AH-64 LOSS OF LUBRICATION STUDY

Test of Isotropic Superfinished AH-64 (Apache) Engine Nose Gearbox Without Black Oxide Coating

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Abstract

Rotorcraft gearboxes are designed to the utmost precision to withstand the tremendous demand and loads required to convert thousands of horsepower and RPM into hundreds of RPM and lift torque. The transmission components and the lubricants utilized incorporate various technologies to enable proper function and longevity. Many of these technologies are “tried and true” over the course of hundreds of thousands of flight hours and decades of real flight experience. As a result, replacement of these legacy technologies requires a tremendous amount of testing and qualification. The US Dept. of Defense conducted a loss of lubrication test of an AH-64 Engine Nose Gearbox (ENGB) with Isotropic Superfinished (ISF) gears instead of the legacy black oxide coated gears. The question addressed in this paper is; will the low Ra value generated by Isotropic Superfinishing lead to scuffing, especially if the Black Oxide Coating is eliminated, and to go deeper, will the gearbox survive the mandatory loss of lubrication test requirements, which is a punishing test designed to simulate a realistic failure scenario within the gearbox. Success for this test is demonstrated by the ability of one gearbox to continue to transmit torque for 60 minutes after loss of lubrication, or of two gearboxes to continue to transmit torque for at least 30 minutes each after loss of lubrication. Upon successful completion of the loss of lubrication test, the gearbox was subjected to a detailed tear-down analysis which indicated no discernable damage occurred to the gear teeth.

1. INTRODUCTION

Isotropic Superfinish (ISF*) technology applied to gears has become the benchmark for surface finishing of rotorcraft gearing. The performance benefits are well documented and the list of flight certified new aircraft grows with each passing year. However, incorporation into legacy aircraft fielded by the US Dept. of Defense (DOD) has been delayed due to flight safety concerns related to the extremely low surface roughness values (Ra) generated by the process and the fact that the legacy Black Oxide coating will no longer be applied. The main question to answer is will the low Ra value lead to scuffing, especially if the Black Oxide coating is eliminated, and to go deeper, will the gearbox survive the mandatory loss of lube requirements.

In an effort to implement Isotropic Superfinishing for rotorcraft gears across multiple platforms, the US DOD has funded several studies including qualification testing for the AH-64D and CH47, as well as coupon level loss of lubrication testing of ISF and Black Oxide surfaces[1]. The test described in this paper was proposed by the DOD as the final acceptance requirement.

2. BACKGROUND

2.1. Qualification Testing

Extensive qualification testing by Boeing has been accomplished for both CH-47 and AH-64 transmissions. The testing utilized the normal acceptance testing protocol (ATP), but a loss of lubrication (LOL) test was not conducted during this initial testing. Qualification of ISF gears on the AH-64D was not granted due to concerns that the loss of lubrication capability of the gearboxes could be compromised as a result of the improved surface finish and/or lack of black oxide on the gear teeth after ISF. It was decided to conduct a LOL test on an AH-64D engine gearbox believing this to be the worst case test with respect to scuffing failure of the gear teeth.

2.2. Why LOL?

The push to design rotorcraft drive systems with longer endurance and range capabilities has led to increased focus on improving the loss of lubrication performance of both military and civil aircraft[2]. The loss of lubrication (LOL) test is designed to simulate a realistic failure scenario in

Presented at 44th European Rotorcraft Forum, Delft, The Netherlands, 19-20 September, 2018

which the drive system is deprived of lubrication. This starved lubrication condition leads to scuffing failure. During scuffing failure, increased frictional heating and thermal runaway eventually cause plastic deformation of the transmission components and loss of torque[3]. Engine performance and temperature are monitored during an LOL test to evaluate the stability of the system during the oil out event. Wear conditions of the transmission components are also evaluated at the end of the test. Wear or damage to the components would indicate an increased risk of mechanical failure during an in-flight LOL event[4].

2.3. ISF vs. Black Oxide

Black Oxide is applied in hot baths of sodium hydroxide, nitrates and nitrites. This chemical mixture converts the surface of the gear into magnetite (Fe_3O_4) by bonding chemically to the surface of the metal and creating a porous base layer. Oil is then applied to the heated part to seal the surface as it works its way into the porous layer. This oil retention property is what imparts Black Oxide's main benefit, corrosion resistance, and it is also thought to extend scuffing resistance under extreme conditions such as a loss of lubrication event.

