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The Effect of ODC-Free Cleaning Techniques on Bearing Lifetimes in the Parched Elastohydrodynamic Regime

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A parched elastohydrodynamic rig was used to determine relative bearing lifetimes as a function of cleaning procedures in a series of accelerated tests. Two ODC-free cleaning procedures (super critical CO₂ and ultraviolet-ozone) were compared to a CFC-113 control. Bearings (52100 steel) were run in the counter rotating mode (equivalent to 4600 rpm) with a full complement (i.e. no retainer) and a single charge of lubricant (Krytox 143 AC). Test conditions included: an air atmosphere, 445N load, ~1.0 GPa mean Hertz stress. There was approximately a 50% reduction in life with bearings cleaned with UV/ozone and a 70% reduction in life with SFE CO₂ when compared to the Freon control. Possible reasons for these decreases in lifetimes are presented.

Keywords: bearings, cleaning, elastohydrodynamics

INTRODUCTION

For many years, CFC 113 (trifluorotrchloroethane) has been used as a solvent in the processing of ball bearings for use in space mechanisms. In addition, CFC 113 has been used as a grease plating medium and solubilizing agent for the popular series of space lubricants known as the perfluoropolyethers (PFPE). PFPE lubricants have been used extensively as lubricants for scanning devices, filter wheels and harmonic drives. Their use has been dictated by their excellent physical properties: thermal stability (1), chemical stability (2) and elastohydrodynamic behavior (3).

However, these fluids are particularly susceptible to catalytic degradation by a variety of different chemical surfaces, both statically and in tribocontacts. (4)-(12). These include: titanium, aluminum and iron based alloys, aluminas, fluorides, chlorides, and oxides. The Montreal protocol has mandated the phaseout of CFC 113 and other ozone depleting substances. This has resulted in a series of new bearing processing and cleaning techniques based on non-ODC chemicals. These new techniques, although adequate for cleaning, result in a series of different surface chemistries whose ramifications for bearing longevity are unknown. In 1994 a workshop was held in Denver, CO to address these issues as they relate to the cleaning and lubrication of space system mechanical components for multi-year operations (13).

One issue covered at this workshop was the use of alternate alkaline aqueous cleaners (14) for spacecraft bearings that had been presoaked in tricresyl phosphate (TCP)(15). TCP presoaks have been used for many years to enhance boundary lubrication for slow speed spacecraft bearings (16). Surface analysis indicated that the aqueous cleaning removed 60 to 85% of the beneficial phosphorus layer. Other results showed the importance of the final solvent rinse on PFPE lubricant degradation (17). At 345 °C in air, an iron coupon rinsed in CFC-113 caused about 25% of a linear PFPE to be degraded. In contrast, a final rinse of water caused about an 80% degradation. Tests with a linear PFPE on 440C steel in oxygen at 316 °C yielded similar results (18).

Recently, new cleaning protocols and solubility tests have been developed for spacecraft bearings and lubricants (19). These protocols recommend the replacement of CFC-113 and 1,1,1-trichloroethane with super critical CO₂ and a series of perfluorinated solvents. Although these procedures adequately solubilized PFPE fluids and cleaned bearing surfaces, the resulting surface chemistries and their effects on bearing lifetimes are unknown. Another cleaning technique, ultraviolet-ozone (20), has been used for many years to remove carbonaceous contamination from surfaces.

Therefore, the objective of this work was to study the effects of two ODC-free cleaning procedures on bearing lifetimes in a transient elastohydrodynamic lubrication apparatus. These procedures are: super critical carbon dioxide and ultraviolet-ozone. Results are compared with conventional CFC-113 cleaning. Test conditions included: a

dry air atmosphere, 891 N load (mean Hz stress, 1.2 GPa), effective bearing speed, 4700 rpm, room temperature and a poly (hexafluoropropene oxide) PFPE lubricant.

