From: [redacted]
To: [redacted]
Cc: [redacted]
Subject: redacted report for ERA16FA023
Date: Thursday, July 20, 2017 2:03:30 PM
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Dan, please find the attached redacted lab report for inclusion into the public docket for ERA16FA023.

Please use this email as approval/permission to apply the attached Lycoming Engines company confidential file into the public docket.

If you need anything further, please let Mike Caldera or myself know.

V/R,

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LYCOMING

"Testing leads to failure, and failure leads to understanding" - Burt Rutan

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Technical Report

Evaluation of Crankshaft and Other Selected Components from

TIO-540-AF1B Engine (S/N L-9457-61E)

In Support of NTSB Accident Investigation ERA16FA023

Report No. LN-17682

April 10, 2017

Prepared by

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Manager, Materials Lab

Reviewed by:

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Vice President of Research,
Development, and Engineering [redacted]

Approved By:

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Senior Vice President and General Manager [redacted]

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COMPANY CONFIDENTIAL
FORM NO. 811A (Rev 10-2014)

652 Oliver Street
Williamsport, PA 17701 U.S. A
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REPORT NO. LN-17682

REQUEST FOR MATERIALS LABORATORY INVESTIGATION

ENGINE DATA	PART DATA	
TYPE TIO-540-AF1B	NAME Crankshaft	DATE RECEIVED 10-27-15
S/N L-9457-61A	NUMBER 75038-70	SIR No. *none*
HOURS unknown	S/N 84516	SUBMITTED BY [redacted]
APPLICATION Mooney M20M N243CW	TIME unknown	PHONE 7212

☒ FIELD ☐ TEST ☐ OTHER

PHOTOGRAPHS: ☒ Y ☐ N

TYPE REPORT: ☐ Informal ☒ Formal ☐ Warranty Pending ☐ Info Only / Self-Assigned

AFTER COMPLETION OF INVESTIGATION:

☐ Dispose parts ☒ Return parts to submitter ☐ Store until __________________ and then dispose

☐ Other ____

REPORT DISTRIBUTION Standard Lycoming Distribution plus NTSB

REASON FOR SUBMITTAL / WORK REQUIRED:
Analyze the crankshaft, bearings, and broken connecting rod from the subject engine and try to determine the cause for the crankshaft failure between the #5 and #6 crankpin journals.

INVESTIGATION RESULTS:

Background and Summary. This engine was involved in a fatal aircraft accident (October 24, 2015 in Worchester, MA, ref: NTSB investigation #ERA16FA023), which occurred shortly after takeoff, with the aircraft impacting propeller-first into the ground. The crankshaft was completely separated, through the #8 cheek, with both counterweight assemblies still attached. In addition, the #6 connecting rod was broken, the #5 connecting rod was twisted, the #5 piston was broken, both rear engine mount brackets were broken, the camshaft was broken, and the rear of the engine experienced severe damage. The crankshaft failed in fatigue, with crack initiation from the rear fillet radius of the #5 crankpin journal, progressing through the #8 cheek and into both counterweight attachment ears. None of the bearings were seized, and there was no evidence of oil starvation. The counterweight rollers, washers, and snap-rings were all still installed, and the counterweights were still attached to the crankshaft, although the final crack separation caused one bushing to release from one of the counterweight attachment lugs of the crankshaft. The prop governor set screw was in place. All connecting rod bolts were intact and had nuts still tightly fastened. All piston pins and the #1-4 and #6 piston rings were in good condition, freely moveable (#5 piston's upper section remained stuck inside the #5 cylinder, and was not examined further). The crankshaft conformed to engineering drawing requirements with two minor exceptions not considered relevant to this incident, and was free of honeycomb or microcrack features. Root cause was not determined, but evidence of possible overstress was found on the crankshaft fracture surface.

Engine History. According to Lycoming records, this engine was originally manufactured as a TIO-540-J2B (ENPL-8945), shipped on 5/18/1993 and entered service on 5/13/1994. The originally manufactured engine was sent to a different owner, was installed on a different aircraft, and had a different crankshaft than the current subject investigation. After accumulating 1792.5 hrs service time, this engine was returned to the factory on 4/23/2001. The engine was then overhauled at Lycoming as a TIO-540-AF1B (HENPL-9906), shipped on 12/21/2001 to a new owner, and entered service on aircraft N243CW on 3/1/2002. Since being shipped in 2001, this overhauled engine had three service incidents reported to Lycoming:

SIR No. 20015R – turbocharger oil leak at 6.5 hours (3/5/2002, replaced wastegate)
SIR No. 37450R – fuel pump high pressure issue at 96.7 hrs (5/27/2002, pump replaced)
SIR No. 41638S – cracked exhaust pipe at 127 hrs (1/10/2003, pipe replaced)

Crankshaft History. The complete history of this crankshaft is not known, because some of the records no longer exist. The oldest record that could be found shows that the crankshaft was returned to the factory on 9/6/2001 as part of a core-returned O-540-E4B5 engine, S/N L-19583-40 (i.e., not the current subject engine). Following core-teardown, the crankshaft was overhauled to "-70" dimensions on 11/3/2001. Part markings indicate it was forged by Wyman Gordon, and was made of AMS-[redacted] (air-melted steel). Based on the forging manufacturer, the part number, the steel alloy used, and the serial number, the crankshaft most likely was originally manufactured no later than the late 1970's (when all Lycoming crankshafts were switched to the vacuum-melted AMS-[redacted] grade of steel).

Components Markings and Visual Appearance. The crankshaft, damaged connecting rod assemblies, main bearings, and the #6 piston were submitted to the Materials Lab for further examination, in the condition shown in Figures 1 - 31, and as described below. The condition of selected other components not submitted to the lab is also presented, in Figures 15-23 (camshaft, crankcase, tappet, propeller governor gear and setscrew).

1. Crankshaft. The prop-flange was marked as follows: **75038-70** (part number), **84516** (serial number), **CT** , circled **LN-226** inspector stamp, keystone inspector stamp number **25**, hexagonal inspector stamp with what looks like a (**B** or **P**, unclear) and a **10** stamped inside. The #2 cheek had a forged-in **$ N** and **9** (*or, possibly a 6*). The $ mark indicates the shaft was forged by Wyman-Gordon. The #5 cheek had a stamped **042** (heat code). The 75038 part number was obsolete in November, 1978 (by Engineering Change Order #20716). The counterweight ear that was broken, was ink-stamped with a **P10**, indicating the counterweight bushing bore was made to the P10 oversize dimension (*this was mated with the #2 bore of counterweight B – see Figure 6 for bore and component labeling system used in this report*).

2. Counterweight Bodies. Both counterweight bodies were marked with part number 73644-85, Rev. D, and had ink stamps of LP194, LN-221, a keystone with a 29 inside. The counterweight bodies were intact, but had numerous impact dents and dings. The counterweight bushings, rollers, washers, and snaprings were all still in their installed positions. See Fig. 6 for explanation for the labeling system used in this report, for identifying the locations of the counterweight bushing bores and their subcomponents.

3. Counterweight Washers. The eight counterweight washers were all marked with part number 71907, 02-01 date code, and 17328 vendor code. All eight were cracked on their outward faces, but no pieces were broken off. Cracking appears consistent with sudden impact loading. Washers were not evaluated any further, except one was checked for case hardness, and it conformed (91 HR15N).

4. Counterweight Washer Snap-rings. All eight snaprings were intact and still in place, and had been properly installed with their sharp edges facing outward. Snaprings were not evaluated further.

5. Counterweight Rollers. One counterweight had two P/N LW-15558 rollers (both marked with vendor code 79960 and date code 13-01), and the other had two P/N 76788 rollers (both marked with vendor code 7207 and date code 27-01). The rollers were all in good condition, except for moderate damage on the OD surfaces of the P/N 76788 roller that was installed where the crankshaft lug fractured and lost its bushing. Rollers all conformed for length and diameter, and were not evaluated further.

6. Counterweight Bushings (installed in counterweights). These were all still installed and remained in good condition. Bushings were not evaluated further.

7. Counterweight Bushings (installed in crankshaft). Three of the four were still installed, and were in good condition. The fourth was missing from the broken counterweight lug (apparently released during crankshaft fracture), and not recovered. Bushings were not evaluated further.

8. Connecting Rods. All were p/n LW-11750 (some were S, some were E). The #1-#4 rods were in good condition. The #5 rod was bent, and the #6 rod was broken through the web section near the crankpin bore end. That fracture surface was severely damaged from post-fracture contacts, but generally presented a rough fracture surface with pronounced shear lips, indicating it was most likely caused by sudden overload. The #5 and #6 connecting rods were most likely damaged by the fracture of the crankshaft and subsequent events. The connecting rods were not investigated further.

9. Crankpin Journal Bearings. The #6 crankpin journal bearings were both p/n LW-13521, date code 5-01, manufacturer's mark of ML-KS. Both halves were in generally good condition, with no overlay fatigue or cracking or delamination. Both displayed some particle embedment and scoring, and a small region of overlay deformation near one edge, that was obviously caused by sudden overload, and not frictional heating. The bearings were not investigated any further.

10. Main Bearings. The #1/#2 main bearings were marked on the steel backing with LW-13884, KS, and 8-01 (date code). The #3, #4, and #5 main bearings were marked with LW-16711, ML-KS, and same date code of 8-01. Front mains were in excellent condition. The #3 and #4 main bearings exhibited some light wear of the overlay, and some particle embedment. The #5 rear main bearing was badly damaged and deformed, apparently from post-fracture contacts – the overlay was still present on the working surfaces. No evidence of bearing seizure was found. The bearings were not examined any further.

11. Piston (*P/N not visible*). The #6 piston was in generally good condition. All piston rings were in place and freely moveable. The broken connecting rod was freely moveable on the still-installed piston pin. After disassembling the piston pin and connecting rod, the piston's crown was lightly sanded, and hardness was measured near the OD (above pin-bore), and near the center, ranging from 65-69 HB/10/500. Without knowing the engine service hours, this hardness cannot be correlated to an operating temperature.

Crankshaft Dimensions. The condition of the crankshaft prevented a complete dimensional inspection; however, the journal diameters and roundness were measured, using Lycoming crankshaft department's production inspection gages (SD-923750 for the main journals, and SD-921240 for the crankpin journals). As a "-70" crankshaft, the main and crankpin journal diameters may deviate up to 0.0013 inch below the standard specification tolerance range shown on the engineering drawing. As shown in Table 1, all journal diameters conformed to the "-70" diameter limits, but two of the crankpins exceeded the engineering drawing limit for out-of-round (#1 and #3 crankpins).

Table 1. Crankshaft Journal Dimensions, inch

Journal	Diameter				Out-of-Round	
	Drawing Spec.	-70 minimum	Actual Deviation, Min*	Actual Deviation, Max*	Actual, Max-min	Drawing Spec.
#1 Main	[redacted]	[redacted]	-0.0003	0.0002	0.0005	[redacted]
#2 Main			0.0001	0.0002	0.0003	
#3 Main	[redacted]	[redacted]	-0.0007	-0.0005	-0.0002	
#4 Main			-0.0007	-0.0008	-0.0001	
#1 Pin	[redacted]	[redacted]	-0.0013	0.0003	0.0016	
#2 Pin			-0.0002	0.0001	0.0003	
#3 Pin			-0.0011	0.0008	0.0019	
#4 Pin			-0.0009	-0.0004	0.0005	
#5 Pin			-0.0004	0	0.0004	

******Average of 3 measurements for crankpins*

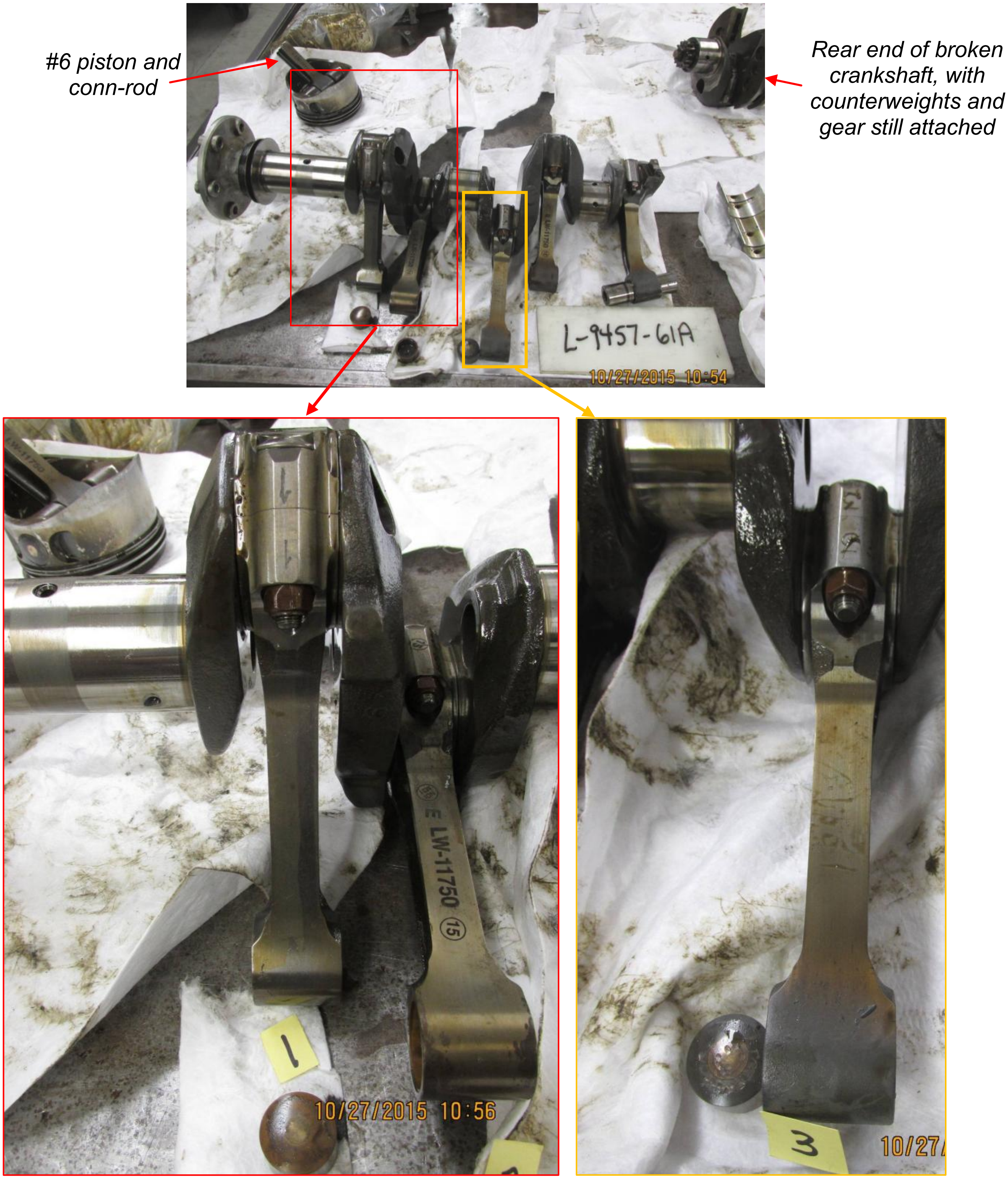


Figure 1. Broken crankshaft as removed from the engine, with closer views of the #1 - #3 connecting rods, still attached. Broken #6 connecting rod with piston still attached also visible in top photo. Also note, clean, undamaged surface of the main journals. See Figure 2 for closer views of the #4 and #5 connecting rods and adjacent areas.

