

National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594



WPR23LA184

MATERIALS LABORATORY

Factual Report 23-068

September 12, 2023

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A. ACCIDENT INFORMATION

Location: Creswell, Oregon
Date: May 9, 2023
Vehicle: Rans S21
Investigator: Zoe Keliher (WPR)

B. COMPONENTS EXAMINED

Engine crankcase, crankshaft with attached connecting rods and bearings, seven pairs of main bearing halves, two filters, and sectioned oil tube, that were disassembled from a UL Power Aero Engines model 520T engine¹.

C. EXAMINATION PARTICIPANTS

Group Chair	Frank Zakar NTSB Washington, DC
Engineering Technician	Ed Komarnicki NTSB Washington, DC
Materials Engineer	Michael Meadows NTSB Washington, DC
Party Member	Ray Lawrence UL Power Aero Engines Sandersville, Georgia

D. EXAMINATION

1.0 Overall View

Figures 1 through 3 show photographs of the as-received engine parts (which included a fractured crankshaft with connecting rods, engine case, bearing shells for the main and rod journals, two oil filters, and oil tube that was cut from the engine case). The UL Power Aero Engines engineering drawing identifies the crankshaft as part number "SBE020502. The cheek portion of the crankshaft was marked

¹ The 520T engine is a six-cylinder, horizontally opposed air-cooled turbocharged gasoline engine made by UL Power Aero Engines, headquartered in Ypres, Belgium.

"2000096/1" which according to a representative from UL Power Aero Engines is an internal tracking number used by their Belgium subcontractor. The crankshaft is numbered front to aft, starting with the #1 main journal (#1MJ) and #1 rod journal (#1RJ), and terminating with the #6 rod journal (#6RJ) and the #7 main journal (#7MJ), as show in figure 1. This convention will be used throughout the report. The fracture on the crankshaft intersected the aft radius of the #2 rod journal (#2RJ). The connecting rod arms for all the rod journals when rotated by hand did not show indications of rotational resistance. The #1RJ and #2RJ were disassembled at the NTSB Materials Laboratory from the crankshaft to expose the rod journal surfaces. The remaining rod journals were not disassembled. Figures 4 through 8 show portions of the crankshaft at various stages of disassembly. According to NTSB preliminary report, the engine accumulated a total of 55 hours since new.

2.0 Crankshaft Fracture

The aft fracture face of the #2RJ contained crack arrest marks, typical of fatigue cracking, that emanated from multiple origins at the surface of the aft (fillet) radius (see figure 9). The surface of the radius exhibited circumferential scoring marks that intersected the fatigue origin area.² The length of the multiple-origin fatigue crack measured approximately 1.6 inches. Fatigue propagation was in the general direction indicated by arrows in figure 9 and extended approximately through 30% of the rod journal cross section. The fatigue crack terminated approximately in the areas indicated by a dashed line in figure 9. The remaining portion of the fracture extended axially through the crank cheek in the area between the #2RJ and the #3MJ. The major portion of the crank cheek fracture face exhibited post fracture mechanical damage. The fracture features outside of the fatigue crack zone (outside the dashed line in figure 9) and in areas that were not that were not damaged exhibited a rough irregular texture consistent with overstress separation.

The forward fracture face of the #2RJ contained the mating fatigue crack origin area, see figure 5. This fracture face was excised from the crankshaft for scanning electron microscope (SEM) examination.³ The fatigue origin area was ultrasonic cleaned with acetone. SEM examination of the fracture face revealed the fine fracture features at the fatigue origin area were obliterated by post fracture mechanical damage. The surface of the radius exhibited evidence of circumferential scoring marks that intersected the fatigue origin area (refer to figure 10).

Stereo microscope examination the crankshaft portion located forward of the fracture revealed the #1MJ, #1RJ, #2MJ, and #2RJ exhibited evidence of superficial

² Scoring - marring or scratching of a smooth surface. It is most often caused by sliding contact with a mating member having a hard projection or embedded particle on its surface.

³ Cuts were made by water cooled abrasive wheel method through the #2RJ and the crank cheek.

cracks at the radii locations. Table 1 indicates the location of each crack and their length. The depth of each crack was not measured. A visual examination of the remainder portion of the crankshaft revealed no evidence of a crack at the radii locations.

2.1 Crankshaft Material Properties

The engineering drawing for the crankshaft specified “42CrMo” steel⁴ in the quenched and tempered condition, where the core hardness is between 28 and 35 HRC (which converts to between approximately HV 286 and HV 345).⁵ The outer surface is required to be hardened by nitride treatment to the condition “nitrate HV 800 Depth 0.2-0.3mm”.⁶ This indicates the specified depth of the nitride case must be in the range between 0.2 mm and 0.3 mm; and the peak hardness of the nitride case is specified as HV 800. The hardness of the nitride case gradually decreases toward the core. Although not specified on the engineering drawing, a representative from UL Power Aero Engines indicated that a load of 1 kilogram is used for making the microhardness measurements.

2.2 Microhardness Testing

Metallurgical cross sections were made through the origin of the fatigue crack in the area and orientation indicated by section line “A-A” in figure 5; and through the #1MJ in the area indicated by section line “B-B” in figure 5. Each section was placed in a metallurgical mount. The prepared sections were etched with 2% nital reagent. Each section contained a white layer (also referred to as a compound layer) at the surface, typical of a steel alloy that received a nitriding treatment. The white layer extended along the rod journal surface (axial flat surface) and radius areas. The white layer in each section measured approximately 0.0004 inch (10 µm). The white layer in several areas contained cracks, see figure 11. The portion below the white layer exhibited a microstructure of tempered martensite.

Traverse microhardness testing was performed on the two metallurgical cross sections to determine the effective case depth of gas nitriding, also referred to as nitriding hardness depth (NHD). The definition and procedure for determining NHD

⁴ Grade 42CrMo steel is a material code designation for steel made to National Standard of Peoples Republic of China GB/T3077, titled “Alloy Structure Steel”. It is similar and, in many cases, recognized as an equivalent, or a substitute, for steel grades such as European (EU) standard 10088-3, grade 42CrMo4; German (DIN) standard EN1.7225, grade 42CrMo4; USA Unified Numbering System (UNS) G41400 which is also known as American Iron and Steel Institute (AISI) 4140 steel. Source: www.starrapid.com/wp-content/uploads/2020/03/Metal-Equivalent-Grades.pdf; and the www.worldmaterial.com

⁵ HRC is an abbreviation for Rockwell “C” hardness, and HV is for Vickers hardness. Hardness conversions in this report were made using tables in ASTM A370, titled “Standard Methods and Determination for Mechanical Testing of Steel Products”.

⁶ “mm” is an abbreviation for millimeters.

is described in ISO 18203, 2016 Edition, titled "Steel – Determination of the thickness of surface-hardened layers". Appendix 1 shows the results of the microhardness testing data and plot for determining the NHD and peak hardness for section "B-B", a section that was made through #1MJ. Based on the plotted data, the NHD was determined to be approximately 0.23 mm, which was within the specified NHD range (0.2 mm – 0.3 mm). The hardness of the nitride case was determined to be as great as 594 HV (55 HRC), which was less than the specified peak hardness value 800 HV (64 HRC). The nitride case depth and peak hardness value for section "A-A" was similar to that of section "B-B".

2.3 Chemical Composition

As a result of preparing metallurgical section "B-B" (see figure 5) from #1MJ, a core portion of the crankshaft was exposed. A core portion of the #1MJ was cut and shipped to IMR Testing Labs, Lansing, New York where it was analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) method. UL Power Aero Engines indicated that the fractured crankshaft was made to grade 42CrMo4 steel. The specified composition and results of the materials analysis are shown in table 2. The composition of the crankshaft sample was consistent with grade 42CrMo4 steel. For comparison, the composition of grade AISI 4140 steel was listed in table 2 (see footnote 4 in this report regarding explanation of equivalent steel grades).

The core portion of the crankshaft also was analyzed with a handheld Olympus Vanta, Series C, handheld XRF alloy analyzer. The alloy analyzer identified the crankshaft as grade AISI 4140 steel.

3.0 Examination of the Rod and Main Journals, their Radii and Shoulder Areas

Stereo binocular microscope examination the crankshaft revealed the #2MJ on one half of the circumference showed evidence of metal transfer⁷ from the corresponding bearing (see figure 7). The remaining half of the #2MJ circumference, and the entire circumference of #1MJ, #3MJ through #7MJ, #1RJ and #2RJ were smooth. The connecting rod for the remaining rod journal were not disassembled. The main and rod journal contained a forward and aft (fillet) radius, as shown in figure 1 and figures 5 through 8, with the exception of the #1MJ that only had an aft radius and the #7MJ that only had a forward radius. The radii of all the main journals and those of the #1RJ and #2RJ in many areas showed evidence of minor scoring. Each crank cheek contained a reinforcement shoulder that extended beyond each relief radius area. With the exception of the #1MJ, the shoulders and areas slightly outside of the shoulders of the remaining main journals, and those from #1RJ and #2RJ, in

⁷ Handheld alloy analyzer showed evidence of copper, aluminum, and lead typically found in bearing material.

many areas showed evidence of moderate to severe circumferential scoring. The complete circumference of the main and rod journals showed no evidence of blue or brown heat tinting (burn marks).

The diameter of the main journals were specified as in the range between 2.748 and 2.750 inches (69.815 and 69.955 mm). The diameter of all the main journals were measured with a micrometer. The diameter of all the main journals measured between 2.749 inches and 2.750 inches (69.83 mm and 69.85 mm), they were within the specified range.

The diameter of the rod journals were specified as in the range between 47.758 and 47.778 mm (1.880 and 1.881 inches). The diameter of the #1RJ and #2RJ measured approximately 1.881 and 1.880 inches, respectively, both within the specified range.

The size of the radii on the main and rod journals of the crankshaft were measured in the segment of the crankshaft that extended forward of the fracture. Measurements were made by two methods: (1) laser scan method; (2) silicone replica method.

The laser scan was performed on a Keyence model VL-500 3D Scanner Coordinated Measuring Machine. Two measurements were made on the journal. A measurement was made on one side of the journal (measurement 1) and another measurement was made on the diametrically opposite side of the journal (measurement 2). Table 3 shows results of the measured radii by the laser scan method. The aft radius on diametrically opposite sides of the #1MJ and #2MJ; and the forward radius at only one side of the #2RJ were below the specified range. A radius that measured below the specified range followed an irregular curvature.

Silicone replicas of the radii were made with a Struers Repliset® in the same areas as measurement 1 that were laser scanned. RepliSet® is a fast curing, two-part, silicone rubber. The silicone rubber compounds are supplied in cartridges and are applied using dispensing guns. According to the Struers, the manufacturer of Repliset®, resolution can be achieved down to 0.1 micro-inch. Once a replica was made from a radius, a cut was made through the silicone replica with a razor blade to expose the side profile of the radius. The size of the radius was measured directly from the cross section of the replica using a Keyence Digital Microscope (model VHX 7000). Table 3 shows results of the measured radii by the silicone replica method. The radii at the #1MJ and #2MJ; the forward radius of the #1RJ, and the aft radius of the #2RJ were below the specified range. A radius that measured below the specified range followed an irregular curvature.

