NASA/TM—2005-213957 ARL–TR–3159

A Study of Spur Gears Lubricated With Grease-Observations From Seven Experiments

Timothy L. Krantz and Robert F. Handschuh
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

September 2005

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2005-213957 ARL–TR–3159

A Study of Spur Gears Lubricated With Grease-Observations From Seven Experiments

Timothy L. Krantz and Robert F. Handschuh
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Prepared for the
58th Meeting of the Society for Machinery Failure Prevention Technology (MFPT)
cosponsored by ONR, NASA, ARL, NAWC, and NSWC
Virginia Beach, Virginia, April 26–30, 2004

National Aeronautics and
Space Administration

Glenn Research Center

September 2005

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

A Study of Spur Gears Lubricated With Grease-Observations From Seven Experiments

Timothy L. Krantz and Robert F. Handschuh
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio 44135

Abstract

To improve understanding of gears operating with a perfluoro type space-qualified grease, seven spur gear experiments were performed. Test conditions were selected to study the influences of torque, lubricant type, and atmosphere. Two testing torques provided nominal pitch-line Hertz stresses greater and lesser than the contact stress limit as recommended by the grease manufacturer. As was expected, all tests resulted in some gear tooth wear. Discoloration of the perfluoro type grease occurred for all tests. Tests in dry nitrogen produced some dark-grey colored perfluoro type grease. Testing in either ambient or dry air produced red debris after short test duration, and for tests of longer duration large amounts of red debris, red grease, and wear were evident. Tests using higher torques produced more debris. The first indications of discoloration occurred more quickly with higher test torques. Total amounts of wear were quite significant, up to four times the profile tolerance for AGMA Class 10 gears.

Introduction

Perfluoro type greases are in use for many space applications including the rudder speed brake actuator gearboxes for space shuttle orbiters. Discussions in support of orbiter actuator gearbox maintenance have highlighted the need for data to better understand the behavior of mechanical components operated using a perfluoro type grease. To develop some needed data and understanding, seven spur gear experiments were completed. The purposes of the experiments were to: (1) develop a test protocol for testing of grease lubricated gears, and (2) to record and document observations to support decisions concerning the maintenance of actuator gearboxes.

Test Rig

The experiments were conducted using the NASA Glenn Research Center Spur Gear Fatigue Test Rigs. These test rigs have been used for more than 30 years to test oil lubricated spur gears, with emphasis on studying contact fatigue (spalling, pitting, and micropitting). The test rig as shown in Figure 1(a) uses the four-square (torque-regenerative) principle of applying test loads, and thus the motor needs to overcome only the frictional losses in the system. The test rig is belt driven using a variable speed electric motor with a belt and pulley system. A schematic of the loading apparatus is shown in Figure 1(b). Hydraulic oil pressure and leakage replacement flow is supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes located inside one of the slave gears, torque is applied to its shaft. This torque is transmitted through the test gears and back to the slave gears. In this way power is circulated, and the desired load and corresponding stress level on the test gear teeth may be obtained by adjusting the hydraulic pressure.

Figure 1 depicts the spur gear rig as has been used for tests operated at 10,000 rpm for the purpose of evaluating the fatigue lives of oil lubricated gears. The test setup as used for the grease tests reported herein differed from the depiction of Figure 1 in two important ways. Figure 1 illustrates the test gears operating with faces offset. The face-offset condition is used to concentrate the Hertz contact stress as is desired for accelerated life testing of high cycle fatigue. For the grease lubricated gear testing, the gears were operated with zero offset (full faces in contact with each other). Also, Figure 1 depicts pressurized labyrinth seals on the two shafts. For the grease testing reported herein, lip seals were used on the two shafts to prevent leakage of the slave gear lubricating oil to the grease lubricated test gear section. The lip seals have used with much success on these rigs to maintain zero-leakage even for speeds of 10,000 rpm. Testing reported herein was done at speeds no greater than 705 rpm.

Test Gears and Lubricants

The test gears used for these experiments were a set of spur gears made from case-carburized AISI 9310 steel. By chemical analysis, the proper alloy content was verified. The gear geometry is 8 pitch, 20° pressure angle, 28 teeth, standard tooth proportion, a 3.5 in. pitch diameter, and AGMA class 11 tolerances. The measured tooth profiles are pure involutes (no designed tip relief), and the teeth have lead crowning of about 0.0005 in. height across the nominal 0.250 in. face width. The primary test lubricant used was from a single cartridge of grade 2 perfluoro type grease. One test was completed using a hydrocarbon-based grade 2 grease. One test was completed with no lubricant on the test gears.

Test Procedures and Operating Conditions

The test gears were cleaned prior to installation of the test rig. The cleaning procedure for all gears was ultrasonic cleaning using alcohol for 5 min. minimum, immediate blow dry with air, installation on the test rig, and application of the test grease. For tests three to six, the test gears were first subjected to a mild glass bead cleaning (cleaning equipment set to 20 psi supply pressure) just prior to ultrasonic cleaning in alcohol.

Table 1 provides the operating conditions for the seven tests. Note, for example, that test one and test two made use of the same pair of gears. The “setup” column of Table 2 documents whether the gears were installed with etched serial numbers facing the back (A) or front (B) of the test rig. Each test began with new tooth surfaces (using both sides of the teeth). For the case of gears used for more than one test, the gears were cleaned using the ultrasonic cleaning procedure after the first and before the second test.

Tests 1, 2, 6, and 7 were conducted with a cover attached, and ports were open to ambient air. Tests 3 and 4 were conducted with a cover attached and a flow of dry nitrogen into the test chamber. Test 5 was conducted with a flow of dry air into the test chamber. Nitrogen and air flows were supplied by a central laboratory supply. The gas flowed through a desiccant before entering the chamber to ensure a dry atmosphere. The air supply was filtered using a new 45 μm rated filter element. The gas flow entered the test chamber by a tube directed at the gear teeth. Gas flow leaving the test chamber flowed through a beaker containing water, and the bubbling of the water in the beaker provided visual indication of positive gas flow for the duration of the test. The gas flowed for 30 min. minimum to purge the test chamber of ambient air and moisture before operating the gears.

