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 Rolls-Royce	Rolls-Royce Corporation 450 S. Meridian Street Indianapolis, Indiana 46225-1103, USA	REPORT NO. 24FAE-061-PR	REV. Initial	PAGES 1 of 54
TITLE METALLURGICAL INVESTIGATION OF A TURBINE TO COMPRESSOR COUPLING, P/N 23032345, INSTALLED IN AN M250-C30P ENGINE, S/N CAE895785, OPERATED BY HELIWORKS FLIGHT SERVICES		PREPARED Signatures on File		
		APPROVED Signatures on File		

IDENTIFICATION

Part Name:	Turbine to Compressor Coupling
Part Number:	23032345
Part Serial Number:	UT265134
Part Time:	7742.2 hours TSN
Engine Model:	M250-C30P
Engine Serial Number:	CAE895785
User:	Heliworks Flight Services
Removal Station:	Rolls-Royce Regional Customer Training Center
Evaluations:	Failure Investigation

1 Foreword

The subject turbine to compressor coupling, P/N 23032345, S/N UT265134, was installed in an M250-C30P, engine S/N CAE895785, operated by Heliworks. The aircraft was reportedly contracted to perform revegetation and reclamation work using an underslung spreader when it experienced a hard landing after approximately 200 feet of climb. The engine was removed and sent to the Rolls-Royce Regional Customer Training Center for disassembly. The turbine to compressor coupling and additional components listed in Table 1 were submitted to the Rolls-Royce Materials Laboratory in Indianapolis, IN for detailed metallurgical investigation.

2 Summary of Findings

- 2.1 The turbine to compressor coupling and the PT inner shaft were fractured, deformed, and thermally distressed. Coked oil buildup was observed in the PT outer shaft, PT inner shaft, and turbine to compressor coupling.
- 2.2 The turbine to compressor coupling and PT inner shaft met their respective component definition requirements for microstructure, composition, case depth, and case and core hardness away from thermally distressed material.
- 2.3 Coked oil material was present in the turbine to compressor coupling, PT inner shaft, PT outer shaft, spur adapter gearshaft, power turbine to pinion gear coupling, 4th stage turbine wheel, 3rd stage turbine wheel, turbine spline adapter, and No. 6 bearing. A layer of dark, flaky material consistent with coked oil was observed on the forward face of the No. 2 bearing outer ring and separator.
- 2.4 The spur adapter gearshaft O-rings were not present during engine disassembly. FTIR analysis of dark deposits on the spur adapter gearshaft revealed chemistry consistent with a fluorocarbon rubber.
- 2.5 CT examination of the oil delivery tube showed low density material buildup that created a blockage in the No. 3 bearing oil jet. The internal cavity walls exhibited buildup of the same low-density material. No other blockages were observed.
- 2.6 The oil screen exhibited a layer of oil sludge and coked oil product that occluded most of the oil screen mesh.

3 Results and Discussion

A partial engine schematic that illustrates the layout of components submitted for evaluation is shown in Figure 1. An overall view of the turbine and shaft components submitted for investigation are shown in Figure 2. The turbine to compressor coupling was fractured in several places and was found embedded in the power turbine (PT) outer shaft, 4th stage turbine wheel, and power turbine to pinion gear coupling. The PT inner shaft was fractured in several places and was found embedded in the PT outer shaft, 4th stage turbine wheel, and 3rd stage turbine wheel.

3.1 *Turbine to Compressor Coupling P/N 23032345 and Surrounding Power Turbine Components*

3.1.1 *Visual Examination*

Overall views of the PT outer shaft are shown in Figure 3 in the as-received condition. The outer surface exhibited a darker grey discoloration that spanned up to approximately 2.6 inches forward of the Curvic teeth. Circumferential score marks were observed on the dimples, which was consistent with disassembly damage from the deformed dimples on the coupling nut. An overall aft looking forward view of the Curvic teeth and fractured and embedded portions of the PT inner tube, turbine to compressor coupling, and PT inner coupling nut is shown in Figure 4. The PT outer shaft walls were sectioned at two diametrically opposed locations and the resulting internal views are shown in Figure 5. The turbine to compressor coupling exhibited outboard deformation where it overlapped the PT inner shaft. The turbine to compressor coupling exhibited a spiral fracture forward of the PT outer shaft Curvic teeth. The PT inner shaft exhibited several fractures and deformed material between the turbine to compressor coupling and PT outer shaft. Dark deposits consistent with coked

oil were observed throughout the internal surfaces of the PT outer shaft and PT inner shaft material, and the outer surface of the turbine to compressor coupling.

Overall views of the 4th stage turbine wheel are shown in Figure 6 in the as-received condition. A span of the fractured turbine to compressor coupling was embedded in the wheel bore along with PT inner shaft material. A detailed aft looking forward view of the 4th stage turbine wheel aft Curvic teeth, embedded PT inner shaft material, and embedded turbine to compressor coupling is shown in Figure 7. The aft portion of the turbine to compressor coupling was deformed outboard and onto the 4th stage turbine wheel aft Curvic teeth. The turbine to compressor coupling internal splines were deformed in a spiral in the direction of engine rotation from forward to aft. PT inner shaft material was observed between the turbine to compressor coupling material and the 4th stage turbine wheel bore. The turbine to compressor coupling material extended forward from the forward face of the Curvic teeth approximately 1.03 inches as shown in Figure 7.

Overall views of the tie bolt are and aft-most portion of the turbine to compressor coupling, assembled by the tie bolt nut, are shown in Figure 8. The fractured portion of the turbine to compressor coupling exhibited deformation and rub damage and was coated with dark deposits consistent with coked oil.

The turbine to compressor coupling fractured pieces were removed from the halves of the PT outer shaft. The turbine to compressor coupling aft fractured piece was removed from the tie bolt by disassembling the tie bolt nut. The fractured pieces of the turbine to compressor coupling, less the portion adhered to the 4th stage turbine wheel were cleaned and are shown in their relative positions in Figure 9.

3.1.2 *Metallographic Examination*

A metallographic cross-section was performed on the PT outer shaft that included the fractured turbine to compressor coupling, PT inner shaft, and the PT inner coupling at the approximate plane shown in Figure 5. Montaged metallographic images of the turbine to compressor coupling, PT inner shaft, PT outer shaft, and PT inner coupling nut are shown in Figure 10. The turbine to compressor coupling exhibited melted, deformed, cracked, and thermally distressed material. The PT inner shaft exhibited several fractures, areas of melted material, and cracking. Figure 11 shows a detailed view of the turbine to compressor coupling outer diameter surface at the extent of thermal distress, which was located approximately 1.37 inch forward of the PT outer shaft internal retaining feature for the power turbine to pinion gear coupling. Figure 12 shows detailed, representative thermally distressed material in the turbine to compressor coupling. Figure 13 shows local areas of thermal distress in the turbine to compressor coupling outer diameter adjacent to melted and re-solidified material from the PT inner shaft. Figure 14 shows detailed views of a span of melted and re-solidified material in the turbine to compressor coupling, which was melted through the wall thickness.

Figure 15 shows detailed views of the PT inner shaft material at the PT inner coupling nut. The outer diameter surface exhibited thermally distressed material diffused into the base material. Energy dispersive X-ray spectroscopy (EDS) of the diffused material revealed higher concentrations of nickel and aluminum.

The PT outer shaft did not exhibit evidence of thermal distress. Representative images of the PT outer shaft inner and outer diameter are shown in Figure 16. Nickel plating on the PT outer shaft inner and outer diameter measured approximately 0.0008 inch thick, which exceeded the component definition requirement. Aluminum coating was preserved on the outer diameter surface approximately 0.001 inch thick. The aluminum coating on the inner diameter was flaked off and no measurement was taken.

The turbine to compressor coupling was sectioned at a radial plane, P2, at the approximate location shown in Figure 9. Metallographic images of the turbine to compressor coupling splines and the case microstructure are shown in Figure 17. The case depth measured approximately 0.012 inch, which met the component definition requirement. Representative microstructure of the turbine to compressor coupling core material is shown in Figure 18.

3.1.3 *Chemistry*

Semi-quantitative EDS analysis determined the turbine to compressor coupling was consistent with the material type required by the component definition.

3.1.4 *Hardness*

The average hardness of the turbine to compressor coupling case measured on cross-section P2 was 93 HR15N (average converted value of 868, 920, and 951 HV500gf), which met the component definition requirement. The average hardness of the turbine to compressor coupling core measured on cross-section P2 was 32 HRC (average converted value of 314, 319, and 330 HV500gf), which met the component definition requirement.

3.2 **Power Turbine Inner Shaft P/N 23071313**

3.2.1 *Visual Examination*

Overall views of the 3rd stage turbine wheel and the fractured and embedded portion of the PT inner shaft are shown in Figure 19. The approximately 1.75 inch aft span of the PT inner shaft was retained in the 3rd stage turbine wheel bore. The forward fracture of the PT inner shaft was flared outboard and smeared. Dark deposits consistent with coked oil were observed in the aft side of the 3rd stage turbine wheel bore and inside the PT inner shaft. A detailed aft looking forward view of the PT inner shaft embedded in the 3rd stage turbine wheel is shown in Figure 20. The PT inner shaft was removed from the 3rd stage turbine wheel and is shown in Figure 21.

3.2.2 *Metallographic Examination*

A metallographic cross-section of the PT inner shaft was performed at the approximate plane shown in Figure 21. Detailed metallographic images of the cross-section at the case material are shown in Figure 22. The case depth measured approximately 0.013 inch, which met the component definition requirement. A metallographic image of the nickel thickness on the inner diameter surface is shown in Figure 23. Nickel thickness measured approximately 0.0007 inch thick. Representative microstructure of the PT inner shaft core material is shown in Figure 24.

3.2.3 *Chemistry*

Semi-quantitative EDS analysis determined the turbine to compressor coupling was consistent with the material type required by the component definition.

3.2.4 *Hardness*

The average hardness of the PT inner shaft case measured on cross-section P3 was 958 HV500gf (average value of three measurements), which met the component definition requirement. The average hardness of the PT inner shaft core measured on cross-section P3 was 44.6 HRC (average converted value of 431, 455, and 436 HV500gf), which met the component definition requirement.

3.3 **Spur Adapter Gearshaft, P/N M250 10022**

3.3.1 *Visual Examination*

Overall views of the spur adapter gearshaft in the as-received condition are shown in Figure 25. Loosely adhered dark deposits were observed aft of the No.2.5 bearing race. Detailed views of O-ring grooves and aft splines are shown in Figure 26. A layer of oil stain was observed in the spline teeth that spanned into the O-ring groove approximately 0.023 inch forward of the spline teeth face. The span of the aft O-ring groove that did not exhibit oil stain was approximately 0.118 inch. The oil stain was observed on the spline tooth tips from the tooth face and on the tooth flanks near the aft face.

3.4 Oil Debris

3.4.1 Chemistry

Solid dark deposits were collected from the spur adapter gearshaft, turbine to compressor coupling, the PT outer shaft, and the 4th stage turbine wheel bore and subjected to Fourier transform infrared (FTIR) spectroscopy at the Rolls-Royce Chemical Laboratory in Indianapolis, IN. The resultant spectra from FTIR are shown in Figure 27. FTIR revealed two samples of deposits collected from the spur adapter gearshaft exhibited a signal at 1050 cm⁻¹, which was consistent with a signal from a fluorocarbon type material, along with carbon material consistent with coked oil. A representative spectrum from the dark deposits collected from components aft of the spur adapter gearshaft did not exhibit the signal at 1050 cm⁻¹, which was consistent with a coked oil type material.

3.5 Oil delivery Tube P/N 23033876 and Oil Screen

3.5.1 Visual and Non-destructive Examination

Overall views of oil delivery tube are shown in Figure 28 in the as-received condition. The oil delivery tube was subjected to the computed topography (CT) examination at the Rolls-Royce Corporation Non-destructive Testing Department in Indianapolis, IN. CT revealed a blocked passage in the No. 3 bearing oil jet as shown in Figure 29. The blockage exhibited a relatively denser material compared to the residual oil that remained in the passageways. The denser material was also observed built up on the internal cavity walls. No other oil jets exhibited evidence of complete blockages.

A detailed view of the oil screen is shown in Figure 30, which exhibited buildup of dark, viscous, oil material that occluded the oil screen surface. The oil sludge material was removed with laboratory solvents and collected onto a filter paper and is shown in Figure 30. The collected deposits were a dark, fine powdery material.

3.6 Power Turbine to Pinion Gear Coupling P/N 6889069

3.6.1 Visual Examination

Overall views of the power turbine to pinion gear coupling, hereafter pinion gear coupling, are shown in Figure 31 in the as-received condition. Dark deposits consistent with coked oil were observed on the inner and outer diameter surfaces and embedded in the spline teeth. The aft Teflon seal was damaged and frayed. Discoloration was observed on the forward half of the pinion gear coupling. Detailed views of the forward and aft Teflon seals are shown in Figure 32. A detailed view of the pinion gear coupling aft side and internal features are shown in Figure 33. The inner diameter exhibited a thin layer of adhered turbine to compressor coupling material.

3.7 Turbine Spline Adapter P/N 23076529

3.7.1 Visual Examination

Overall views of the turbine spline adapter are shown in Figure 34 in the as-received condition. Dark deposits consistent with coked oil were observed in the spline teeth and inner and outer diameter surfaces.

3.8 No. 6 Roller Bearing P/N 23007202

3.8.1 Visual Examination

Overall views of the No. 6 roller bearing are shown in Figure 35 in the as-received condition. The bearing surfaces and rollers exhibited dark deposits consistent with coked oil. The bearing exhibited resistance when turned.

3.9 No. 2 Bearing P/N 23009670

3.9.1 Visual Examination

Overall views of the No. 2 bearing are shown in Figure 36 in the as-received condition. The forward side exhibited a darker discoloration in the inner ring and separator. Detailed views of the separator inner diameter and balls are shown in Figure 37. The separator exhibited a dark discoloration that was flaked off in areas consistent with a layer of coked oil material. The coked oil layer spanned from the approximate axial mid-span onto the forward face. The separator forward face at each ball pocket exhibited radially oriented banded features in the coked oil layer. The outer ring forward face exhibited a darker layer of material located approximately 0.13 inch inboard of the outer diameter chamfer. Detailed views of the separator outer diameter are shown in Figure 38. Detailed views of the separator forward and aft rails are shown in Figure 39. The separator outer diameter exhibited a dark discoloration. Detailed views of the outer ring raceway are shown in Figure 40. Detailed views of the forward inner race are shown in Figure 41. A dark discoloration was observed on the forward portion of the raceway and onto the forward shoulder. Detailed views of the aft inner race are shown in Figure 42.

3.9.2 Metallographic Examination

Metallographic cross-sections of the No. 2 bearing separator and outer ring were performed at plane P4 as shown in Figure 37. Metallographic images of the separator forward rail are shown in Figure 43. The forward face and adjacent inboard chamfer exhibited a layer of dark, flaky material consistent with coked oil up to approximately 0.004 inch thick. Metallographic images of the outer ring are shown in Figure 44. The forward face and shoulder exhibited a layer of dark, flaky material consistent with coked oil up to approximately 0.003 inch.

3.10 No. 3 and 4 Roller Bearing and Pinion Gear

3.10.1 Visual Examination

Overall views of the No. 3 bearing, No. 4 bearing, and pinion gear assembly are shown in Figure 45. Dark deposits consistent with coked oil were observed on the internal surfaces of the pinion gear. The No. 3 and No. 4 bearings rotated freely.

3.11 No. 5 Bearing P/N M250-10797

3.11.1 Visual Examination

Overall views of the No. 5 bearing are shown in Figure 46 in the as-received condition. Dark deposits consistent with coked oil were observed on the outer race, separator, and in the ball assembly. The No. 5 bearing rotated freely.

3.12 No. 8 Bearing P/N 23031478

3.12.1 Visual Examination

Overall views of the No. 8 bearing are shown in Figure 47 in the as-received condition. The No. 8 bearing rotated freely.

4 Revision History

Issue	Change Summary	Date
Initial	Not applicable	11 OCT 2024

5 Figures and Tables

Table 1 List of components submitted to the laboratory for investigation.

Part Name	Part Number	Serial Number
Turbine to compressor coupling	23032345	UT265134
Spur adapter gearshaft	M250-10022	YJ36388
Power turbine to pinion gear coupling	6889069	GK20542
Power turbine outer shaft	23038136	UF25880
Power turbine inner shaft	23071313	GK565458
Power turbine outer shaft nut	23001801*	-
Power turbine inner coupling nut	23030982*	-
Oil delivery tube	23033876	52637
Tie bolt	6889320*	-
Tie bolt nut	23076531*	-
Turbine spline adapter	23076529*	-
4 th stage turbine wheel	23066744*	X586066
3 rd stage turbine wheel	M250-10748*	X589965
No. 6 bearing	23007202	MP073756
No. 2 bearing	23009670*	MP002216
Pinion gear	6893678	NN73448
No. 3 bearing	23066678	JJ03902
No. 4 bearing	23066678	JJ02865
No. 5 bearing	M250-10797	NWA-0829
No. 8 bearing	23031478	MP15407

*Indicates information taken from the illustrated parts catalog

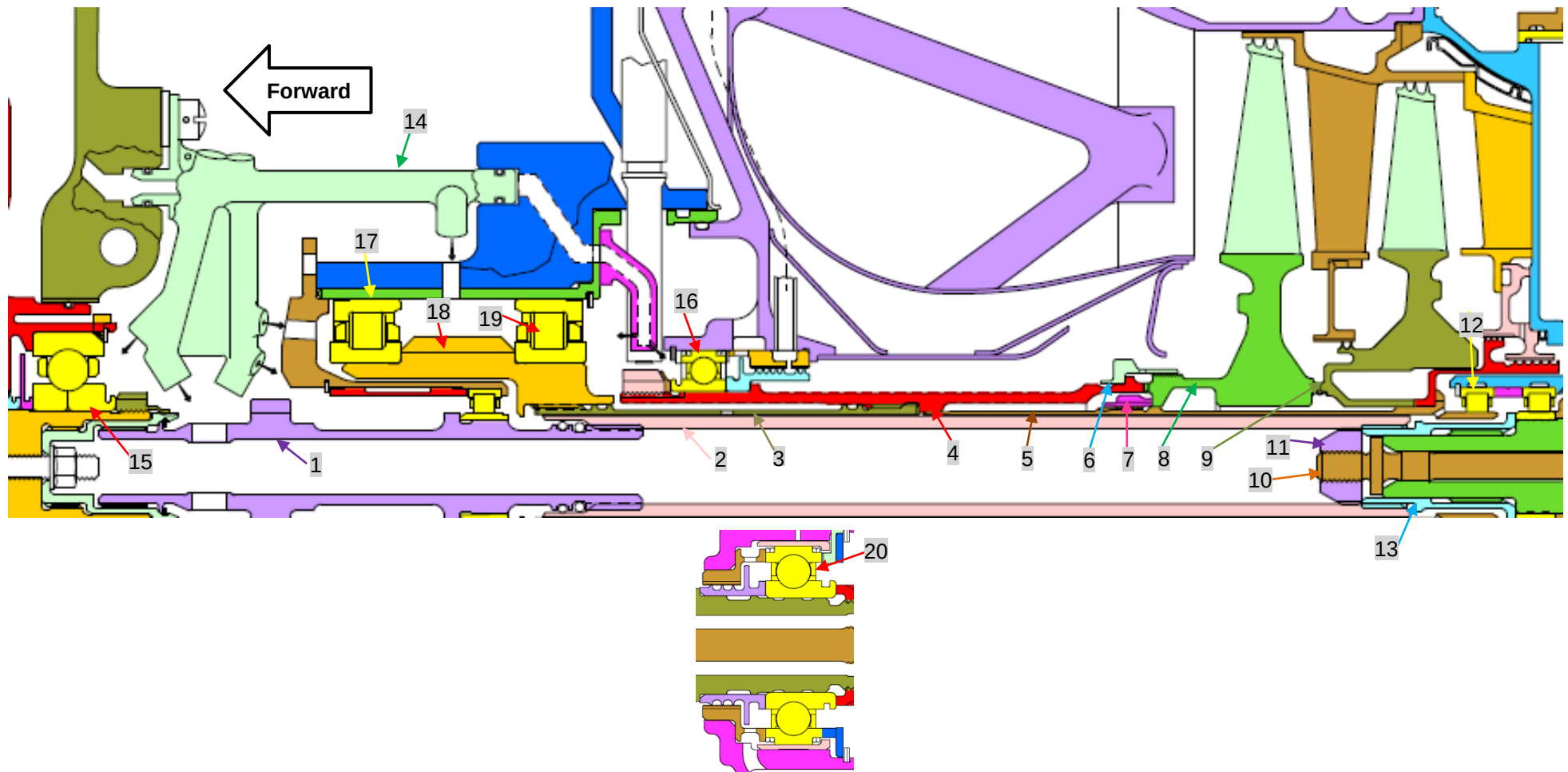


Figure 1. Partial schematics showing the spur adapter gearshaft (1), turbine to compressor coupling (2), power turbine to pinion gear coupling (3), power turbine outer shaft (4), power turbine inner shaft (5), power turbine outer shaft nut (6), power turbine inner coupling nut (7), 4th stage turbine wheel (8), 3rd stage turbine wheel (9), tie bolt (10), tie bolt nut (11), No. 6 bearing (12), turbine spline adapter (13), oil delivery tube (14), No. 2 bearing (15), No. 5 bearing (16), No. 3 bearing (17), No. 4 bearing (18), power turbine pinion gear (19), and No. 8 bearing (20). Schematics not to scale.