Stereo microscope examination of the radius areas of the crankshaft revealed evidence of superficial cracks at the #1RJ aft radius, #2MJ forward radius, #2MJ aft radius, and #2RJ forward radius (see Appendix 3).

3.0 Bearings Shells

Figure 12 shows a photograph of the inner surface of the main journals bearing. The bearing shell halves for the #2MJ at the inner surface contained evidence of severe circumferential scoring, that exposed the steel core layer, and the inner layers of copper, aluminum, lead, and tin (see figure 9). The inner surface of the remaining main journal bearings showed evidence of moderate circumferential scoring. Each bearing half contained a tang portion at the corner edge that was designed to prevent rotation of the bearing when the crankshaft was rotating. The tang portion for both halves of the bearing for the #2MJ were severely deformed and flattened, whereas the tang portions for the remaining main journal bearings showed no evidence of deformation. The inner surface of the #1RJ and #2RJ are not shown but exhibited severe scoring.

4.0 Engine Case

A handheld alloy analyzer indicated the engine case was made from an aluminum alloy. The inside surface of the engine case was covered with fragments containing metals such as copper, aluminum, lead, and tin, typically found in bearing shells. The engine case contained a saddle that accommodated each respective main journal (see figures 13 through 15). The saddle for the #2RJ showed evidence of severe circumferential gouge damage (see figure 14). The saddle (flat-axial portion) for the #1MJ and those on the remaining saddles were smooth and showed no evidence of circumferential gouge damage (see figure 15).

The forward and aft edges of a saddle contain a corner (a corner is intersected by the axially flat surface of the saddle and lateral wall of the saddle). Figure 14 shows an example of a forward and aft corners for a saddle. The saddle for #1MJ at the forward and aft corners showed no evidence of damage. The saddle for the #2MJ at the forward corner (see figure 13) showed evidence of compression deformation damage without circumferential gouge damage, but the aft corner (see figure 14) showed evidence of circumferential gouge damage. The saddles for the remaining main journals (#3MJ through #7MJ) at the forward corners (see figure 13) showed circumferential gouge damage that was similar those at the forward corner of the #2MJ, with the severity of damage decreasing toward the aft end of the crankshaft. The saddles for #3MJ through #7MJ at the aft corners (see figure 15) showed no evidence of damage.

5.0 Thrust Bearing Disc Springs

The thrust bearing mount was disassembled to expose the internal pieces, such as the thrust bearing disc springs, and bearings (see figure 16). The mount and internal pieces, including the thrust bearing disc spring and bearings, were intact and showed no evidence of a crack, deformation, or wear damage. The thrust bearing

disc springs were specified as "50CrV4" steel, which is similar/equivalent to AISI 6150 steel.⁸ The thrust bearing mount contained two sets of disc springs, one set where the concave sides of the spring discs were facing each other and another set where the convex sides of the spring discs were facing away from each other. The concave spring discs were located at the forward end and the convex spring discs were located at the aft end of the thrust bearing mount. The size of the thrust bearing disc springs were measured with a caliper and the results are shown in tables 4 and 5. The size of the springs were within specified dimensions.

6.0 Oil Filters

Two oil filters were submitted for examination (see figure 3) The accordion-like fabric portion of a filter was submitted without its canister casing (this oil filter was removed from the engine prior to the accident). The fabric from the other oil filter was attached to its canister casing (an oil filter that was removed from the airplane after the accident). Stereo microscope examination of the exterior surface of the fabric portions of the filters revealed evidence of metallic particles. Metal particles that contained aluminum, lead, copper, iron, zinc, nickel, molybdenum, and chromium in various proportions were detected by a handheld alloy analyzer.

7.0 Propeller Flange Bolt

The specified torque for the propeller flange bolt was 221 foot-pounds (ft-lbs) or 300 Newton-meters(Nm).⁹ According to a representative from UL Power Aero Engines, the propeller flange bolt was installed at the factory, and was not removed from the propeller flange since its initial installation. The propeller flange bolt was disassembled at the NTSB Materials Laboratory. The torque was not recorded during disassembly of the bolt. The following observations were observed during disassembly of the bolt. The bolt was tightened by hand with an 18 inch length socket wrench, using moderate hand force, causing the bolt to rotate approximately 20 degrees. Following this step, the bolt was untightened (unscrewed) with the wrench without great difficulty. The threads from the disassembled bolt showed no evidence of mechanical damage.

Submitted by:
Frank Zakar
Senior Metallurgist

⁸ 50CrV4 is a German standard spring steel (DIN material number 1.8159). It is similar and, in many cases, recognized as an equivalent, or a substitute, for steel standards such as China GB grade 50CrVA; American grade G61500; Japanese grade SUP10; British grade 735A51; and French grade 50CrV4. Source: www.wixsteel.com/products/alloy-steel-bar/spring-steel-wire/50crv4.

⁹ 1 ft-lbs = 1.356 Nm

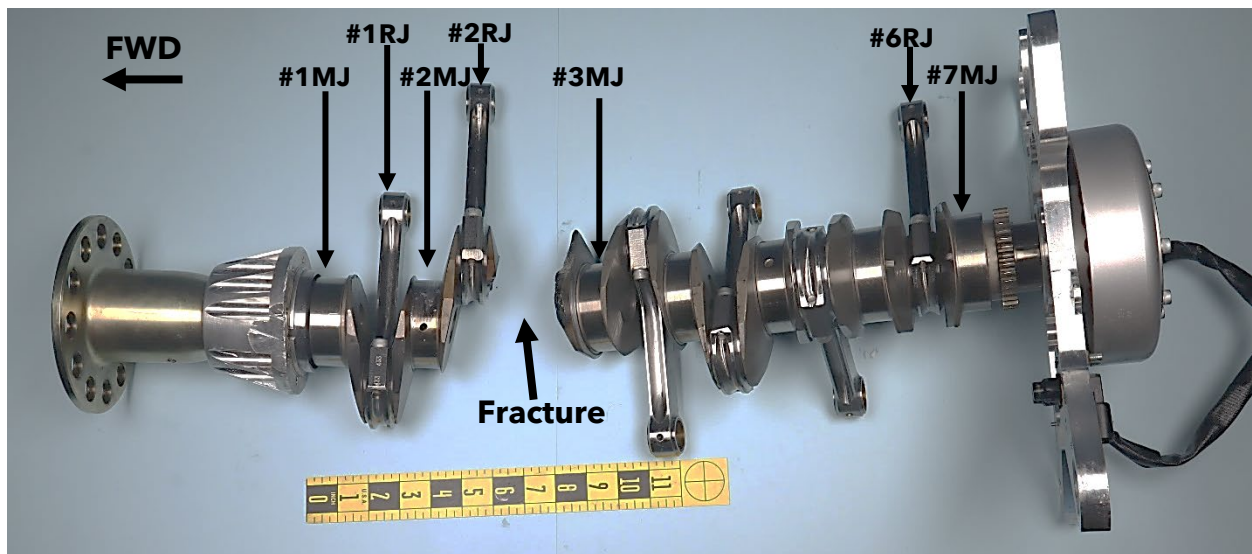


Figure 1. Photograph of the as-received crankshaft, shown on top of page. The crankshaft is numbered front to aft, starting with the #1 main journal (#1MJ) and #1 rod journal (#1RJ), and ending with the #7 main journal (#7MJ). The crankshaft contained a fracture that intersected the aft radius of the #2 rod journal (#2RJ). The crank cheek of the crankshaft (between the #1 main journal [#1MJ] and the #1 rod journal [#1RJ]) was engraved with an identification mark, shown on bottom of page. Units on the ruler are in inches.

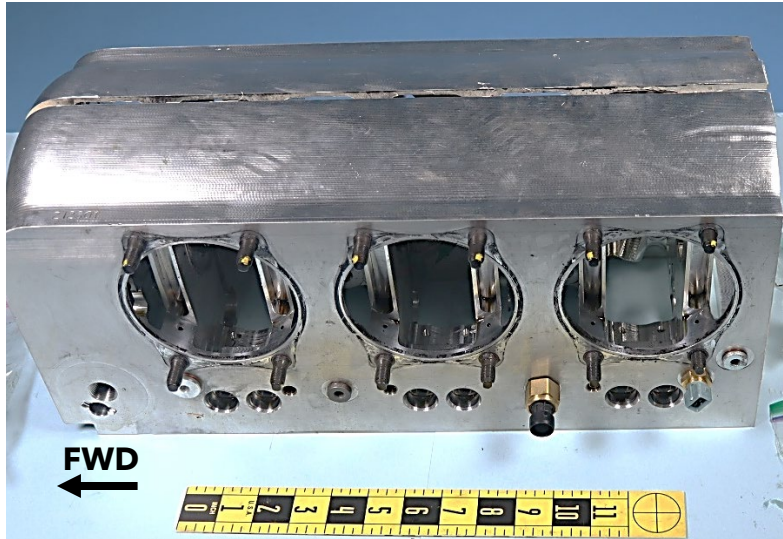


Figure 2. As-received engine case halves.



Figure 3. As-received parts consisting of seven pairs of main bearing halves; two filters (on left removed prior to accident and on right removed from airplane after the accident); and oil tube that was cut from the engine case to facilitate shipping.

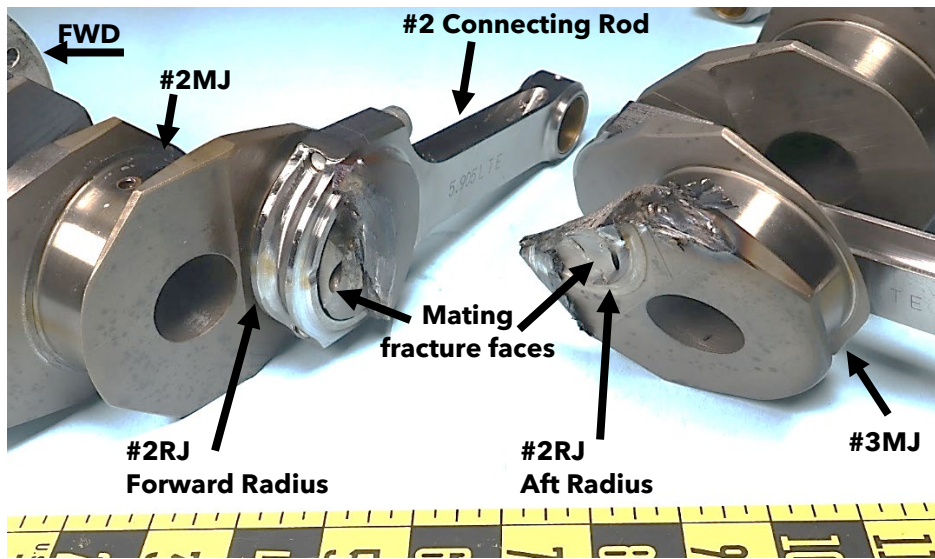


Figure 4. Close-up photograph of the crankshaft mating fractures.