All testing was done at a constant load and speed for the duration of a particular test. However, speeds and loads varied from test to test (per Table 2) since test protocol and procedures were being developed as part of the testing objectives. Test speed and loads were selected to provide tribological conditions similar to the rudder speed brake actuator gearing, but further analysis is required to understand how closely these test conditions relate to actual actuator operation.

Test Results and Observations

Testing results will be presented in manner to facilitate understanding, and the order is not necessarily the chronological order of testing. Five gear tests were completed using perfluoro type grease, one test was completed using a hydrocarbon-based grease, and one test was completed using no lubricant. Two test conditions were adjusted to investigate effects of the operating condition: (1) the testing torque (a low torque level, and a high torque level) and (2) the atmosphere in the test chamber (ambient air, dry nitrogen flow, or dry air flow). The maximum Hertz contact stress pressure on the gear teeth surfaces corresponding to the two test torques were estimated using a nominal 0.0005 in. lead crown and considering gears operating at the pitch-point position. Using this approximation as a load index, the lower test torque of 2 ft-lb resulted in a peak pitch-line Hertz stress index of about 90 ksi. The higher test torque of 5 ft-lb resulted in a peak pitch-line Hertz stress index of about 120 ksi. The manufacturer of the perfluoro type grease suggests limiting the use of this grease to applications having less than 100 ksi Hertz stress.

The first grease test was conducted at 5 ft-lb of torque, ambient air, and a speed of 515 rpm. Red colored debris was present after 1 hr of operation. Figure 2 documents the appearance of the test hardware after 3 hr of operation. Significant wear was observed, and the grease and contact areas of the gears have a red color. The test was then run an additional 26 hr unattended. The total test duration in terms of shaft revolutions was 927,000. At the completion of the test, a significant amount of red "dust" covered the test chamber, shafts, and gear teeth sides (Fig. 3). The grease was discolored, including some red colored grease. It is not known at this time if the red grease samples contain red colored wear debris or if the red color also indicates some chemical breakdown of the grease. Grease samples were collected and stored for post-test evaluations.

Profilometer inspections of a gear tooth made in the profile direction both before and after test number 1 revealed significant wear of the tooth surface (Fig. 4(a)). By overlaying the tooth traces to match-up the profiles in non-contacting areas and then subtracting the tested profile from the new profile, wear as a function of position along the tooth profile was determined (Fig. 4(b)). Maximum wear depths occurred in the dedendum (root region) below the pitch line, and wear depth amounts were on the order of 50 µm (0.002 in.). The measured wear depth is quite significant, about four times the tolerance for the profile for an AGMA (American Gear Manufacturer's Association) class 10 gear of this size.

Profilometer inspections of gear teeth were also made in the lead direction (across the tooth face). Before testing, gear tooth surfaces were all of a crowned, convex shape in the lead direction (Fig. 5(a)). Measurements of mating gear teeth after testing revealed that the convex shape of the mating gear's tooth tip region has worn a concave shape into the root region of the driving gear (Fig. 5(b)). It is also of significance that the worn surfaces are much rougher than the original ground gear surfaces. The increased roughness will promote higher wear rates and will tend to increase vibration.

The second perfluoro type grease lubricated gear test was conducted at 2 ft-lb of torque (less torque than test number 1) and in ambient air. The test was run with shaft speed of 200 rpm. To provide a more complete evaluation of test progression, the testing was temporarily stopped after 15, 30, and 60 min. of cumulative testing time. When the test was stopped temporarily, the cover was removed for close inspections of the working tooth surfaces. Inspections after the 15 and 30 min. test durations revealed only the appearance of the expected contact patterns. No discolored debris or grease was observed. However, at the completion of 60 min. total test duration, the centers of contact patterns of the working surfaces of some teeth had some red colored areas. Most of the grease still had the original white color at that time. The test was then restarted and run for an addition 15 hr unattended. At completion of 194,000 shaft revolutions, the test was stopped. A significant amount of red debris and red colored grease was present at the end of the test (Fig. 6).

The two tests conducted using perfluoro type grease and ambient air environment suggests that wear debris is created rather quickly even for mild load conditions. It is probable that the red colored dust is oxidized wear debris that was introduced to the air. The colored grease might be due either to the oxidized wear debris becoming trapped in the grease, or due to a breakdown of the grease itself producing by-products, or due to both events. Post-test evaluations of collected grease samples should clarify the end-of-test condition.

The third perfluoro type grease lubricated gear test was conducted to closely match the speed and torque of grease test number 2 (the test described above). However, for this test the chamber contained a dry nitrogen atmosphere. The "Test Procedure and Operating Conditions" section of this report describes the manner for introducing flows of dry gas. The test was not stopped for close inspections of the teeth to avoid introducing air and moisture into the test chamber. Neither red colored wear debris, nor red colored grease was generated during this third test. The duration of the test was 18.5 hr and comprised 238,000 shaft revolutions, somewhat longer than the equivalent test done in ambient air. The gear contact patterns reveal that, as expected, some wear occurred during this test number 3 (Fig. 7). Some grey grease streaks were observed on the tips of some of the gear teeth after completion of the tests. The composition of the grey streaks is not known at this time.

The fourth perfluoro type grease lubricated gear test was conducted to closely match the speed and torque of grease test number 1. However, for this test the chamber contained a dry nitrogen atmosphere. The test torque was the higher of the two test torques (5 ft-lb). Once again, the test was not stopped for occasional close inspection of the teeth to avoid introducing air and moisture into the test chamber. The total test duration was 16 hr and comprised 205,000 shaft revolutions. At the end of the test there was a mixture of original white and dark-grey colored grease (Fig. 8). The grey colored grease tended to be collected in the roots of the driven gear and towards the tips of the driving gear, suggesting that the dark color is due to wear debris that has been pushed to the end of tooth contact. At this time, it is not known if the discoloration is only due to wear debris, chemical degradation of the grease, physical separation of oil and grease base, or some combination of these phenomena.