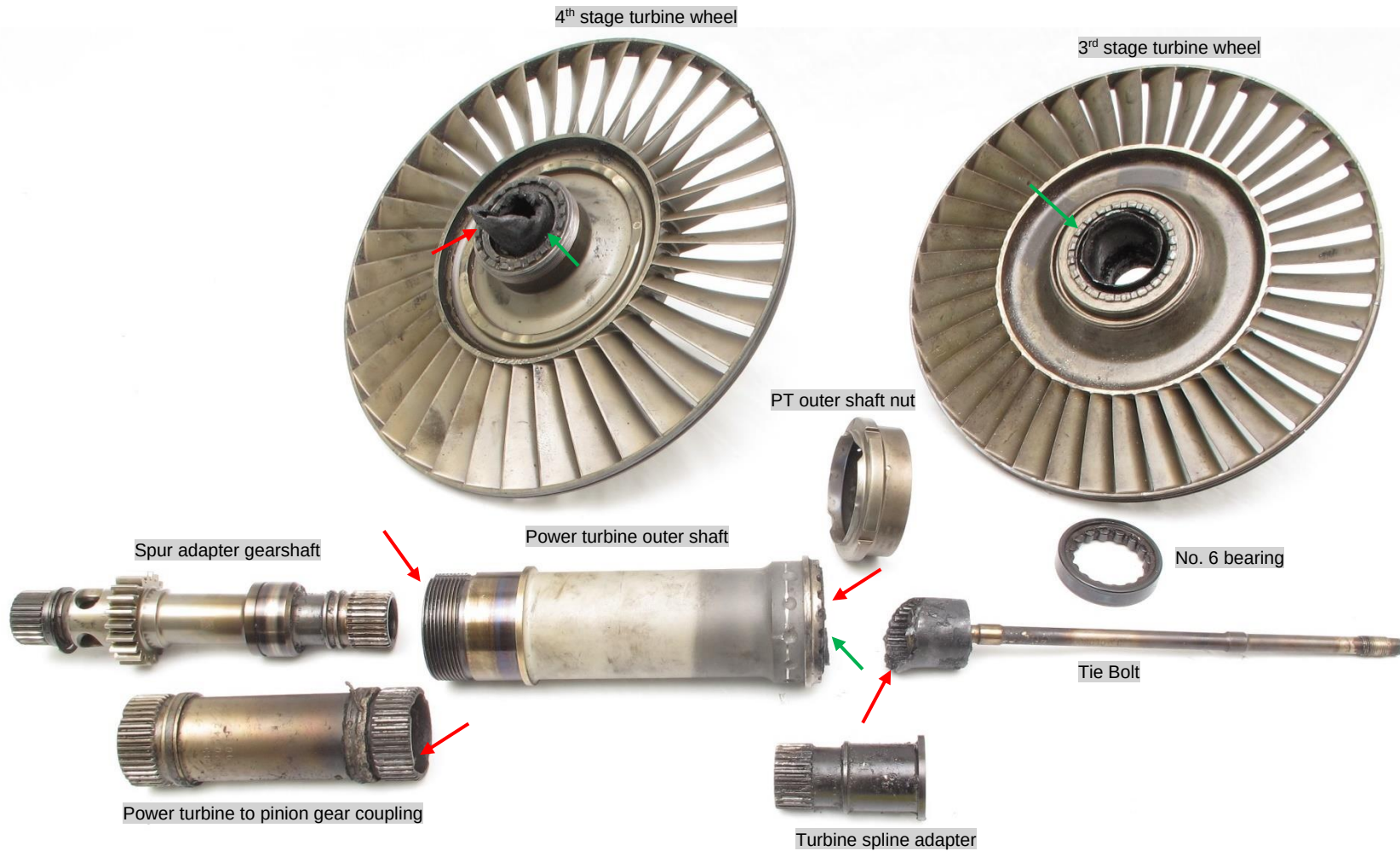


Figure 2. Overall view of the components submitted for investigation in the as-received condition. The red and green arrows indicate locations where the turbine to compressor coupling and PT inner shaft, respectively, were fractured and retained within the surrounding components.



Figure 3. Overall outboard looking inboard views of the power turbine outer shaft in the as-received condition. Each image is rotated approximately 180° from the previous. The red arrows indicate circumferential score marks consistent with disassembly damage from the PT coupling nut.



Figure 4. Overall aft looking forward views of the power turbine outer shaft in the as-received condition. Smeared PT inner shaft, PT inner coupling nut, and turbine to compressor coupling material was observed on the aft end along with coked oil.

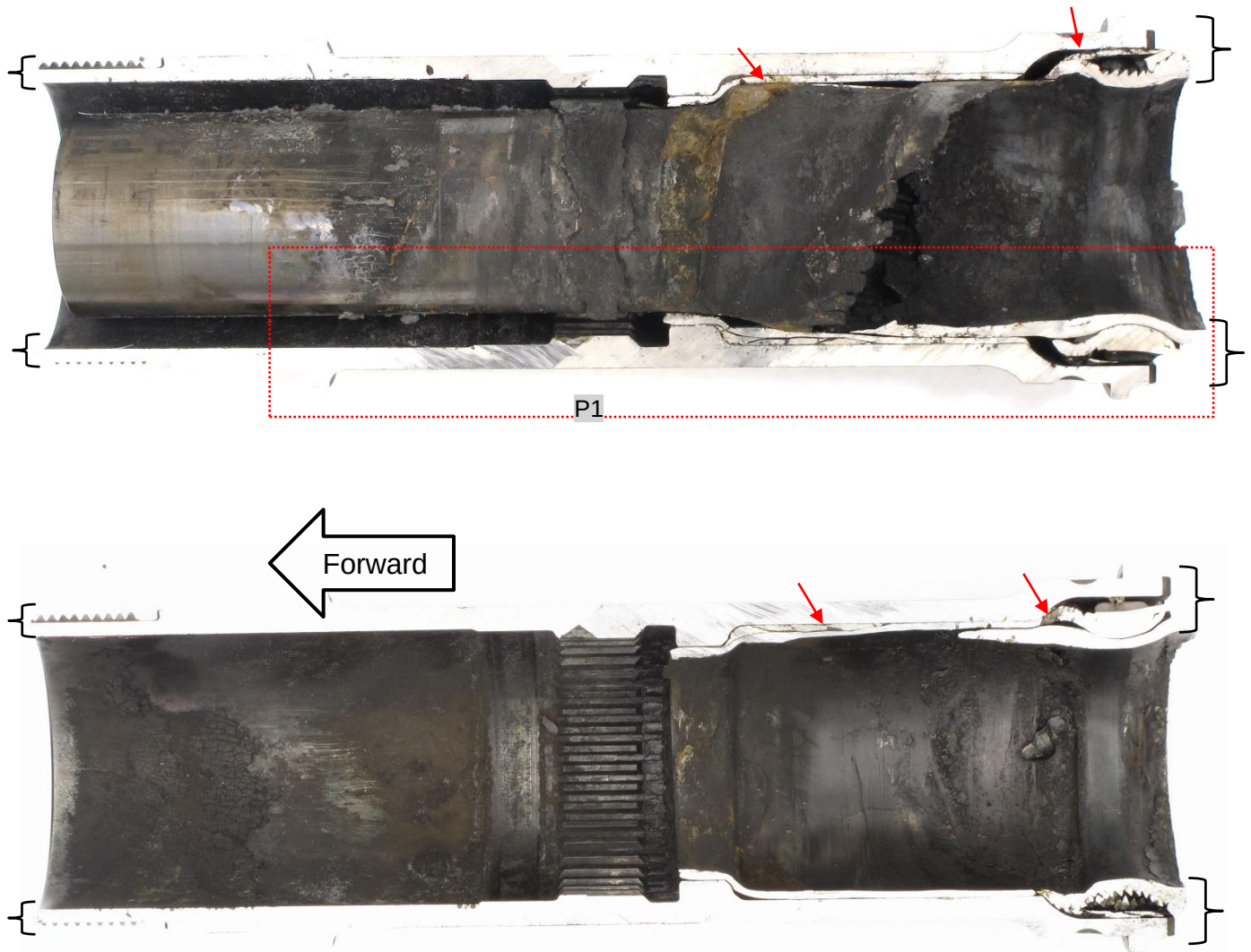


Figure 5. Overall views of the two halves of the PT outer shaft following laboratory cuts (black braces), showing fracture and deformed material from the PT inner shaft, PT inner coupling nut, and turbine to compressor coupling. Coked oil product was observed throughout the inboard surfaces of the PT outer shaft and outboard surfaces of the turbine to compressor coupling. Rust product on the laboratory cut surfaces from exposure to tool coolant is indicated by the red arrows (not all are noted). The plane (P1) indicated by the red box was selected for metallographic examination shown in Figure 10.

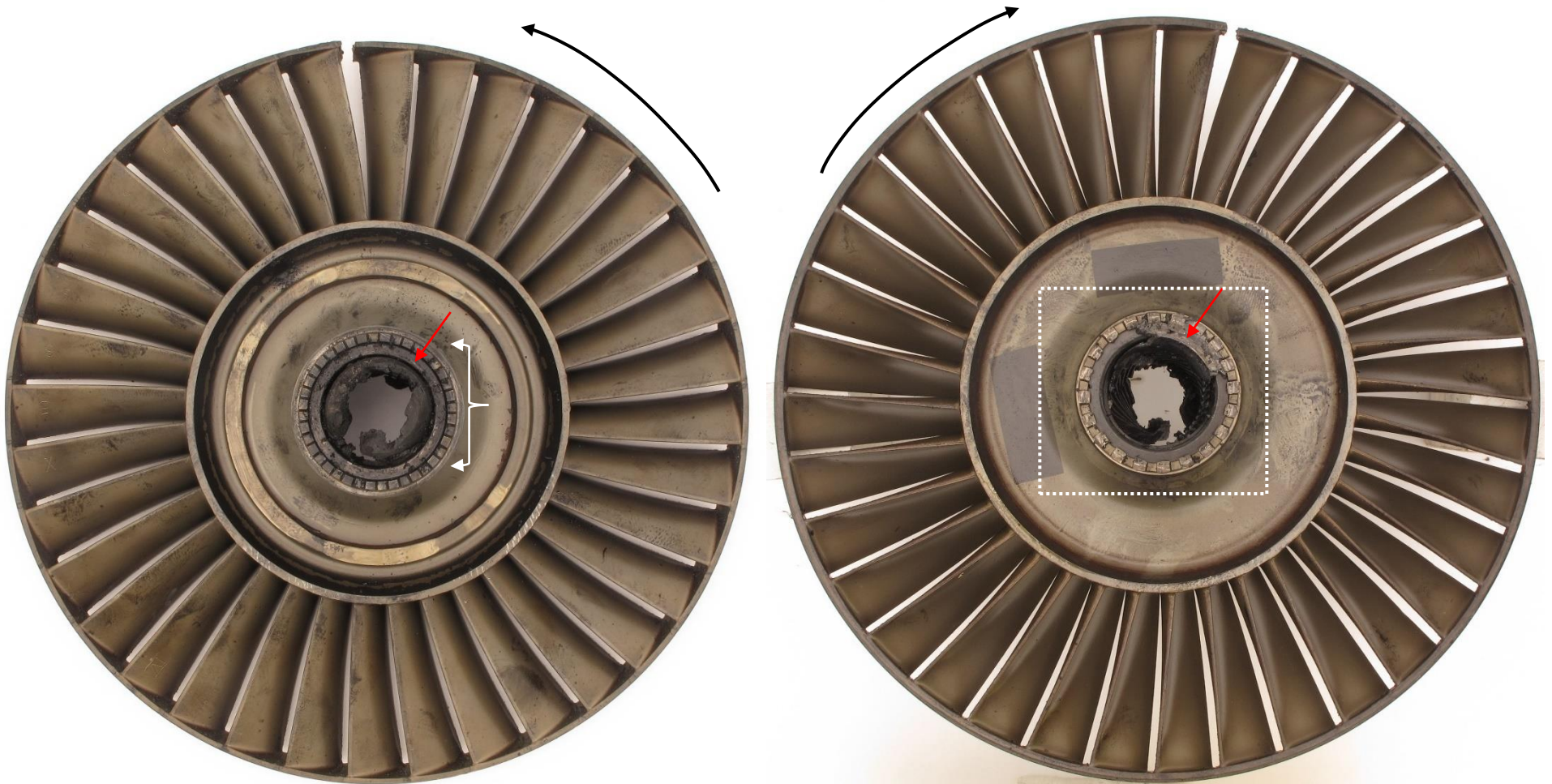


Figure 6. Overall forward looking aft (left) and aft looking forward (right) views of the 4th stage turbine wheel. Turbine to compressor coupling material is indicated by the red arrows. The black arrows indicate the direction of engine rotation. The areas indicated by the white box and brace are shown in more detail in Figure 7.

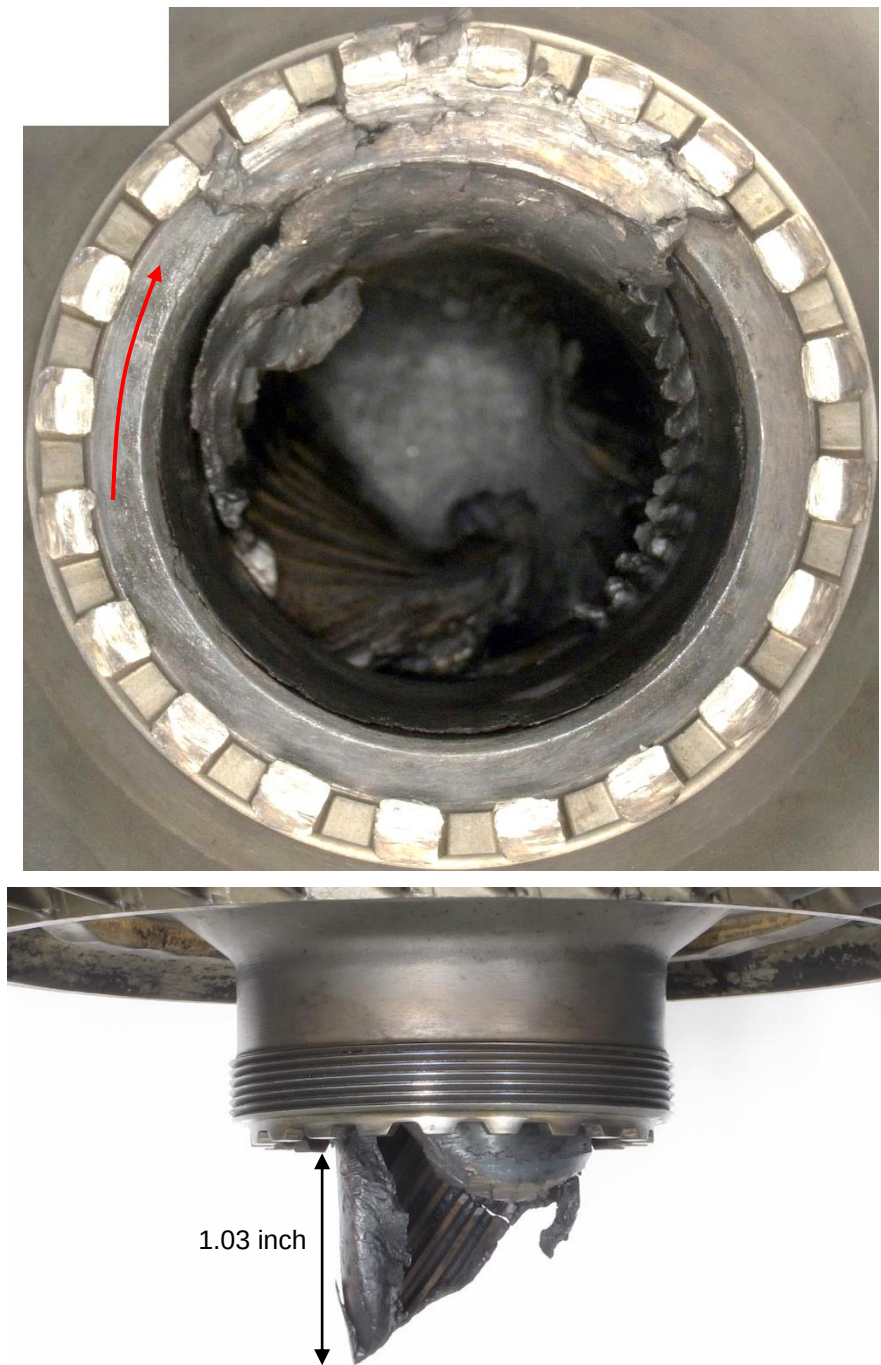


Figure 7. Top: Detailed aft looking forward view of the 4th stage turbine wheel showing rub on the Curvic teeth and fractured and deformed turbine to compressor coupling and PT inner shaft material. The red arrow indicates the direction of engine rotation.
Bottom: Outboard looking inboard view of the forward Curvic coupling showing the turbine to compressor coupling material.