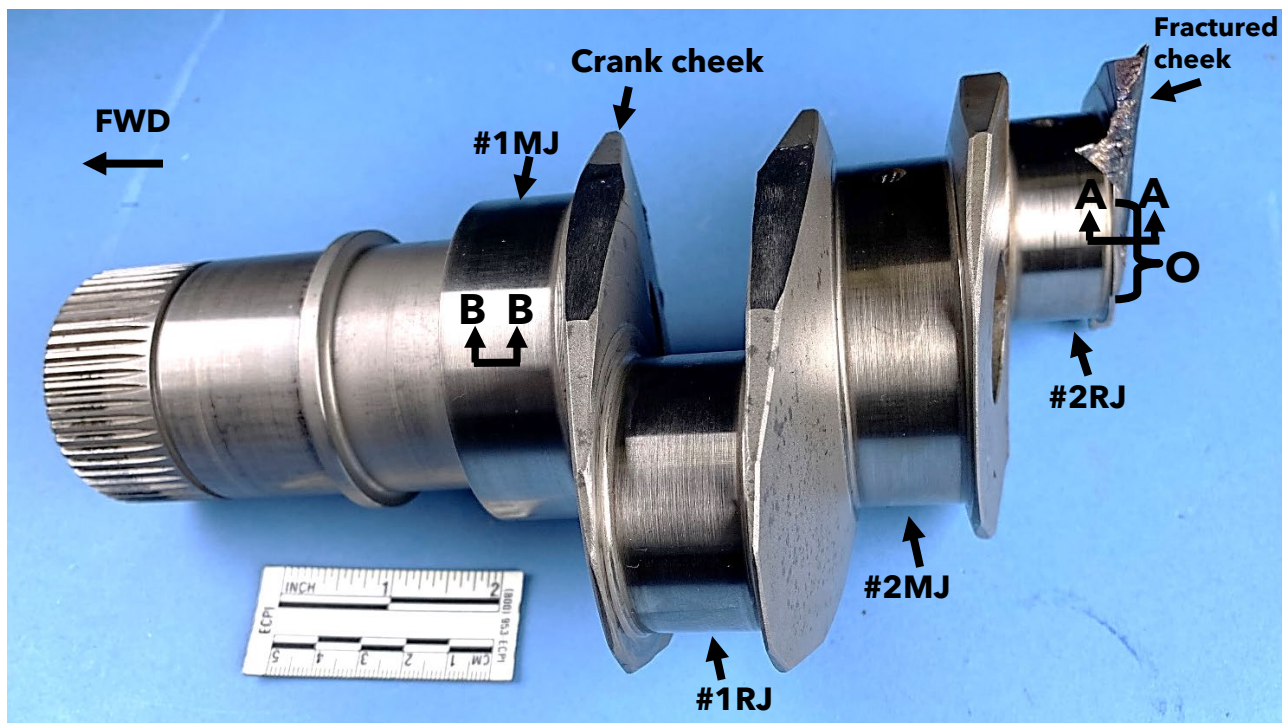


Figure 5. Close-up view of the forward end of the crankshaft after disassembly of the connecting rods from the #1 and #2 main journals (#1MJ and #1RJ); and #1 and #2 rod journals (#1RJ and #2 RJ), respectively. Fatigue origin is indicated by bracket "O". Metallurgical sections were prepared from the areas indicated by section lines "A-A" and "B-B".

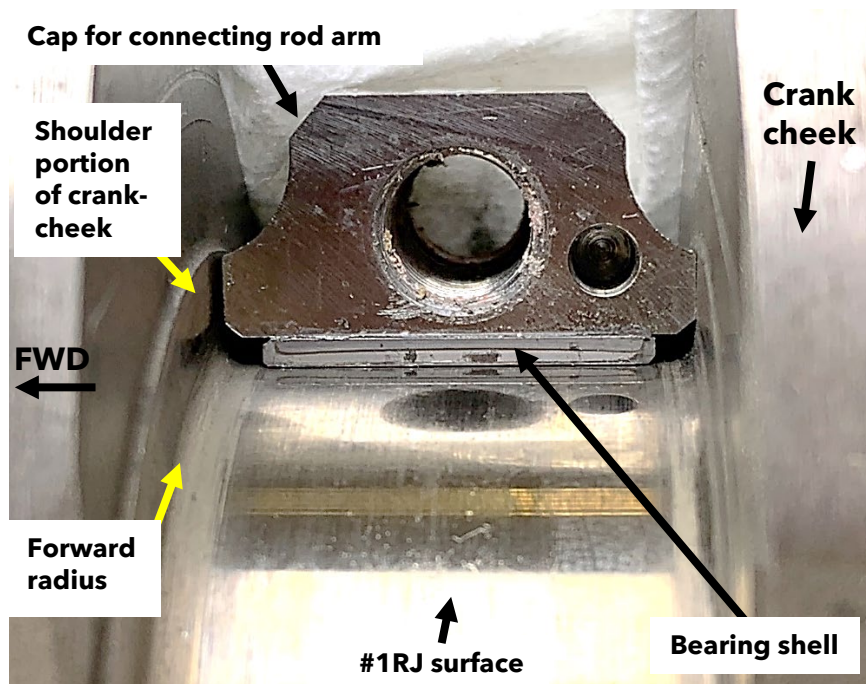


Figure 6. Side view of the #1 rod journal (#1RJ) surface with one half of the cap inserted into the rod journal surface; showing the relative position of an intact bearing shell relative to the forward and aft radii.

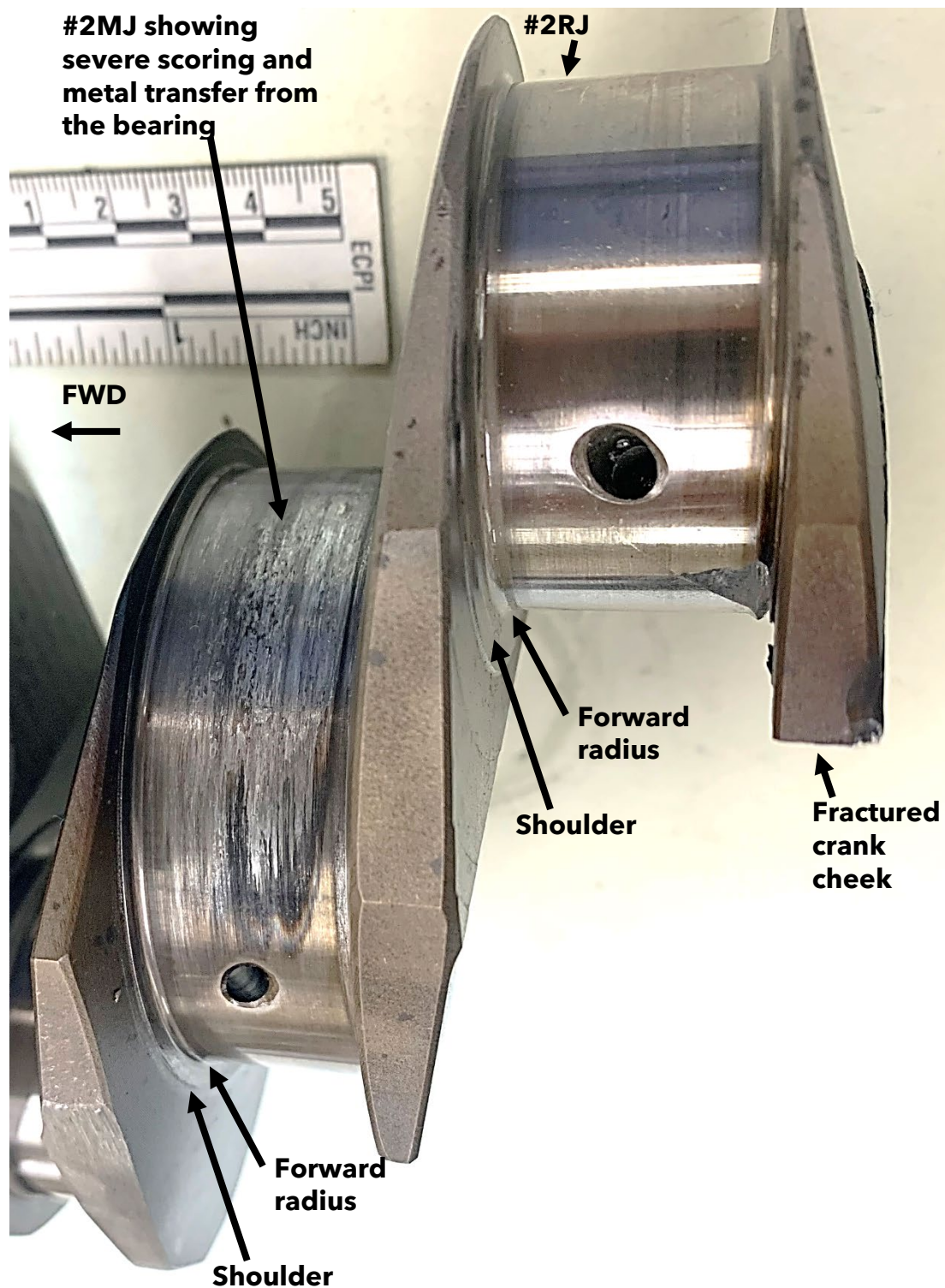


Figure 7. View of the #2 main journal (#2MJ) and #2 rod journal (#2RJ) surface. The #2MJ showed evidence of metal transfer from the corresponding bearing shell and localized heat tinting (black/blue/brown) on one half of the journal circumference.

