

652 Oliver Street
Williamsport, PA 17701 U.S.A
(570) 323-6181

REPORT NO. LN-xxxxxx REISSUE

MATERIALS LABORATORY INVESTIGATION REPORT

ENGINE DATA

TYPE: IO-540-K1A5

S/N: L-24411-48E

HOURS: ~500

APPLICATION: ---

PART DATA

NAME: Crankshaft, #5 and #6 conn
rods, and counterweights

NUMBER: Various

S/N: N/A

TIME: ~500 hours

DATE RECEIVED: 24 Aug 2022

SIR No.: N/A (COS-xxxx)

SUBMITTED BY: [REDACTED]

PHONE: [REDACTED]

☒ 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: [REDACTED]

REASON FOR SUBMITTAL / WORK REQUIRED:

Analyze crankshaft/counterweights/#5 and #6 connecting rods to find potential causes of failure.

Please provide investigation conclusion to [REDACTED] by the end of September 2022. COS-xxxx

INVESTIGATION RESULTS

Summary

An IO-540-K1A5 engine, serial number L-24411-48E, was delivered disassembled to the Lycoming [REDACTED] and examined in the NTSB (National Transportation Safety Board) room on 24 August 2022. The engine had been operated for about 500 hours since it was boxed at Lycoming on 10 December 2011. During flight on 11 January 2022, the engine sputtered and began expelling oil, requiring the pilot to make an emergency landing. There were no fatalities or injuries. The engine and plane both sustained significant damage, and the investigation on 24 August 2022 at Lycoming did not lead to a determination of what initially caused the engine to malfunction. Details and images from the NTSB teardown are available in the Service Teardown Inspection Report in Appendix A.

The post-teardown report in Appendix A documents multiple findings of problems and failures in the engine. The significant facts and observations of the Appendix A report are summarized in the Background section of this report. The goal of this Materials Lab investigation following that teardown was to examine the crankshaft, counterweights, and #5 and #6 connecting rods from the engine more closely to determine, if possible, the probable cause(s) of the engine malfunction.

The following are the significant findings and conclusions from the Materials Lab investigation:

1. One of the counterweight circlips failed in fatigue. The failed circlip corresponds to a counterweight roller that was ejected from the counterweight assembly.
2. The #6 connecting rod showed evidence of fatigue failure in multiple areas. The areas showing fatigue are located
 - a. Both on the main body of the rod and on the cap, along the bearing surfaces in the area where the connecting rod bolt joins them together, and
 - b. Where the I-beam of the rod transitions to the bearing end of the rod.
3. It could not be determined which failure occurred first (either the circlip or the #6 connecting rod).
4. The #5 and #6 piston crowns, valve faces, and cylinder head domes were clean and free of combustion residue, consistent with detonation, indicating that the engine was run in lean conditions for a substantial amount of flight time.

Background

Additional detailed background information, including photographs, is available in the Service Teardown Inspection Report in Appendix A. Significant facts and observations from that report are summarized below:

1. The #6 connecting rod area of the crankcase showed the most severe damage, with multiple fractured punctures through the top and both the left and right sides. That damage was caused by the #6 connecting rod.
2. The #5 and #6 connecting rods were both fractured.
3. The #6 piston crown and cylinder head dome showed detonation signatures. The engine was operated in lean conditions for a substantial amount of flight time. The piston crown edge was completely rounded, and the compression and oil rings were fully compressed into the ring wells. The cylinder dome was also rounded. It was clean of lead deposits and the valve surfaces and seat surfaces were clean.
4. All connecting rod bolts that had intact threads were missing their connecting rod bolt nuts. The nuts were likely shattered as debris was tossed throughout the engine. No nut debris was found during the investigation.
5. The #5 piston crown and cylinder head dome also showed detonation signatures. The edge of the piston crown and cylinder head dome were rounded.
6. The engine was returned with a counterweight roller, retaining washer, and a third of a circlip secured in a bag. The counterweight roller was found inside the engine. The Lycoming Air Safety representative who completed the field investigation asserted that the counterweight circlip broke, which ejected the counterweight roller, which initiated the entire failure.
7. The crankshaft and connecting rod journals did not show signs of oil starvation. No blockages were found in the oil feed passages or crankcase oil galleries. Damage found on the #5 and #6 connecting rod journals on the crankshaft were from contact with the #5 and #6 connecting rods, respectively.
8. It was unable to be determined which failure occurred first.

Results

The parts of the engine delivered to Lycoming were examined in the Materials Lab for evidence of the root cause of the engine failure. Observations additional to those documented in the Service Teardown Inspection Report in Appendix A are documented below.

1. Crankshaft counterweight hardware

The restrictions stated on the first page of this document are applicable to all pages of this document.

The hardware from the crankshaft counterweights (rollers, circlips, and washers) arrived in the Materials Lab in bags that were zip-tied to the counterweights and still attached to the crankshaft, as shown in Figure 1. The crankshaft itself was not examined in detail for this investigation since the relevant damage was sustained on the crankshaft counterweights, the counterweight hardware, and the connecting rods.

Each set of counterweight hardware was labeled to keep track of where it came from on the crankshaft. One counterweight was identified as A, the other as B. Hardware Set 1 from each counterweight was at the top of the box (coming out of the page, looking at Figure 1) that the crankshaft was in and hardware Set 2 was at the bottom of the box (going into the page, looking at Figure 1).

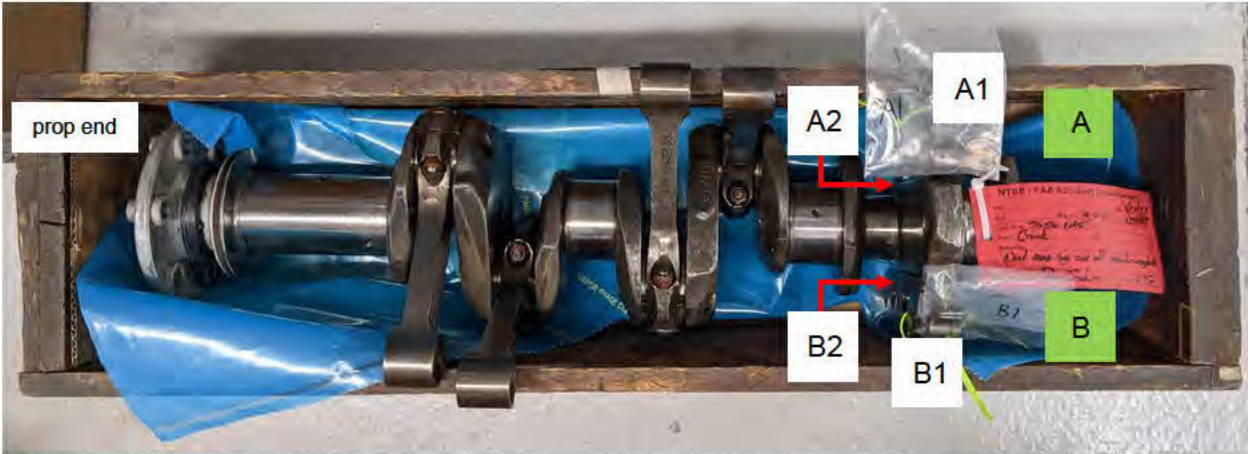


Figure 1. Image of the crankshaft with counterweights and hardware of interest attached in the as-received condition. The green labels A and B identify the two crankshaft counterweights and the white labels A1, A2, B1, and B2 identify the four sets of counterweight hardware (rollers, circlips, and washers).

For reference, part numbers and other identifying markings (where applicable) of crankshaft counterweight hardware pieces are provided in Table 1. Parts are identified as counterweights A and B (or corresponding with counterweights A and B) where applicable.

Table 1. Table providing part numbers and identifying markings on the crankshaft counterweight hardware pieces.

Part (if applicable, associated counterweight)	Quantity (total)	Lycoming part number	Identifying markings (meaning)
Counterweight assembly	2		Counterweight A: ASSY (assembly), XXXXXXXXXX Counterweight B: ASSY (assembly), XXXXXXXXXX
Counterweight roller (A)	2		
Counterweight roller (B)	2		
Counterweight circlip	8		
Counterweight washer	8		

The counterweight hardware pieces that arrived in the lab already out of the crankshaft/counterweight assembly are shown with labels in Figure 2. In addition to what is shown in Figure 2, a bag of (fractured) washer pieces was sent to the lab. These washer pieces

are resultant from fracturing a washer in position A2 with an air hammer during the NTSB investigation at Lycoming on 24 August 2022 to remove the A2 roller from the counterweight (for more details on counterweights, see section 2, *Crankshaft counterweights*).

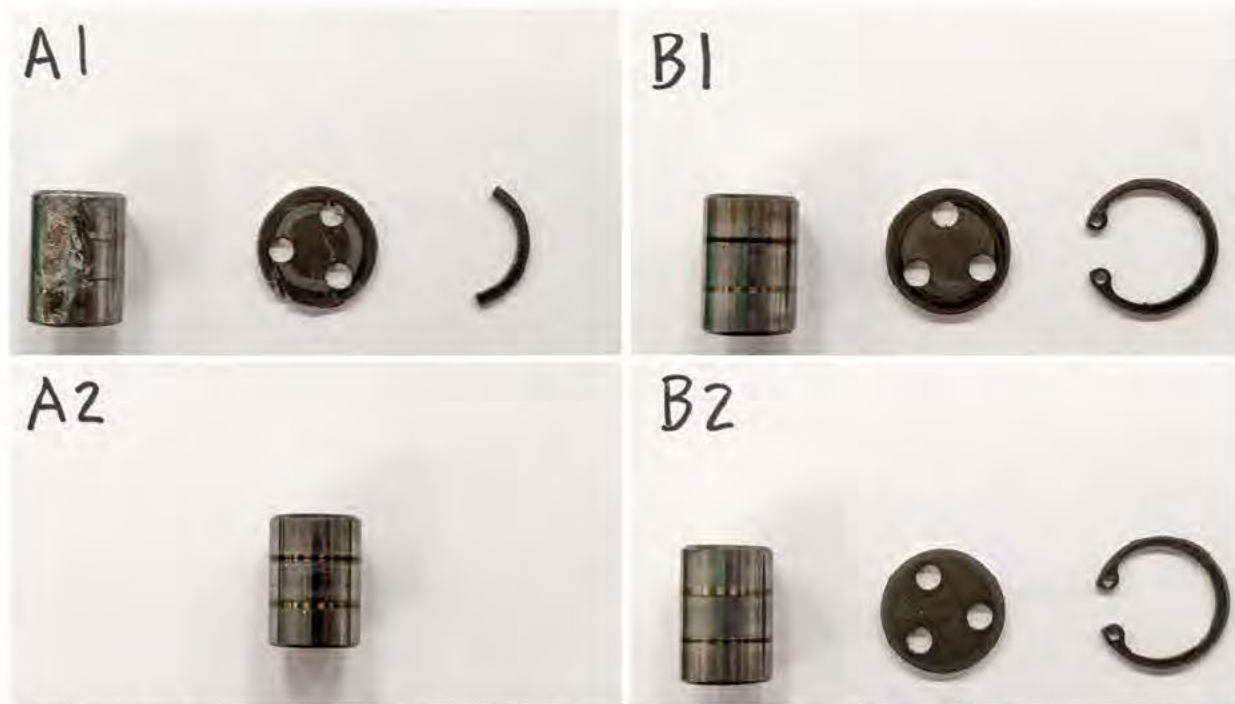


Figure 2. Crankshaft counterweight hardware, labeled as bagged and identified in Figure 1.

The roller, partial circlip, and washer that are labeled A1 are the ones described on page 8 of 10 of the Appendix A report. As shown in Figure 3 and noted in Appendix A, the A1 counterweight washer shows cracks emanating from one of its three central holes and a crack around its circumference. It also shows wear marks on its part-marked (front) face from contact with the circlip. The back surface of the washer shows heavy wear from contact with the counterweight roller. As noted in Appendix A, all washers from the A counterweight showed some evidence of fracture.

The A1 counterweight roller shows witness marks from being tossed around inside the engine and copper plating marks from contact with the camshaft (see page 8 of 10 of Appendix A for images).

The A1 circlip (a piece that is approximately a third of a circlip) was fractured in two places and missing both ends that contained its removal/installation hole tabs. As asserted in the Appendix A report, the wear mark on the edge of the part-marked (front) face of the counterweight washer (Figure 3) indicates that the circlip was installed properly during operation. This is important to note because historically, improper installation of the circlip has been implicated in circlip failure.



Figure 3. Close-up image of washer shown in the A1 panel of Figure 2.

Both fractured ends of the circlip section show evidence of fatigue failure in the form of beach marks, as shown in Figure 4. The blue stars on both fracture surfaces mark the crack origin, as identified by the beach marks emanating away from those locations (beach mark propagation direction shown by red arrows in Figure 4). Beach marks on a fracture surface are created from irregular periods of loading during fatigue and typically propagate away from the crack origin and are curved, with the center of the curvature at the crack origin.

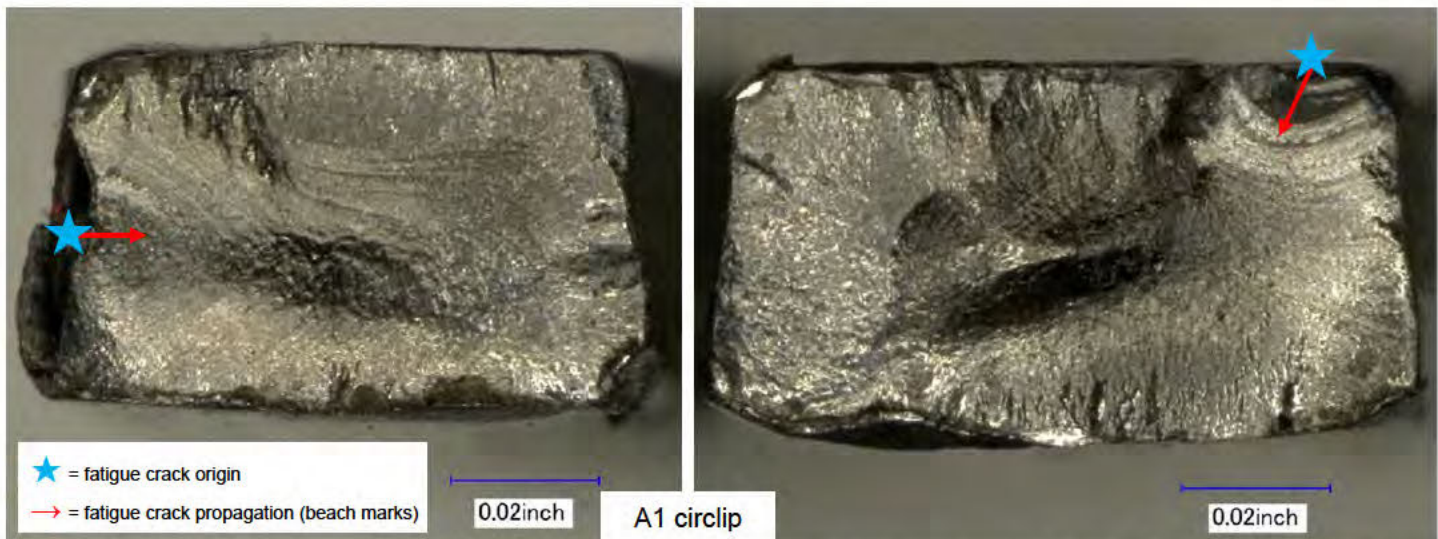


Figure 4. Images of both fracture surfaces (both ends) of the A1 partial circlip shown in Figure 2. Both fracture surfaces show evidence of fatigue (beach marks).