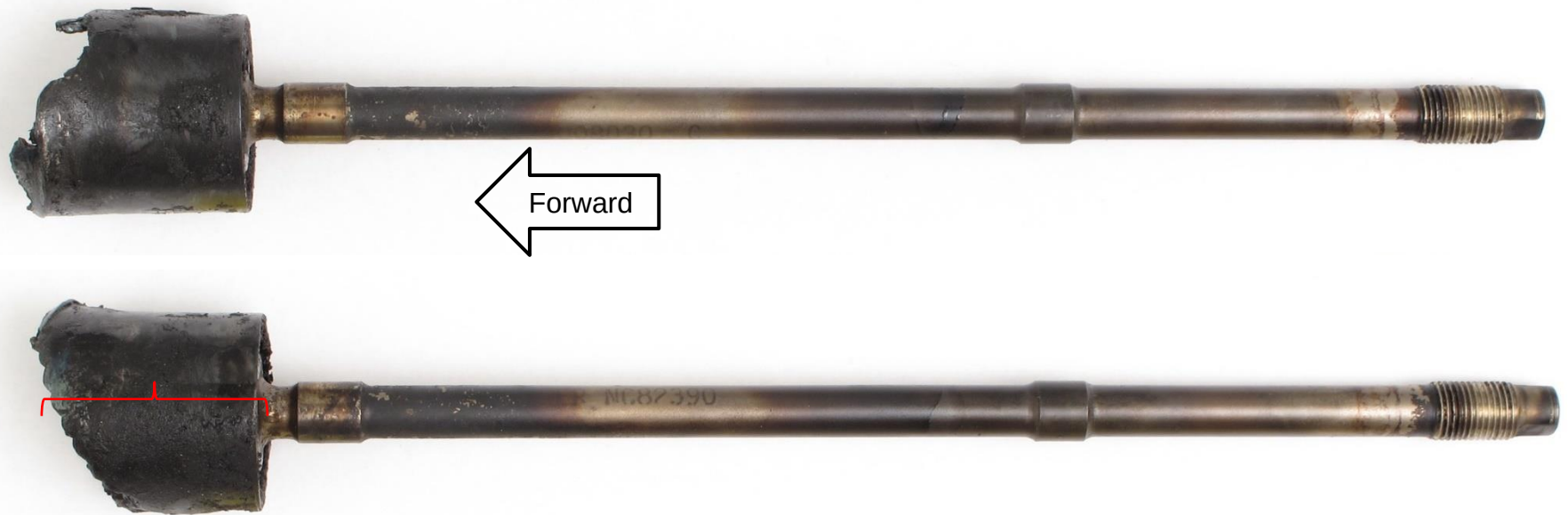


Figure 8. Overall outboard looking inboard views of the tie bolt in the as-received condition. Each image is rotated approximately 180° from the previous. The portion of the turbine to compressor coupling is indicated by red braces.



Figure 9. Overall view of the turbine to compressor coupling pieces. Not pictured: portions of the turbine to compressor coupling embedded in the 4th stage turbine wheel (see Figure 6) and the PT outer shaft (see Figure 5). The green brace indicates PT inner shaft material and the PT inner coupling nut adhered to the turbine to compressor coupling. The white dashed line indicates the approximate cross-section (P2) selected for metallographic examination as shown in Figure 17.

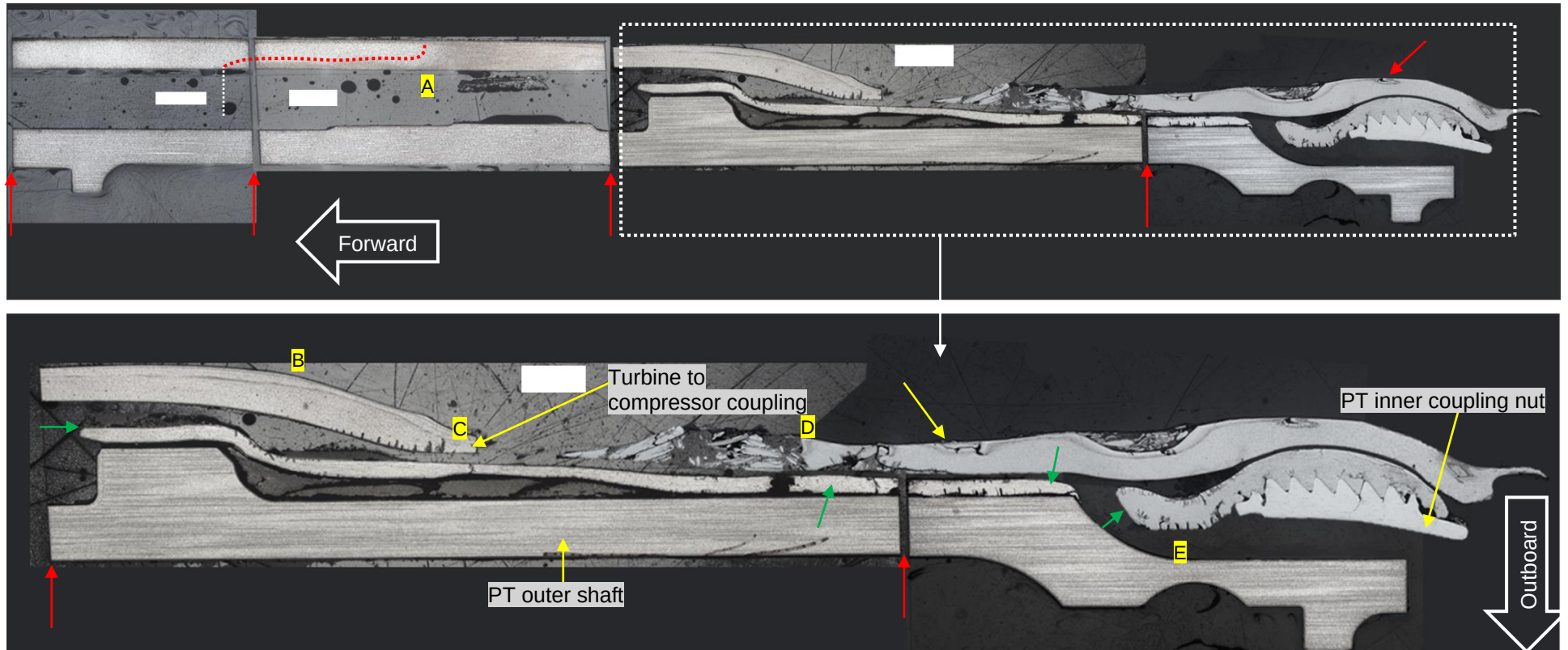


Figure 10. Montaged metallographic images of the cross-section (P1, see Figure 5) of the PT outer shaft, PT inner shaft (green arrows, bottom image), turbine to compressor coupling, and PT inner coupling nut showing the extent of thermally distressed material in the turbine to compressor coupling (red border, top image). The extent of thermal distress is shown by the white double arrows, measured forward of the pinion gear coupling retaining arm. The red arrows indicate laboratory cuts. Locations A through E are shown in more detail in the following figures. Etchant: Nital.

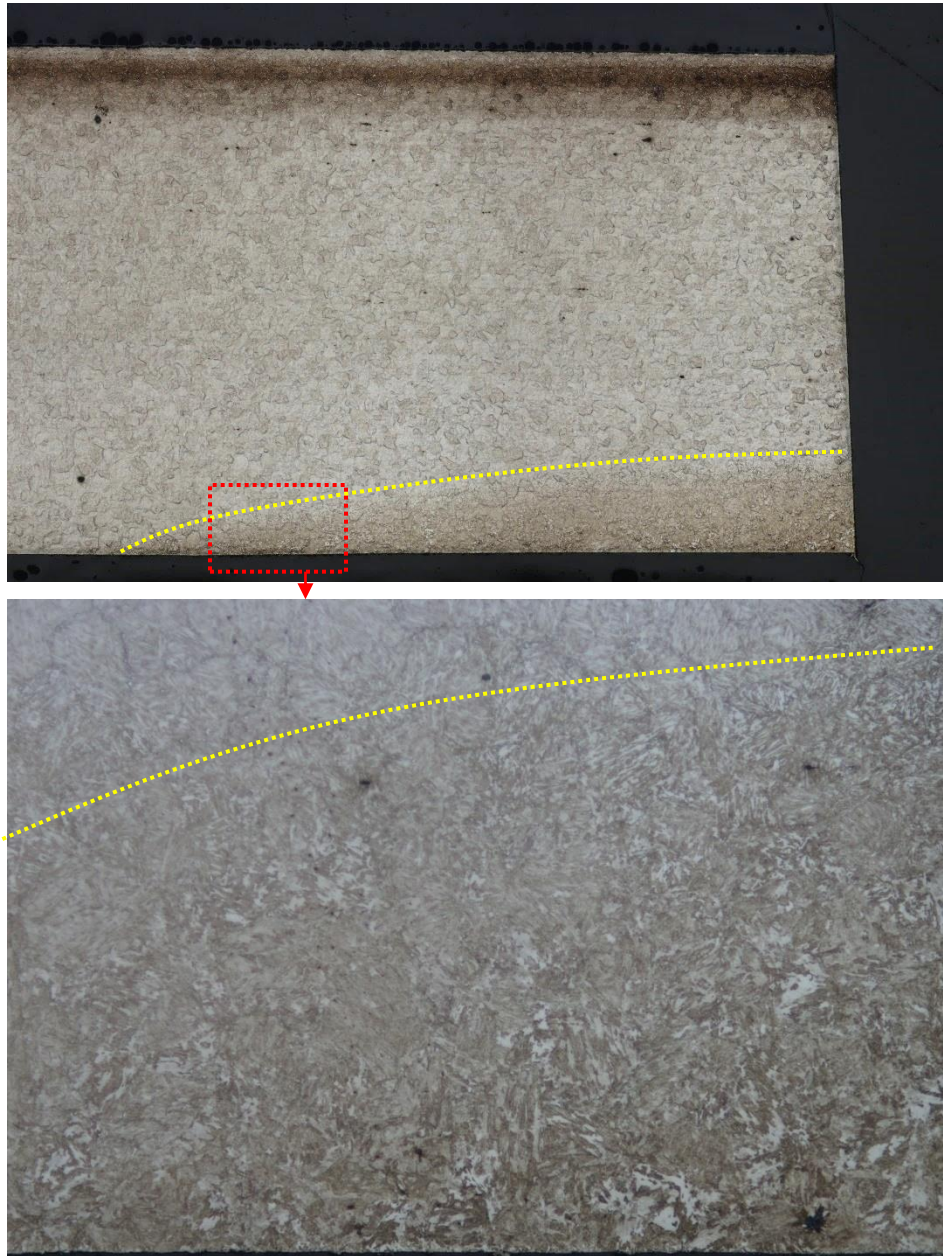


Figure 11. Detailed metallographic images of the turbine to compressor coupling at the forward extent of thermal distress (location A from Figure 10). The yellow dashed line indicates the extent of thermal distress. Etchant: Nital.

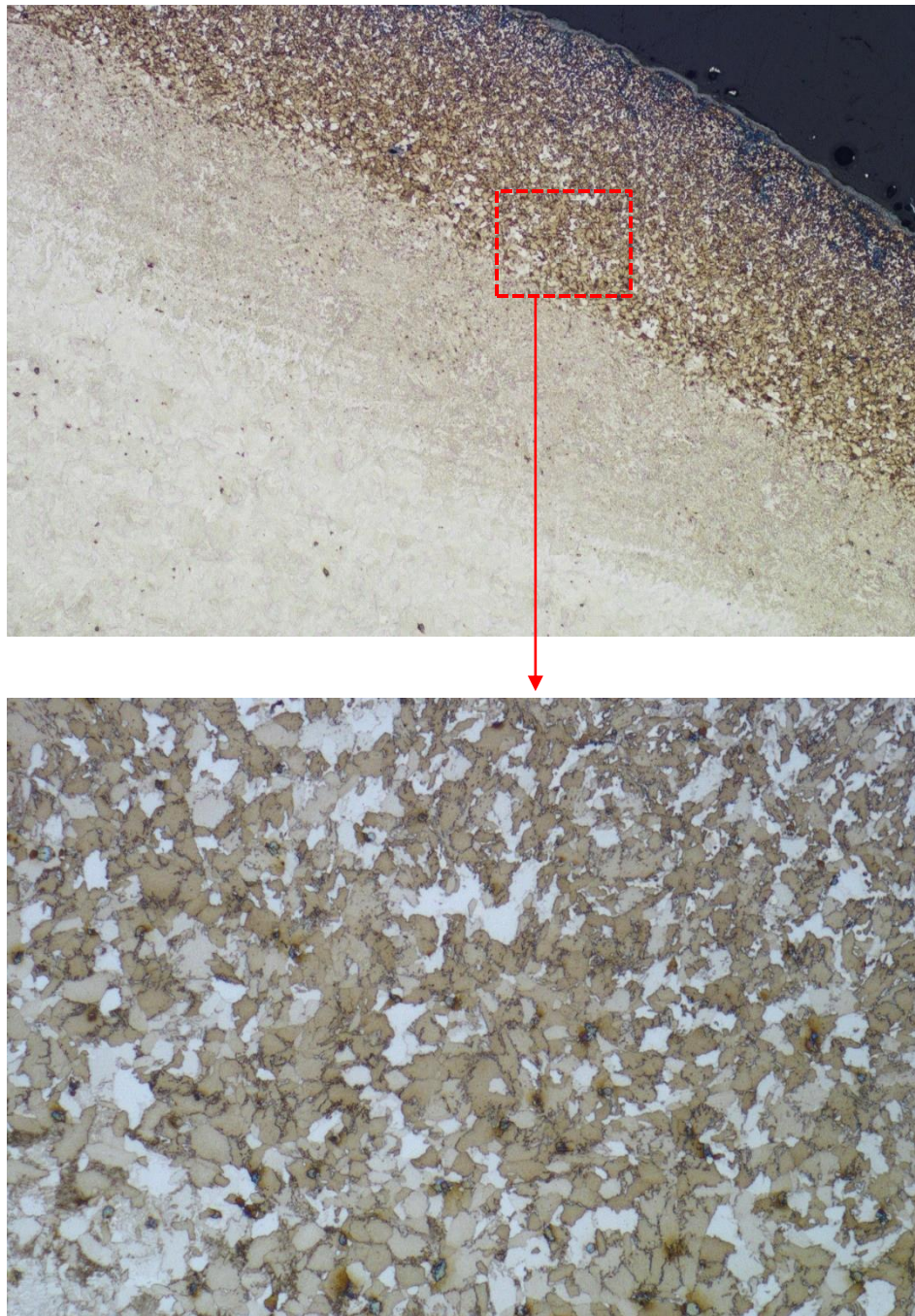


Figure 12. Detailed metallographic images of the turbine to compressor coupling (location B from Figure 10) showing thermally distressed nitride case microstructure. Etchant: Nital.



Figure 13. Detailed metallographic images of the turbine to compressor coupling (black braces) and PT inner shaft material (yellow braces) (location C from Figure 10) showing localized areas of transformed material (red arrows). Melted PT inner shaft material is indicated by the yellow braces. Etchant: Nital.

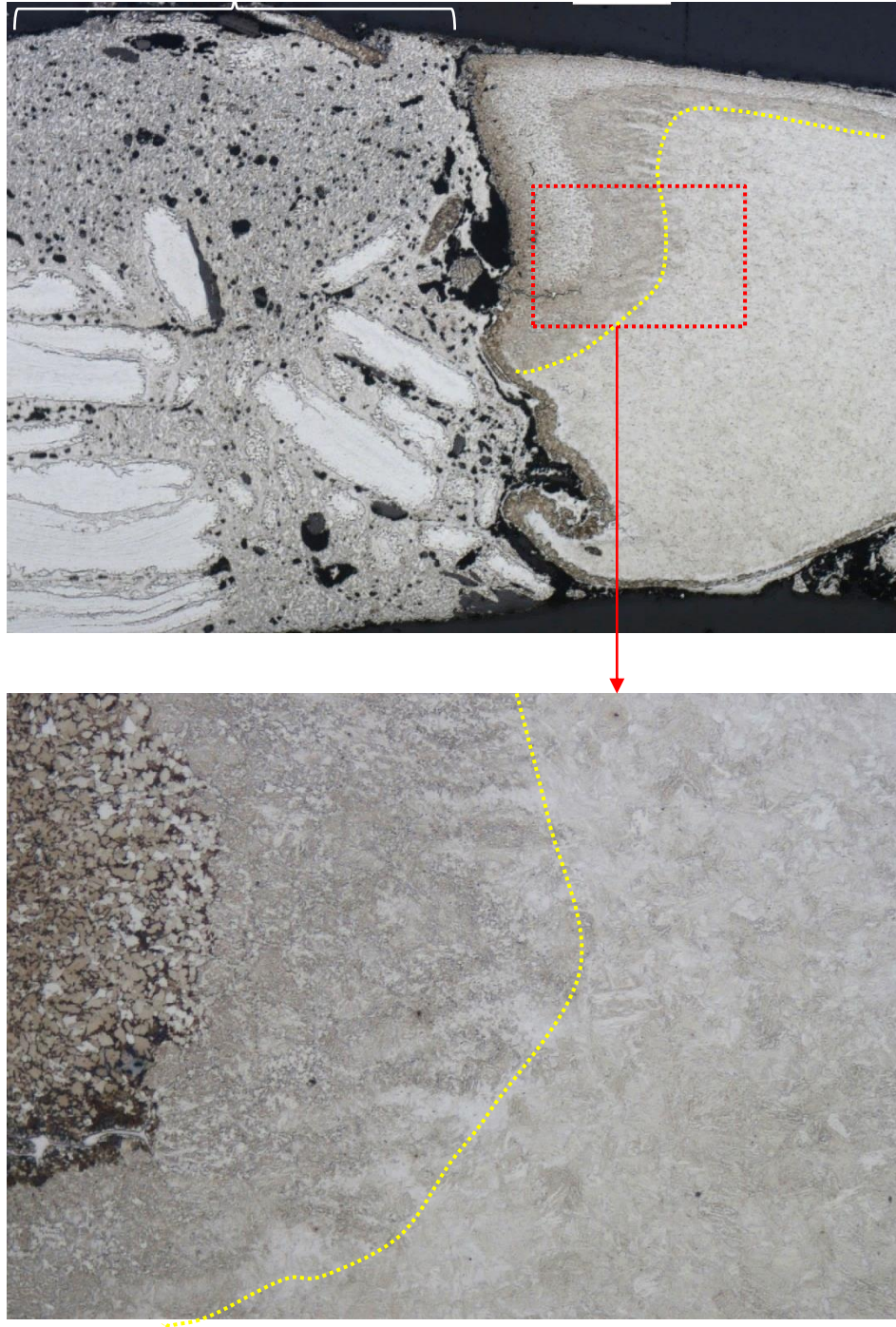


Figure 14. Detailed metallographic images of the turbine to compressor coupling at location D from Figure 10 showing resolidified material (white brace) and deformed and thermally distressed nitride case (yellow border) and core material. Etchant: Nital.