The fifth perfluoro type grease lubricated gear test was conducted to closely match the speed and torque of grease test number 4 (the test just described in preceding text). The test torque was the higher of the two test torques (5 ft-lb). For this test the chamber contained a dry air atmosphere while for the previous test the chamber contained a dry nitrogen atmosphere. The "Test Procedure and Operating Conditions" section of this report describes the manner for introducing flows of dry gas. The test chamber cover was not removed for the duration of the test to avoid introducing moisture into the test atmosphere. The front cover of the test chamber was a clear plate that permitted observation of the gear teeth. The test was stopped temporarily after 2 hr of cumulative testing time, and red deposits were observed on the working surfaces of the teeth. After the completion of 16 hr (210,000 shaft revolutions) the gears had a significant amount of discolored grease including red deposits and red grease (Fig. 9). At this time, it is not known if the discoloration is only due to wear debris, chemical degradation of the grease, physical separation of oil and grease base, or some combination of these phenomena.

To provide a baseline for comparison, one gear test was conducted using a hydrocarbon-based grease. The grease was grade 2 (selected to match the grade of the perfluoro type grease) and described as appropriate for wheel bearings. The test chamber atmosphere was ambient air, and the test load and speed were chosen to provide direct comparison to grease test number 2. A test duration of 1 hr was selected since red coloring within the tooth contact patterns was observed after 1 hr of testing with the perfluoro type grease. After the 1 hr test comprising 13,000 shaft revolutions, red deposits were found on all of the gear teeth contact areas (Fig. 10). Any differences in wear rates or composition of wear debris (as compared to operation with perfluoro type grease) will require further inspections and analysis.

To provide another baseline for comparison, one gear test was conducted using no lubricant on the test gears. The atmosphere was ambient air. The running speed was somewhat higher than for the other testing. The test was conducted for 1 hr comprising 42,000 shaft revolutions. As was expected, wear of the teeth occurred, and red colored wear debris was present at the end of the test (Fig. 11).

Summary

Seven grease lubricated gear tests were completed using spur gears. Tests were done using two testing torque levels, with differing atmosphere (ambient air, dry nitrogen flow, dry air flow), and with differing lubricant types (perfluoro type grade 2 grease, hydrocarbon based grade 2 grease, no lubricant). The two testing torque levels (2 and 5 ft-lb) provided nominal pitch-line Hertz stresses somewhat above and somewhat below the limit for the grease as recommended by the manufacturer. Further post-test analysis is needed to determine the composition of discolored grease. Further analysis is also needed to quantify any differences in wear rates, wear debris characteristics, or grease breakdown phenomena owing to differing operating conditions. The following observations were made.

1. Some wear occurred, as expected, during all testing.
2. Testing done using perfluoro type grease in ambient air produced red colored debris. Red debris was observed after 1 hr of testing at 2 ft-lb of torque and 200 rpm shaft speed (12,000 shaft revolutions). Large amounts of red debris were produced during tests of extended duration (30 hr). Profilometry traces reveal significant wear of the gear teeth.
3. Testing done using perfluoro type grease in dry nitrogen and 2 ft-lb of torque did not produce any red colored debris or red colored grease even after extended test duration. Some dark-grey streaks of grease were found on the tips of some teeth. The composition of the grey streaks is not yet known.
4. Testing done using perfluoro type grease in dry nitrogen and 5 ft-lb of torque produced some dark-grey colored grease.
5. Testing done using perfluoro type grease in a dry air atmosphere produced red colored deposits.
6. Testing done using a hydrocarbon-based grease in ambient air produced some red colored deposits and wear debris after short test duration.
7. Testing done using no lubricant in ambient air produced some red colored deposits and debris after short test duration.

TABLE 1.—TESTING CONDITIONS AND DOCUMENTATION.

TEST	GEAR PAIR	SETUP	LUBE	TORQUE (FT-LB)	SPEED (RPM)	TOTAL SHAFT REVOLUTIONS	OPERATING GEARS EXPOSED TO
1	1	A	PERFLUORO	5	515	927,000	AMBIENT AIR
2	1	B	PERFLUORO	2	200	194,000	AMBIENT AIR
3	3	A	PERFLUORO	2	214	238,000	DRY NITROGEN
4	4	A	PERFLUORO	5	214	205,000	DRY NITROGEN
5	5	B	PERFLUORO	5	219	210,000	DRY AIR
6	2	A	NO LUBE	2	705	42,000	AMBIENT AIR
7	2	B	HYROCARBON	2	214	13,000	AMBIENT AIR