In contrast to Black Oxide, Isotropic Superfinishing (ISF) is not a coating; it is a finishing technique that utilizes vibratory machines, high-density, non-abrasive ceramic media, and a process chemistry to achieve an extremely low roughness surface. The resulting surface has a microtexture that is free of peaks and asperities, with shallow valleys to facilitate lubrication. This finish has demonstrated improvements in performance including: scuffing resistance, corrosion resistance, part durability, reduced friction, and reduced wear. Additionally, coupon testing utilizing a ball-on-disc tribometer suggests that ISF gears would last longer than traditional black oxide coated gears during a loss of lubrication event[1].

3. LOL TEST PLAN

The test plan was designed to duplicate as closely as possible the original LOL qualification test successfully conducted in 1981 and detailed in the US Army Aeronautical Design Standard ADS-50 (Rotorcraft Propulsion Performance and Qualification Requirements and Guidelines for Rotorcraft Drive Systems)[5]. As referenced above, success for this test is demonstrated by the ability of one gearbox to continue to transmit torque for 60 minutes after loss of lubrication, or of two gearboxes to continue to transmit torque for at least 30 minutes each after loss of lubrication. This is required by ADS-50-PRF-5-4.3.5 for the purpose of designing an aircraft that can sustain flight for an emergency landing in the event of an improperly lubed gearbox.

3.1. Isotropic Superfinishing

ENGB Input Pinion (7-211320021-9, SN 1074), and ENGB Output Gear (PN 7-311320092, SN 00286-5389) were used for the LOL testing. These gears were first ISF processed by REM Surface Engineering for the qualification testing. The gears were run through a cleaning cycle to remove the black oxide coating, then they were ISF processed to a surface finish of Ra ≤ 4 µin on the gear teeth, followed by a neutralizing/burnish cycle. After qualification testing, the gears were placed in storage at the Aviation Missile Research Development Engineering Center's (AMRDEC) Storage Analysis Failure Reclamation (SAFR) facility. They were sent back to REM in 2016 for a short clean-up cycle after being deemed acceptable by AMRDEC for use in the LOL test. The start condition of gears with black oxide coating and test condition after ISF processing is shown in Figures 1-4.

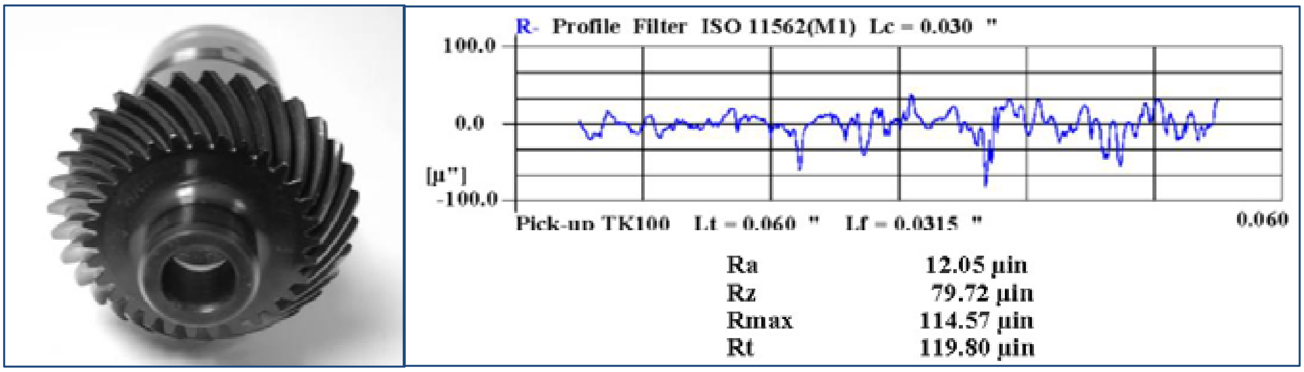

Figure 1. START CONDITION, Image and gear tooth surface roughness measurement of black oxide coated input pinion 7-211320021-9 SN 1074.

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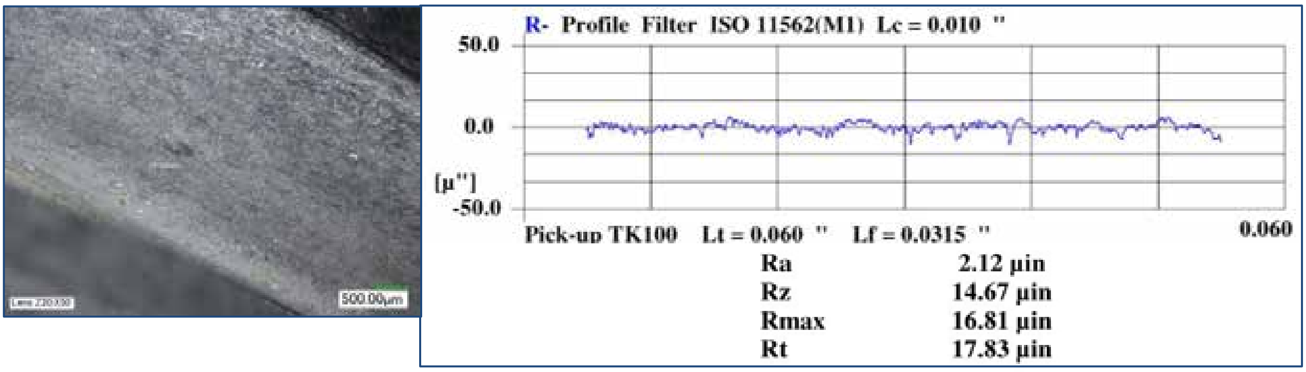