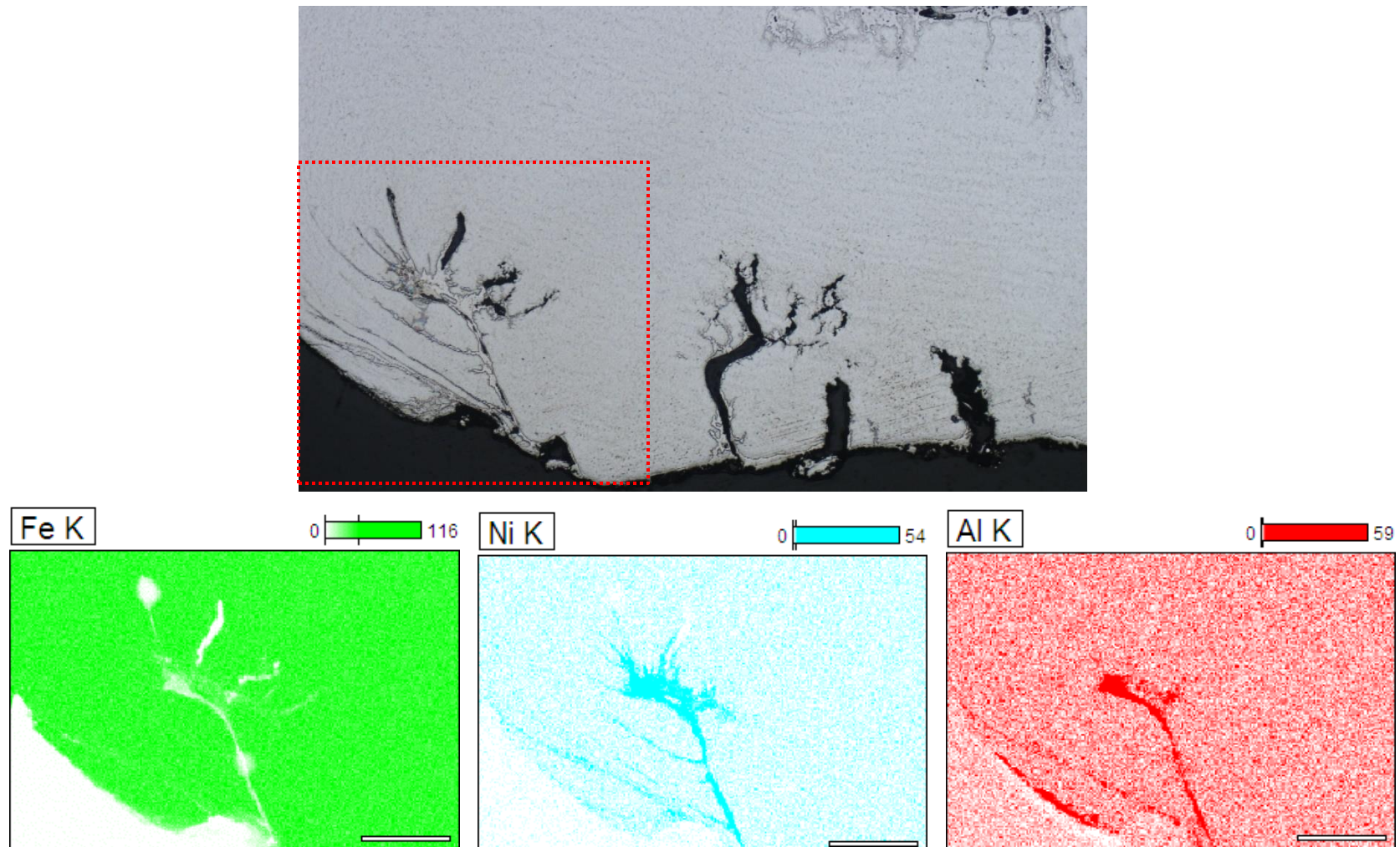


Figure 15. Top: Detailed metallographic image (top) and EDS maps (bottom) of the PT inner shaft outer diameter surface at location E from Figure 10. Etchant: Nital.
Bottom: EDS element maps showing spatial concentrations of iron (left), nickel (center), and aluminum (right), which show diffusion of the nickel plate and aluminum coating into the base material.

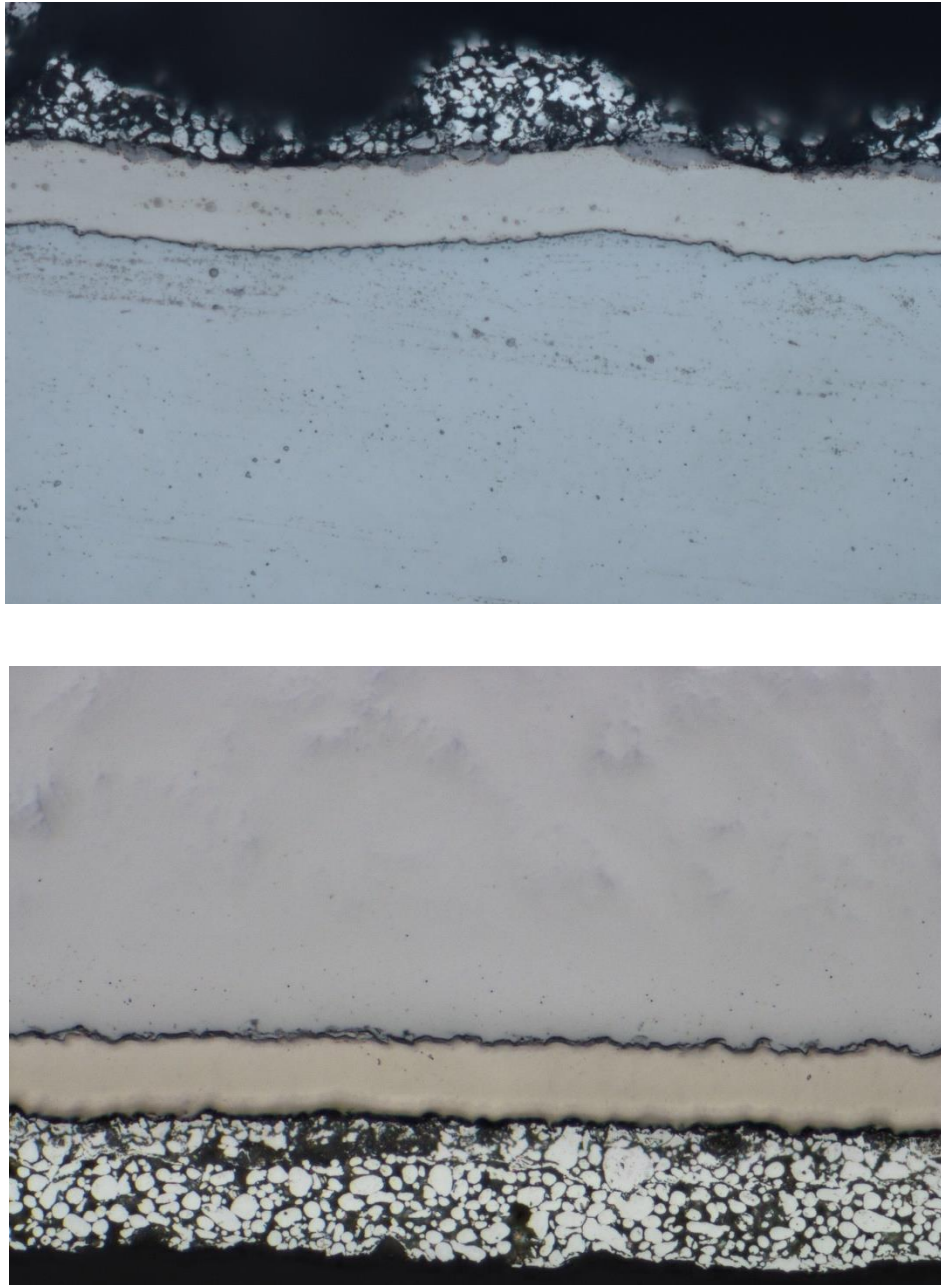
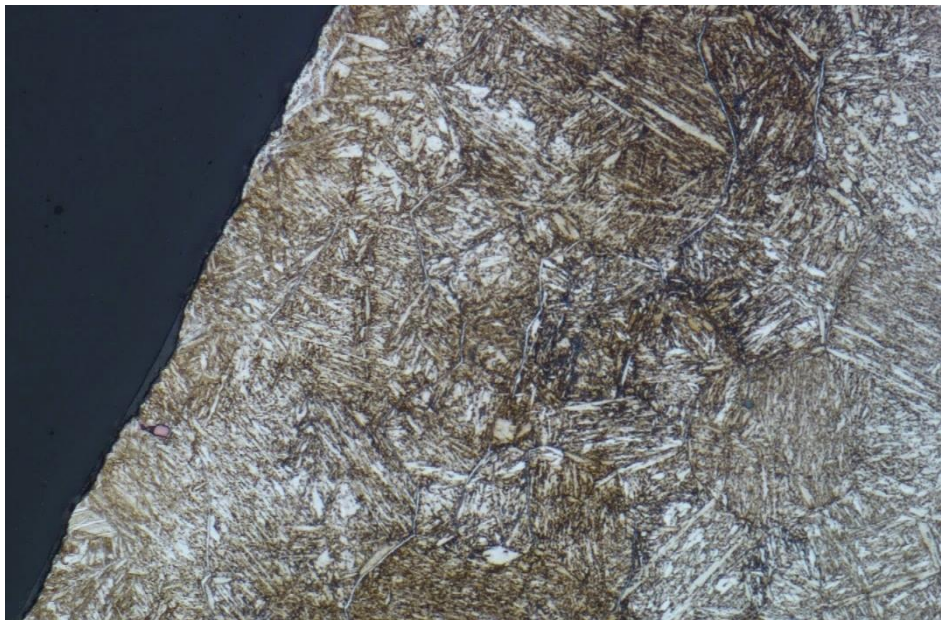
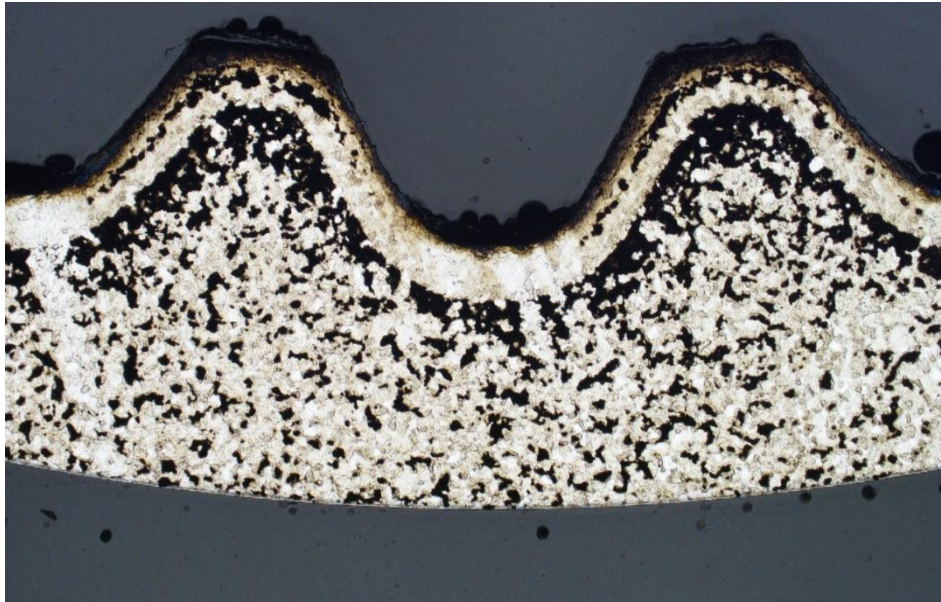


Figure 16. Representative metallographic images of the PT outer shaft inner (top) and outer (bottom) diameter surfaces showing nickel plating (red double arrow) and aluminum coating (yellow double arrow). Etchant: None.



Original Magnification = 500X

Figure 17. Top: Metallographic image of the cross-section at plane P2, white dashed line in Figure 9, showing the spline teeth and case depth in the turbine to compressor coupling. Etchant: Marbles. Bottom: Representative microstructure of the turbine to compressor coupling case material. Etchant: Nital.

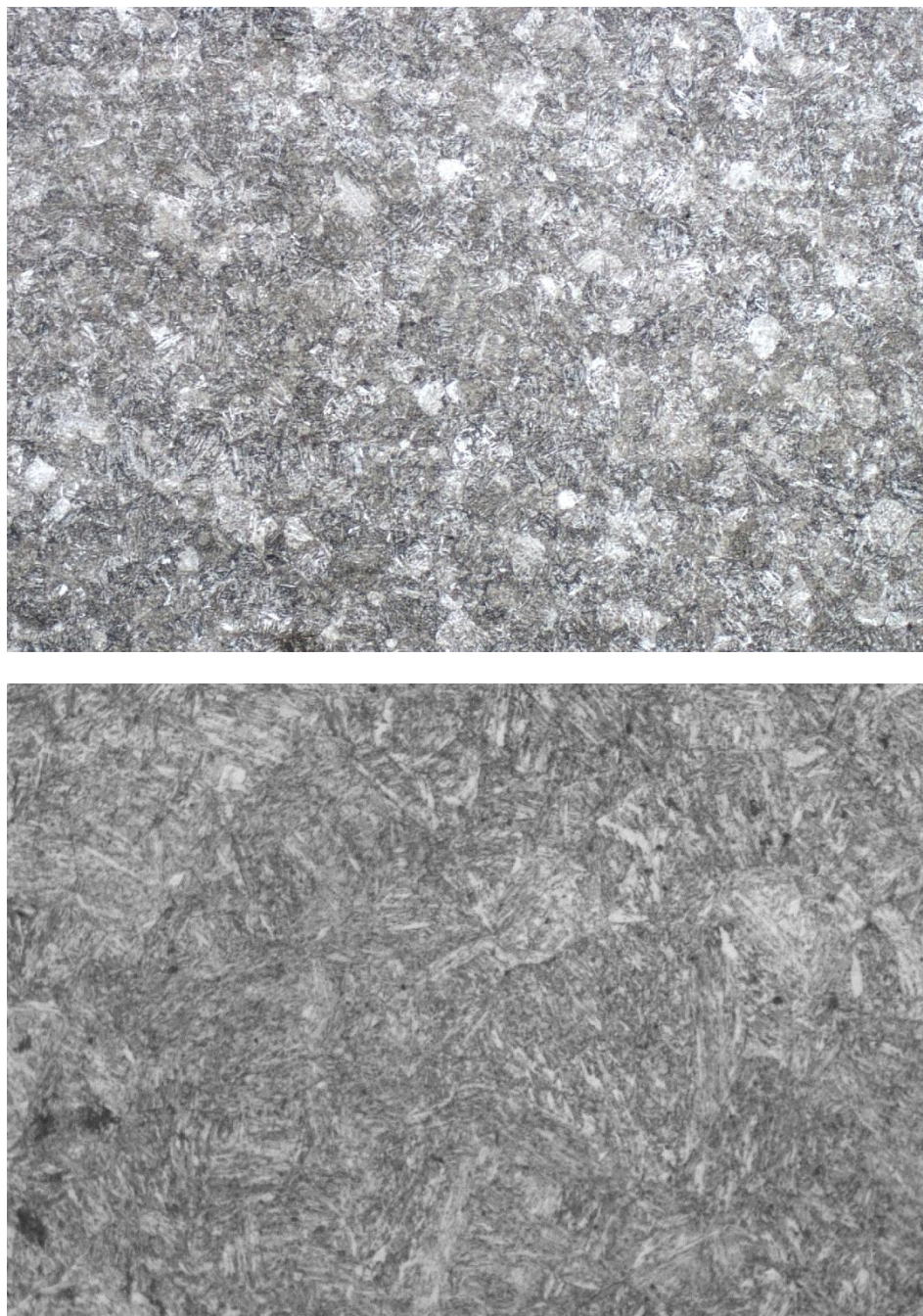


Figure 18. Representative microstructure of the turbine to compressor coupling core material from cross-section P2 (see Figure 9). Etchant: Nital.

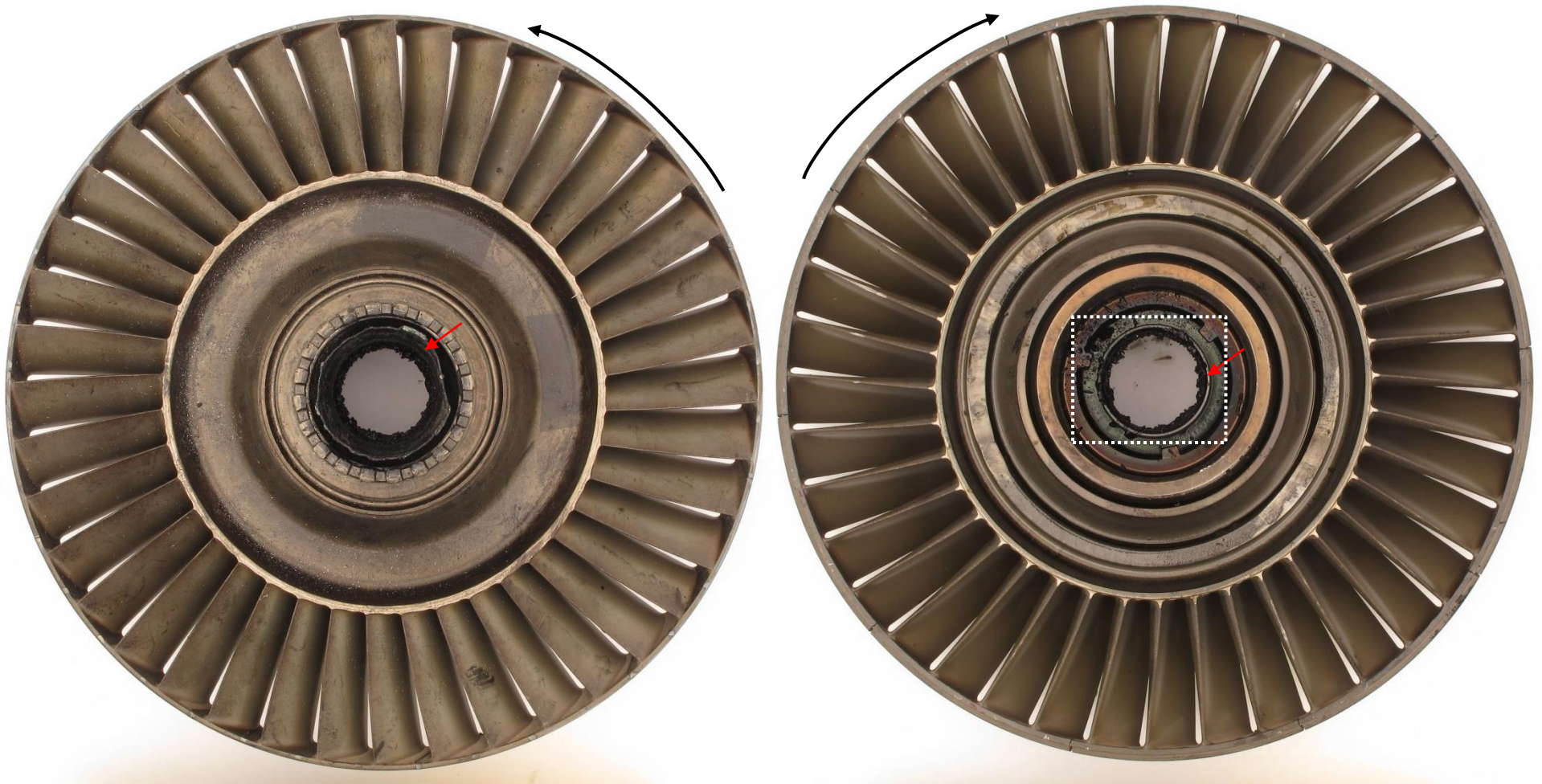


Figure 19. Overall forward looking aft (left) and aft looking forward (right) views of the 3rd stage turbine wheel and PT inner shaft remnants (red arrows). The area indicated by the white box is shown in more detail in the following figure.