It is possible that the failure of the A1 circlip shown in Figures 2 and 4 initiated the failure of the engine by allowing the A1 roller to be ejected from the A counterweight, which caused further destruction inside the engine, including the breaking of the #5 and #6 connecting rods.

2. Crankshaft counterweights

As shown in Figure 1, the two counterweights were identified and labeled as A and B. Both sides of both counterweights are shown in Figure 5. The counterweight identified and labeled as A is hand-labeled with "L/H" and the counterweight identified and labeled as B is hand-labeled with "R/H."

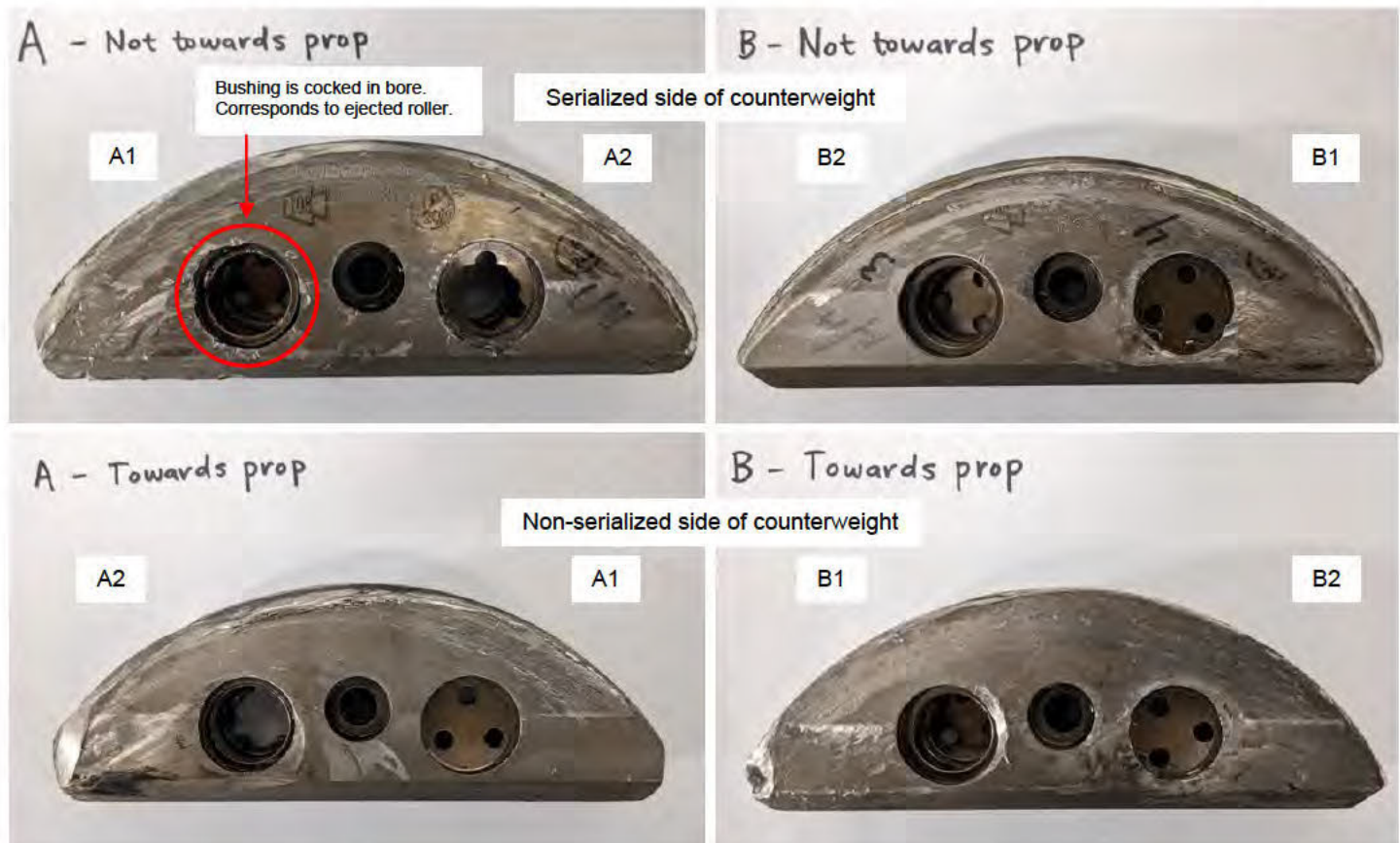


Figure 5. Images of both side of both counterweights A and B. Locations of hardware that is identified in Figures 1 and 2 are labeled. The side of each counterweight that was not towards the propeller flange (prop) included part number and identification markings, and the side that was towards the propeller did not include part numbers and identification markings. The red circled bushing is cocked sideways in the counterweight bore. This bushing corresponds to the counterweight roller that was ejected from the crankshaft assembly.

The set of two counterweights contained eight total counterweight bushings, all part number [REDACTED]. The inner diameter (ID) and surrounding surfaces of each counterweight bushing were examined for evidence of unusual and/or heavy wear. The bushing circled in red in Figure 5 is cocked sideways in the counterweight bore. This bushing corresponds to the counterweight roller that was ejected from the crankshaft assembly.

Selected images of some of the bushings are shown in Figure 6. None of the bushing IDs showed anything alarming or unusual. The dark marks on the IDs in the images labeled A, F, G, and H of Figure 6 are embedded oil/debris that was able to be removed with rigorous scrubbing using ethanol and a cotton swab. Images A through D of Figure 6 show the A2 bushing on the propeller side of the A counterweight, and there is visible impact damage to both the ID corner of the bushing and the counterweight surface adjacent to the bushing.

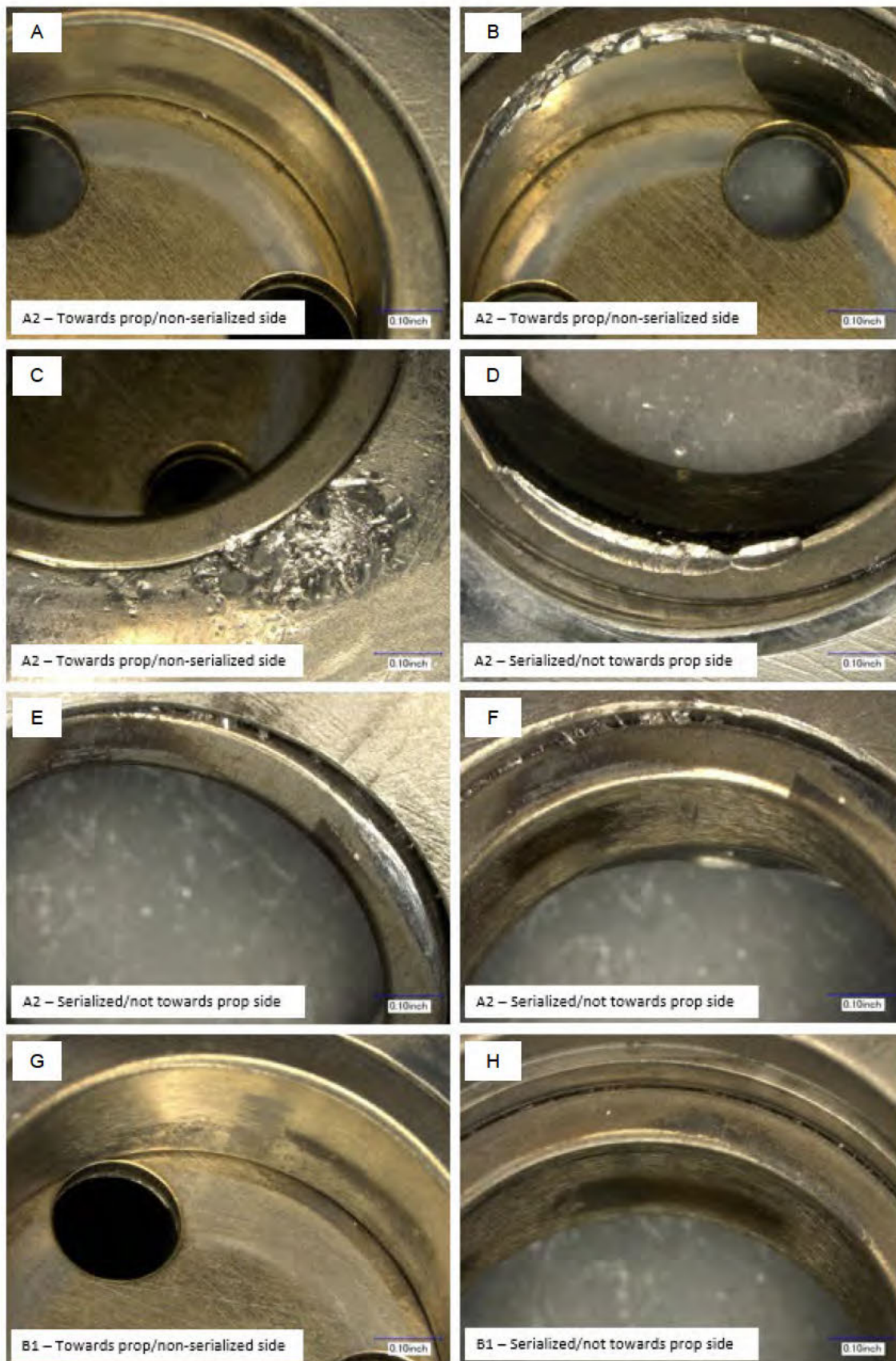


Figure 6. Images of counterweight bushing inner diameters and surrounding counterweight surfaces.

The restrictions stated on the first page of this document are applicable to all pages of this document.

3. *Fractured pieces of bearings, connecting rods, and connecting rod bolts*

The 23 individual fractured pieces of bearings, connecting rods, and connecting rod bolts that were sent to the Materials Lab were labeled and evaluated to see if any of their fracture surfaces were salvageable (meaning they contained potentially undamaged areas that might have been able to provide useful information about failure mode), as shown in Figure 7. The pieces shown in Figure 7 are described in Table 2 based on the label on the bag they came in when they were delivered to the lab. Table 2 also documents observations made with the naked eye about each piece, including whether it looked like it was salvageable based on fracture surface appearance.

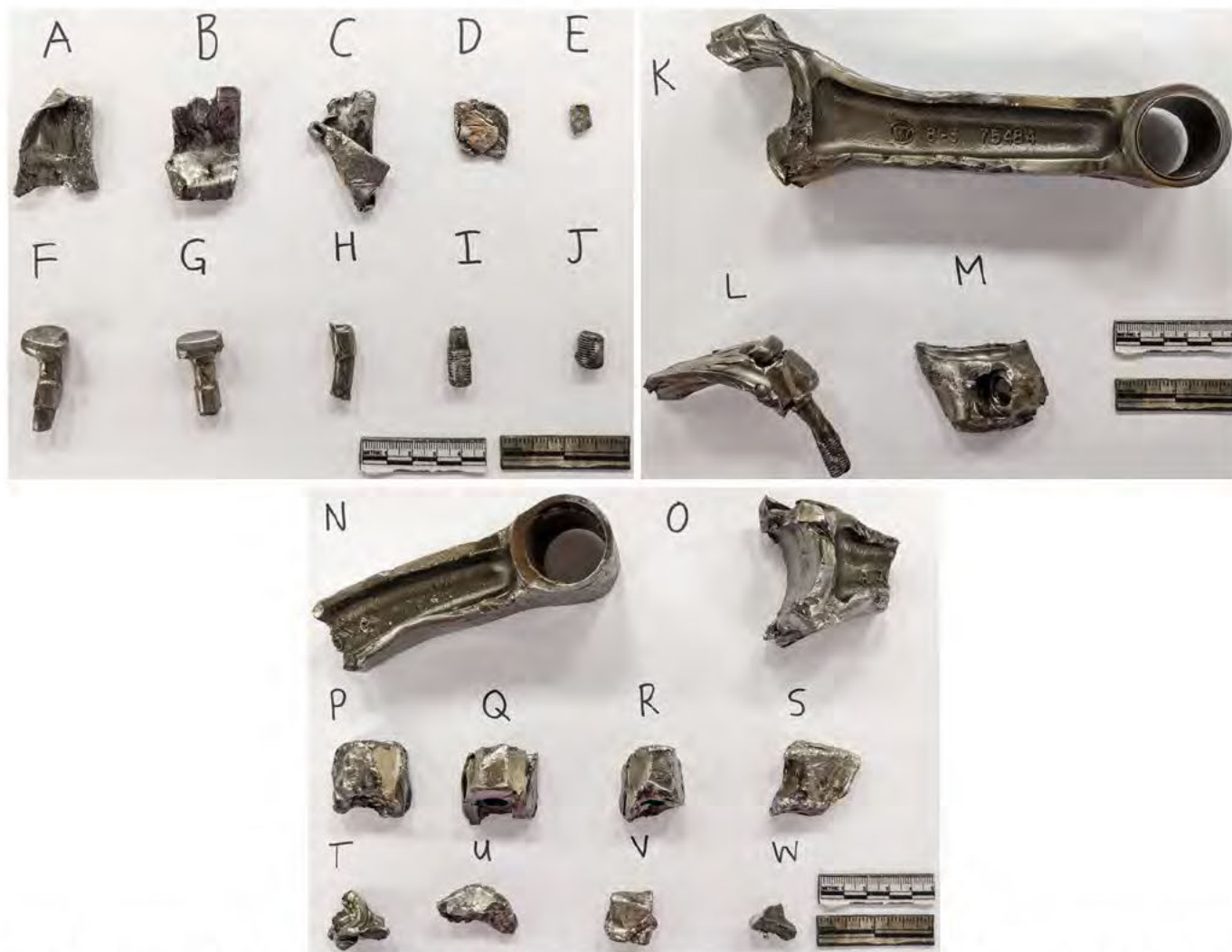


Figure 7. Images of all 23 remnant pieces (bearings, connecting rods, connecting rod bolts, and an unidentified part), labeled pre-cleaning.

Table 2. Table reporting observations of fracture surfaces on pieces delivered to the Materials Lab. It should be noted that all pieces overall showed significant damage, but the observations in the table focus on the condition of the fracture surfaces and whether they may provide useful information about failure mode of the part. Rows with a green background indicate pieces that were observed pre-cleaning to possibly have salvageable fracture surfaces.