Figure 2. TEST CONDITION, Gear tooth image at 50x magnification and surface roughness measurement of ISF processed input pinion 7-211320021-9 SN 1074 used for LOL test.

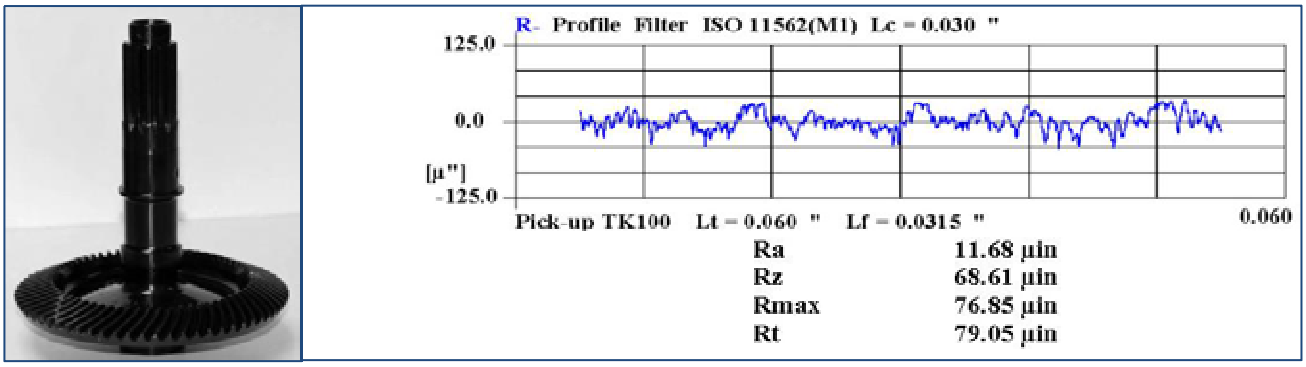

Figure 3. START CONDITION, Image and gear tooth surface roughness measurement of black oxide coated output gear 7-311320092 SN 00286-5389.

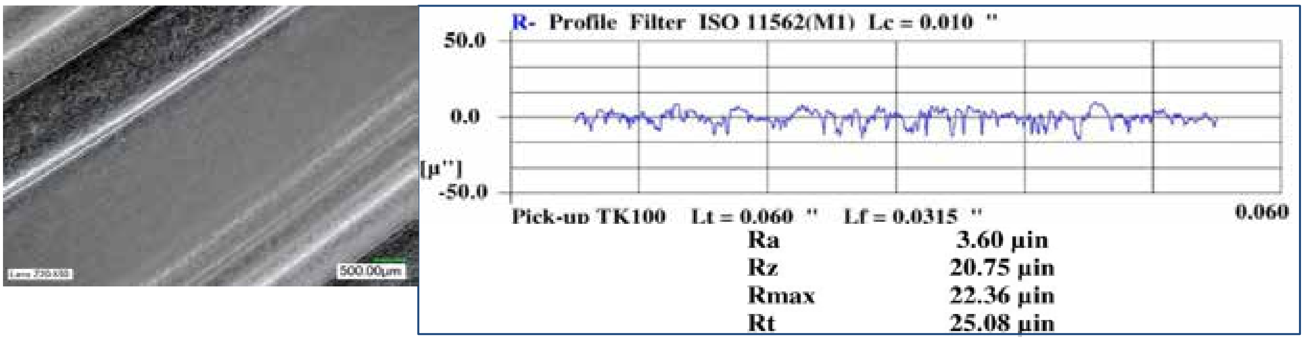

Figure 4. TEST CONDITION, Gear tooth image at 50x magnification and surface roughness measurement of ISF processed output gear 7-311320092 SN 00286-5389 used for LOL test.

