in the power turbine.

The trailing edge side curvic teeth, shown in Figure 9, did not exhibit any damage. The trailing edge side interstage knife seals, however, exhibited asymmetric rub damage similar to that found on the intact portion of the shroud as shown in Figure 10. Part of the seal was missing in the middle of the rub damage, centered approximately 90° in the direction of engine rotation from the center of the packet of missing airfoils.

3.2.2 *Non-Destructive Examination*

The third stage turbine wheel was subjected to FPI after ultrasonic cleaning in the laboratory. No crack-like indications were found on any unfractured airfoils.

3.2.3 *Fractography*

Detailed optical examination of the airfoil fracture surfaces (prior to cleaning for FPI) revealed interdendritic features consistent with overload fracture intermixed with smearing damage. Figure 11 shows detailed views of the fracture surfaces on the first (#1) and last (#7) airfoils in the packet before cleaning, both of which exhibited interdendritic fracture features consistent with overload. The fracture surfaces on the other airfoils, shown after ultrasonic cleaning in Figure 12 through Figure 14, also exhibited interdendritic features consistent with overload.

After the wheel was cleaned for FPI, a segment of the wheel containing the fractured airfoils was sectioned and washed in soapy water before ultrasonic agitation in solvent. The segment was placed in a scanning electron microscope (SEM) for detailed fractographic examination of all the airfoil fracture surfaces.

Representative fracture features from each blade are shown in Figure 15 through Figure 21. All the fracture surfaces exhibited interdendritic features consistent with overload, and some also exhibited intermittent smearing damage. There was no evidence of progressive fracture on any of the fracture surfaces.

3.2.4 *Metallographic Examination*

Blades #1, #4, and #8 were selected for metallographic examination as shown in Figure 11 and Figure 13. Longitudinal cross-sections were prepared through blades #1 and #4 near the leading edge (LE1 and LE4). Longitudinal cross-sections were prepared through blades #1 and #8 near the trailing edge (TE1 and TE8).

Figure 22 shows overall views of cross-section LE1 near the leading edge of blade #1. The outboard portion of the blade etched lighter than the inboard span. There was no evidence of stress rupture void formation on the cross-section as shown in Figure 23. Detailed views of the microstructure in the rim of the wheel, the root of the blade, the lighter etching area, and near the fracture surface are shown in Figure 24 through Figure 27. In the lighter etching area, the gamma prime structure appeared finer than in the rest of the blade consistent with re-solutioned and re-precipitated gamma prime from elevated temperature exposure. SEM examination of other third stage turbine blade cross-sections with similar lighter etching areas where the gamma prime appeared finer, including the trailing edge section of the same airfoil, revealed refined gamma prime, discussed later. SEM examination was not conducted on cross-section LE1.

Figure 28 shows overall views of cross-section TE1 near the trailing edge of blade #1. The outboard portion of the blade etched lighter than the inboard span. There was no evidence of stress rupture void formation on the cross-section as shown in Figure 29. The cross-section was examined in the etched condition with an optical metallograph and in the SEM under backscattered electron imaging, and representative images showing the microstructure and gamma prime structure in the rim of the wheel, in the root of the blade inboard of the thermal

distress, and in the thermally distressed region are shown in Figure 30 through Figure 35. In the lighter etching area, the gamma prime was finer than in the root and platform, consistent with re-precipitated gamma prime formed after exposure above the re-solutioning temperature of approximately 2150°F for an EMS73648-3 (IN-713) type material. A re-crystallization layer was found on the airfoil surfaces in the thermally distressed area that was not present away from the thermal distress.

Figure 36 shows overall views of cross-section LE4 near the leading edge of blade #4. The outboard portion of the blade etched lighter than the inboard span. There was no evidence of stress rupture void formation on the cross-section as shown in Figure 37. The cross-section was examined in the etched condition with an optical metallograph, and representative images showing the microstructure in the rim of the wheel, in the root of the blade inboard of the thermal distress, in the thermally distressed region, and at the fracture surface are shown in Figure 38 through Figure 41. In the lighter etching area, which extended to the fracture surface, the gamma prime was finer than in the root and platform consistent with re-precipitated gamma prime.

Figure 42 and Figure 43 show overall views of cross-section TE8 near the trailing edge of blade #8, which was unfractured. The microstructure etched lighter in an area measuring approximately 60% of the total airfoil span centered slightly outboard of midspan, consistent with thermal distress. There was no evidence of stress rupture void formation on the cross-section. The cross-section was examined in the etched condition with an optical metallograph and in the SEM under backscattered electron imaging, and representative images showing the microstructure and gamma prime structure in the rim of the wheel, in the root of the blade inboard of the thermal distress, in the thermally distressed region, and in the shroud are shown in Figure 45 through Figure 51. In the thermally distressed region, the gamma prime was finer than in the root and platform, consistent with re-precipitated gamma prime formed after exposure above the re-solutioning temperature of approximately 2150°F for an EMS73648-3 (IN-713) type material. There was also a re-crystallization layer present on the airfoil surfaces in the thermally distressed area that measured up to 0.002 inch deep that was not present away from the thermal distress.

3.2.5 Chemistry

Semi-quantitative X-ray fluorescence (XRF) analysis determined the third stage turbine wheel was an EMS73648-3 (IN-713) type material as required by the component definition.

3.3 Fourth Stage Turbine Wheel P/N M250-10445 S/N X651648

3.3.1 Visual Examination

Figure 52 shows the condition of the fourth stage turbine wheel after it was cut during disassembly of the PT rotor. The wheel was covered in airframe fire retardant on the gas path surfaces. Detailed examination of the wheel revealed asymmetric rub damage to the shroud knife seals as shown in Figure 53. The circumferential location of the most severe rub damage to the shroud matched the location of the most severe rub damage found on the third stage turbine wheel. Cracking was found on the shroud near the location of the heaviest rub shown in Figure 54, including one location where the shroud was fractured through. Figure 55 shows detailed views showing the representative condition of the airfoil leading edges and pressure side surfaces. The leading edges did not exhibit any impact damage and the pressure side surfaces of the airfoils exhibited intermittent deposited material. The deposited material was consistent with re-deposited material from the rub damage to the shrouds and blade tracks in the power turbine. The leading edge side web of the wheel exhibited a circumferential band of rub damage located near the transition from the sloped surface of the bore to the flat surface of the web, shown in Figure 56. Corresponding rub was found on the interstage seal in the fourth stage turbine nozzle diaphragm as discussed later.

3.3.2 Metallographic Examination

A longitudinal cross-section was prepared through blade #21 near the leading edge, shown in Figure 57. There was no apparent gradient in the etch response along the height of the airfoil. The cross-section was examined in the etched condition with an optical metallograph and in the SEM under backscattered electron imaging, and representative images showing the microstructure and gamma prime structure in the root of the blade, at approximately midspan, and in the shroud are shown in Figure 58 through Figure 63. The gamma prime in the

midspan area was slightly coarser than in the root and shroud and exhibited rafting, both of which are expected changes from exposure to normal engine operating temperatures over the life of the component. It could not be conclusively determined if there was any re-precipitated gamma prime or if the amount of coarsening and rafting were indicative of exposure to higher than normal engine operating temperatures.

3.4 Non-Destructive Examination

After the fourth stage turbine wheel was sectioned for metallographic examination, the major remnant of the wheel containing approximately 22 airfoils was cleaned in an ultrasonic cleaner in the laboratory. No crack-like indications were found during FPI.

3.5 Third Stage Turbine Nozzle P/N 23069744 S/N X584067

3.5.1 Visual Examination

Figure 64 shows the as-received condition of the third stage turbine nozzle assembly. A span of 10 airfoils exhibited dark gray discoloration on the suction side surface consistent with oil staining. One airfoil exhibited impact damage to the trailing edge, and two of the mounting tabs on the diaphragm were fractured. There was no evidence of impact damage to the leading edges of any of the vane airfoils.

3.6 Fourth Stage Turbine Nozzle P/N 23055939 S/N X591526

3.6.1 Visual Examination and Fractography

The leading and trailing edge sides of the fourth stage turbine nozzle are shown in Figure 65. The airfoils were covered intermittently in a powdery white residue consistent with airframe fire retardant. There was no evidence of impact damage to the leading edges of the vane airfoils. All the hub castellations on the trailing edge side between the vane inner band and the diaphragm were fractured and deformed inboard.

Detailed inspection of the vane airfoils revealed two of them, each the first in its respective packet, were fractured at the trailing edge root as shown in Figure 66. The fractures were jagged and rough in appearance, consistent with overload. One of the vanes was fractured along the entire chord length and was cut from the nozzle. The fracture surface was examined in the SEM. The fracture exhibited interdendritic features consistent with overload as shown in Figure 67 and Figure 68. The fracture also exhibited smearing damage.

The third stage blade track, shown in Figure 69 and Figure 70, exhibited rub damage around the entire circumference. The rub damage obliterated any evidence of the knife seals cutting into the blade track. There were no apparent embedded fragments from the liberated portion of the third stage turbine wheel. The fourth stage blade track, shown in Figure 71 and Figure 72, exhibited similar rub damage around the entire circumference. The interstage abrasion seal in the bore of the fourth stage nozzle is shown in Figure 73. The seal exhibited rub damage on both the leading and trailing edge sides; the trailing edge side rub damage corresponded to the circumferential rub damage to the hub of the fourth stage turbine wheel, and the leading edge side damage corresponded to the damage on the interstage knife seals on the third stage turbine wheel.

3.7 Power Turbine Shafting

3.7.1 Visual Examination

Figure 74 shows the power turbine labyrinth seal before the PT rotor was disassembled. The seal exhibited asymmetric rub damage, with the most severe rub damage located approximately 180° from the rotor match mark. Upon disassembly of the PT rotor, FAA-PMA part markings (Figure 75) were discovered on the labyrinth seal and it was not investigated further.

Figure 76 and Figure 77 show the aft end of the power turbine inner shaft (PTIS) inside the power turbine labyrinth seal in the PT rotor assembly before it was cut in half during disassembly. The aft end of the PTIS was deformed outboard and the inner diameter surface of the labyrinth seal was circumferentially rub damaged at the approximate location of the match mark in the center of the liberated shroud segment. The inner diameter

surface at the outboard deformation of the PTIS was smeared and discolored black consistent with rub damage as shown in Figure 78. After the PT rotor was disassembled, an approximately roller-width groove in the No.6 bearing raceway on the PTIS was found diametrically opposed to the outboard deformation as shown in Figure 79 and Figure 80. Additionally, a circumferential crack was found on the shaft forward of the flange in line with the outboard deformation. The remainder of the raceway surface was relatively less severely damaged and did not exhibit any evidence of the bearing operating with insufficient lubrication. The outboard deformation, circumferential fracture, and groove in the raceway are consistent with an instantaneous high load condition on the shaft and the attached rotor.

Figure 81 and Figure 82 show the power turbine outer shaft (PTOS) before the PT rotor was disassembled. The shaft exhibited rub damage into the EPS16802 coating spanning approximately 300° against the direction of engine rotation from the location of the rotor match mark.

3.8 First Stage Turbine Wheel P/N M250-10223 S/N X653697

3.8.1 Visual Examination

Figure 83 shows the as-received condition of the first stage turbine wheel. The airfoils exhibited powdery white deposits consistent with airframe fire retardant, and there was some debris found on the leading edge side web. Detailed examination of the first stage turbine airfoils revealed erosion to the leading edge tips as shown in Figure 84. The blade tips exhibited circumferential witness marking consistent with tip rub as shown in Figure 85. The tip witness marking was consistent around the wheel and did not exhibit any apparent asymmetry.

3.8.2 Metallographic Examination

A longitudinal cross-section was prepared through a representative first stage turbine blade near the trailing edge as shown in Figure 86. The cross-section was examined in the etched condition with an optical metallograph and in the SEM under backscattered electron imaging, and representative images showing the microstructure and gamma prime structure in the rim of the wheel, in the root of the blade, and near midspan are shown in Figure 87 through Figure 92. In the rim and the root of the wheel, the gamma prime structure was mostly cuboidal and did not exhibit any apparent coarsening or rafting. At midspan, the gamma prime was coarser and less regularly shaped, with some rafting. Coarsening and rafting are expected changes from exposure to normal engine operating temperatures over the life of the component. It could not be conclusively determined if there was any re-precipitated gamma prime or if the amount of coarsening and rafting were indicative of exposure to higher than normal engine operating temperatures.

3.9 Second Stage Turbine Wheel S/N 23073854 S/N X670623

3.9.1 Visual Examination

Figure 93 shows the as-received condition of the second stage turbine wheel. The airfoils exhibited powdery white deposits consistent with airframe fire retardant, and there was some debris found on the leading edge side web. Detailed examination of the blade tips revealed circumferential witness marking consistent with tip rub as shown in Figure 94. The tip witness marking was consistent around the wheel and did not exhibit any apparent asymmetry.

3.10 Other Components

Figure 95 shows the No. 6 bearing, which had FAA PMA part markings and was not examined in detail. Figure 96 and Figure 97 show the Nos. 6 and 7 bearing sump in the PT support assembly. The No. 7 bearing and the spacer between the Nos. 6 and 7 outer rings were still installed in the bore of the PT support. An axial cut was made in the spacer to reveal the No. 7 bearing outer ring and part markings, which are shown in Figure 98. The No. 7 bearing had FAA PMA part markings and was not investigated further. Figure 99 shows the No. 8 bearing, which was still able to rotate smoothly and did not exhibit any evidence of operation with insufficient lubrication.

The second stage turbine nozzle assembly was an FAA PMA component as shown in Figure 100 and was not examined in detail.

4 Distribution

Dave Riser
Joe Henderkott

Joe Smith

5 Revision History

Issue	Change Summary	Date
Initial	Not applicable	02 May 2022

6 Figures and Tables



Figure 1. Leading edge side view showing the as-received condition of the power turbine rotor and T4 nozzle. The blue line shows the location of the match mark applied to the rotor in the laboratory. Divisions =cm.



Figure 2. Trailing edge side view showing the as-received condition of the PT rotor and T4 nozzle. The blue line shows the location of the match mark applied to the rotor in the laboratory. The red dashed line shows the approximate location of the band saw cut made to disassemble the PT rotor and shafting. Divisions = cm.

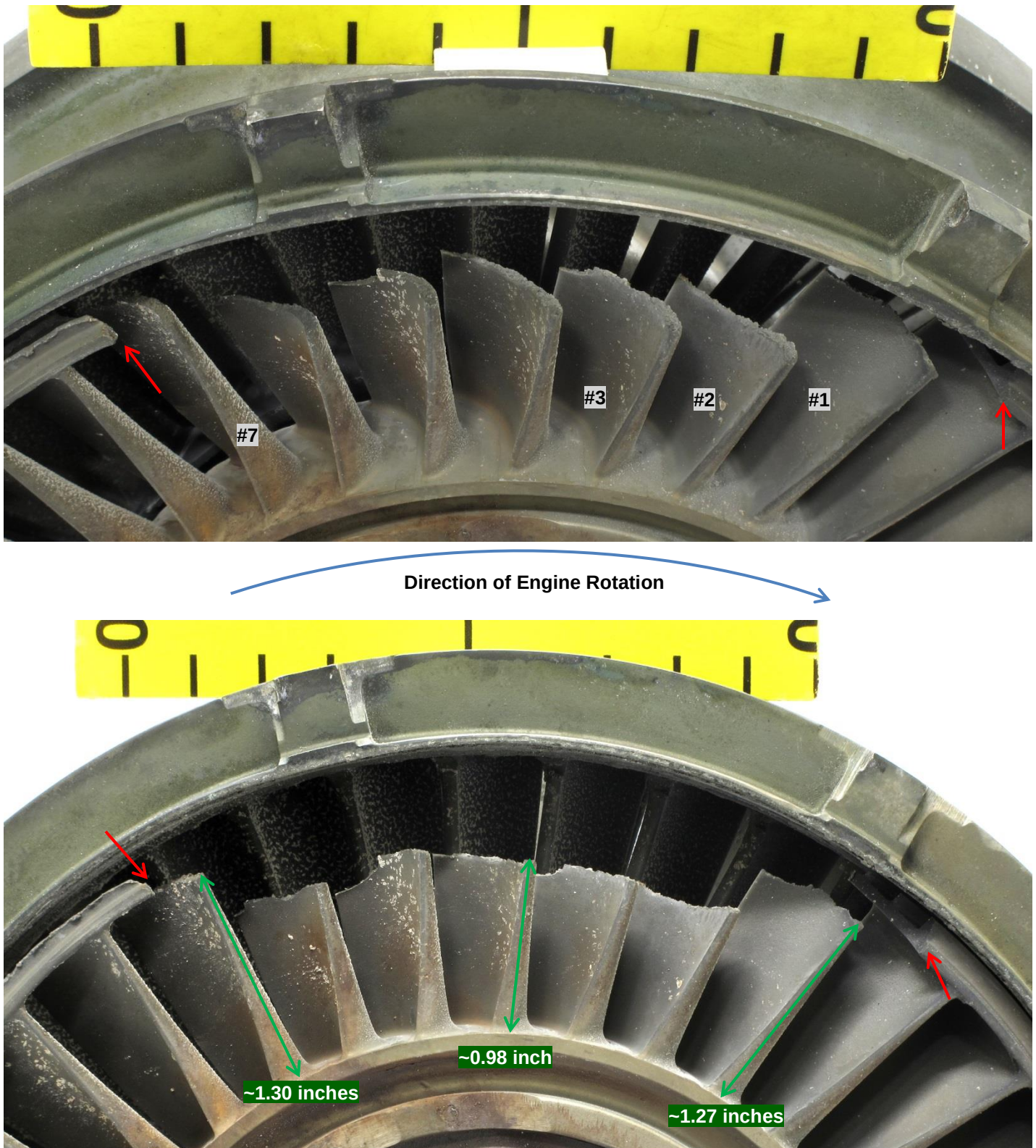


Figure 3. Detailed leading edge side views showing the seven (7) fractured third stage turbine blades. All of the fractured blades were in the same packet of seven blades between slots in the shroud (red arrows). The blades were numbered starting with #1 for the leading fractured blade and increasing opposite the direction of engine rotation (blue arrow) as shown at top. Divisions = cm.

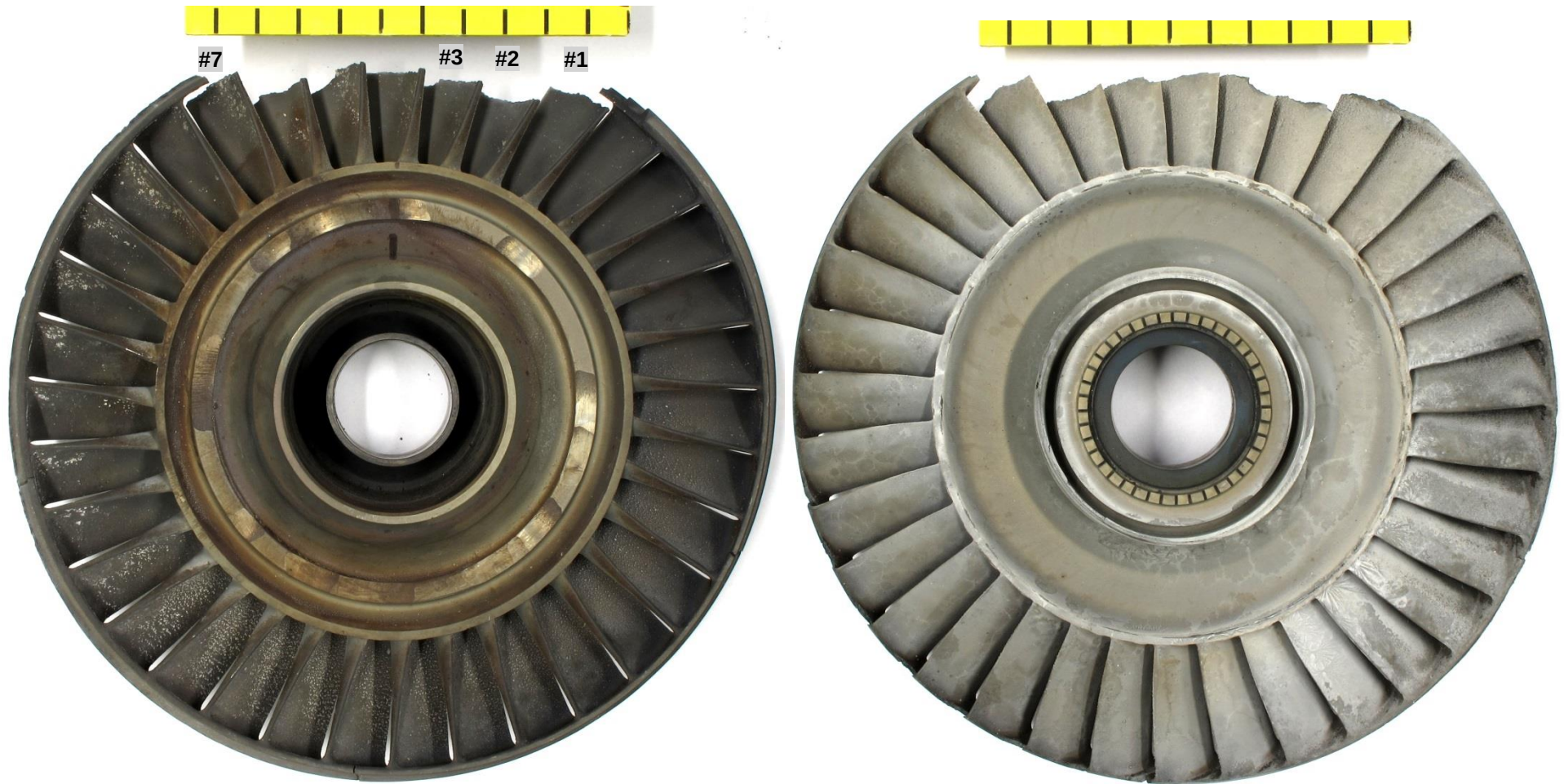


Figure 4. Leading edge (left) and trailing edge (right) side views showing the third stage turbine wheel after rotor disassembly. The black temporary match markings on the leading edge side hub and rim (left) were applied in the laboratory before the PT rotor was sectioned and separated. Divisions = cm.

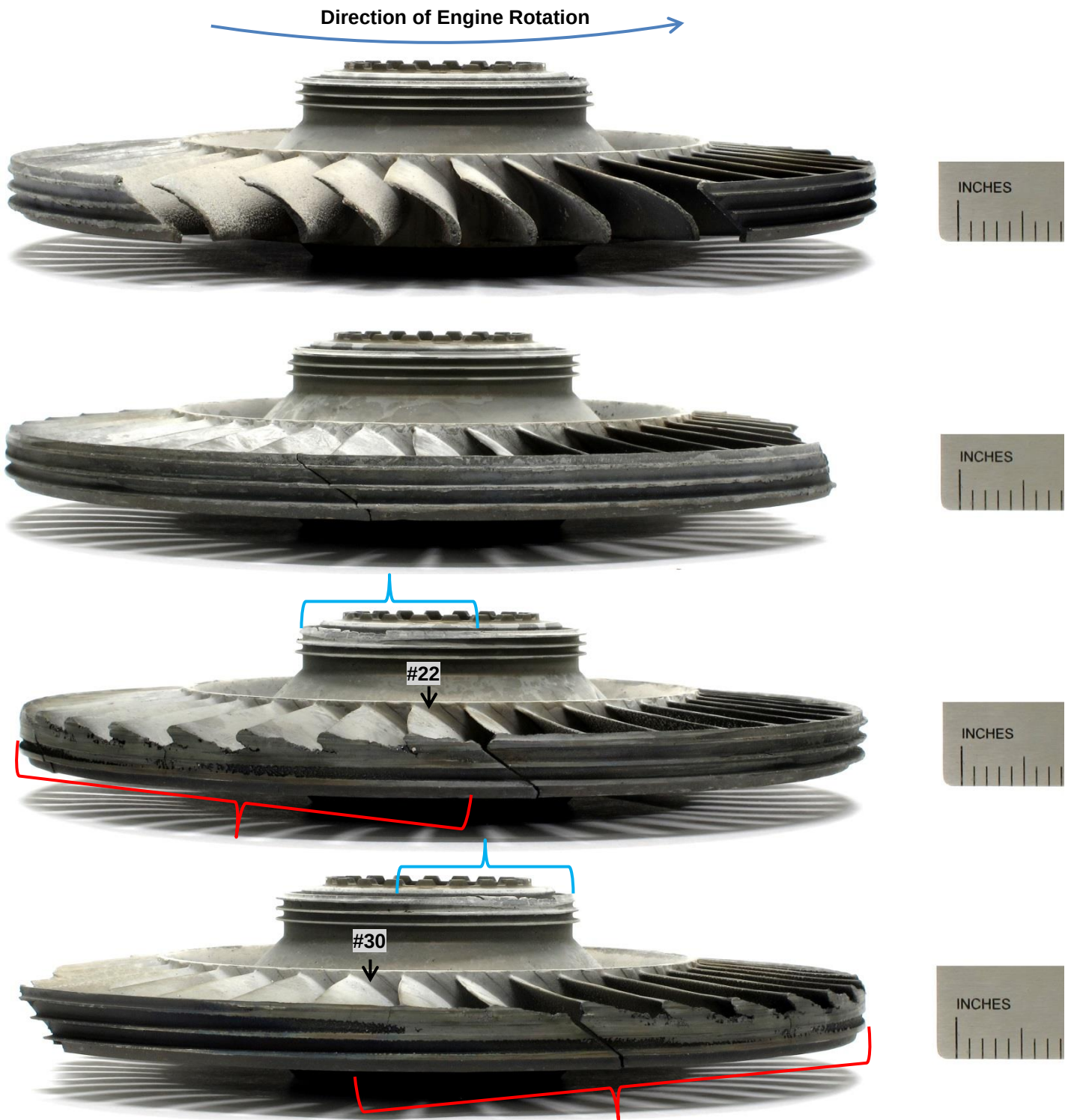


Figure 5. Radial views showing the third stage turbine wheel fractured airfoils (top) and shroud. The wheel was rotated 90° in the direction of engine rotation for this succession of images. The most severe rub damage to the shroud (red braces) and trailing edge side knife seals (blue braces) spanned between blades #22 and #30, centered on a location approximately 90° in the direction of engine rotation from the center of the packet of missing airfoils. Divisions = 0.1 inch.

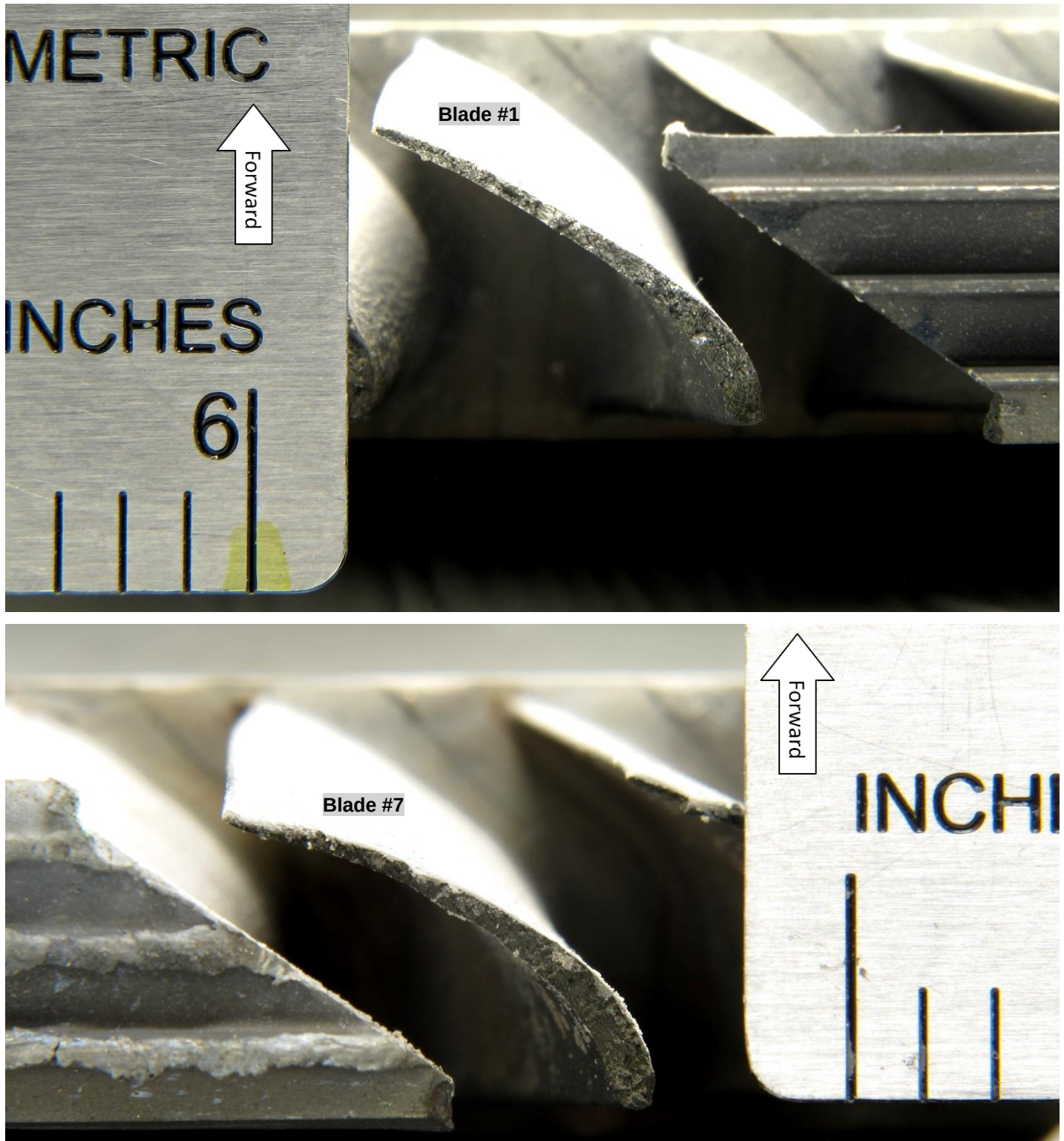


Figure 6. Detailed views of the shroud knife seals adjacent to the leading (top) and trailing (bottom) EDM slots surrounding the liberated portion of the shroud. The knife seals adjacent to the trailing EDM slot exhibited rub damage that flattened the knife edges, while the knife seals adjacent to the leading EDM slot were relatively undamaged. Divisions = 0.1 inch.



Figure 7. Detailed views showing the leading edges and pressure side surfaces of several representative unfractured third stage turbine airfoils. There was no impact damage to the leading edges and the pressure side surfaces exhibited intermittent deposited material consistent with re-deposited material from the rub damage to the shrouds and blade tracks in the power turbine. No scale provided.

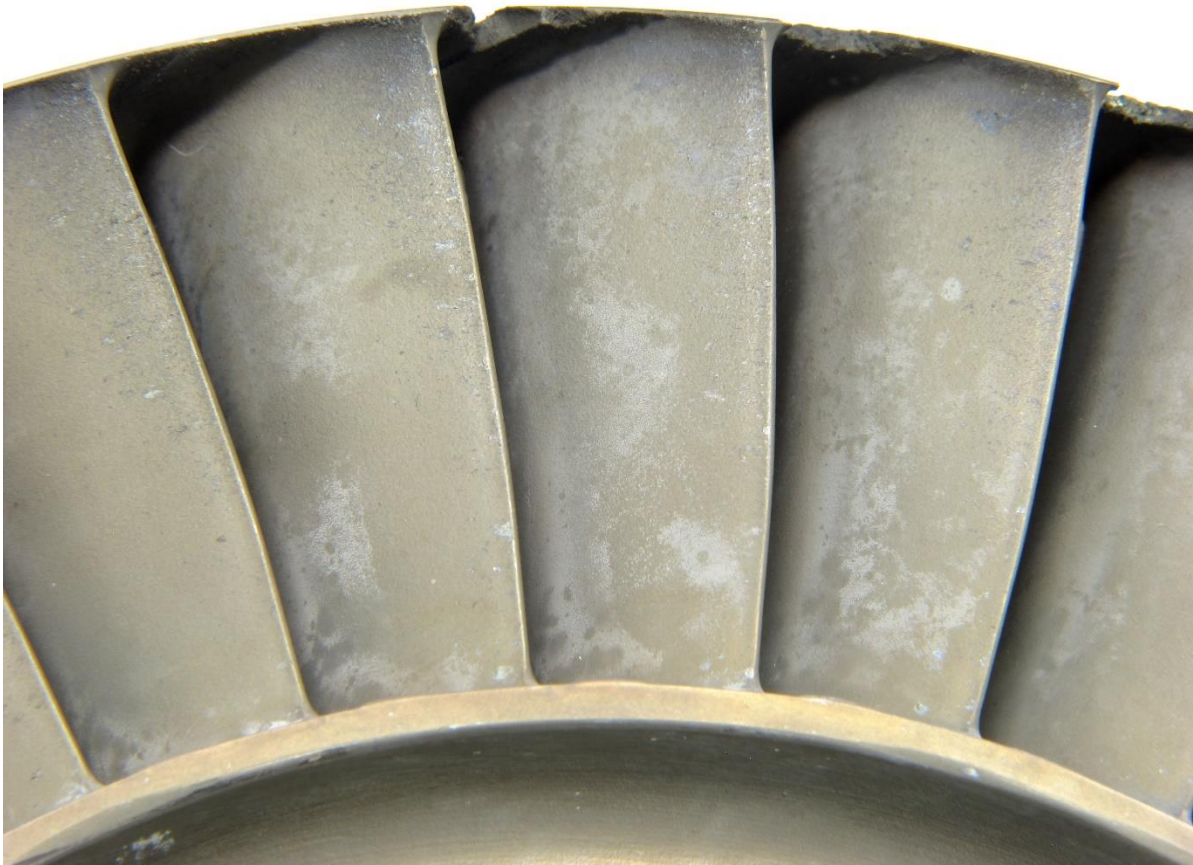


Figure 8. Detailed view showing the trailing edges and suction side surfaces of several representative third stage turbine airfoils. The trailing edges did not exhibit any impact damage. No scale provided.