Piece ID	Description (based on labeled bag the piece was delivered to the lab in)	Pre-cleaning observations
A	Bearing remnant	Fracture surfaces destroyed, nothing useful
B	Bearing remnant	Fracture surfaces destroyed, nothing useful
C	Bearing remnant	Possible salvageable fracture surface near bent flap – Clean and re-evaluate
D	Bearing remnant	Fracture surfaces destroyed, nothing useful
E	Bearing remnant	Fracture surfaces destroyed, nothing useful; Has a green chunk of FOD on it
F	Connecting rod bolt – Head section	Marked with P/N: ARP xxxxxx?? ?(?) and following characters not visible, but very likely the same as on Piece G); Fracture surface near neck might be salvageable – Clean and re-evaluate
G	Connecting rod bolt – Head section	Marked with P/N: ARP xxxxxxxx xxx (vendor, part number, lot); Fracture surface on shank might be salvageable – Clean and re-evaluate
H	Connecting rod bolt – Unthreaded section	Fracture surfaces at both ends may be salvageable – Clean and re-evaluate
I	Connecting rod bolt – Threaded section	Severely necked (evidence of overload); Fracture surface might be salvageable – Clean and re-evaluate
J	Connecting rod bolt – Threaded section	Thread end is smashed flat; Fracture surface might be salvageable – Clean and re-evaluate
K	#5 connecting rod main body, including bearing end	Fracture surfaces destroyed, nothing useful
L	#5 connecting rod cap chunk with connecting rod bolt attached	Surface is torn (evidence of overload); Fracture surfaces destroyed, nothing useful
M	#5 connecting rod cap chunk with connecting rod bolt hole	Fracture surface might be salvageable – Clean and re-evaluate
N	#6 connecting rod main body, excluding bearing end	End fracture surface might be salvageable – Clean and re-evaluate
O	#6 connecting rod main body chunk, bearing end only	End fracture surface might be salvageable – Clean and re-evaluate
P	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface might be salvageable – Clean and re-evaluate
Q	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface might be salvageable – Clean and re-evaluate
R	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface might be salvageable – Clean and re-evaluate
S	#6 connecting rod chunk with connecting rod bolt hole	Fracture surfaces destroyed, nothing useful
T	#6 connecting rod cap chunk	Fracture surface might be salvageable – Clean and re-evaluate
U	#6 connecting rod chunk (undetermined if from body or cap)	Fracture surfaces destroyed, nothing useful
V	#6 connecting rod chunk (undetermined if from body or cap)	Fracture surfaces destroyed, nothing useful
W	Mystery chunk of non-steel metal	Not relevant; Probably aluminum, likely part of crankcase

The observations in Table 2 generally discuss the state of the fracture surface, not the entire piece at large. It should be noted that all pieces were severely damaged. They all showed physical evidence (impact marks, bending, twisting) of being violently tossed around inside the engine once failure occurred (additional details are available in the report in Appendix A). The parts from Table 2 that have the note “Clean and re-evaluate” in their Observation field (that are in rows with green backgrounds) were ultrasonically cleaned in Alconox and then in ethanol, and they are pictured in their clean state in Figure 8.

The restrictions stated on the first page of this document are applicable to all pages of this document.



Figure 8. Image of all 13 remnant pieces judged to have fracture surfaces with potentially salvageable (at least partially undamaged) fracture surfaces, labeled and cleaned.

Once cleaned, each lettered piece pictured in Figure 8 was visually (with the naked eye and with microscopes) examined further. Observations are summarized in Table 3. Pieces that were deemed to provide useful failure information or show interesting surface characteristics are shown in Figures 9-23.

Table 3. Table reporting observations of fracture surfaces from Table 2 deemed to be salvageable. Rows with a red background indicate pieces that were observed post-cleaning to have fracture surfaces that were too damaged to provide information about failure mode. Non-highlighted rows have key observations (failure mode assertions) bolded and highlighted in blue. The information contained in this table and additional information about these surfaces and images can be found in the text following this table.

Piece ID	Description (based on labeled bag the piece was delivered to the lab in)	Post-cleaning observations
C	Bearing remnant	This section of a bearing was folded over on itself and severely damaged. The visible fracture surface was smeared and coated in places with a bronze-colored layer (likely the bronze surface layer of the bearing). No information about fracture mode. Close-up image not presented in this report.
F	Connecting rod bolt – Head section	This section of a connecting rod bolt was badly beaten up. The non-threaded part of the shank was visibly bent, and the unthreaded part of the shank near the fracture surface shows necking, indicative of failure by overload . There is blue heat tint on a small part of the fracture surface. See Figure 9.
G	Connecting rod bolt – Head section	Fracture surface appears to be the cup end of a cup-and-cone fracture (indicative of failure by overload) with a high-angle lip that spans about 50% of the circumference of the bolt with some smashing. Embedded material from being tossed around in engine. See Figure 10.
H	Connecting rod bolt – Unthreaded section	Unthreaded end of this section has a shear lip and looks like a cup-and-cone fracture (indicative of failure by overload) with some smashing. The threaded end has a large shear lip and appears to be the cup end of a cup-and-cone fracture (indicative of failure by overload). This end tore in the first few threads. See Figures 11 and 12.
I	Connecting rod bolt – Threaded section	Threads are severely damaged, and the fracture surface is smashed. The shank shows necking, indicative of failure by overload . There is a small spot of blue heat tint on the base of the threaded end. See Figure 13.
J	Connecting rod bolt – Threaded section	The fracture surface appears to be the cup end of a cup-and-cone fracture (indicative of failure by overload) and shows smashing. There is what appears to be a shear lip that is severely smashed. Threads are severely damaged. See Figures 14 and 15.
M	#5 connecting rod cap chunk with connecting rod bolt hole	Fracture surface is jagged and smashed. There is clear evidence of severe damage, including a tear across the width of the connecting rod cap and physical distortion of the part. Macroscopically, part of the fracture surface appears woody and part of it appears to show microvoid coalescence (MVC), indicative of failure by overload . There is an area that looks like it could have been fatigued but based on the severe damage and distortion of the part and that particular area, it is likely that the fatigue-appearing region was smashed into the pattern it shows. See Figure 16.
N	#6 connecting rod main body, excluding bearing end	Mating surface with part O. Fracture surface is flat and shiny in some areas and textured and shiny in others. Shows fatigue and evidence of smashing. The piston pin end shows severe heat tinting. See Figures 17 and 18.
O	#6 connecting rod main body, bearing end only	Has three fracture surfaces (one where I-beam of rod transitions to bearing end of rod, and two each end of the connecting rod bearing end where the bolt hole is). The mating surface with part N shows some smashing and evidence of fatigue . There are two ends that mate with the connecting rod cap—one end (with wave-shaped curl) shows evidence of fatigue, some smashing, and a woody section. The other end is completely smashed and will provide no useful information. See Figures 19-21 and Appendix B Figures i-ix.
P	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface is smashed and smeared. Surface appears dark gray and not shiny. Provides no useful information about failure mode. See Figure 22.
Q	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface is smashed and smeared. Provides no useful information about failure mode. Surface appears dark gray and not shiny, like part of the P fracture surface. Close-up image not presented in this report.
R	#6 connecting rod cap chunk with connecting rod bolt hole	Fracture surface has multiple planes, some that meet at 90° angles, and shows evidence of fatigue . One section appears woody and others are flat and shiny. See Figure 23 and Appendix B Figures x-xii.
T	#6 connecting rod cap chunk	The fracture surface of Piece T was completely smashed and provided no useful information. Close-up image not presented in this report.

Piece F (connecting rod bolt – head section)

Piece F is shown in Figure 9. The tapered end containing the fracture surface shows necking, evidence of failure by overload.



Figure 9. Image of Piece F showing necking.

Piece G (connecting rod bolt – head section)

Figure 10 shows Piece G. The fracture surface has a cup-and cone appearance and a high-angle shear lip that spans about 50% of the circumference of the bolt, all consistent with sudden overload. Some areas of the surface are smashed and there is some embedded material from the bolt being tossed around in the engine.

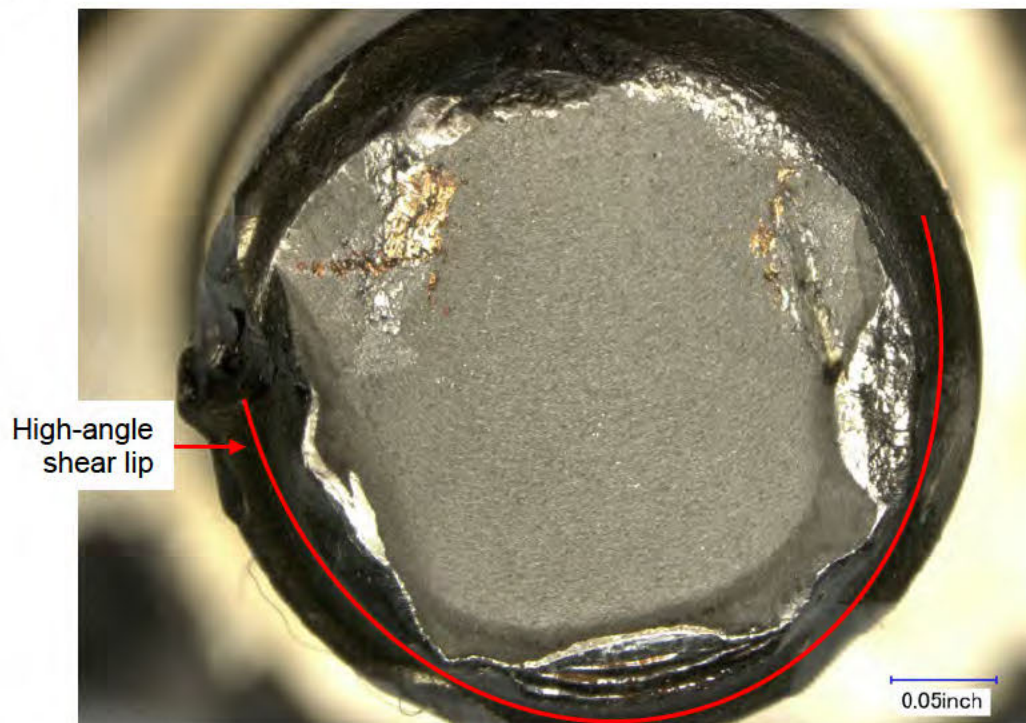


Figure 10. Image of Piece G showing cup-and-cone fracture with a high-angle lip.

Piece H (connecting rod bolt – unthreaded section)

Figure 11 shows the unthreaded end Piece H. The fracture surface has a cup-and-cone appearance and a very high-angle shear lip, all consistent with sudden overload.



Figure 11. Image of the unthreaded end of Piece H showing cup-and-cone fracture surface and very high-angle shear lip.

Figure 12 shows the threaded end of Piece H. There is a high-angle shear lip and the surface is smashed around its circumference.

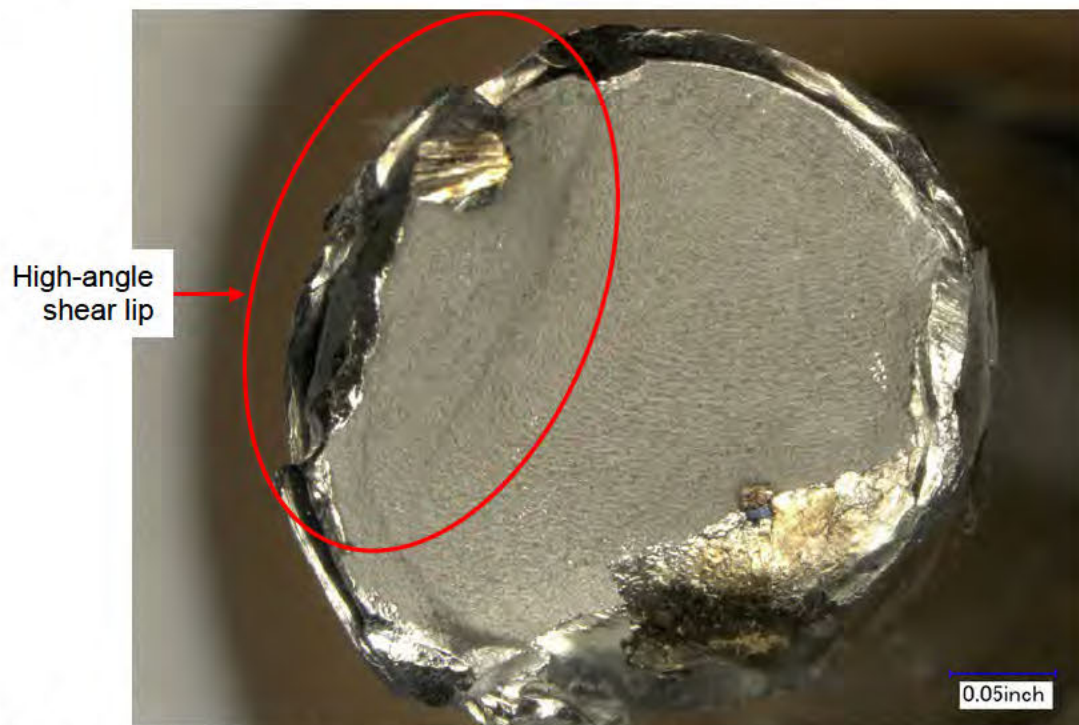


Figure 12. Image of the threaded end of Piece H showing a high-angle shear lip and smashing around the circumference.

Piece I (connecting rod bolt – threaded section)

Figure 13 shows Piece I. The bolt is necked, and the threads experienced significant smashing. The fracture surface is smashed and provided no useful information about failure mode; however, the necking clearly indicates ductile overload failure.

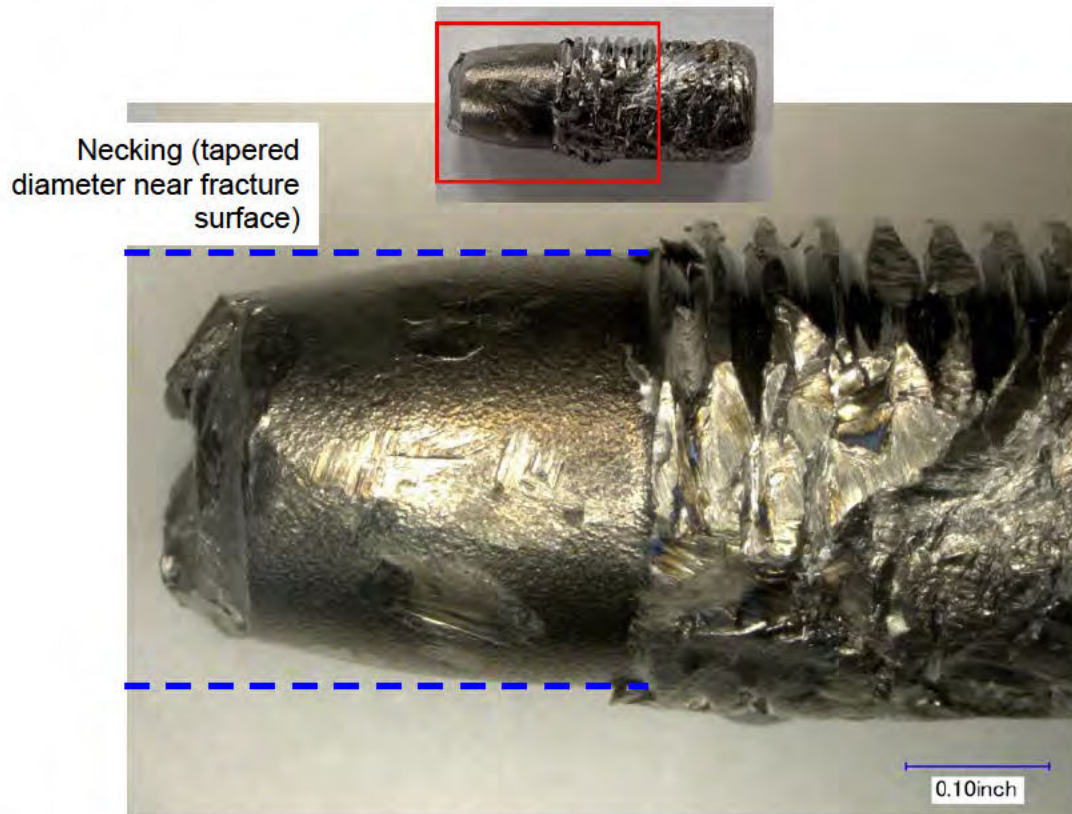


Figure 13. Image of Piece I showing necking and smashed threads.