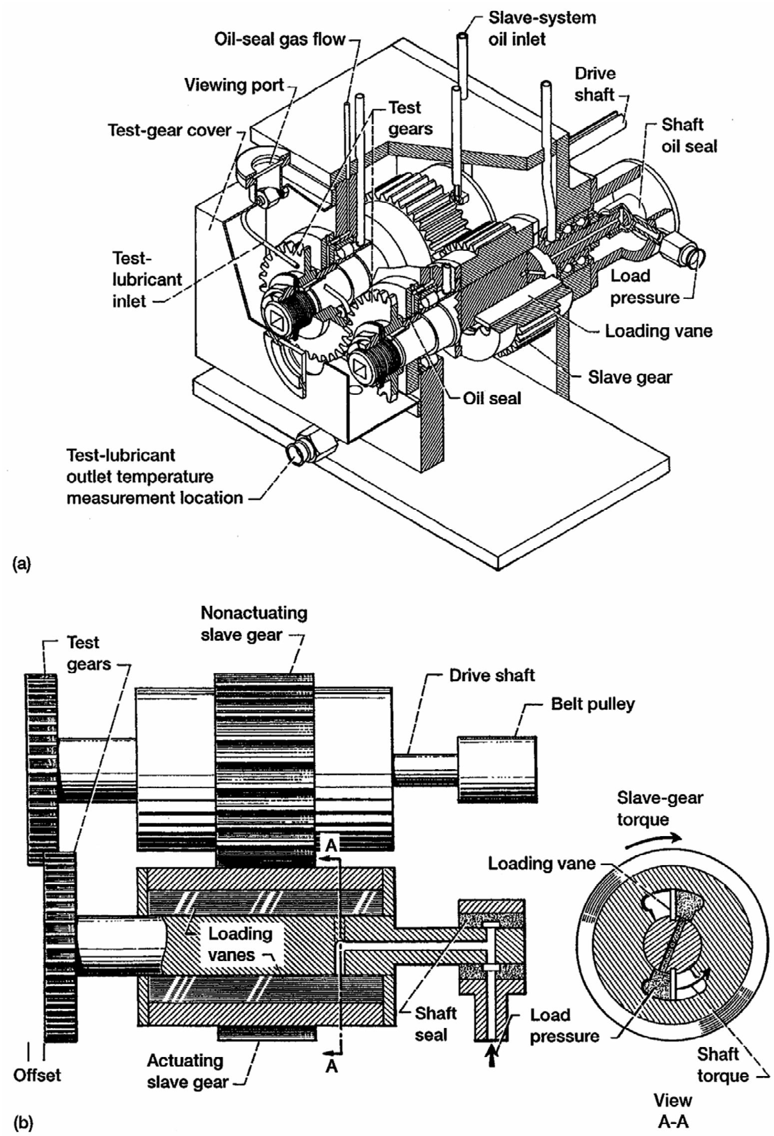

Figure 1.—NASA Glenn Research Center gear fatigue test apparatus. (a) Cutaway view. (b) Schematic view.

Figure 2.—Condition of the test gears after 3 hr of operation for test number 1 having test conditions of perfluoro type grease, 515 rpm shaft speed, 5 ft-lb torque, and ambient air atmosphere.

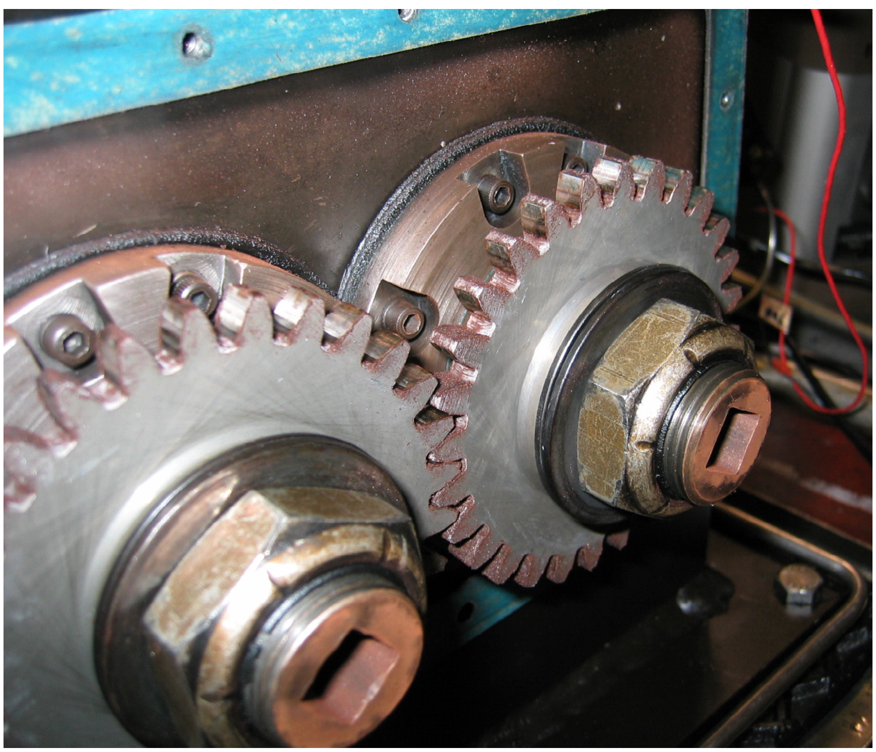

Figure 3.—Condition of the test gears after 30 hr of operation for test number 1 having test conditions of perfluoro type grease, 515 rpm shaft speed, 5 ft-lb torque, and ambient air atmosphere.