3.2. Test Configuration

The test was conducted at Naval Air Warfare Helicopter Drive Systems Test Facility (HeDS) Center in Patuxent River, Maryland on May 11, 2017. The Naval Air Systems Command Propulsion and Power Department (AIR 4.4) provided test facilities, installed the test articles into the HeDS Test Facility, and conducted the loss of lubricant test on a test article Engine Nose Gearbox with ISF gears. An Apache configured test stand was created by AIR 4.4.6 to be used in the HeDS facility. For this test, the Apache drive system consisted only of a main gearbox (MGB), two ENGBs, and two T700-701C engines. There was no shafting coming out of the aft of the MGB, and no intermediate gearbox (IGB) or tail gearbox (TGB). Only the starboard ENGB (right hand) was used as a test article (P/N: 7-311320001-16, S/N: A14-0509), and the test article was installed after a check out run was performed with a legacy starboard ENGB with black oxide gears. To simulate forward flight, a Dayton Motor Model 4C330 blower (rated for 1319 ~ 1741 CFM) was installed that blew air across the starboard ENGB through a 6" diameter hose (a blower-hose combination had also been used on the previous ENGB loss of lube test). The lubricant used during the evaluation was MIL-PRF0-23699.

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A 40 minute check out run with the legacy starboard ENGB provided the baseline expectation of test conditions. After the shakedown and checkout testing, a few deviations were made to the original plan. It was determined that one engine would be the best course of action instead of the planned two. The second engine was disconnected from the Main Gearbox (MGB) leaving all input running through only the test engine nose gearbox. It was also determined that the engine should be run in ECU lockout mode to disable RPM (Np) governing, which was causing oscillations at flight speeds. ECU lockout mode locks out the electrical control unit (ECU) from all control/limiting functions except Np over-speed protection, which remains operational. This method was shown to be the only effective way to maintain consistent torque and engine speed. An over-speed safety with limit of 22,500 RPM was implemented as an extra layer of precaution while in ECU lockout operation. Lastly, the AH64 static mast and rotor hub sub-assembly was incorporated into the stand to eliminate an unacceptable amount of wobble in the main facility shaft. This orientation was able to achieve flight speed with acceptable amounts of shaft wobble.

3.3 Test Procedure

Engine temperatures, torque, rpm, and vibrations were closely monitored during the test. A thermal imaging camera mounted in front of the test article was used for infrared (IR) monitoring of the input triplex bearing, output triplex bearing, and ENGB housing. The system would be shut down upon loss of drive, above limit vibration, rapid increase in engine torque, or after 60 minutes of operation.

Upon coming to flight speed, the engine was held as close to 20,952 Np RPM and 188 ft-lbs of torque as possible. Once stable oil temperatures were achieved, the oil was drained. Upon verification of low oil as indicated by the sump oil pressure switch, the 60 minute clock was started on the loss of lube test. The ENGB temperatures were monitored throughout the test. The engine operated continuously at approximately 188 ft-lbs. input torque for 60 minutes after loss of lube.