Piece J (connecting rod bolt – threaded section)

Figure 14 shows the fracture surface of Piece J. It is the cup end of a cup-and-cone fracture and shows smashing. There is also a severely smeared high-angle shear lip.



Figure 14. Image of fracture surface of Piece J showing a smeared shear lip and cup-and-cone fracture.

The restrictions stated on the first page of this document are applicable to all pages of this document.

Figure 15 shows the smashed threads of Piece J.



Figure 15. Image showing smashed threads of Piece J.

Piece M (#5 connecting rod cap chunk with connecting rod bolt hole)

Figure 16 shows the fracture surface of Piece M. There is clear evidence of severe damage, including impact-induced waviness of the part and a tear across its width, indicating failure by overload. The fracture surface has areas that appear woody and ones that appear to show microvoid coalescence (MVC). There is an area (pointed out with a blue line in Figure 16) that looks like it could be fatigue, but given the level of damage the part sustained, it is more likely that the region was smashed into the pattern it shows.

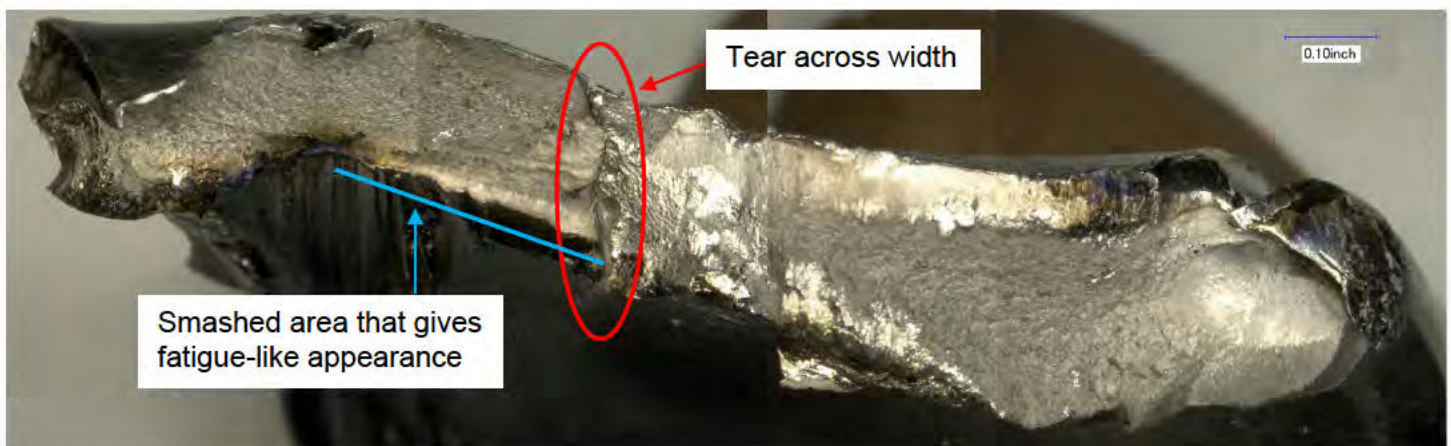


Figure 16. Image showing fracture surface of Piece M.

Piece N (#6 connecting rod main body, excluding bearing end)

Figure 17 shows the fracture surface at the bearing end of the #6 connecting rod, Piece N. The rod fractured where the I-beam of the rod transitions to the bearing end of the rod. This fracture surface is the mating surface to one of the fracture surfaces of Piece O. It shows fatigue and evidence of smashing. Like Piece M, there is a region pointed out with a blue line that looks like it could be fatigued or could have been smashed into that pattern from impact in the damaged engine.

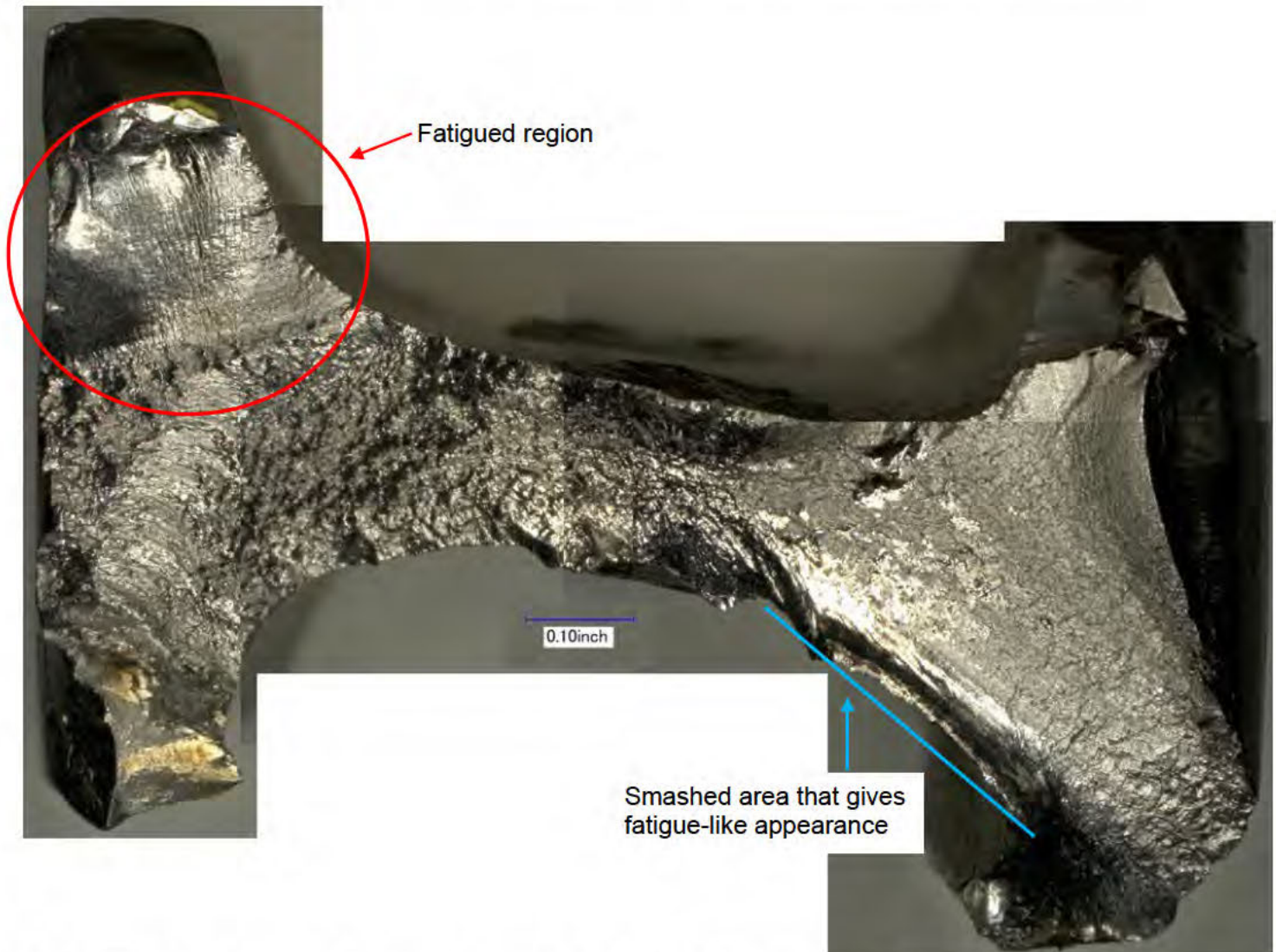


Figure 17. Image showing the fracture surface at the bearing end of the #6 connecting rod, Piece N.

Once the combustion/detonation debris was ultrasonically cleaned off Piece N (#6 connecting rod main body, excluding bearing end) it became clear that the piece saw high service temperatures, based on the heat coloring on the piston pin end. Piece K (#5 connecting rod main body, including bearing end), although its fracture surfaces were deemed to be too damaged to be salvageable, was also cleaned to examine its piston pin end for similar heat coloring. As shown in Figure 18, both Pieces N and K show a deep purple/bright blue coloration, which corresponds to operating temperatures in the (approximate) 540°F to 590°F range.

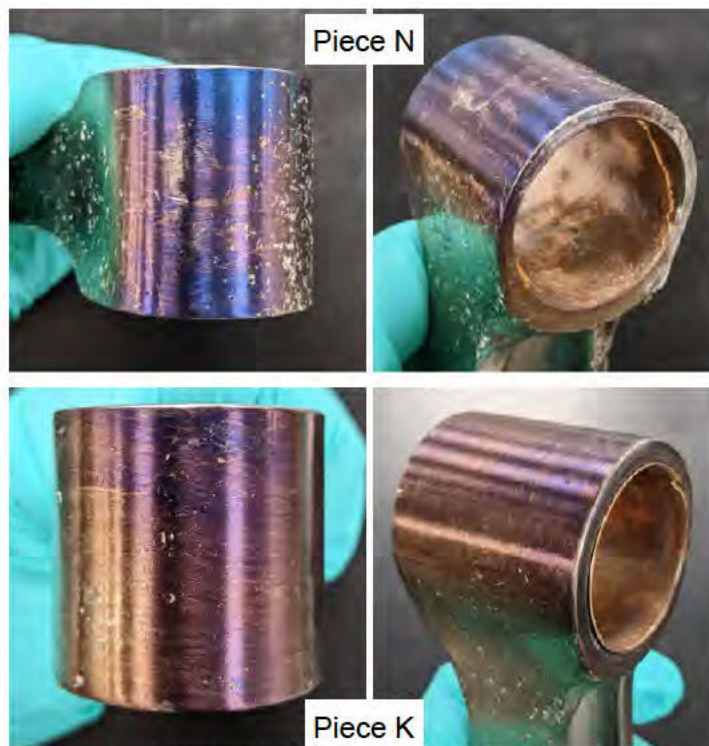


Figure 18. Image showing heat tinting of pieces N and K.

It is notable that this (approximate) temperature range experienced by the connecting rods exceeds what is recommended in the Lycoming Operator's Manual (60297-10), which notes that for maximum engine service life, the cylinder head temperature should be maintained between 150°F and 435°F during continuous operation, and the maximum acceptable cylinder head temperature is 500°F. Parts that are interior to the crankcase and indirectly in contact with the cylinder head, such as the connecting rods, should experience lower temperatures than what the cylinder head experiences, since these parts are oil-cooled and the piston acts as a physical heat barrier. If the connecting rods experienced temperatures in the 540°F to 590°F range, the interior of the cylinder barrel was operating at even higher temperatures than those in that range.

Piece O (#6 connecting rod main body, bearing end only)

Figure 19 shows the bearing end of the connecting rod, the mating surface to Piece N (Figure 17), Piece O. This surface is where the I-beam of the rod transitions to the bearing end of the rod. The mating fatigue region to Piece N is circled in red in Figure 19. Like Piece M (Figure 16), there is a region (pointed out with a blue line in Figure 19) that looks like it could be fatigue. Given the level of damage the part sustained, it is also possible that the region was smashed into the pattern it shows.

Additional micrographs of this surface taken using the scanning electron microscope (SEM) are available in Appendix B, Figures i-iii.

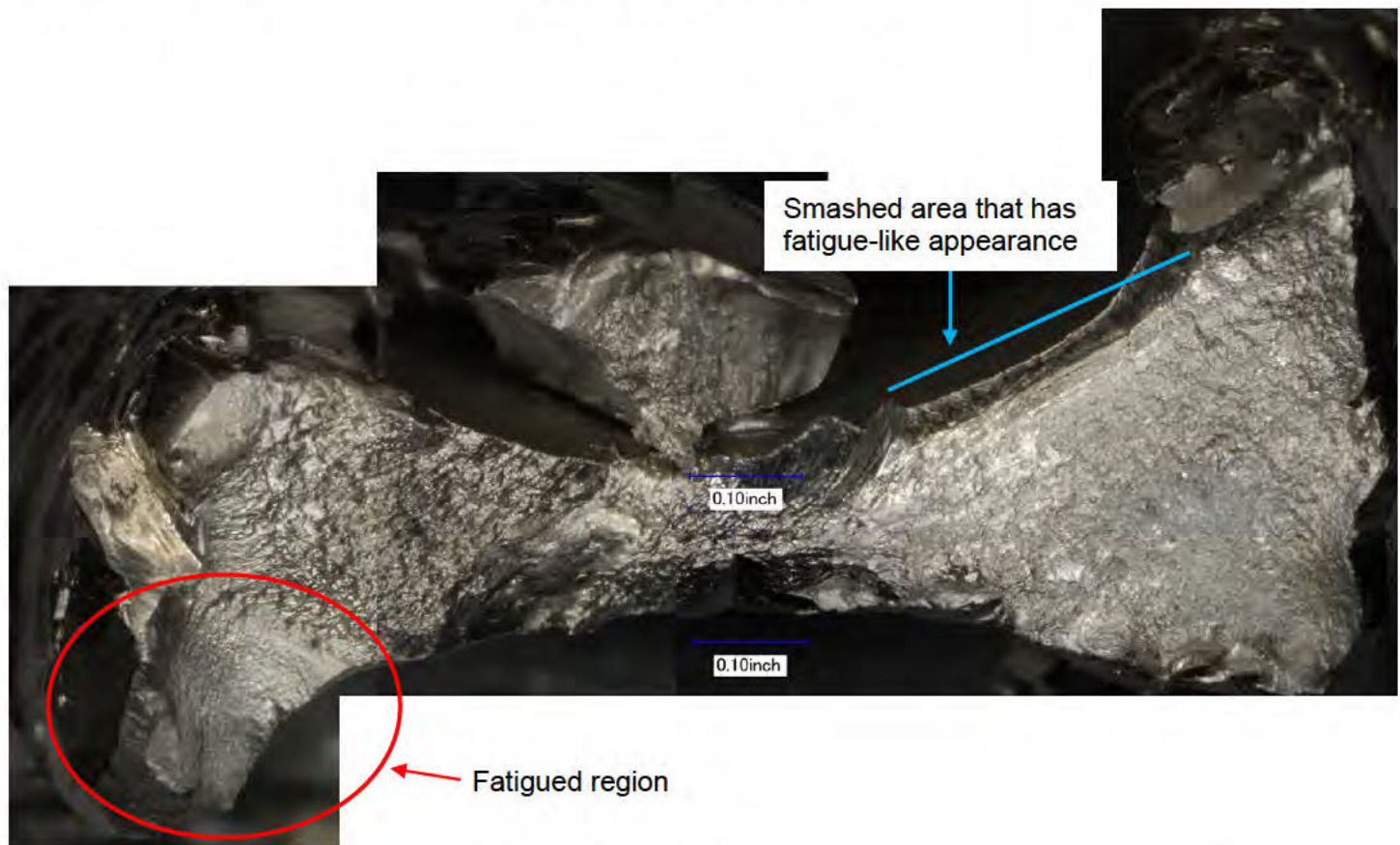


Figure 19. Image showing fracture surface of the bearing end of the connecting rod, one of the Piece O fracture surfaces. This surface is where the I-beam of the rod transitions to the bearing end of the rod. The circled fatigued region mates with circled fatigued region in Figure 17. The blue line shows a region that looks like fatigue or could possibly be smashed into that pattern from impact.

Figure 20 shows one of the bolt hole ends of the #6 connecting rod (Piece O). There is clear evidence of fatigue, with multiple sets of beach marks and crack initiation sites.