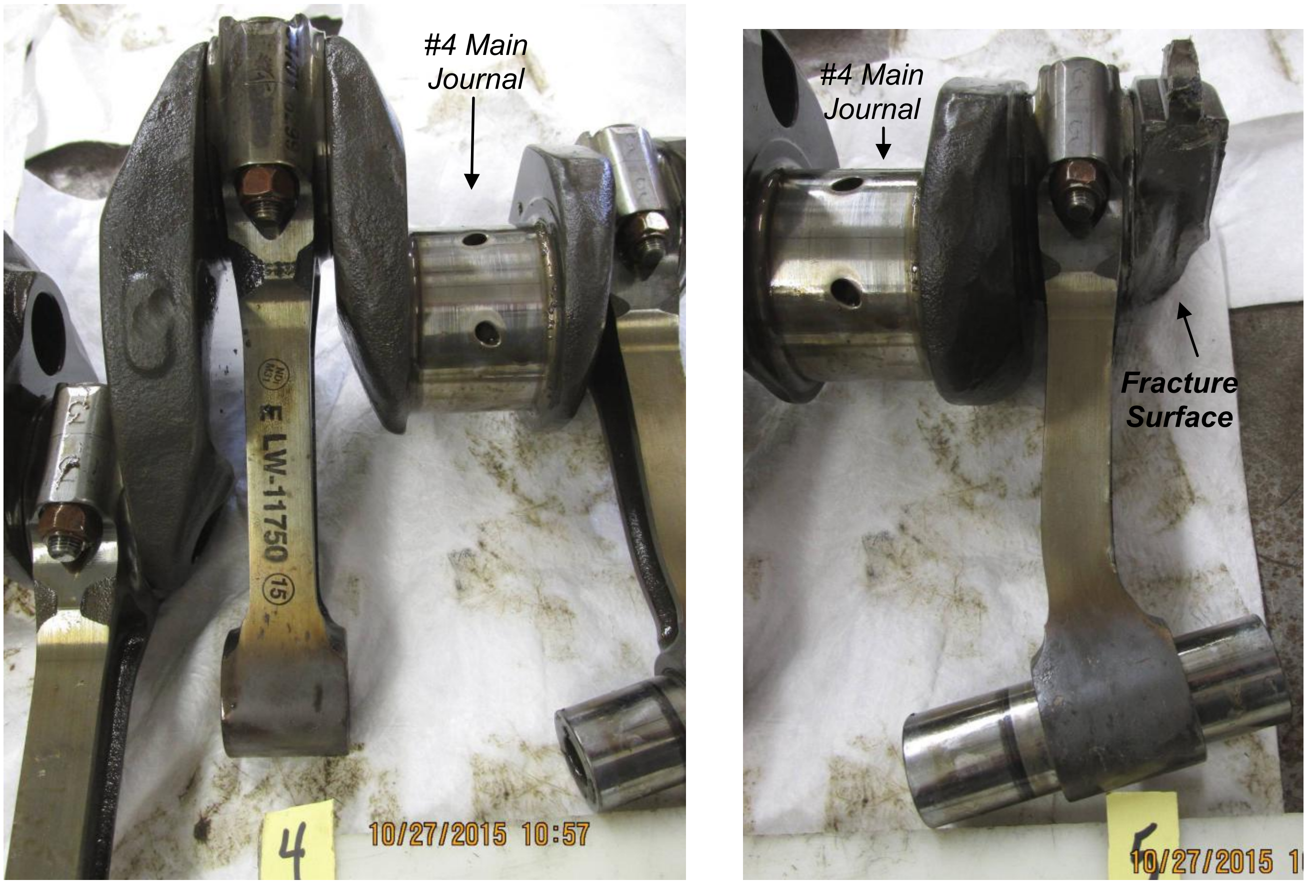


Figure 2. Closer views of the #4 and #5 connecting rods, still attached to the broken crankshaft, as removed from the engine. Note #5 rod is twisted, and both connecting rods have darkened appearance at the piston end. Note clean, undamaged surface of the #4 main journal. Fracture surface visible in right photo.

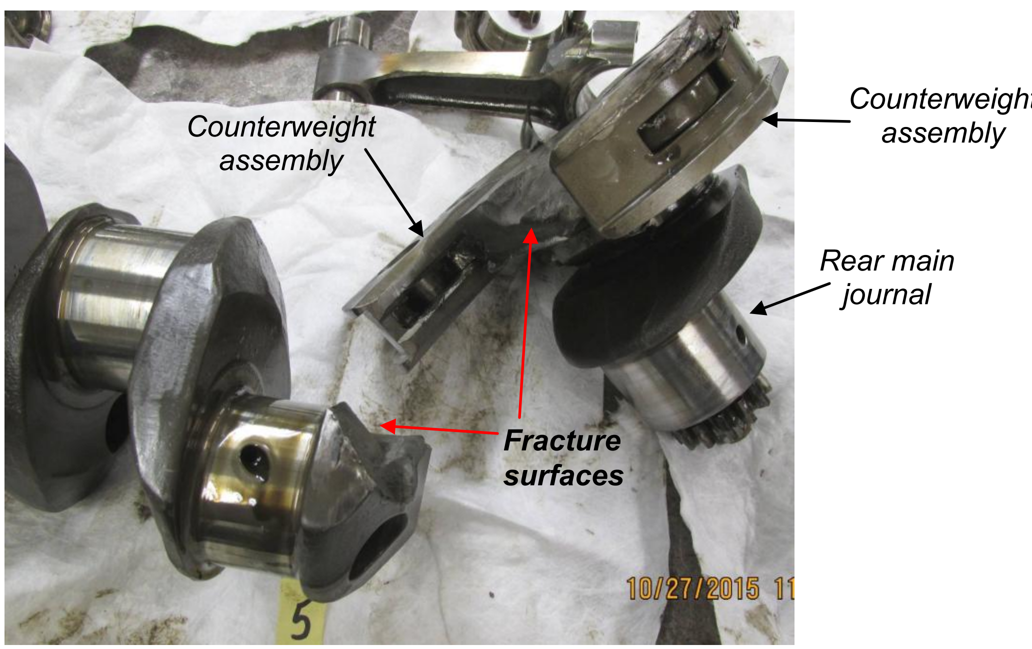


Figure 3. Rear section of the broken crankshaft, after removal of the #5 connecting rod, with the mating piece placed alongside (counterweights still attached). Note generally clean, undamaged, and lubricated surface of the #5 crankpin journal adjacent to the fracture surface.

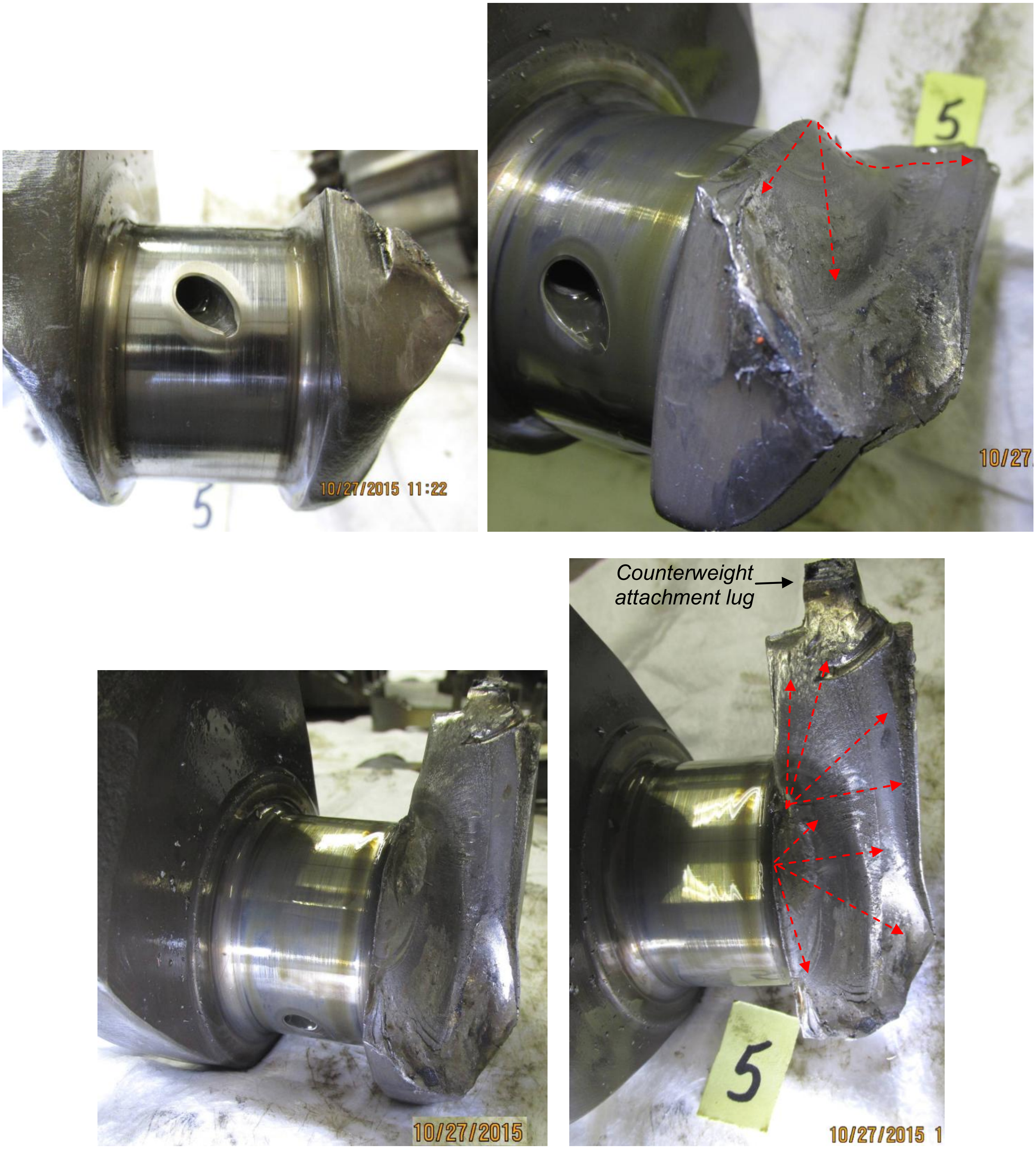


Figure 4. Fracture surface of the crankshaft adjacent to the #5 crankpin journal, viewed from four different perspectives. Journal surface was in good condition, and clearly had not experienced bearing seizure. Beach marks visible in top/right and bottom two photos, indicate fatigue crack initiation from the rear fillet radius of the #5 crankpin journal, followed by stable fatigue crack growth through nearly the entire section thickness of the #8 cheek, in directions as indicated by the dashed arrows.