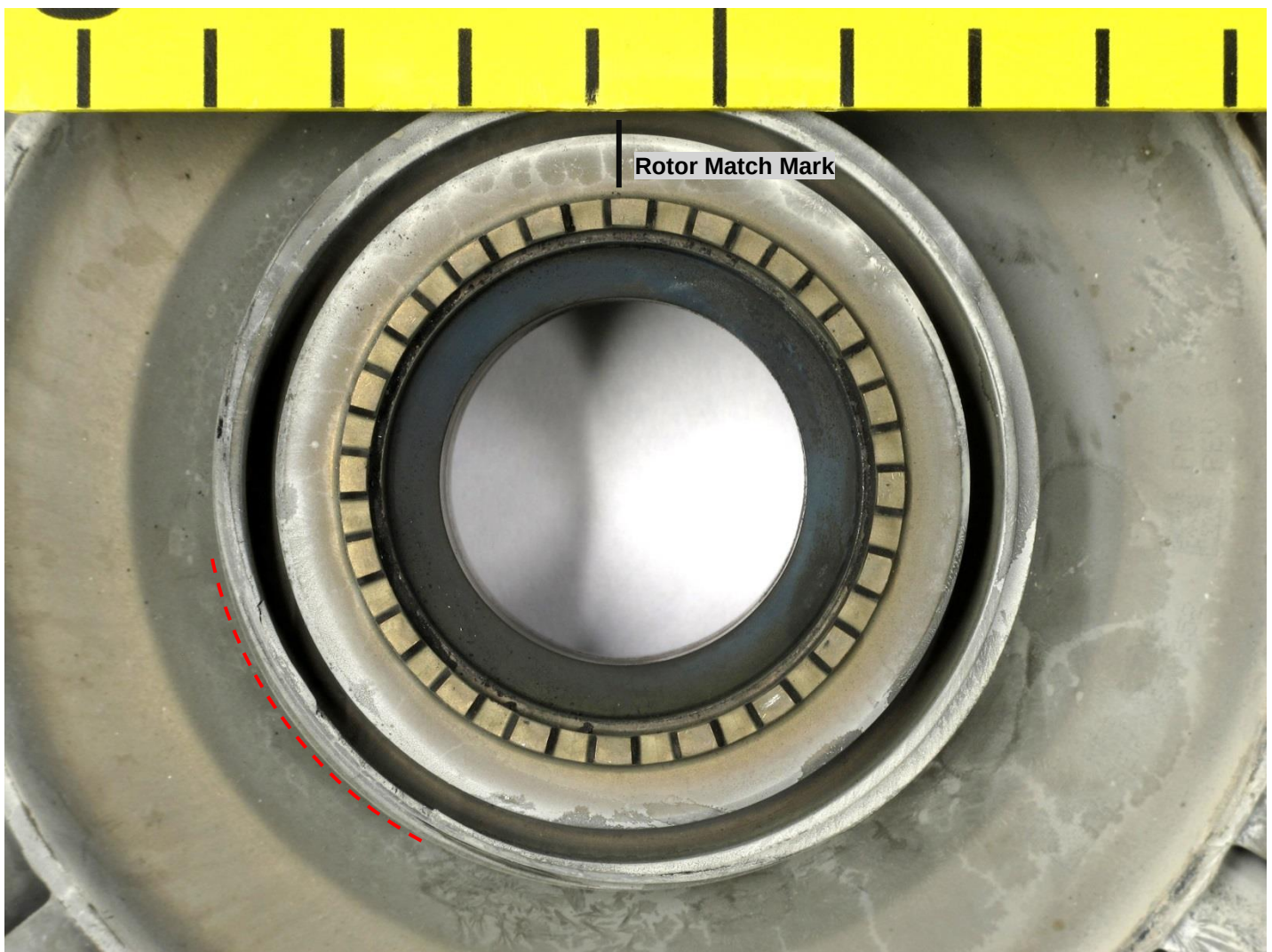


Figure 9. Detailed view showing the trailing edge side curvic teeth. The red dashed line indicates the arc where a part of the knife seals was missing. The black line shows the approximate location of the rotor match mark. Divisions = cm.

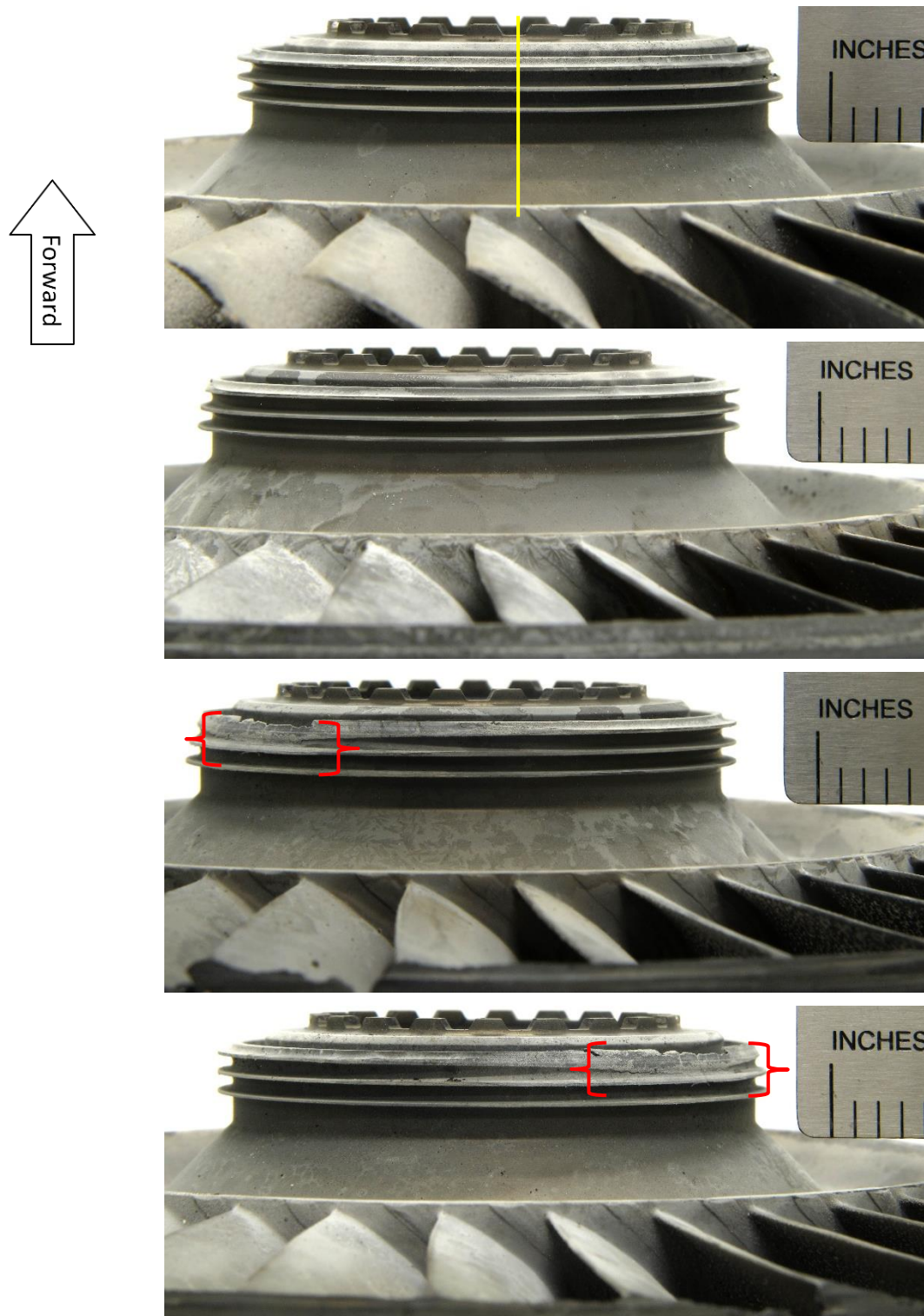


Figure 10. Radial views showing the trailing edge side knife seals on the third stage turbine wheel. The wheel was rotated 90° in the direction of engine rotation for this succession of images. The most severe rub damage to the shroud (red braces) was centered on a location approximately 90° in the direction of engine rotation from the center of the packet of missing airfoils. The yellow line shows the location of the PT rotor match mark. Divisions = 0.1 inch.

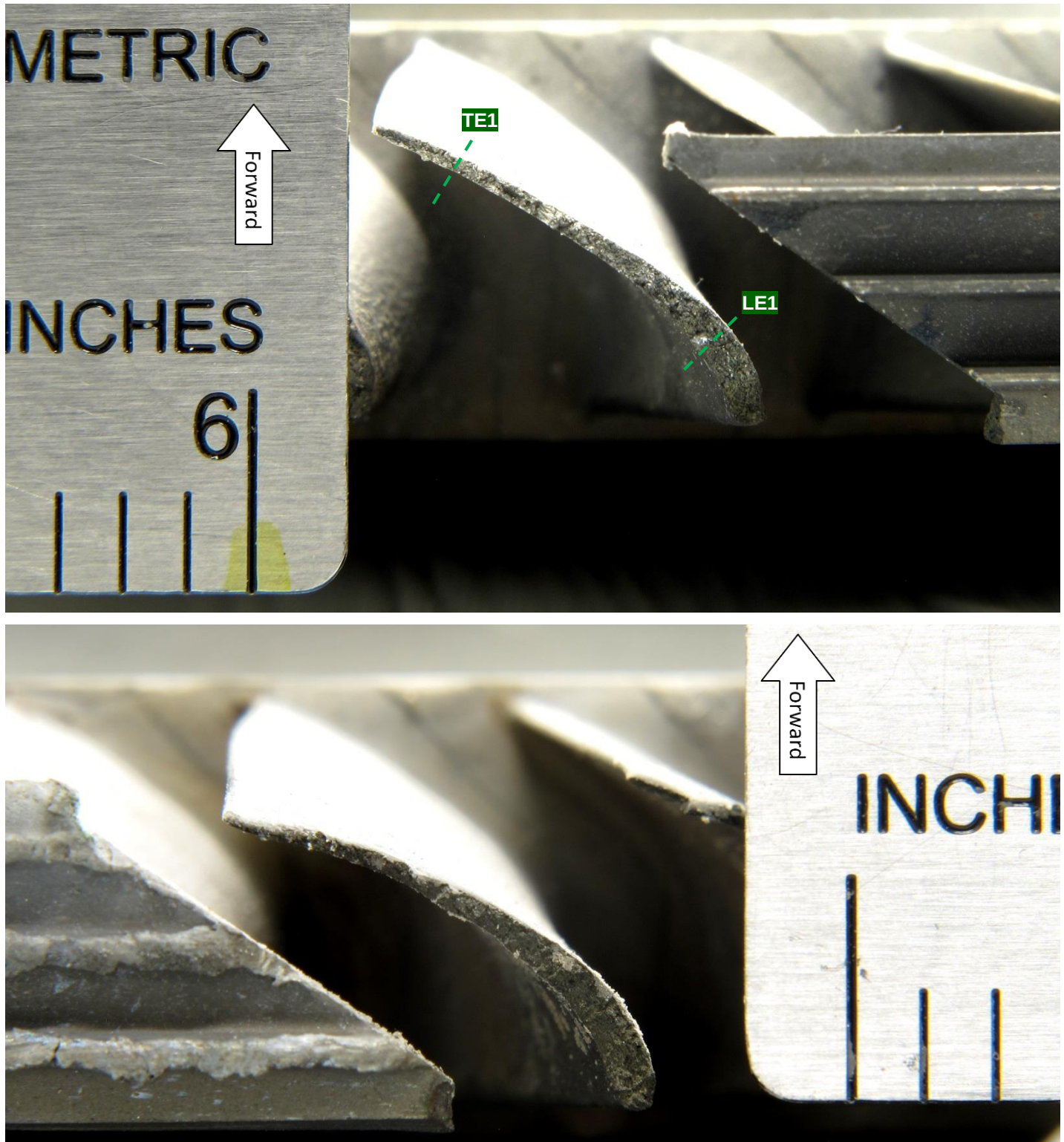


Figure 11. Detailed views showing the fracture surfaces on the blade #1 (top) and blade #7 (bottom) airfoils in the packet where the shroud was liberated. The green dashed lines at top show the approximate locations of the radial-longitudinal sections through blade #1 near the leading edge (LE1) and trailing edge (TE1). The remaining fracture surfaces are shown in the following figures. Divisions = 0.1 inch.

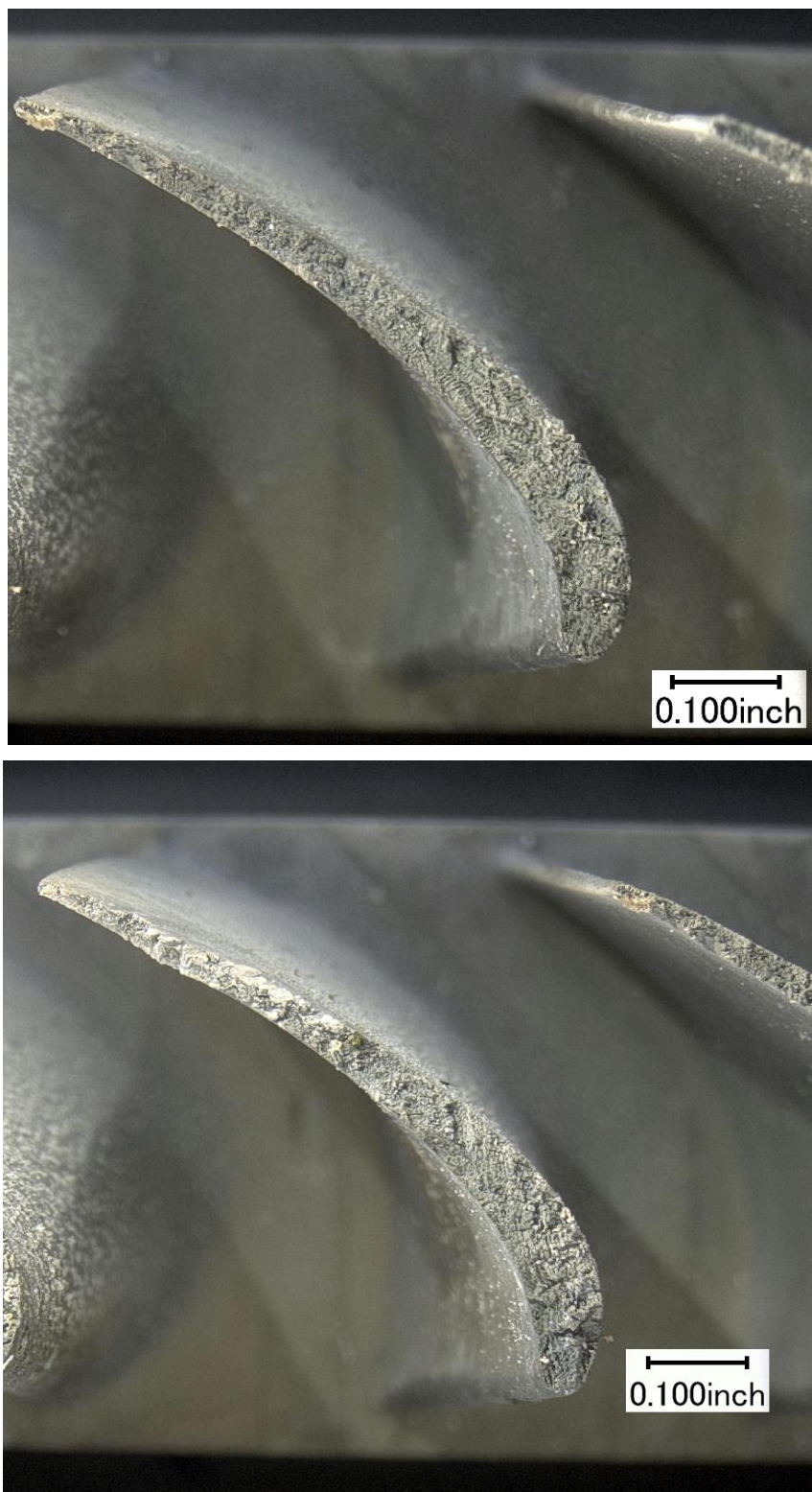


Figure 12. Fracture surfaces on blades #2 (top) and #3 (bottom) prior to cleaning.

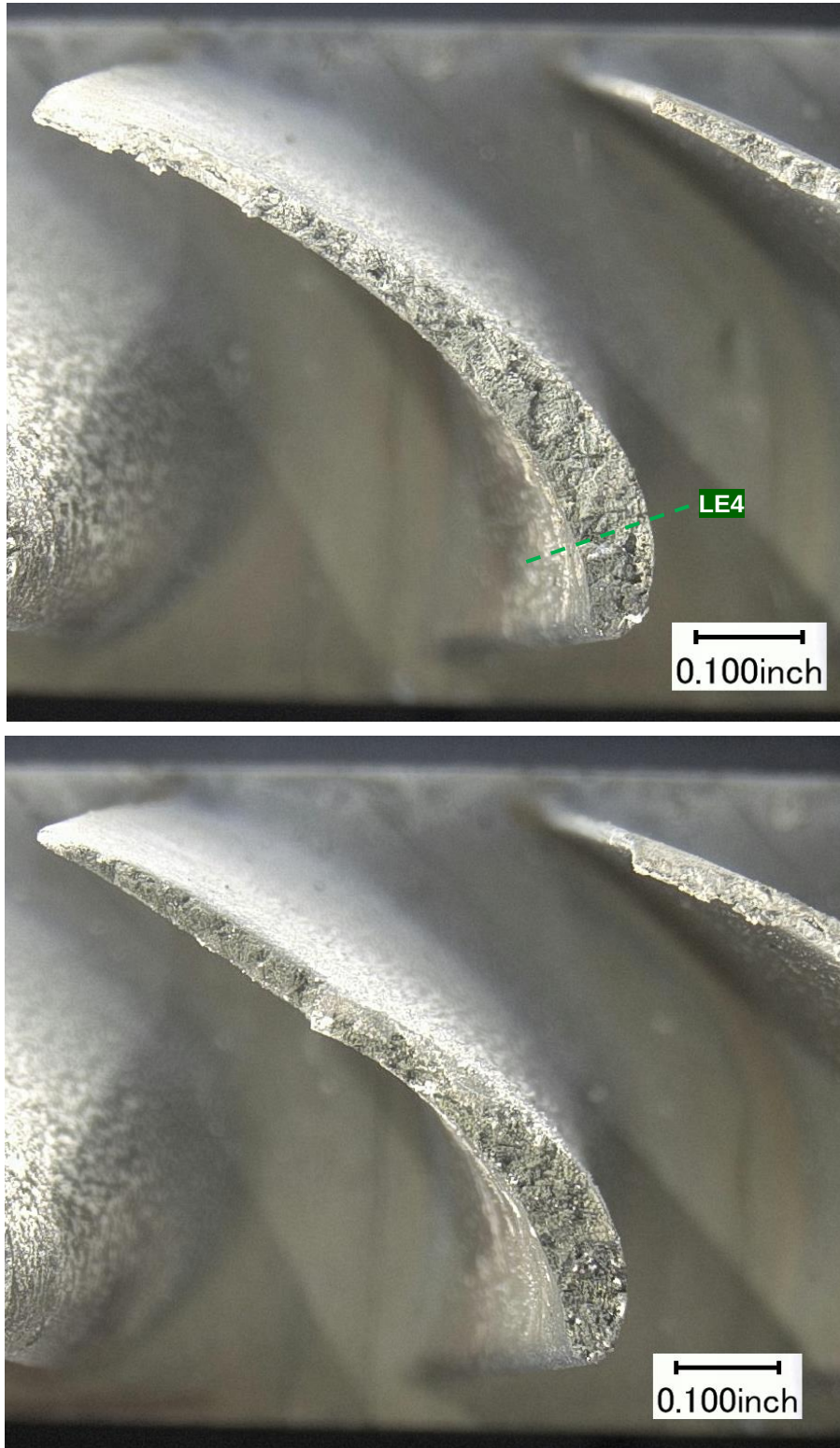


Figure 13. Fracture surfaces on blades #4 (top) and #5 (bottom) prior to cleaning. The green dashed line shows the approximate location of the radial-longitudinal section near the leading edge of blade #4 (LE4).

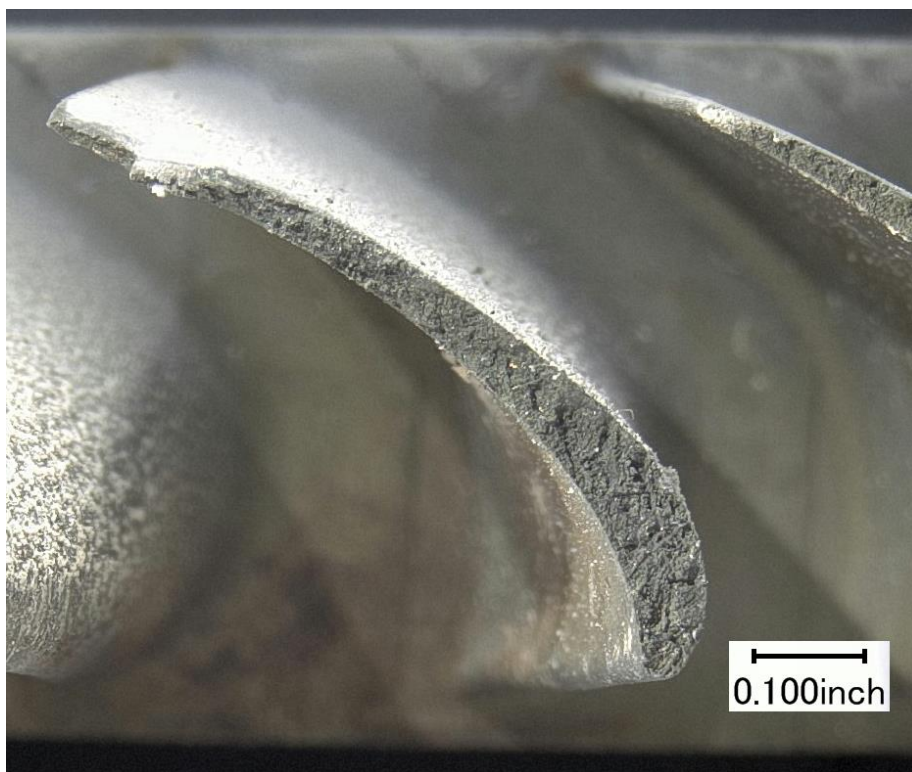


Figure 14. Fracture surface on blade #6 prior to cleaning.

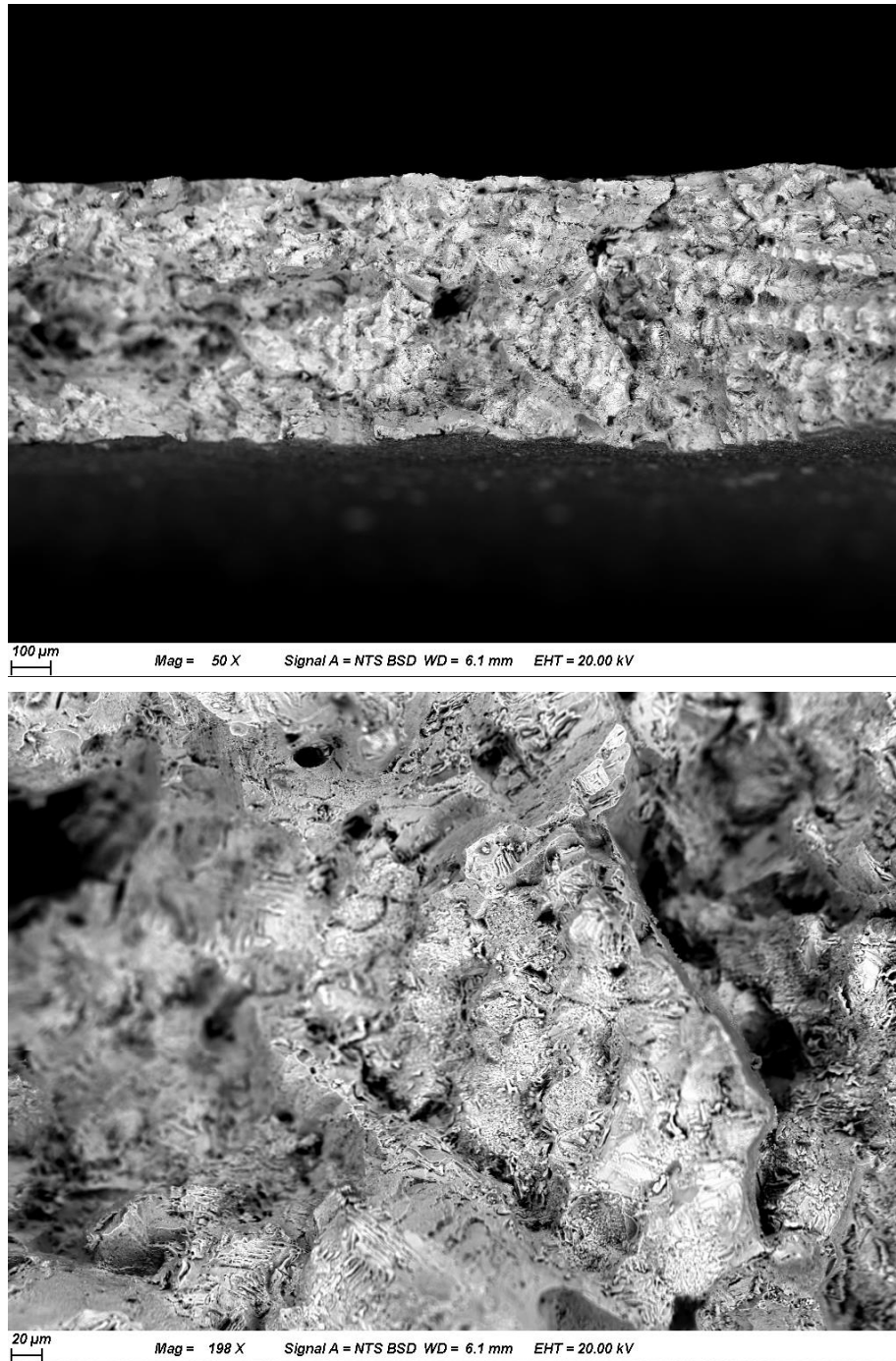


Figure 15. Backscattered electron SEM images showing representative fracture features found on blade #1.

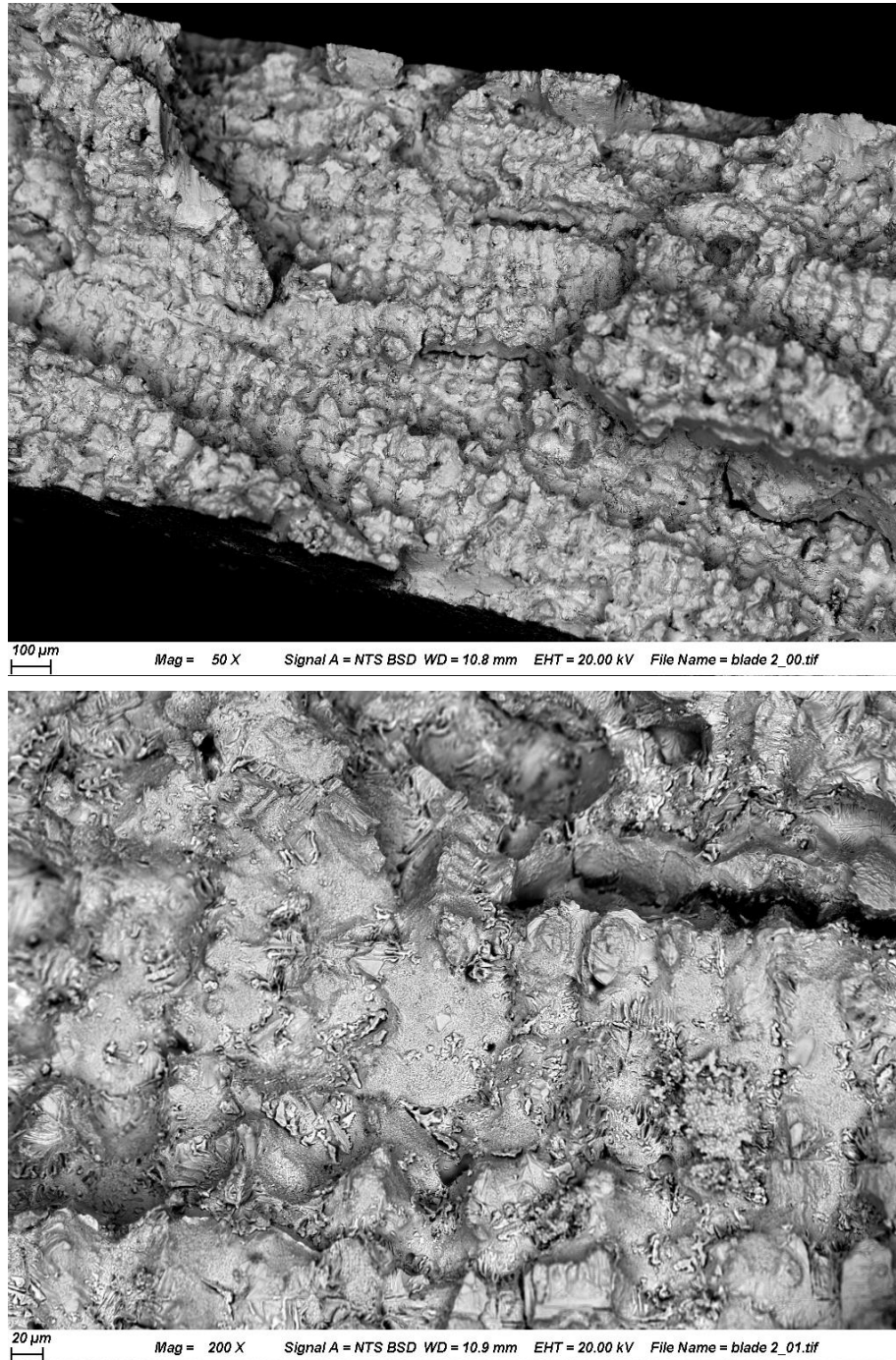


Figure 16. Backscattered electron SEM images showing representative fracture features found on blade #2.

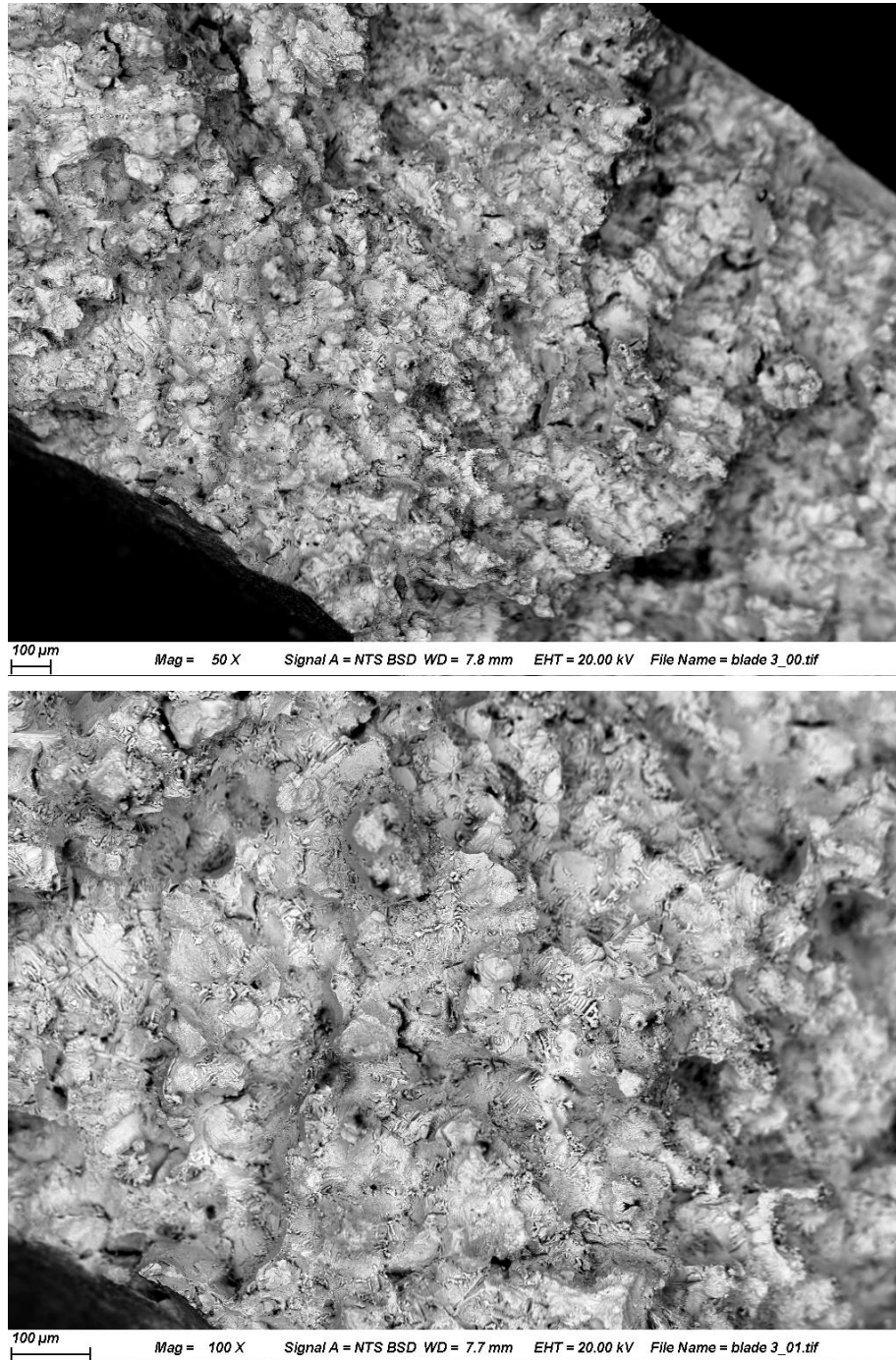


Figure 17. Backscattered electron SEM images showing representative fracture features found on blade #3.

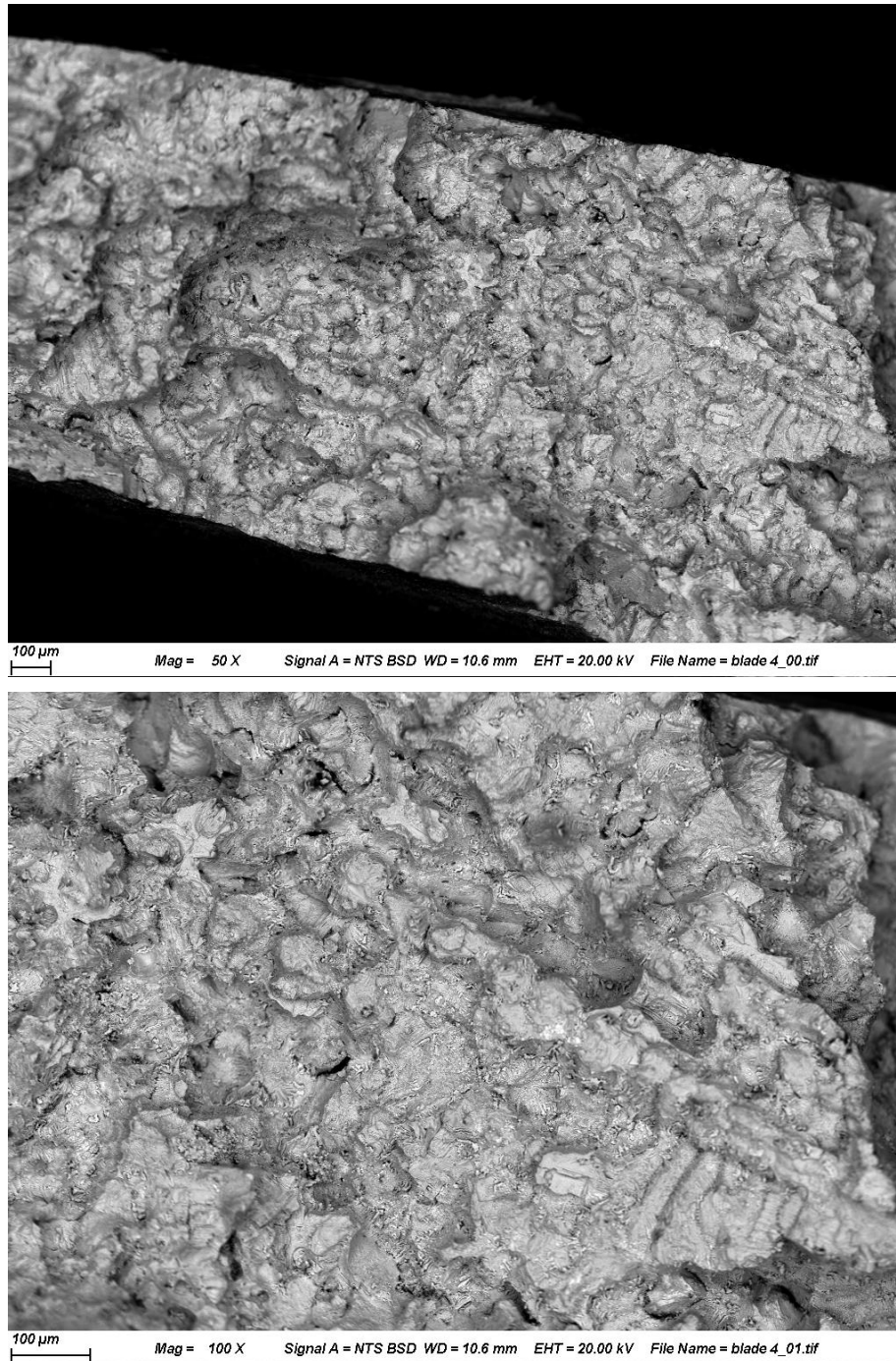


Figure 18. Backscattered electron SEM images showing representative fracture features found on blade #4.