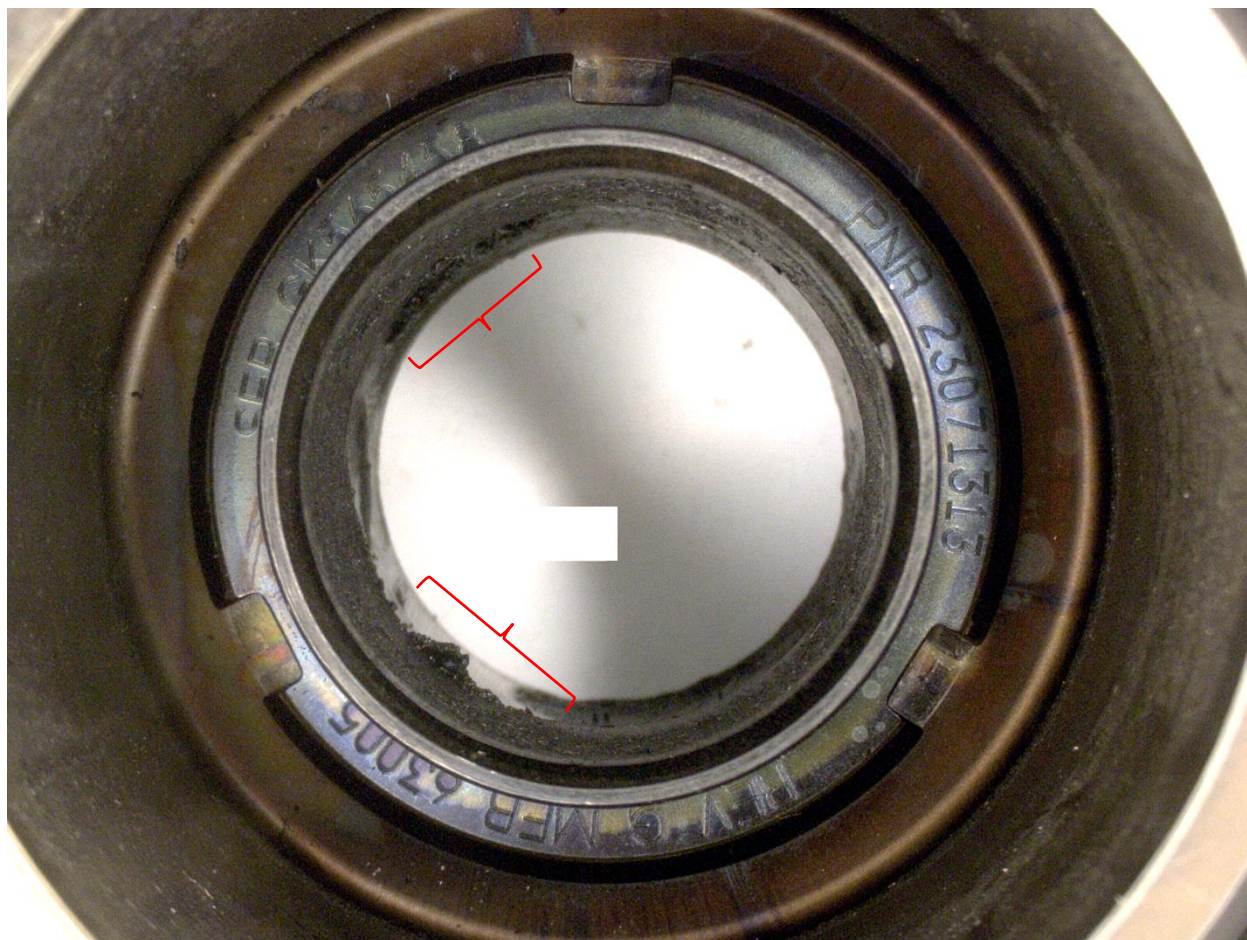


Figure 20. Detailed view of the PT inner shaft aft end as assembled in the 3rd stage turbine wheel. The red braces indicate dark deposits on the PT inner shaft inner diameter consistent with coked oil.

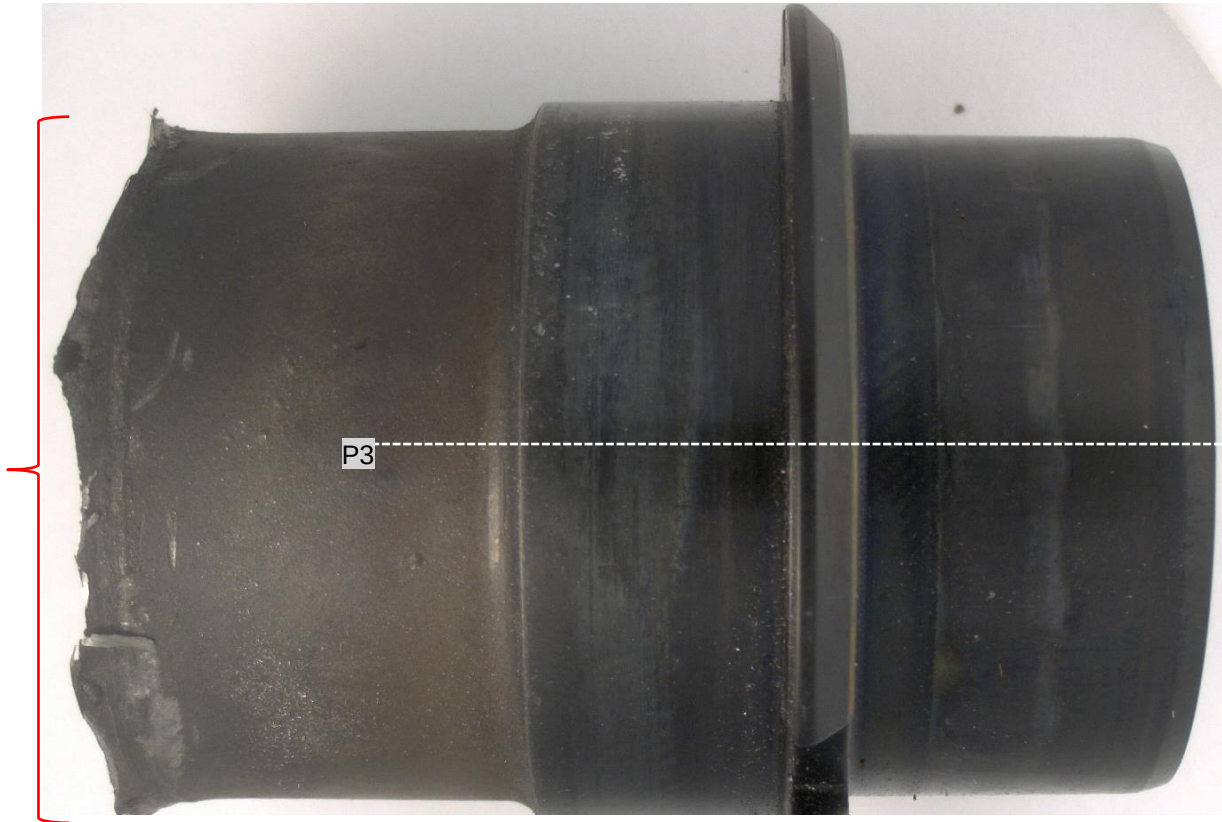
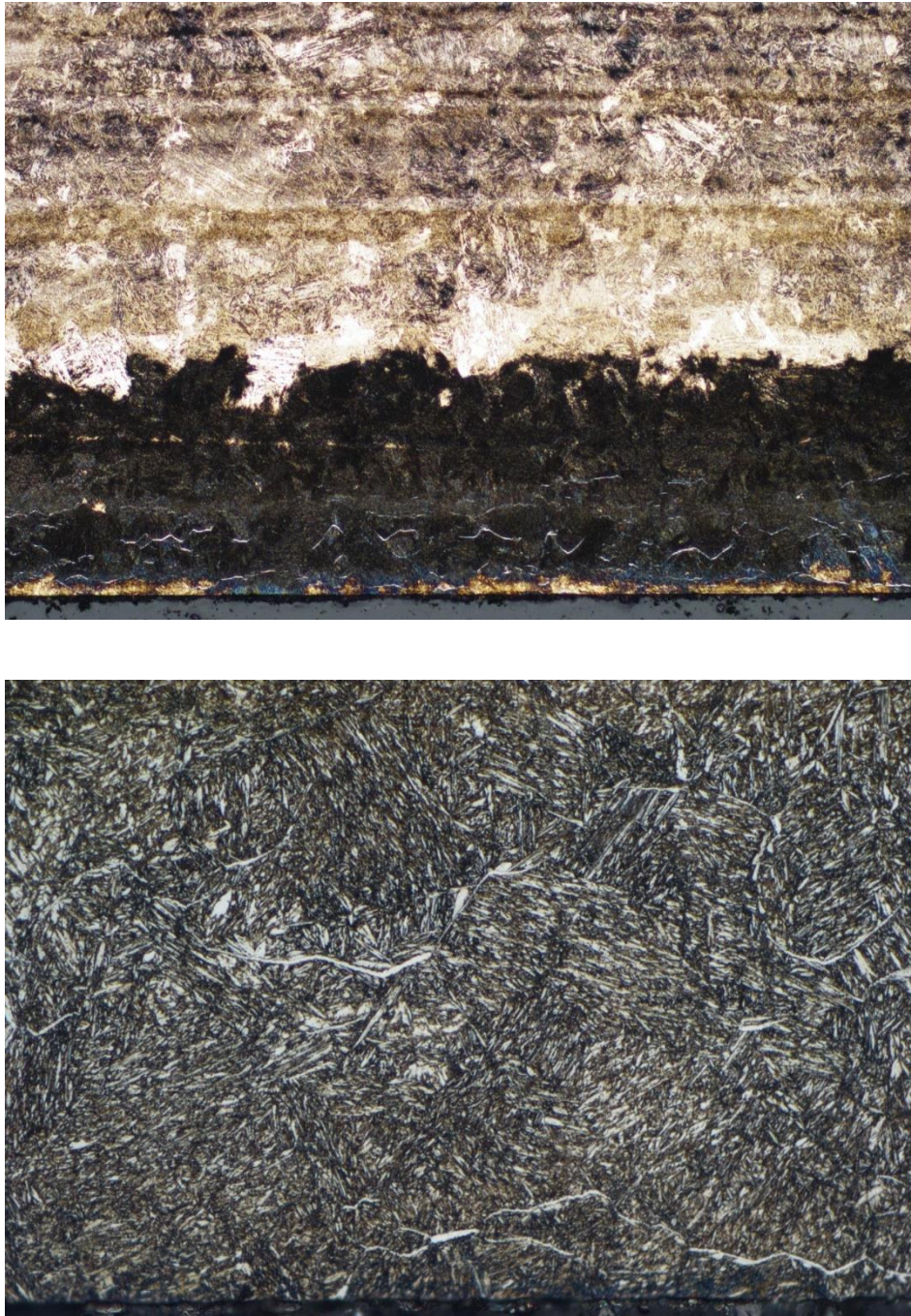


Figure 21. Detailed outboard looking inboard view of the PT inner shaft aft remnant following removal from the 3rd stage turbine wheel. The red brace indicates laboratory cuts made to excise the PT inner shaft from the 3rd stage turbine wheel bore. The white dashed line indicates the approximate cross-section (P3) selected for metallographic examination of the PT inner shaft shown in Figure 22.



0.001 inch

Figure 22. Detailed metallographic images of the PT inner shaft nitride case material from cross-section P3 (see Figure 21).
Etchants: Top: Marbles; Bottom: Nital.

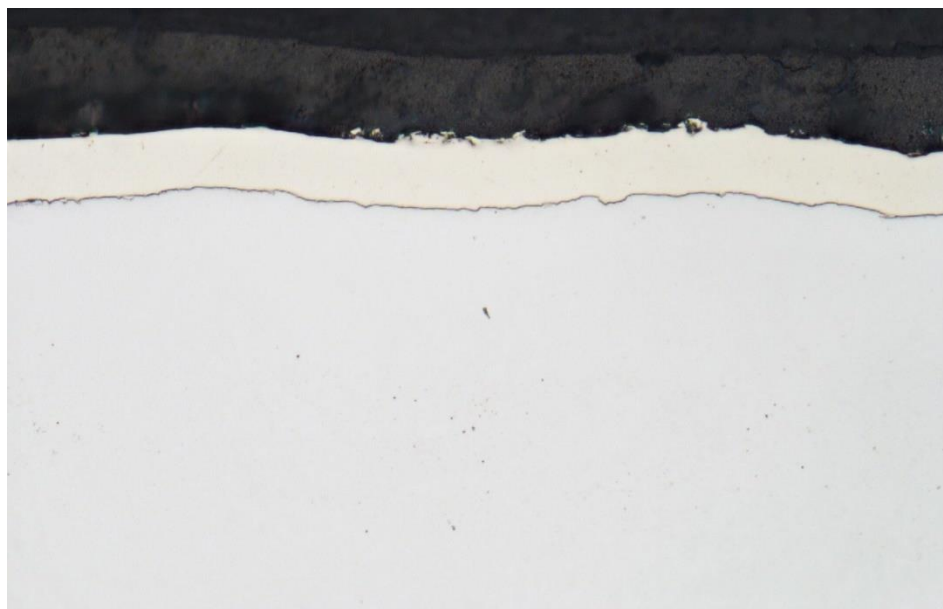


Figure 23. Metallographic image of the PT inner shaft nickel plating from cross-section P3 (see Figure 21). Etchant: None.



Figure 24. Representative microstructure of the PT inner shaft core material from cross-section P3 (see Figure 21). Etchant: Nital.

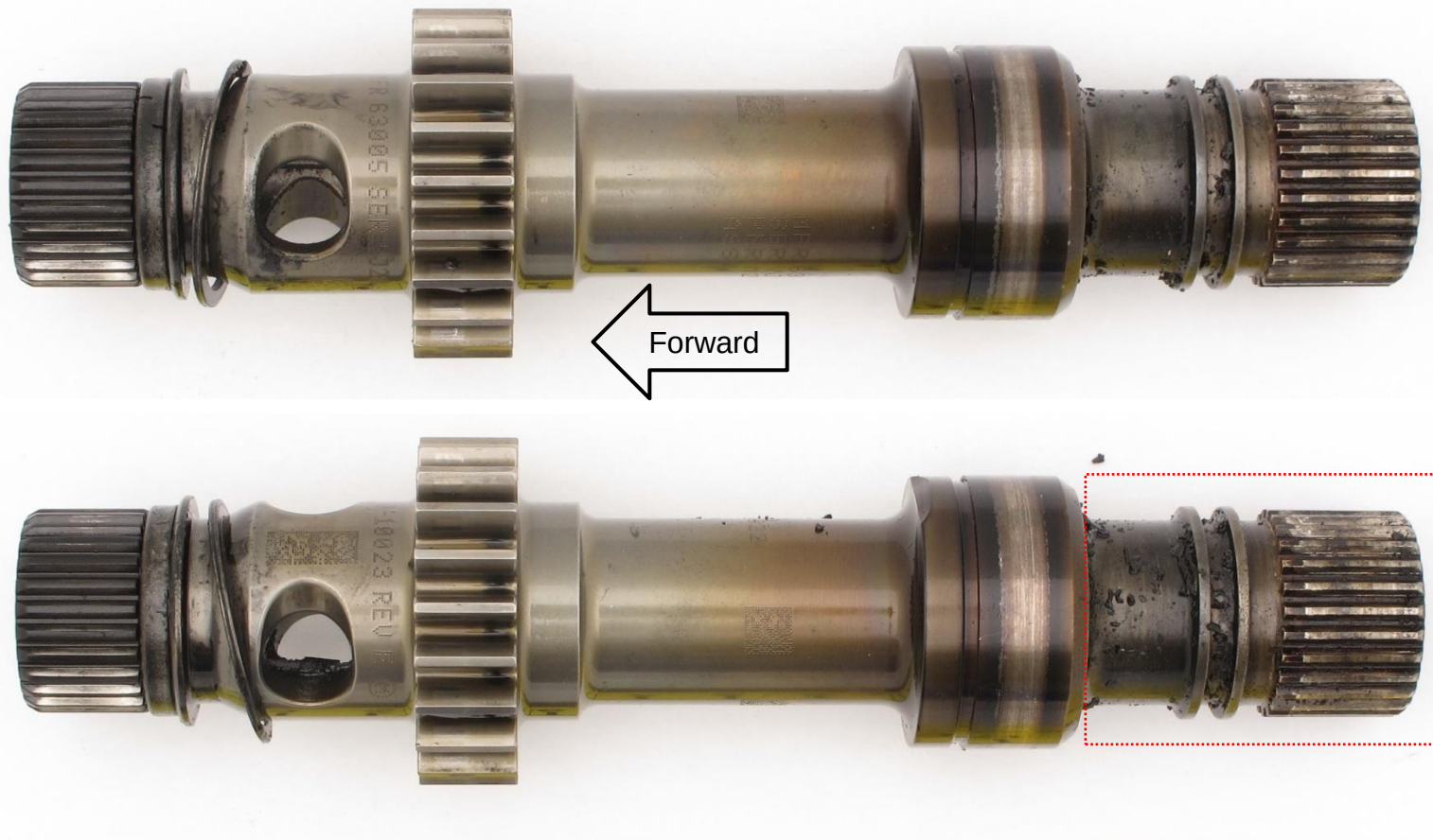


Figure 25. Overall outboard looking inboard views of the spur adapter gearshaft in the as-received condition. Each image is rotated approximately 180° from the previous. The red boxed area is shown in more detail in the following figure.