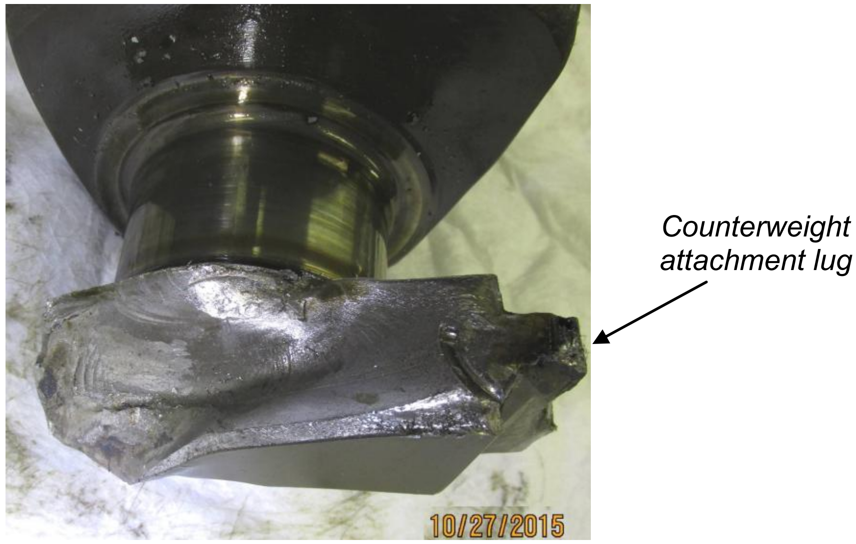
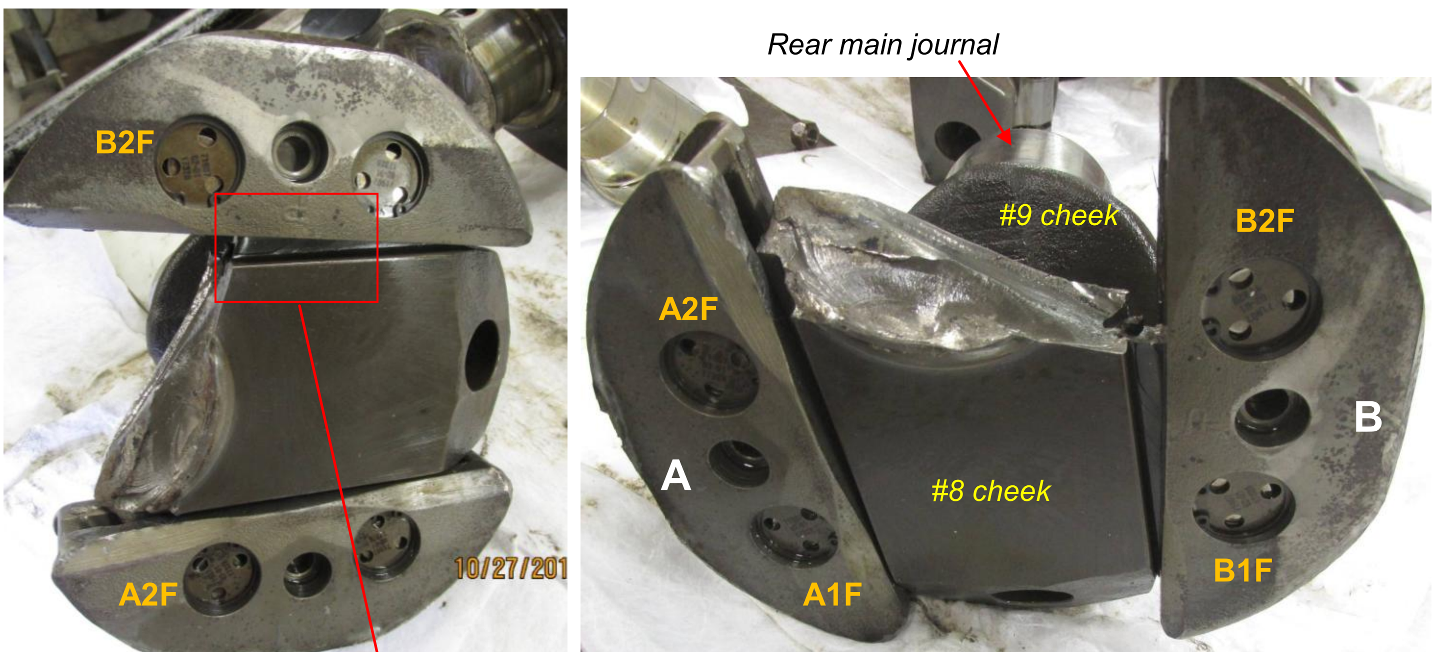
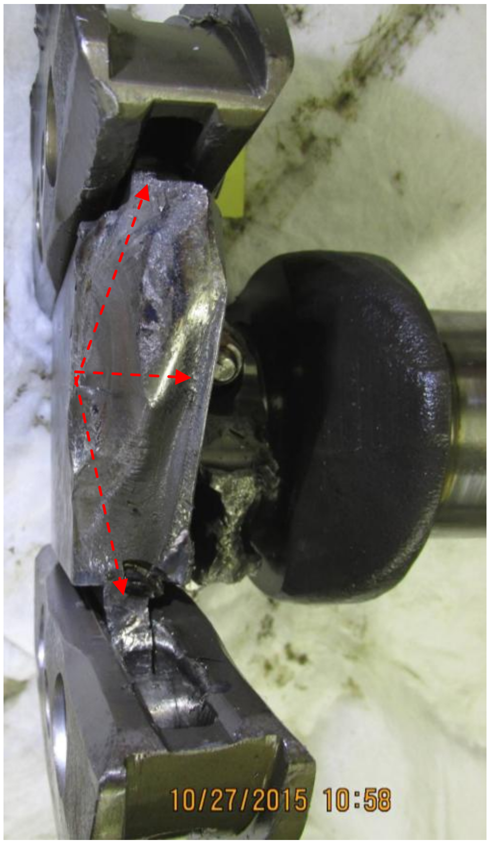


Figure 5. Additional view of the fracture surface of the crankshaft adjacent to the #5 crankpin journal, better showing the crack path from the rear journal fillet radius, through the cheek and into the counterweight attachment lug.



Counterweight bore and component labeling system – 3 characters:
1st letter: A or B, for arbitrarily assigned counterweight body identification
2nd number: 1 or 2, for arbitrarily assigned bushing bore number
3rd letter: F or R, for front or rear side
Example: B2F washer is in the frontward side of the #2 bore of counterweight B

Figure 6. Mating (rear) piece of the broken crankshaft. Fracture proceeded through the #8 cheek, and out into both counterweight attachment lugs, but both counterweight assemblies and their subcomponents remained attached to the shaft. At bottom, a closer view of some secondary cracking in the counterweight attachment zone, adjacent to the main fracture surface.



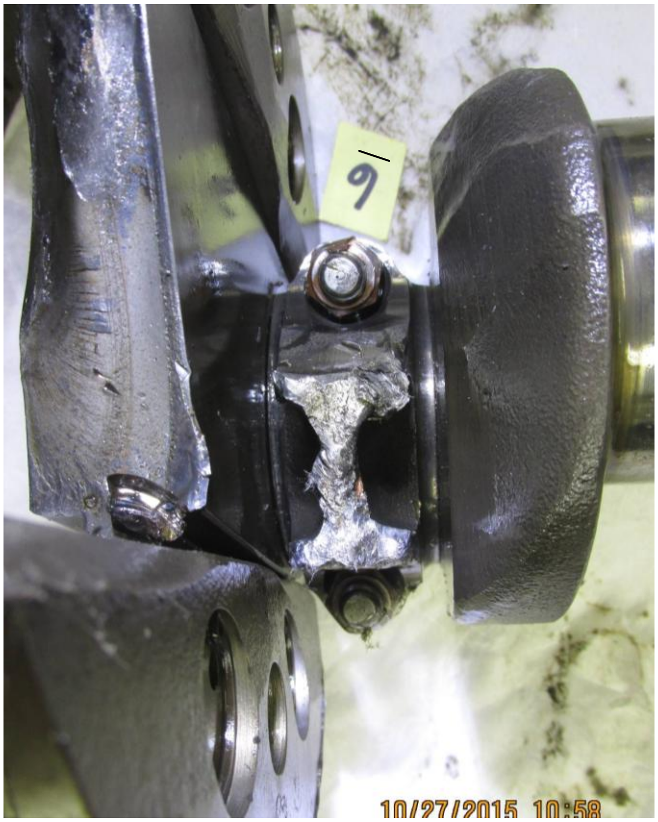


Figure 7. Mating (rear) fracture section of crankshaft, shown from three more perspectives. Top left, with #6 conn-rod cap visible, still attached. Top & Bottom/right, with #6 conn-rod's broken web section visible (and badly smashed by secondary impacts). Direction of crack growth indicated by dashed arrows.

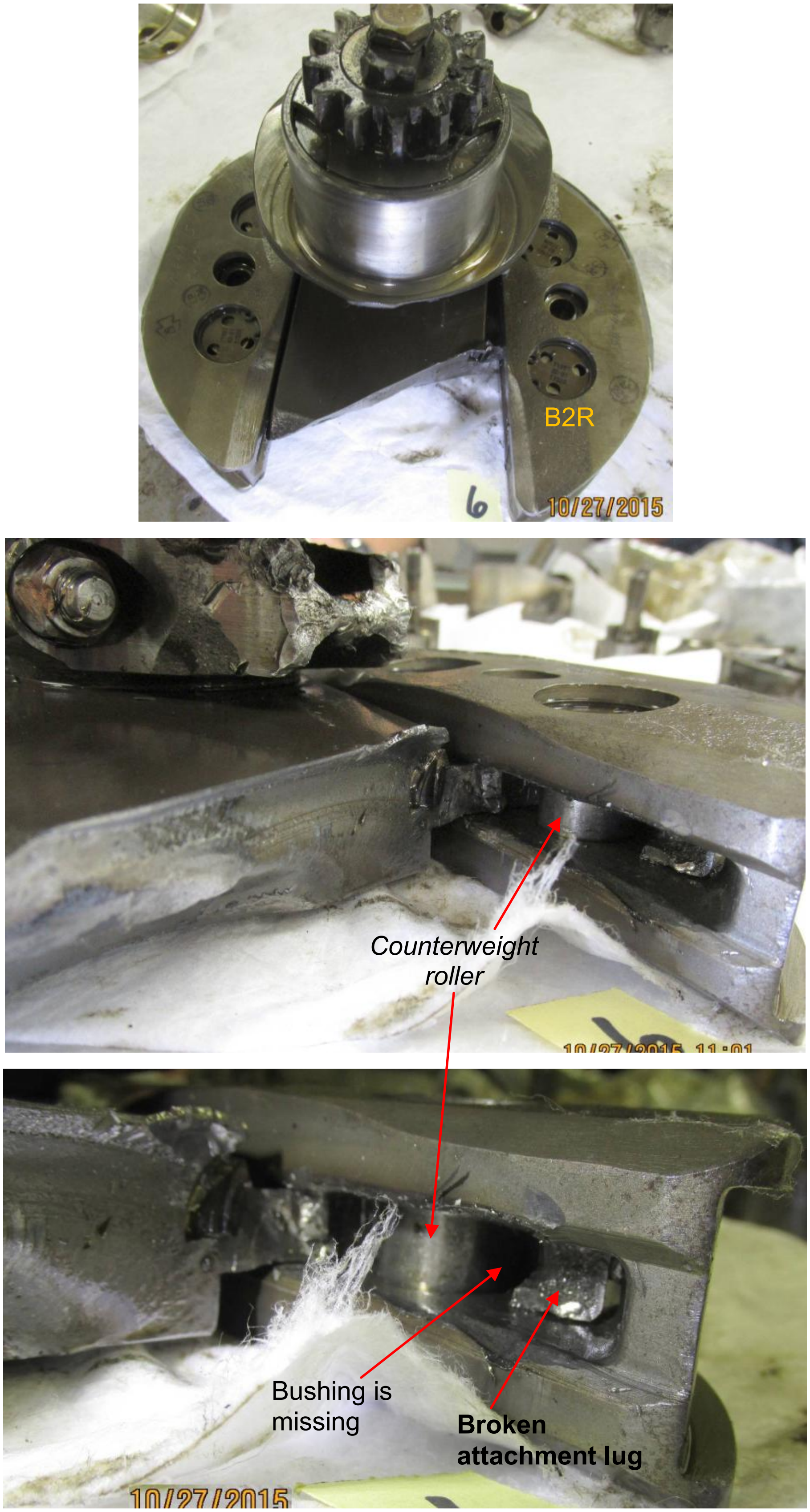


Figure 8. Additional views of the broken rear section. At middle and bottom, two views into the counterweight attachment lug area, showing roller in place, but bushing missing from the crankshaft's lug (apparently ejected after fracture of the attachment lug).

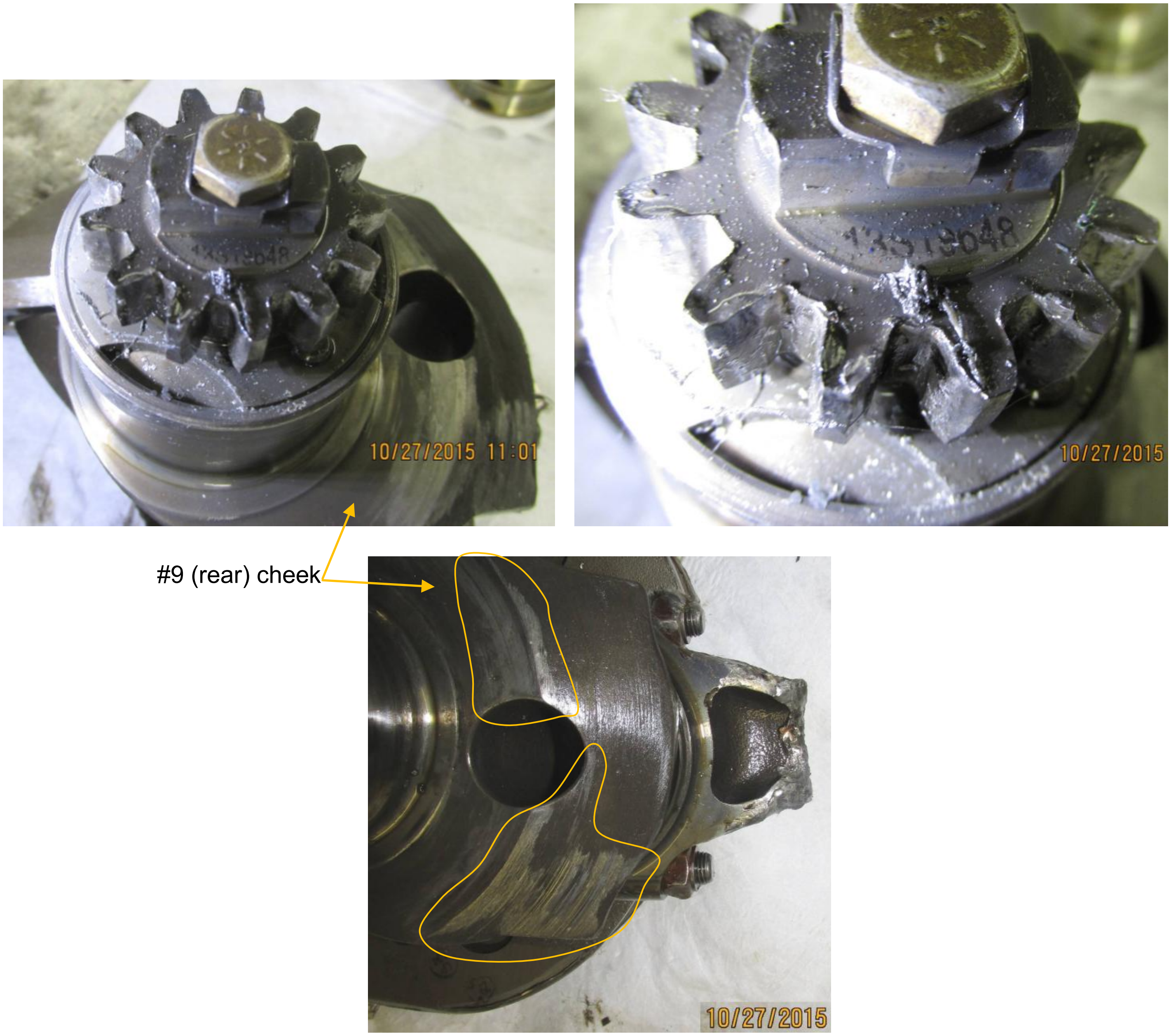


Figure 9. The rear end of the crankshaft, with gear still installed (top photos). Note severely damaged gear teeth, most likely caused by the impact with the ground. Also note, gear bolt and bolt locking plate both still installed and undamaged. Also note, in left and bottom photos, the rear side of the #9 cheek exhibits wear and scoring marks (circled), from contacting the crankcase saddle during final fracture. Broken #6 connecting rod also visible in bottom photo, with connecting rod bolts and nuts still attached tightly.