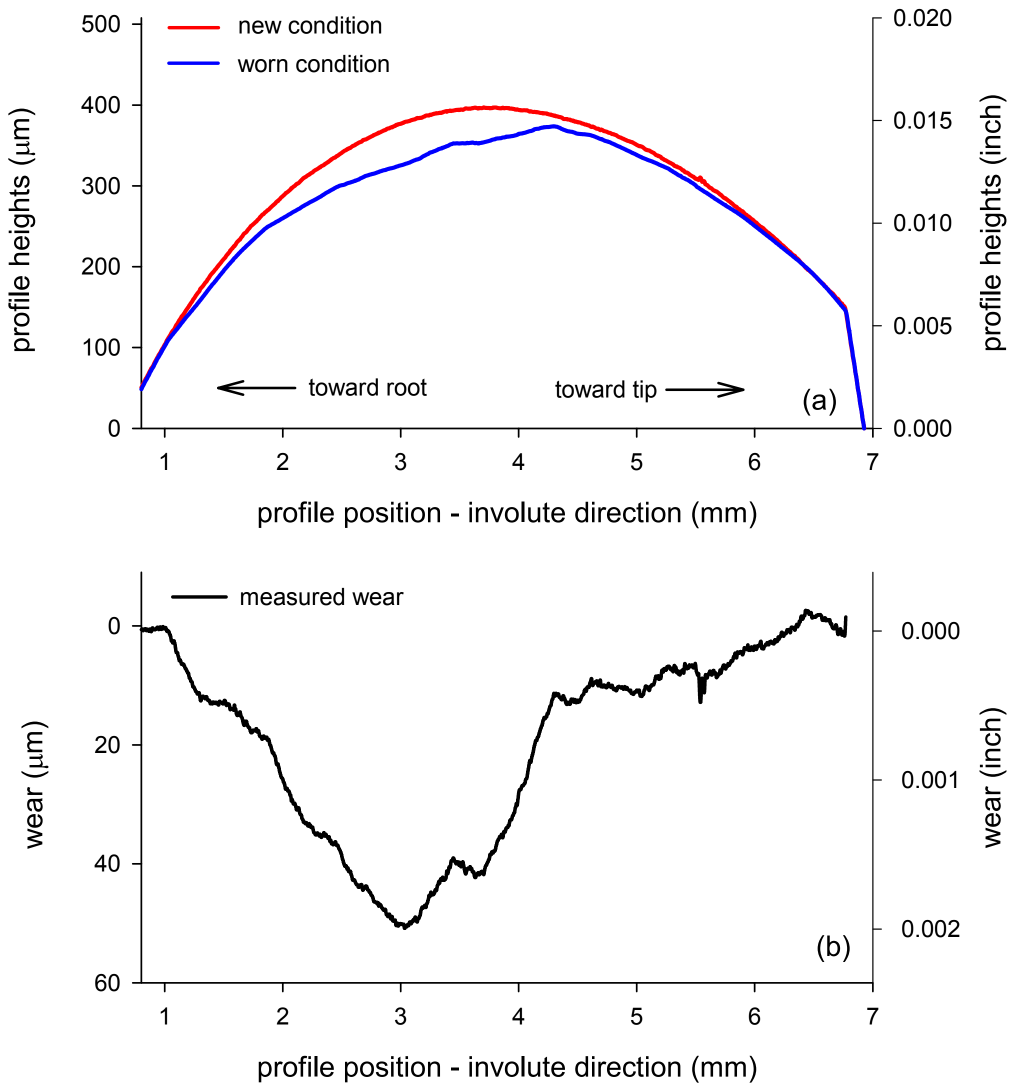

Figure 4.—Analysis of profilometry traces of a gear tooth in the profile direction reveal significant wear during test number 1. (a) Profile traces of tooth number 1 on gear 6-28-2A (the driving gear) at approximately the middle of the tooth face width measured before and after testing. (b) Wear depths determined as the difference of the new and worn profiles.

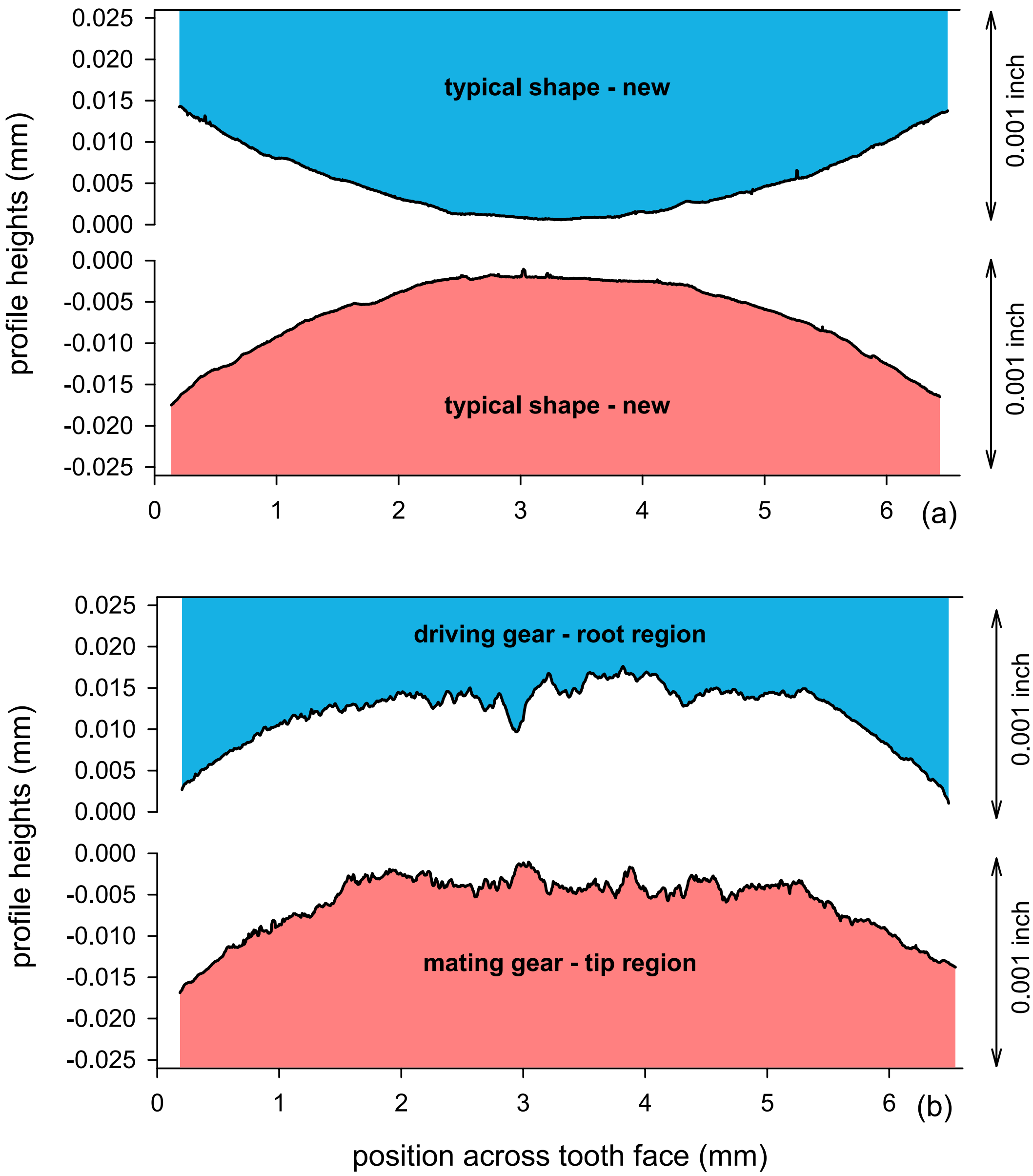

Figure 5.—Profilometry traces of a gear teeth in the lead direction reveal that the original crowned geometry is significantly changed with increase of roughness due to wear during test number 1. (a) Typical measurements of gear teeth before running shows crowned lead geometry. (b) Measurements of mating teeth after running show that the crowned geometry of the mating gear's tip region has been worn into the driving gear's root region.

.