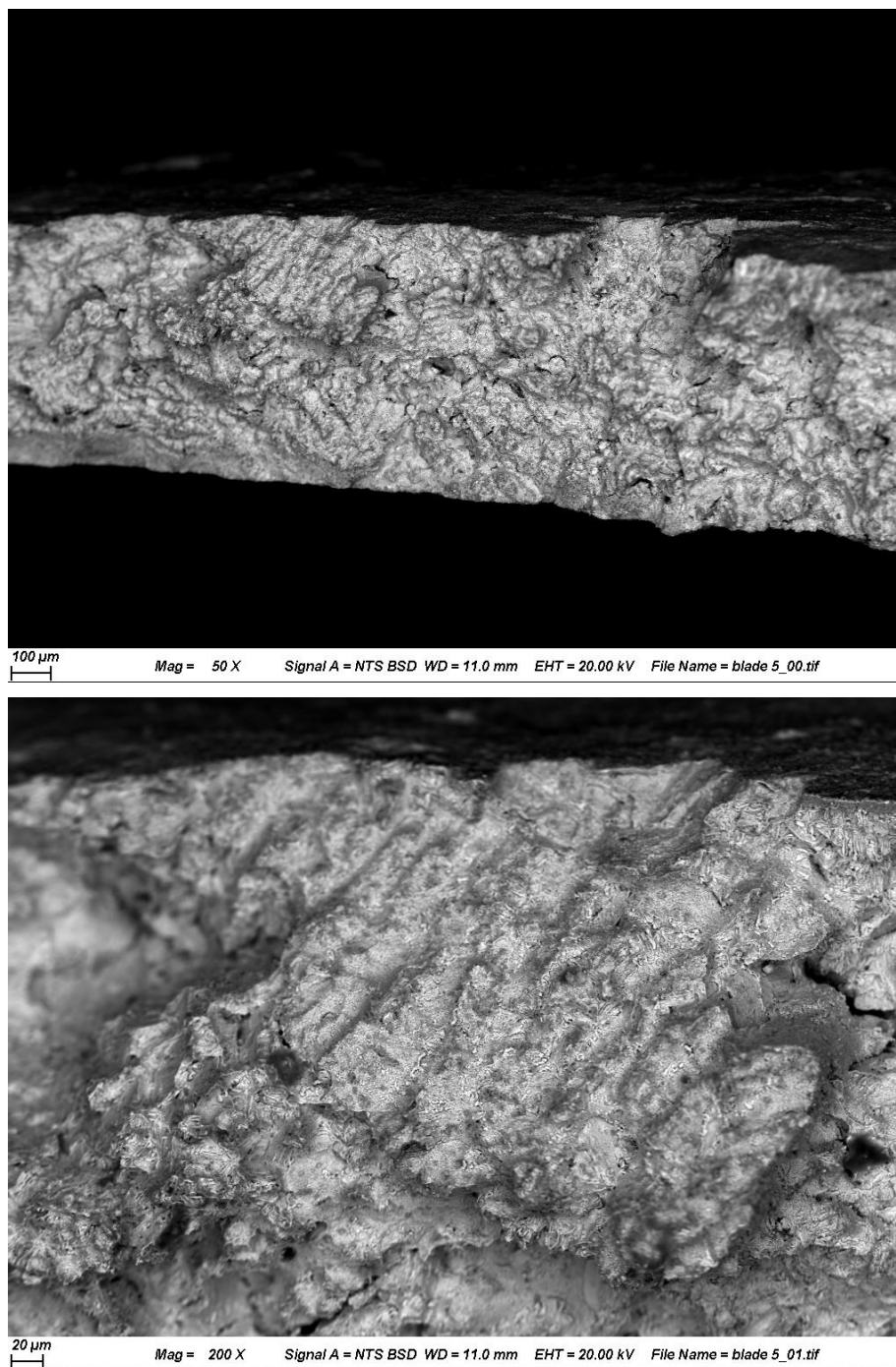


Figure 19. Backscattered electron SEM images showing representative fracture features found on blade #5.

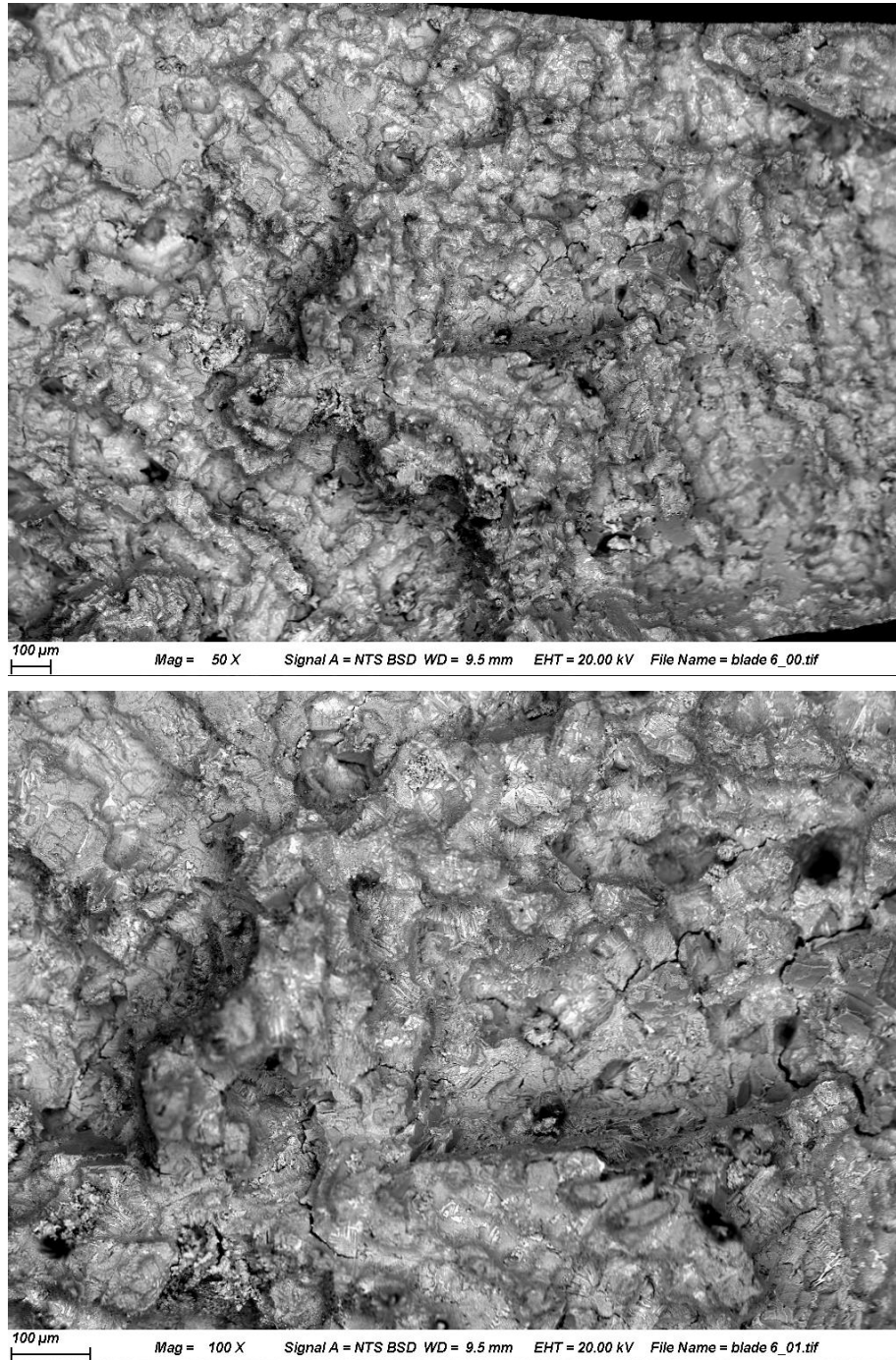


Figure 20. Backscattered electron SEM images showing representative fracture features found on blade #6.

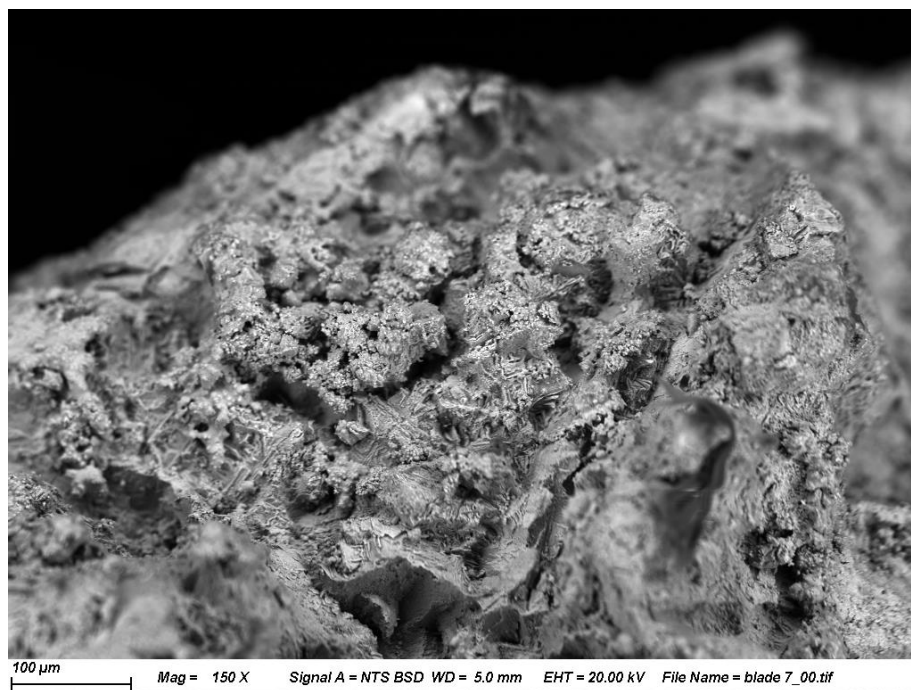


Figure 21. Backscattered electron SEM image showing representative fracture features found on blade #7.



Figure 22. Overall views of longitudinal cross-section LE1 near the leading edge of fractured blade #1. There was no evidence of stress rupture void formation on the cross-section. The red brace indicates the lighter-etching microstructure consistent with thermal distress. Left: Unetched; Right etchant: MT.

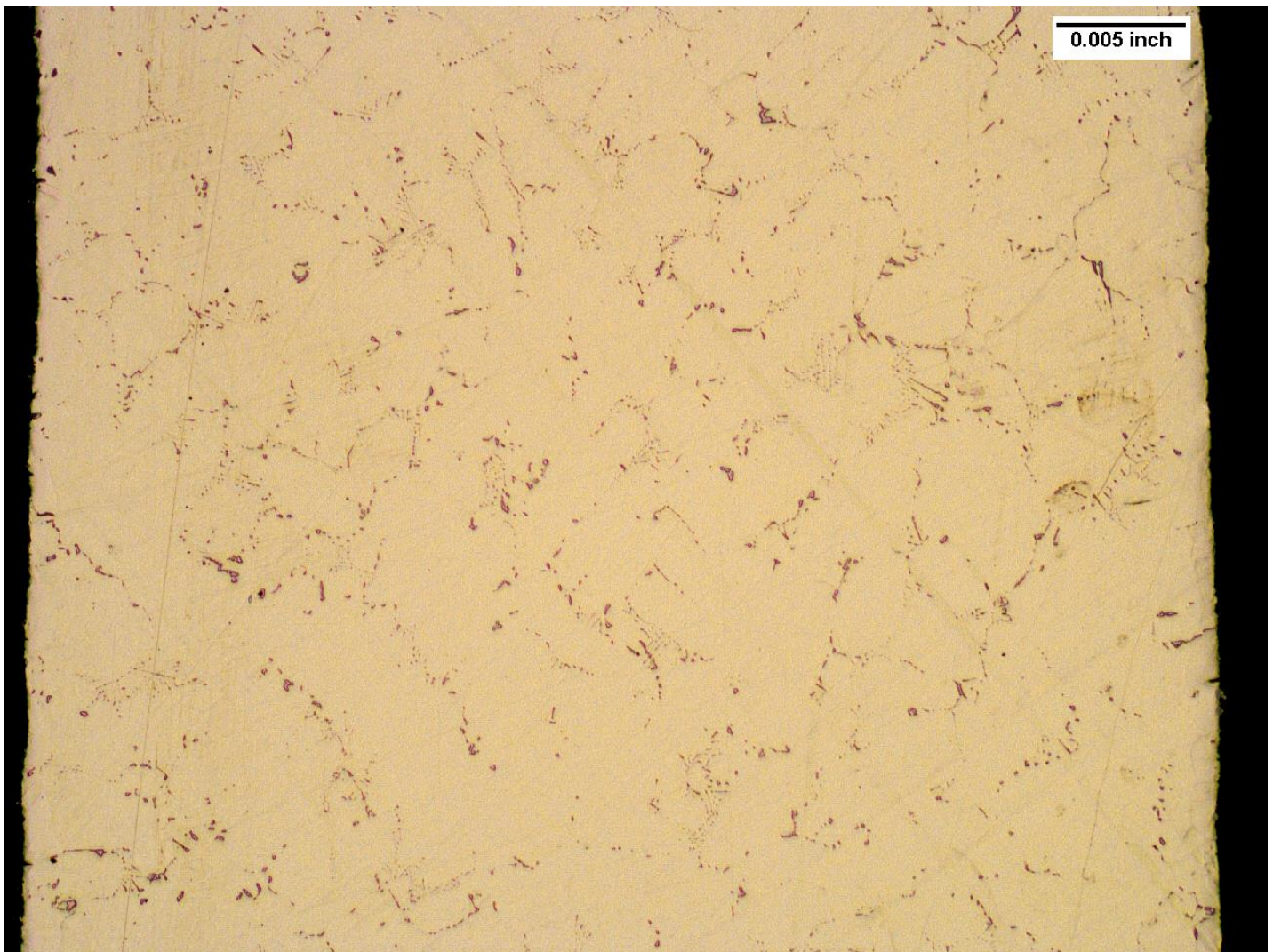
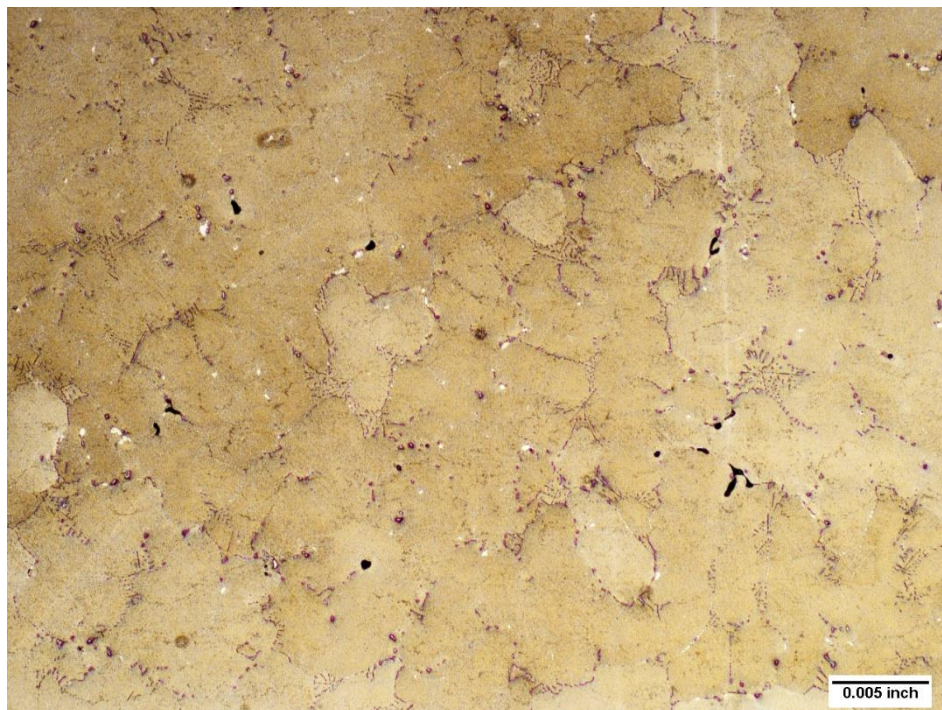


Figure 23. Representative unetched view of cross-section LE1 near the middle of the intact span of the airfoil showing no evidence of stress-rupture void formation.



Original Magnification: 100x

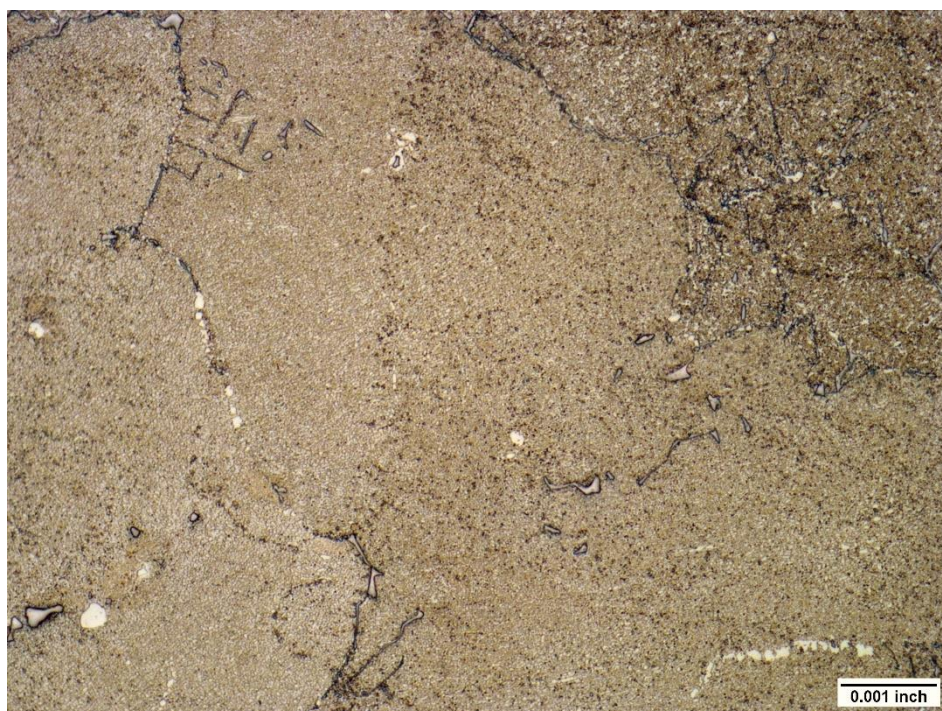


Original Magnification: 500x

Figure 24. Representative microstructure in the rim of the wheel on cross-section LE1. Etchant: MT.

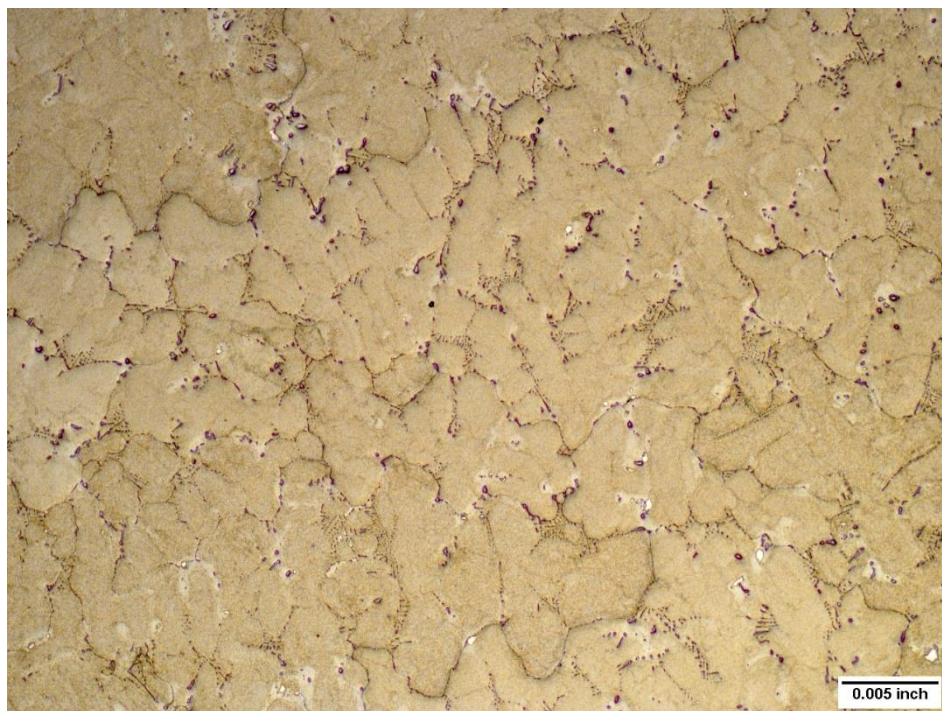


Original Magnification: 100x

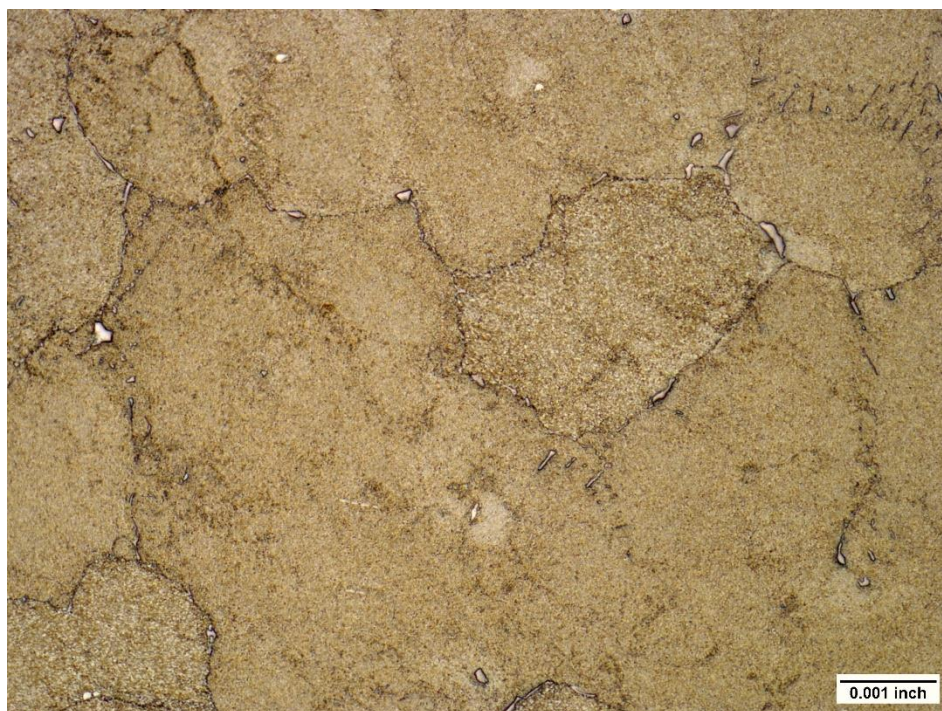


Original Magnification: 500x

Figure 25. Representative microstructure in the root of the blade on cross-section LE1. Etchant: MT.

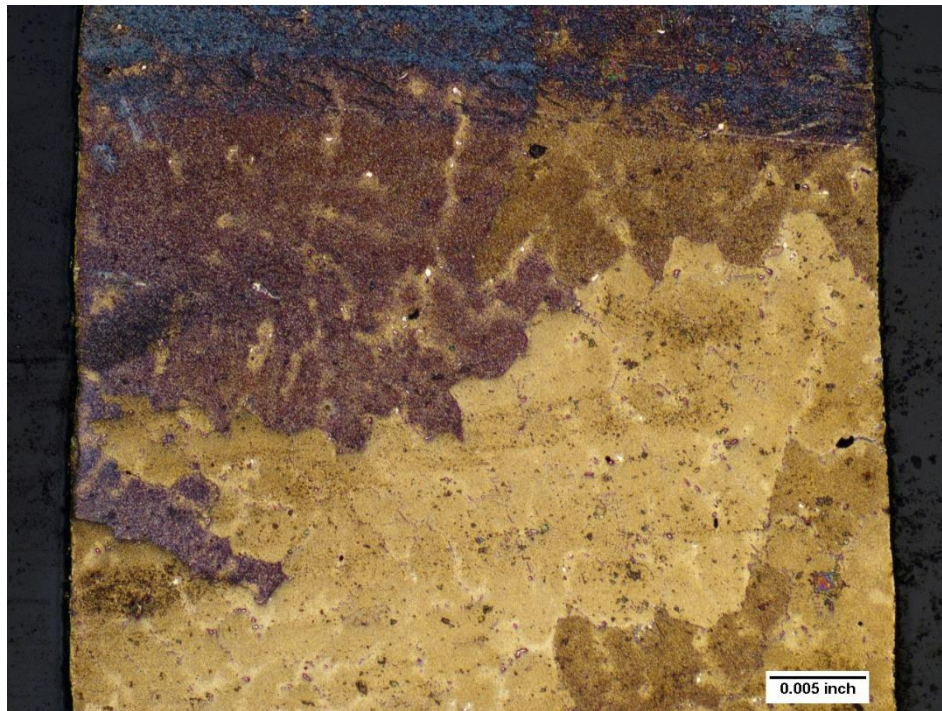


Original Magnification: 100x



Original Magnification: 500x

Figure 26. Representative microstructure in the lighter etching thermally distressed area of the blade on cross-section LE1. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 27. Representative microstructure near the fracture on cross-section LE1. The dark purple-etching area near the tip was overetched during etching and does not indicate thermal distress to the microstructure. Etchant: MT.

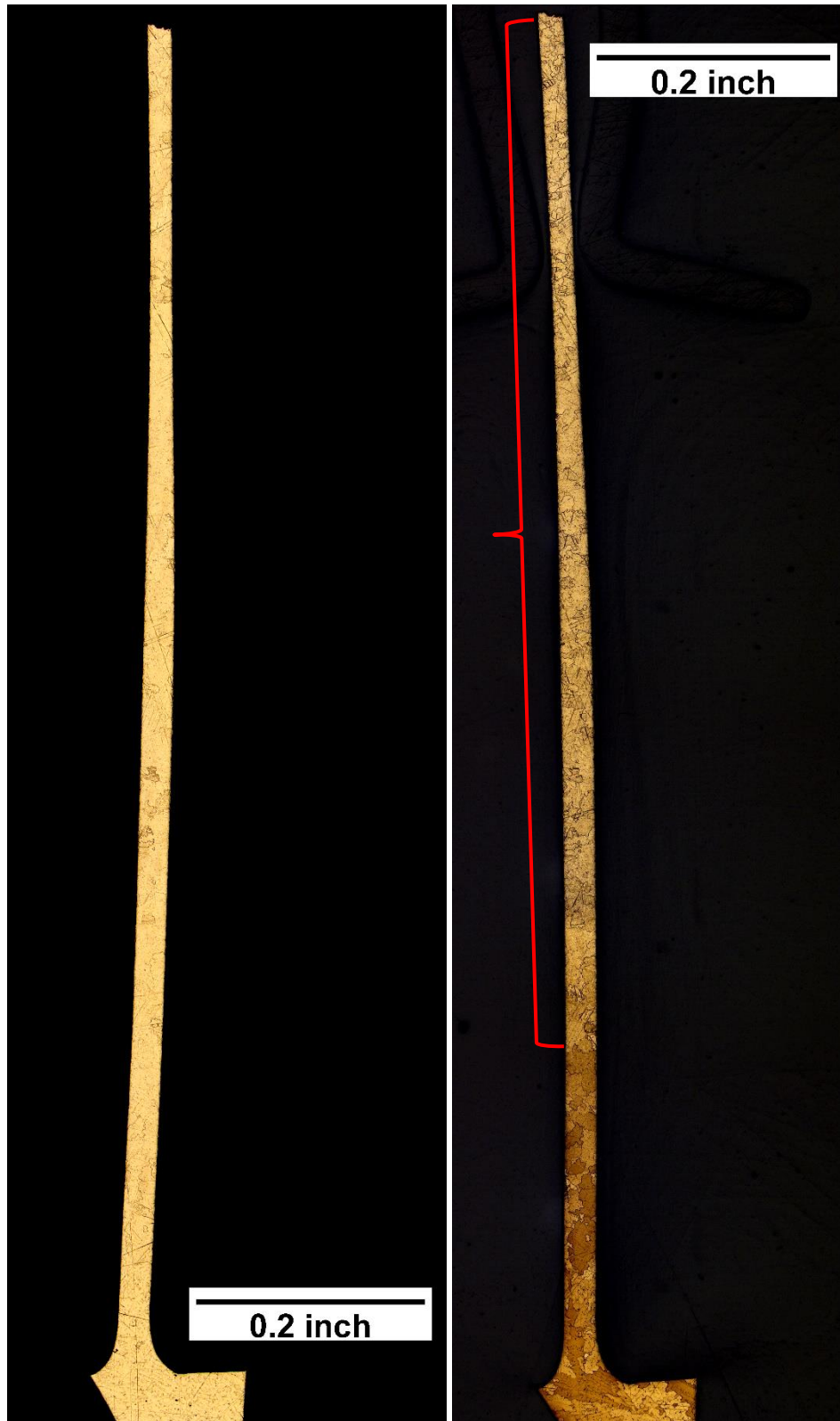


Figure 28. Overall views of longitudinal cross-section TE1 near the trailing edge of fractured blade #1. There was no evidence of stress rupture void formation on the cross-section. The red brace indicates the lighter-etching microstructure consistent with thermal distress. Left: Unetched; Right etchant: MT.

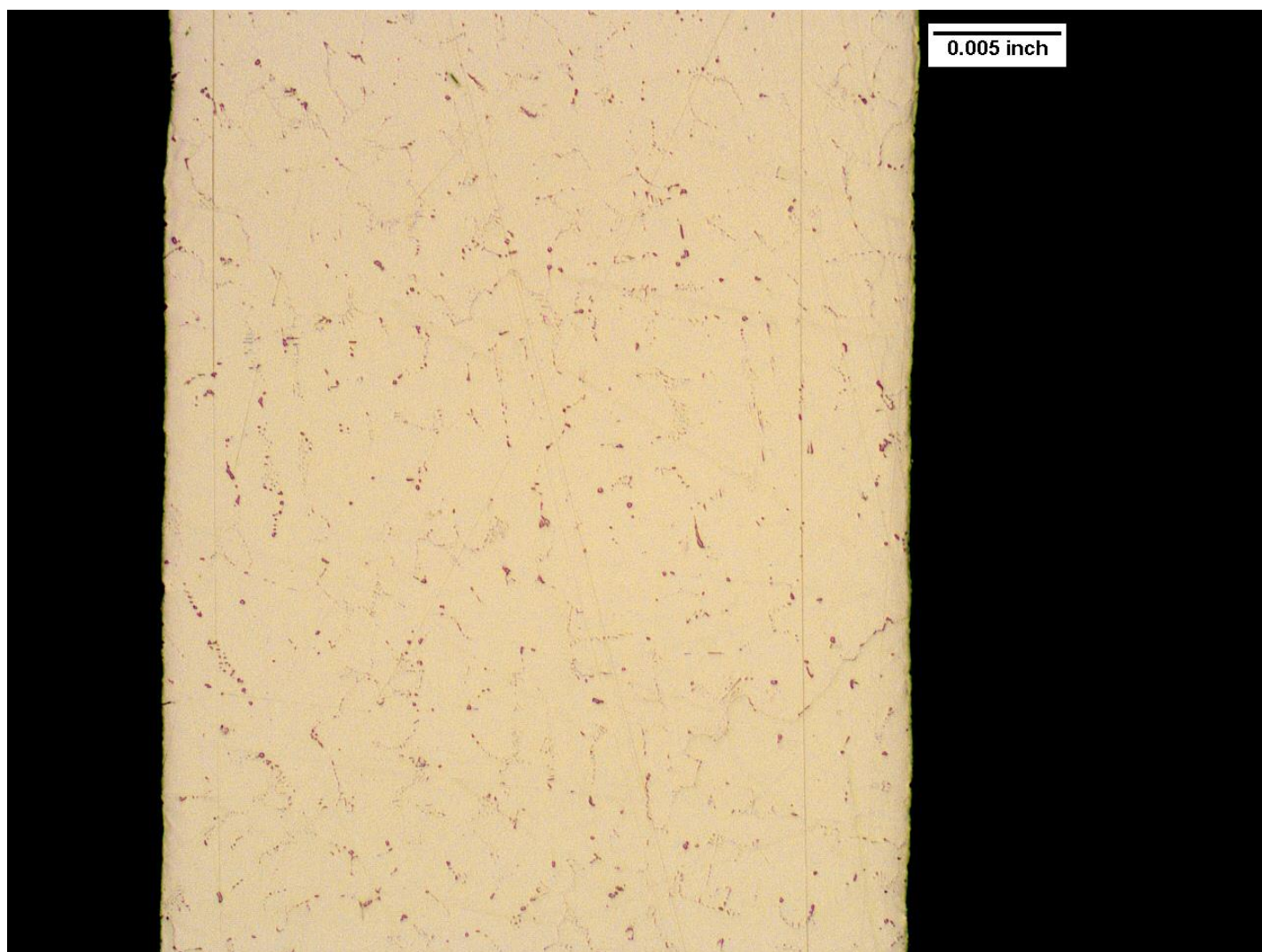
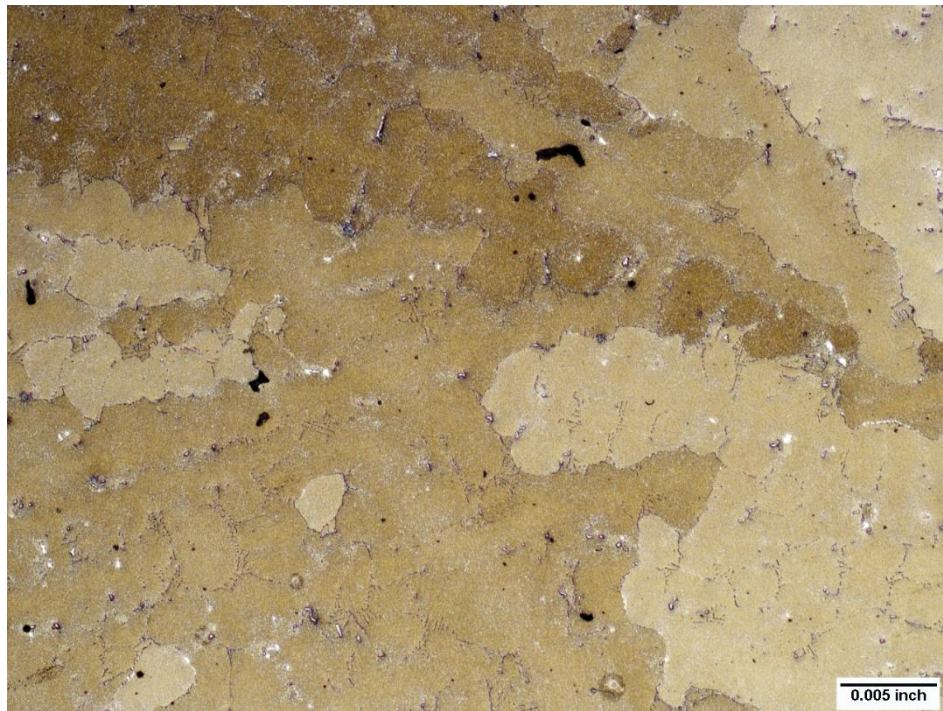
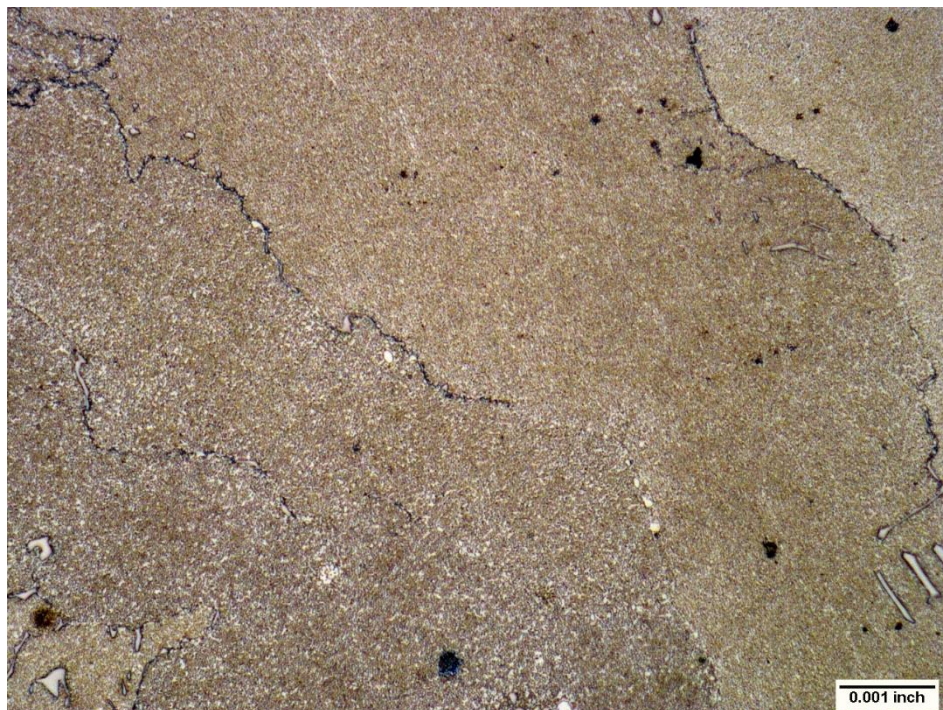


Figure 29. Representative unetched view of cross-section TE1 showing no evidence of stress-rupture void formation.