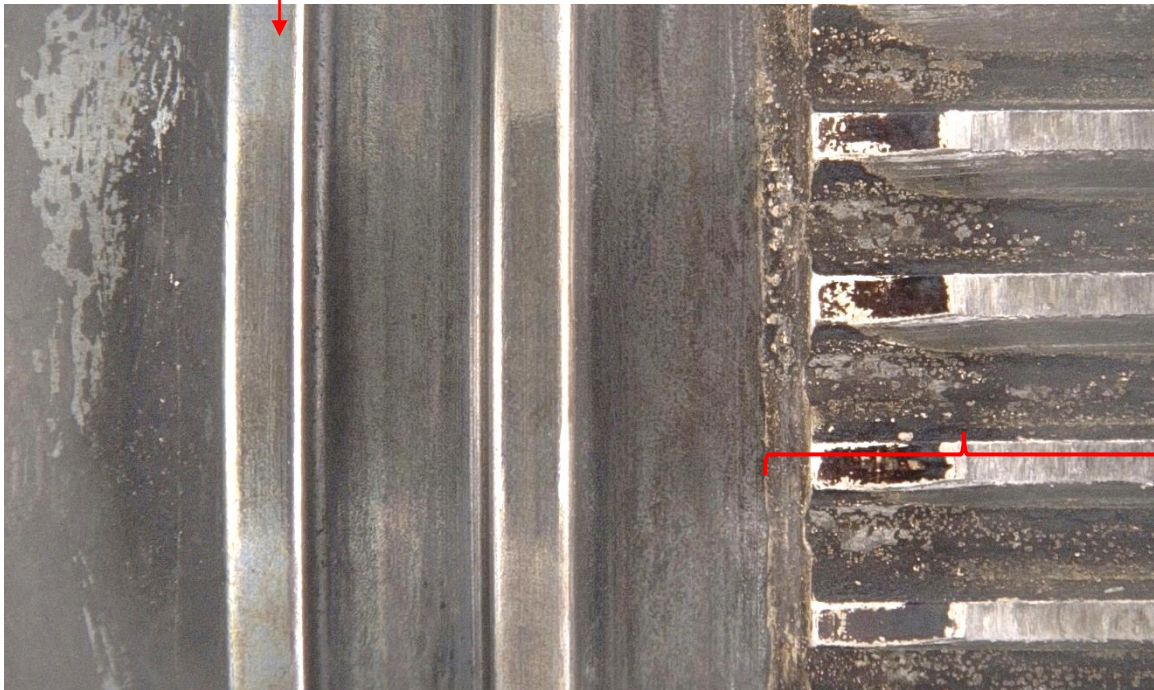
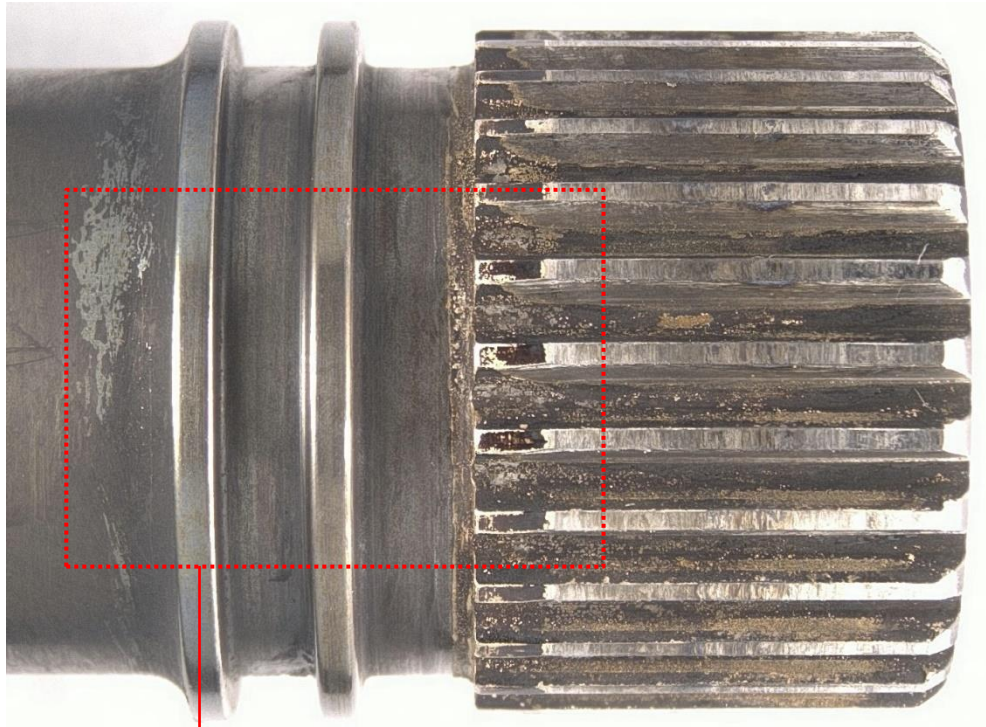


Figure 26. Detailed outboard looking inboard views of the spur adapter gearshaft O-ring grooves (black braces) and aft spline. The axial span of coked oil is indicated by the red braces and was observed in the spline roots, tooth tips, and forward into the O-ring groove. No evidence of coked oil was observed in the forward O-ring groove.

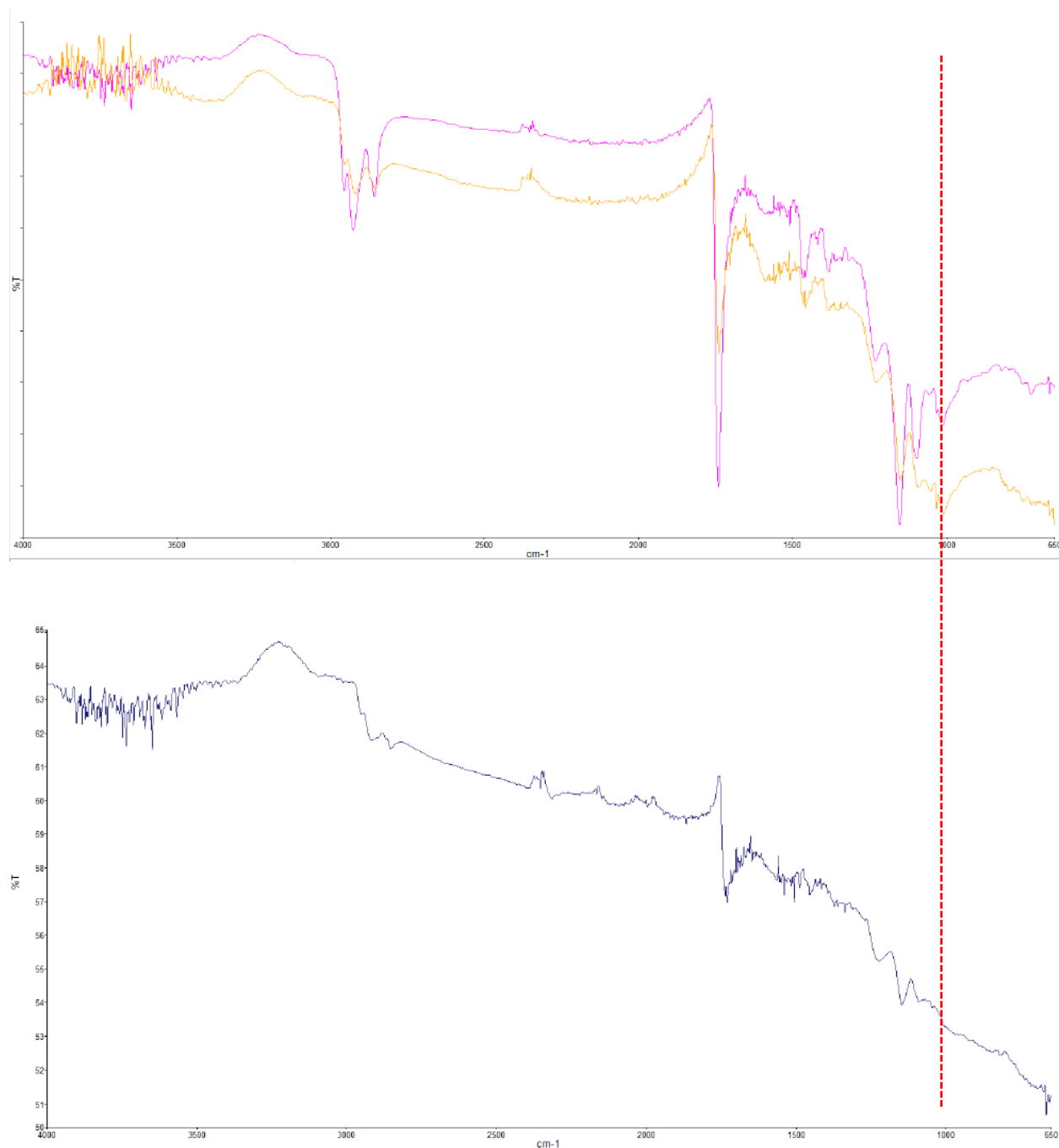


Figure 27. FTIR results showing spectra from coked oil material recovered from the spur adapter gearshaft (top) and the 4th stage turbine wheel (bottom). The red dashed line indicates the C-F stretch at 1050 cm⁻¹ that was observed in the spur adapter gearshaft material and not observed in the 4th stage turbine wheel material. This signal is associated with a fluorocarbon rubber consistent with O-ring material installed on the spur adapter gearshaft.

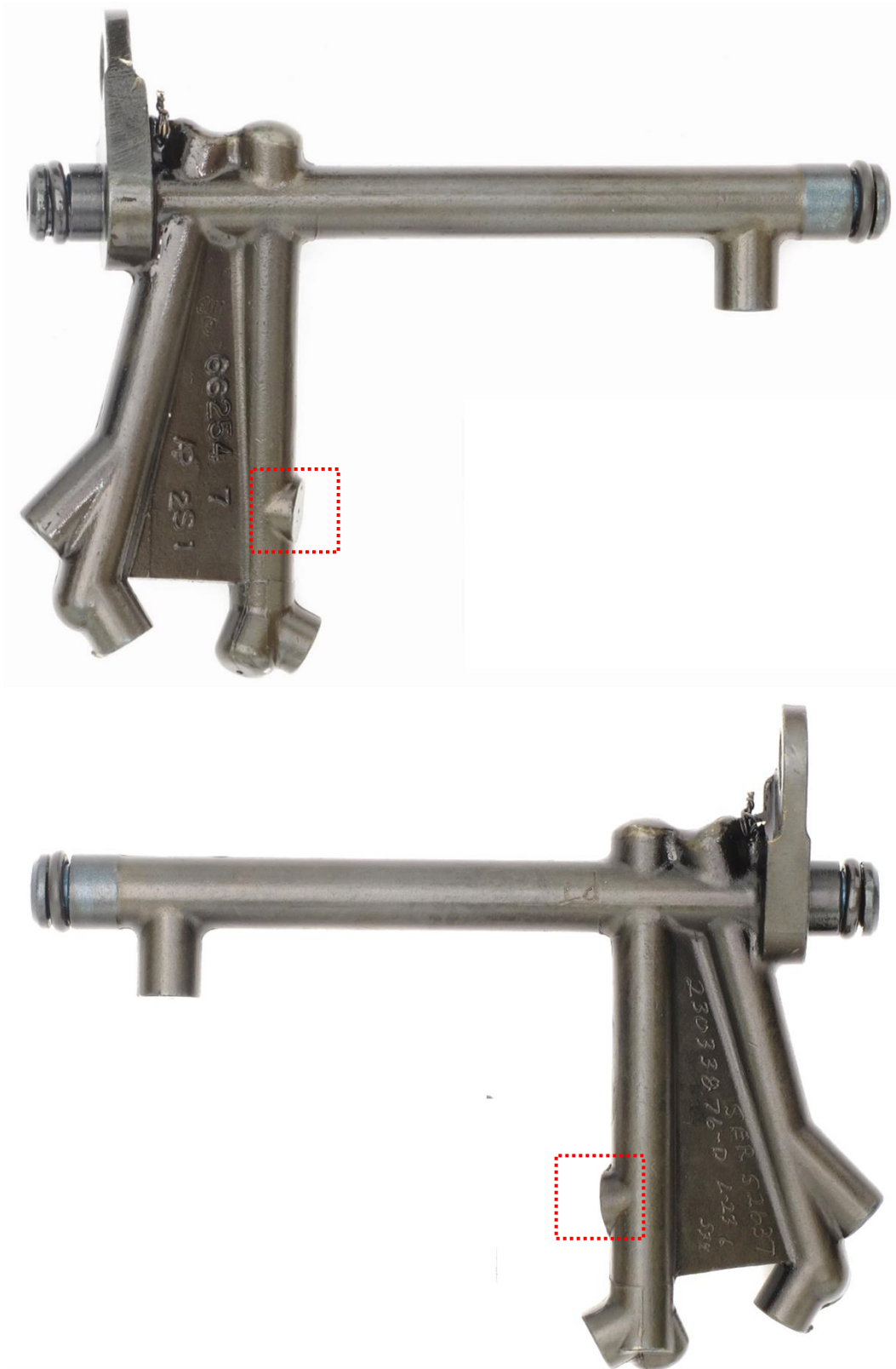


Figure 28. Overall views of the oil delivery tube in the as-received condition. The No. 3 bearing oil jet indicated by the red boxes is shown in more detail in the following figure.

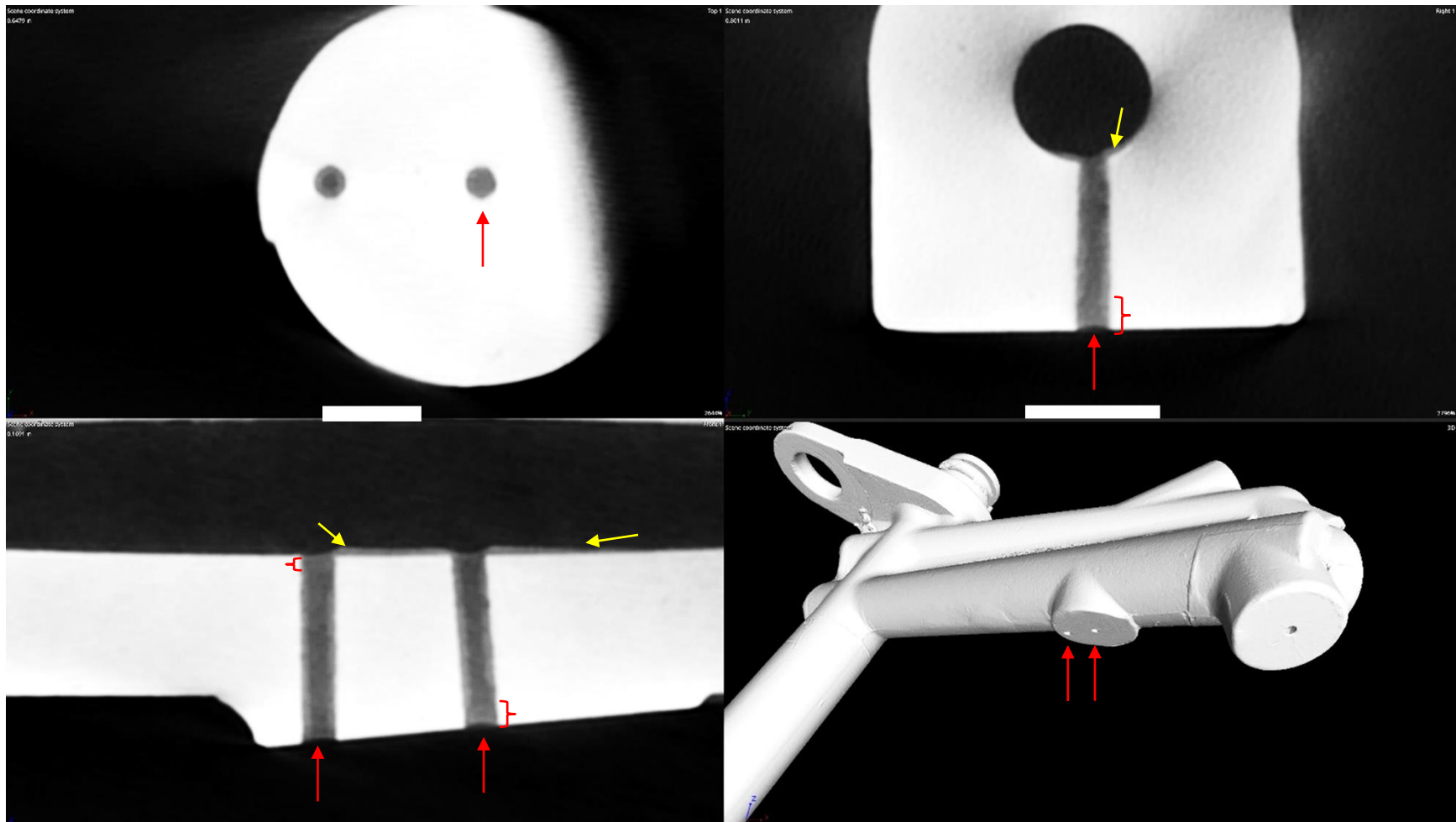


Figure 29. CT radiograph of the oil jet to the No. 3 bearing (red box in previous figure) showing a blocked passage (red arrows), which exhibited higher density material in the blockage and the inner cavity walls (yellow arrows) and spanned the entire diameter at the passage exit (red braces).



Figure 30. Top: Detailed view of the oil screen back lit from the aft end. Dark deposits consistent with coked oil product were observed around a majority of the screen surface. Bottom: overall view of filtered product from the oil screen. The product consisted of a black powder type material consistent with coked oil.

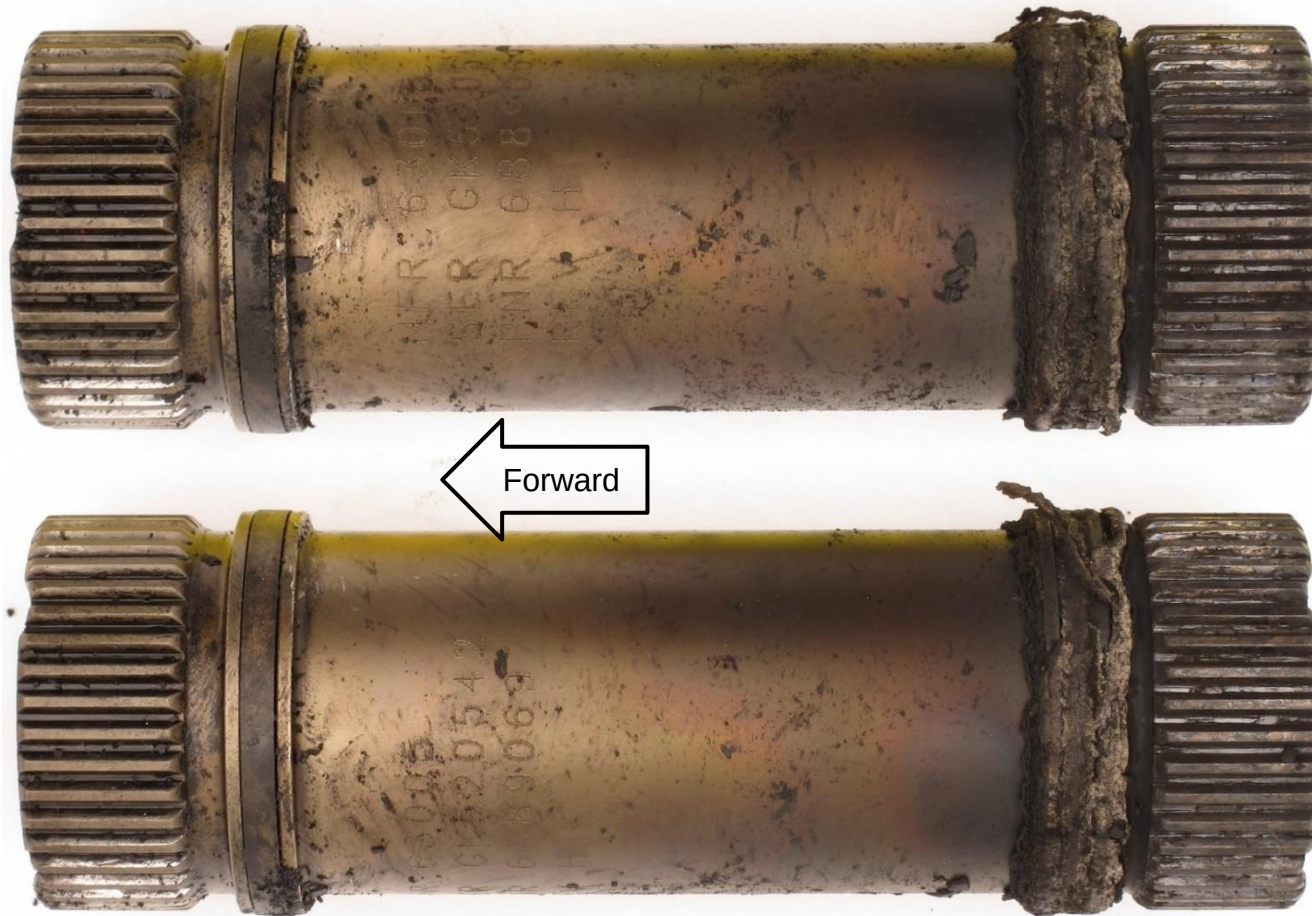


Figure 31. Overall outboard looking inboard views of the power turbine to pinion gear coupling in the as-received condition. Each image is rotated approximately 180° from the previous. Dark deposits consistent with coked oil were observed throughout the surface. The aft side exhibited discoloration consistent with heat tint.