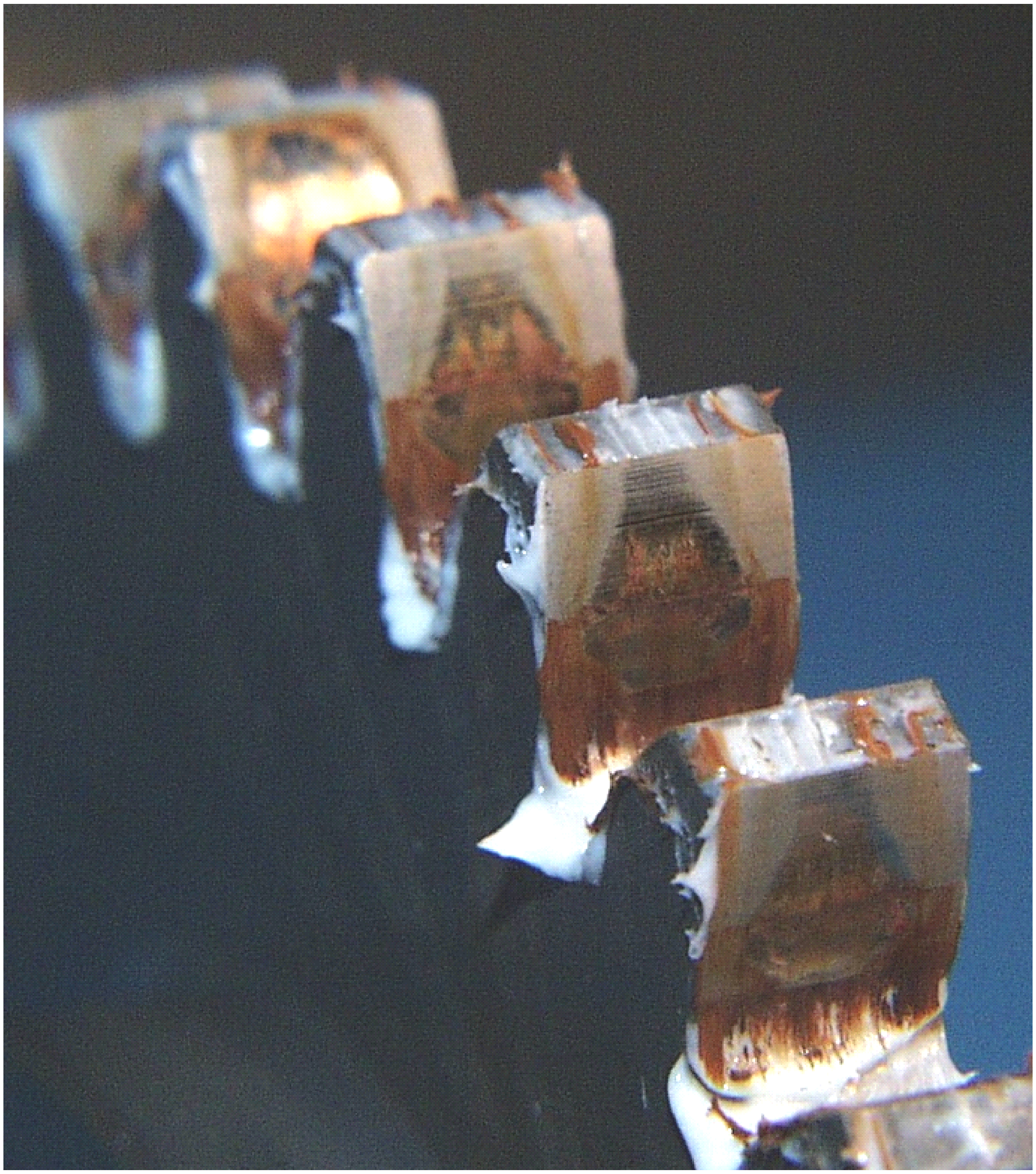

Figure 6.—Condition of the driven gear after 15 hr of testing for test number 2 having test conditions of perfluoro type grease, 200 rpm shaft speed, 2 ft-lb torque, and ambient air atmosphere. A mixture of original white and red colored grease is evident along with wear patterns.

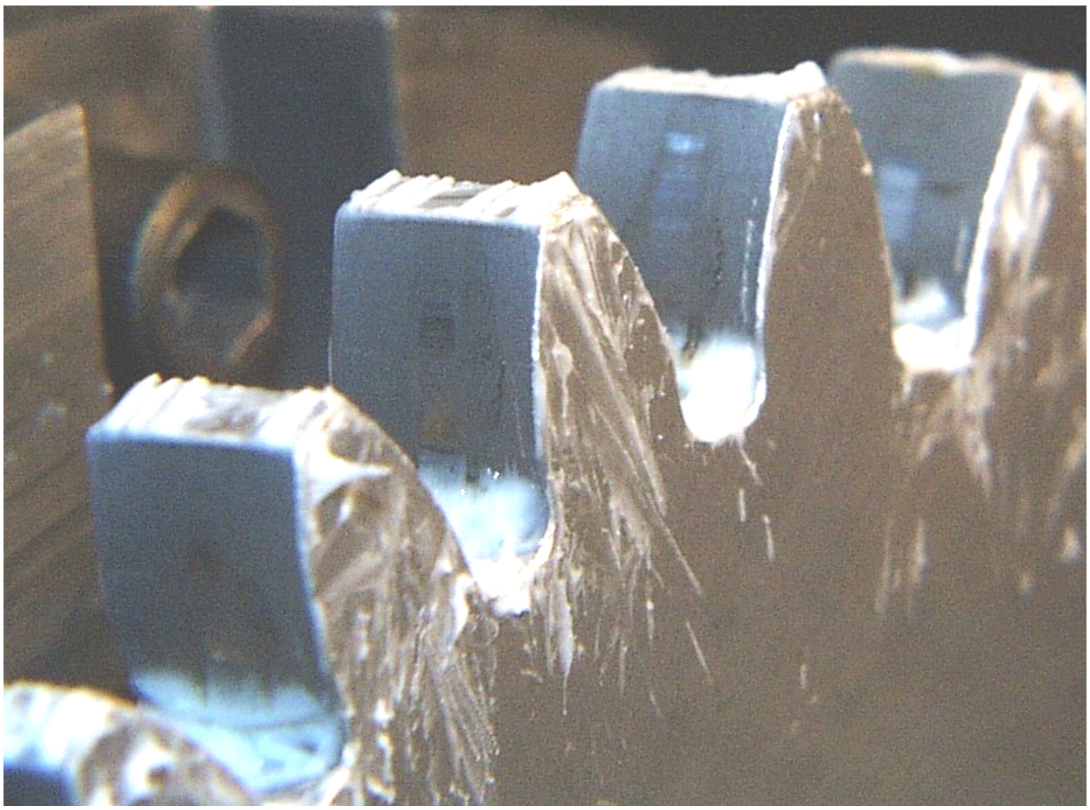

Figure 7.—Condition of the driven gear after 18.5 hr of testing for test number 3 having test conditions of perfluoro type grease, 214 rpm shaft speed, 2 ft-lb torque, and dry nitrogen atmosphere.