Original Magnification: 100x



Original Magnification: 500x

Figure 30. Representative microstructure in the rim of the wheel on cross-section TE1. Etchant: MT.

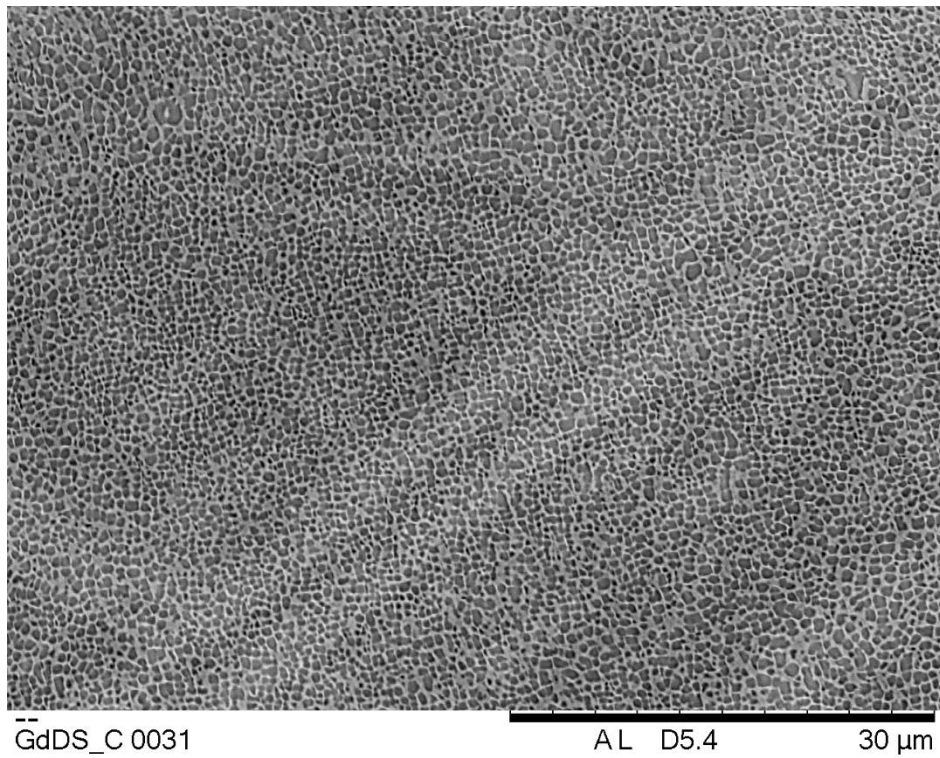
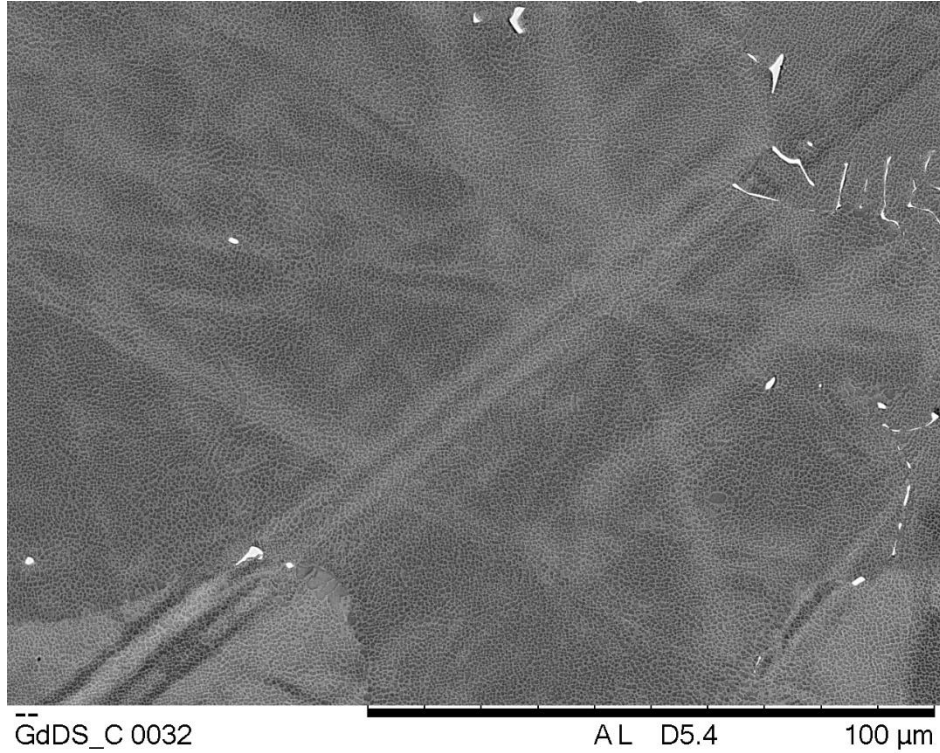
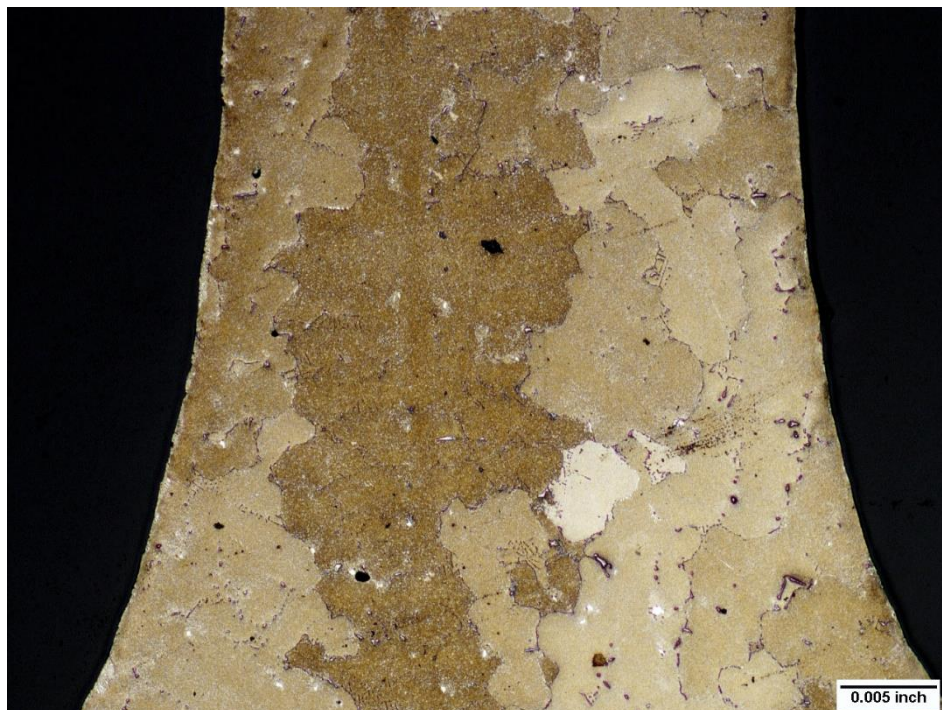


Figure 31. Backscattered electron SEM images showing the gamma prime structure in the rim of the wheel on cross-section TE1. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 32. Representative microstructure in the root of the blade on cross-section TE1. Etchant: MT.

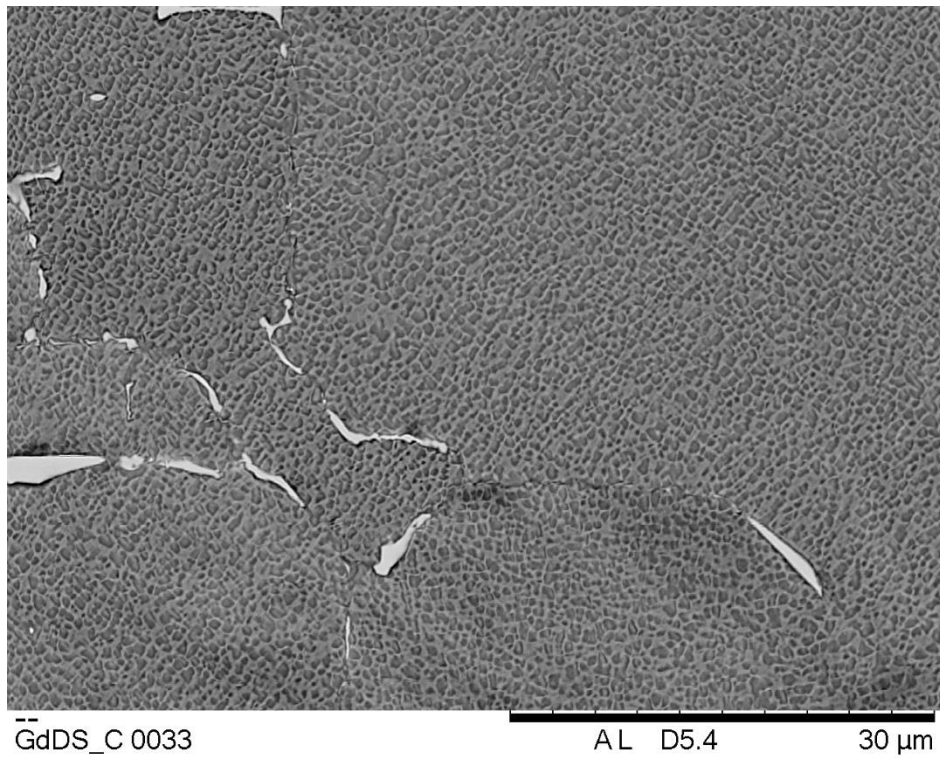
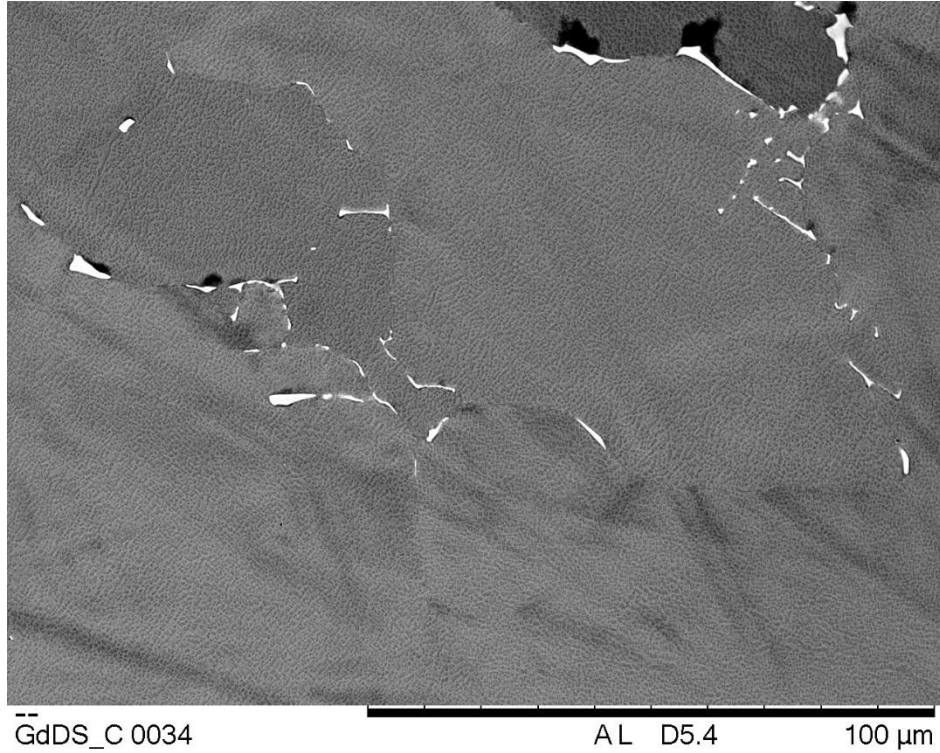
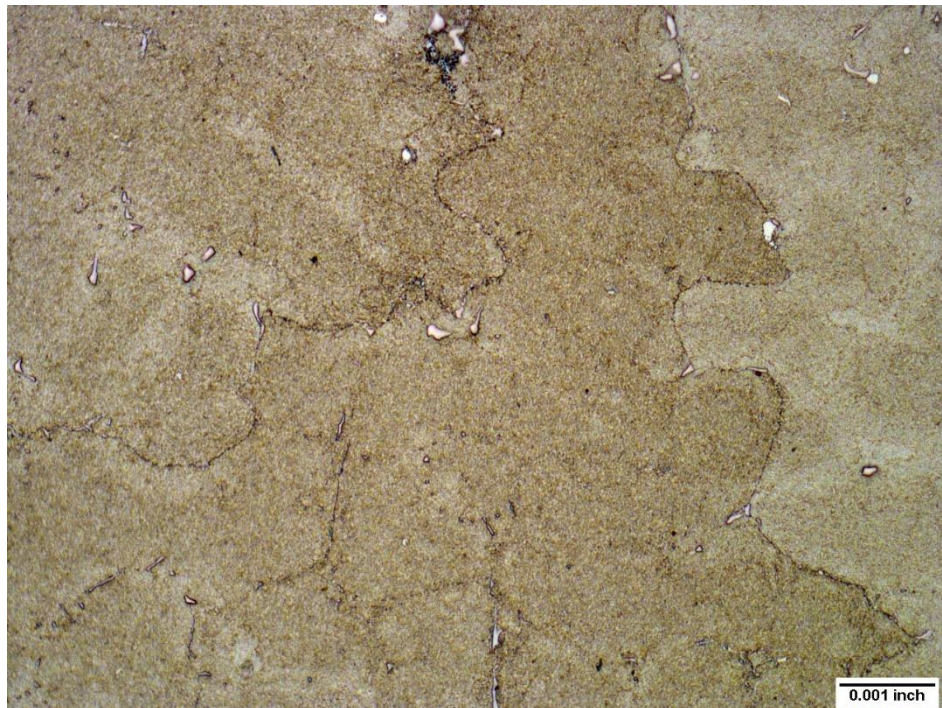


Figure 33. Backscattered electron SEM images showing the gamma prime structure in the root of the blade on cross-section TE1. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 34. Representative microstructure in the lighter etching thermally distressed area inboard of the fracture on cross-section TE1. Representative re-crystallization at the airfoil surfaces in the thermally-distressed area indicated by the green brace. Etchant: MT.

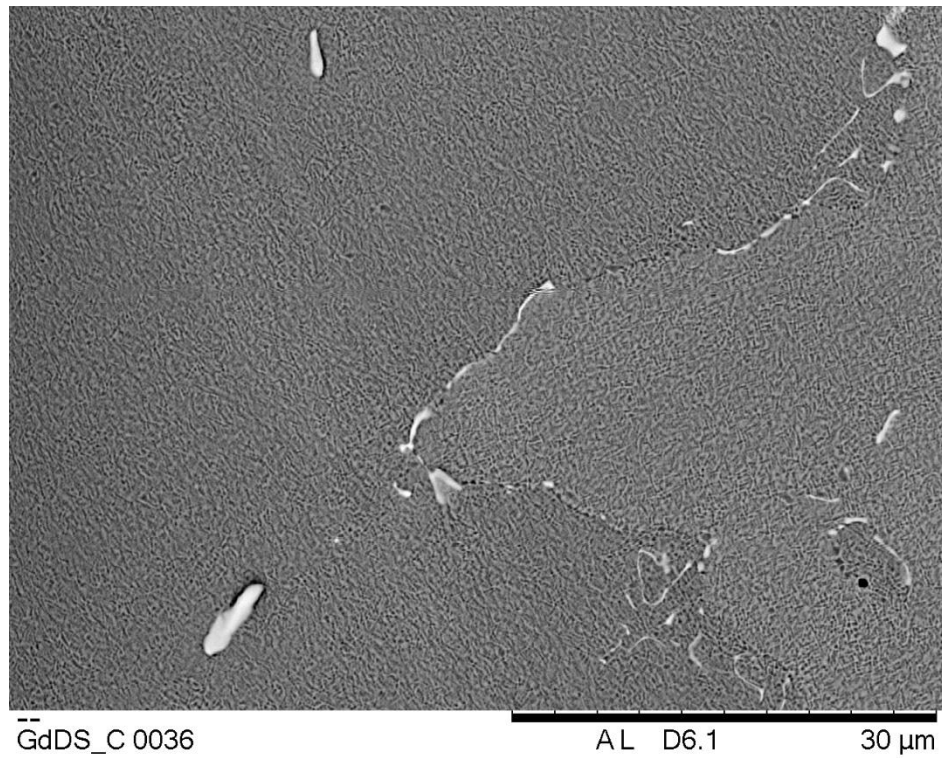
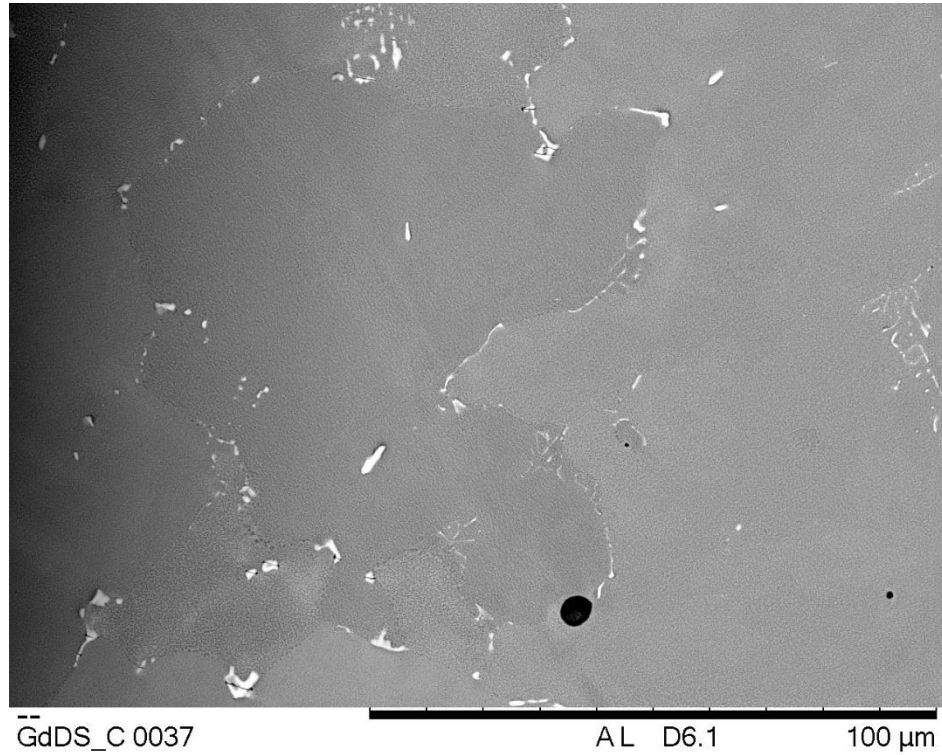


Figure 35. Backscattered electron SEM images showing the gamma prime structure in the thermally distressed area inboard of the fracture on cross-section TE1. Etchant: MT.



Figure 36. Overall views of longitudinal cross-section LE4 near the leading edge of fractured blade #4. There was no evidence of stress rupture void formation on the cross-section. The red brace indicates the lighter-etching microstructure consistent with thermal distress. Left: Unetched; Right etchant: MT.

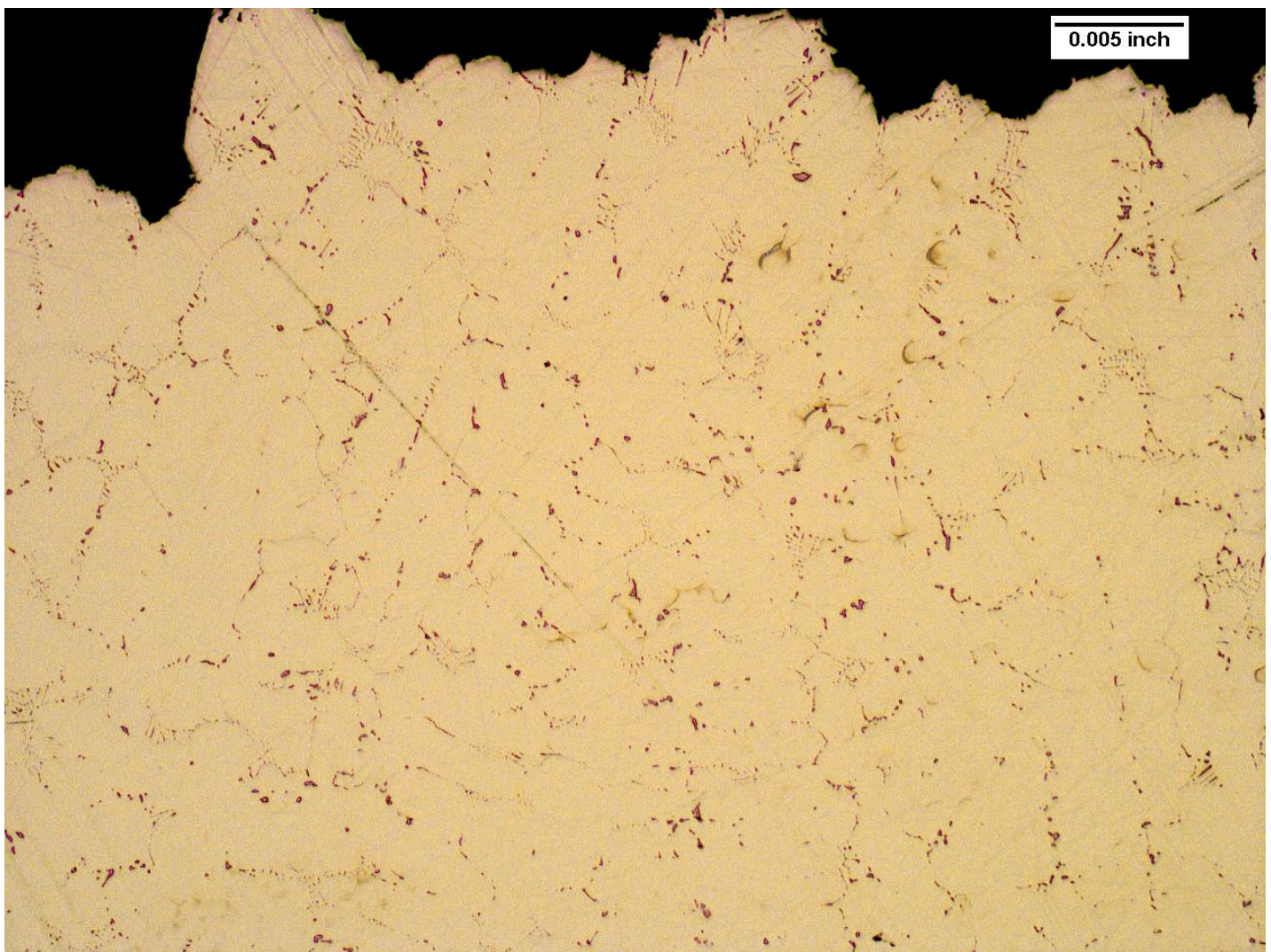
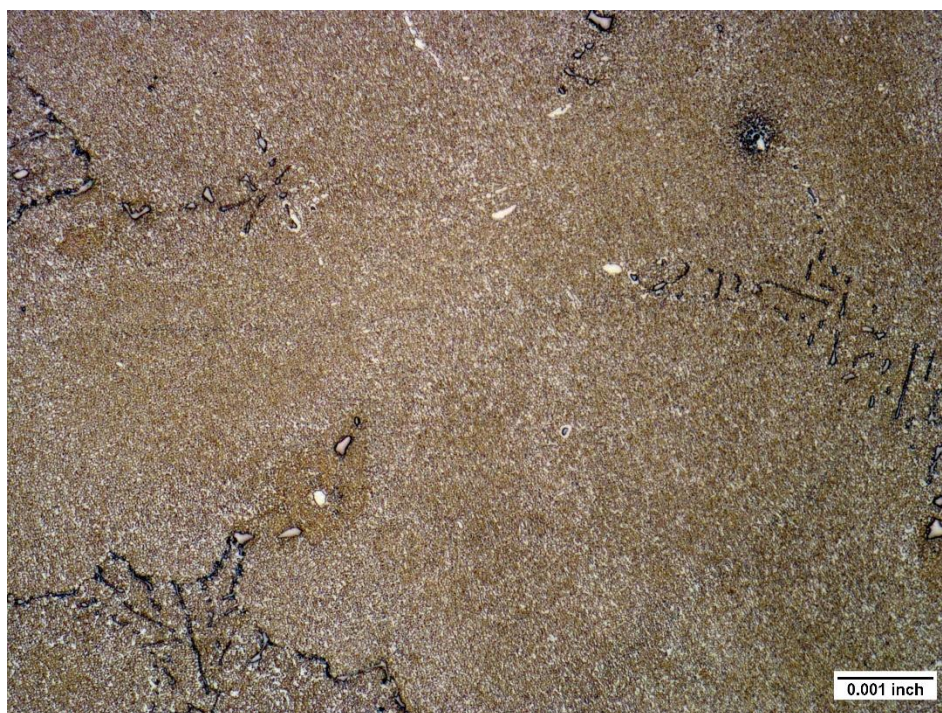


Figure 37. Representative unetched view of cross-section LE4 near the fracture surface. There was no evidence of stress rupture void formation.

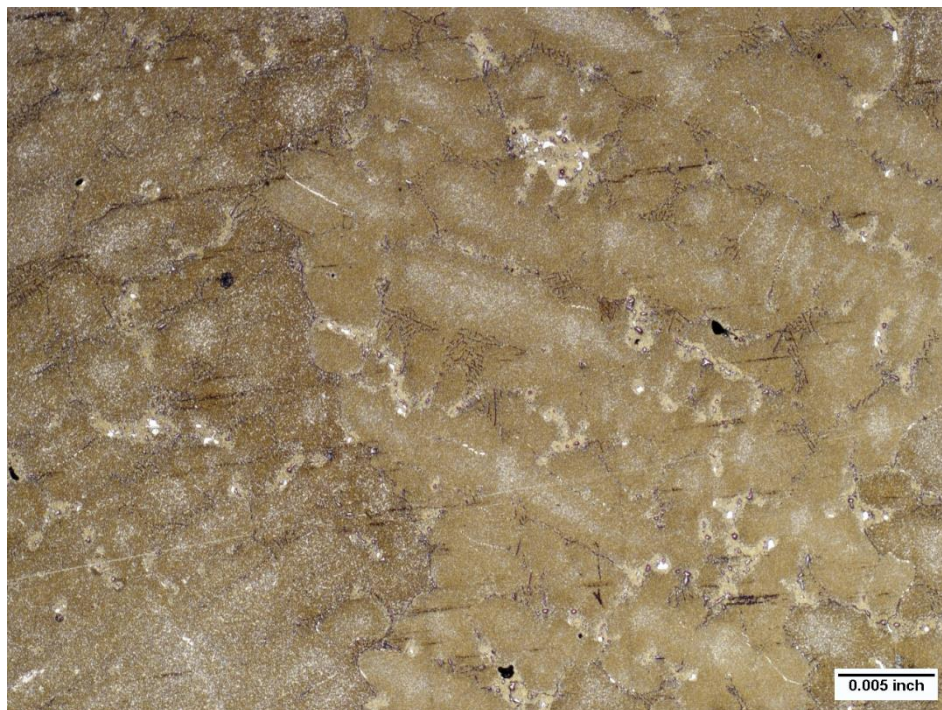


Original Magnification: 100x



Original Magnification: 500x

Figure 38. Representative microstructure in the rim of the wheel on cross-section LE4. Etchant: MT.

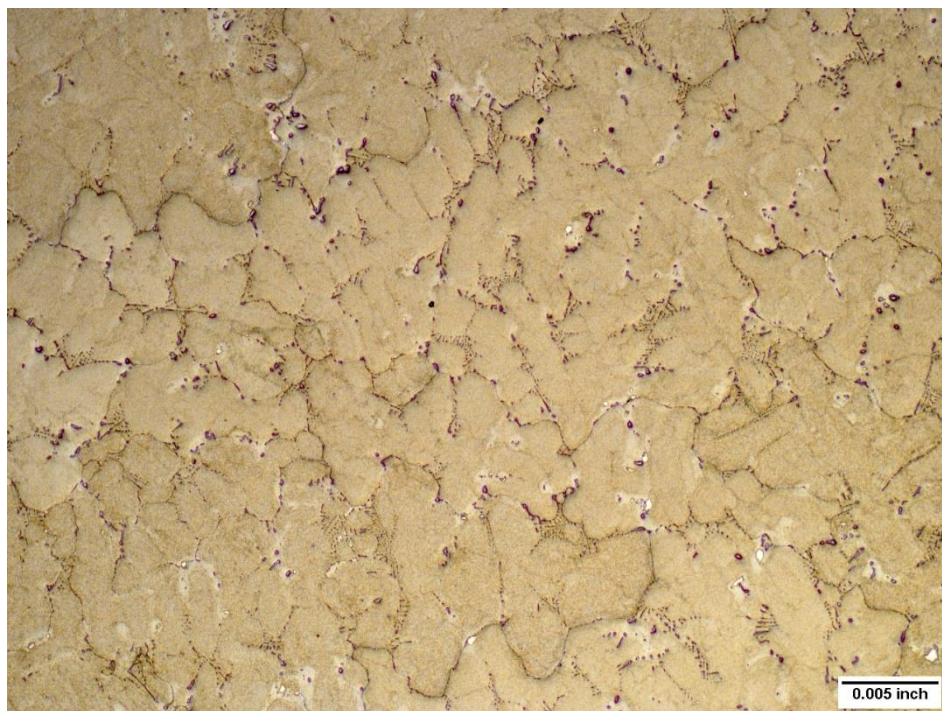


Original Magnification: 100x

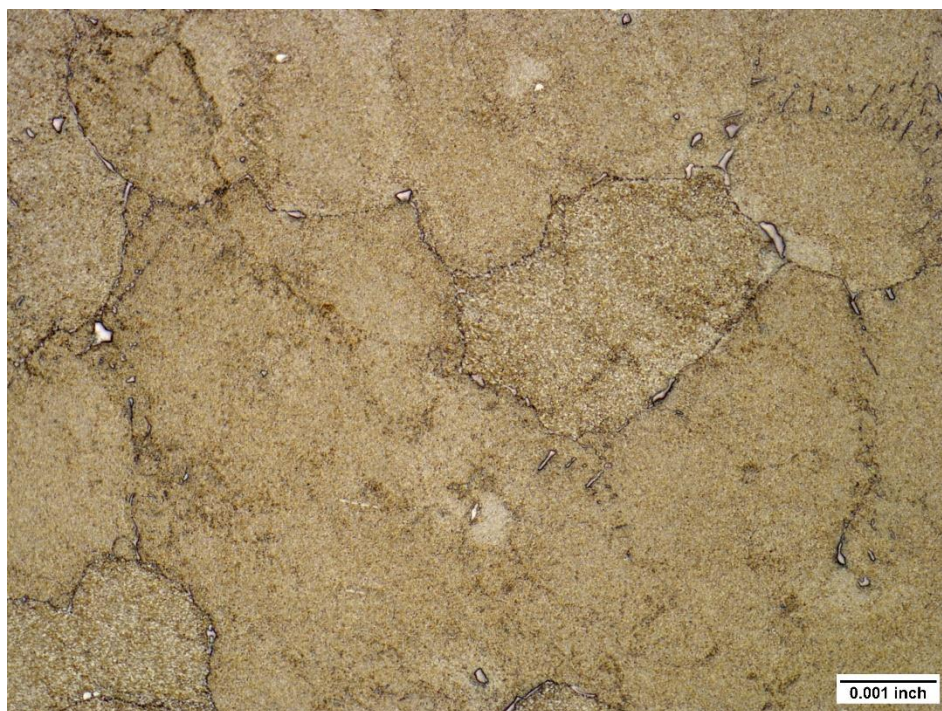


Original Magnification: 500x

Figure 39. Representative microstructure in the root of the blade on cross-section LE4. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 40. Representative microstructure in the lighter etching thermally distressed area inboard of the fracture on cross-section LE4. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 41. Representative microstructure near the fracture on cross-section LE4. Etchant: MT.