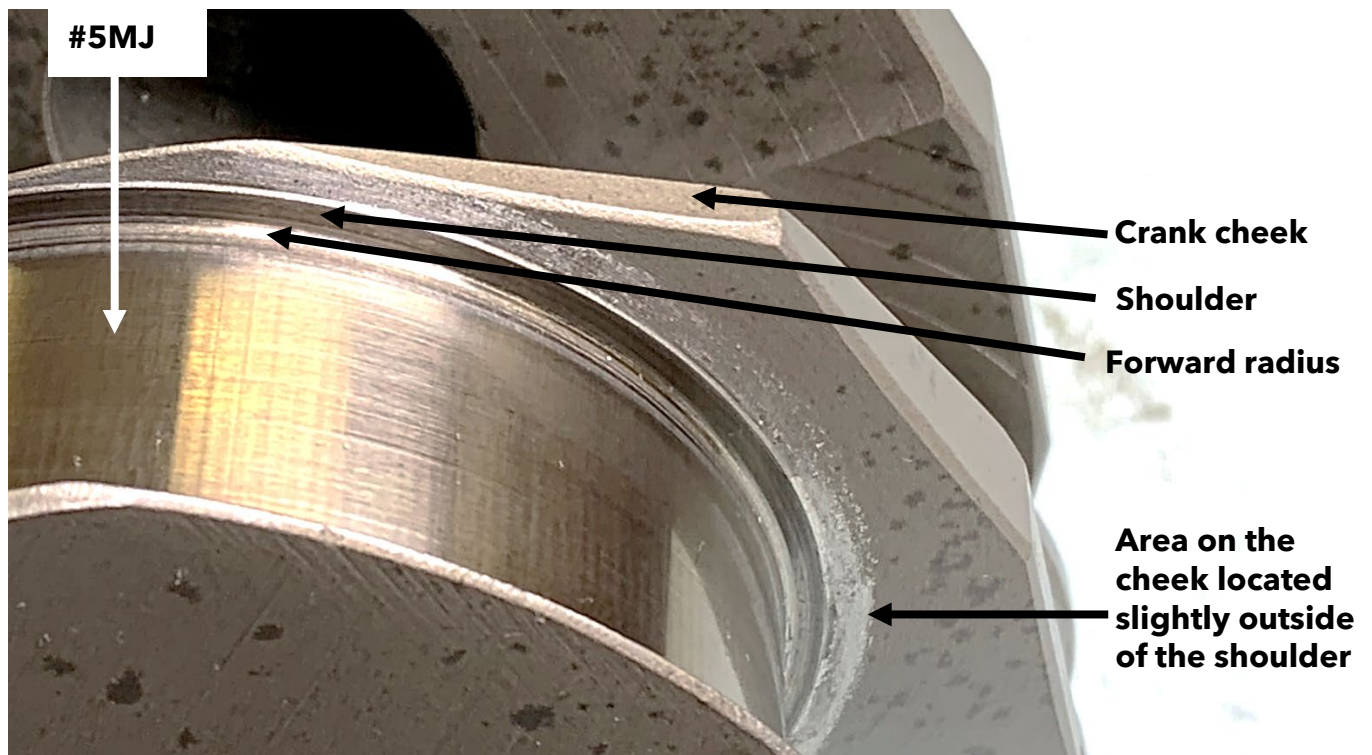


Figure 8. View looking forward at the #5 main journal (#5MJ).

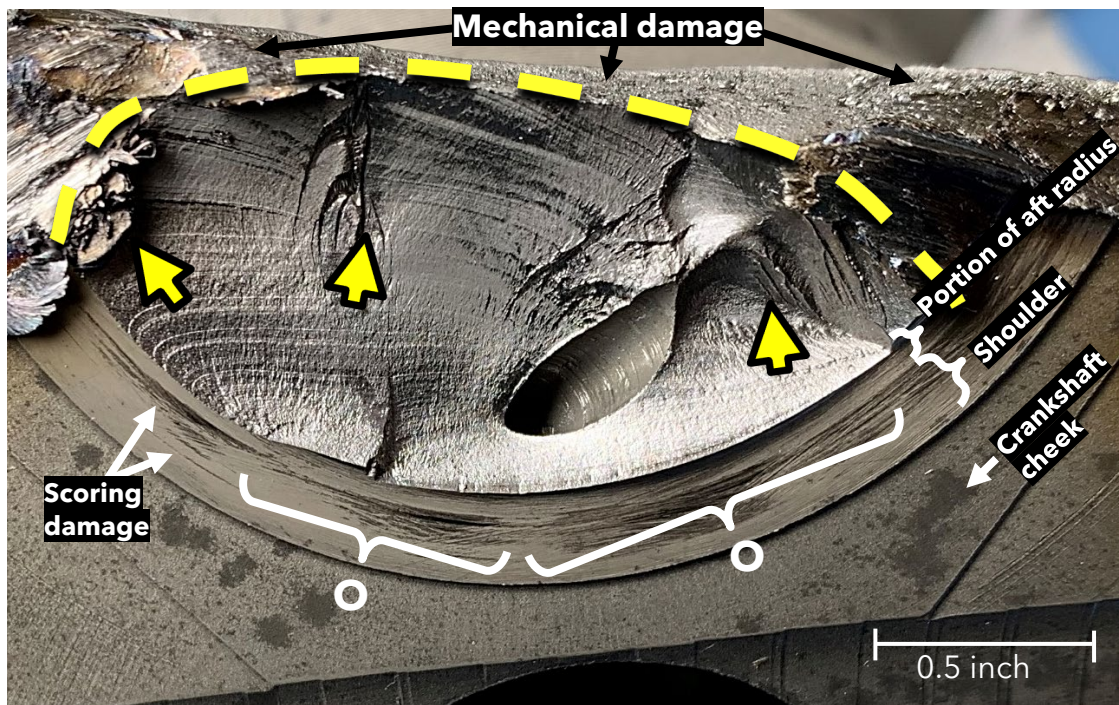


Figure 9. Close-up photograph of the aft face of the crankshaft fracture showing a fatigue crack that emanated from multiple origins at the aft radius of the #2 rod journal (#2RJ). Fatigue crack emanated from multiple origins, indicated by brackets "O", and propagated in the general direction indicated by arrows. The fatigue crack terminated approximately in the area indicated by a dashed line.

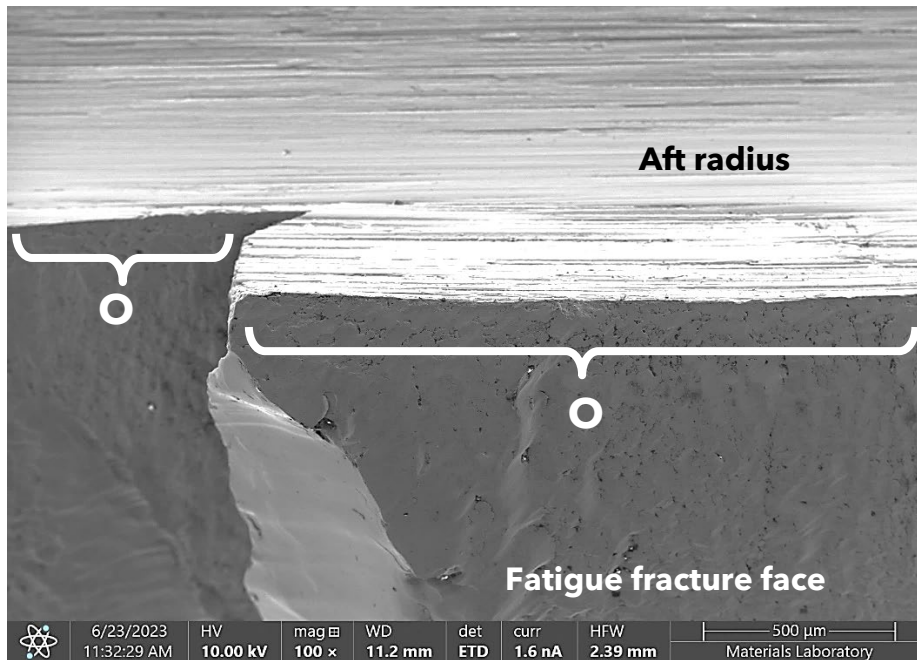


Figure 10. SEM image on the forward face of the crankshaft fracture showing a portion of the multiple origin fatigue crack, indicated by brackets "O", that emanated from the aft radius. Circumferential scoring is noted on the aft radius surface.

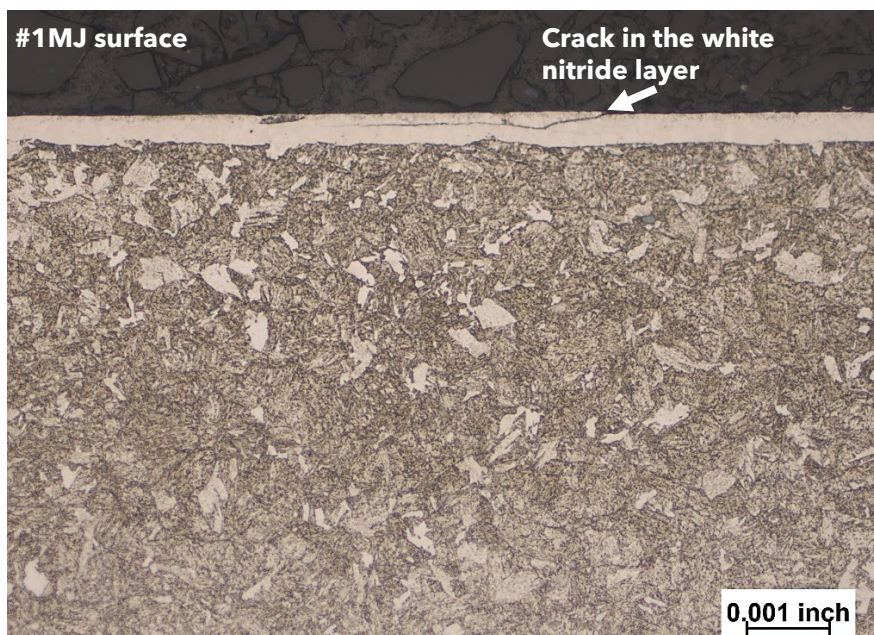


Figure 11. Metallurgical cross section "A-A" showing a microstructure of tempered martensite with a white nitride layer at the surface. The white layer contained a crack (2% nital etch).

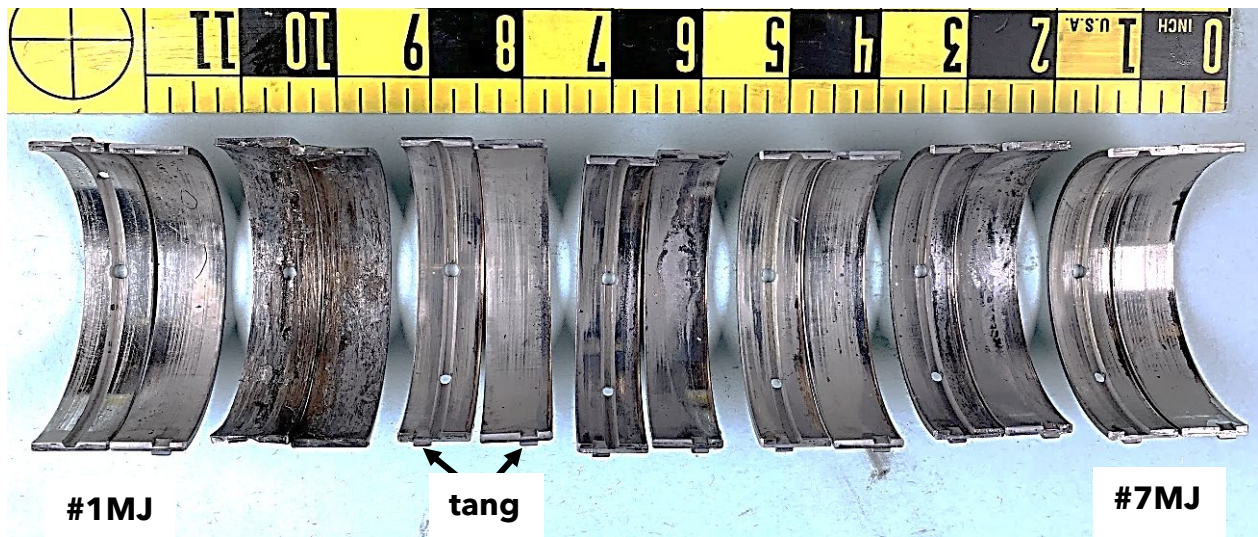


Figure 12. View looking at the inner surface of the bearing shell halves for the #1 main journal (#1MJ) through the #7 main journal (#7MJ), left to right. The tang portions from the #2MJ were deformed whereas the tangs from the remaining main journals were intact and showed no evidence of deformation.