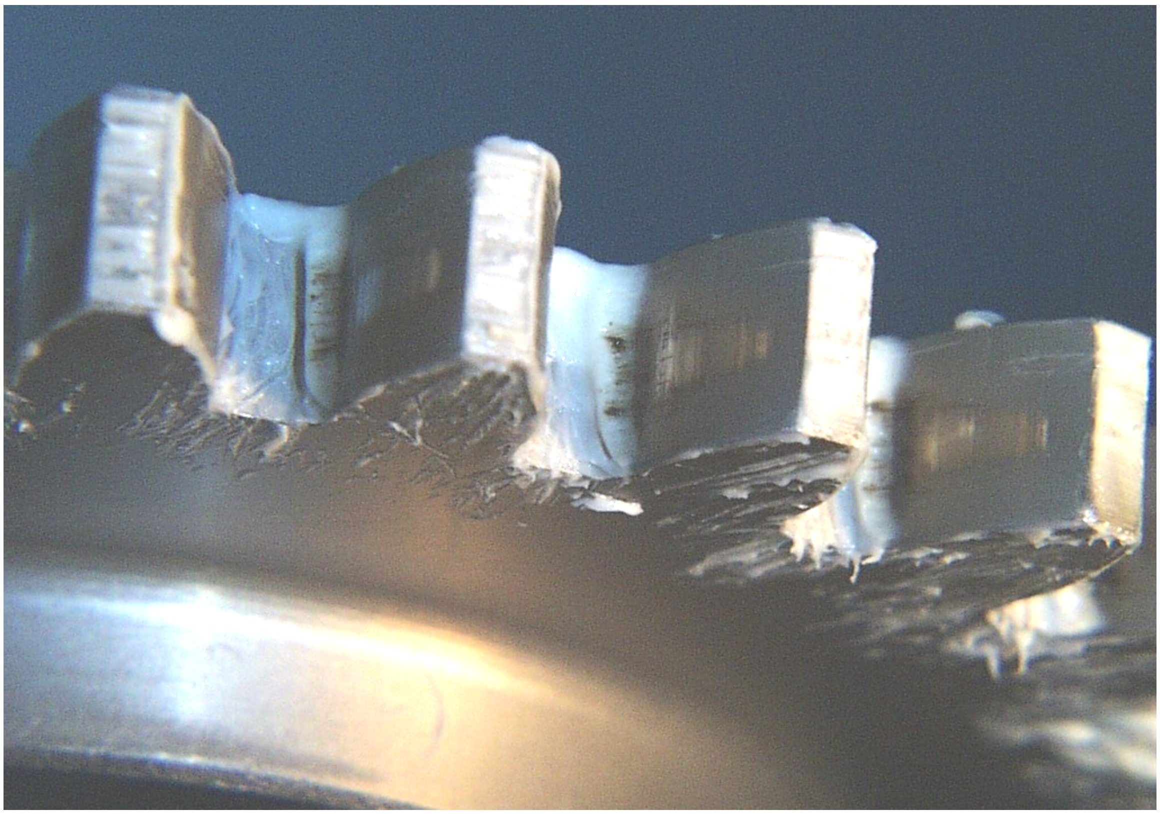

Figure 8.—Condition of the driven gear after 16 hr of testing for test number 4 having test conditions of perfluoro type grease, 214 rpm shaft speed, 5 ft-lb torque, and dry nitrogen atmosphere.

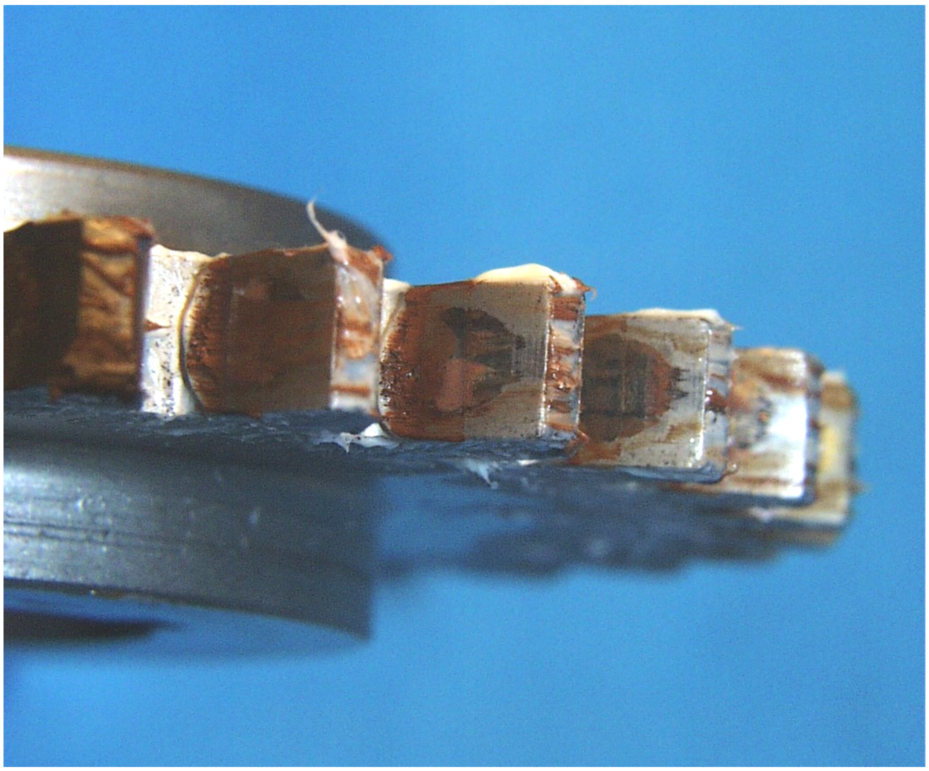

Figure 9.—Condition of the driven gear after 16 hr of testing for test number 5 having test conditions of perfluoro type grease, 214 rpm shaft speed, 5 ft-lb torque, and dry air atmosphere.