Additional micrographs of this surface taken using the SEM are available in Appendix B, Figures iv-ix.

The other bolt hole end of the #6 connecting rod (Piece O) is shown in Figure 21. This fracture surface is very damaged and will not provide any useful fracture information.

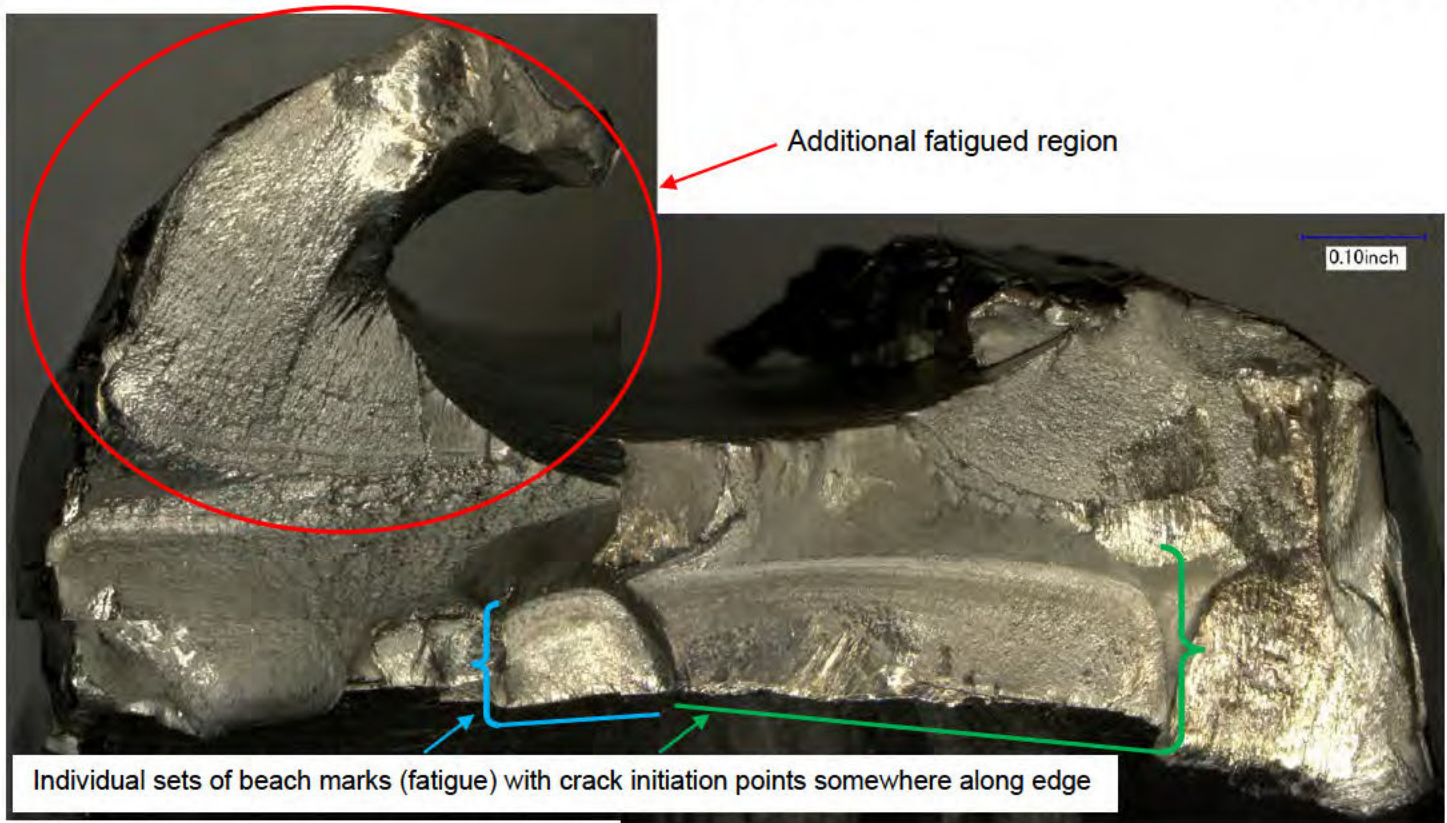


Figure 20. Image of one of the bolt hole ends of the #6 connecting rods, Piece O. There is clear evidence of fatigue, with multiple sets of beach marks and crack initiation sites.

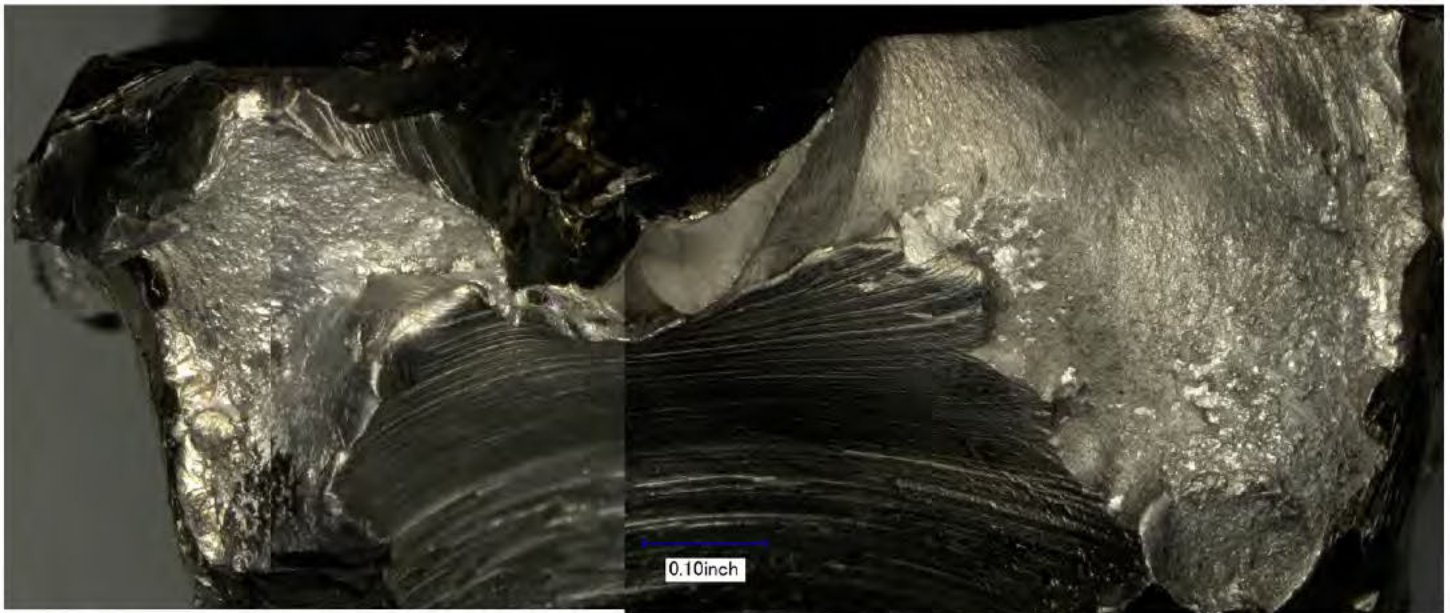


Figure 21. Image of one of the bolt hole ends of the #6 connecting rods, Piece O. There surface is very damaged and will not provide useful information about failure mode.

Piece P (#6 connecting rod cap chunk with connecting rod bolt hole)

Figure 22 shows the fracture surface of Piece P. The fracture surface is very damaged and provides no useful information.



Figure 22. Image of fracture surface of Piece P. Provides no useful failure information.

Piece R (#6 connecting rod cap chunk with connecting rod bolt hole)

Figure 23 shows the fracture surface of Piece R. The piece has multiple planes, some that meet at 90° angles, and shows evidence of fatigue. Additional micrographs of this surface taken using the SEM are available in Appendix B, Figures x-xii.

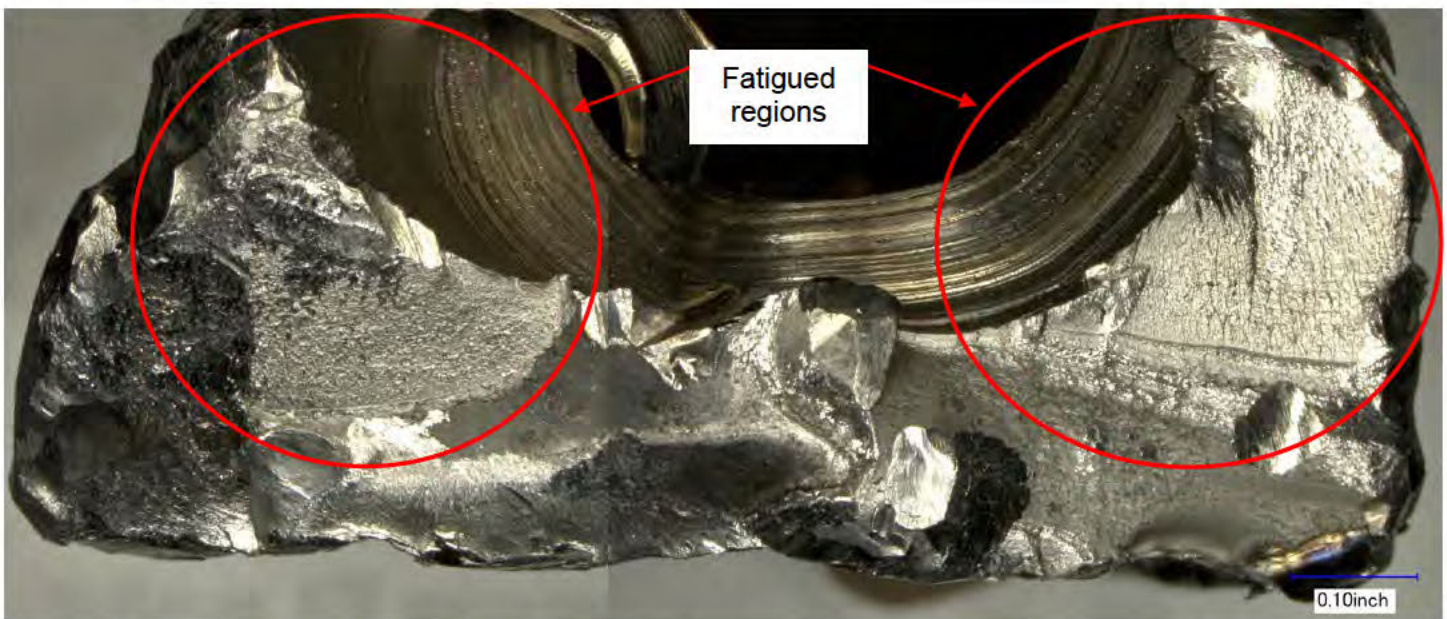


Figure 23. Image of fracture surface of Piece R. Contains multiple planes and shows evidence of fatigue.

Summary

There are multiple possible causes for the fatigue that is seen in the #6 connecting rod main body and cap near the bolt holes, and it cannot be determined what the exact cause of the fatigue was. It is possible that the connecting rod bolts were not installed properly into the connecting rod bolt holes, and in that regard, it is noted the nuts were not recovered for examination. On the other hand, the bolt fracture surfaces that retained useful fracture markings indicate they failed under sudden overload conditions. If the counterweight circlip failed before the #6 connecting rod, it is possible that the ejection of the counterweight roller led to non-standard conditions inside the

The restrictions stated on the first page of this document are applicable to all pages of this document.

engine that promoted fatigue crack growth and propagation (loosening of connecting rod bolts, impact with the connecting rod that allowed for fatigue conditions to occur). Given that the connecting rod showed fatigue in the bolt hole and bearing areas, it is possible that there was some pre-existing damage present from the prior service life that was not completely removed and eventually led to fatigue crack initiation. The evidence of operation under conditions of abnormal combustion may also have contributed to the distress evident in the counterweight assemblies, leading to failure of the circlip and ejection of the roller.

Conclusions

An IO-540-K1A5 engine was delivered disassembled to the Lycoming factory and examined in the NTSB room on 24 August 2022. The engine had been operated for about 500 hours since it was boxed at Lycoming on 10 December 2011 and had to make an emergency landing during flight on 11 January 2022. There were no fatalities or injuries. The engine and plane both sustained significant damage, and the investigation on 24 August 2022 at Lycoming did not lead to a determination of what initially caused the engine to malfunction. The post-teardown report in Appendix A documents multiple findings of problems and failures in the engine. The goal of this Materials Lab investigation following that teardown was to examine the crankshaft, counterweights, and #5 and #6 connecting rods from the engine more closely to determine, if possible, the probable cause(s) of the engine malfunction.

The following are the significant findings and conclusions from the Materials Lab investigation:

1. One of the counterweight circlips failed in fatigue. The failed circlip corresponds to a counterweight roller that was ejected from the counterweight assembly.
2. The #6 connecting rod showed evidence of fatigue failure in multiple areas. The areas showing fatigue are located
 - a. Both on the main body of the rod and on the cap, along the bearing surfaces in the area where the connecting rod bolt joins them together, and
 - b. Where the I-beam of the rod transitions to the bearing end of the rod.
3. It could not be determined which failure occurred first (either the circlip or the #6 connecting rod).
4. The #5 and #6 piston crowns, valve faces, and cylinder head domes were clean and free of combustion residue, consistent with detonation, indicating that the engine was run in lean conditions for a substantial amount of flight time.