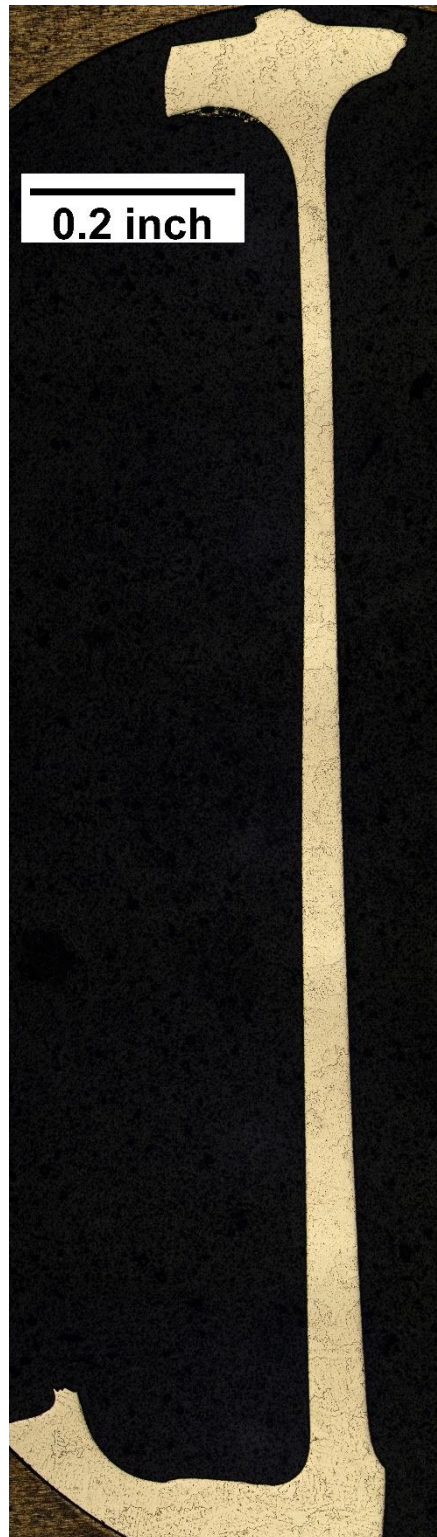


Figure 42. Overall view of longitudinal cross-section TE8 near the trailing edge on unfractured blade #8. There was no evidence of stress rupture void formation on the cross-section. Unetched.

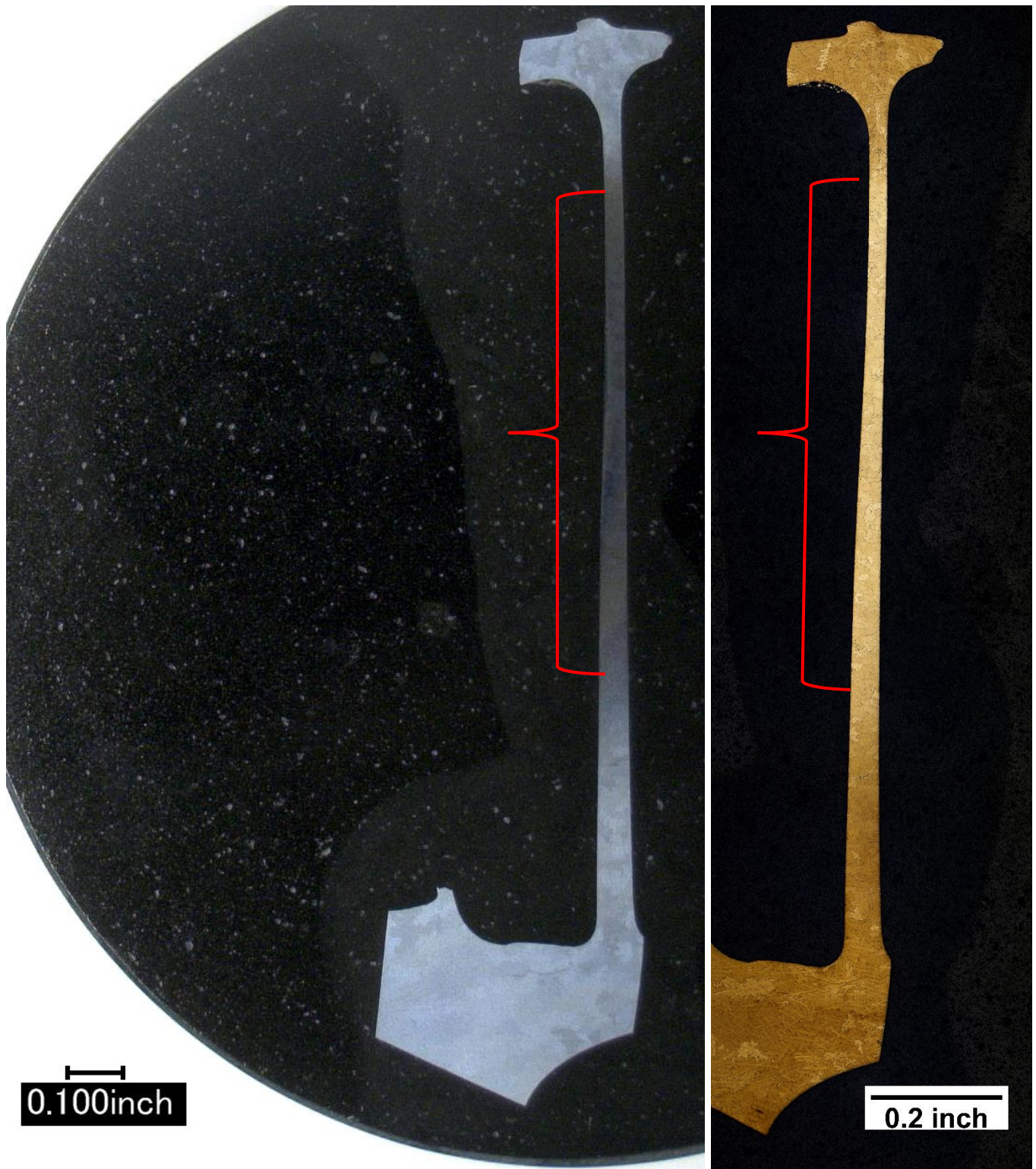


Figure 43. Optical (left) and metallographic (right) images showing cross-section TE8 in the etched condition. The red brace indicates the span exhibiting thermal distress to the microstructure. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 44. Representative microstructure in the rim of the wheel on cross-section TE8. Etchant: MT.

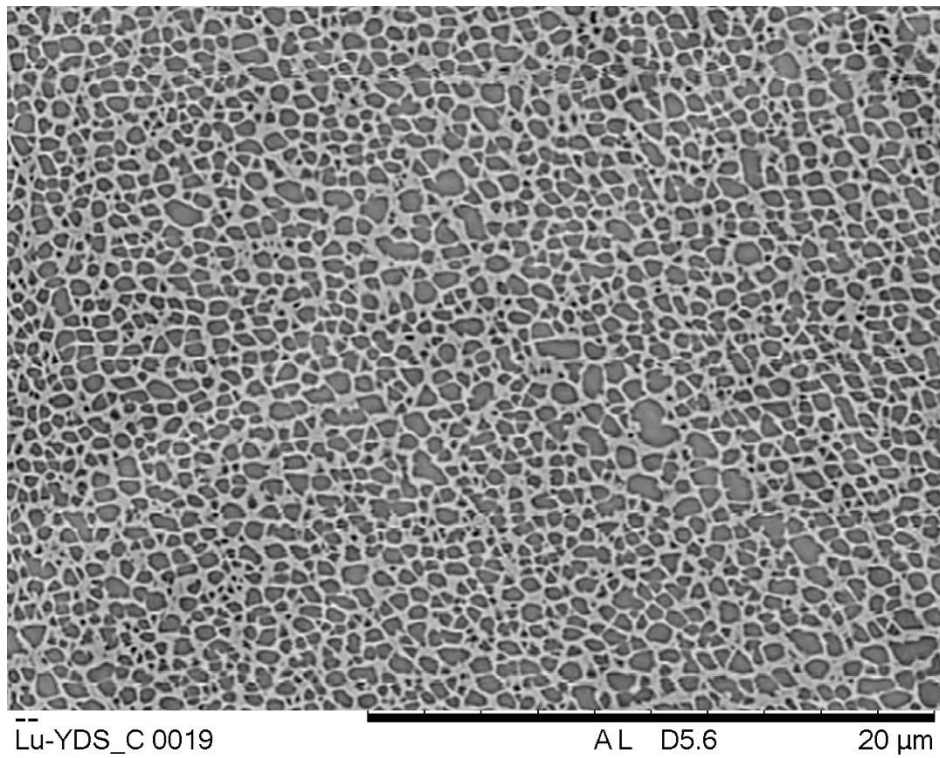
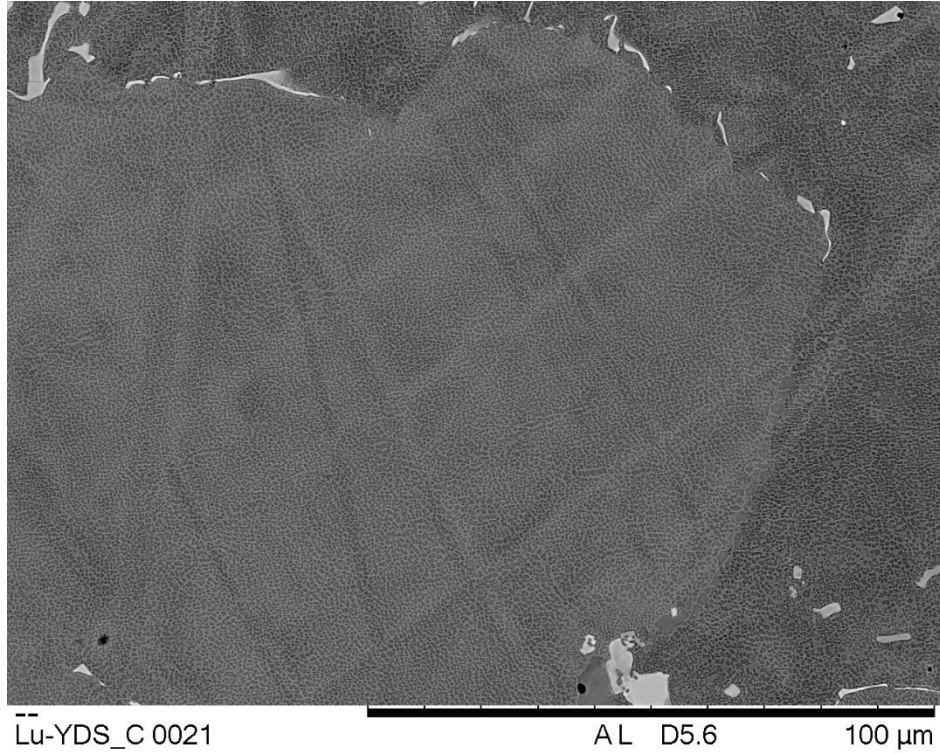


Figure 45. Backscattered electron SEM images showing the gamma prime structure in the rim of the wheel on cross-section TE8. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 46. Representative microstructure in the root of the blade on cross-section LE4. Etchant: MT.

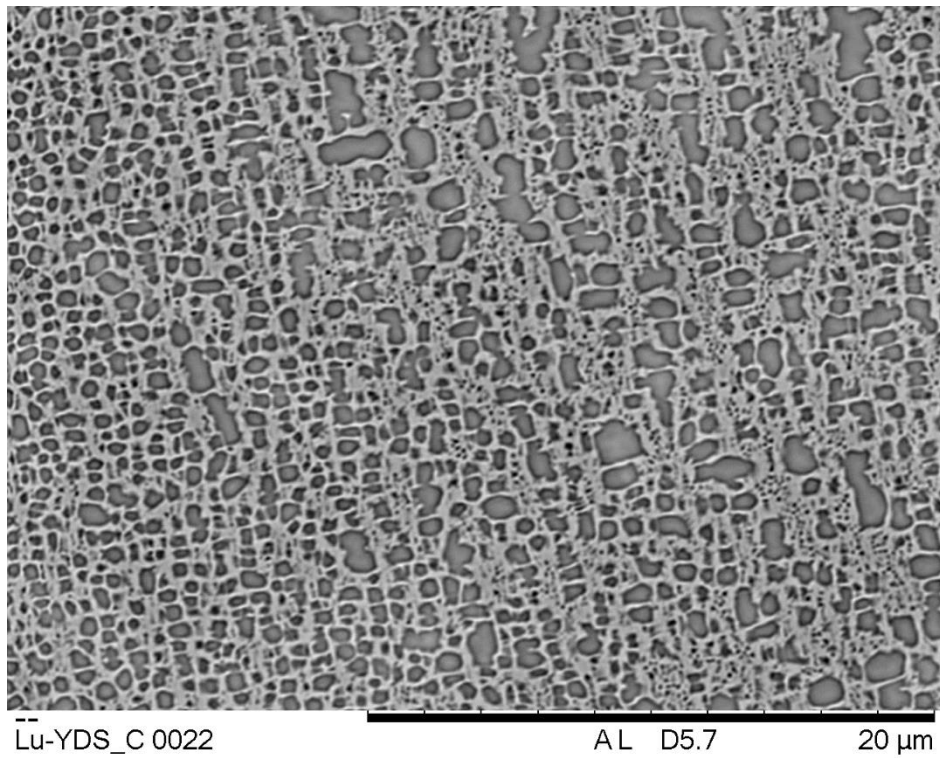
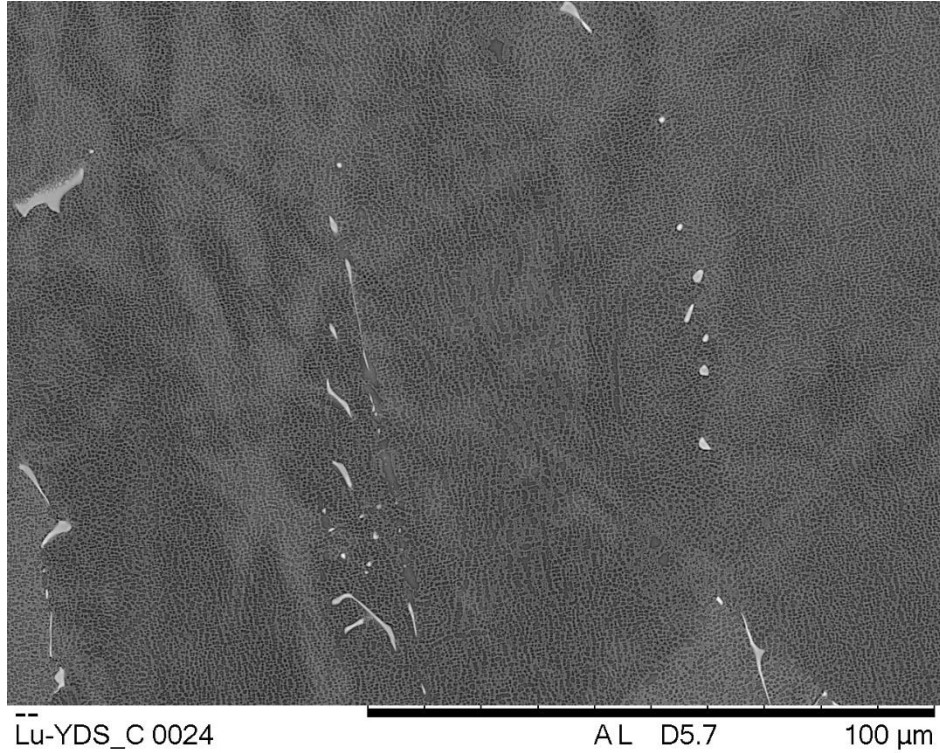
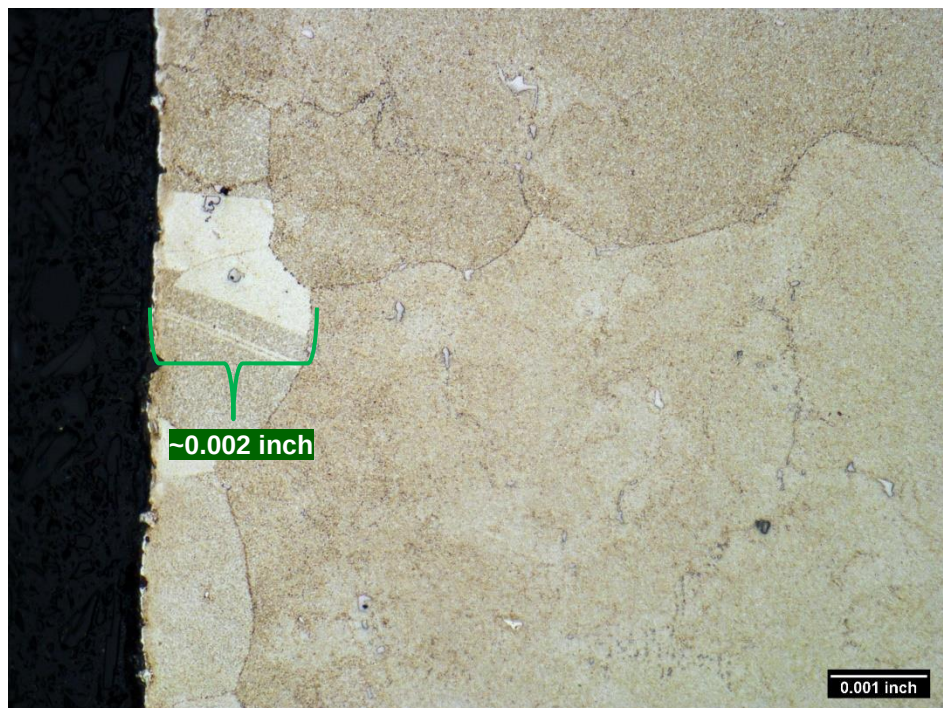


Figure 47. Backscattered electron SEM images showing the gamma prime structure in the root of the blade on cross-section TE8. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 48. Representative microstructure in the lighter etching thermally distressed area surrounding midspan on cross-section TE8. Representative re-crystallization at the airfoil surfaces in the thermally-distressed area indicated by the green brace. Etchant: MT.

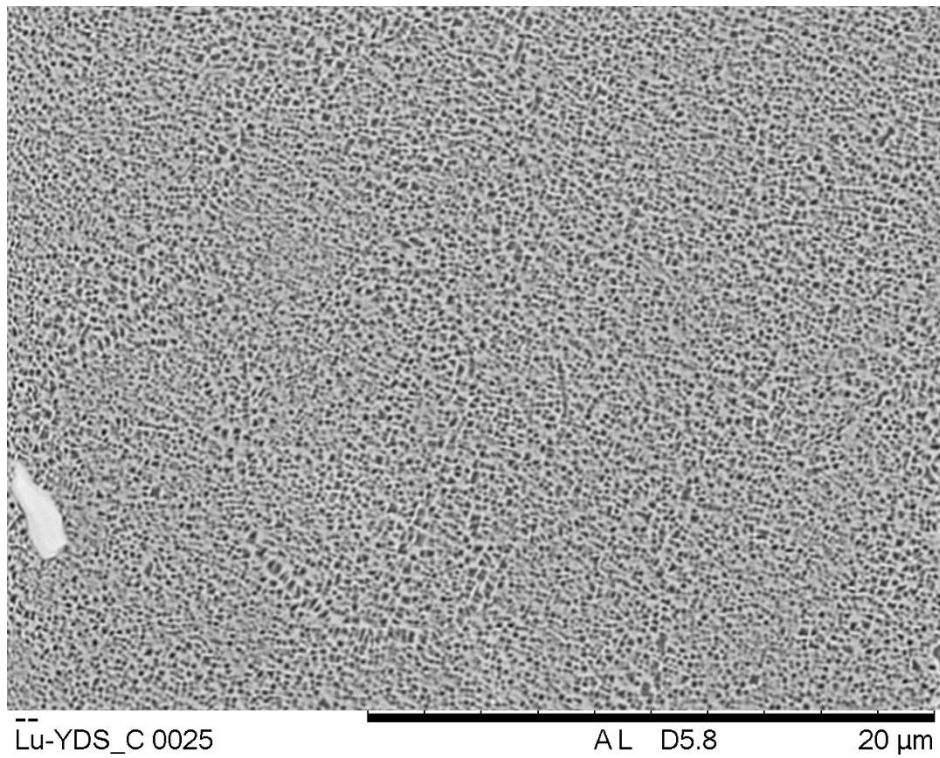
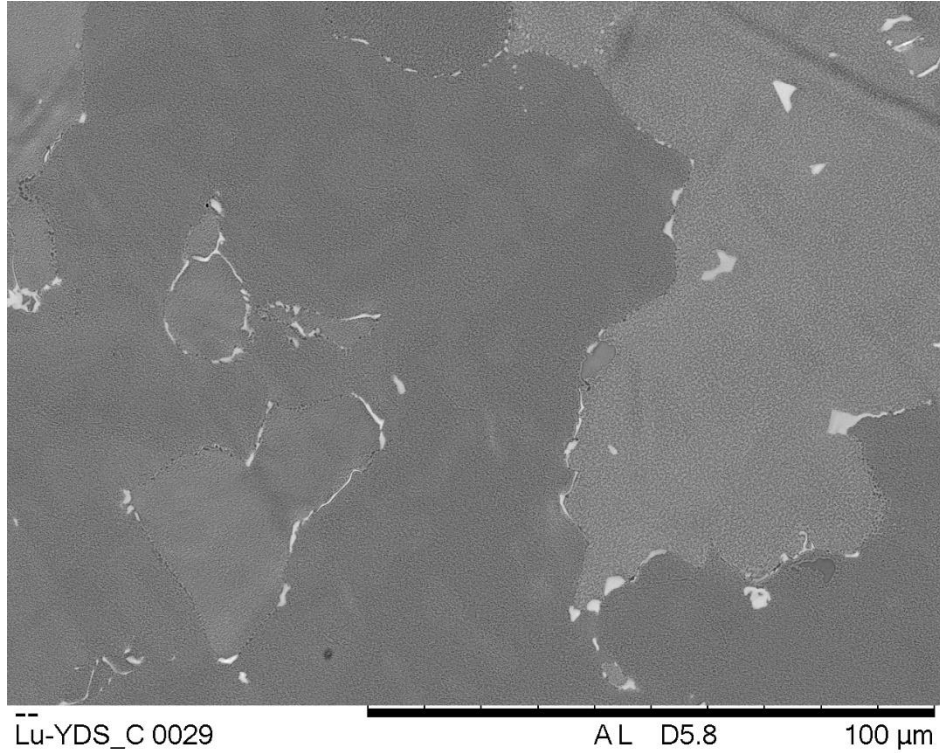


Figure 49. Backscattered electron SEM images showing the gamma prime structure in the thermally distressed midspan area on cross-section TE8. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 50. Representative microstructure in the shroud on cross-section TE8. Etchant: MT.

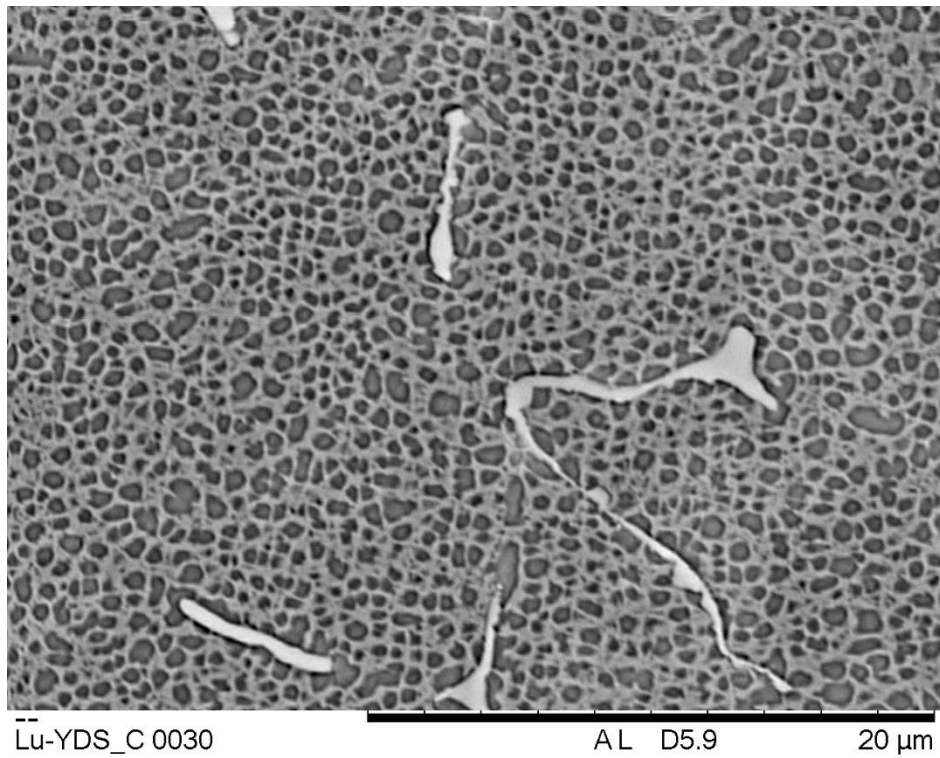
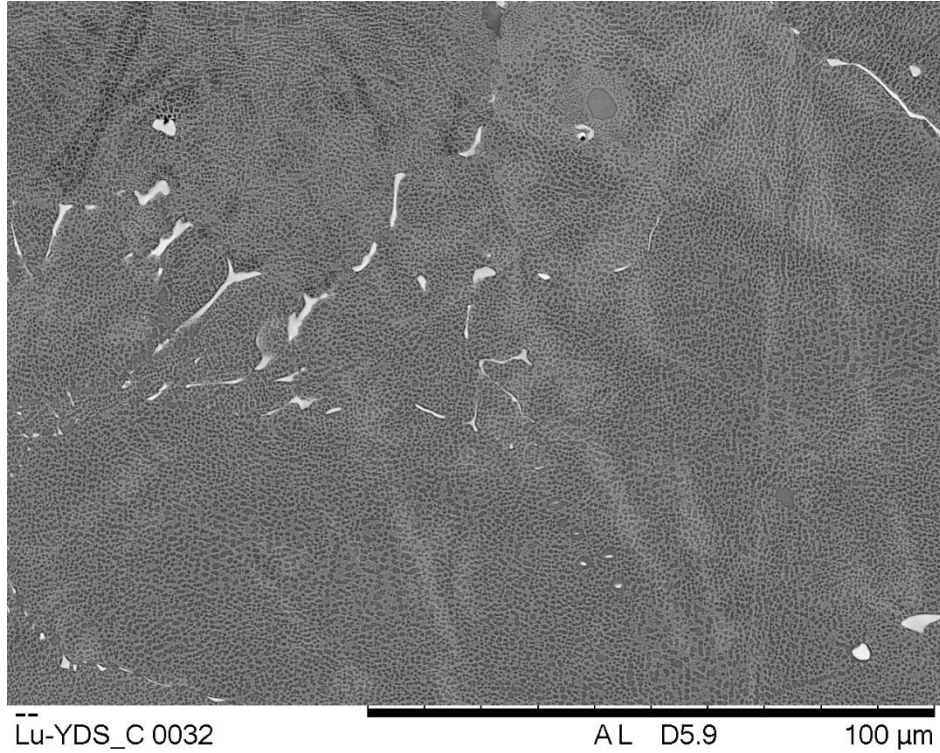


Figure 51. Backscattered electron SEM images showing the gamma prime structure in the shroud on cross-section TE8. Etchant: MT.

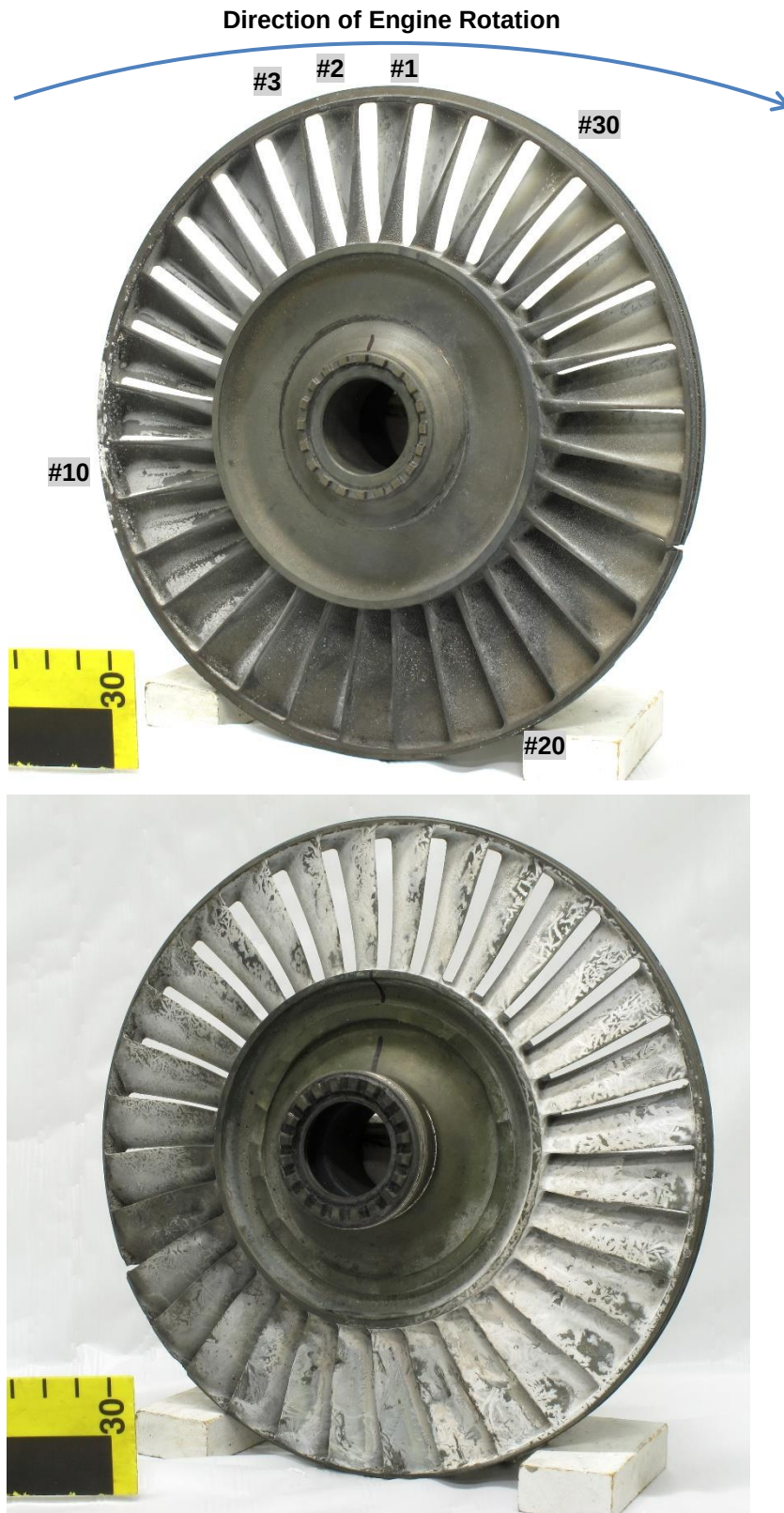


Figure 52. Leading edge (top) and trailing edge (bottom) side views showing the condition of the fourth stage turbine wheel after the PT rotor was disassembled. The blades were numbered starting with #1 for the blade immediately in line with the rotor match mark (black lines) and increasing opposite the direction of engine rotation. Divisions = cm.



Figure 53. Radial views showing the fourth stage turbine wheel shroud. The component was rotated 90° in the direction of engine rotation for this succession of images. The most severe rub damage to the shroud (red braces) spanned between blades #19 and #26, centered on a location approximately 90° in the direction of engine rotation from the center of the packet of missing airfoils. Divisions = cm.

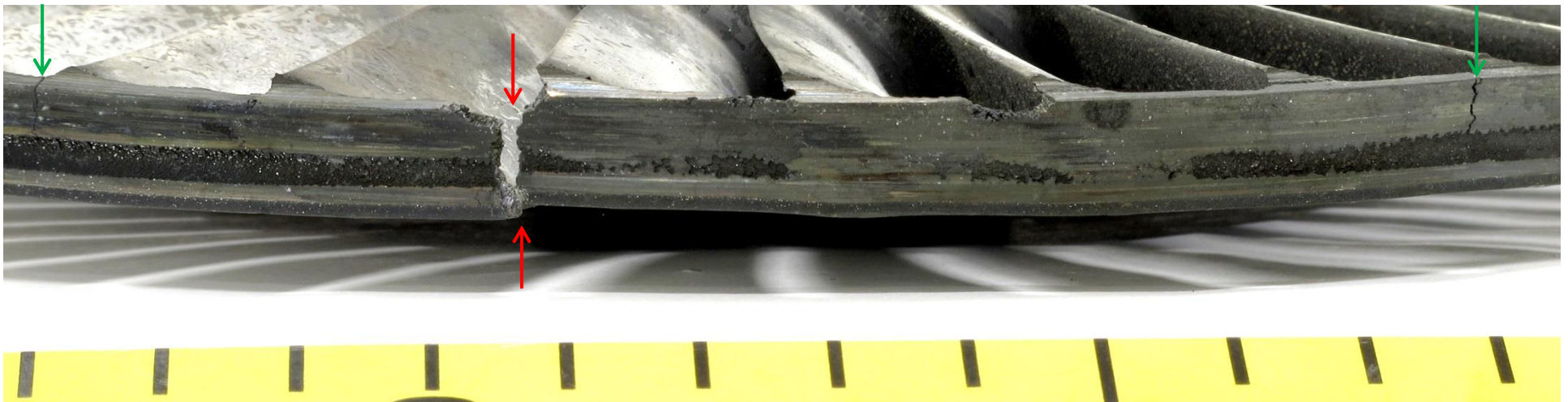


Figure 54. Detailed view showing the shroud where it was fractured between airfoils. The red arrows indicate a crack through the shroud and the green arrows indicate cracks that did not extend through the thickness of the shroud from the trailing edge side. Divisions = cm.



Figure 55. Detailed views showing the leading edges and pressure side surfaces of several representative fourth stage turbine airfoils. There was no impact damage to the leading edges and the pressure side surfaces exhibited intermittent deposited material consistent with re-deposited material from the rub damage to the shrouds and blade tracks in the power turbine. Top: Divisions = mm. Bottom: No scale provided.

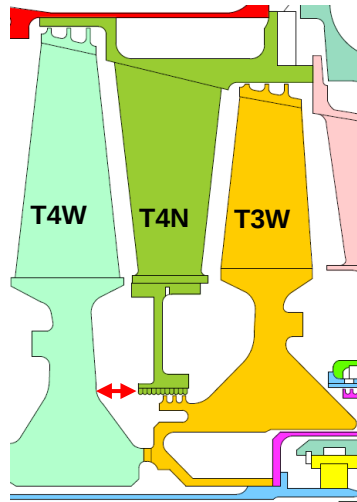


Figure 56. Detailed leading edge side view showing circumferential rub damage to the web near the transition to the thicker portion of the bore. The black temporary part mark above the curvic teeth was applied in the laboratory as a match mark after separating the PT rotor to reveal the leading edge side. The part markings are also shown. The inset image at top shows the corresponding rub locations on the fourth stage wheel and nozzle (red arrow; schematic for illustration purposes only). No scale provided.