EXPERIMENTAL

Transient Elastohydrodynamic Apparatus (TEHL)

The overall apparatus is shown in Fig. 1. It consists of the TEHL apparatus itself, inner and outer race drive motors (the latter containing a torque sensor) and a loading mechanism. The TEHL apparatus appears in Fig. 2. The upper bearing is the test bearing. The outer race of this bearing is driven by a synchronous hysteresis motor through a toothed belt drive. A keyed bushing is press-fit into the inner race. The load ring is keyed into the bushing and a spindle, which is driven by a second synchronous motor through another toothed belt drive. This allows the bearing to be run in a counter-rotating mode, where the races spin in opposite directions such that the ball complement is stationary. The bearing is loaded axially through the load ring and the central load shaft that extends down through the spindle. A lever arm system and a scissors jack are used to load the shaft. The four lower bearings provide support and alignment. More details about rig design, instrumentation and operation appear in reference (21).

Bearing Measurements

A data acquisition and control system monitors test bearing health. Parameters monitored include: test bearing, housing, upper support bearing and ambient temperatures; test bearing film capacitance and conductivity; inner and outer race speeds and ball spin; relative humidity, basic speed ratio (BSR) and motor torque. Test bearing torque is calculated from a thermal model and lubricant film thickness from capacitance measurements (21).

Materials

The lubricant used for this study was a perfluoropolyether based on hexafluoropropene oxide (22). Properties for this fluid appear in Table I. Test bearings (ABEC 5) were made of AISI 52100 steel and were operated in a retainerless mode using a full complement (21 balls)(7.9375×10^{-3} m diameter, grade 10). Bearing bore was 0.04 m and the pitch diameter was 5.40×10^{-2} m.

Cleaning Procedures

Bearing balls and races were ultrasonically cleaned for 10 minutes in hexane, then scrubbed with 0.3 μ m alumina powder and tap water and rinsed with deionized water. Specimens were then either: (1) UV-ozone cleaned for 30 minutes, (2) cleaned in a super critical CO₂ device for one hour at 80 °C and 225 atmospheres or (3) ultrasonically cleaned in Freon 113 for 10 minutes. Procedure (3) included a step, prior to the Freon

rinse, to simulate removal of machining oil by coating the specimens with a thin film of an unformulated super refined mineral oil (KG-80).

Experimental Procedure

Immediately after cleaning, the ball complement is weighed. Then, the ball complement is placed in a beaker of a 50/1 dilution of the lubricant in Freon 113. Each ball is removed and dried in a gaseous nitrogen stream. Then, the entire complement is weighed again and the bearing is assembled. The total amount of lubricant is recorded and is typically 3 to 6 mg. The races are not lubricated. After assembly, the complement is rotated by hand for several revolutions to distribute lubricant to the raceways. Then the test bearing is placed in the test rig. The rig is enclosed and purged with a dry air atmosphere ($RH < 2\%$) for a minimum of 30 minutes.

The apparatus is operated in a counter-rotating mode with an inner race speed of ~ 44 Hz and an outer race speed of ~ 33 Hz. This yields an effective bearing speed of ~ 4600 rpm. Bearing temperatures (test, upper support, housing and ambient) are continuously monitored. Typical data appear in figure 3. Bearing capacitance, conductance (resistance) and motor torque are also monitored. Typical traces for capacitance and resistance as a function of test time appear in figures 4 and 5, respectively. Approach to bearing failure is indicated by a rise in capacitance and a decrease resistance. Tests are automatically terminated when preset values of test bearing temperature, capacitance or resistance are attained.

Normally, the automatic termination procedure is sensitive enough to prevent major damage to the test bearing. The test bearing races are inspected, cleaned and reused. New bearing balls are used for each test. Used test balls are retained for surface analysis.

Statistical Analysis

The bearing lifetime data was statistically analyzed (23) in order to establish the confidence levels for comparisons between the three cleaning techniques. The data set for each cleaning technique was first checked for normality. It was necessary to perform a (ln) transformation to yield normally distributed data sets so that the common statistical tests could be applied. The means of the transformed data sets were then compared simultaneously using a one-way ANOVA. It was found that the means were statistically different from one another at a 95% confidence level. This allowed a simultaneous comparison of the standard deviations to be performed using a Foster-Burr test. A further SNK test on the transformed means indicated that they were significantly different from each other at a 95% confidence level.