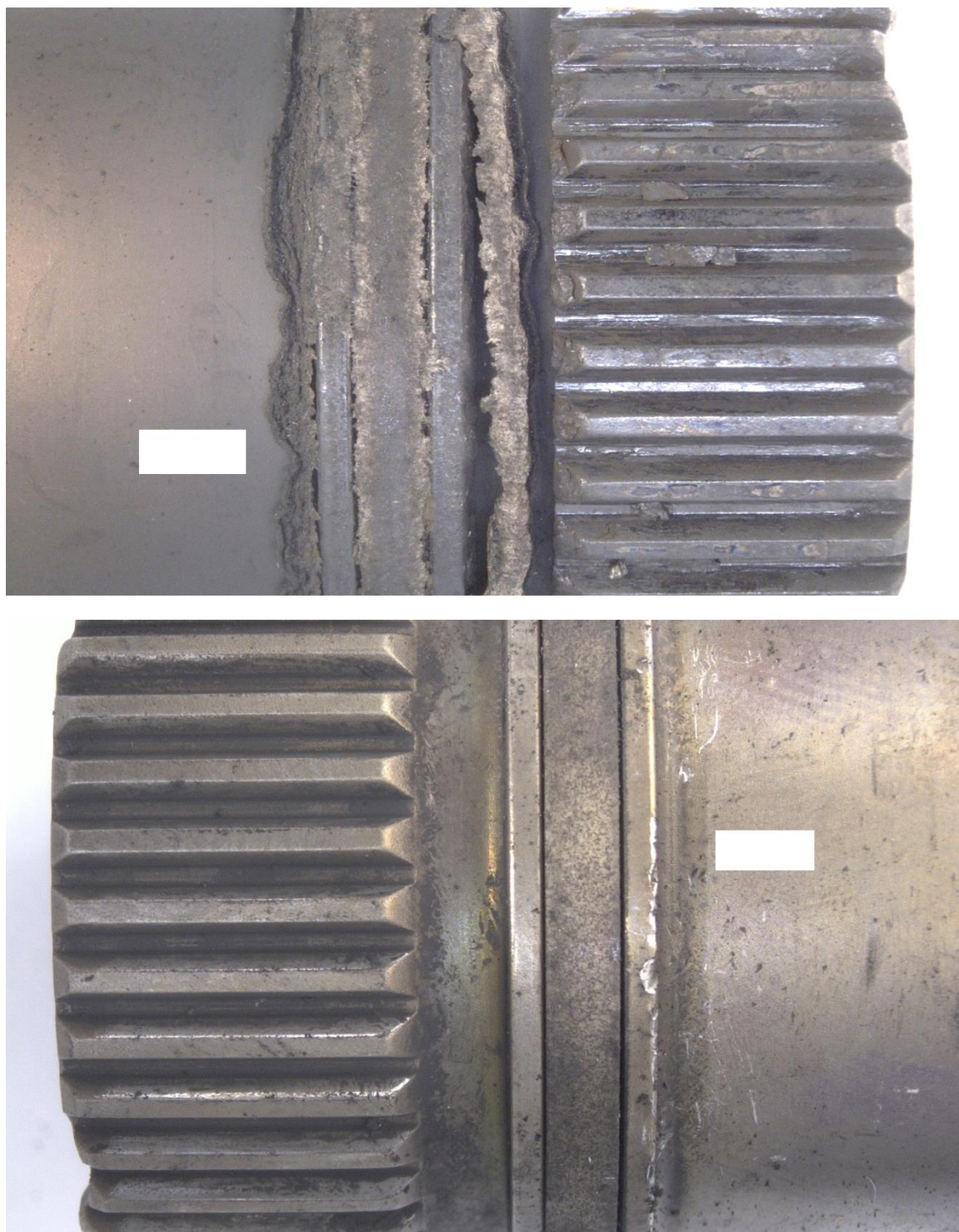


Figure 32. Detailed views of the aft (top) and forward (bottom) splines and Teflon seals on the pinion gear coupling. The aft Teflon seal exhibited damage.



Figure 33. Overall aft looking forward view of the pinion gear coupling showing turbine to compressor coupling material (red braces) in the inner diameter.

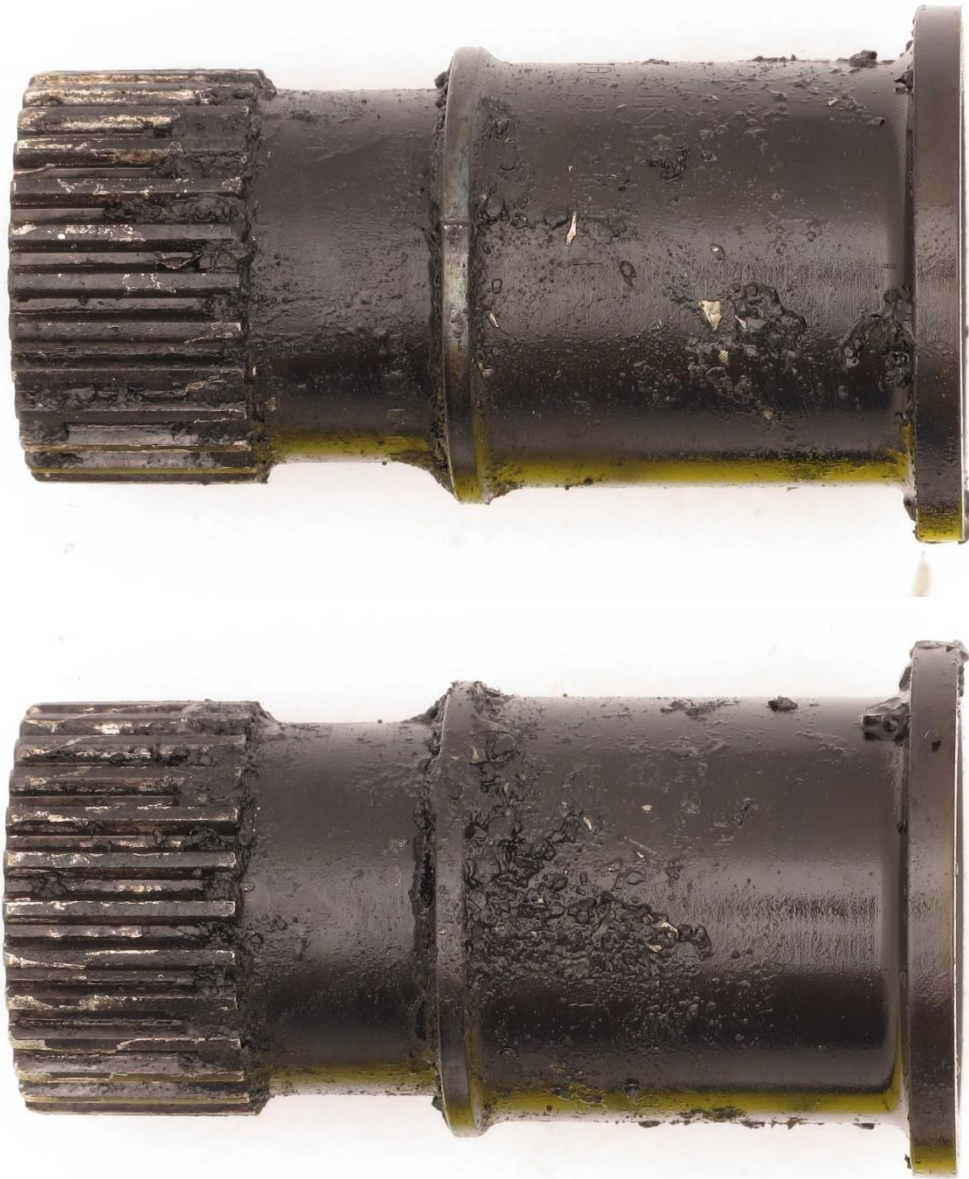


Figure 34. Overall outboard looking inboard views of the turbine spline adapter in the as-received condition. Each image is rotated approximately 180° from the previous. Dark deposits consistent with coked oil were observed throughout the part.



Figure 35. Overall forward looking aft (top) and aft looking forward (bottom) of the No. 6 bearing.



Figure 36. Overall forward looking aft (left) and aft looking forward (right) of the No. 2 bearing in the as-received condition.

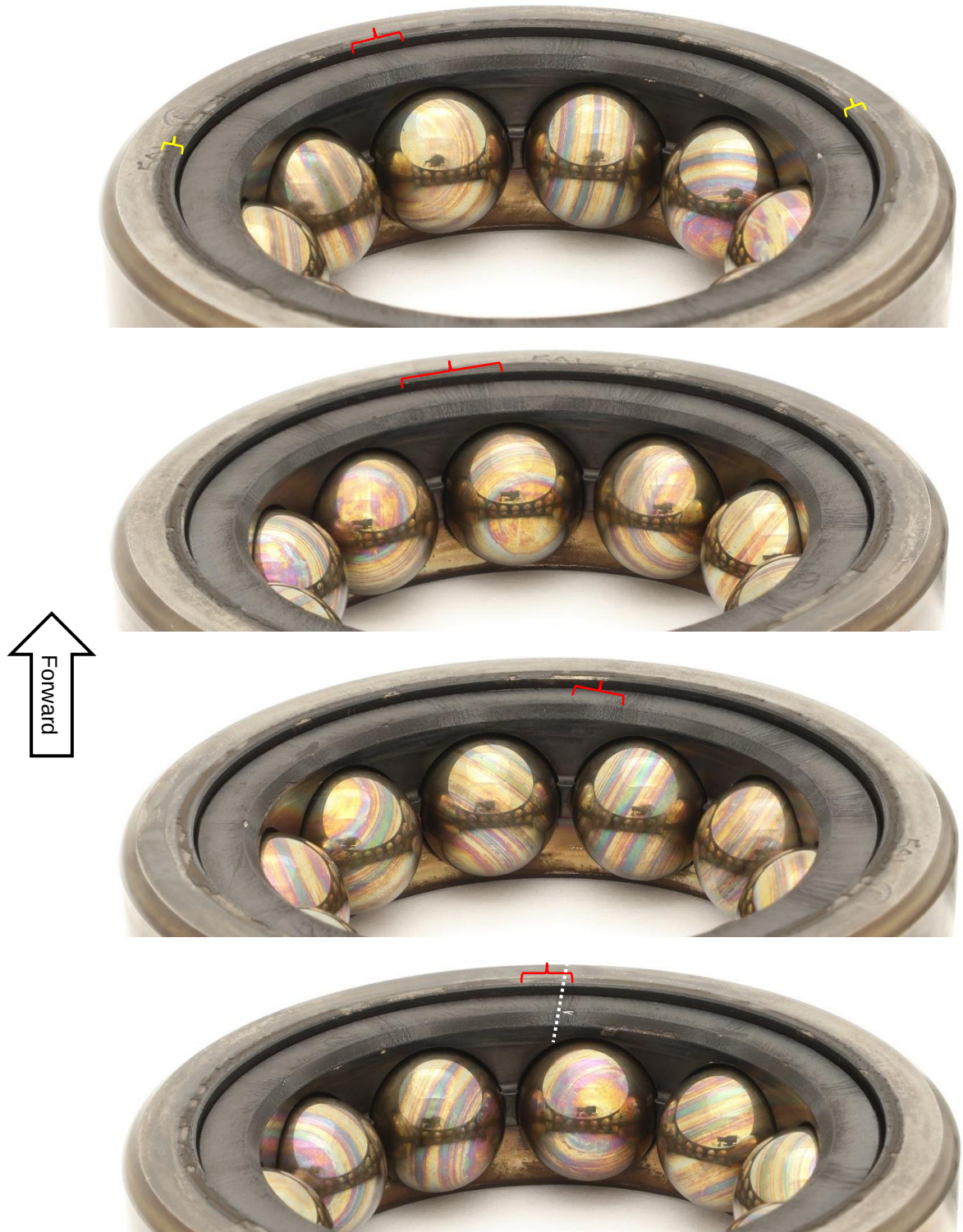


Figure 37. Detailed views of the No. 2 bearing outer race, ball, and separator assembly. Each image is rotated approximately 90° from the previous. The separator forward rail exhibited darker discoloration and radially oriented banded features (red braces, not all are noted). A layer of circumferential dark, tinted transferred material on the outer ring forward face is indicated by the yellow braces (top image). The white dashed line indicates the approximate cross-section (P4) of the separator and outer race selected for metallographic examination shown in Figure 43.

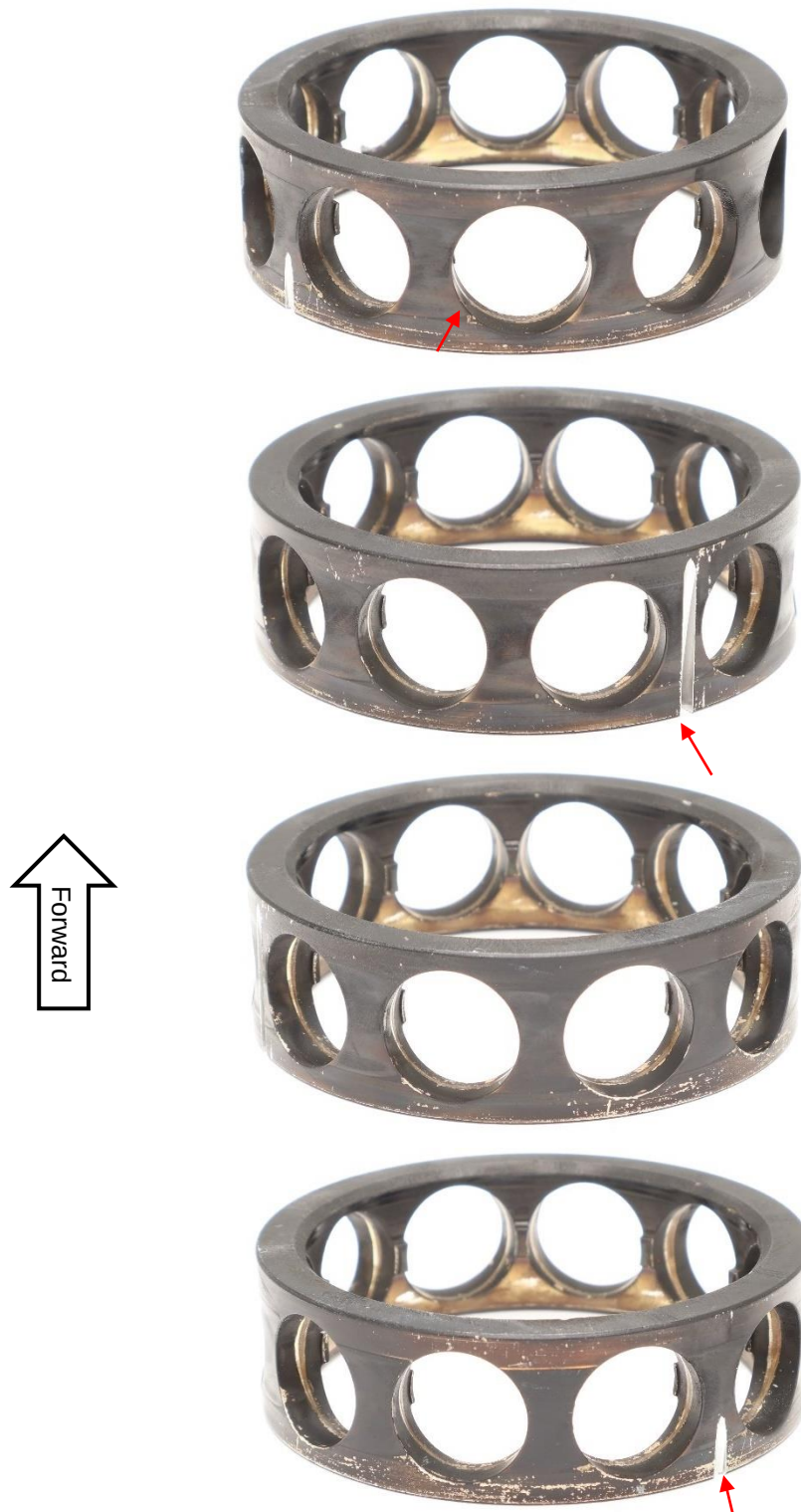


Figure 38. Photographs showing outer diameter views of the No. 2 bearing separator. The red arrows indicate marks made by the cutting tool used to remove the outer ring.



Figure 39. Detailed views of the No. 2 bearing separator forward (top) and aft (bottom) rail. The forward rail exhibited a dark discoloration and linear features (red braces).