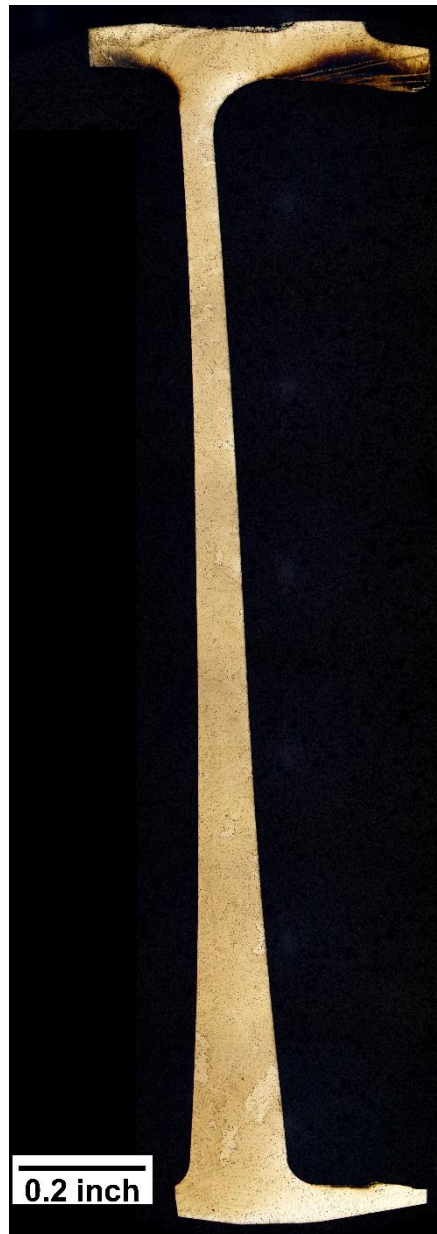
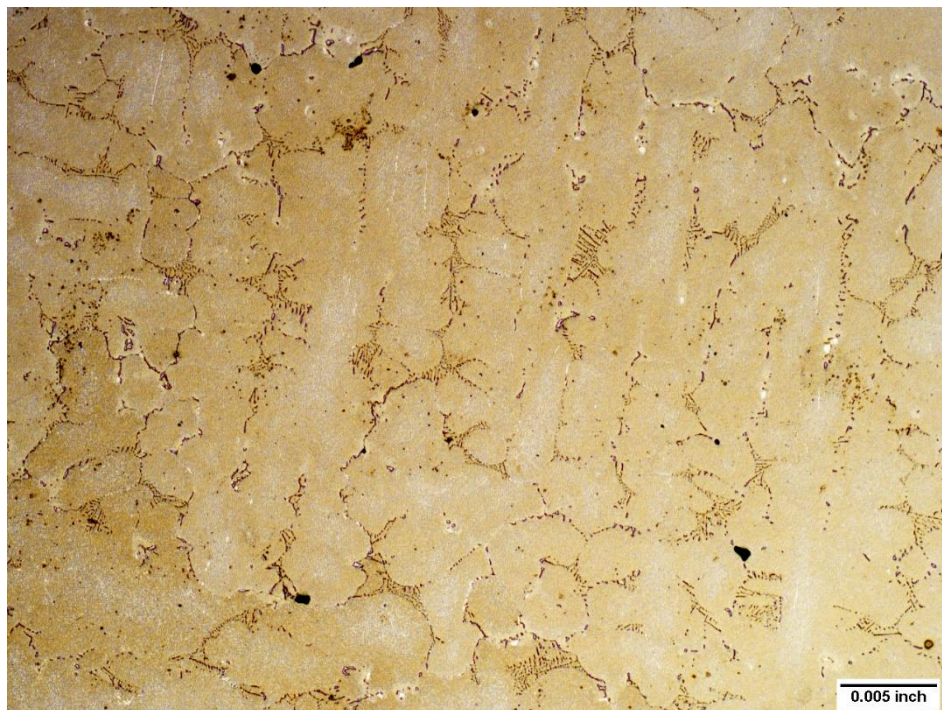


Figure 57. Overall view of the longitudinal cross-section 4LE21 near the leading edge on fourth stage turbine blade #21. The dark brown areas in the shroud were overetched and the lighter-etching area in the rim of the wheel was underetched and are not consistent with thermal distress to the microstructure. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 58. Representative microstructure in the root of the blade on cross-section 4LE21. Etchant: MT.

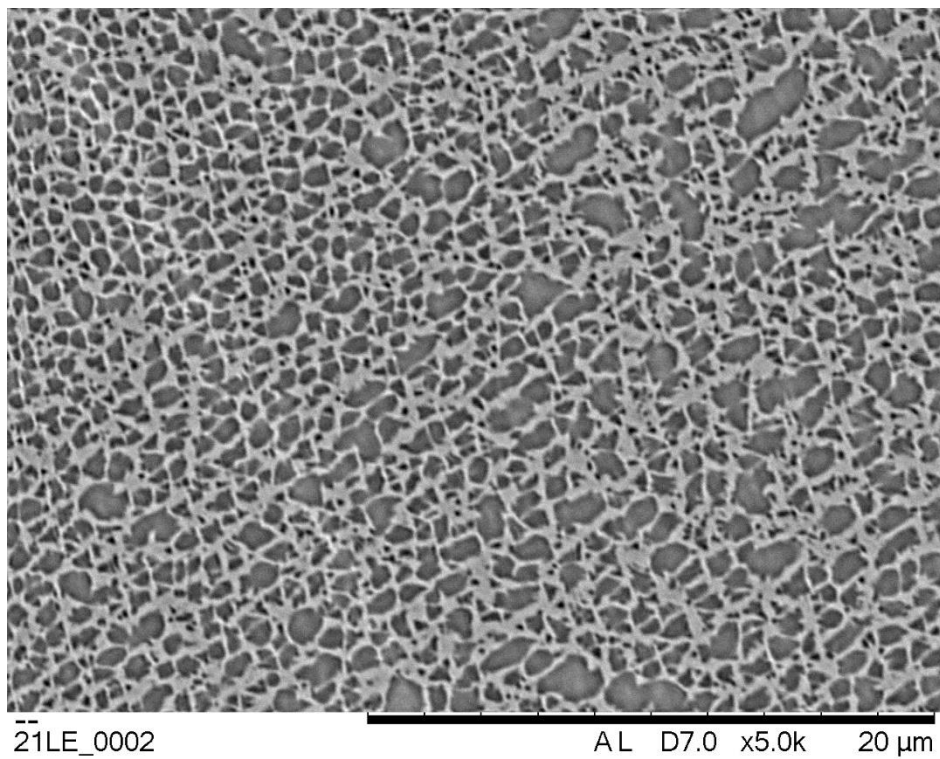
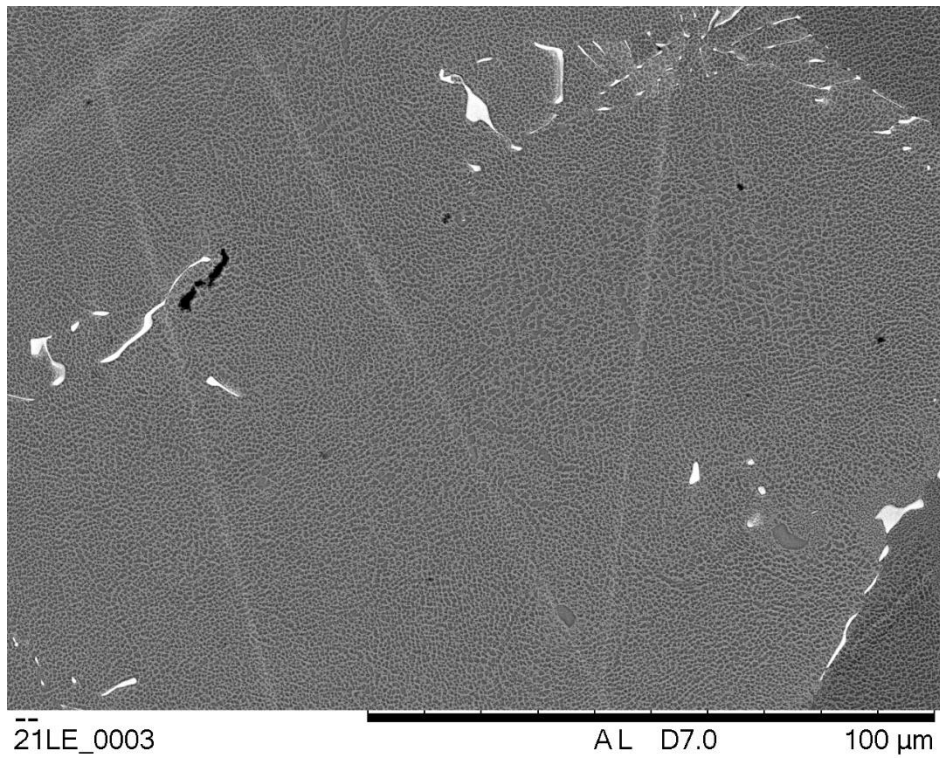
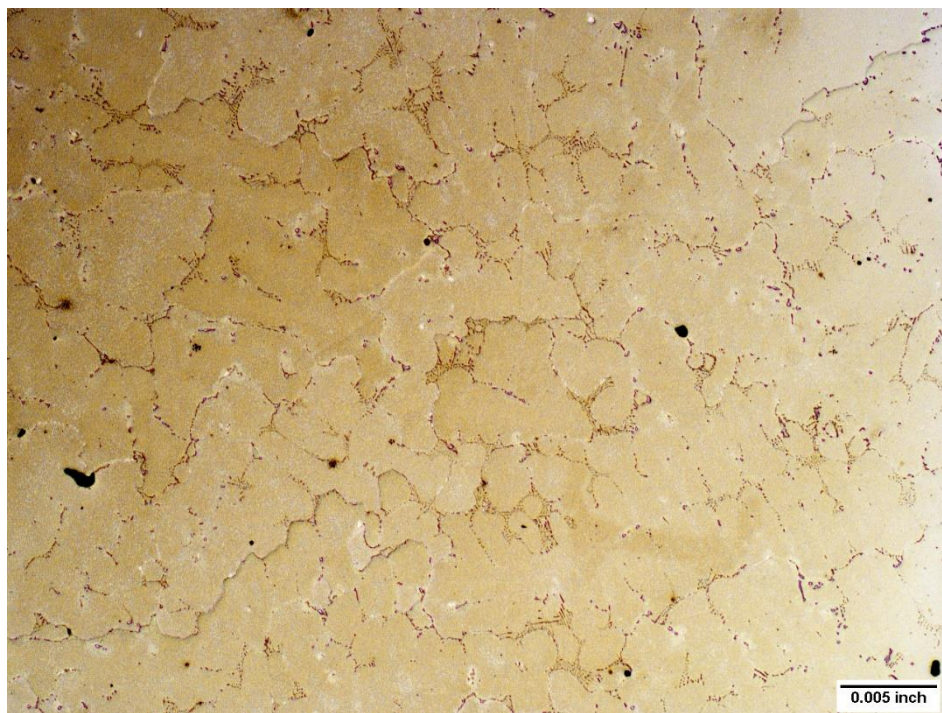


Figure 59. Backscattered electron SEM images showing the gamma prime structure in the root of the blade on cross-section 4LE21. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 60. Representative microstructure near midspan on cross-section 4LE21. Etchant: MT.

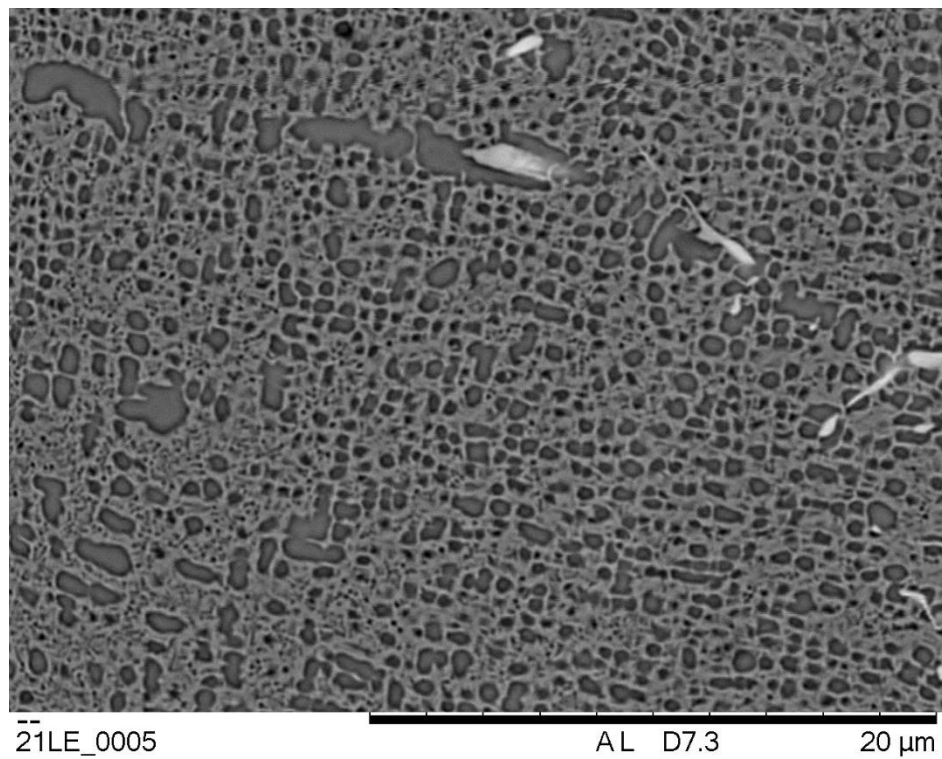
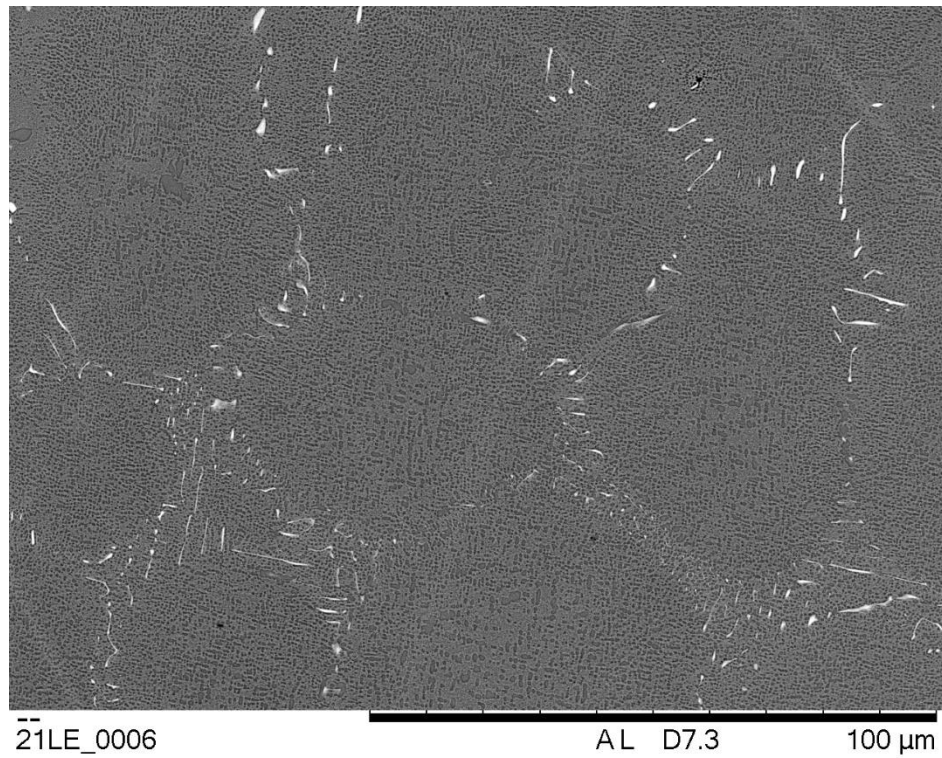
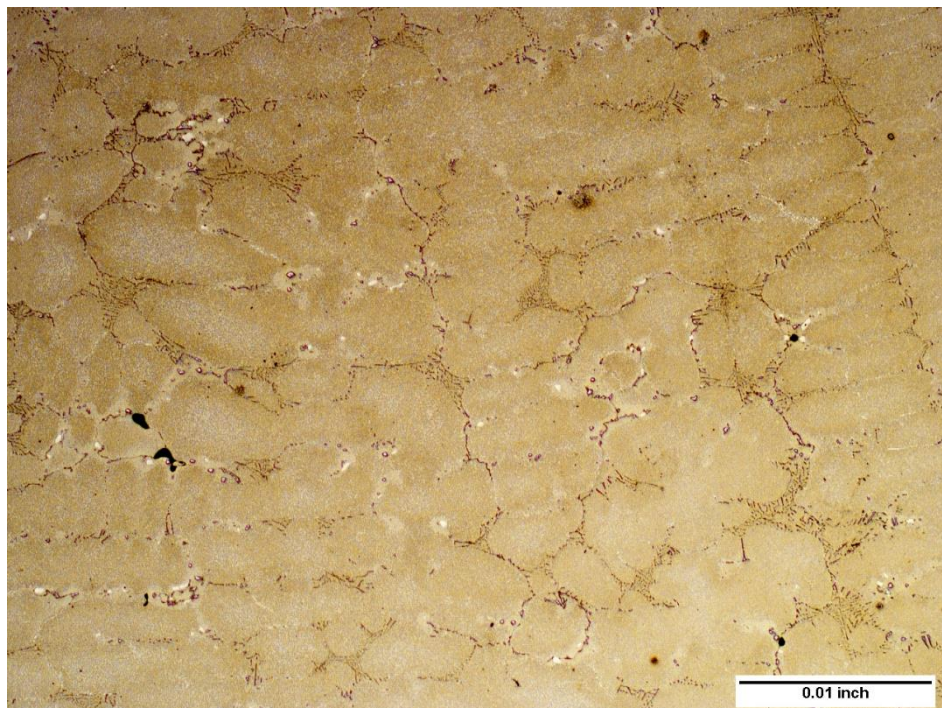


Figure 61. Backscattered electron SEM images showing the gamma prime structure at midspan on cross-section 4LE21. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 62. Representative microstructure in the shroud on cross-section 4LE21. Etchant: MT.

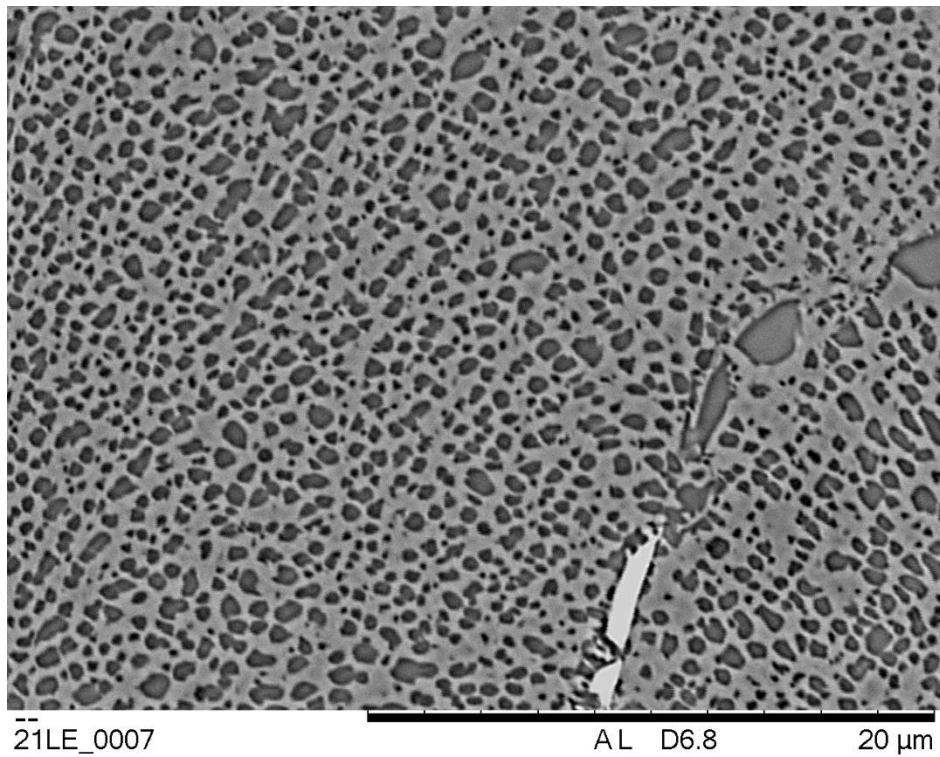
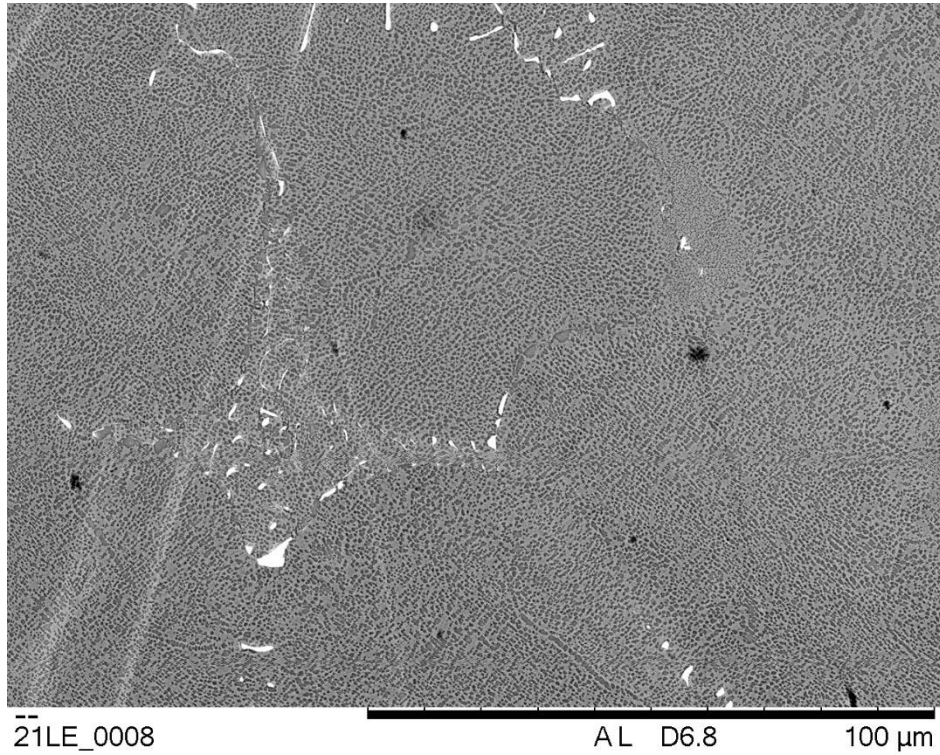


Figure 63. Backscattered electron SEM images showing the gamma prime structure in the shroud on cross-section 4LE21. Etchant: MT.

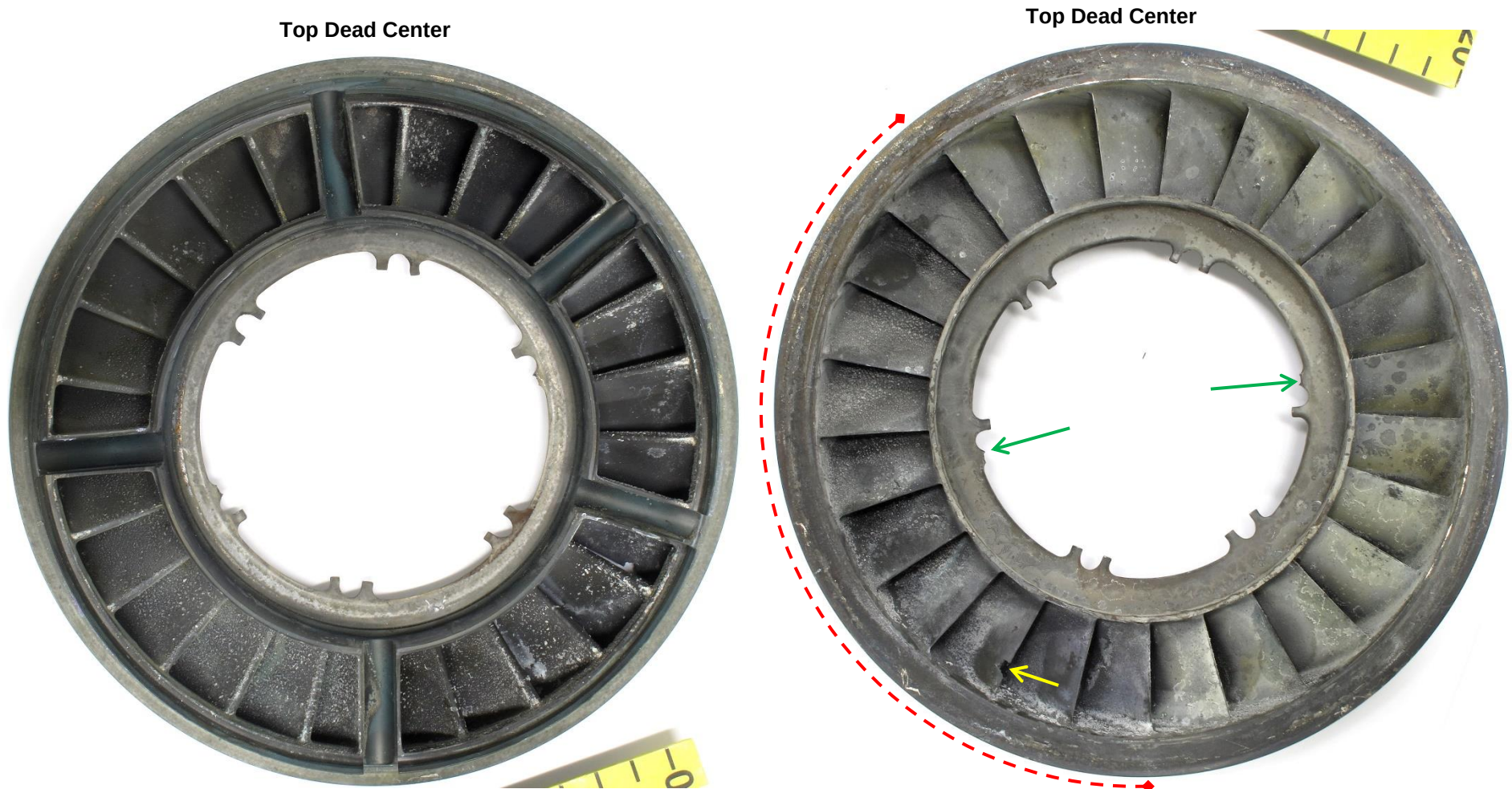


Figure 64. Leading edge side (left) and trailing edge side (right) views of the third stage turbine nozzle assembly. On the trailing edge side a span of approximately 10 vane airfoils exhibited darker discoloration on the suction side than the rest of the airfoils (along red dashed line) consistent with oil staining. One airfoil was missing material from the trailing edge consistent with impact damage (yellow arrow). Two of the diaphragm tabs were fractured (green arrows). Divisions = cm.

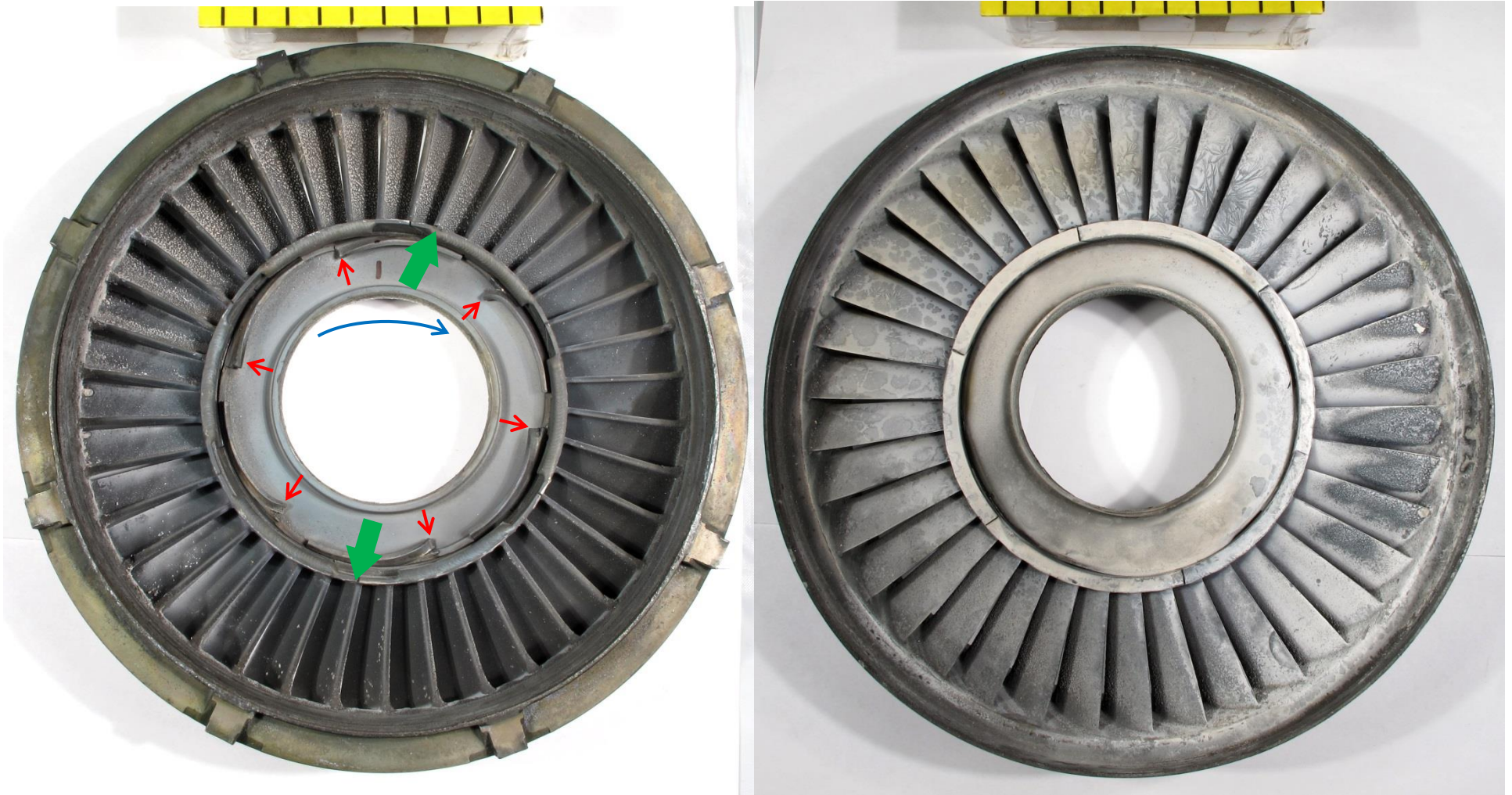


Figure 65. Leading edge side (left) and trailing edge side (right) views of the fourth stage turbine nozzle assembly. The airfoils were covered in a powdery white material consistent with fire retardant. Two airfoils were fractured at the trailing edge near the inner band (green arrows). The following side (relative to the direction of engine rotation, blue arrow) of the hub castellations were fractured and deformed inboard (red arrows). The black temporary part mark was applied in the laboratory for reference to the rotor match mark location at the time of disassembly. Divisions = cm.

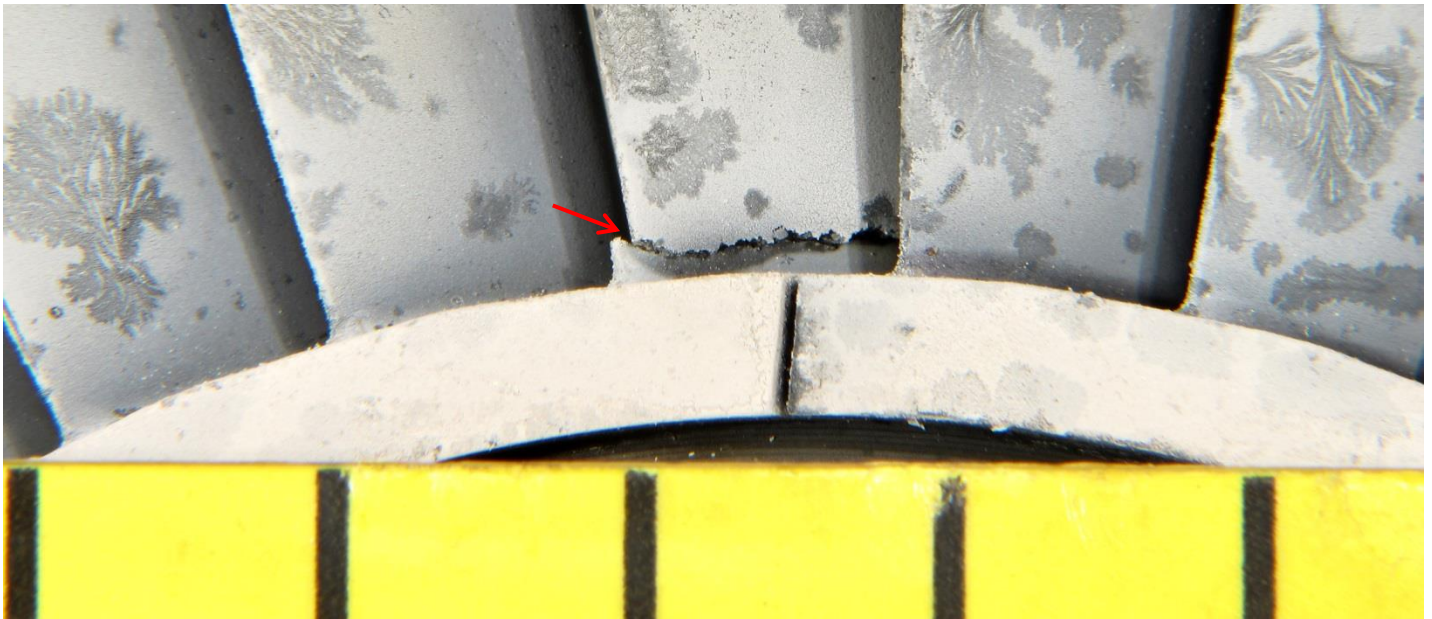
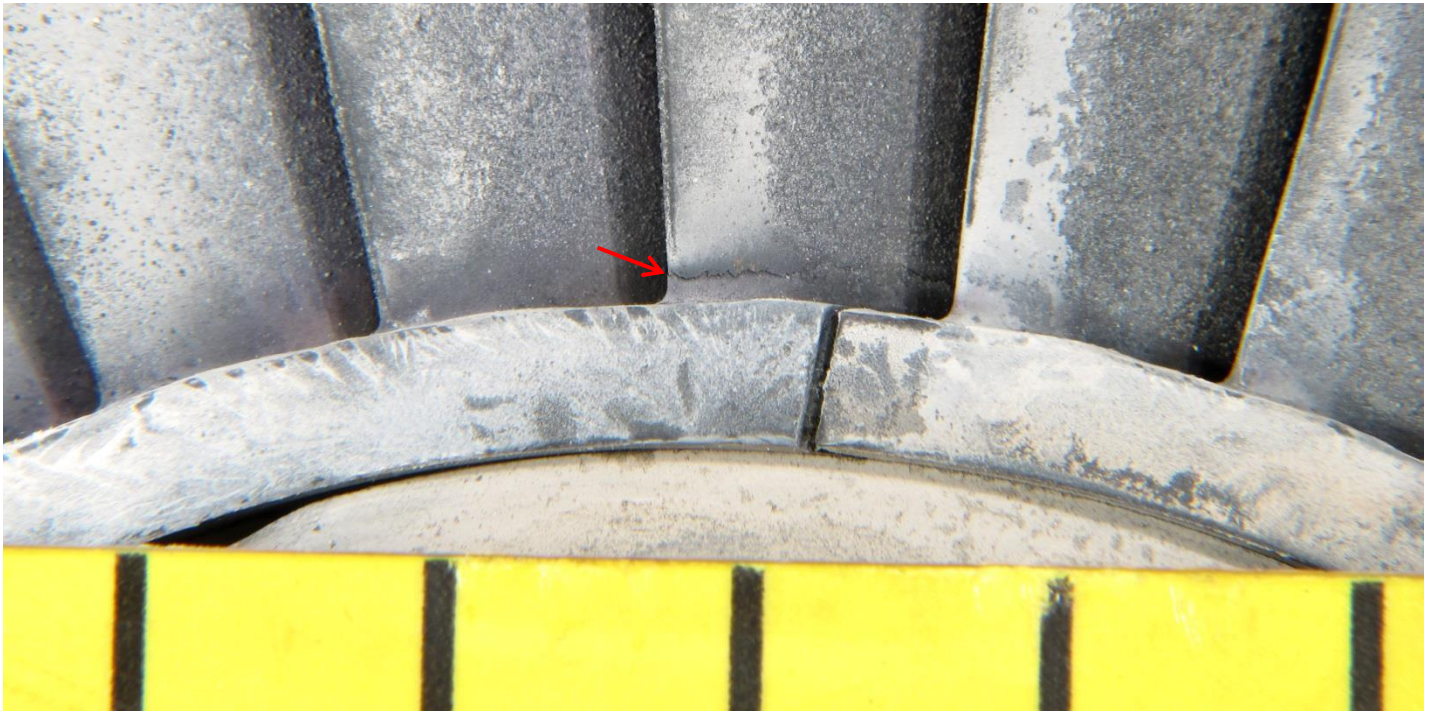


Figure 66. Two airfoils, each the first in its respective packet relative to the direction of engine rotation (blue arrow), exhibiting fractures at the trailing edge near the inner band (red arrows). The airfoil in the bottom image was fractured along the entire chord length and was revealed in the laboratory by cutting the airfoil from the outer band. Divisions = cm.