INVESTIGATOR: _____ Date: 5 January 2023*

** The original version of this report was issued on 20 December 2022. This reissue adds finding/conclusion #4 to both the Summary and Conclusions sections to ensure that the reader does not miss important information that is contained in the body of the report and Appendix A. No new evidence is provided in this reissued version of the report. The Appendixes are unchanged from the original version of this report.*

LN-xxxxx

Appendix B:
Selected Scanning Electron Micrographs

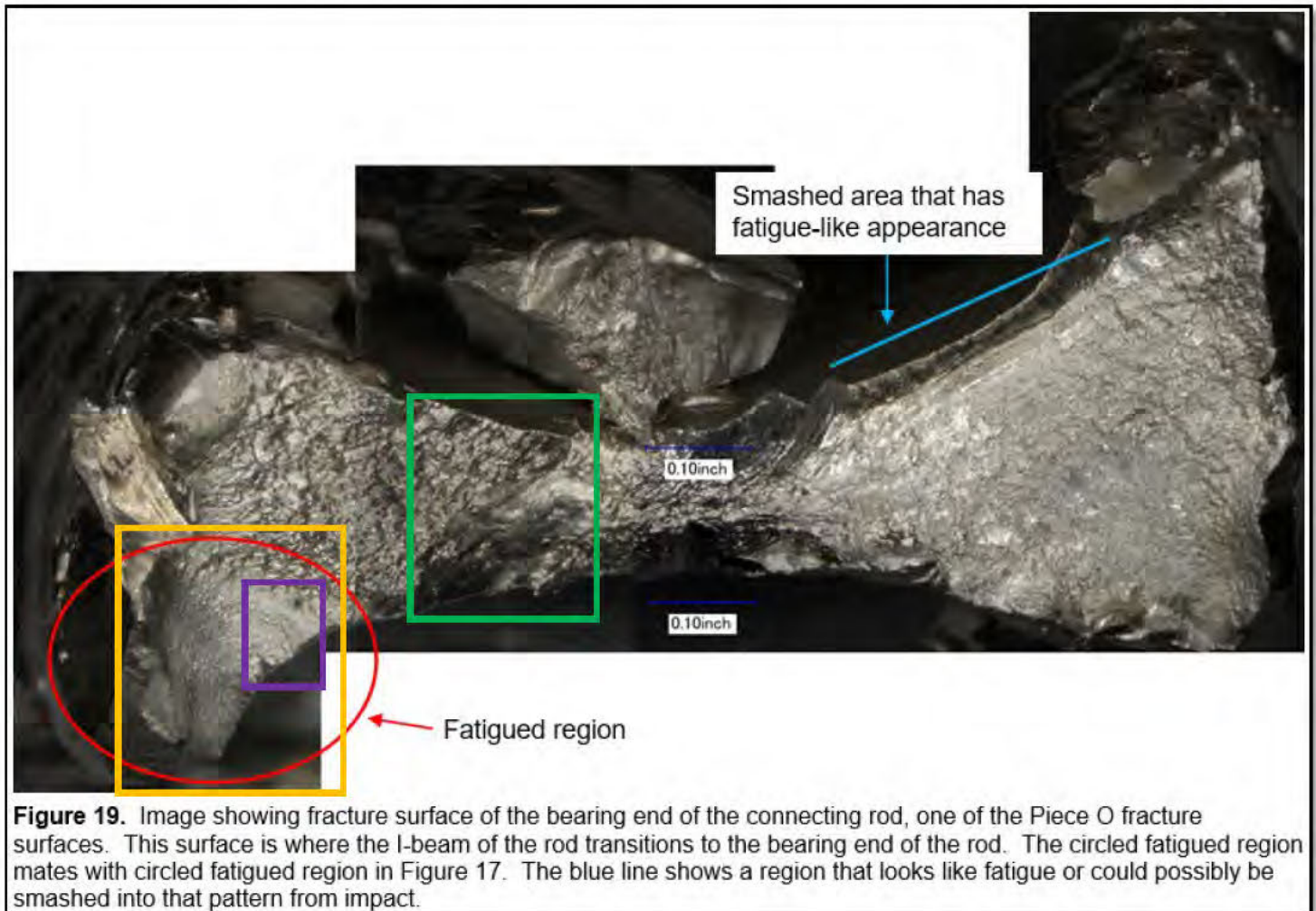
Appendix B: Selected Scanning Electron Micrographs

Purpose: This Appendix provides scanning electron microscope (SEM) images of selected fracture surfaces for more detail. In each section, the macroscopic fracture surface to which the SEM images correspond is shown for ease of reference. On the reference macroscopic images there are rectangles outlined in different colors that correspond to the outline colors on the SEM images that follow. SEM images and corresponding outlined rectangles are oriented similarly for ease of matching SEM images to the macroscopic region they show in the orientation in which it is shown.

I. Piece O (#6 connecting rod main body, bearing end only)

Surface where I-beam of rod transitions to bearing end of rod – Mating surface with rod

Images correspond to fracture surface shown in Figure 19 of the main report, shown below for reference.



Appendix B: Selected Scanning Electron Micrographs

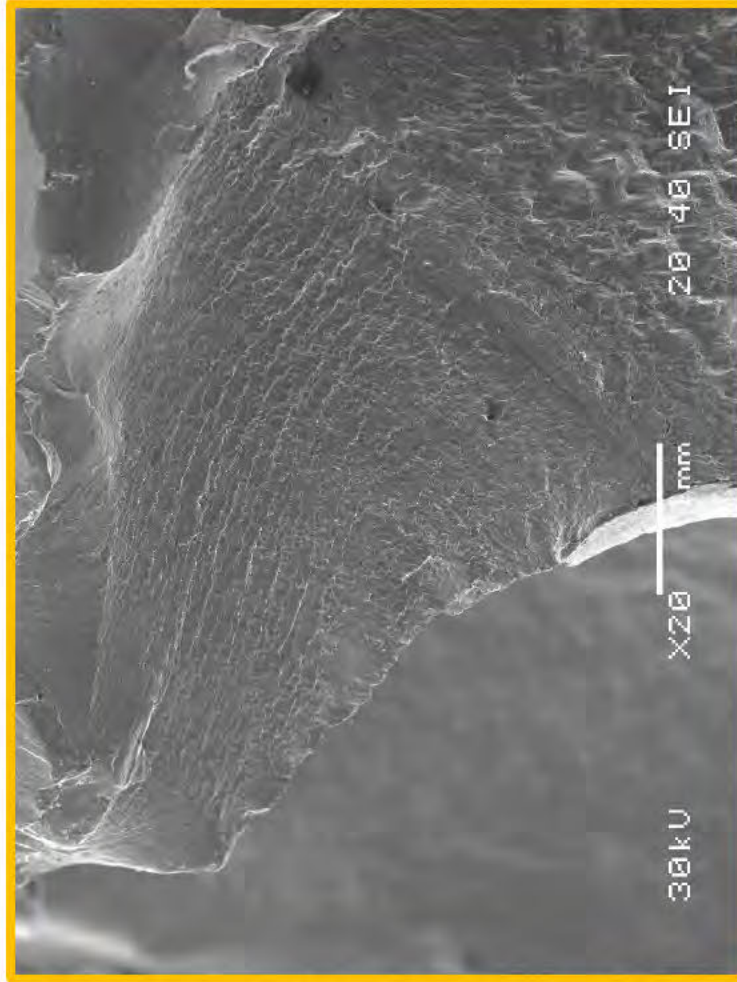


Figure i. SEM micrograph of Piece O, mating surface with connecting rod, where I-beam end of rod transitions to the bearing end of the rod. Region shows evidence of fatigue crack growth.

Appendix B: Selected Scanning Electron Micrographs

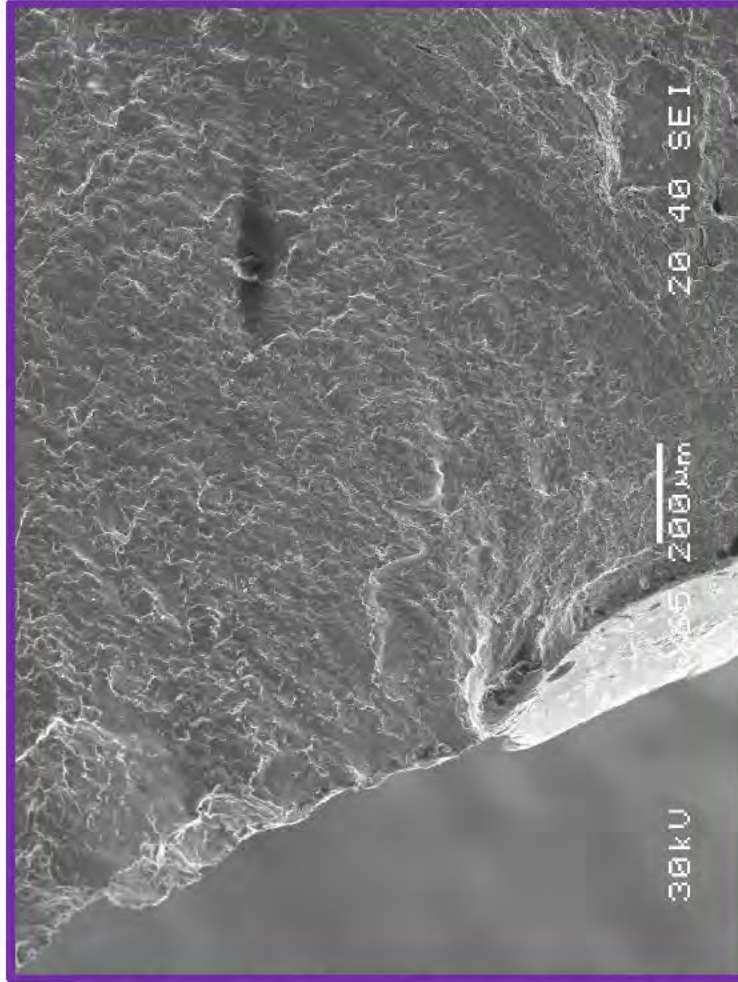


Figure ii. SEM micrograph of Piece O, mating surface with connecting rod, where I-beam end of rod transitions to the bearing end of the rod. Higher magnification image of Figure i. Region shows evidence of fatigue crack growth.

Appendix B: Selected Scanning Electron Micrographs

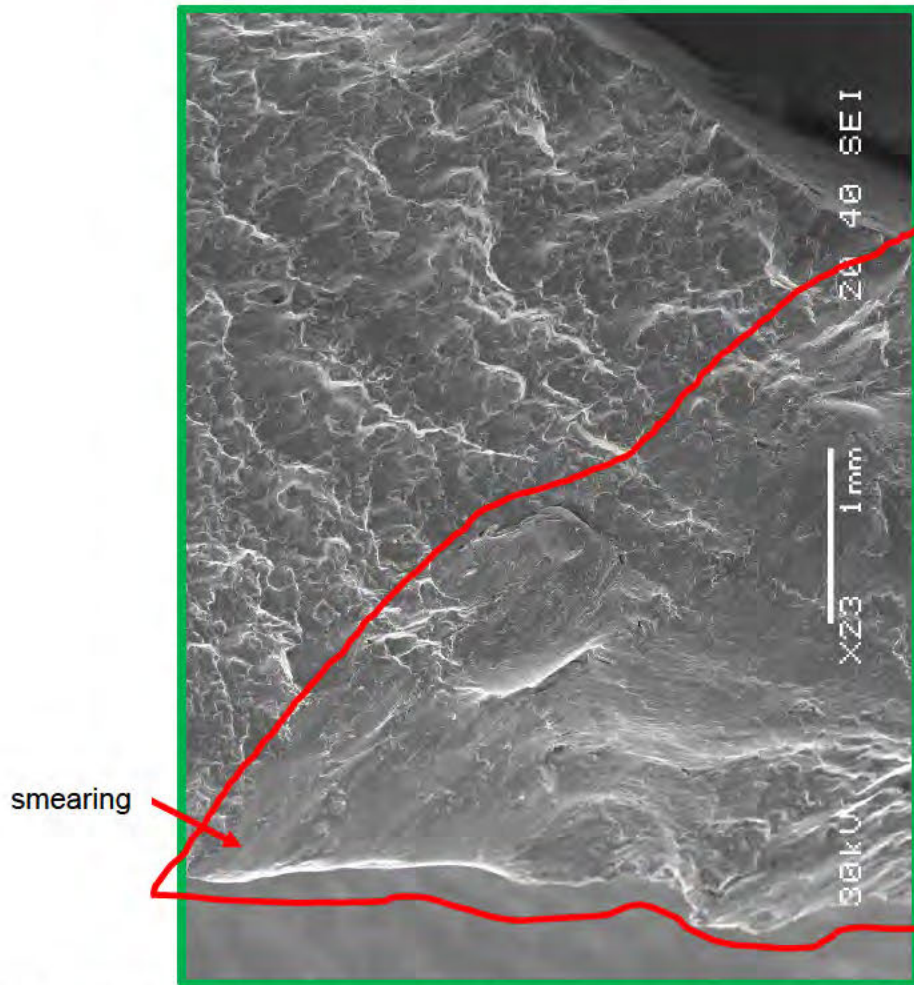


Figure iii. SEM micrograph of Piece O, mating surface with connecting rod, where I-beam end of rod transitions to the bearing end of the rod. Region near exact center of cross-section. There is a region of severe smearing outlined in red. Outside of the severely smeared region there is another damaged region that may show rough ductile tearing, possibly with some shear-type directionality, which is consistent with overload.

Appendix B: Selected Scanning Electron Micrographs

II. Piece O (#6 connecting rod main body, bearing end only)

Bolt hole end

Images correspond to the fracture surface shown in Figure 20 of the main report, shown below for reference.

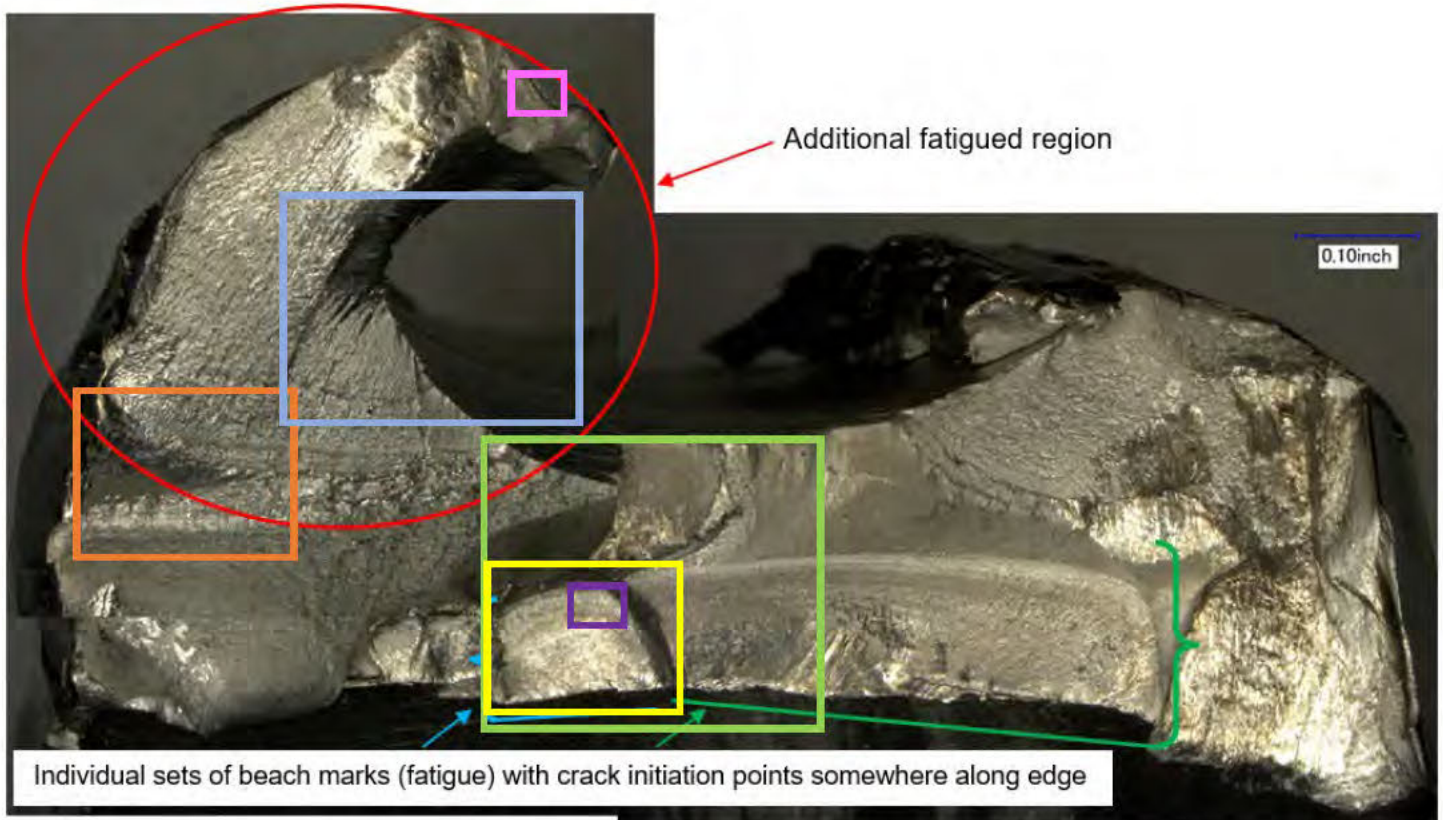


Figure 20. Image of one of the bolt hole ends of the #6 connecting rods, Piece O. There is clear evidence of fatigue, with multiple sets of beach marks and crack initiation sites.