AF

BF

AR

BR

Figure 10. The front and rear sides of the two counterweight assemblies, still attached to the crankshaft. Front sides – top photos. Rear sides – bottom photos. Left photos – counterweight A. Right photos – counterweight B. Note all washers, snaprings, and rollers still attached.

Figure 11. The outer surfaces of the A counterweight body, still attached to crankshaft. Note severe damage from contact with other engine components during final stages of fracture and/or impact with the ground.

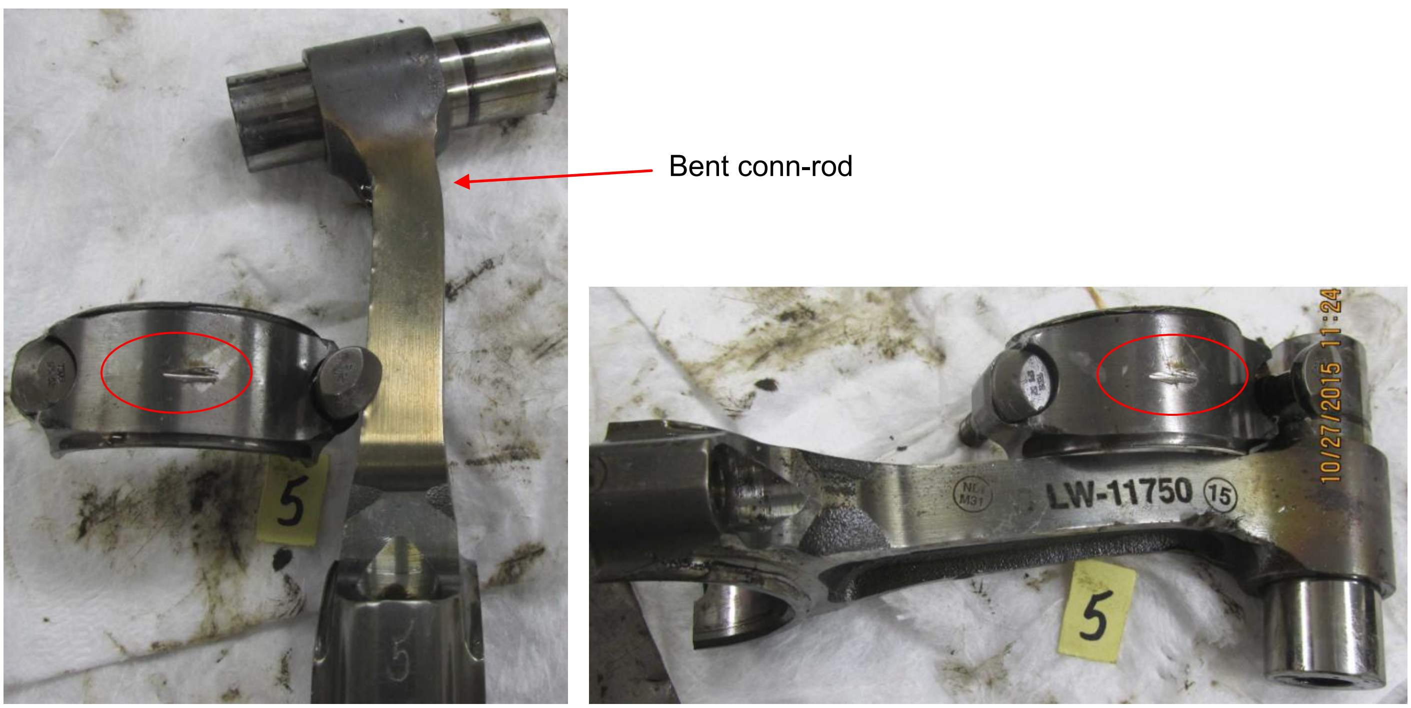


Figure 12. The #5 connecting rod was bent near the piston pin end, and the #5 connecting rod cap experienced a hard impact on its outer top surface (circled).

Figure 13. The #5 connecting rod's side faces were worn from contact with the crankshaft's #8 cheek thrust face, adjacent to the #5 crankpin journal. This most likely occurred during fracture, as the crankshaft's fatigue crack opening displacement grew progressively larger.

Figure 14. The #6 connecting rod was fractured through the web section, near the crankpin bore end. This fracture surface was very badly damaged from post-fracture contacts.

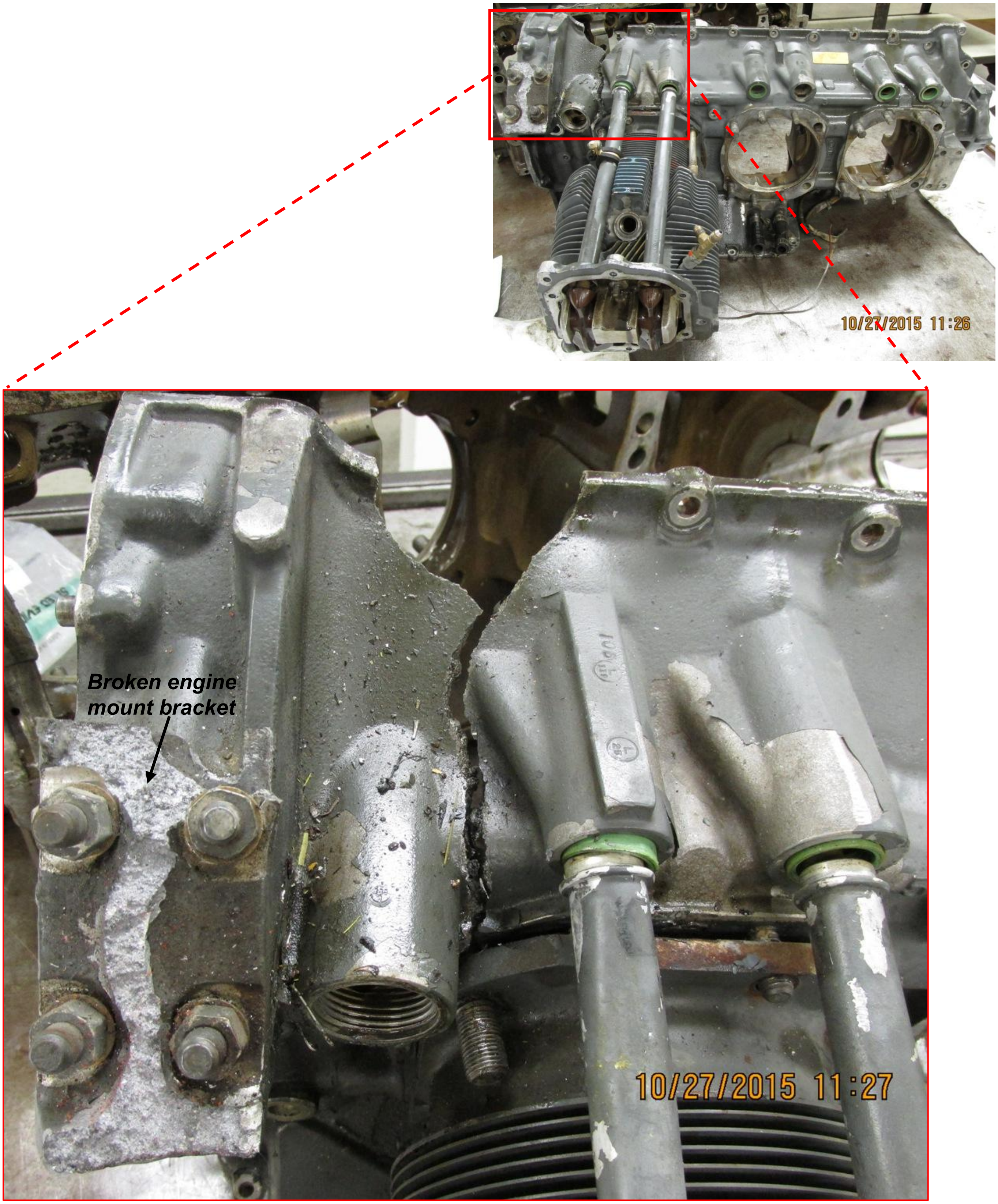


Figure 15. The right crankcase half. At bottom, closer view of the severe damage in the rear section. Note broken engine mount bracket and large cracks in the crankcase adjacent to the #5 cylinder.

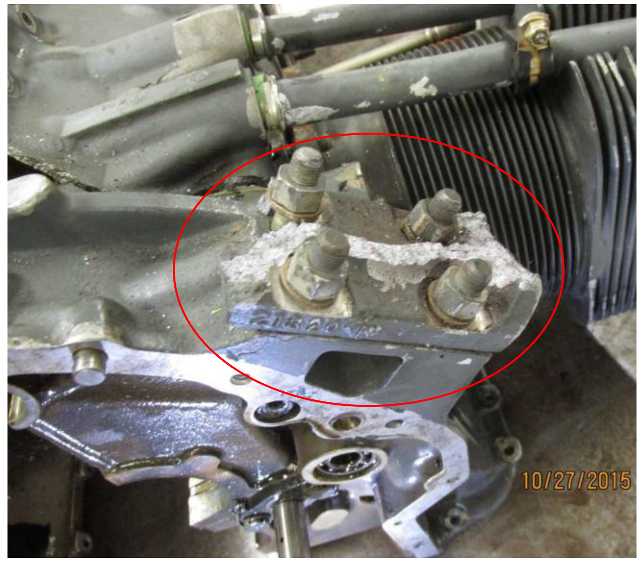



Figure 16. Rear view of the right crankcase half, and a view from different perspective, showing the broken engine mount bracket (*right, circled*).

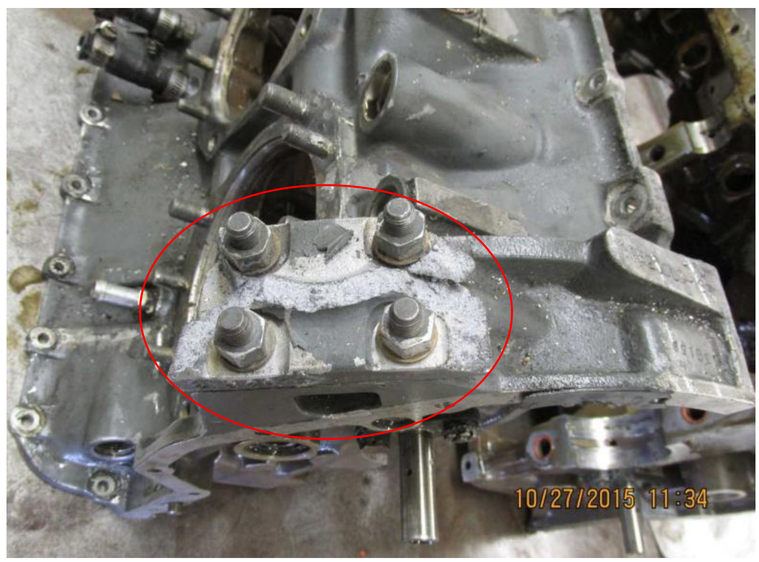



Figure 17. Rear view of the left crankcase half (left). At right, a view showing the engine mount bracket on this side was also broken (*right, circled*).

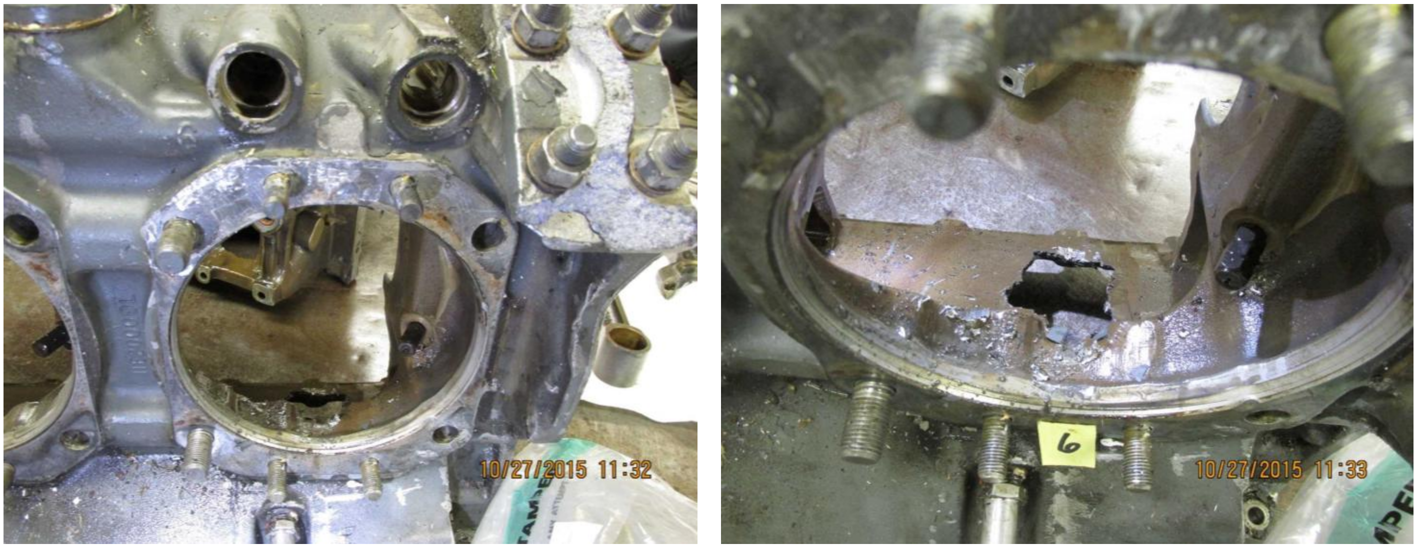


Figure 18. Two views of the #6 cylinder mounting area of the left crankcase half (note: damage visible on deck mounting surface was caused during disassembly). At right, large hole punched through the inside wall of the crankcase, by hard impact from the #6 connecting rod or other broken component.