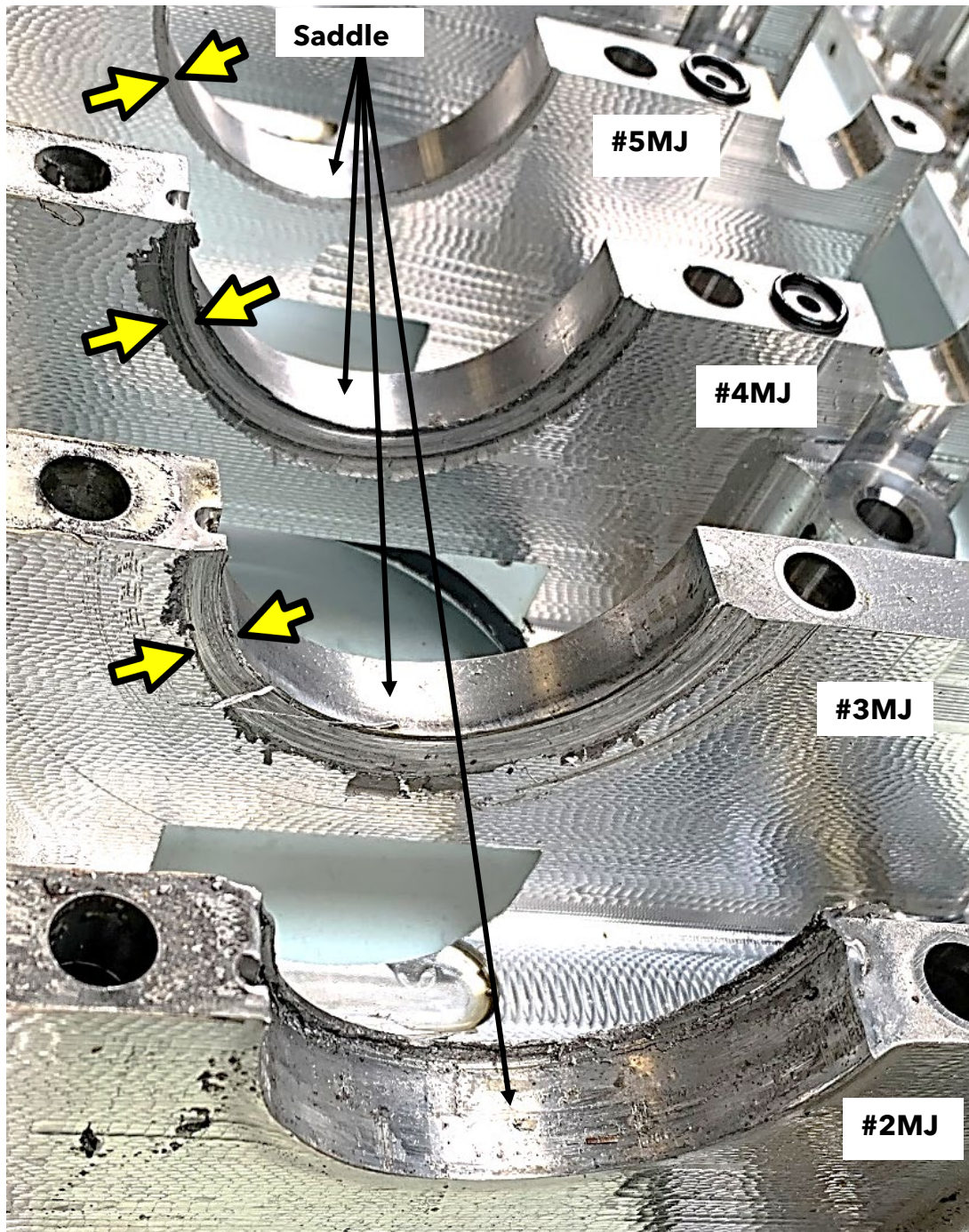


Figure 13. View of the inner surface of the engine case looking aft at the saddles for the #2MJ through the #5MJ (foreground to background). The saddles for the #3MJ through #7MJ showed evidence of scoring damage at the forward corners in the areas indicated between arrows. The exception is that the saddle for the #2MJ at the forward corner showed no evidence of scoring damage but showed evidence of compression deformation damage. The saddles for the #6MJ and #7MJ are not shown.

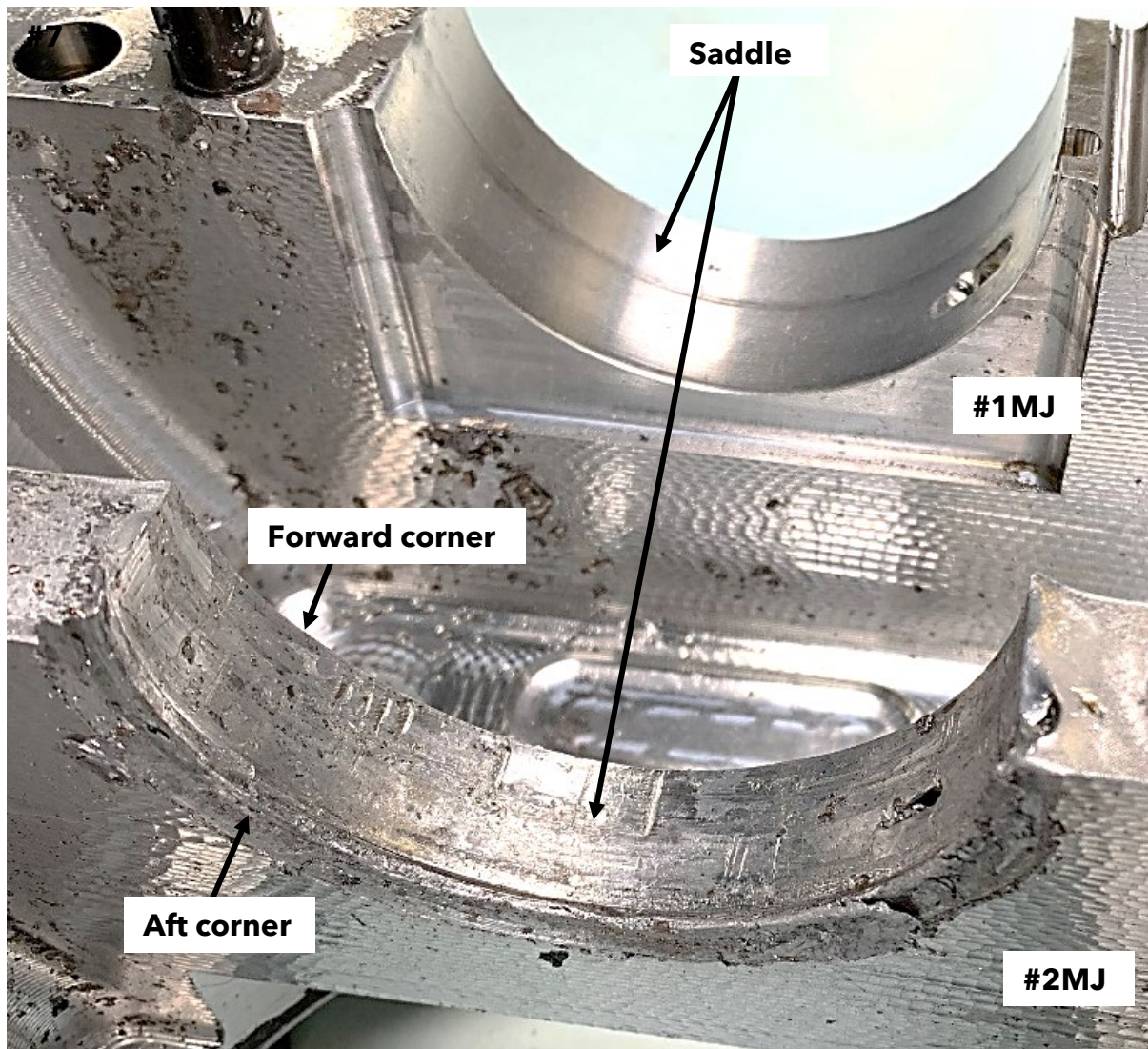


Figure 14. Close-up view of the inner surface of the engine case looking forward at the #2MJ and #1MJ (foreground to background). The saddle surface for the #2MJ at the aft corner exhibited severe circumferential scoring damage; compared with the saddle surface for the #1MJ at the aft corner which exhibited no evidence of damage.