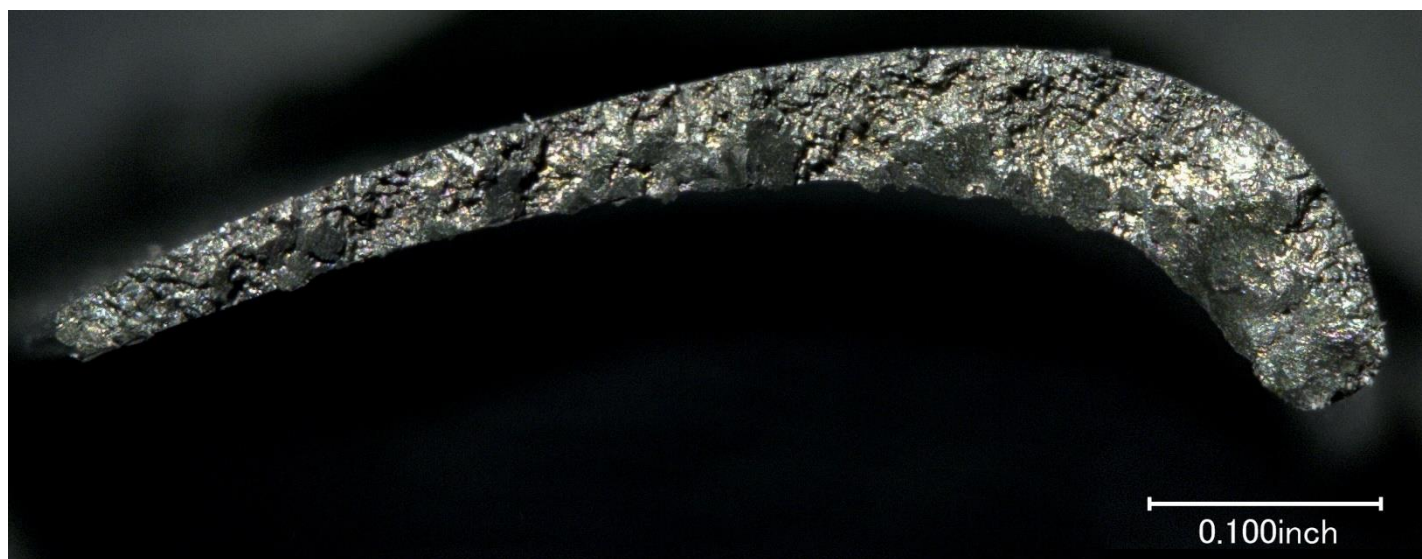


Figure 67. Detailed view showing the revealed fracture surface on the stage 4 vane airfoil that was fractured along the entire chord length.

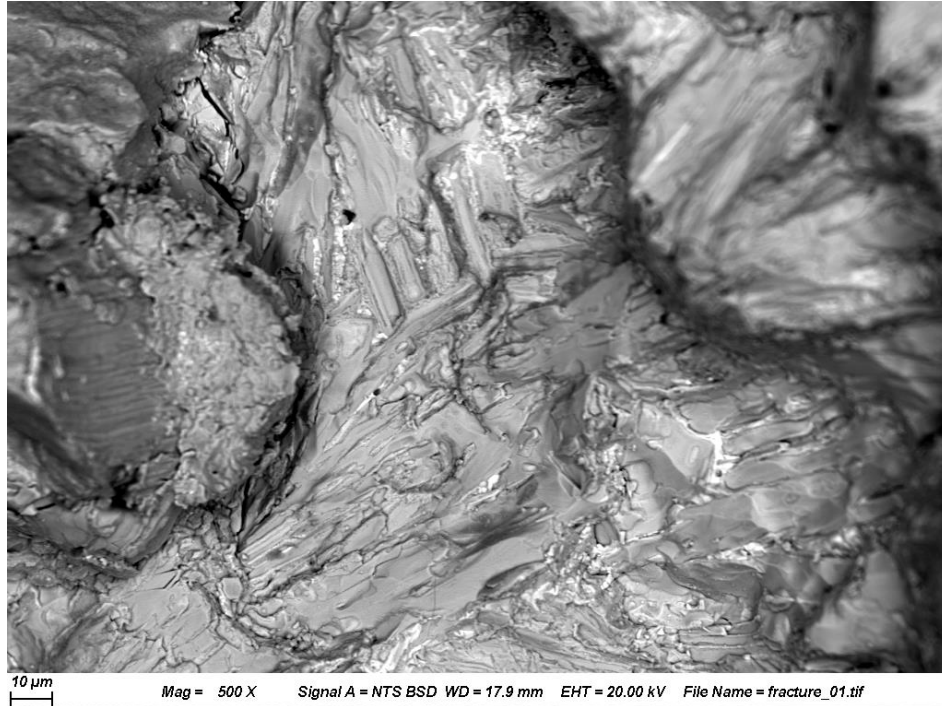
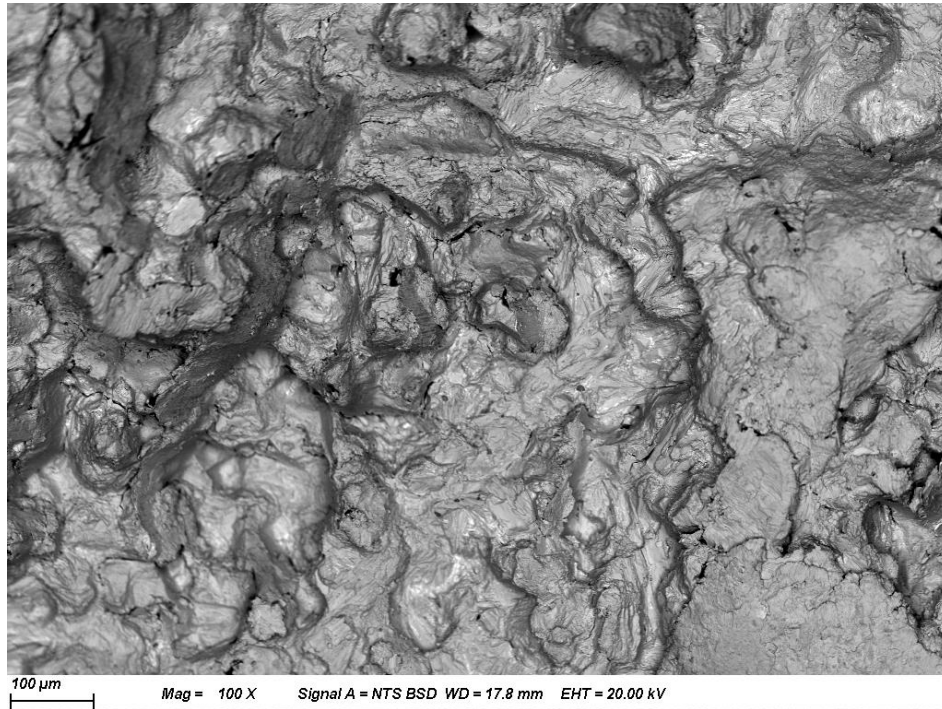


Figure 68. Backscattered electron SEM images showing representative interdendritic fracture features found on the fractured fourth stage turbine nozzle airfoil.



Figure 69. Detailed views showing the third stage turbine blade track in the fourth stage turbine nozzle. The nozzle was rotated 90° clockwise (ALF) for this succession of images. The blade track exhibited rub damage and intermittent transferred material around the entire circumference. Divisions = cm.



Figure 70. Detailed views showing the third stage turbine blade track in the fourth stage turbine nozzle. The nozzle was rotated 90° clockwise (ALF) for this succession of images. The blade track exhibited rub damage and intermittent transferred material around the entire circumference. Divisions = cm.

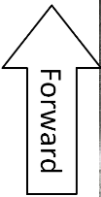


Figure 71. Detailed views showing the fourth stage turbine blade track in the fourth stage turbine nozzle. The nozzle was rotated 90° counterclockwise (FLA) for this succession of images. The blade track exhibited rub damage around the entire circumference. Divisions = cm.



Figure 72. Detailed views showing the fourth stage turbine blade track in the fourth stage turbine nozzle. The nozzle was rotated 90° counterclockwise (FLA) for this succession of images. The blade track exhibited rub damage and intermittent transferred material around the entire circumference. Divisions = cm.



Figure 73. Detailed views showing the inner diameter abradsable seal surface in the fourth stage turbine nozzle. The seal exhibited smearing damage on both the leading and trailing edge sides (red braces). The nozzle was rotated 90° counterclockwise (FLA) for this succession of images. No scale provided.

← Direction of Engine Rotation

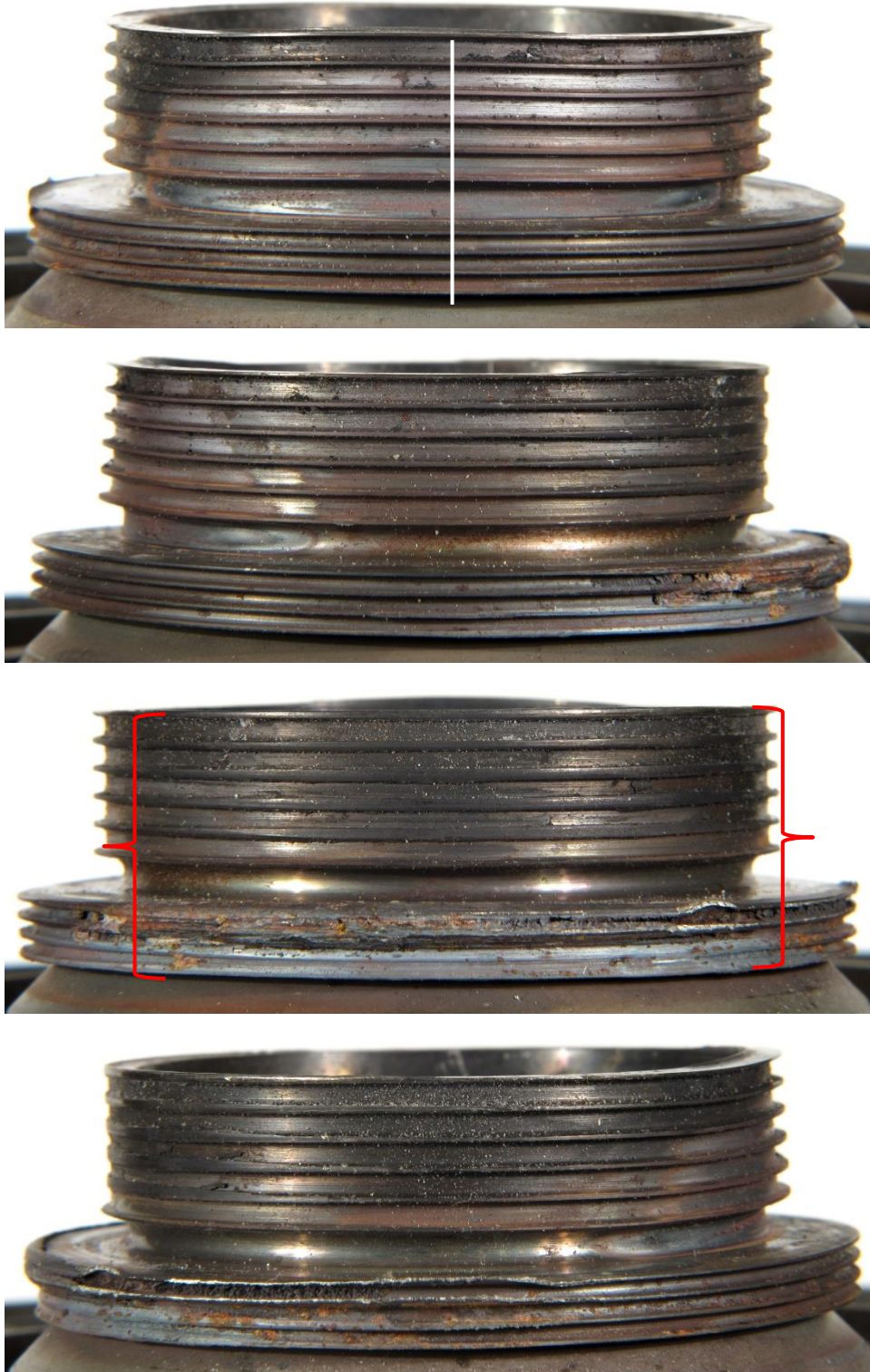


Figure 74. Radial views showing the power turbine labyrinth seal before the PT rotor was disassembled. The white line at top indicates the location of the match mark for the rotor. The rotor was rotated 90° in the direction of engine rotation for this succession of images. The most severe rub damage to the labyrinth knife seals (red braces) was located approximately 180° from the match mark. No scale provided.



Figure 75. PMA part markings found on the power turbine labyrinth seal.

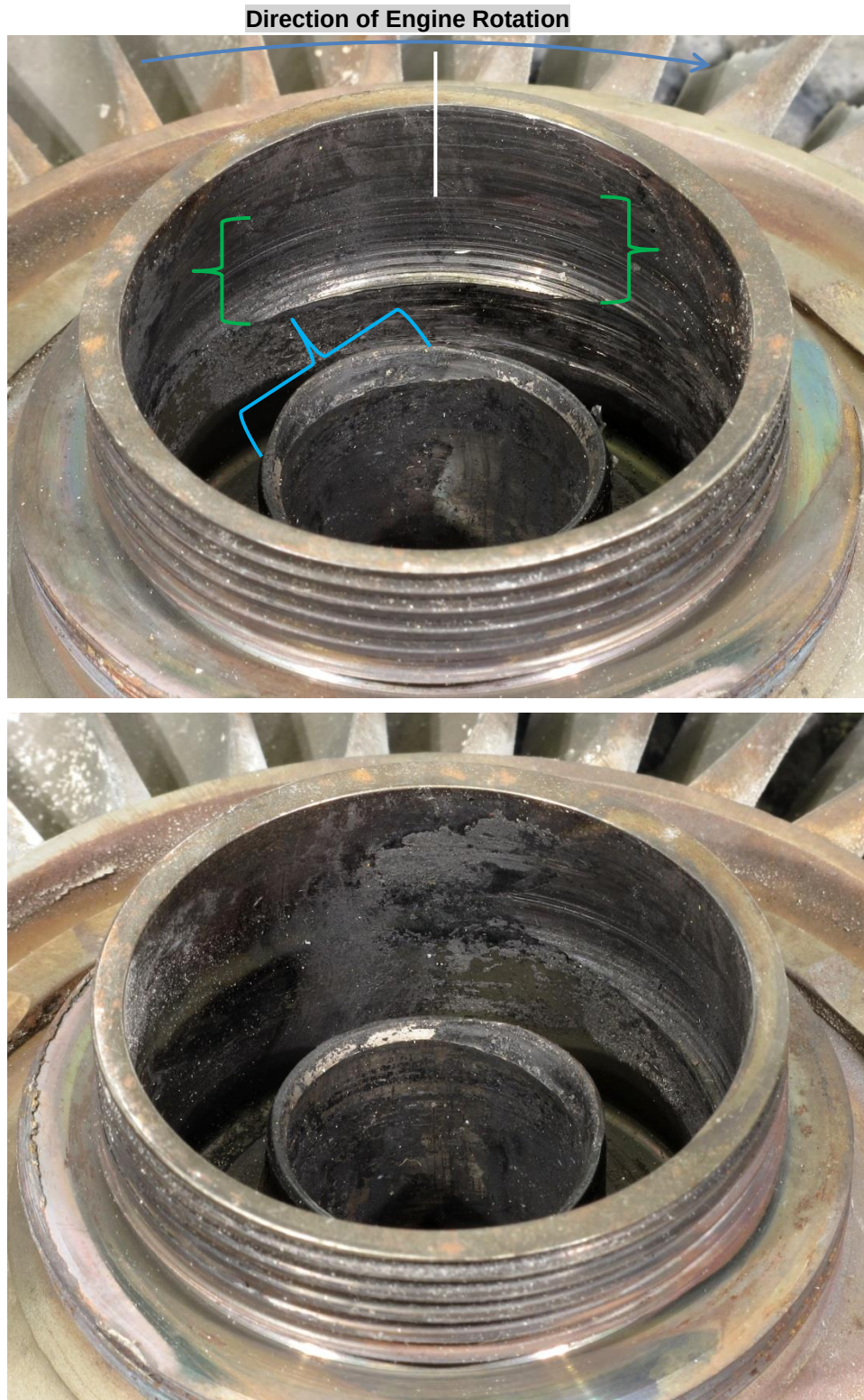


Figure 76. Detailed views showing the aft end of the power turbine inner shaft inside the power turbine labyrinth seal before the PT rotor was disassembled. The white line at top indicates the location of the match mark for the rotor. The rotor was rotated 90° in the direction of engine rotation for this succession of images. The PTIS was distorted outboard (blue brace) and the inner diameter of the labyrinth seal exhibited rub damage (green braces) near the location of the match mark. No scale provided.



Figure 77. Detailed views showing the aft end of the power turbine inner shaft inside the power turbine labyrinth seal before the PT rotor was disassembled. The rotor was rotated 90° in the direction of engine rotation for this succession of images. No scale provided.



Figure 78. Detailed views showing the inner diameter of the PTIS at the outboard deformation (top) and opposite the deformation (bottom). The surface at the deformation was smeared and discolored. No scale provided.



Figure 79. Detailed view of the No. 6 bearing inner raceway on the power turbine inner shaft after the PT rotor was disassembled. The raceway exhibited a groove on one side that corresponded to the width of the bearing rollers (red brace). The groove was located opposite the outboard deformation of the shaft (green arrow) shown in the previous figures. No scale provided.

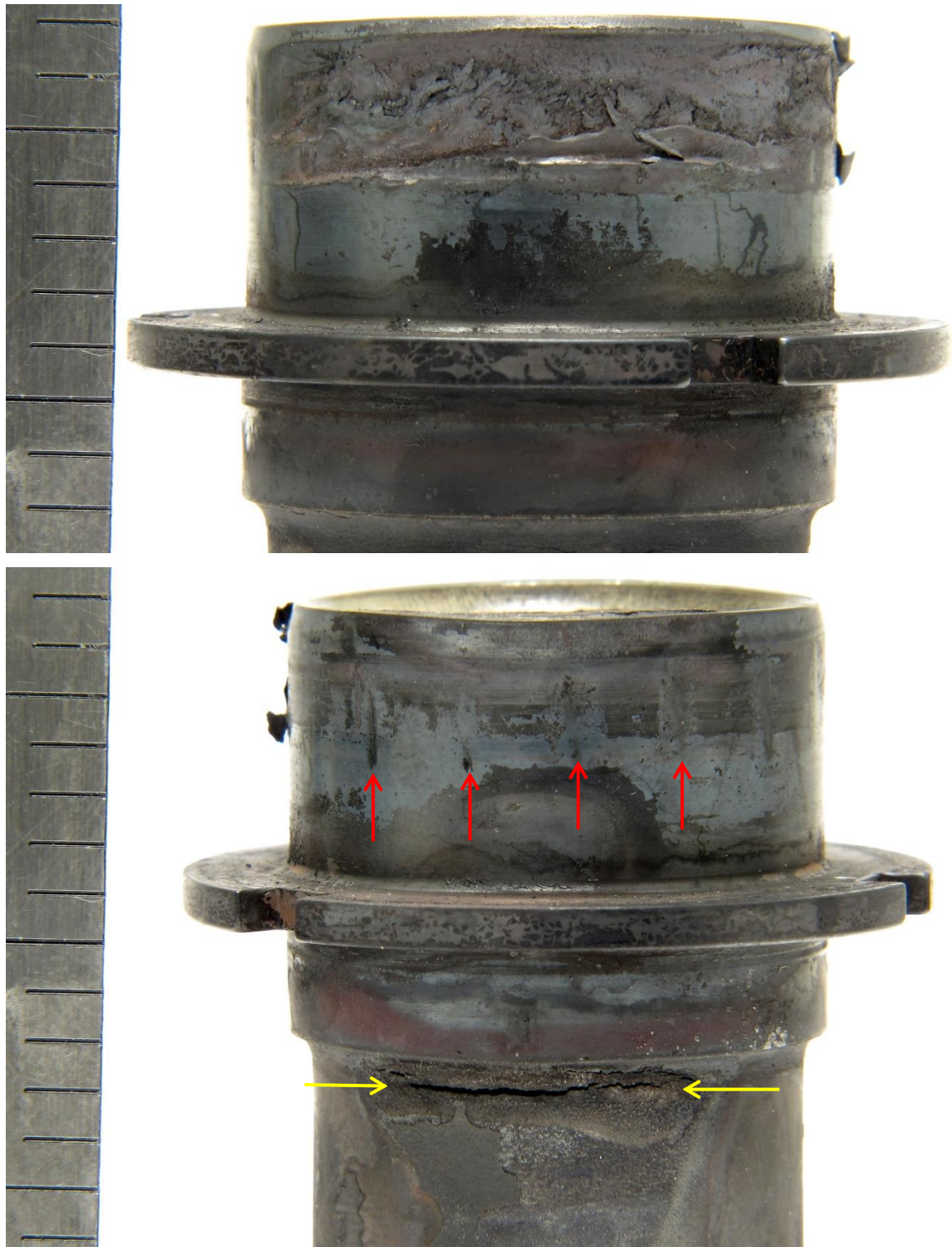


Figure 80. Detailed views showing the No. 6 bearing raceway surface in the groove (top) and opposite the groove (bottom). Roller-spaced black axial stains were present on the raceway away from the groove (red arrows), and the shaft was fractured (between yellow arrows) forward of the raceway located approximately in-line with the outboard deformation of the aft end of the shaft. Divisions = 0.1 inch.



Figure 81. Detailed views showing the power turbine outer shaft before the PT rotor was separated. The black line shows the location of the match mark for the PT rotor. The rotor was rotated 90° in the direction of engine rotation for this succession of images. Rub damage on the outer diameter of the shaft (red braces) spanned approximately 300° around the circumference, opposite the direction of engine rotation.



Figure 82. Detailed views showing the power turbine outer shaft before the PT rotor was separated. The rotor was rotated 90° in the direction of engine rotation for this succession of images. Rub damage on the outer diameter of the shaft (red braces) spanned approximately 300° around the circumference, opposite the direction of engine rotation. The yellow brace marks the span of the shaft that did not exhibit rub damage through the coating thickness. Divisions = cm.

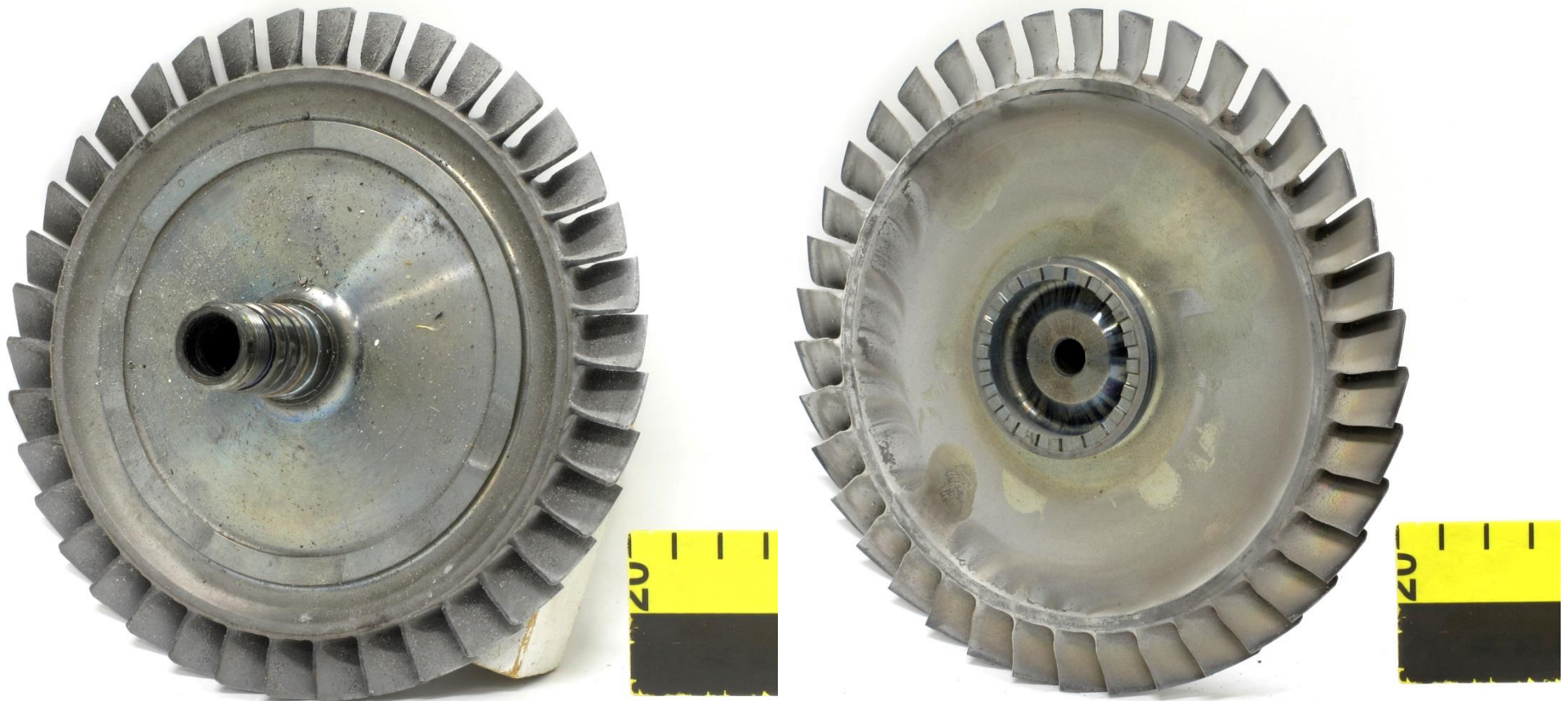


Figure 83. Leading edge (left) and trailing edge (right) side views showing the first stage turbine wheel. The airfoils exhibited white powdery deposits and there was debris on the leading edge side web. Divisions = cm.



Figure 84. Leading edge side view showing representative leading edge tip erosion (red braces) on the first stage turbine blades. Divisions = mm.

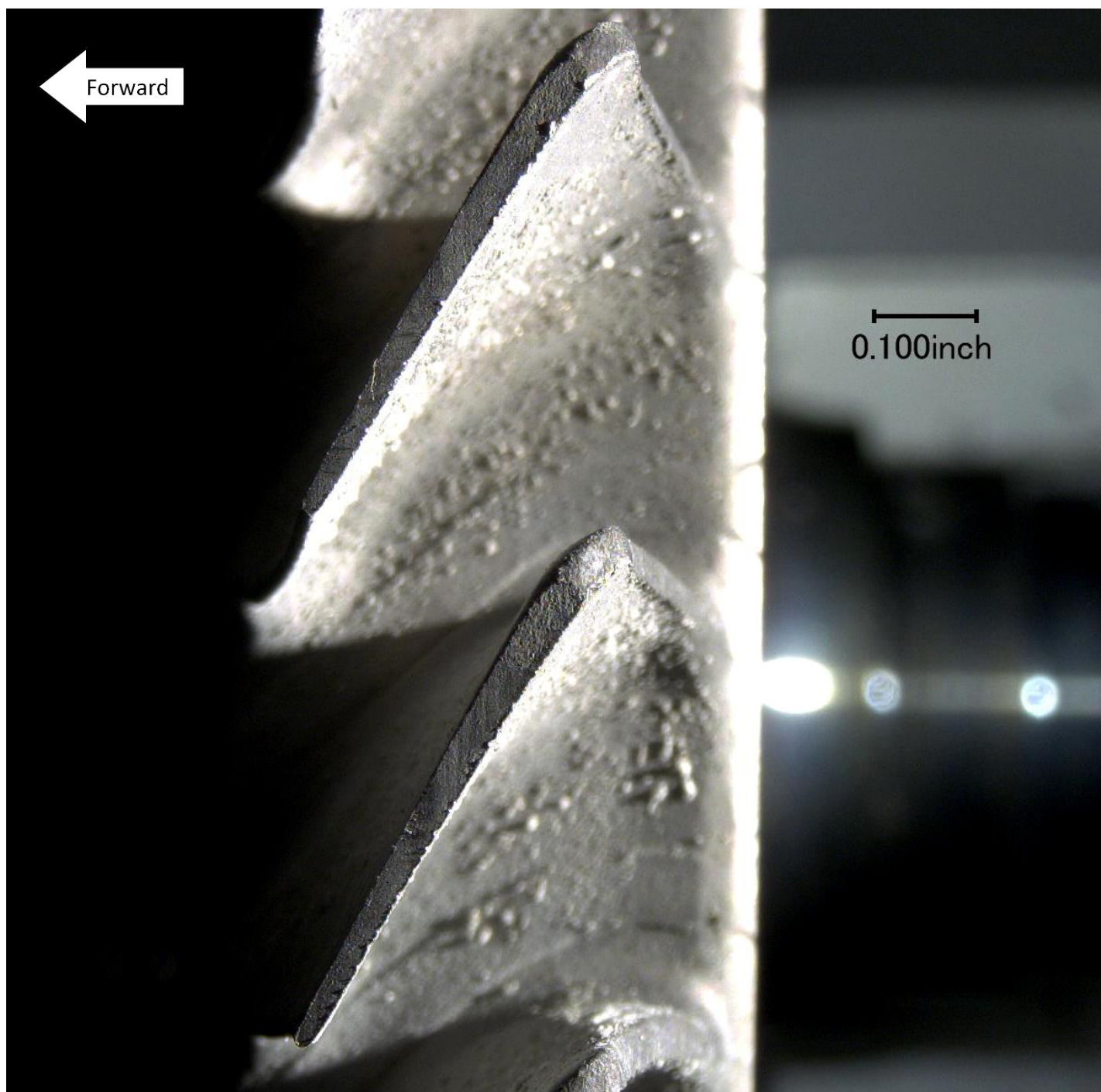


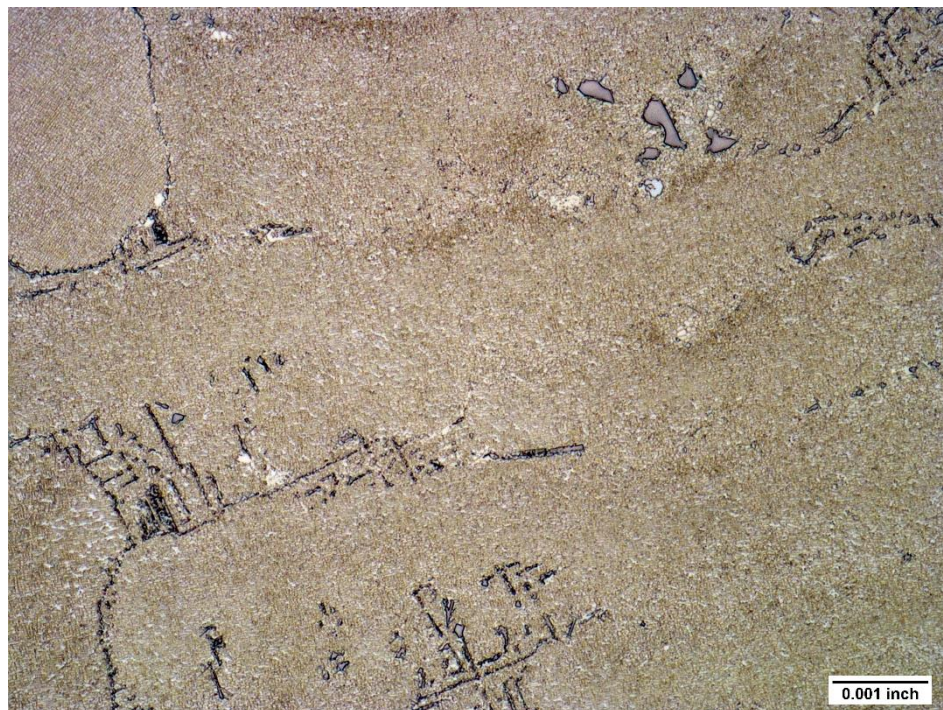
Figure 85. Detailed view showing representative circumferential rub damage on the first stage turbine blade tips.



Figure 86. Overall view of the longitudinal cross-section 1TE near the trailing edge on a representative first stage turbine blade. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 87. Representative microstructure in the rim of the wheel on cross-section 1TE. Etchant: MT.