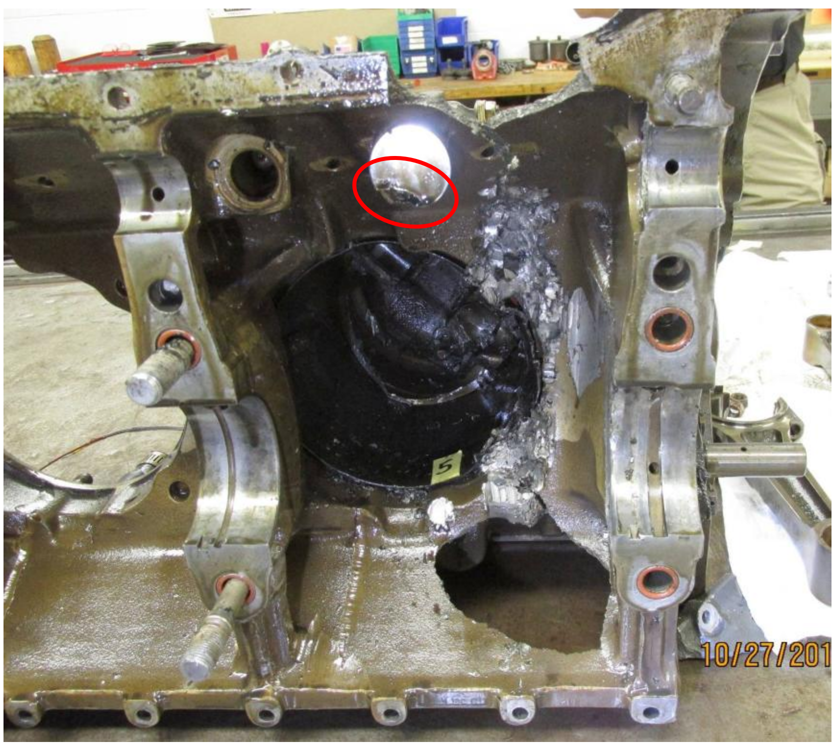


Figure 19. Inside view of the right crankcase, showing extensive damage to the crankcase walls. Also note the #5 cylinder still has the upper section of the piston stuck inside, and one of the #5 tappets has a piece broken off from its head (*circled*). See Figure 20 for additional views.

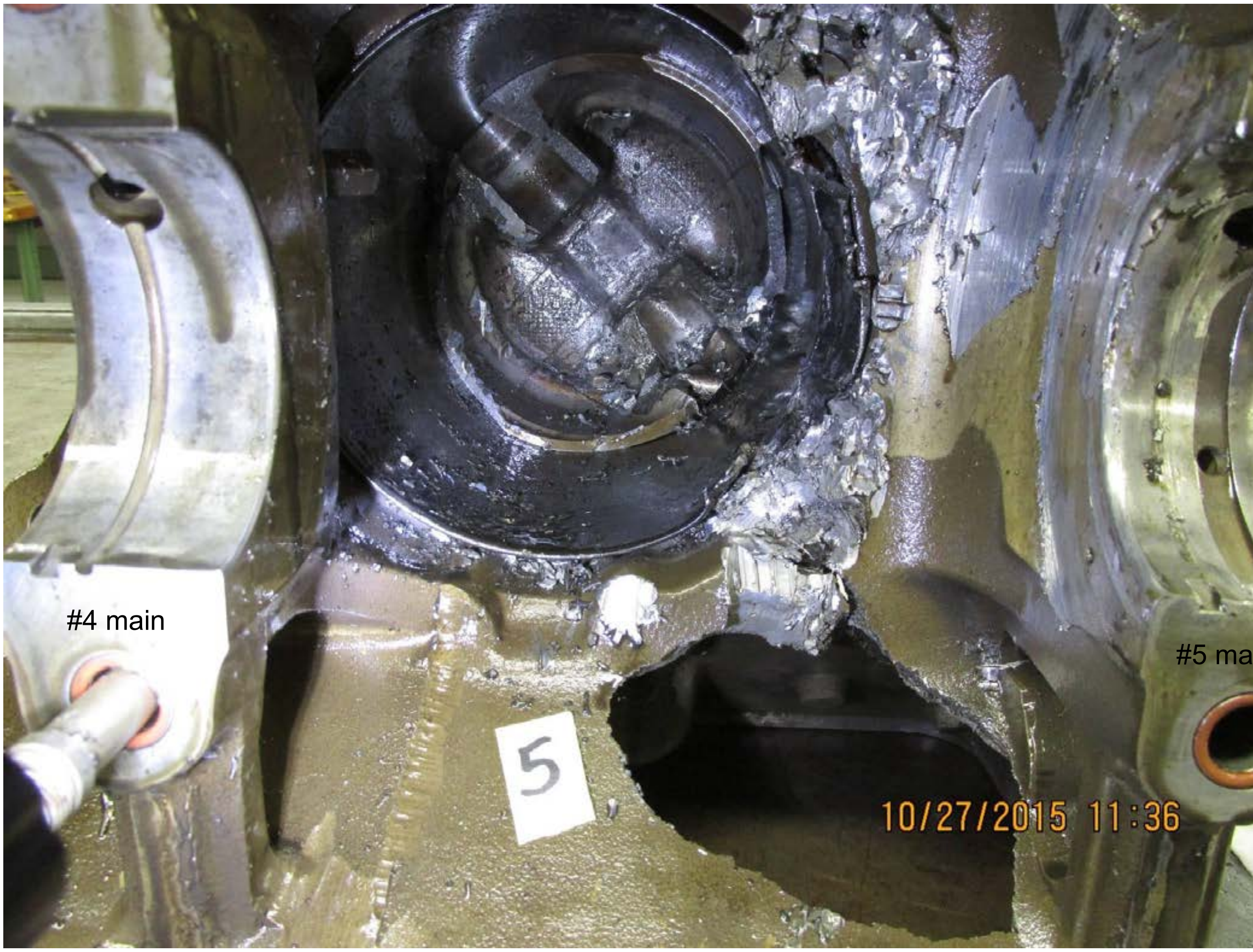


Figure 20. Severely damaged crankcase walls in the vicinity of the #5 cylinder barrel. Note damage to the #5 rear main journal support saddle (right side of photo), caused by hard contact with the crankshaft's #9 cheek. Also note the #5 piston stuck inside the cylinder, twisted from its normal installed orientation, and with several chunks ripped free by the connecting rod and piston pin (the #5 connecting rod was bent, but not broken, and still had the piston attached – see Figures 1, 2, and 12).

Figure 21. Broken camshaft, with hard impacts visible in several locations (circled).

Figure 22. Mating piece of the broken camshaft, also exhibited several hard contact marks. Shaft was broken through the non-carburized region between the #5/#6 intake and the #6 exhaust camlobes. Fracture surface was completely smashed and could not be evaluated, but evidence indicates fracture was most likely caused by hard impacts from other engine components.

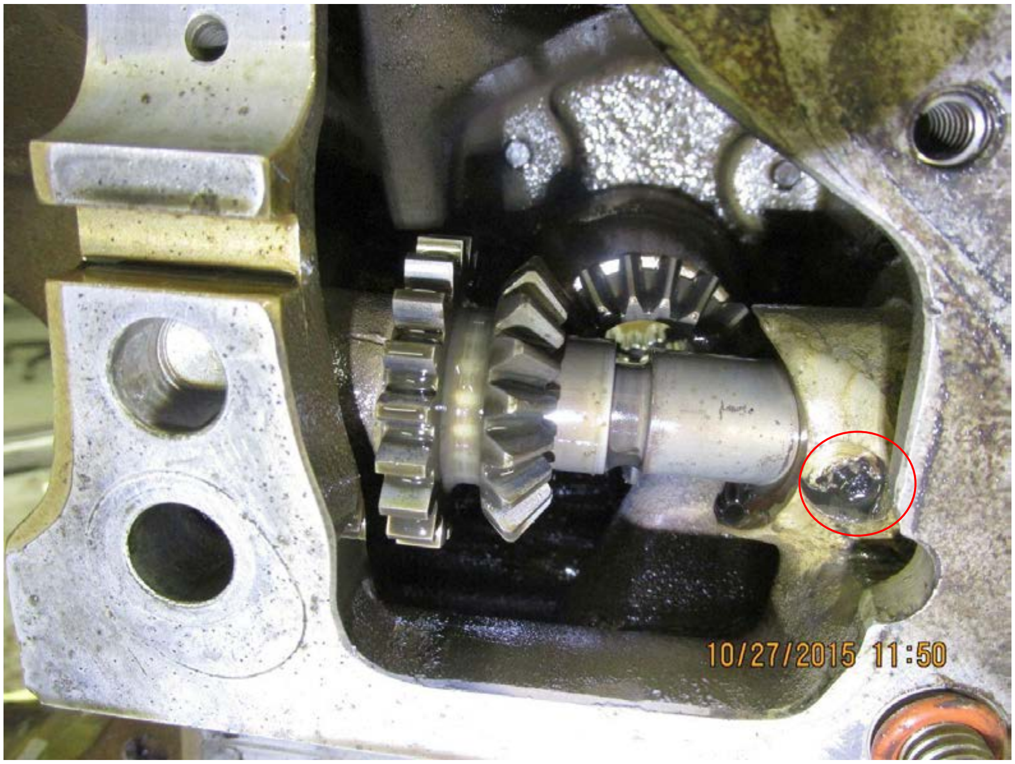


Figure 23. Propeller governor gears and shaft were in good condition, and the set screw was present (circled, with peening marks visible surrounding it, for retention).

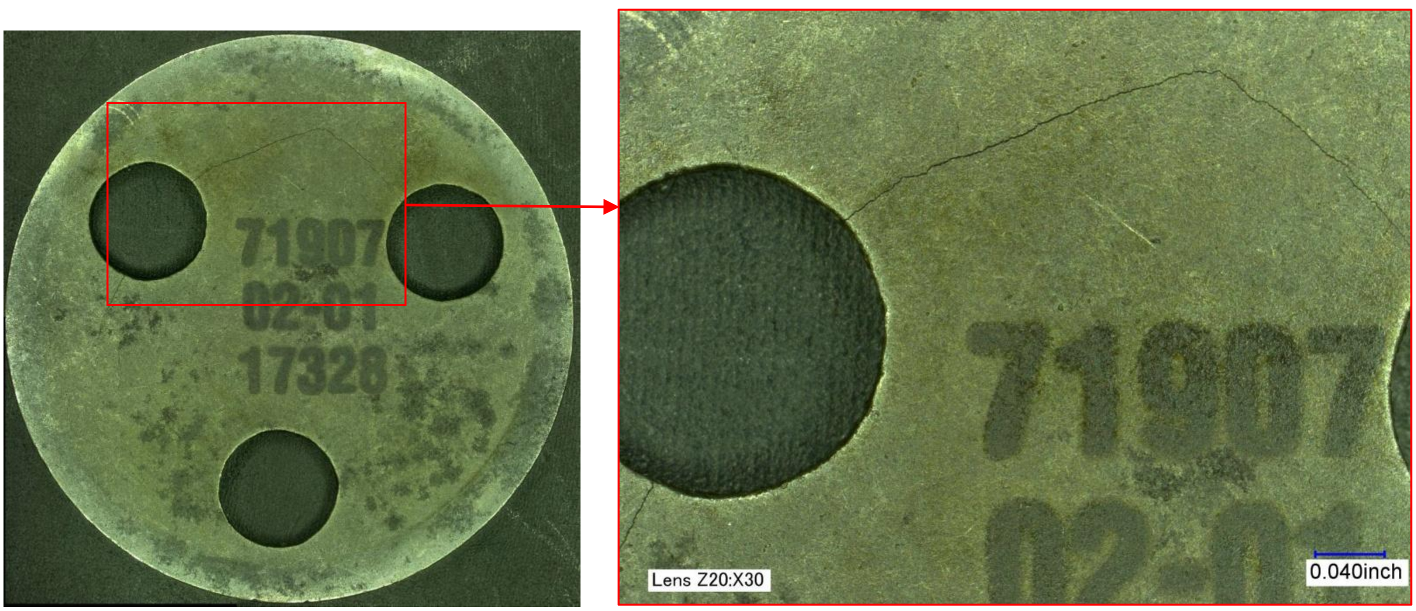


Figure 24. Counterweight washer AF1 (from counterweight body A, bore F1, see Fig. 6 for explanation of labeling system), displayed cracking on its outward face.