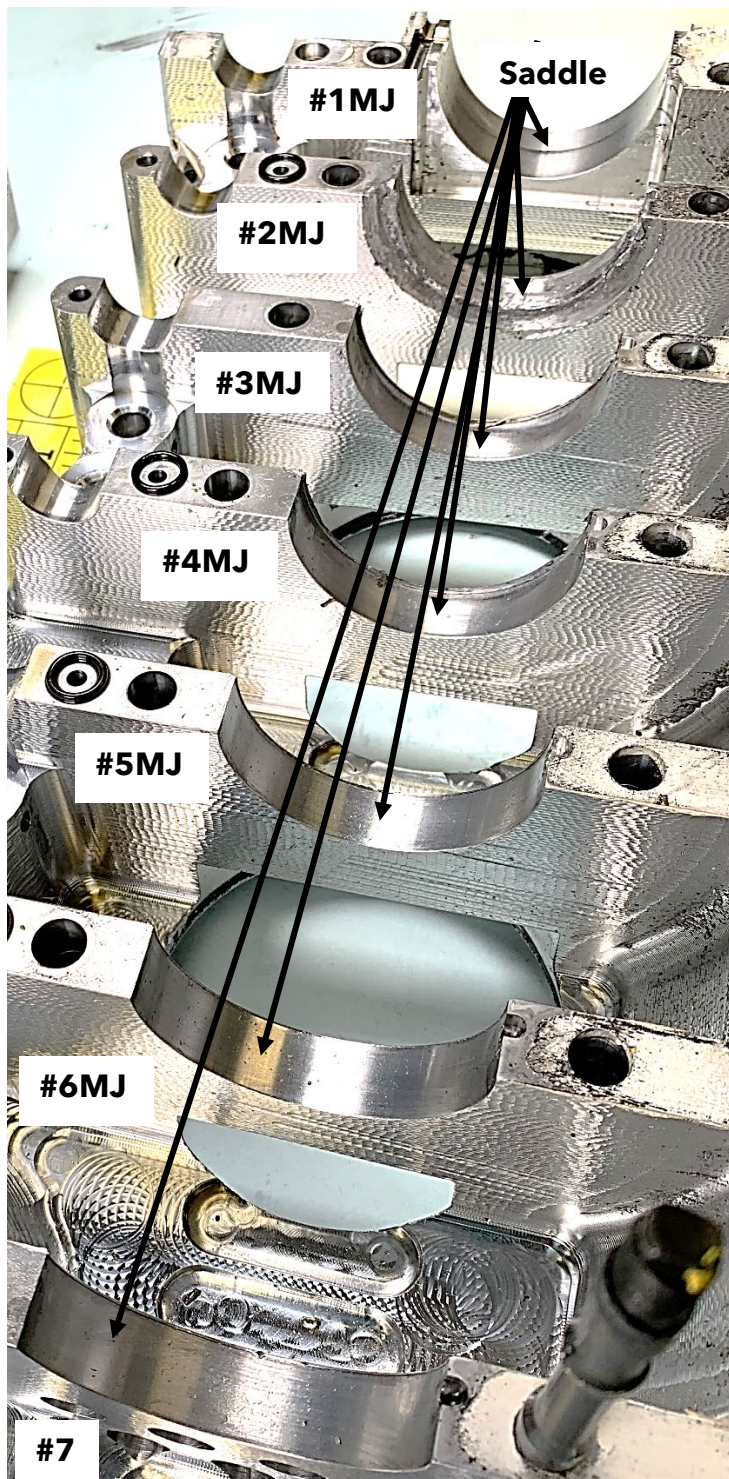


Figure 15. View of the inner surface of the engine case looking forward at the saddles for the #1MJ through #7MJ surfaces (background to foreground). The saddle surface for the #1MJ, and #3MJ through #7MJ, at the aft corners showed no evidence of damage.

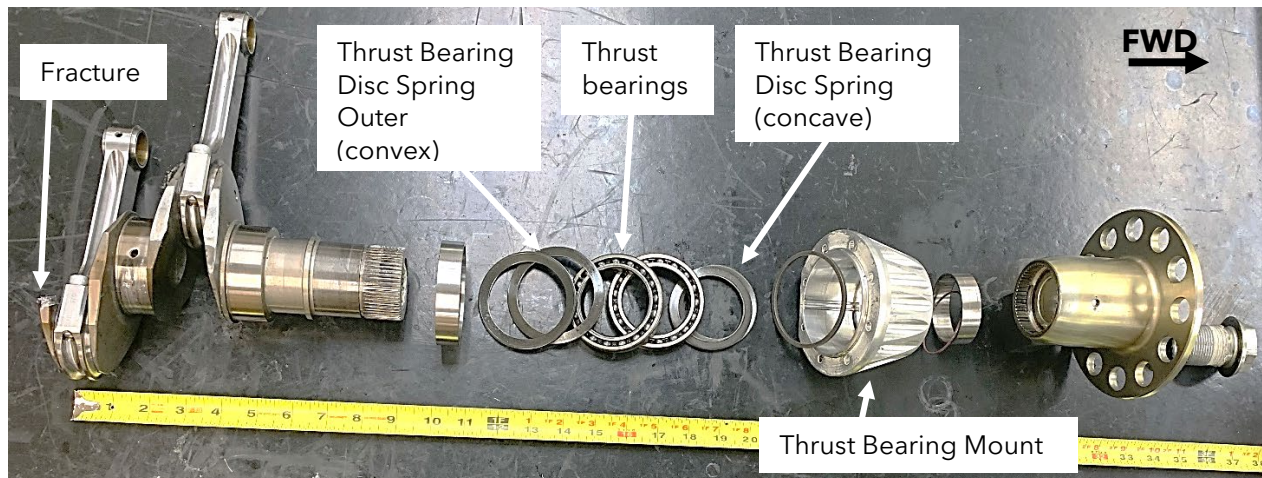


Figure 16. View of the disassembled propeller flange bolt; propeller flange; pieces from the thrust bearing mount; and fractured portion of the crankshaft that was located forward of the fracture (right to left).

Table 1. Location and Size of Superficial Cracks Found on the Radii of the Crankshaft				
Journal	Radius	Length of Crack		Location of the Crack on the Respective Journal Relative to the Fatigue Origin
		Inches	mm	
#1MR	Aft	None	None	No cracks
#1RJ	Forward	None	None	No cracks
	Aft	1.4	35.6	Diametrically opposite side of fatigue origin
#2MJ	Forward	1.8	45.7	Same side as fatigue origin
	Aft	0.8	20.3	Diametrically opposite side of fatigue origin
#2RJ	Forward	1.3	33.0	Same side as fatigue origin
	Aft	1.6	40.6	Fatigue Origin

Table 2. Composition of the crankshaft (wt%).			
Element	42CrMo4 Specified	AISI 4140 Compare	Measured
Carbon	0.38-0.45	0.38 - 0.43	0.40
Chromium	0.90-1.20	0.80 - 1.10	1.10
Manganese	0.60-0.90	0.75 - 1.00	0.81
Molybdenum	0.15-0.30	0.15 - 0.25	0.17
Phosphorus	0.025 max	0.035 max	0.010
Sulfur	0.035 max	0.04 max	0.027
Silicon	0.4 max	0.15 - 0.30	0.20
Aluminum	-	---	0.02
Copper	-	---	0.09
Nickel	-	---	0.12
Iron	Balance	Balance	Balance

Table 3. Crankshaft Journal Radius Measurements								
Item	Radius	Specified	Laser scan method				Replica method	
			Measurement 1		Measurement 2		Measured	
			inch	mm	inch	mm	inch	mm
#1MJ	AFT	0.041-0.074 inches	0.039	1.00	0.037	0.95	0.039	1.00
#1RJ	FWD		0.044	1.11	0.052	1.32	0.039	1.00
	AFT		0.048	1.22	0.054	1.37	0.050	1.27
#2MJ	FWD	(1.04-1.88 mm)	0.043	1.09	0.037	0.940	0.040	1.02
	AFT		0.036	0.91	0.034	0.864	0.036	0.91
#2RJ	FWD		0.044	1.11	0.052	1.32	0.049	1.24
	AFT		0.049	1.24	0.073	1.85	0.039	1.00

Notes:

- (1) Red indicates measurements are outside the specified limits.
- (2) Measurements 2 were made on diametrically opposite side of those made by measurement 1.
- (3) Radius measurements that were less than specified are shown in red.
- (4) FWD indicates forward.

Table 4. Thrust Bearing Disc Spring Inside and Outside Diameters (mm)					
Type	Random Sample Number	Inside Diameter (ID)		Outside Diameter (OD)	
		Specified	Measured	Specified	Measured
Concave Disc P/N E021502	1	54.8-55.2	55.18	70.7-71.3	70.96
	2		55.13		70.86
Convex Disc P/N E021510A	1	62.8-63.2	63.08	79.7-80.3	79.80
	2		63.07		79.80

Table 5. Thrust Bearing Disc Spring Outer Thickness and Axial Length (mm)					
Type	Random Sample Number	Wall Thickness		Axial Length (most forward edge to most aft edge)	
		Specified	Measured	Specified	Measured
Concave Disc P/N E021502	1	2.3-2.7	2.49	3.22-3.62	3.30
	2		2.5		3.23
Convex Disc P/N E021510A	1	2.05-2.45	2.2	3.32-3.72	3.43
	2		2.2		3.35

APPENDIX 1

Nitride Case Depth and Hardness (Definition and Measurement)

Appendix 1.

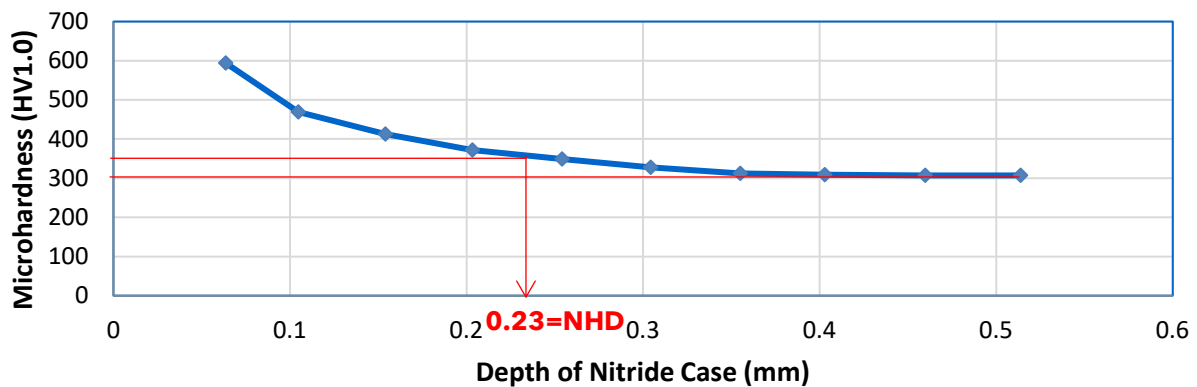
Determining Nitride Case Depth and Hardness

The definition and procedure for determining the effective case depth of a nitriding treatment, also referred to as nitriding hardness depth (NHD), is described in DIN 50190-3, titled "Hardness depth of heat-treated parts; determination of the effective depth of hardening after nitriding", and ISO 18203:2016(en) "Steel – Determination of the thickness of surface-hardened layers". The nitriding hardness depth (NHD) is defined as the distance from the surface of nitride layer to the point where the material hardness limit is 50 HV above core hardness. The procedure requires plotting the hardness of the nitride layer versus the depth of the nitride layer on a graph. The core hardness is determined by at least three hardness measurements and rounded to the nearest multiple of 10 HV. A point on the plotted curve must be identified where the average core hardness value plus 50 HV (4 HRC points) intersects the curve. The point on the curve that corresponds to a distance from surface defines NHD.

Traverse microhardness testing, using a LECO Microhardness Tester LM248AT instrument, 1 kilogram load, was performed on section "B-B" in figure 5, through the #1 main journal (#1MJ). Hardness indentations were made from an area located adjacent to the nitride surface to an area extending below the surface (toward the core), until the hardness values levelled off to the core hardness. The hardness adjacent to the surface (white layer) measured as great as 594HV. A plot of the measured hardness values versus the corresponding depth measurements is shown at the bottom of the page. The average core hardness (310HV) plus 50 HV (4 HRC points) was calculated to be 360HV, which is also referred to as the hardness limit. The hardness limit (360HV) intersected a point on the curve that corresponded to a distance from surface of approximately 0.23 mm, referred to as NHD.