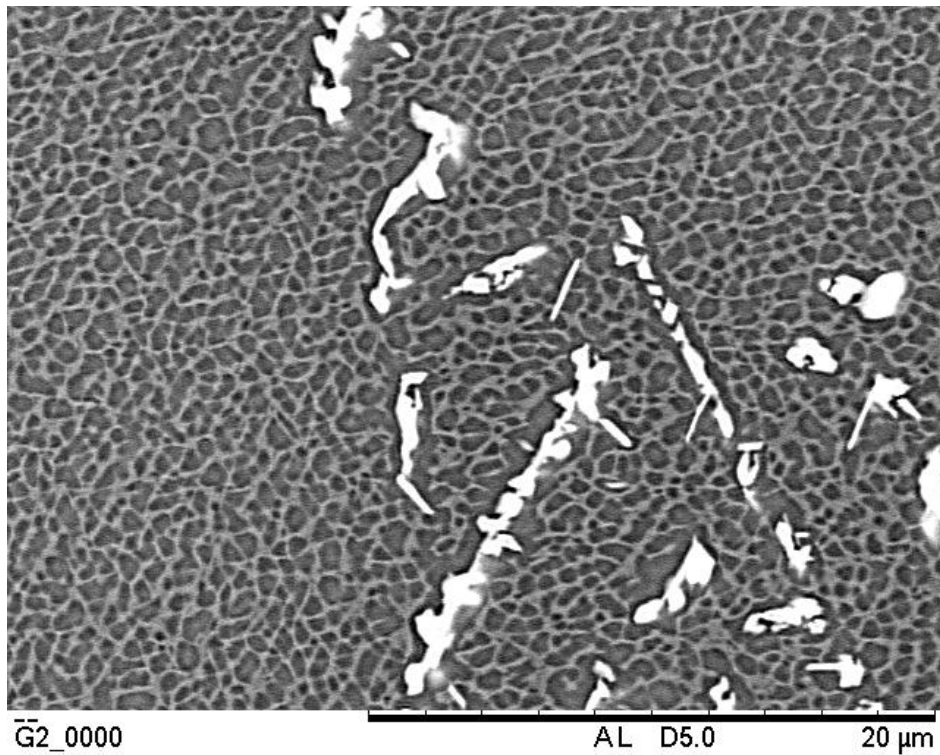
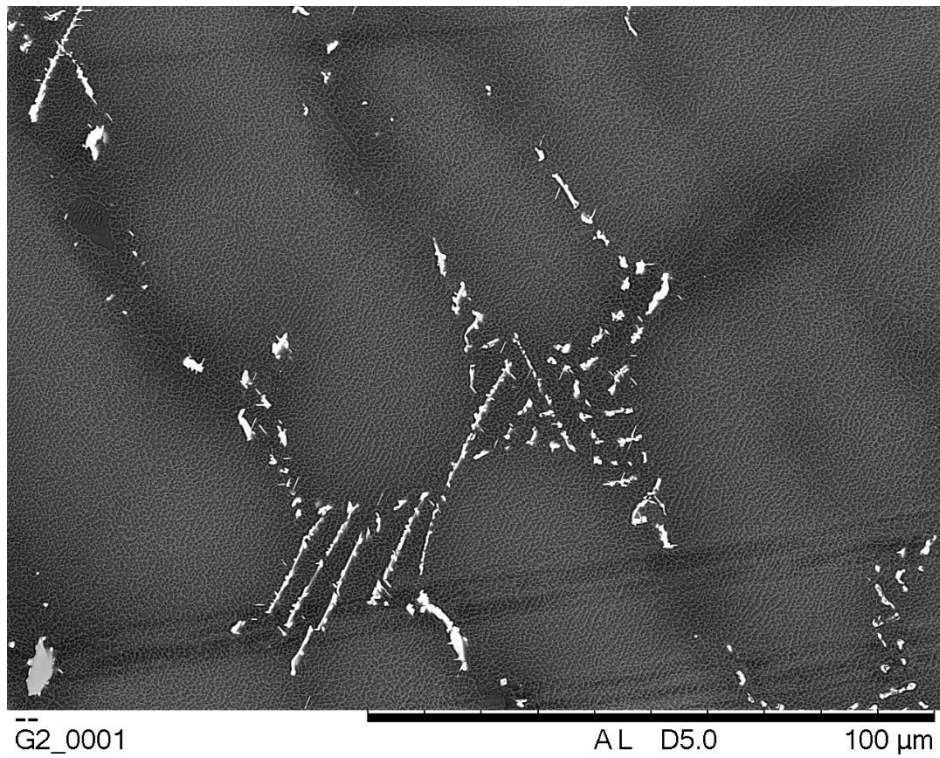
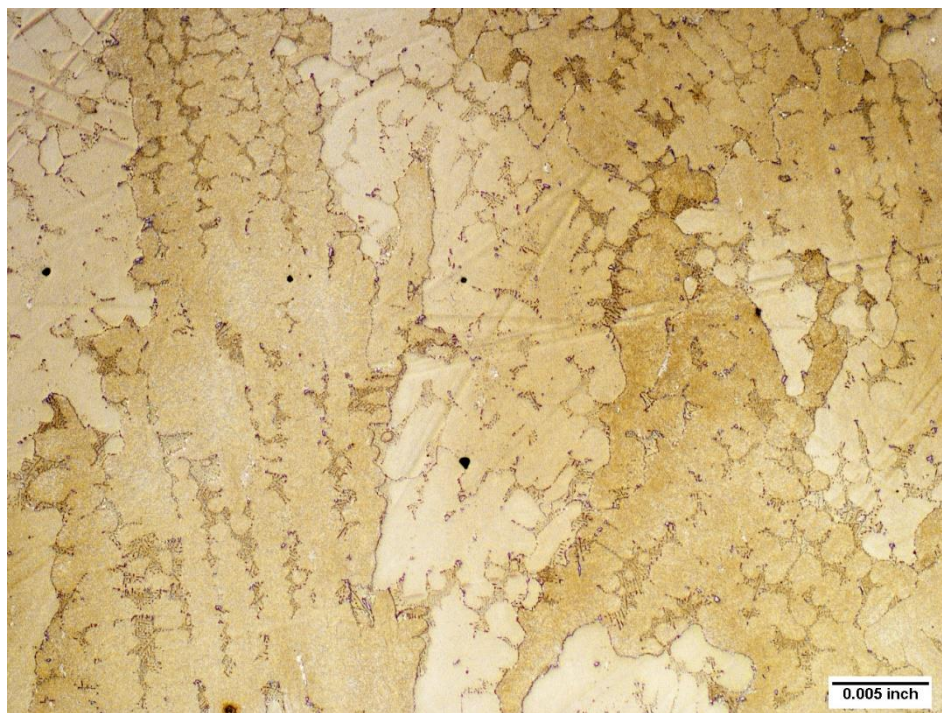
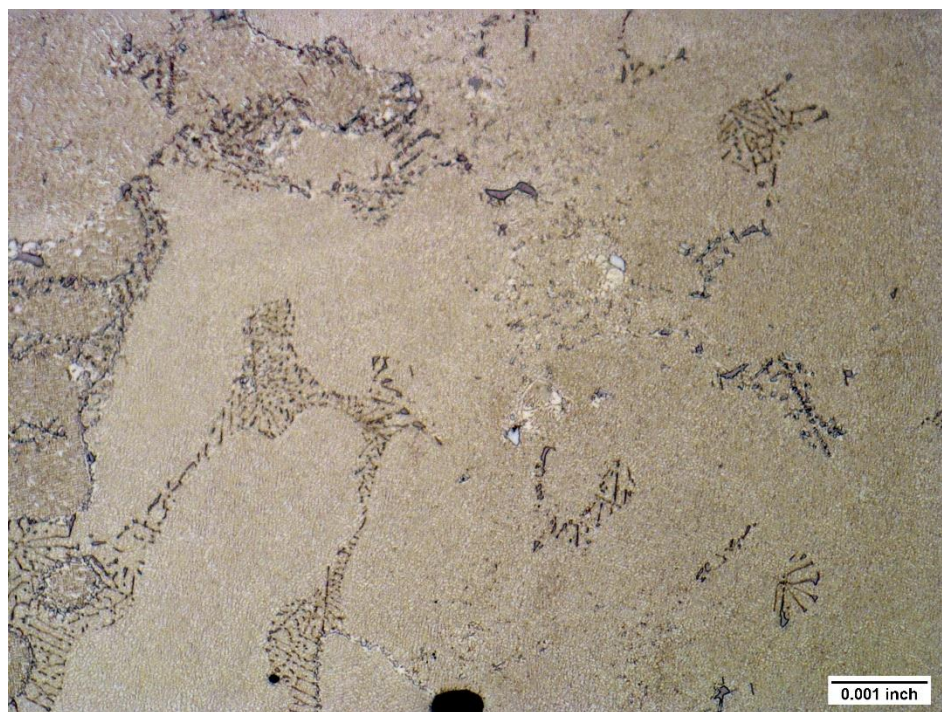


Figure 88. Backscattered electron SEM images showing the gamma prime structure in the rim of the wheel on cross-section 1TE. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 89. Representative microstructure in the root of the blade on cross-section 1TE. Etchant: MT.

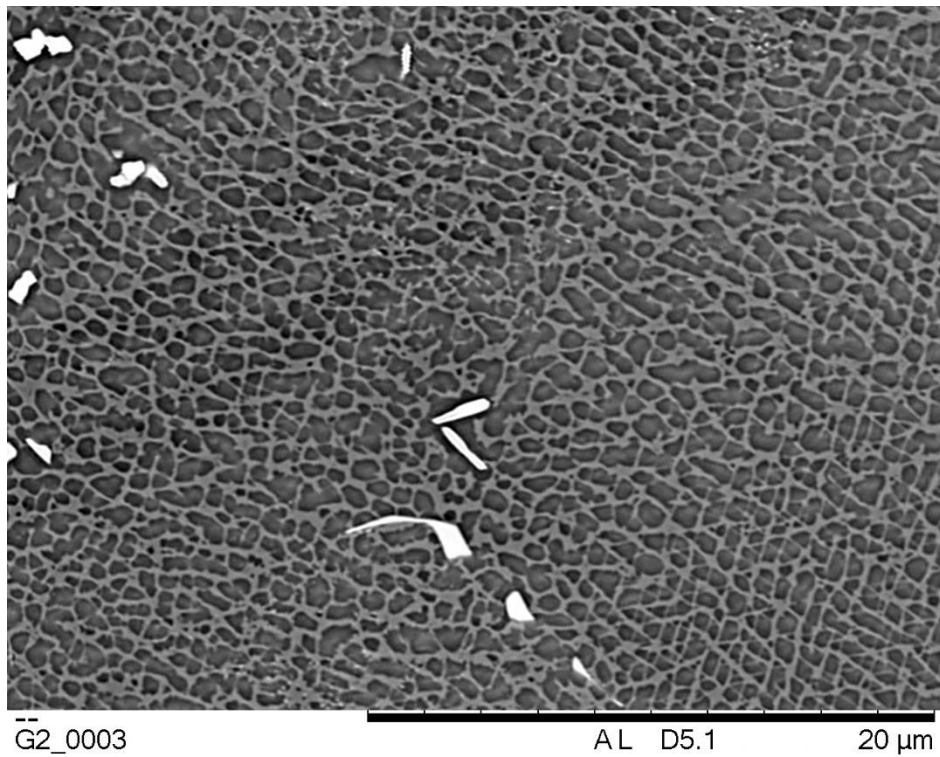
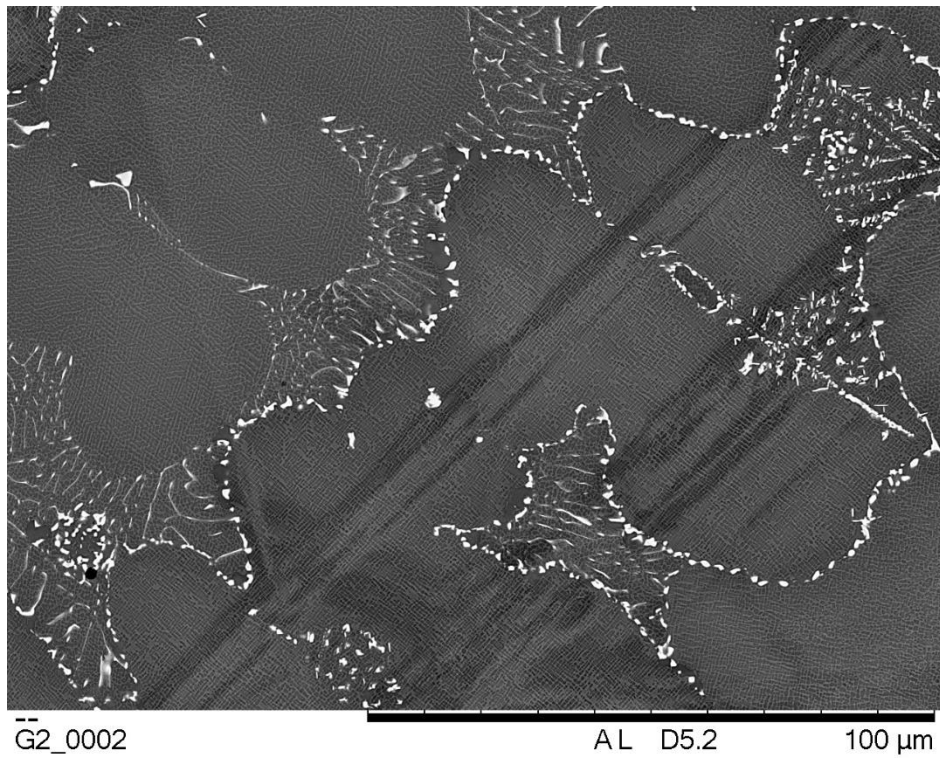
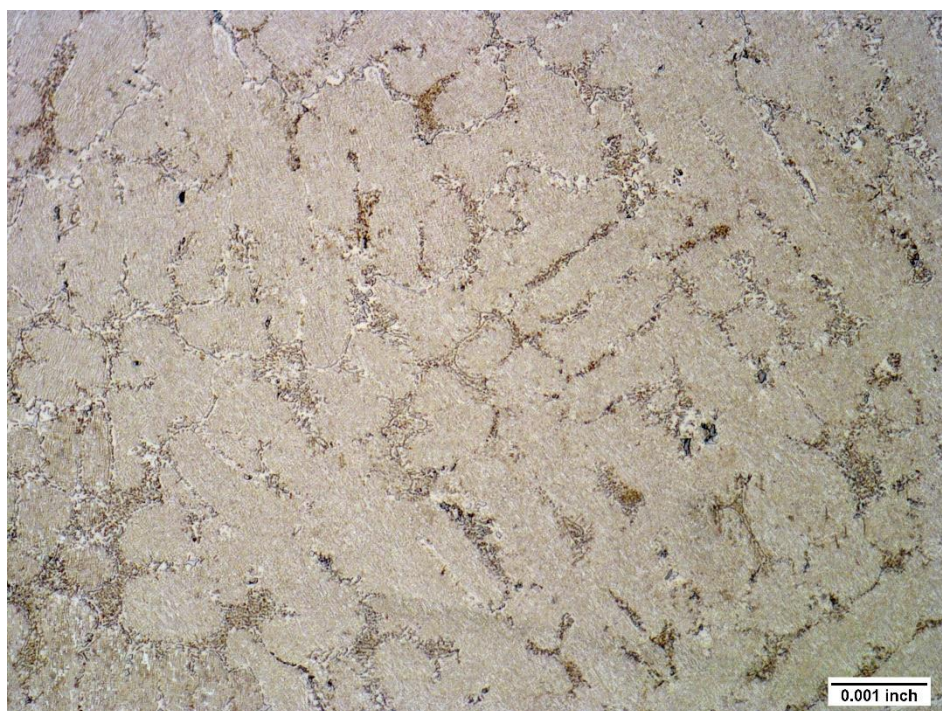


Figure 90. Backscattered electron SEM images showing the gamma prime structure in the root of the blade on cross-section 1TE. Etchant: MT.



Original Magnification: 100x



Original Magnification: 500x

Figure 91. Representative microstructure near midspan on cross-section 1TE. Etchant: MT.

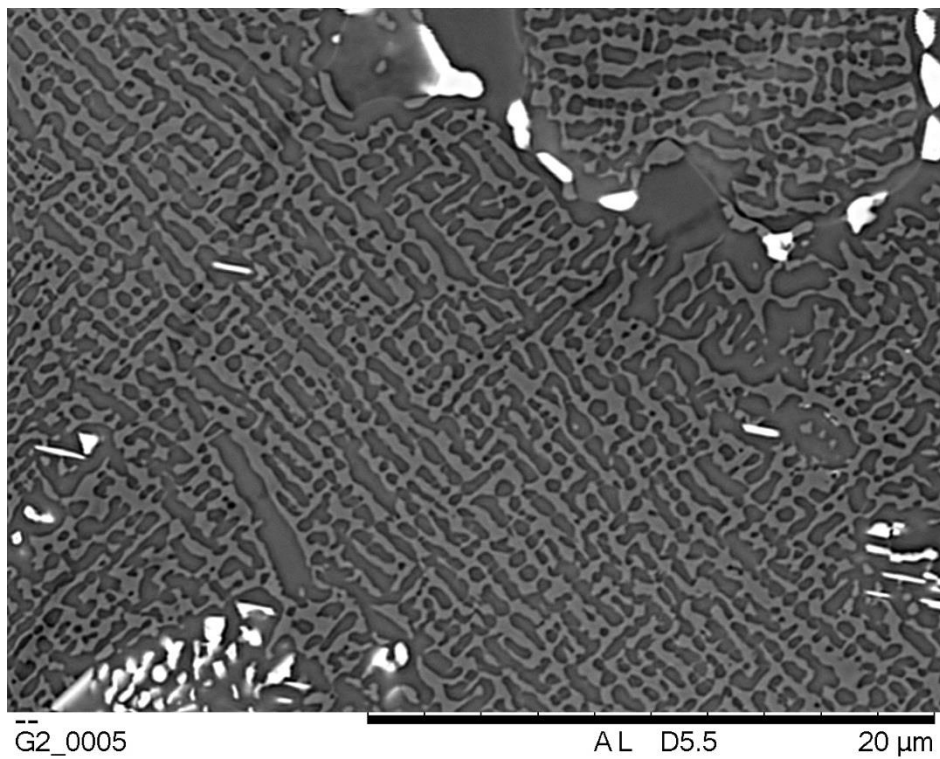
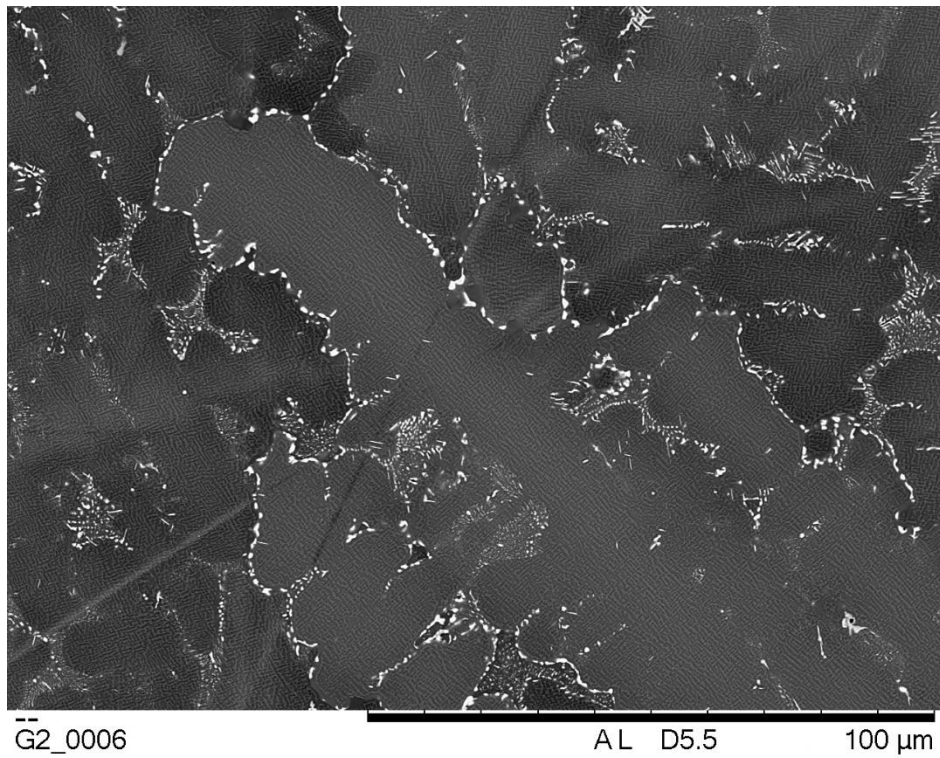


Figure 92. Backscattered electron SEM images showing the gamma prime structure near midspan on cross-section 1TE. Etchant: MT.



Figure 93. Leading edge (left) and trailing edge (right) side views showing the second stage turbine wheel. The airfoils exhibited white powdery deposits consistent with airframe fire retardant. Divisions = cm.

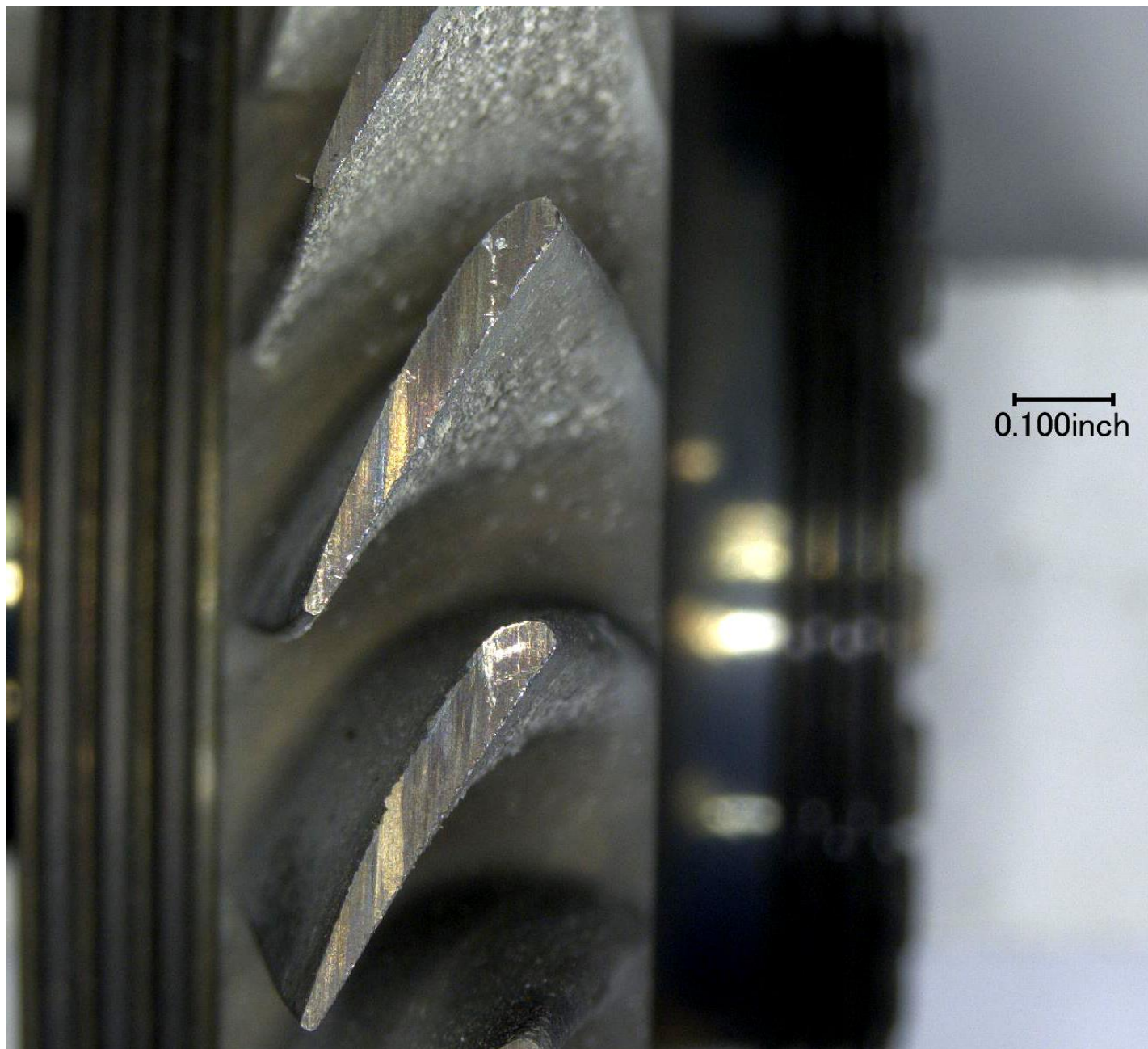


Figure 94. Detailed view showing representative circumferential rub damage on the second stage turbine blade tips.



Figure 95. Overall view showing the No. 6 bearing (top) and the PMA part markings (bottom).
Top: Divisions = mm.

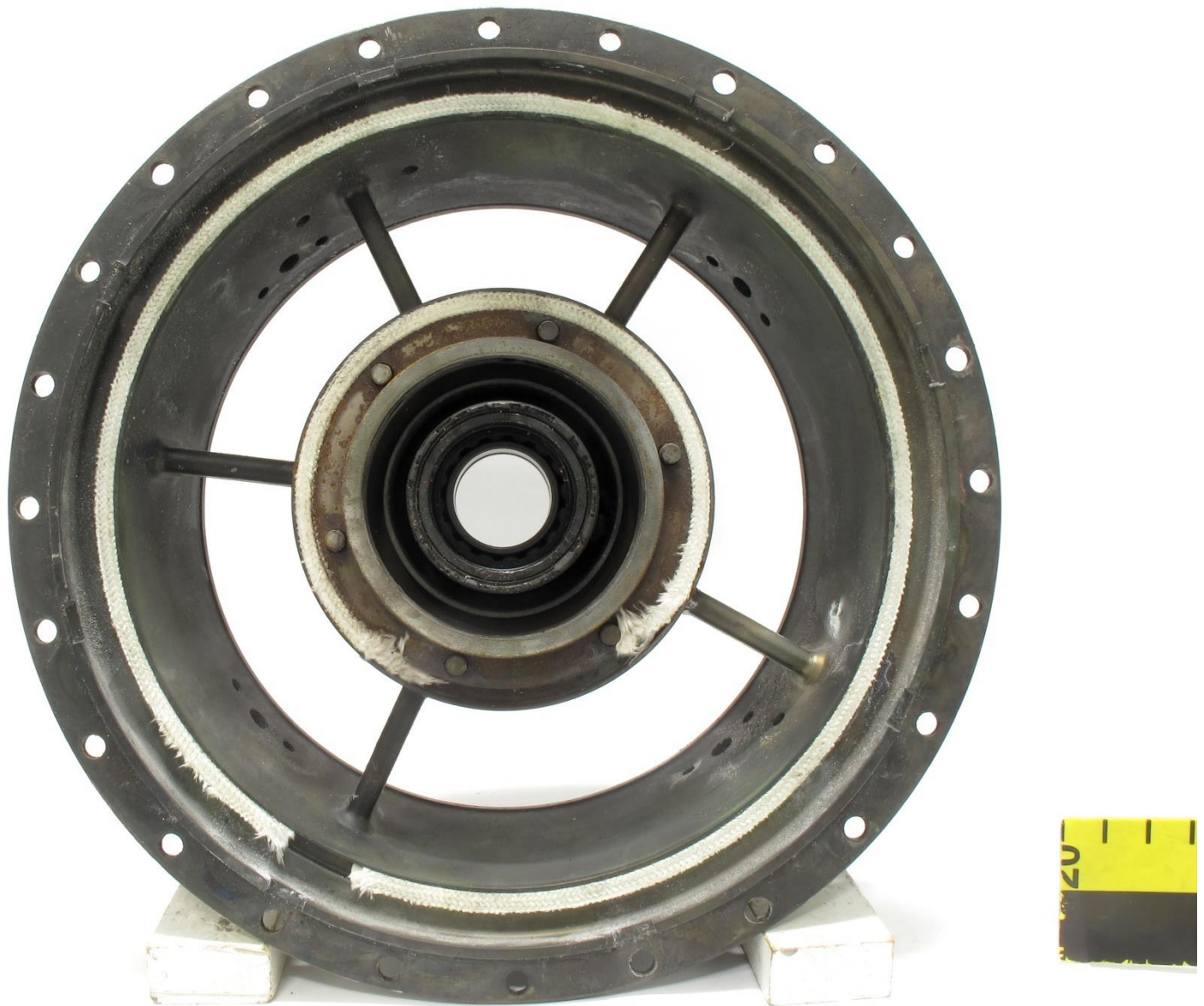


Figure 96. Forward looking aft view showing the as-received condition of the PT support assembly. The No. 7 bearing was still installed in the bore, which is shown in more detail in the following figure. Divisions = cm.

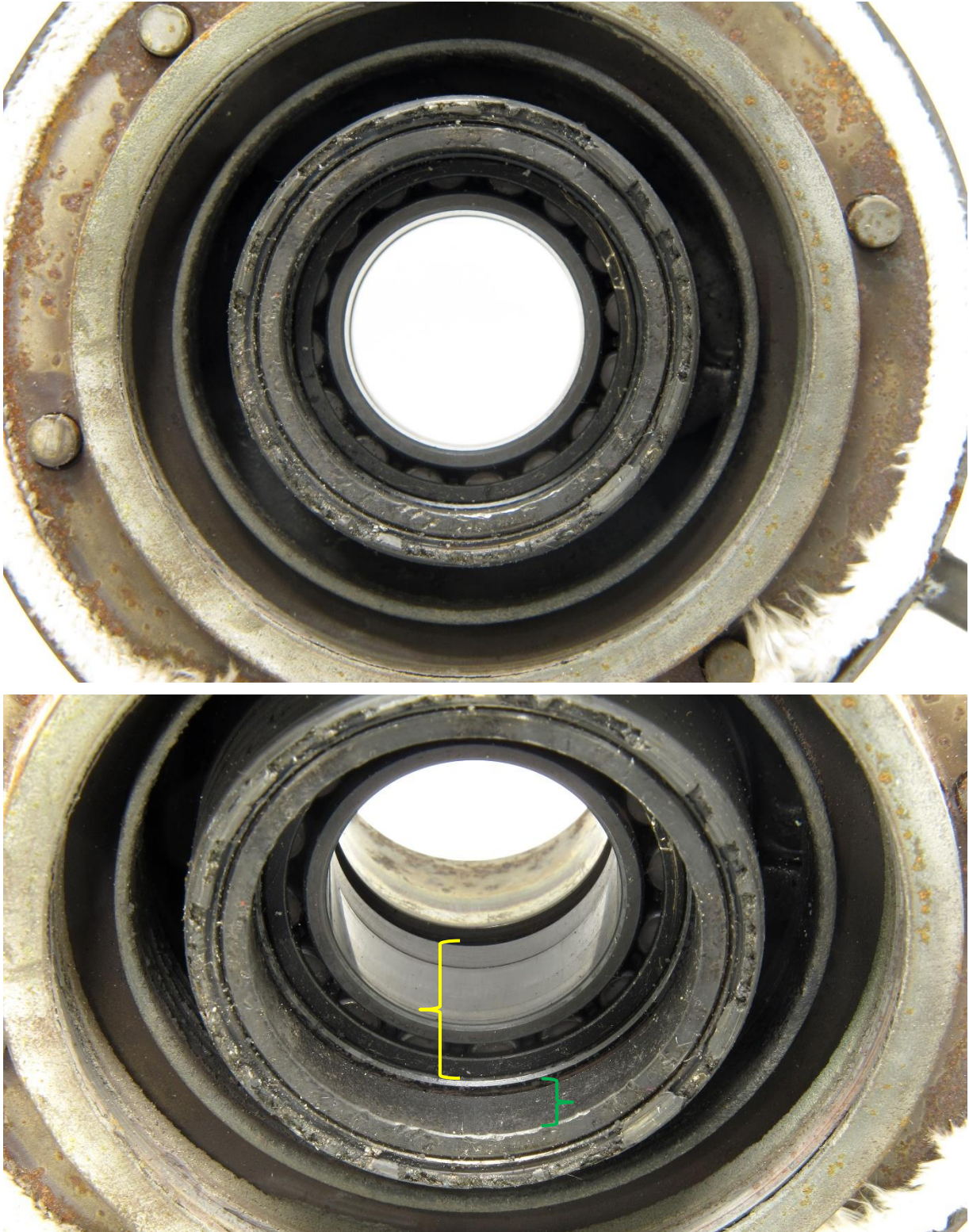


Figure 97. Detailed forward looking aft views showing the Nos. 6 and 7 bearing sump in the PT support. The No.6 bearing was returned to the laboratory separately, but the spacer (green brace) and the No. 7 bearing (yellow brace) were still installed in the sump. The spacer and No. 7 bearing were shifted forward from their nominal positions when assembled in the engine. No scale provided.



Figure 98. Detailed views showing the part number (top) and PMA (bottom) part markings on the No. 7 bearing. No scale provided.

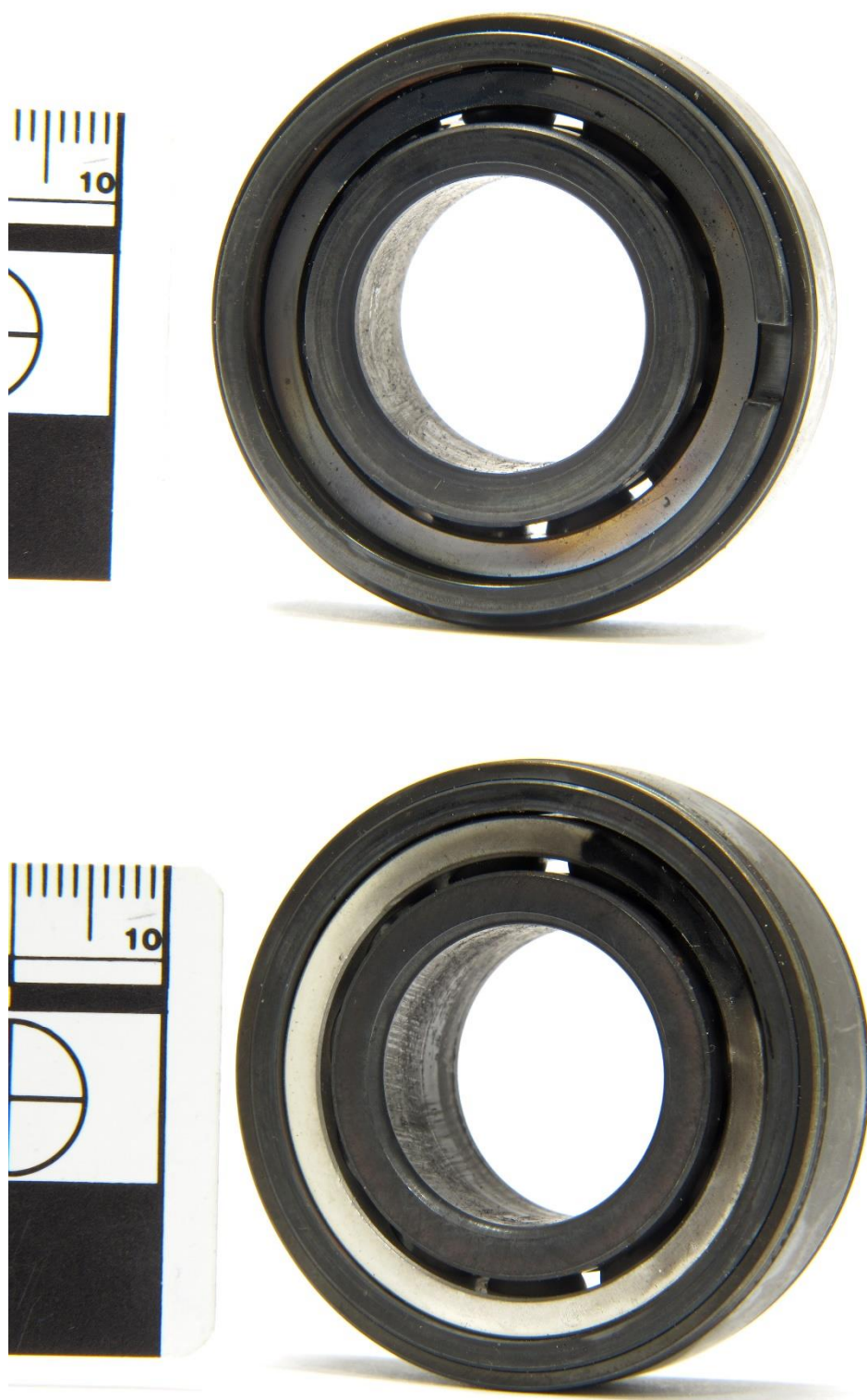


Figure 99. Forward side (top) and aft side (bottom) views of the No. 8 bearing. Divisions = mm.



**Figure 100. Part markings on the second stage turbine nozzle assembly, which was a PMA component (bottom).
No scale provided.**