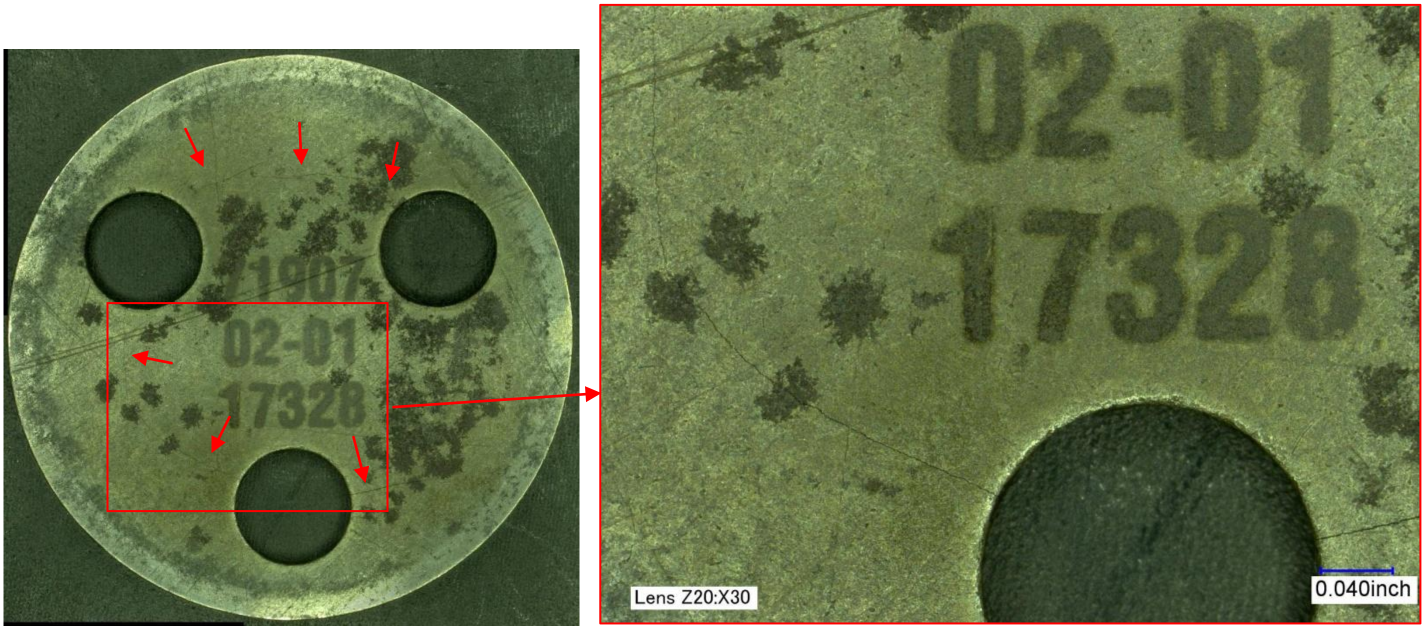


Figure 25. Counterweight washer AF2 (from counterweight body A, bore F2, see Fig. 6 for explanation of labeling system), displayed cracking on its outward face (arrows).

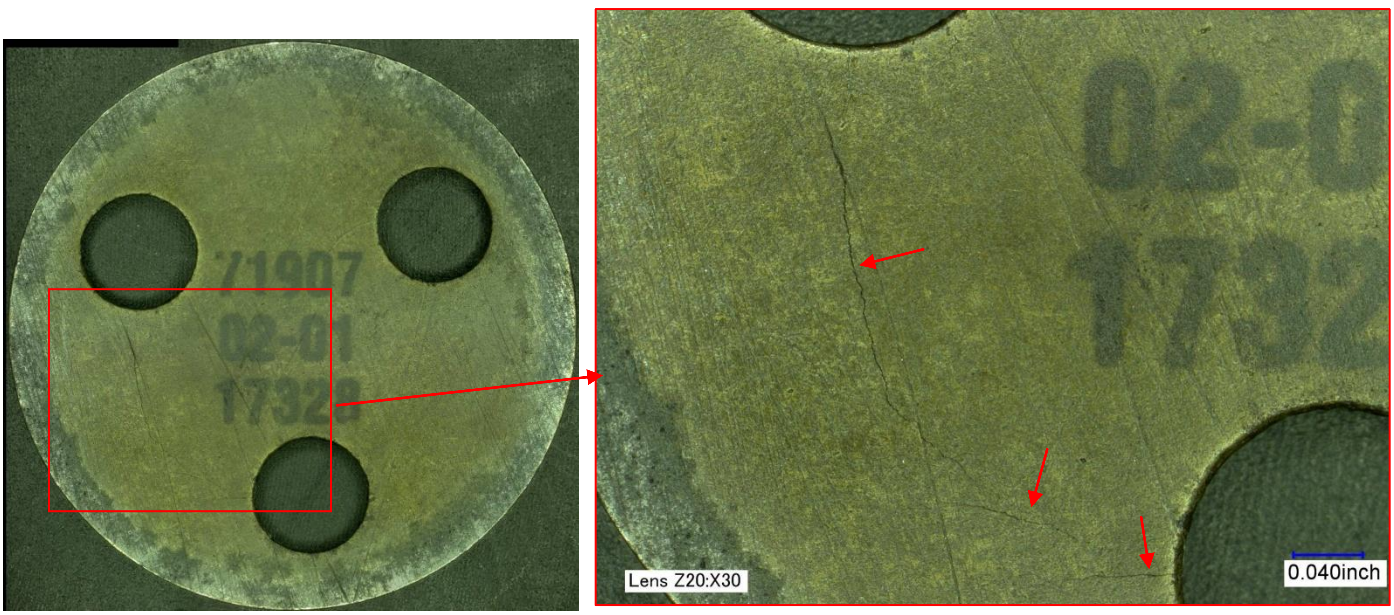


Figure 26. Counterweight washer AR1 (see Fig. 6 for explanation of labeling system), displayed cracking on its outward face (arrows).

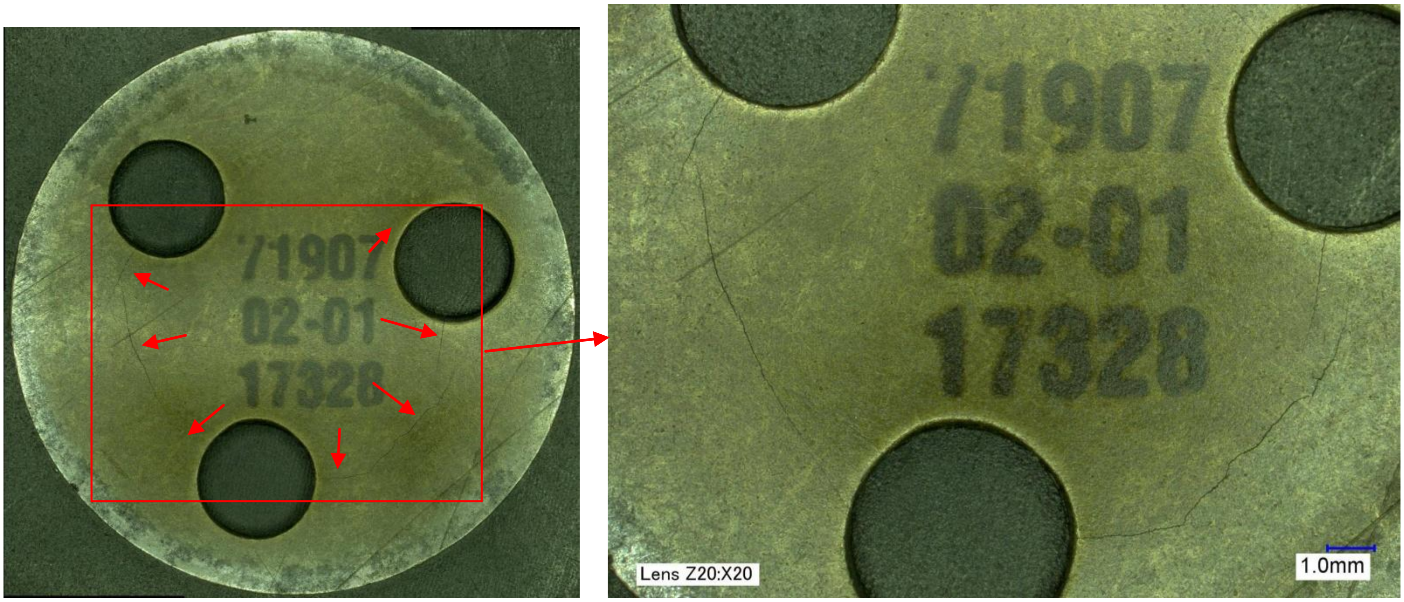


Figure 27. Counterweight washer AR2 (see Fig. 6 for explanation of labeling system), displayed cracking on its outward face (arrows).

Figure 28. Counterweight washer BF1 (see Fig. 6 for explanation of labeling system), displayed cracking on its outward face (arrows).

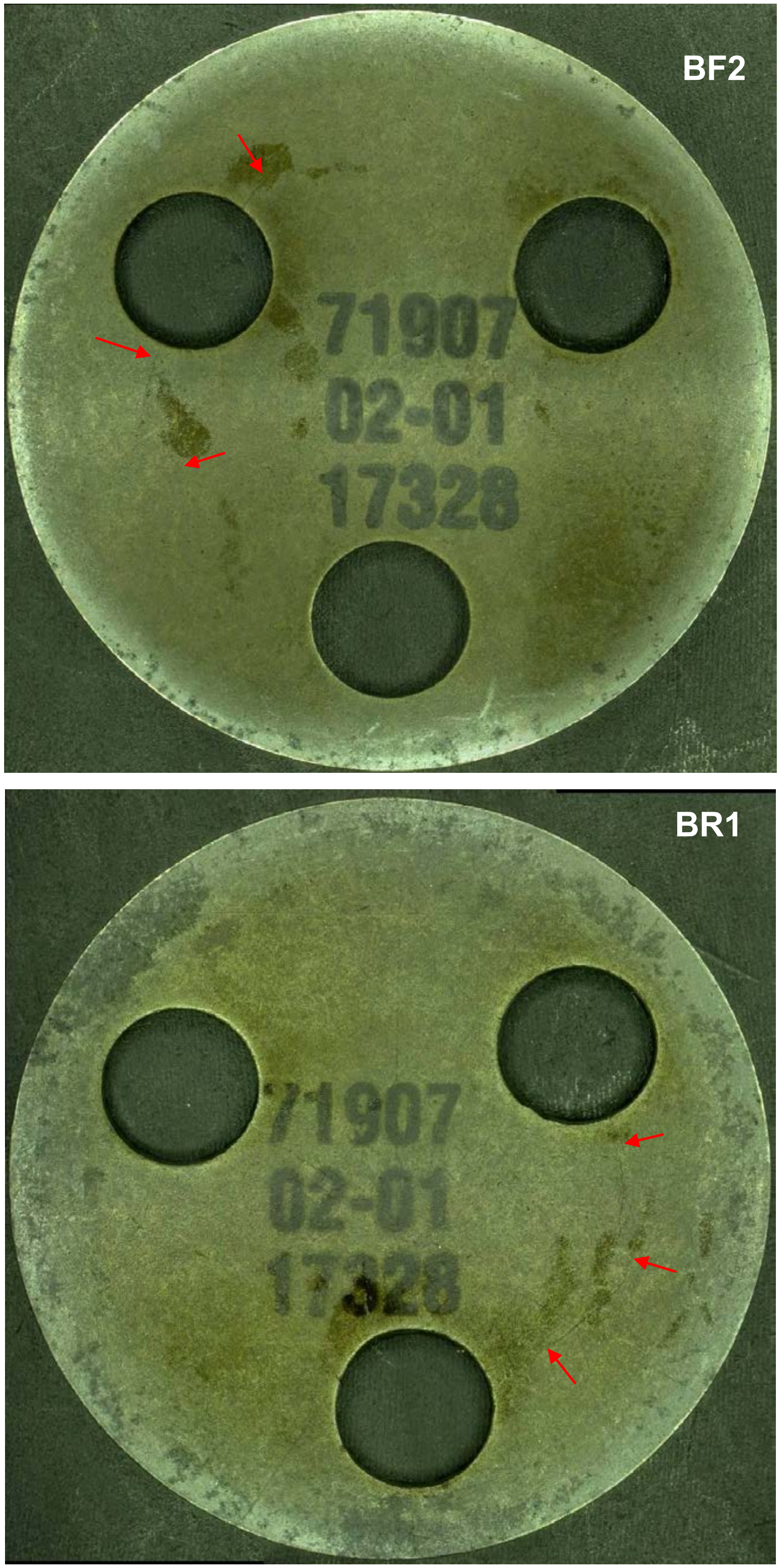
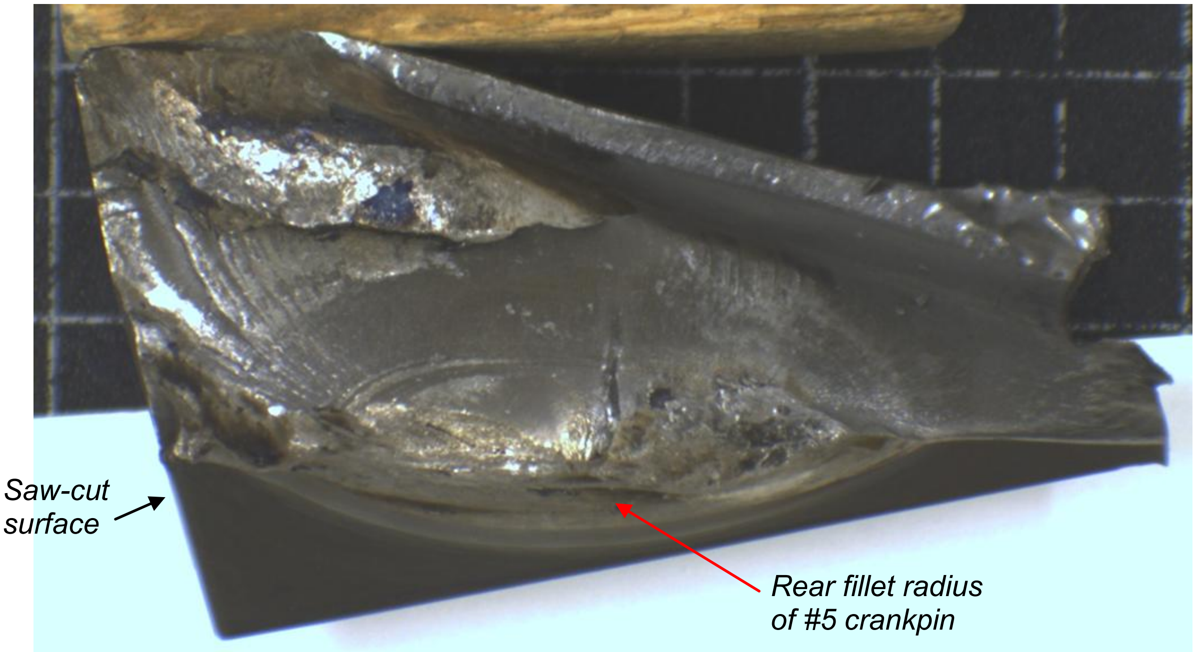


Figure 29. Counterweight washers BF2 and BR1displayed cracking on their outward faces (arrows).

Figure 30. Counterweight washer BR2 displayed cracking on its outward face (arrows).

