Grease Degradation in R0F Bearing Tests

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This paper is the second in a series that examines grease lubrication mechanisms and failure in rolling element bearings. The aim of the work was to understand the grease condition changes during use and the relationship to lubrication performance and failure. R0F bearing tests were carried out with two lithium hydroxystearate greases and the effects of the temperature, the speed, and the additive package on lubrication life was studied. Post-test, one pair of bearings (fail and non-fail) was dismantled and grease distribution and condition assessed. IR spectroscopy was then used to determine the lubricant composition and the oxidation level of the grease remaining on the shields, the inner raceway, and the cage pockets.

The additive package increased the grease life by 100-700% depending on the test condition. Most of the grease remaining in the bearing was found on the shields, with only trace amounts in the cage pockets or close to the rolling track. The IR analysis showed that the composition of the shield sample was similar to the fresh grease although the base oil oxidation was evident and this increased with the running time. The cage pocket and inner raceway films contained a number of chemical species; these included the base oil and the thickener and their oxidation products.

The study concludes that after an initial running-in period the "active" lubricant is heavily degraded grease, which contains oxidized species from the base oil and the thickener. Different failure mechanisms are identified depending on the test condition. High-speed tests that fail relatively quickly are due to poor boundary lubrication performance or cage failure rather than the lubricant reaching its "oxidation" limit. Long-term tests at slower speeds suffer considerable base oil oxidation. Under these conditions, failure is due to a reduction in the amount and/or mobility of the raceway lubricant.

KEY WORDS
Grease Lubrication; Rolling Element Bearings; Lubricant Degradation

INTRODUCTION—GREASE DEGRADATION IN ROLLING ELEMENT BEARINGS

Increasingly, rolling element bearings are required to operate at higher speeds, loads, and temperatures and for extended relubrication intervals. This imposes severe demands on the grease and it is necessary to accurately predict the lubricating life or the relubrication interval to prevent lubrication or component failure. With this objective in mind, this paper examines the basic mechanisms of grease lubrication and failure in rolling element bearings and the relationship to the bulk grease properties.

In many bearing applications, grease is subject to high operating temperatures and severe shear stresses. Over an extended operation, the grease will undergo mechanical and chemical degradation that will result in failure of the lubrication action and, ultimately, the bearing. High operating temperatures are seen to be the most significant factor; the usual figure quoted is a 50% reduction in grease life for every 10°C increase (Bartz (1)). Thus, grease lubricating life at high temperatures is usually linked to the oxidation stability of the base oil (Araki, et al. (2)); however, other factors including the thickener type, the presence of additives, and the bearing operating conditions also have an effect. Lubrication failure in bearing tests is indicated by a rapid increase in torque or the temperature. It is usually assumed that this is due to the lubricating film dropping below a certain critical thickness, and thus the friction increases. Depending upon the severity of the condition, this might be accompanied by surface damage and debris formation. The conclusion is that the mechanism of film generation has failed and this might be due to a reduction in the amount of lubricant available (Ito and Suzuki (3)) or a change in the lubricant properties.

Carré and co-workers (4) give the most comprehensive analysis of grease degradation changes in bearing tests, and from this and other studies (Bailey and Pratt (5); Komatsuzaki, et al. (6); Hosoya and Hayano (7)) the following conclusions can be drawn:
1. Grease undergoes both chemical and physical deterioration during use.

2. Chemical changes include:
   - Loss of antioxidant due to the oxidation reactions rather than evaporation
   - Increase in acidity (after depletion of the antioxidant)
   - Formation of oxidized hydrocarbon species leading to the formation of acidic and/or high viscosity products
   - Loss of carboxyl bands of soap thickener

3. Physical deterioration includes:
   - Increase in bleeding rate and oil leakage
   - Destruction of the thickener structure, either due to working or the chemical breakdown
   - Loss of the base oil due to evaporation or loss of volatile oxidation products.

There is limited published research into the effects of grease additives on lubrication life. It is to be expected that the antioxidant additives will have the greatest effect. One of the most comprehensive studies was by McClintock (8), who carried out lubrication life tests for a range of greases (both model and commercial) and additive packages. Typical increases in lubrication life of 30-80% were observed for additized greases. Oxidation inhibitors generally increased the lubrication life and this was found for both peroxide decomposers and radical inhibitors, although the response does depend on the thickener type (Cann and Lubrecht (9)). EP/AW additives also increased life, probably because they reduce the severity of contact conditions and thus the operating temperature.