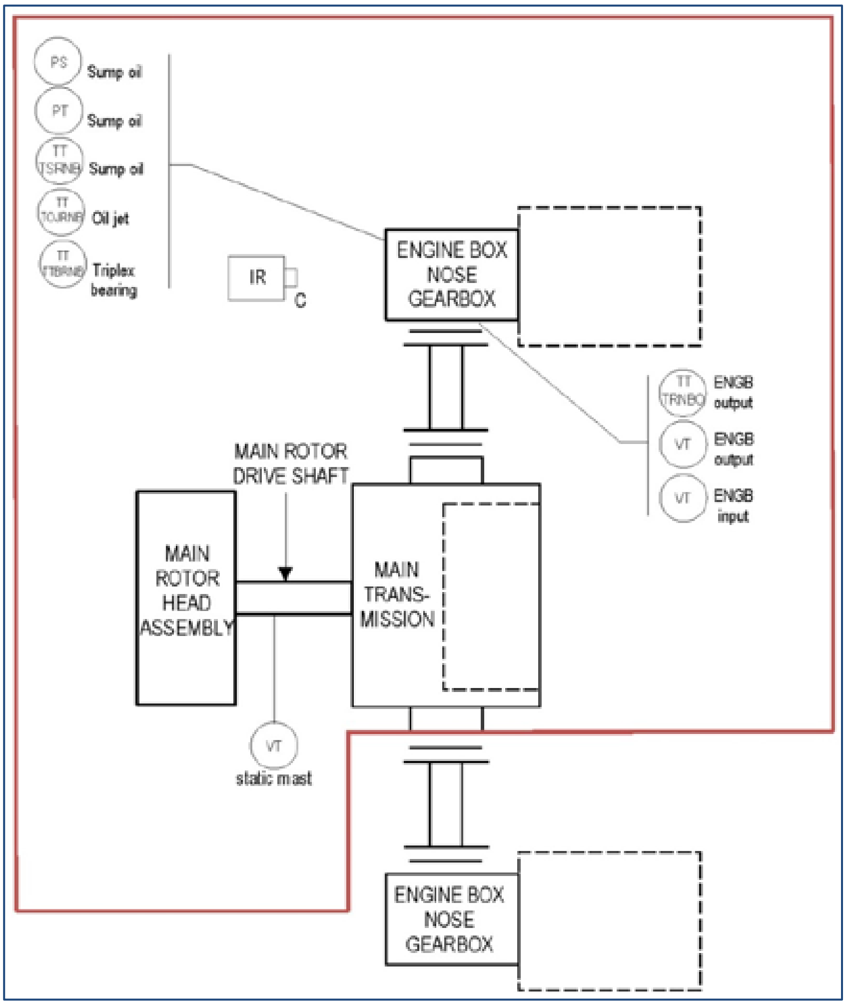

Figure 5. Schematic of the AH-64 Apache drive system components and key instrumentation used during the test.

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Figure 6. AH64 Apache Test Stand as configured for the LOL test.

Figure 7. Front view of the Engine Nose Gearbox used in the LOL test.

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4. RESULTS AND ANALYSIS

At the conclusion of the test, the remaining oil was collected from the gearbox (400 mL). Samples of this drained oil were analyzed at the Naval Air Warfare Fuels and Lubricants Chemistry Laboratory. The ICP-AES analysis showed no metal content in the 400 mL of oil that remained in the ENGB during the LOL event. A final test report was generated by AIR 4.4.

The Np vs. Torque plot shows the stability with which the operators were able to maintain Np RPM and torque load on the engine while in ECU lockout. For comparison, the baseline 40 minute checkout run (legacy black-oxide gears) and the 60 minute LOL test run (ISF gears) are shown in Fig. 8 and 9. Though there were minor variations in the Np speed and engine torque, the trend was stable during the 60 minute test run.

The temperature readings and IR images of the ENGB during the checkout run and LOL test are shown in Fig. 12 - 15. For the checkout run, the parameter TRNBO reads room temperature. This is because it was not installed for the checkout run. All other parameters show what to expect when oil is flowing in the gearbox. For the LOL test, the ENGB temperatures were monitored by thermocouples attached to the surface of the gearbox. An approximate 5 psi oil pressure was indicated throughout the test. After an initial drop in temperature upon loss of lubrication, the ENGB temperatures steadied out and remained stable during the 60 minute test. The IR images confirm the thermocouple results.

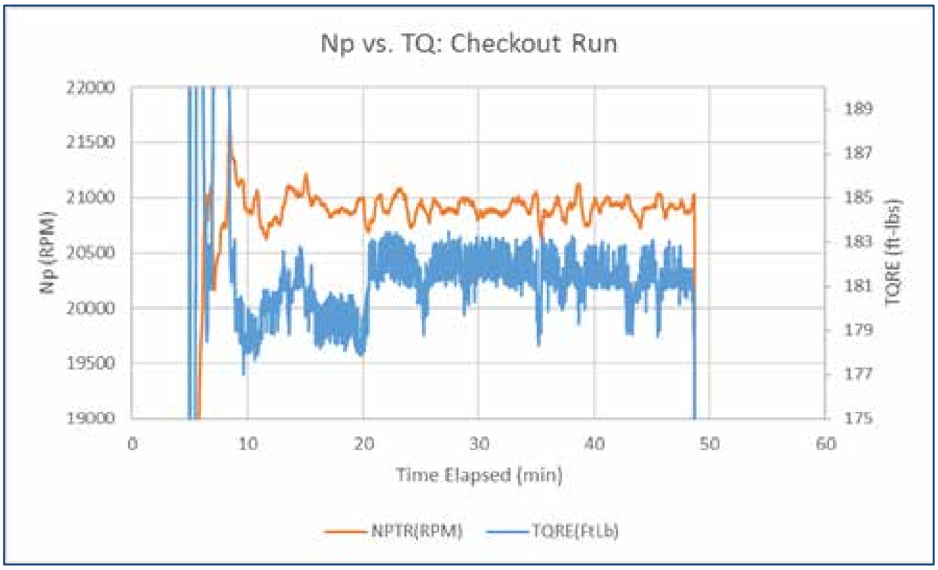

Figure 8. CHECKOUT RUN, Np RPM vs. Torque load on the engine.