Figure 31. Counterweight rollers that were installed in bores A1, A2, B1, and B2 (left to right). Note, the crack grew into the B2 lug, releasing the crankshaft's bushing, and causing some wear on the B2 and the B1 rollers. Otherwise, all four rollers were in good condition.

<u>Crankshaft Fracture Surface Examination</u>. The rear piece of the crankshaft was sectioned with a bandsaw, then an abrasive cutoff saw, to remove the fracture surface for easier examination under stereo-optical microscope. Fracture surface displayed beach marks, indicating fatigue crack initiation from at least one origin (and possibly 2-3) on or near the rear fillet radius of the #5 crankpin journal. The crack then propagated under fatigue loading conditions, through nearly the entire section of the #8 cheek and outward to the counterweight attachment lugs. The fracture surface and nearby thrust face were badly damaged by post-fracture contacts, in the immediate vicinity of the crack origin(s). See Figures 32-36. Examination of fracture surface in SEM did not reveal any additional information.



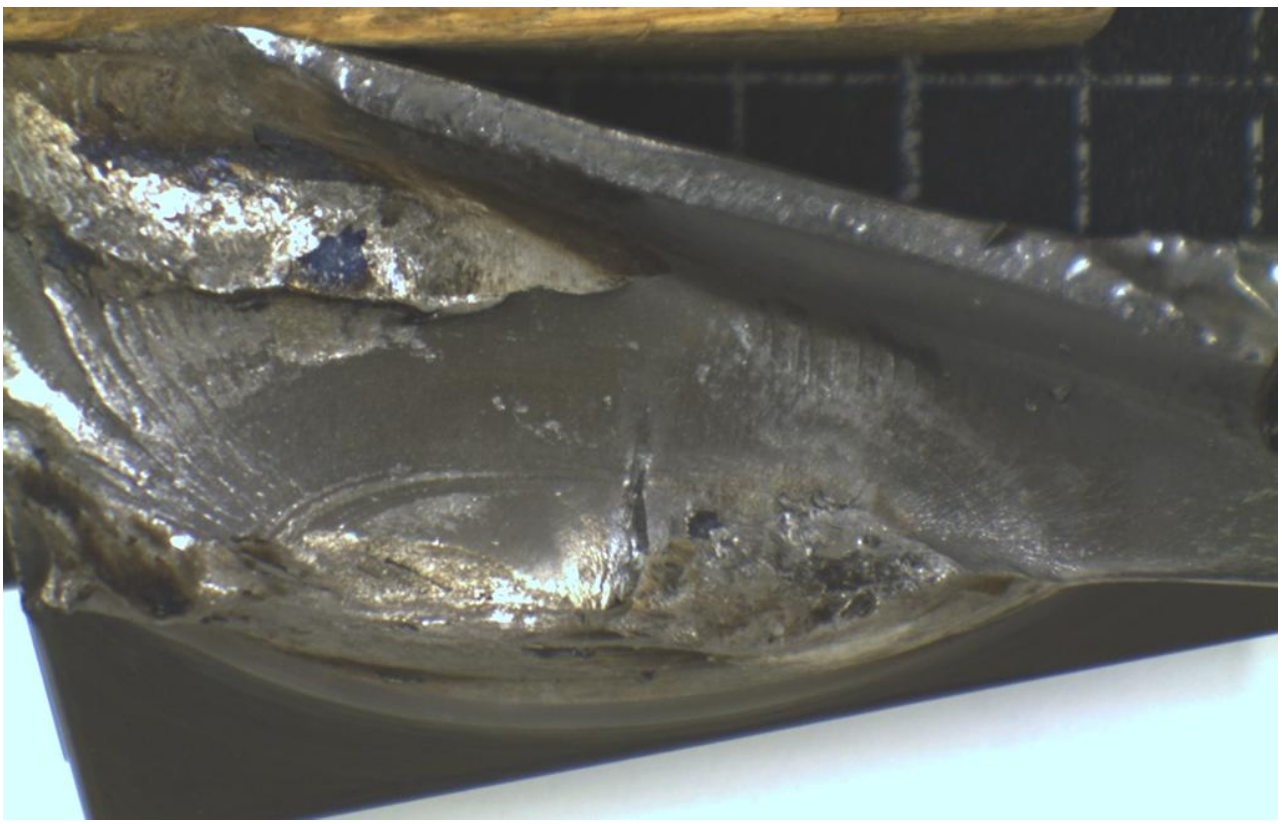


Figure 32. Crankshaft fracture surface, displaying beach marks indicating fatigue crack initiation near the rear crankpin journal fillet radius, from at least one and possibly two or three origin sites. See Figure 33 for closer views of the origin area. *White gridlines = 1 cm.*

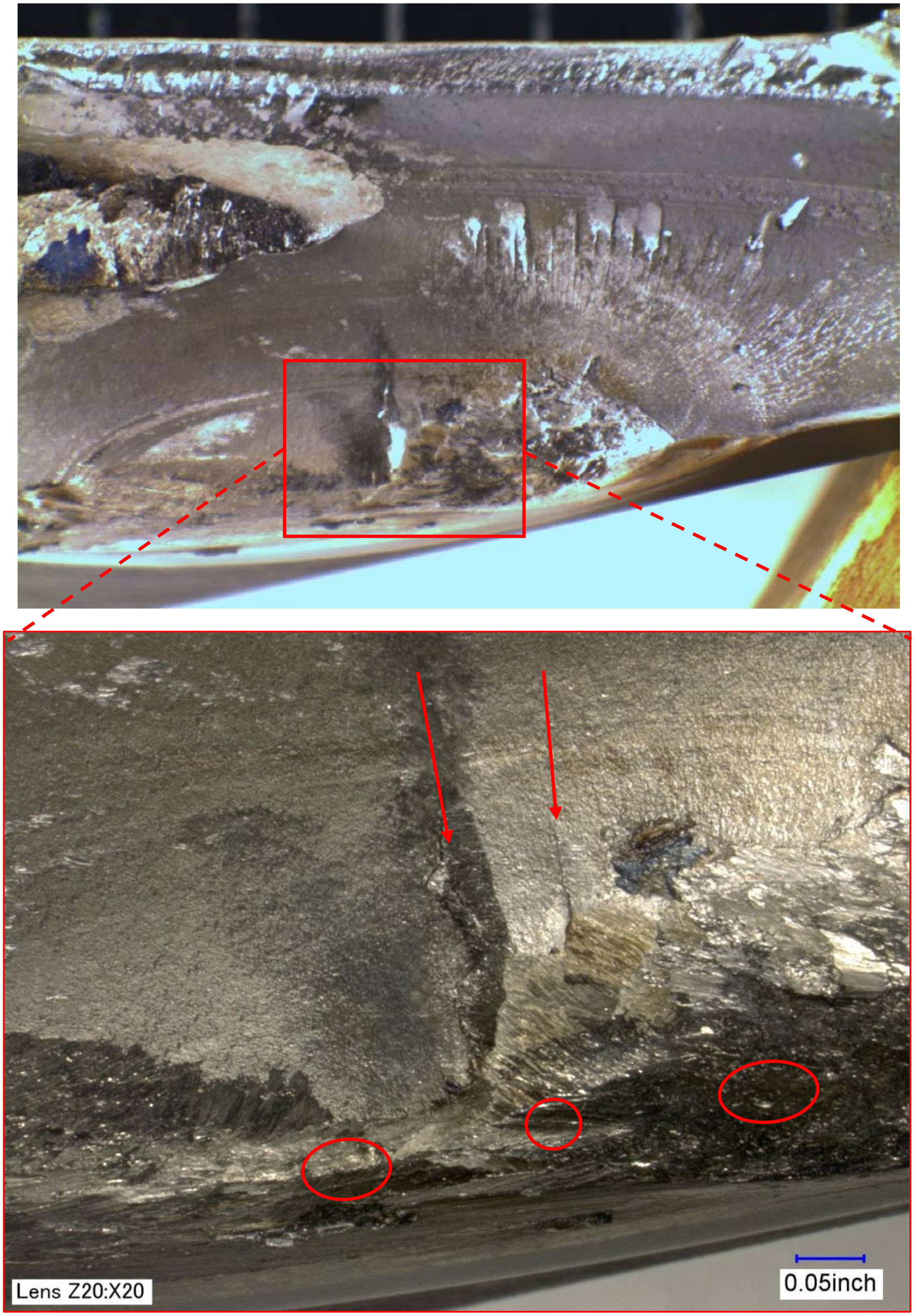


Figure 33. Closer views of the crankshaft's fatigue crack origin area. The badly damaged surfaces prevent determination of the exact crack initiation site(s), but the curvature of the beach marks and presence of two possible ratchet marks (*arrows*), indicate the possibility of three separately initiated fatigue cracks, all near each other, at or just below the crankpin journal fillet radius, at approximate locations circled. Three origins would indicate crack initiation under conditions of high local stress or short-time high stress excursions; and the generally flat, smooth macroscopic appearance of the fatigue crack surface indicates propagation under relatively low nominal stress (low stress, high cycle fatigue).

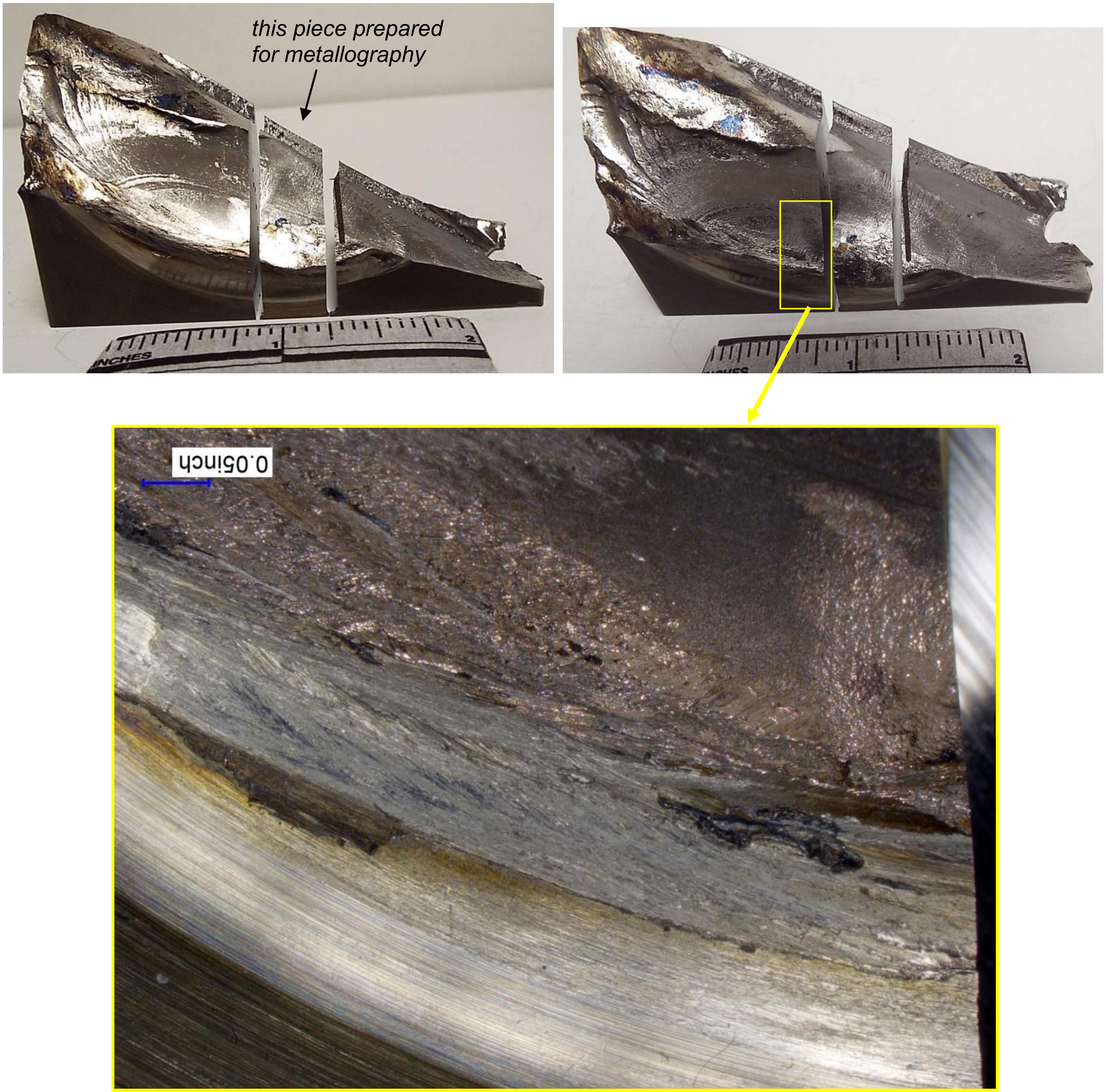


Figure 34. Sections cut by abrasive cutoff saw, through the fatigue crack origin area, fracture surface, thrust face and rear journal fillet radius of the #5 crankpin journal and #8 cheek. Top photos show same view, but different lighting conditions. The thin, center slice was sectioned further to remove the far side of the fracture surface (away from crack origin area), then mounted and polished (left side surface was polished, for metallographic evaluation). Bottom photo is magnified image of larger, left-most piece, after rotating to present a better view of the severely damaged fillet radius, thrust face, and fracture surface, in the immediate neighborhood of the crack origin area. See Figure 35, for view of at the cut section surface of this same piece.