RESULTS

Test Duration

Figure 6 contains the average test times to failure for the three different cleaning procedures. These averages represent a total of 11 tests for UV-ozone cleaning, 9 tests with Freon cleaning and 11 with SFE CO₂ cleaning. As indicated, the Freon cleaned bearings ran the longest. There was ~ 50 % reduction in life with UV/ozone cleaning and ~ 70% reduction with SFE CO₂. Error bars represent one standard deviation.

Surface Analysis

Figure 7 contains a micrograph of a track on a test ball from one of the tests. Typically, as the balls establish a stable orbit, a well defined band of degraded lubricant is evident. Raman analysis on and off this track appears in figures 8(a) and (b), respectively. Inside the band, the typical Raman signature for a degraded PFPE is shown. The well known G and D peaks are evident. A complete interpretation of these spectra appears in reference 24.

DISCUSSION

The phasing out of ODC cleaning agents has raised many concerns about the long term consequences on spacecraft lubrication systems. Almost all heritage systems had utilized Freon 113 or trichloroethane for final bearing processing. New bearing cleaning processes may alter surface chemistries in such a way as to decrease the lifetimes of bearings for critical instruments. Therefore, the objective of this research was to determine bearing lifetimes for two ODC-free cleaning processes (UV-ozone and SFE CO₂) and compare these results to that obtained by standard Freon 113 cleaning. As indicated above, both new processes adversely affected average bearing lifetimes. The 50 and 70% decreases in average lifetime were shown to be statistically significant at a 95% confidence level.

All of the bearings in these tests were operated in the parched EHL regime (25). This is a subdivision of starved lubrication where there is no free bulk oil in the system. The lubricant films are so thin that they are immobile outside the Hertzian contact region. Many spacecraft bearings operate in this regime because it requires the least driving torque and has the most precisely defined spin axis. The lubricant inside the Hertzian zone is not immobile and is eventually squeezed out, resulting in thinning transients which leads to lubricant film failure and subsequently to bearing failure.

As the lubricant film thins, shear rate increases and this shear energy is concentrated in smaller and smaller Hertzian volumes. Eventually, this shear energy

causes irreversible chemical changes in the lubricant film, resulting in degradation and/or polymerization (26). It is during this process that surface chemical effects can come into play. If the bearing surface is too active, the film degradation progression can be accelerated, resulting in earlier bearing failure. Conversely, if the bearing surface is less active, this progression can be delayed, resulting in longer duration tests.

Of course, these are greatly accelerated tests because of the limited amount of lubricant and the fact that no additional lubricant is added during the test. In addition, all tests were run in an air atmosphere. Whether these results can be extrapolated to long duration non-accelerated tests in vacuum, remains to be seen. Standard bearing gimbal tests in vacuum are now in progress. Nevertheless, the fact that statistically significant reductions in bearing lives were observed for two ODC-free cleaning processes, is a cause for concern.

CONCLUSION

Two ODC-free cleaning processes (UV-ozone and super critical CO₂) can produce residual surface chemistries that reduce lifetimes in accelerated bearing tests and may affect bearings for long-lived space missions.