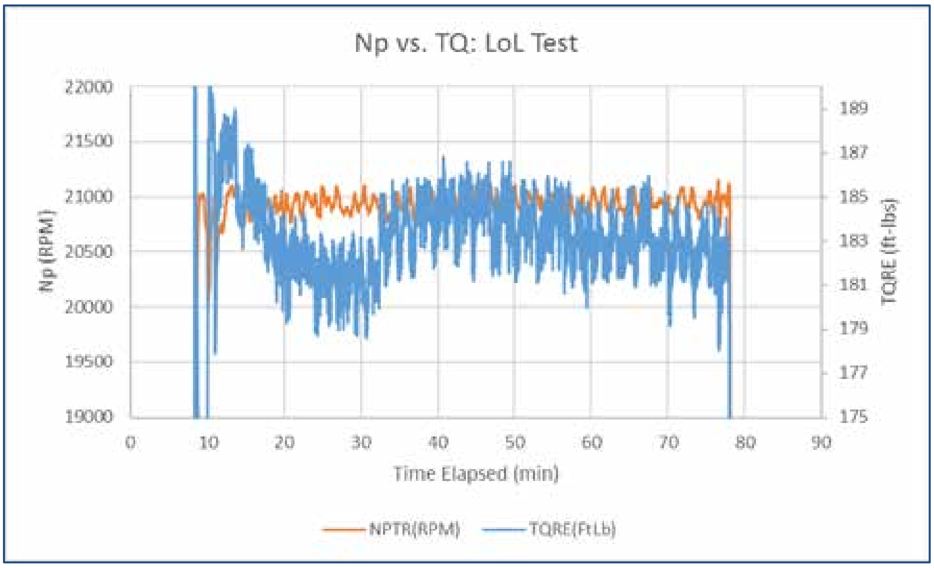

Figure 9. LOL TEST RUN, Np RPM vs. Torque load on the engine.

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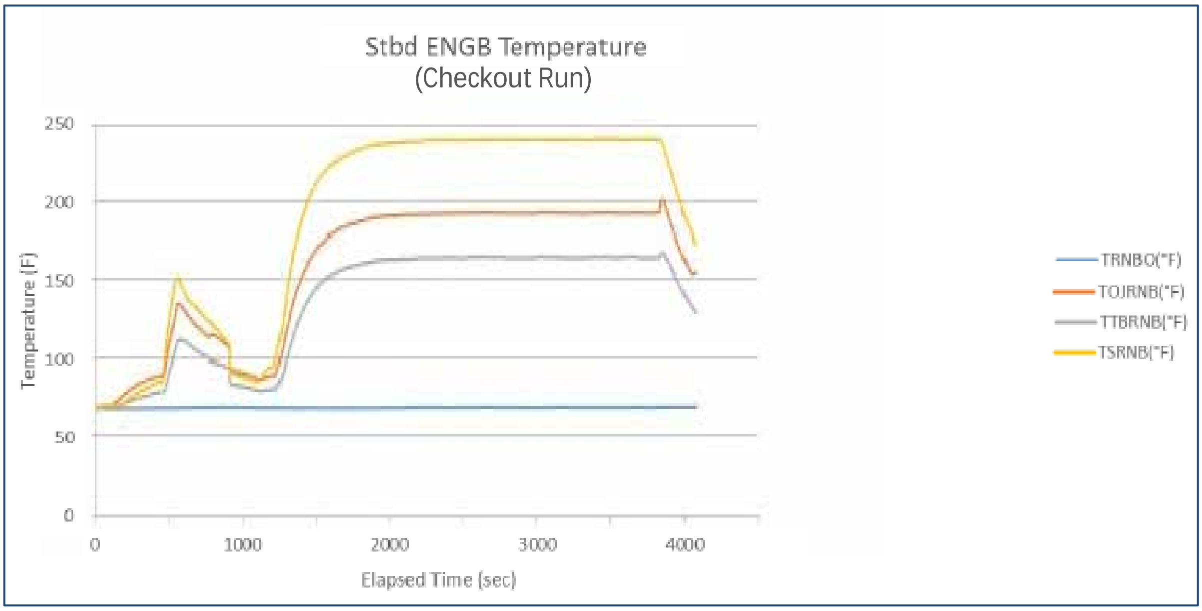

Figure 10. CHECKOUT RUN, ENGB temperatures (TRNBO was not installed for this run).