Appendix B: Selected Scanning Electron Micrographs

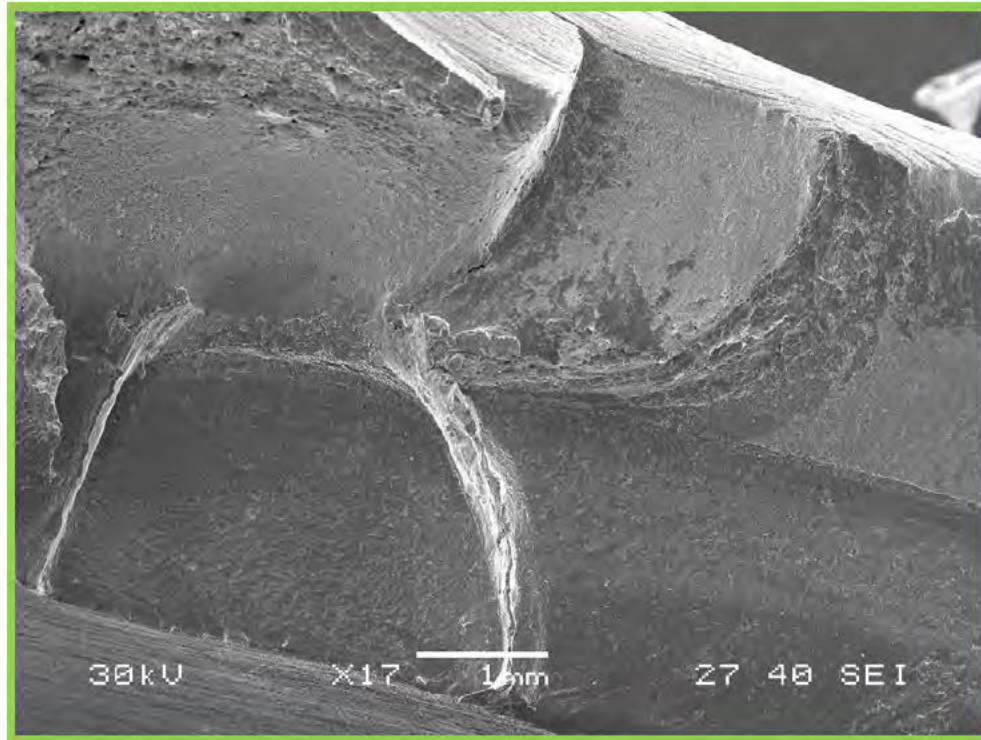


Figure iv. SEM micrograph of Piece O, bolt hole end. Region shows the convergence of multiple individual areas of fatigue crack growth.

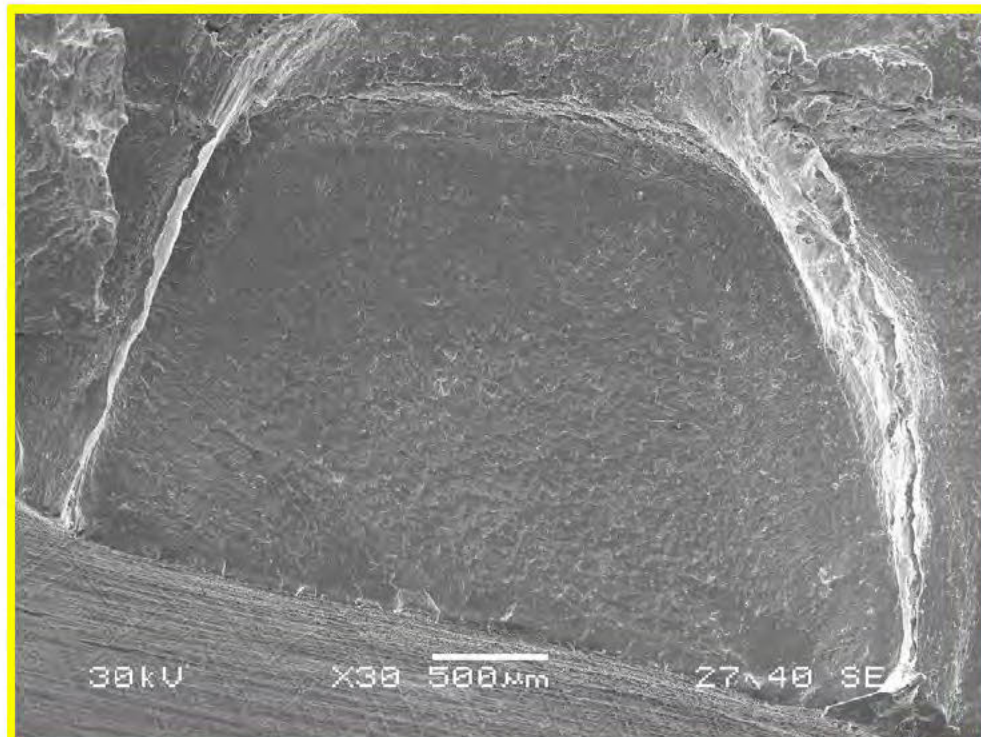


Figure v. SEM micrograph of Piece O, bolt hole end. Region shows a recessed area of fatigue crack growth, a closer view of a part of Figure iv.

The restrictions stated on the first page of this document are applicable to all pages of this document.

Appendix B: Selected Scanning Electron Micrographs

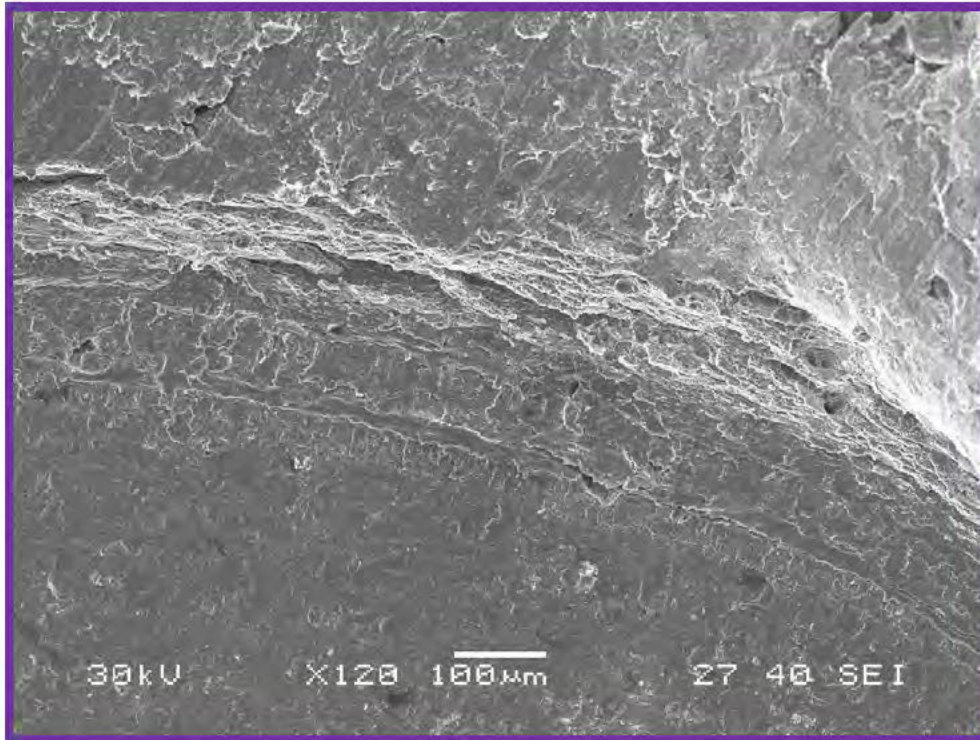


Figure vi. SEM micrograph of Piece O, bolt hole end. Region shows a closer view of the recessed area of fatigue crack growth in Figure v.

Appendix B: Selected Scanning Electron Micrographs

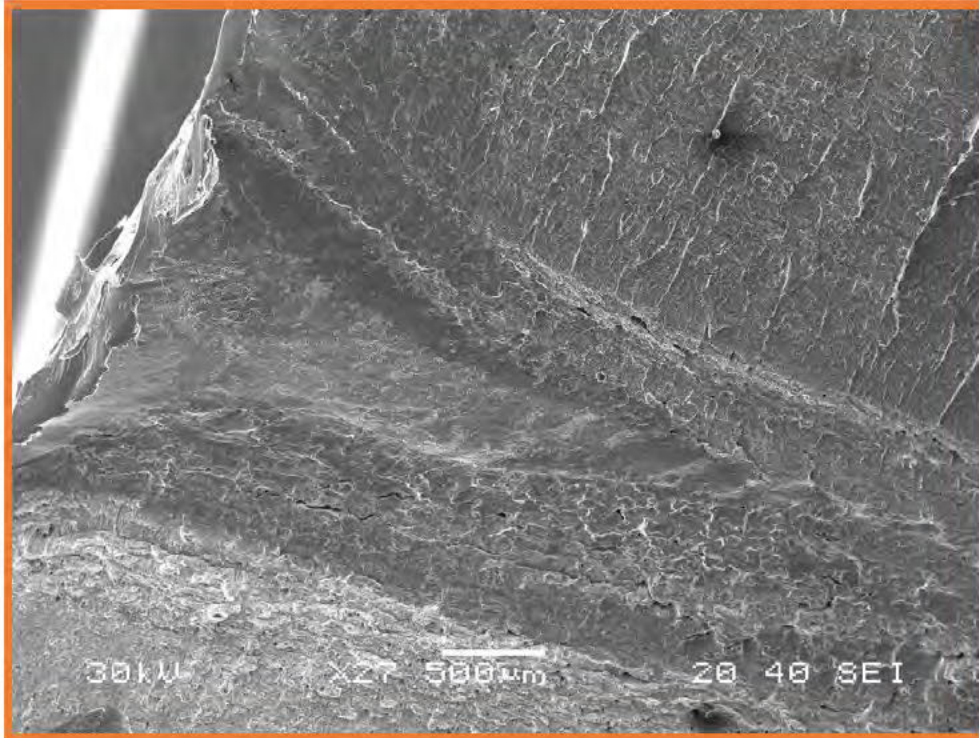


Figure vii. SEM micrograph of Piece O, bolt hole end. Region shows evidence of fatigue crack growth.

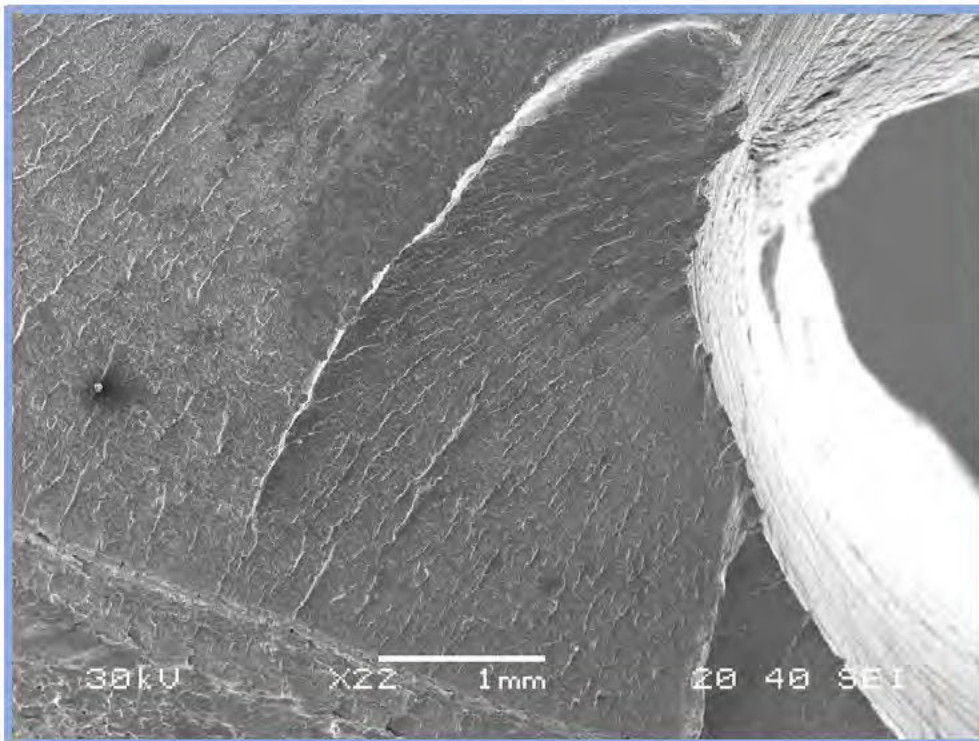


Figure viii. SEM micrograph of Piece O, bolt hole end. Region shows evidence of fatigue crack growth.

The restrictions stated on the first page of this document are applicable to all pages of this document.

Appendix B: Selected Scanning Electron Micrographs

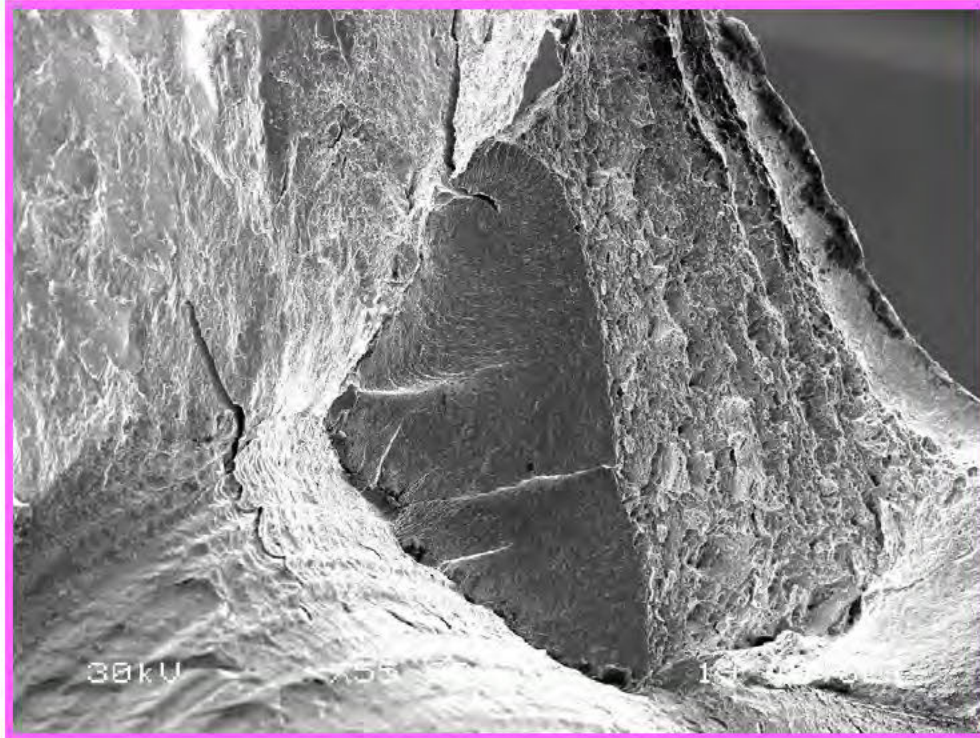


Figure ix. SEM micrograph of Piece O, bolt hole end. Region shows a recessed area with evidence of fatigue crack growth.