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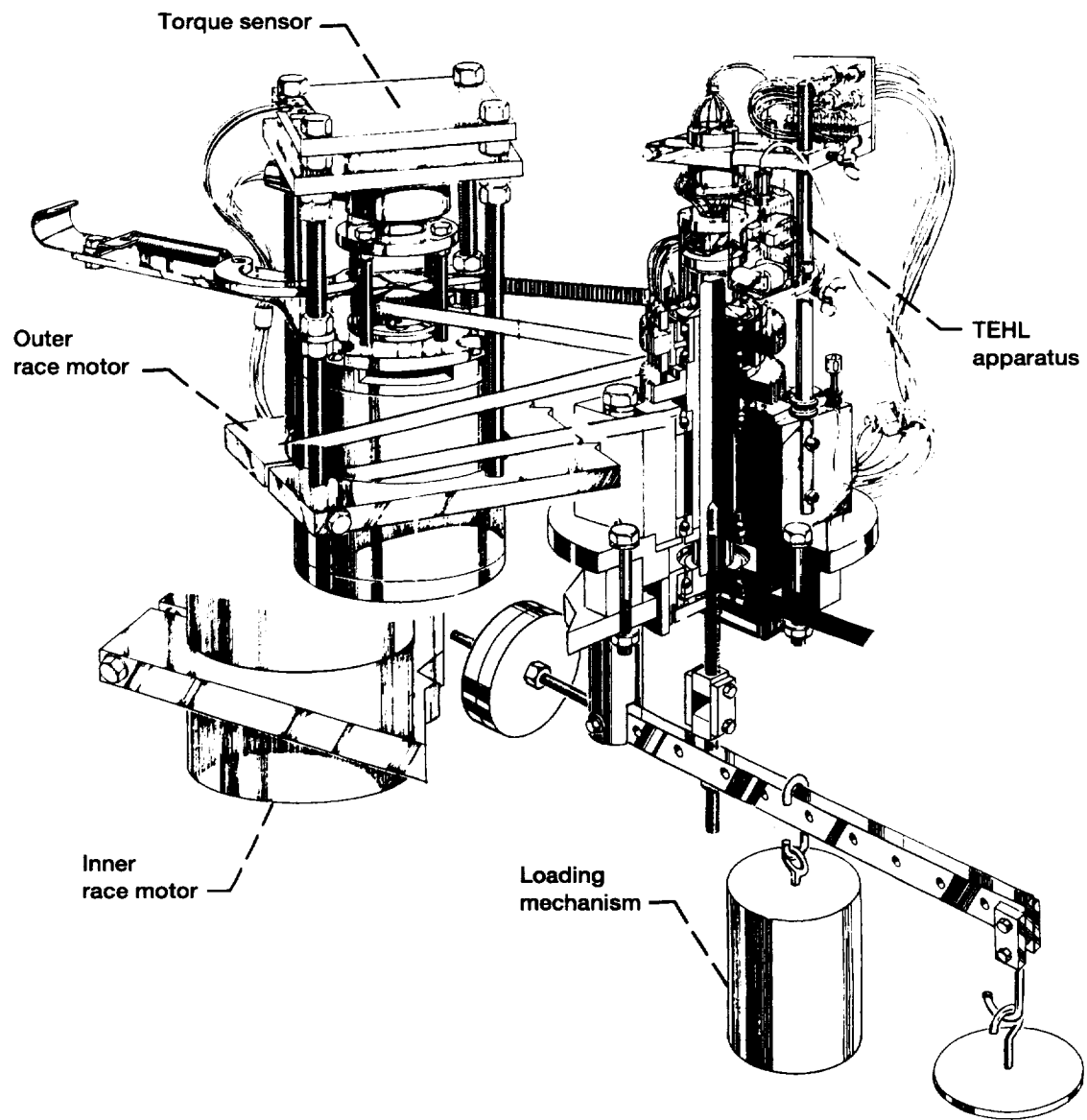


Figure 1.—Overall experimental apparatus.