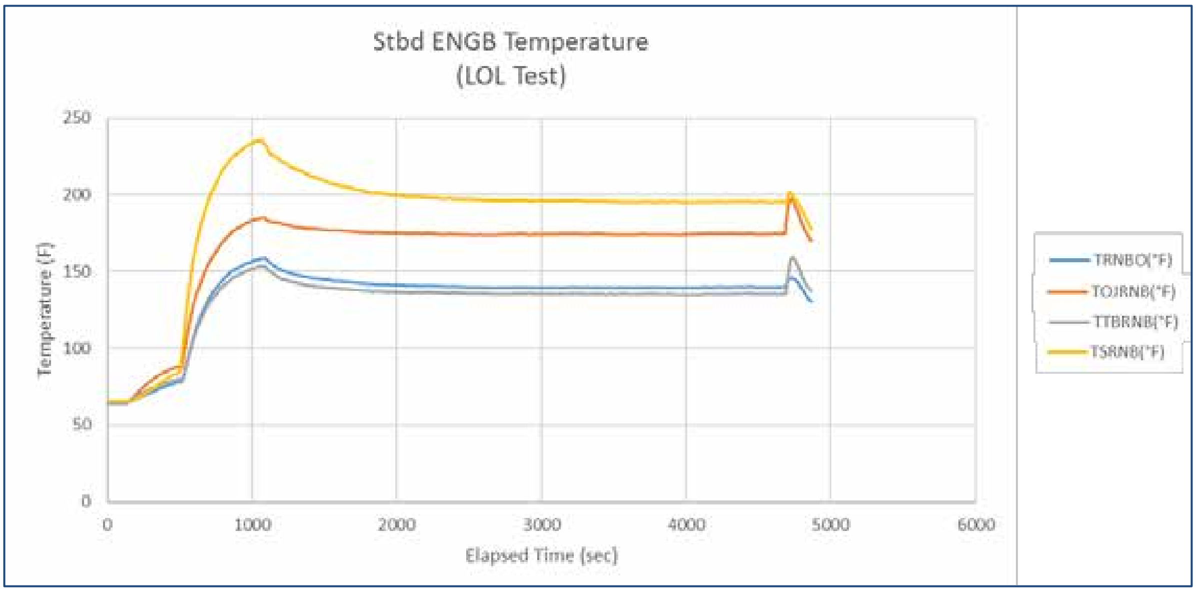

Figure 11. LOL TEST RUN, ENGB temperature

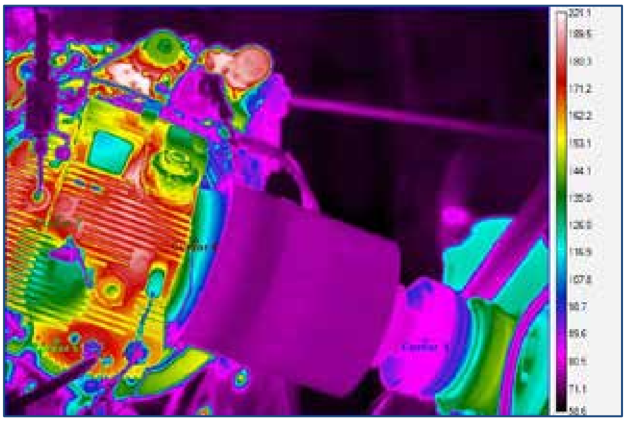

Figure 12. IR Image with oil, 5 minutes before oil was dumped.

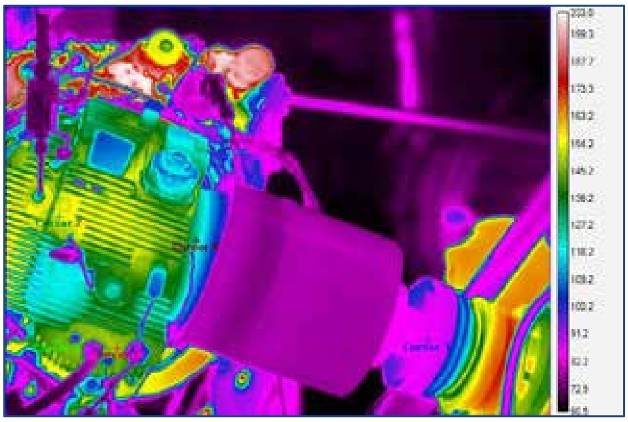

Figure 13. IR image without oil, 40 minutes after oil was dumped.

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4.1. Tear-down Analysis (TDA)

AIR 4.4 shipped the test article and data back to the Army for post-test analysis at Redstone Testing Center (RTC). There, the gearbox was disassembled and inspected. The gear teeth showed no evidence of any distress (scuffing, pitting, heat related damage, etc.) on either the pinion or the gear. There was also no distress discovered on any of the gearbox bearings.

The pre-test and post-test backlash and surface roughness measurements are given in the table below. The measurements are consistent with the visible inspection, showing the surface finish and gear backlash remained basically unaffected. Additionally, no distress was discovered on any of the gearbox bearings.