Appendix B: Selected Scanning Electron Micrographs

III. Piece R (#6 connecting rod cap chunk with connecting rod bolt hole)

Images correspond to the fracture surface shown in Figure 23 of the main report, shown below for reference.

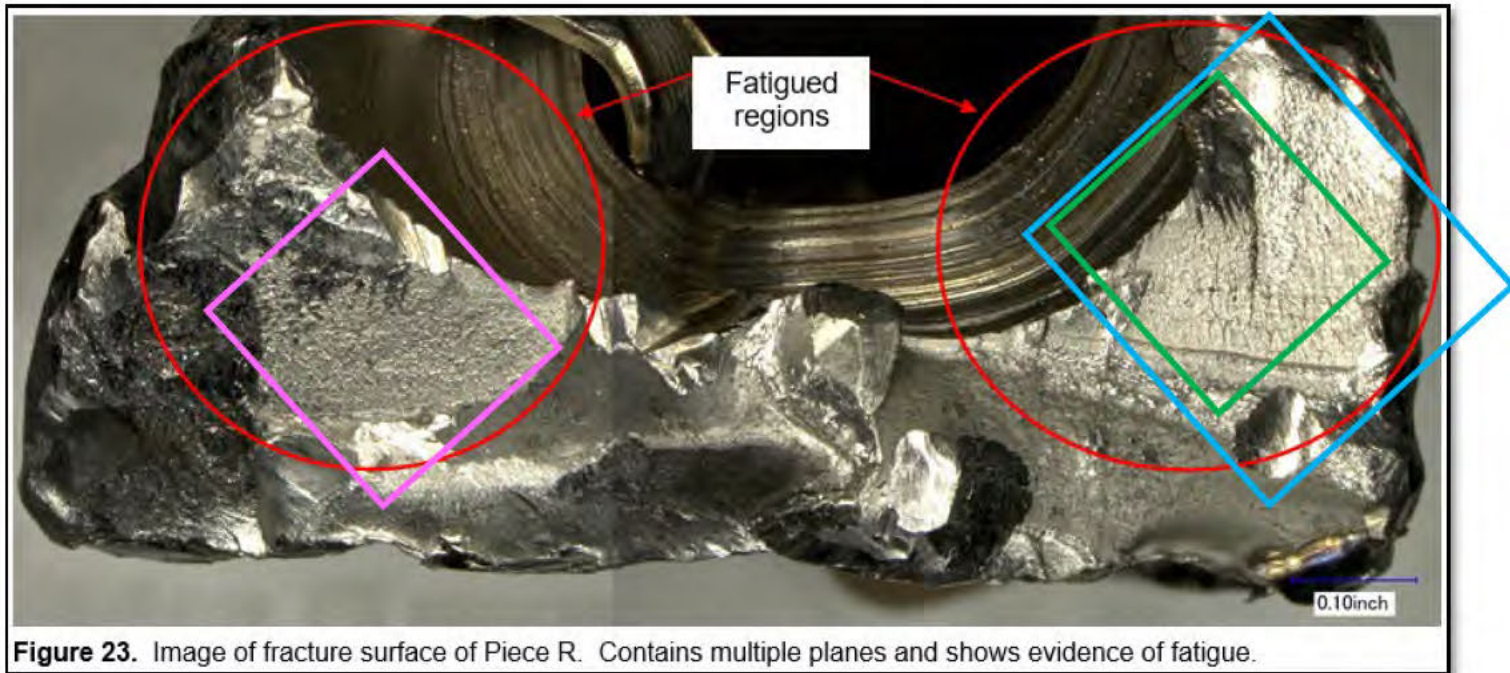


Figure 23. Image of fracture surface of Piece R. Contains multiple planes and shows evidence of fatigue.

Appendix B: Selected Scanning Electron Micrographs

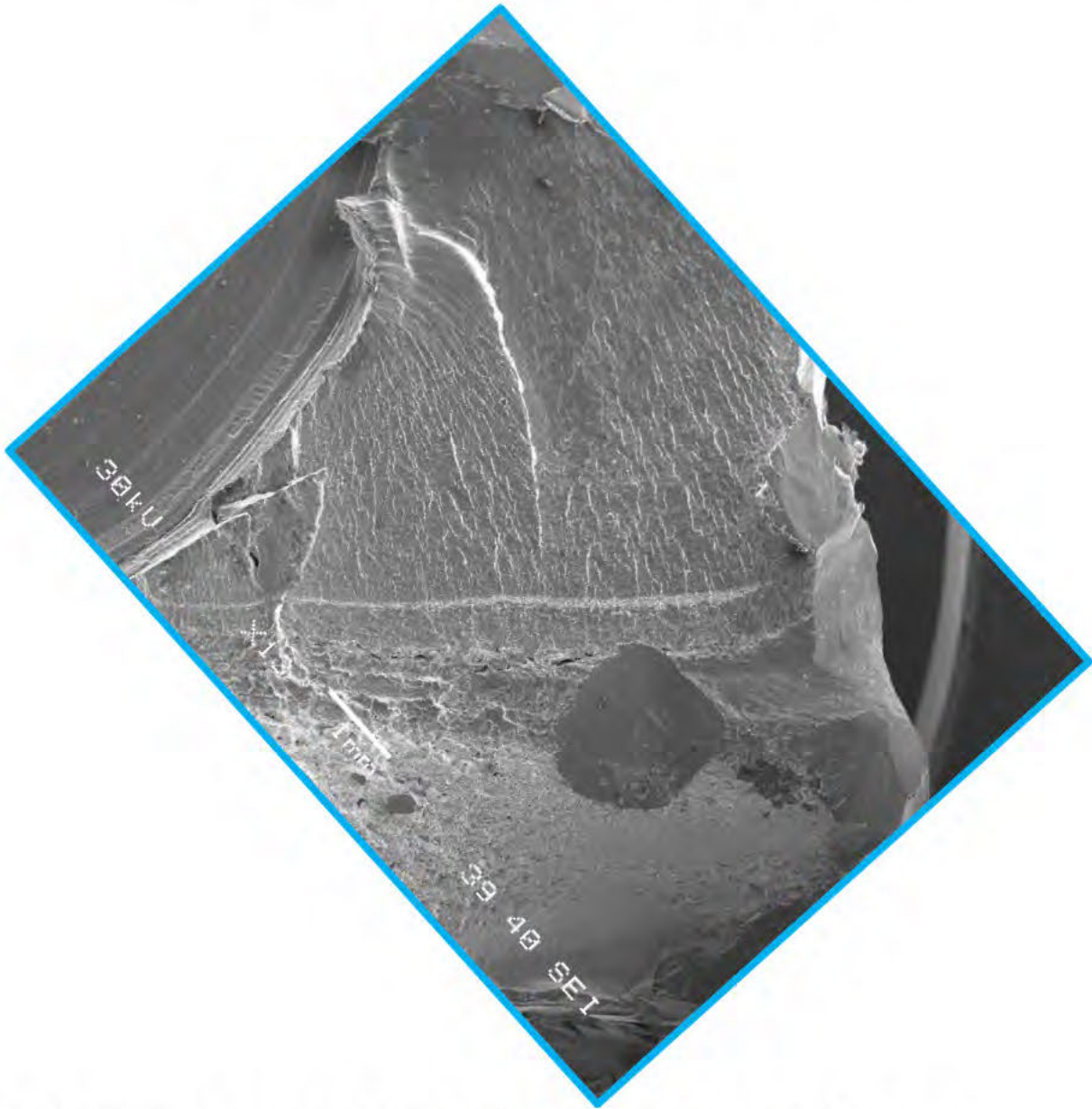


Figure x. SEM micrograph of Piece R. Region shows evidence of fatigue crack growth.

Appendix B: Selected Scanning Electron Micrographs

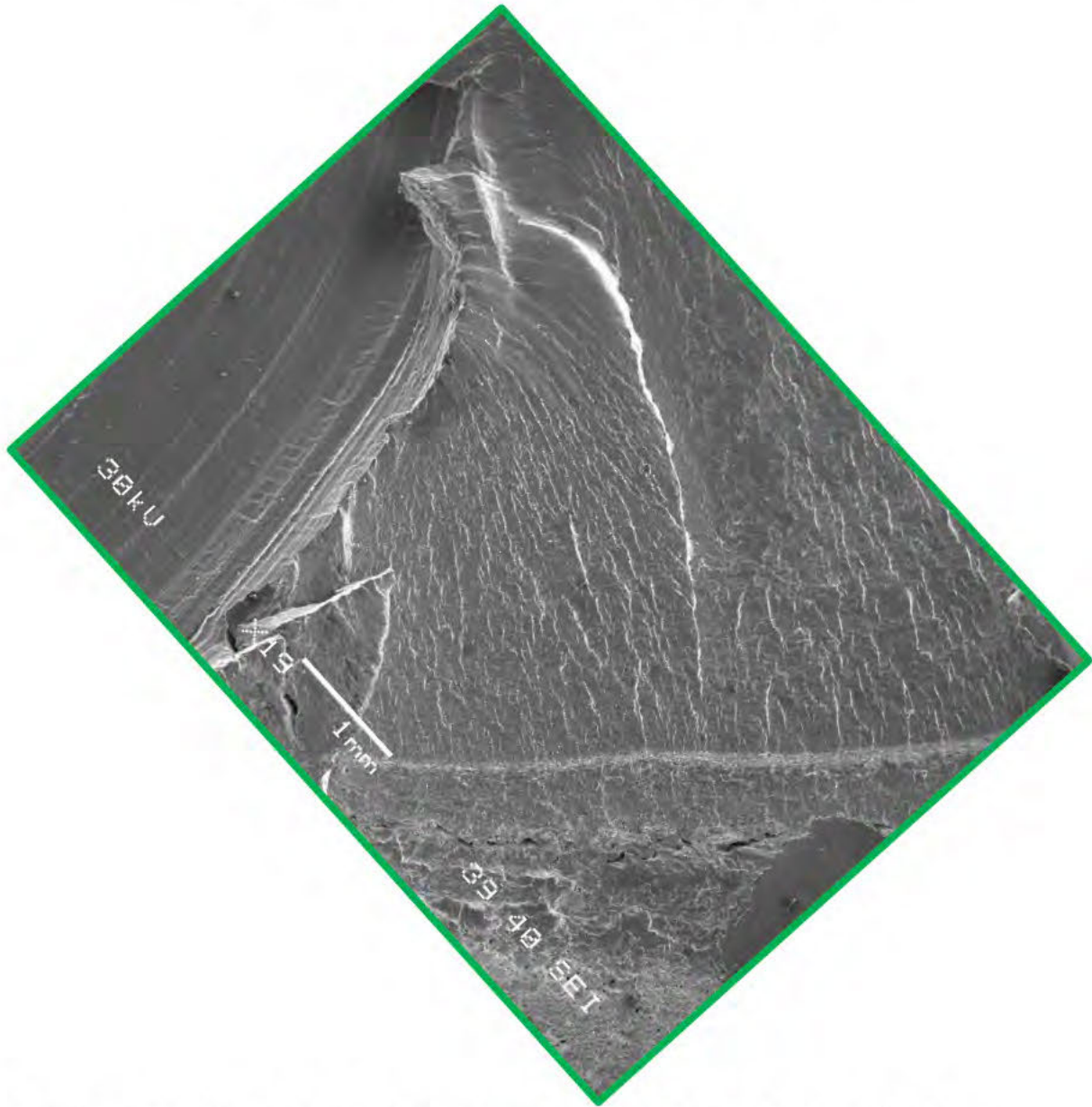


Figure xi. SEM micrograph of Piece R. Region shows evidence of fatigue crack growth.

Appendix B: Selected Scanning Electron Micrographs

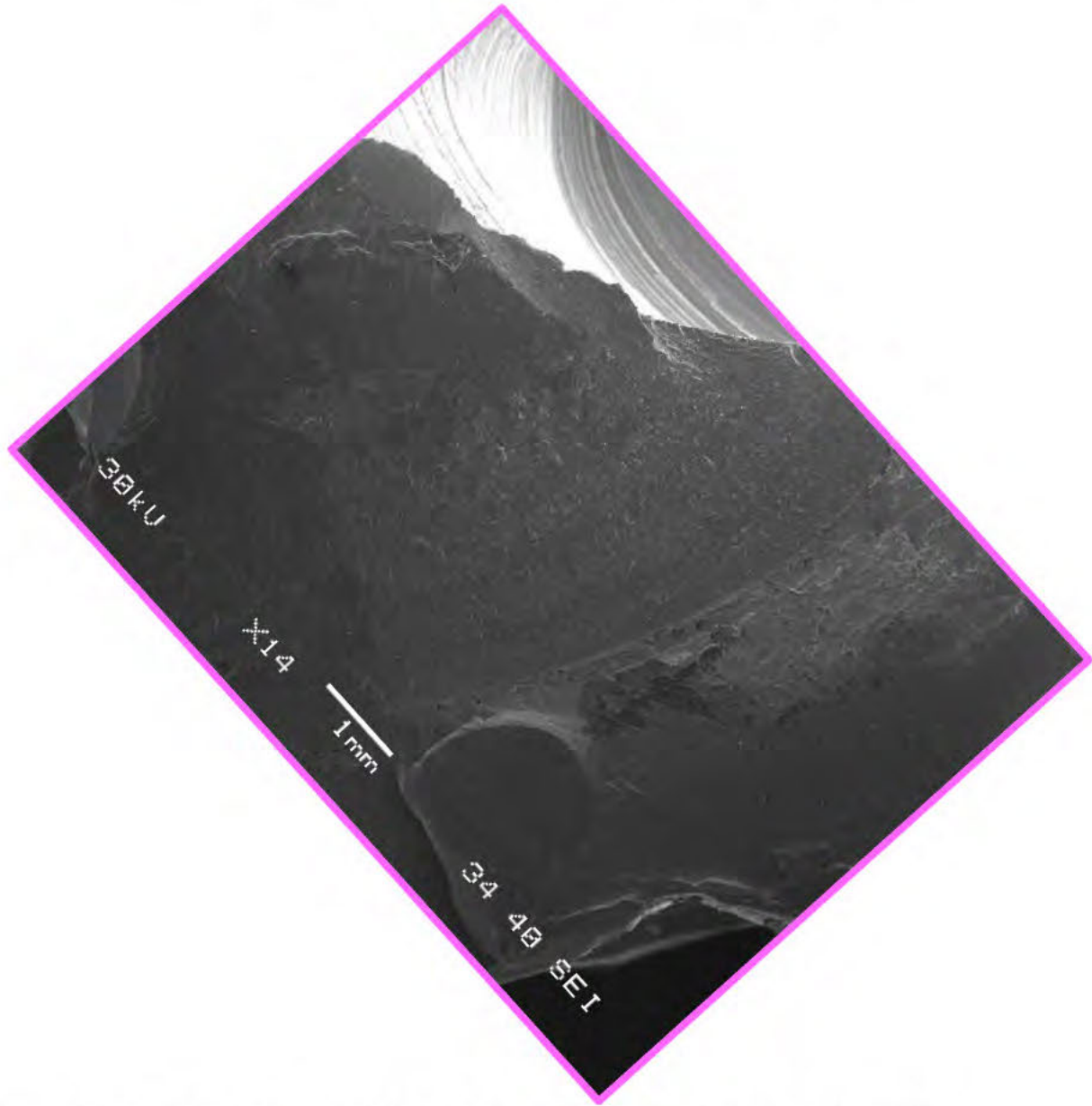


Figure xii. SEM micrograph of Piece R. Region shows evidence of fatigue crack growth.