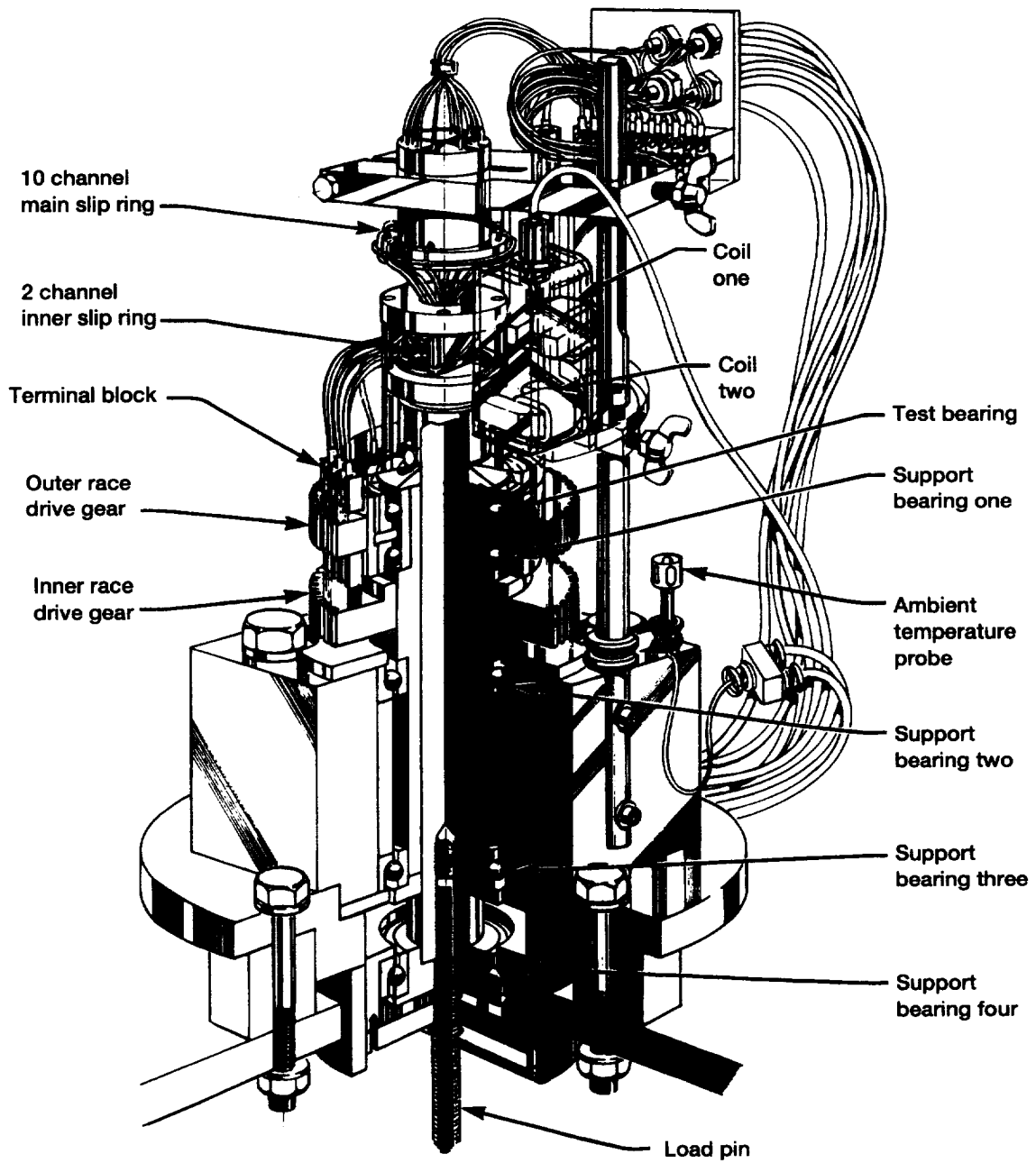


Figure 2.—TEHL apparatus.