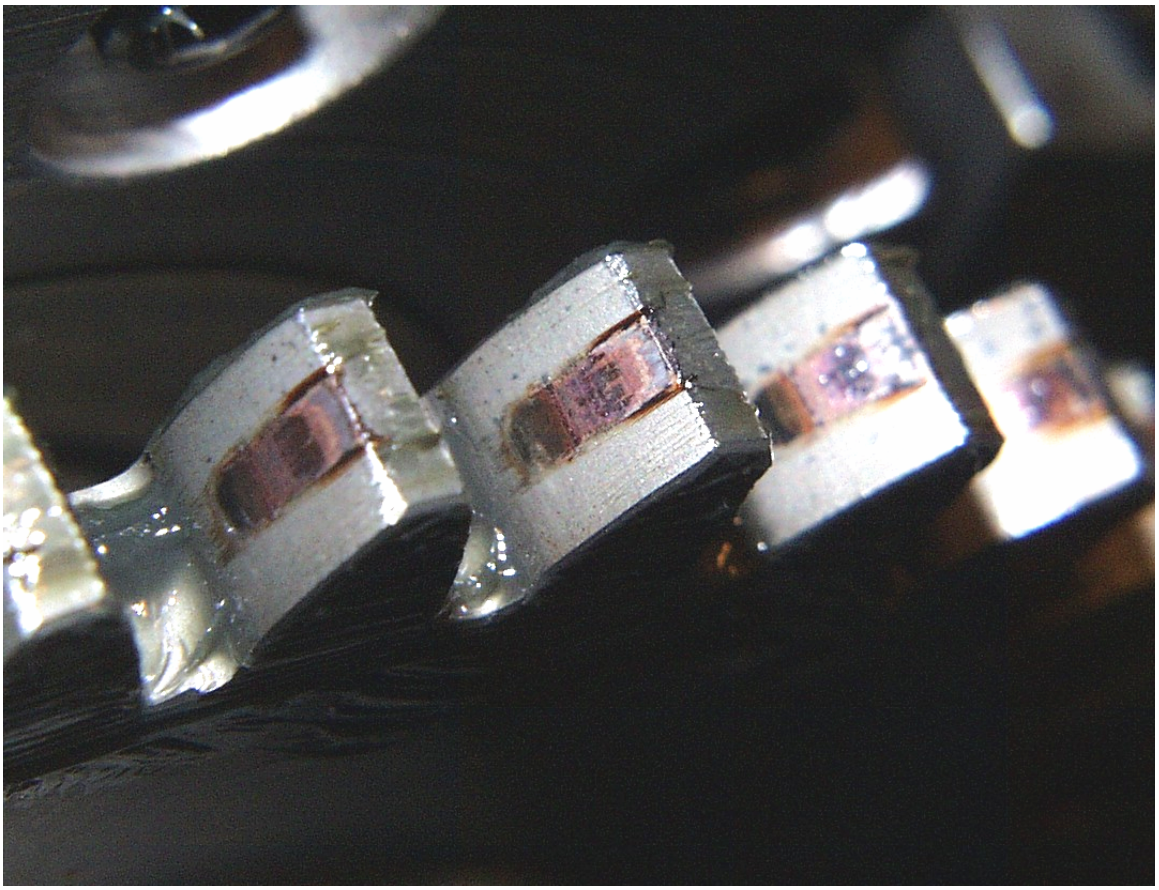

Figure 10.—Condition of the driven gear after 1 hr of testing for test number 6 having test conditions of hydrocarbon-based grade 2 grease, 214 rpm shaft speed, 2 ft-lb torque, and ambient air atmosphere.

Figure 11.—Condition of the driven gear after 1 hr of testing for test number 7 having test conditions of no lubricant, 705 rpm shaft speed, 2 ft-lb torque, and ambient air atmosphere.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
September 2005

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
A Study of Spur Gears Lubricated With Grease-Observations From Seven Experiments

5. FUNDING NUMBERS
WBS–22–714–90–03
1L161102AF20

6. AUTHOR(S)
Timothy L. Krantz and Robert F. Handschuh

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–15273

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001
and
U.S. Army Research Laboratory
Adelphi, Maryland 20783–1145

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2005-213957
ARL–TR–3159

11. SUPPLEMENTARY NOTES
Prepared for the 58th Meeting of the Society for Machinery Failure Prevention Technology (MFPT) cosponsored by ONR, NASA, ARL, NAWC, and NSWC, Virginia Beach, Virginia, April 26–30, 2004. Responsible person, Timothy L. Krantz, e-mail: Timothy.L.Krantz@grc.nasa.gov, organization code RSM, 216–433–3580.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 37
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

To improve understanding of gears operating with a perfluoro type space-qualified grease, seven spur gear experiments were performed. Test conditions were selected to study the influences of torque, lubricant type, and atmosphere. Two testing torques provided nominal pitch-line Hertz stresses greater and lesser than the contact stress limit as recommended by the grease manufacturer. As was expected, all tests resulted in some gear tooth wear. Discoloration of the perfluoro type grease occurred for all tests. Tests in dry nitrogen produced some dark-grey colored perfluoro type grease. Testing in either ambient or dry air produced red debris after short test duration, and for tests of longer duration large amounts of red debris, red grease, and wear were evident. Tests using higher torques produced more debris. The first indications of discoloration occurred more quickly with higher test torques. Total amounts of wear were quite significant, up to four times the profile tolerance for AGMA Class 10 gears.

14. SUBJECT TERMS
Grease; Wear; Debris; Gears; Lubrication

15. NUMBER OF PAGES
21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	