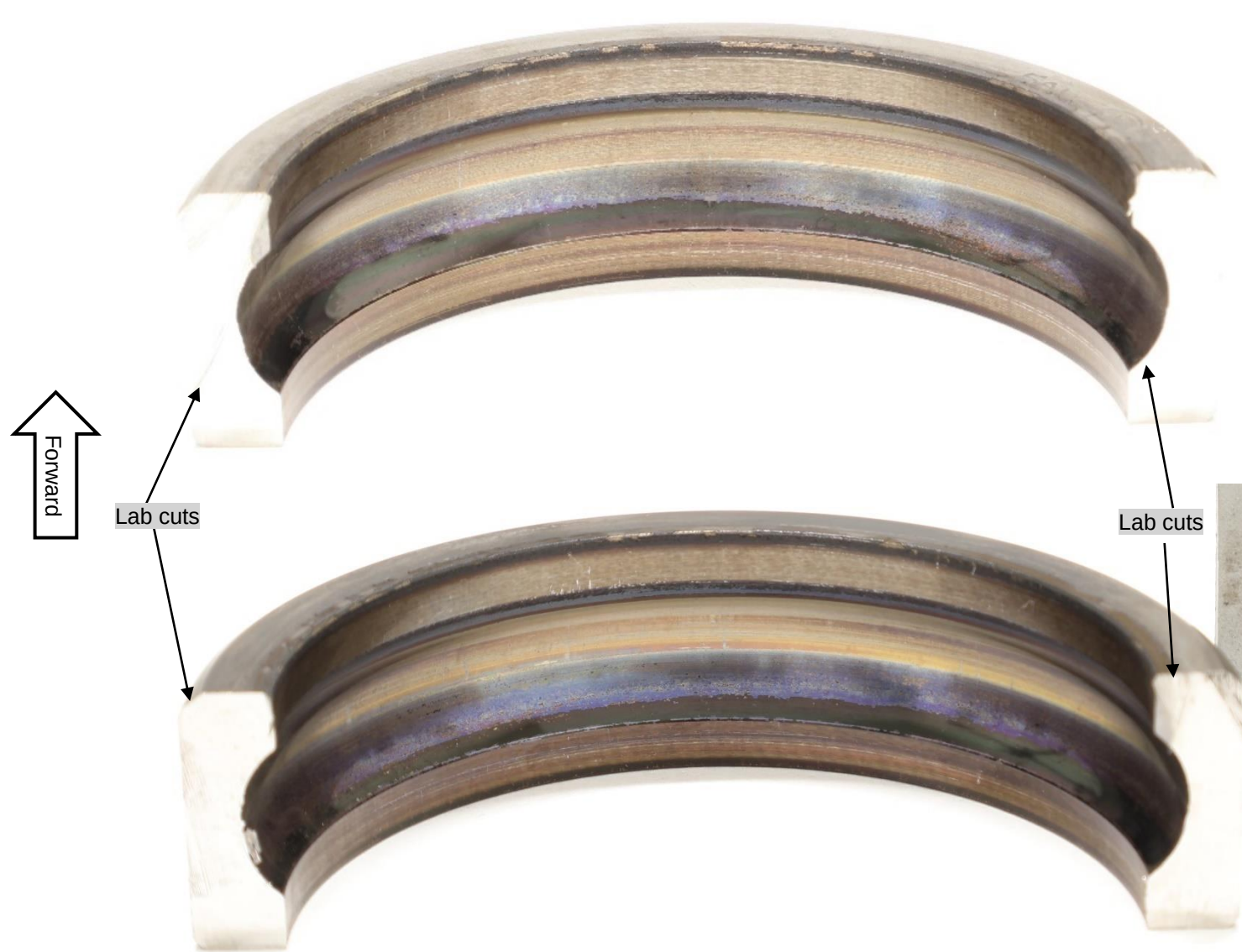


Figure 40. Overall images of the No. 2 bearing outer ring raceway showing two halves following axial cuts made to disassemble the bearing.

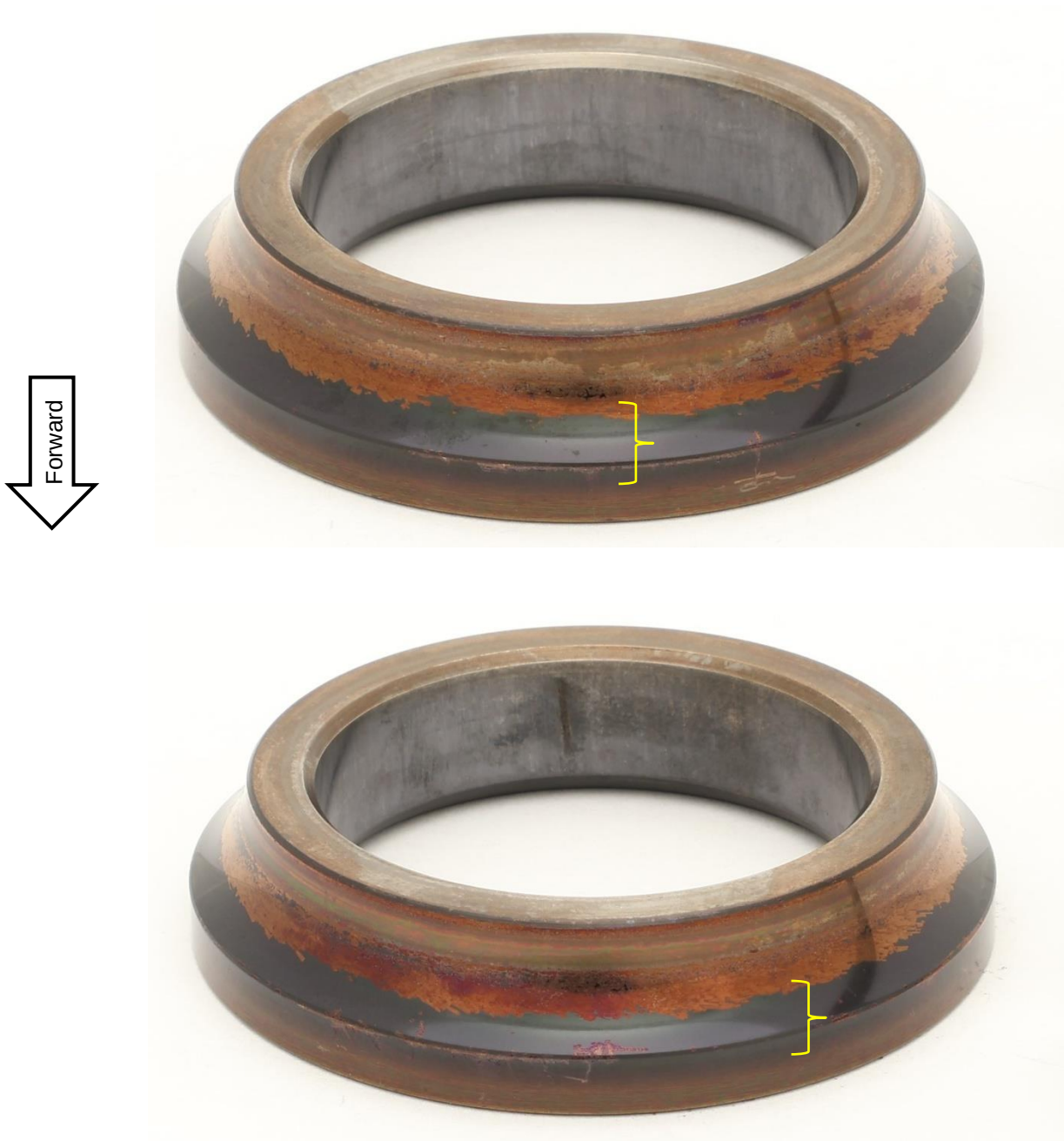
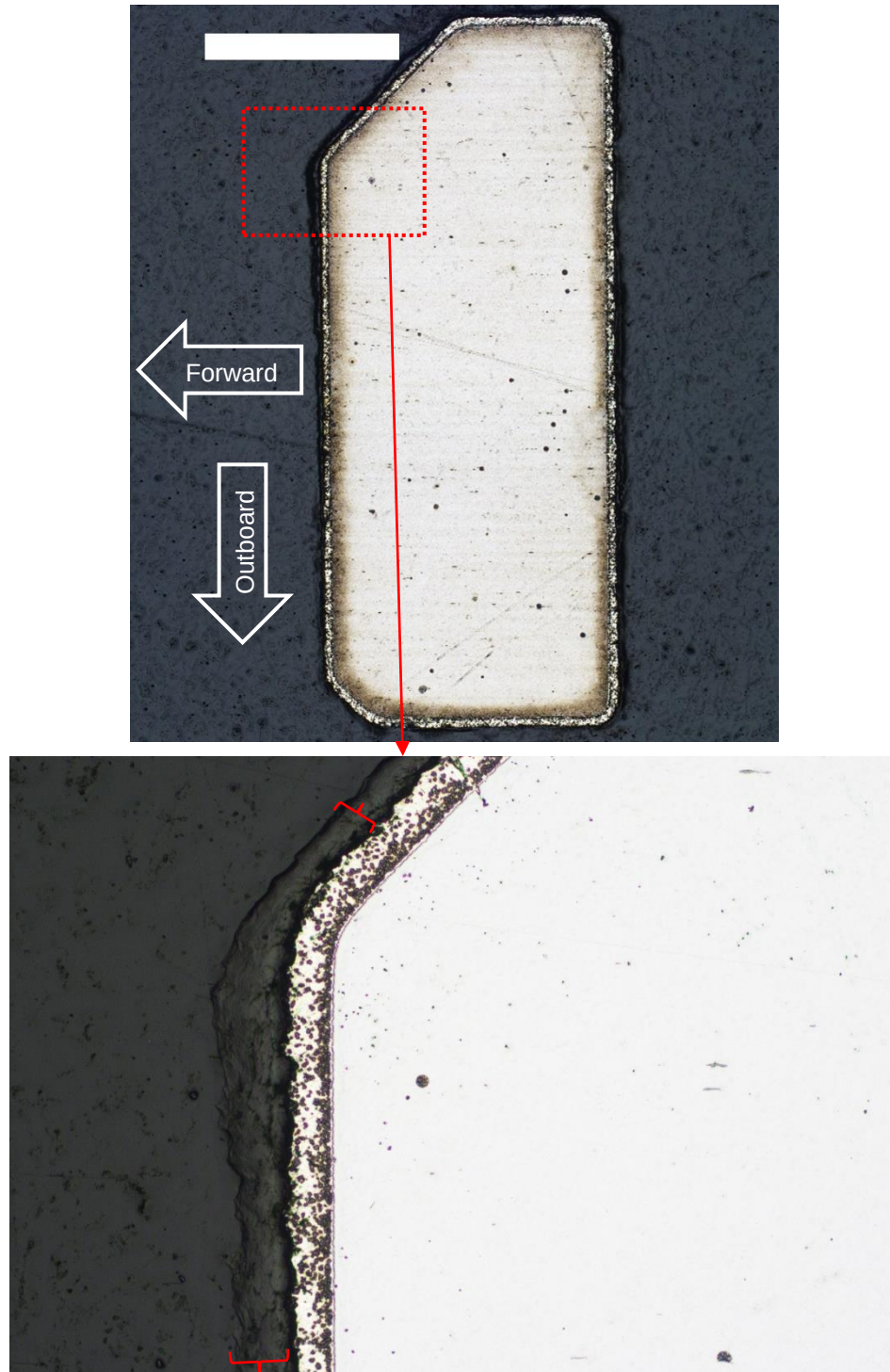


Figure 41. Detailed views of the No. 2 bearing forward inner race. Each image is rotated approximately 180° from the previous. The forward portion of the raceway and adjacent shoulder exhibited a layer of dark discoloration (yellow braces).



Figure 42. Detailed views of the No. 2 bearing aft inner race. Each image is rotated approximately 180° from the previous.



**Figure 43. Montaged (top) and detailed (bottom) micrographs showing cross-section P4 (see Figure 37) through the separator forward rail. A layer of dark, flaky material consistent with coked oil is indicated by the red braces. No evidence of thermal distress was observed.
Etchant: Top: Nital; Bottom: None.**

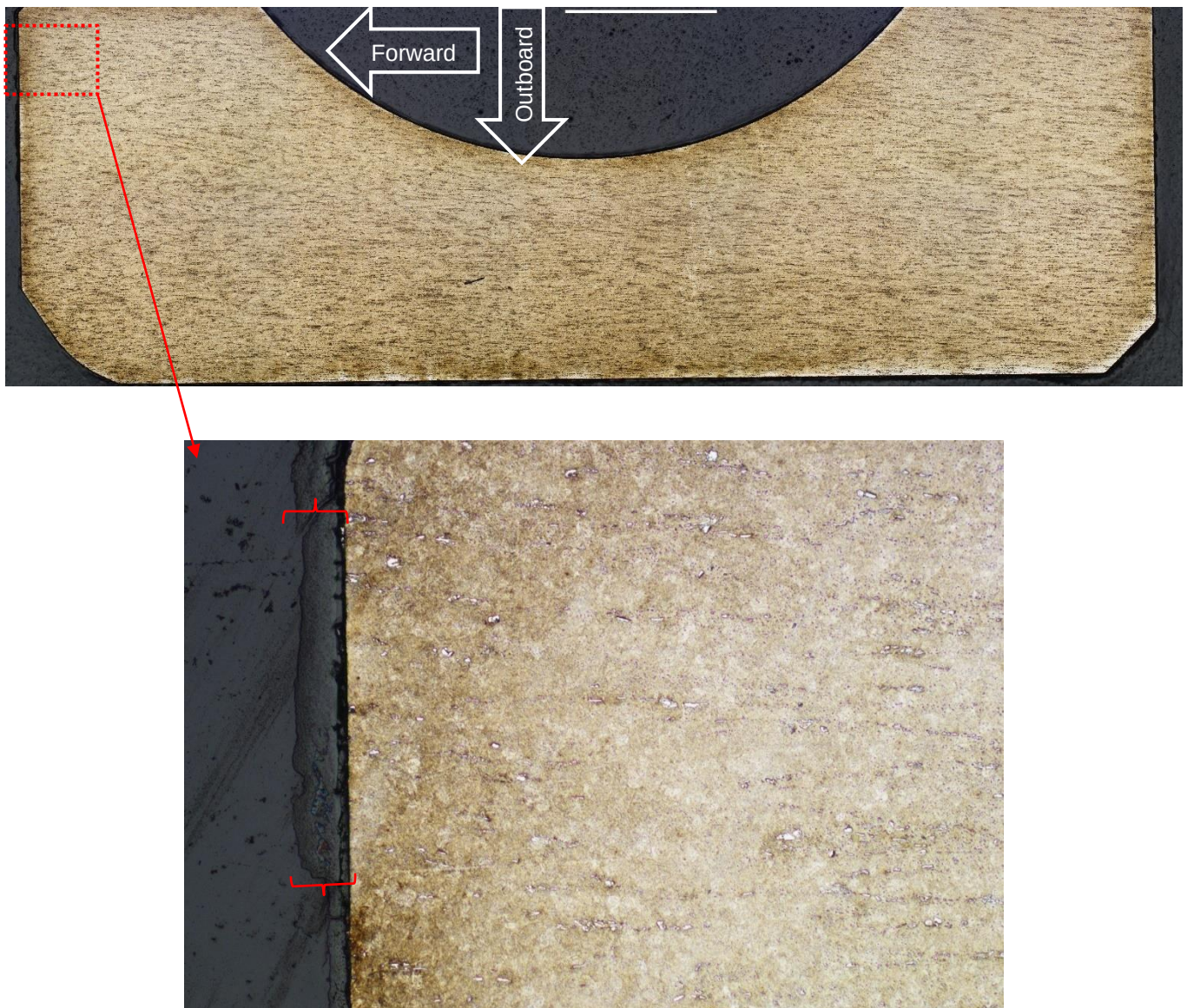


Figure 44. Montaged (top) and detailed (bottom) micrographs showing cross-section P4 through the outer ring. A layer of dark, flaky material consistent with coked oil is indicated by the red braces. No evidence of thermal distress was observed. Etchant: Vilellas

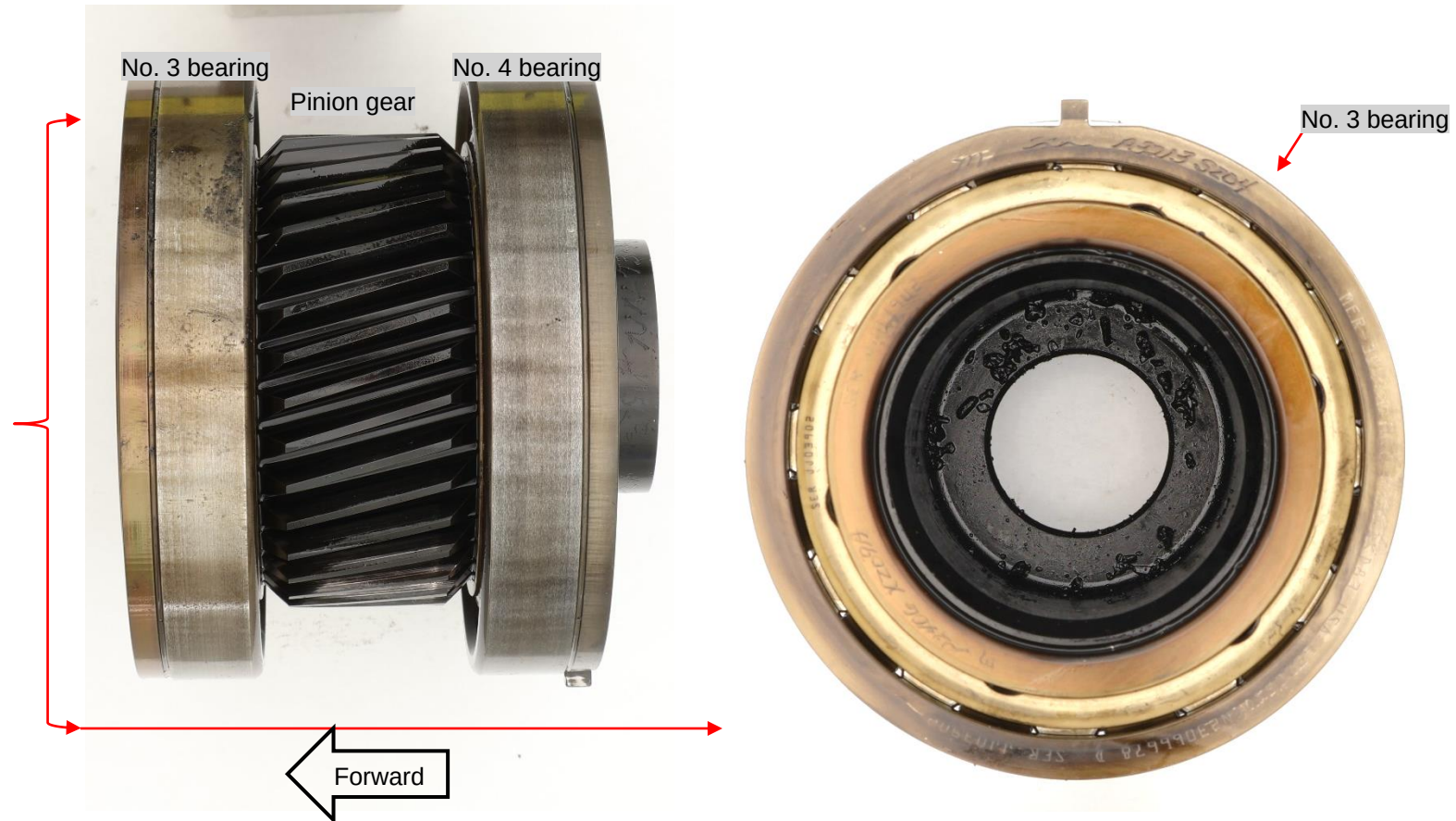


Figure 45. Overall outboard looking inboard (Left) and forward looking aft (right) views of the No. 3 and No. 4 roller bearing and pinion gear assembly. Dark deposits consistent with coked oil were observed on the pinion gear internal surfaces.



Figure 46. Overall forward looking aft (left) and aft looking forward (right) views of the No. 5 bearing in the as-received condition.



Figure 47. Overall forward looking aft (left) and aft looking forward (right) views of the No. 8 bearing in the as-received condition.