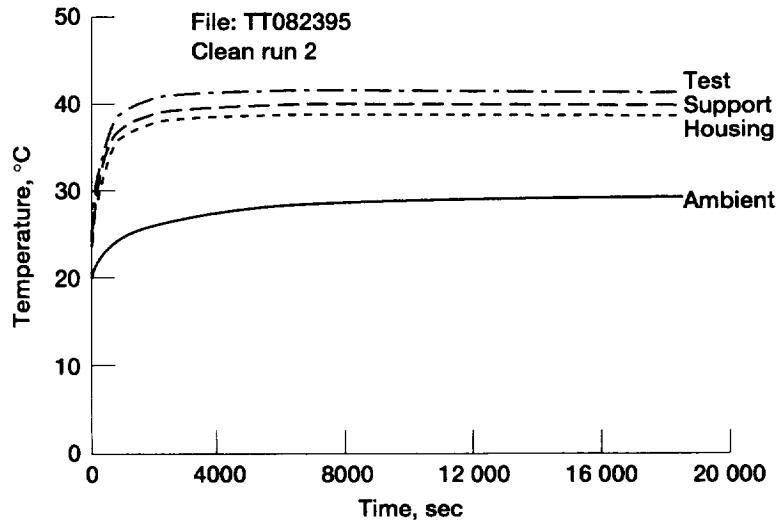


Figure 3.—Test and support bearing, housing and ambient temperatures as a function of test time.

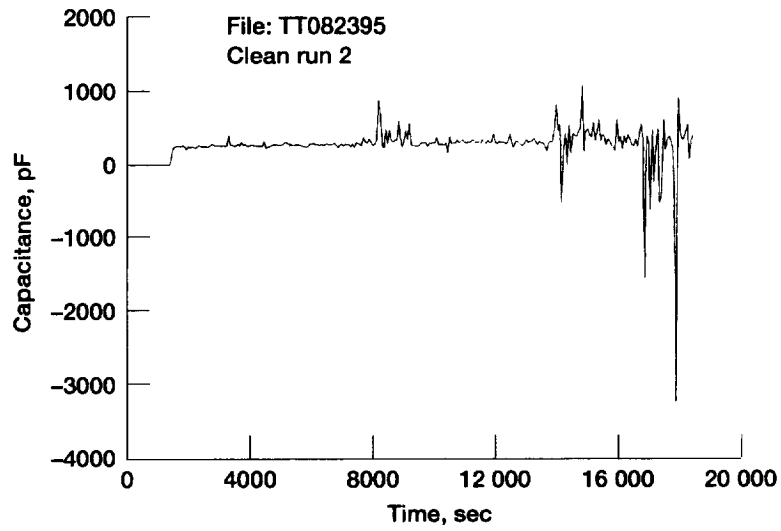


Figure 4.—Bearing capacitance as a function of test time.

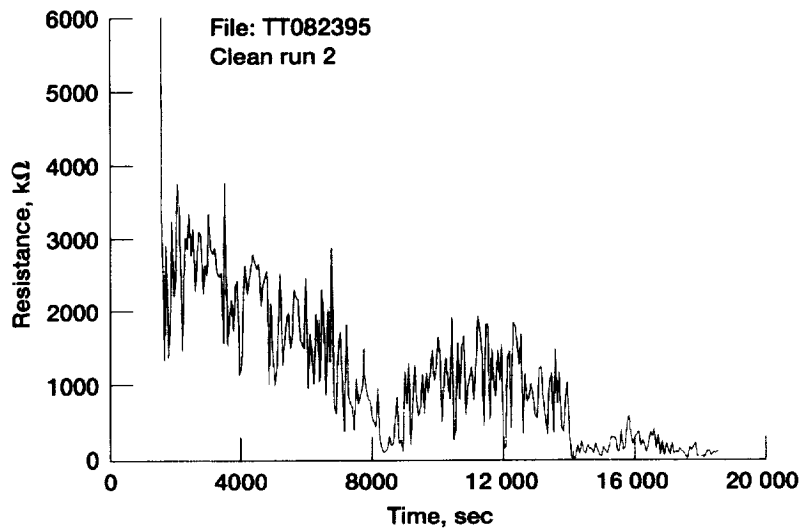


Figure 5.—Bearing resistance as a function of test time.