#2 Rod Journal Hardness Vs. Depth of Nitride Case (1.0 Kilogram Load)				
Indent #	Distance from Surface		Hardness	
	mm	inches	HV	HRC
1	0.0636	0.0025	594	55
2	0.1048	0.0041	469	47
3	0.1541	0.0061	413	42
4	0.2034	0.0080	372	38
5	0.2540	0.0100	349	36
6	0.3042	0.0120	328	33
7	0.3551	0.0134	312	31
8	0.4029	0.0159	309	31
9	0.4598	0.0181	307	31
10	0.5138	0.0202	307	31

Plot of Hardness vs. Depth of Nitride Case

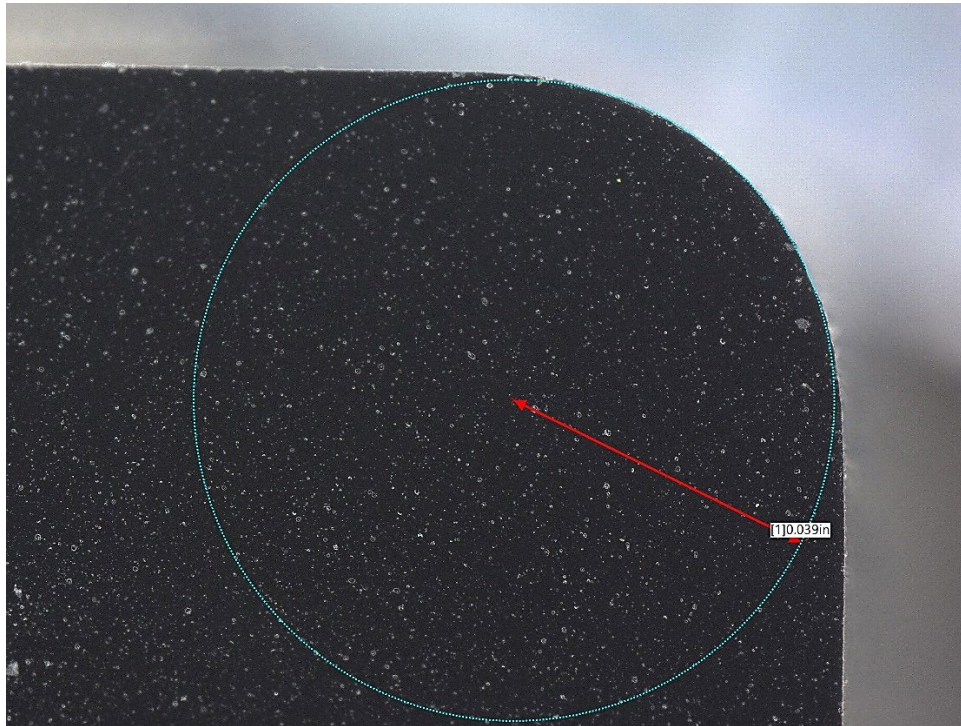


Average core hardness of the crankshaft = 308HV (to the nearest 10 is 310HV)

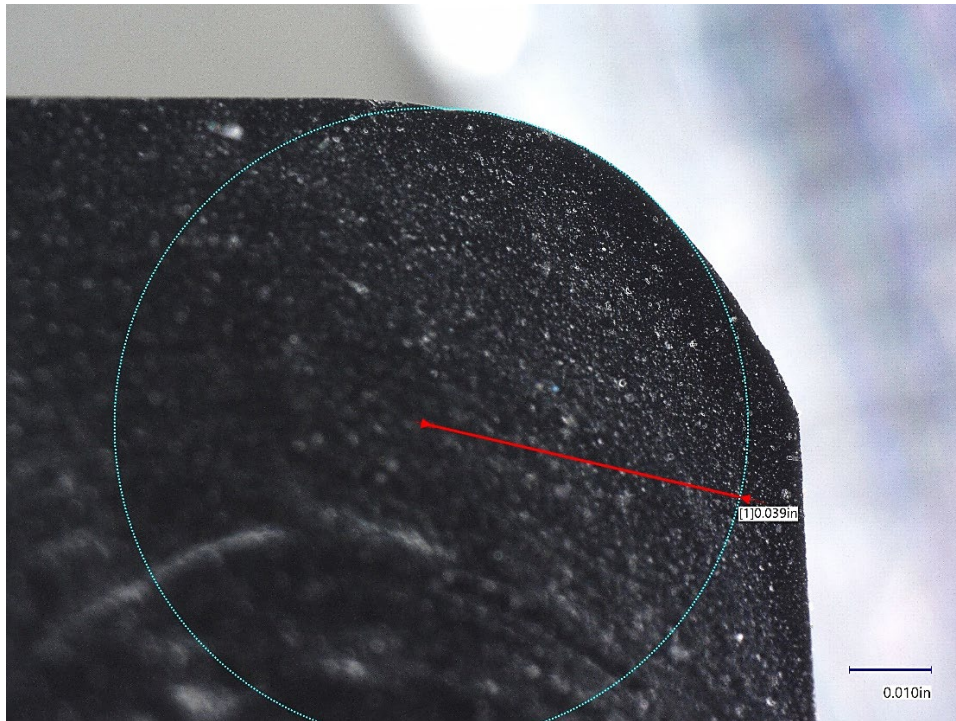
Limit hardness is equal to an average core hardness + 50HV = 360HV

Nitride Hardness Depth (NHD) at 594HV1.0 = 0.23 mm

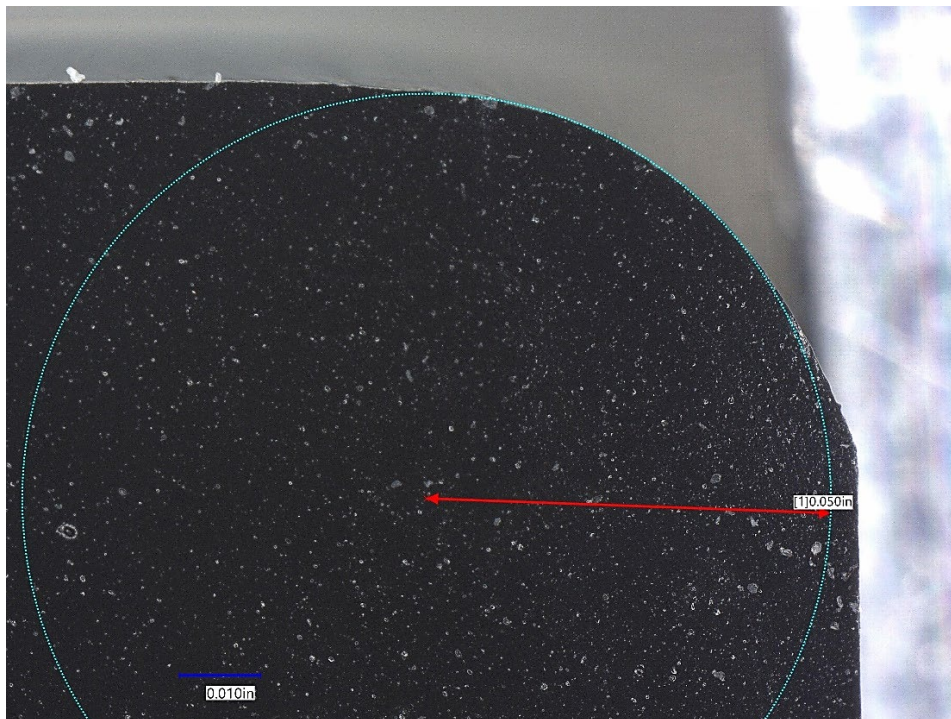
APPENDIX 2
Radius Measurements
by
Silicone Replica Method



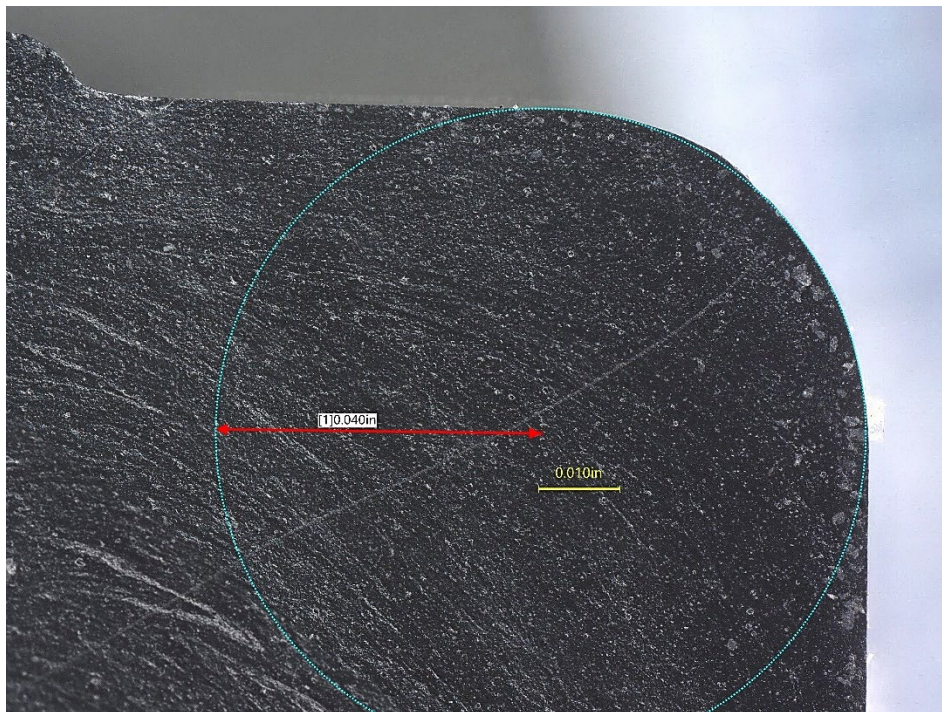
#1MJ Aft Radius (0.039 inch)