Table 1. Pre-Test and Post-Test Measurement Results

Parameter	Pre-Test	Post Test
Backlash	0.024 in	0.031 in
Input Pinion Surface Roughness (Ra)	2 µin	2 µin
Output Gear Surface Roughness (Ra)	3-4 µin	3-5 µin

Figure 14. Input Pinion

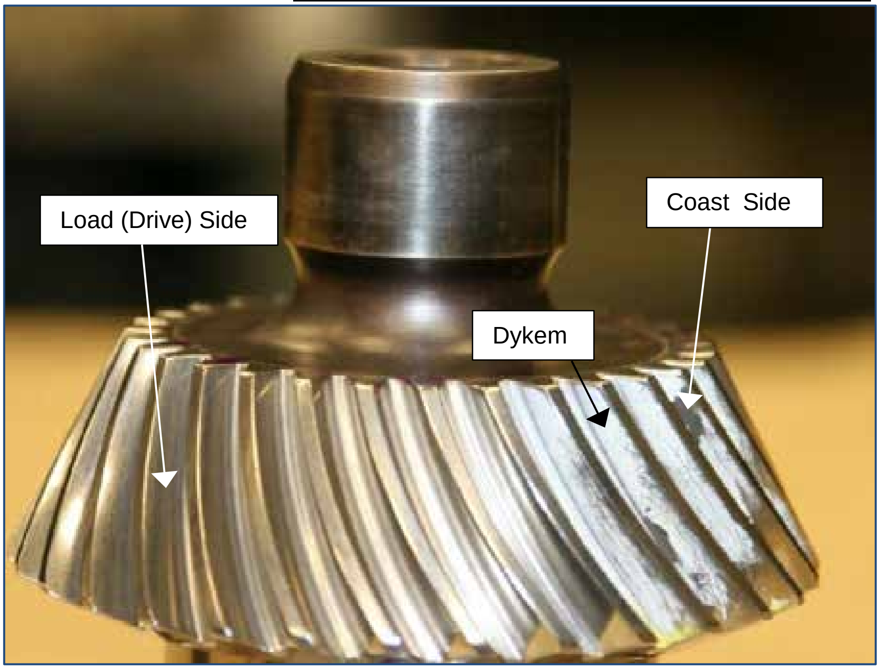

Figure 15. Input Pinion Teeth (Dykem coating was applied for patterns)

Figure 16. Output Gear

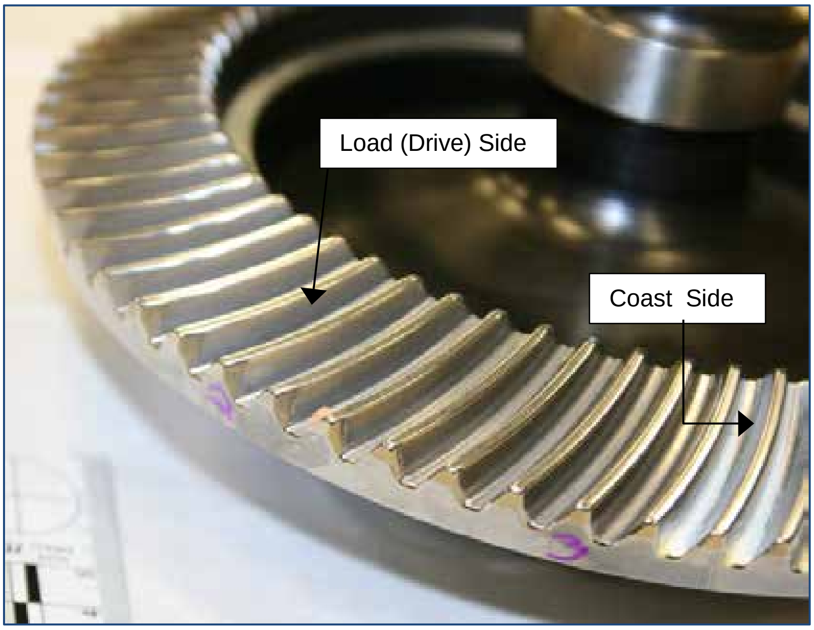

Figure 17. Output Gear Teeth

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5. CONCLUSION

From the test data, it can be seen that the ENGB with ISF gears showed no signs of distress during the 60 minute loss of lube test. Within the scope of this test, temperatures, bearing temperatures, and vibration levels were all within normal operating limits. The only indication that lubrication was lost was the low oil pressure light, low oil pressure, and lower than normal ENGB temperatures. No other limits were exceeded during the 60 minute run.

The engine nose gearbox with ISF gears without black oxide satisfied the loss of lubrication requirement by continuing to transmit the applied torque for the duration of the 60 minute test. The gears performed equally as well with respect to surface degradation as the gears from the 1981 loss of lubricant test. The test demonstrated that ISF gears without black oxide do not degrade loss of lubrication performance and thus, there is no airworthiness impact associated with ISF AH-64D gears. These results are analogous to the coupon level testing performed by the Army Research Lab (ARL), which actually showed ISF coupons to perform better than as-ground and black oxide coated coupons in simulated loss of lubrication tests.

6. REFERENCES

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