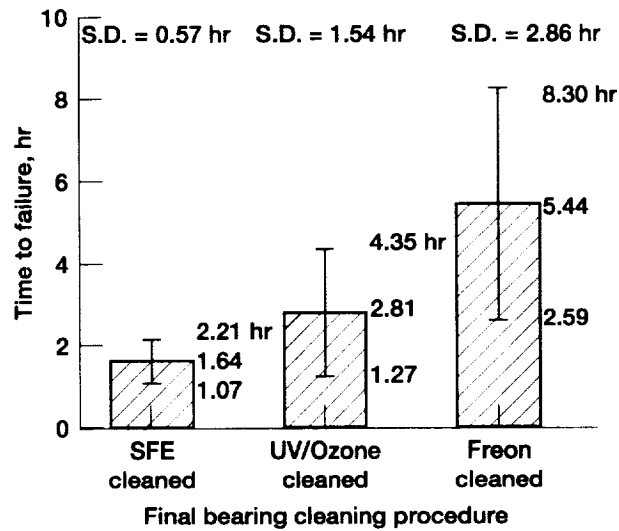


Figure 6.—Freon-free bearing cleaning summary parched EHL apparatus (air; 4500 rpm, room temperature).

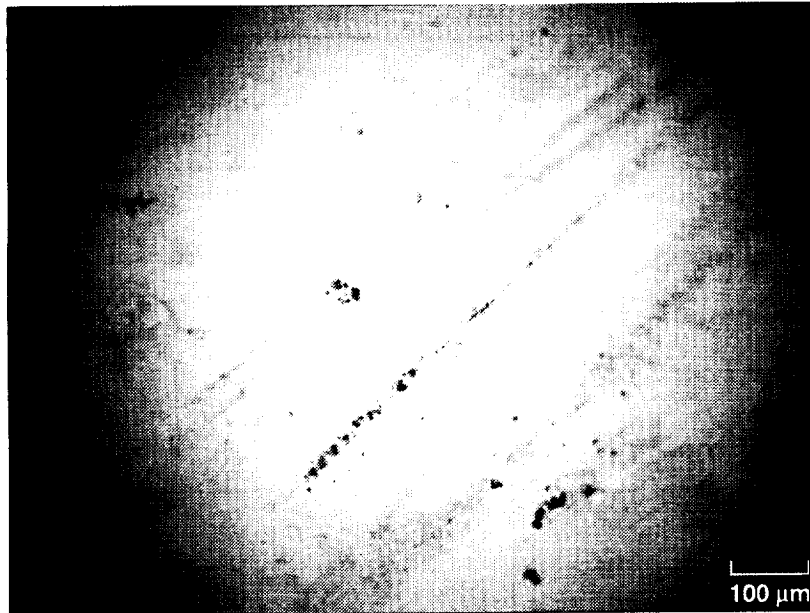


Figure 7.—Micrograph of a wear track on a bearing ball.

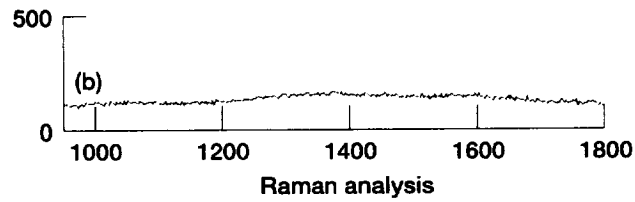
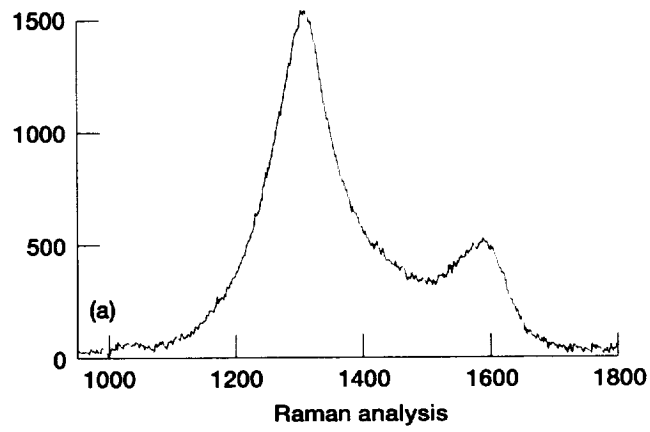


Figure 8.—Raman analysis of test ball. (a) On track.
(b) Off track

REPORT DOCUMENTATION PAGE

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