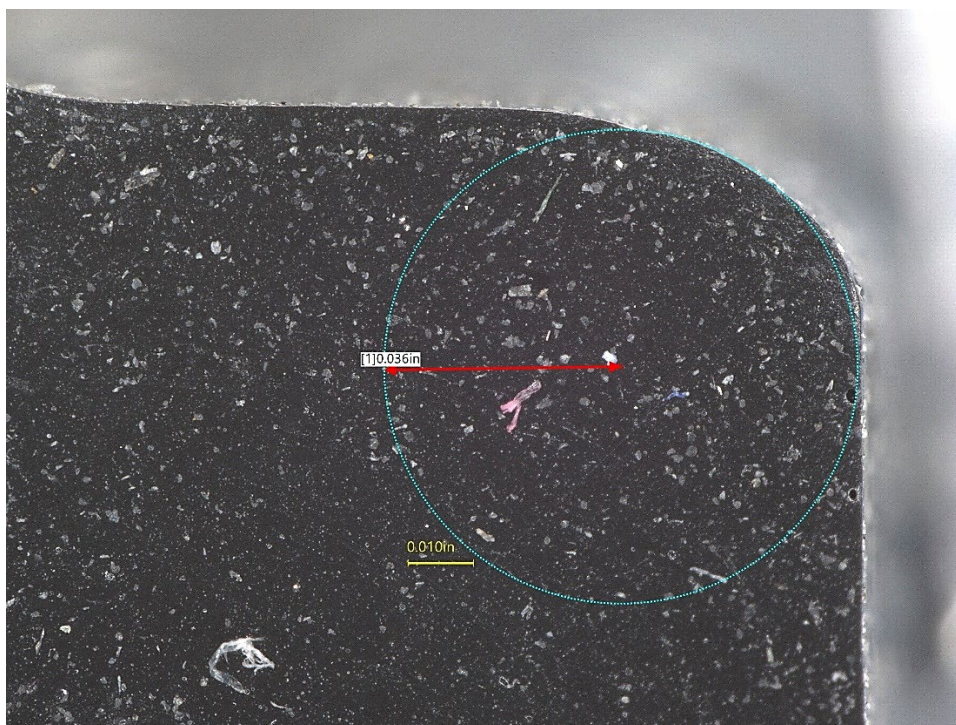
#1RJ Forward Radius (0.039 inch)



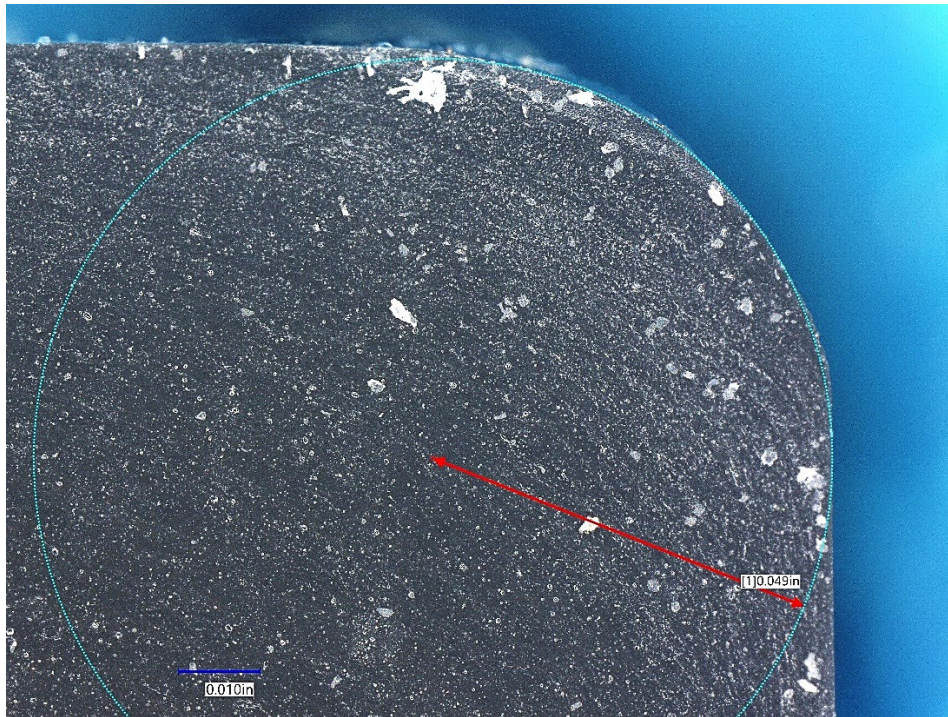
#1RJ Aft Radius (0.050 inch)



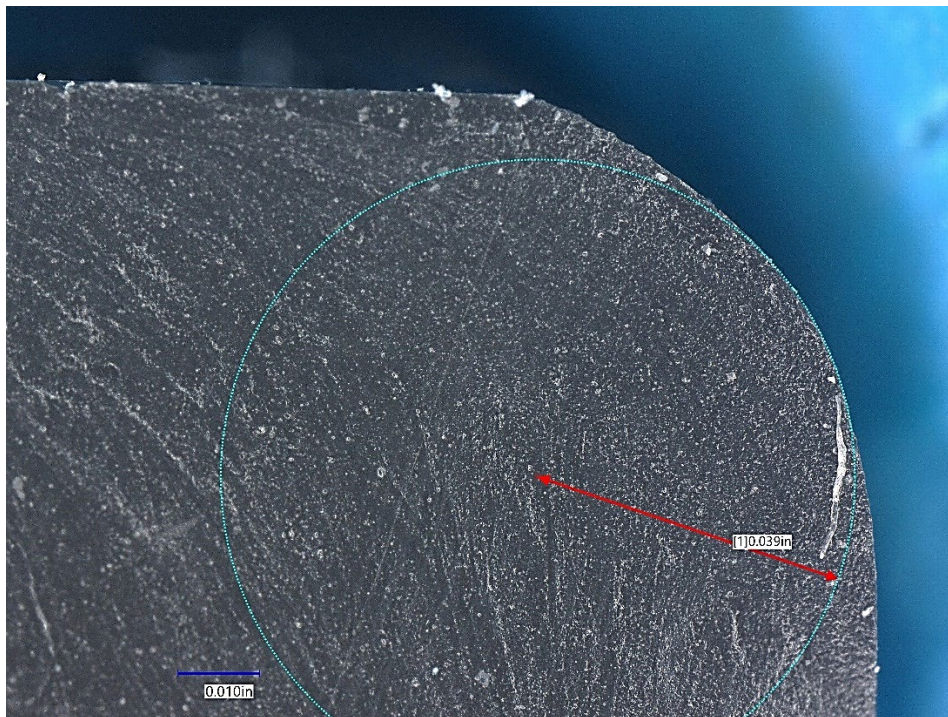
#2MJ Forward Radius (0.040 inch)



#2MJ Aft Radius (0.036 inch)



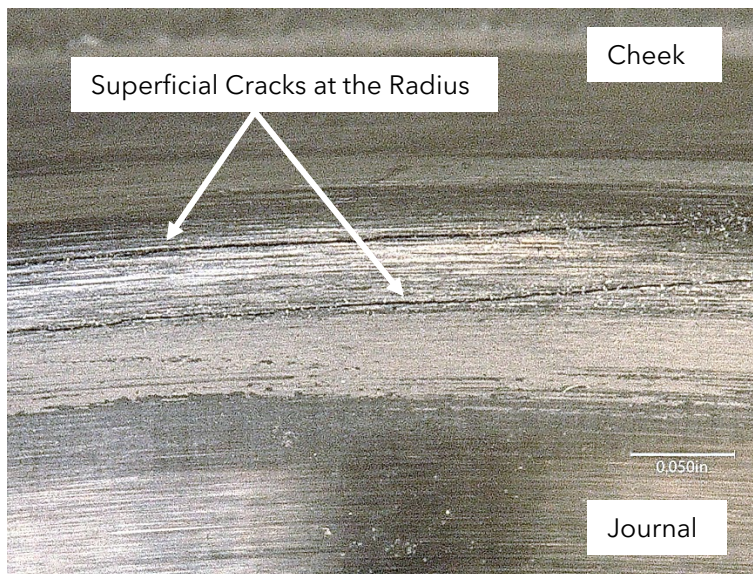
#2RJ Forward Radius (0.049 inch)



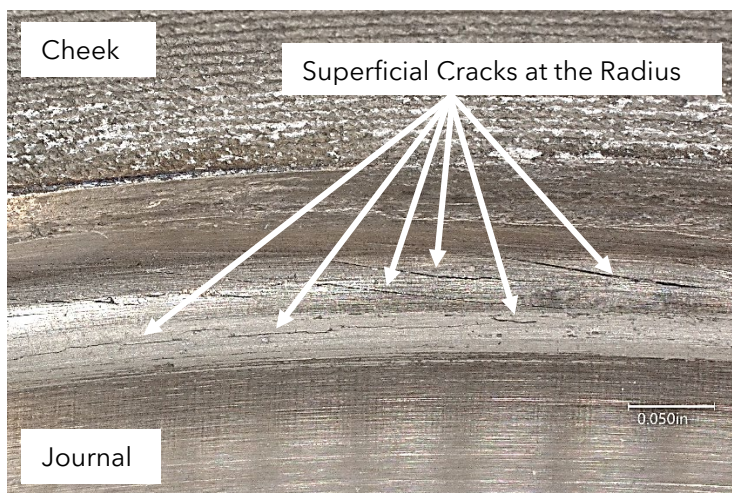
#2RJ Aft Radius (0.039 inch)

APPENDIX 3

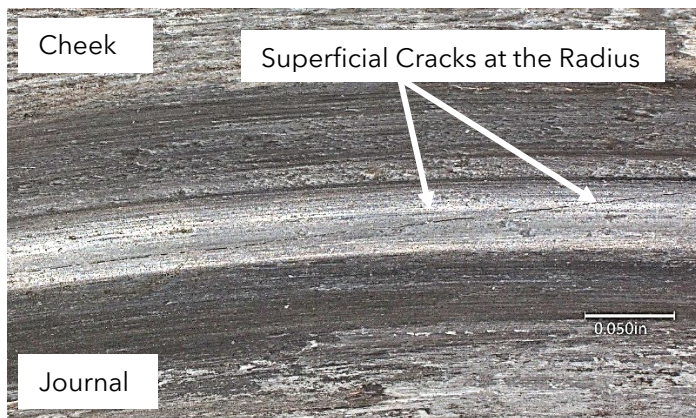
**Photographs of Superficial Cracks
Found at the Radius Areas**



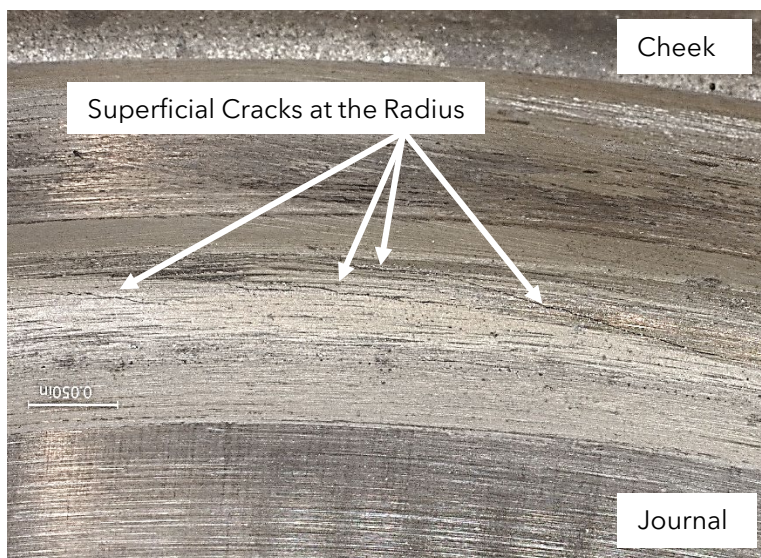
#1 rod journal aft radius



#2 main journal forward radius



#2 main journal aft radius



#2 rod journal forward radius