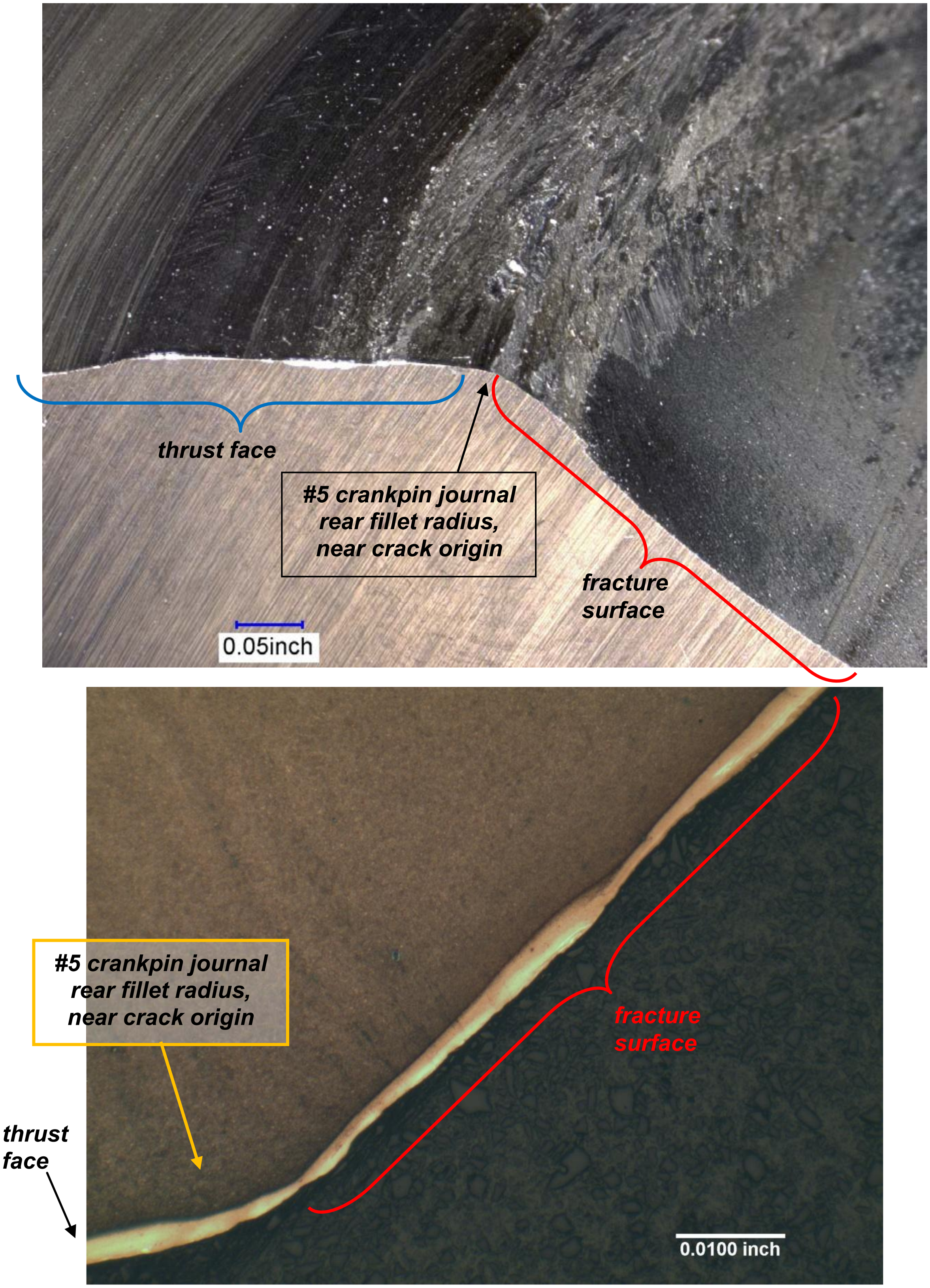


Figure 35. ***Top –*** angled view of the cut-section surface of same piece as shown at bottom of Fig. 34. Note severe contact damage at and near the rear fillet radius. ***Bottom –*** polished, nital etched cross-section of mating surface, showing severe contact damage and surface deformation, along the fracture surface, and adjacent thrust face. This region has been hammered by post-fracture contact events. White-etching zones along the surfaces have been re-hardened by intense frictional heat, from metal-to-metal contact.

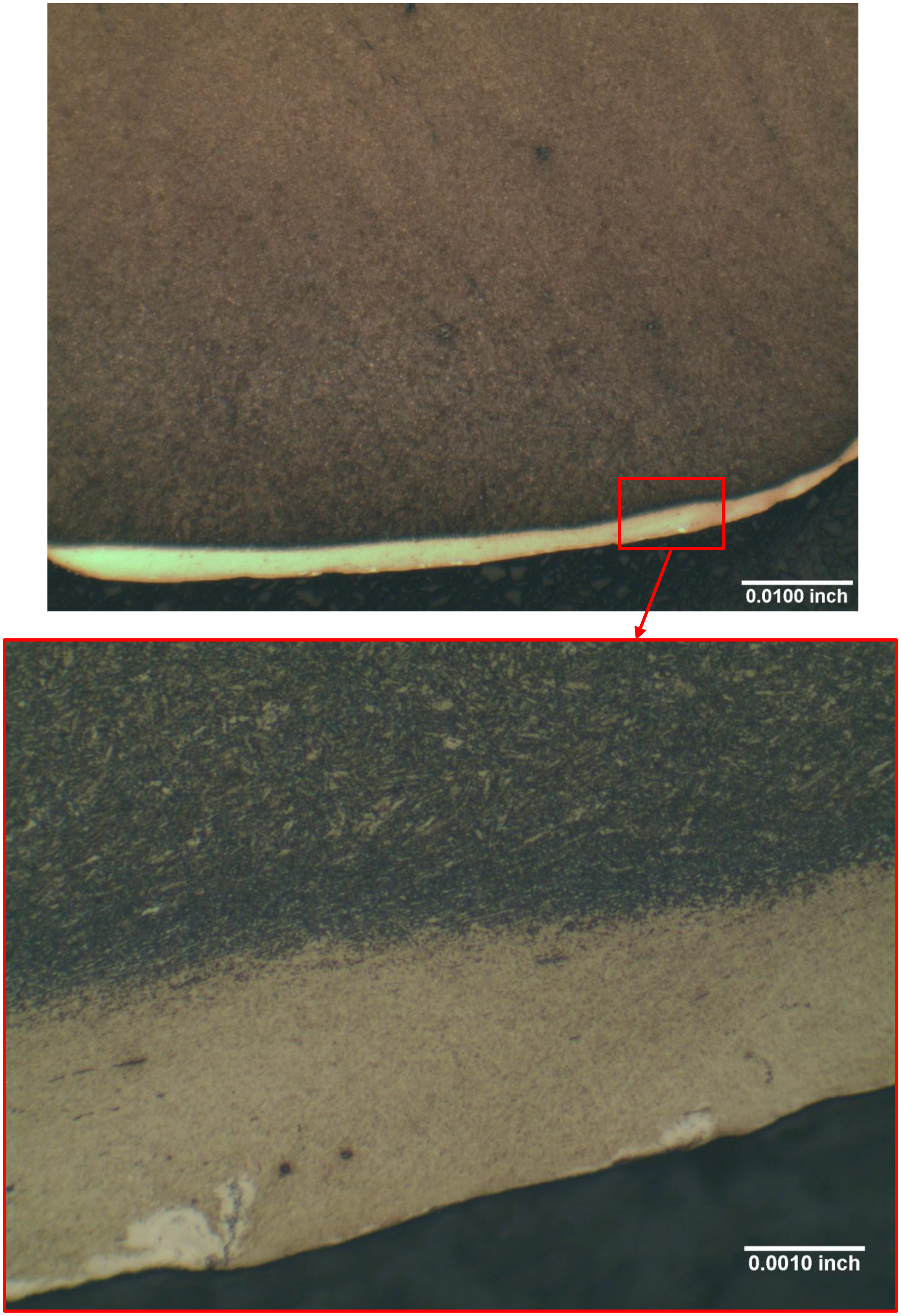


Figure 36. Severe rehardening contact damage on the thrust face, adjacent to the #5 crankpin journal rear fillet radius. Region shown is just to the left of the field of view shown in bottom photo of Figure 35. *Nital-etched.*

Crankshaft Material Conformance. The case hardness was 68.3 HR30N (average of six measurements, ranging from 67.2 – 69.1 HR30N, measured on the broken counterweight attachment lug of the #8 cheek, after sectioning). Core hardness was 31.3 HRC (average of 11 measurements, on Charpy test bars cut from the #8 cheek), which is slightly below the [redacted] HRC range specified on the engineering drawing. Alloy chemistry was analyzed by Optical Emission Spectroscopy (see appended analysis report), and conformed to AMS-[redacted] (air-melted 4340 steel). The vanadium level was 0.0089%, indicating it was not vanadium-modified steel. Total case depth was 0.0197 inch, measured by Vickers microhardness traverse, on the polished cross-section through the fatigue crack origin (i.e., measured on the nearby #5 crankpin journal's rear thrust face, on the #8 cheek, adjacent to the fracture surface). Microstructure was tempered martensite in the core, and tempered martensite plus dispersed nitrides in the case (Figure 37). The as-nitrided region of the #8 cheek just above the thrust face had a white layer thickness of 0.00067 inch, while the thrust face itself had no remaining white layer. There was also a zone of intense surface damage, indicative of rehardening and retempering, consistent with frictional heating caused by metal-to-metal contact (see Figures 35-36). This zone of re-hardening damage extended for approximately 0.17 inch along the thrust face and journal radius, and extended along the fracture surface for approximately 0.19 inch. Most likely, this damage was produced during final rupture, as the crack-opening displacement was increasing rapidly; and the damage on the fracture surface was caused by post-separation secondary contact events. Three Charpy impact bars were machined from the #8 cheek, and tested in accordance with ASTM [redacted]. Impact energies ranged from 39.9 – 40.1 ft-lbs, which is typical for AMS-[redacted] steel tempered to this hardness. Charpy bar fracture surfaces were examined by Scanning Electron Microscope, and no honeycomb or microcrack features were found. All metallurgical characteristics conformed to the engineering drawing requirements, except the slightly low core hardness.

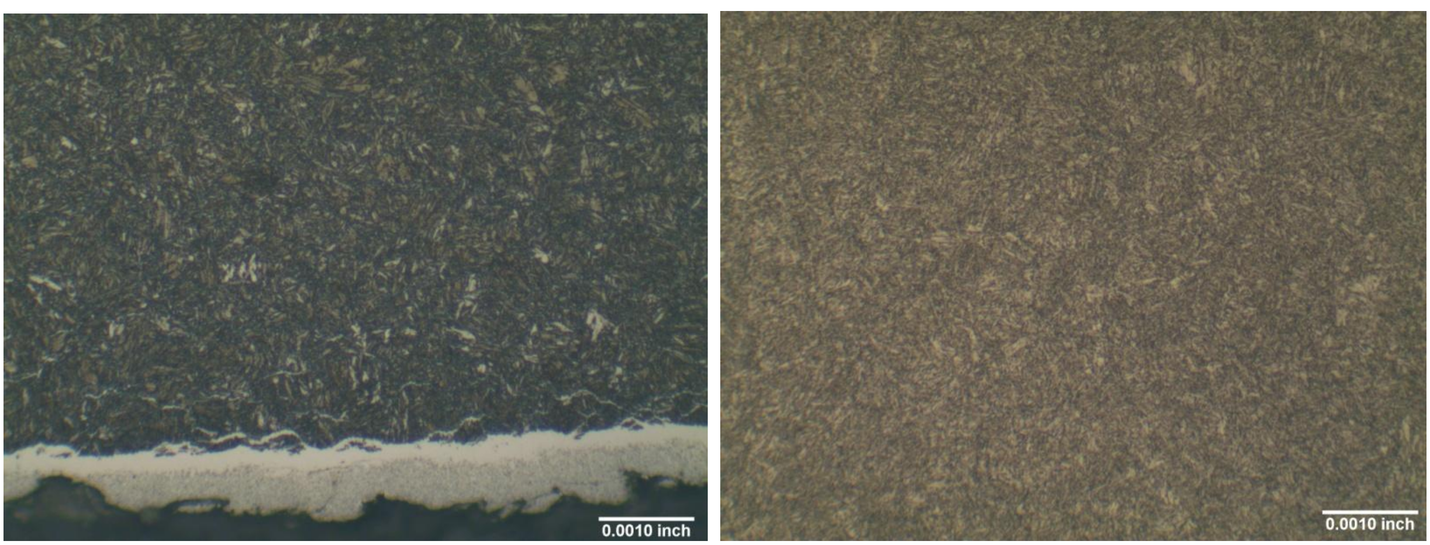


Figure 37. Case and core microstructures from the broken #8 cheek. ***Left –*** tempered martensite with dispersed nitrides, and white layer of approximately 0.00067 inch thickness, on the as-nitrided surface just above the thrust face, not far from the fracture orgin. ***Right –*** core microstructure from same section. *Nital etched.*

Summary and Conclusions. The crankshaft failed in fatigue, with crack initiation from the rear fillet radius of the #5 crankpin journal, followed by stable fatigue crack growth through nearly the entire section thickness of the #8 cheek. Fracture surface markings indicate a likelihood of multiple fatigue crack initiation sites. Multiple origins indicate high stress conditions; however, the majority of crack growth through the #8 cheek occurred under high cycle fatigue loading, consistent with relatively lower nominal stress conditions. This cracking pattern suggests overstress conditions of relatively short duration acted to initiate the fatigue cracks. The root cause for this overstress was not determined, but it was not related to any material non-conformance. The crankshaft conformed to engineering drawing requirements for alloy chemistry, case hardness, case depth, case and core microstructure. It was slightly below the core hardness specification, but within the Lycoming MRB limits, and the slightly low core hardness is not considered relevant for this fracture. Charpy impact test bars cut from the undamaged regions of the #8 cheek were free of any honeycomb or microcrack features, indicating the steel had not been exposed to excessively high temperatures during billet forging or crankshaft forging. The crankshaft journal diameters conformed to engineering specifications. The crankshaft journals also conformed for roundness, except for the #1 and #3 crankpin journals -- these exceeded the specification tolerance for out-of-round; however, these crankpin journals were undamaged.

There was no evidence for lack or loss of lubrication, and the crankshaft bearings were relatively undamaged. The counterweights and their subcomponents were still in their installed positions, and exhibited only secondary damage consistent with post-fracture events. The fracture through the counterweight attachment lug was an extension of the primary fatigue crack which initiated a significant distance away, on the #5 crankpin journal. The fractured lug obviously occurred near the end of the fatigue crack growth period. All other broken components exhibited evidence consistent with impact loading, most likely all occurring as secondary events, after the crankshaft fractured and/or as a result of the impact with the ground.

INVESTIGATOR: [redacted] DATE: 4-11-17