Little published work considers explicitly the mechanisms of lubrication failure. The assumption in this study is that failure is due to the grease being unable to maintain a lubricant film sufficient to separate the surfaces. This could be due to changes in the amount (Ito and Suzuki (3)) or condition of the grease “reservoir” in the bearing (Hosoya and Hayano (7)) or more localized failure due to degradation of the lubricant film in the rolled track. Komatsuzaki and co-workers (Komatsuzaki and co-workers (8)) reported the loss of the base oil due to the evaporation of the volatile oxidation products as the predominant factor controlling the lubrication life of grease in the cylindrical roller bearing tests. A critical base oil content of 50-60% by weight was identified. However, the failure process and the way in which grease degradation affects this will depend on the dominant mechanism of lubrication in the bearing. This is normally assumed to be the “base oil reflow” model (Cann and Lubrecht (9)) where a low-viscosity lubricant is released by the grease to replenish the rolling track. Under these conditions, it is the amount and viscosity of the available lubricant that will determine when failure occurs. If the base oil viscosity increases due to the oxidation, then the replenishment of the contact will be reduced (Cann (10)). Similarly, if there is a significant loss of volatile material due to evaporation (Ito and Suzuki (3); Hosoya and Hayano (7)), then the amount of the low-viscosity lubricant available for replenishment will decrease. Both of these occurrences could lead to failure due to the starvation of the contact. However, other lubrication models are possible depending on the operating conditions and the design of the bearing (Cann and Lubrecht (9)). The supposition of a lubricant model is important, as it is the mechanisms of lubricant supply to the contact and the way in which the oxidation/degradation affects these that will determine the onset of failure. It is the mechanism of the lubricant failure and the relationship to the grease condition that is considered in this paper.

**RESEARCH PROGRAM**

**Experimental**

In an earlier paper (Cann, et al. (11)), the grease degradation and distribution in a 6309 deep-groove ball bearing were studied. In these tests, the bearings were run for varying times and under different load and temperature conditions. The bearings were not run to failure, as the intention was to study grease distribution and degradation within the bearing during normal operation. At the end of the test, the bearings were dismantled and the grease distribution on the shields, the rolling surfaces, and within the cage pockets was noted. IR spectroscopy was used to evaluate the composition and the condition of the lubricant in these regions.

The current work extends this approach to examine bearings that have been run to failure. In this case, 6204 deep-groove ball bearings with a metal cage were used with the same additized and non-additized lithium hydroxystearate greases (Cann, et al. (11)). A series of R0F bearing tests were run under different conditions of speed and temperature to determine the grease lubrication life. The tests were run until one of the bearings in the pair failed, and this was denoted by a rise in the outer ring temperature to 130°C. For each test condition, six pairs of bearings were run and the L₅₀ life determined. At the end of the test, one pair of bearings containing a failed and non-failed specimen was selected for further analysis. The failed and non-failed bearing pairs were later dismantled and the grease condition and distribution assessed. IR spectroscopic analysis was carried out on the grease from different parts of the bearing. Three areas were selected:

(a) Shield sample to determine the grease “reservoir” condition
(b) Cage pocket to determine the condition of the lubricant close to the ball bearings
(c) Inner raceway to determine the condition of the lubricant in the rolling track.

It is hoped that the comparison of the grease condition in both bearings of the test pair will shed some light on the grease condition at failure. However, any differences in the grease condition must be interpreted with care, as it is unclear whether this is the underlying cause of the failure or merely a result of the excessive temperatures occurring during the failure process. It is also misleading to assume that the grease condition in the non-fail bearing represents that found in the partner bearing immediately before failure.

**Test Greases**

The two test greases were lithium hydroxystearate thickened, with and without an additive package. The greases are described in Table 1. The soap thickeners of the test greases were manufactured by reacting 12-hydroxystearic acid and lithium hydroxide in a naphthenic base oil, which was then homogenized, and a
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### Table 1—Composition of Grease Samples

<table>
<thead>
<tr>
<th>Grease</th>
<th>Base Oil (Wt %)</th>
<th>Thickener (Wt %)</th>
<th>Additives (Wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>91.5 Mineral oil</td>
<td>8.5 Lithium hydroxystearate</td>
<td>none</td>
</tr>
<tr>
<td>B</td>
<td>87.5 Mineral oil</td>
<td>8.5 Lithium hydroxystearate</td>
<td>Rust inhibitor 0.5, ZDDP (primary) 1.5, Copper passivator 0.1, S/P EP 1.0, DPA antioxidant 0.5, Friction modifier 1.0</td>
</tr>
</tbody>
</table>

A paraffinic base oil was added. The base oil viscosity was 150 cSt at 40 °C. For other properties, please refer to Cann, et al. (11).

### R0F Bearing Test Program

The greases were run in an R0F bearing test under different sets of operating conditions (load, speed, temperature, and test time). The conditions are summarized in Table 2. The test specimens were 6204 deep-groove ball bearings with a steel cage mounted symmetrically around the balls. Two series of tests were run:

(a) Short-term tests without failure—bearings were run for 40 and 240 h and then removed before failure could occur.
(b) Lubrication life tests where the bearing test pairs were run until one failed (indicated by an increase in the outer ring temperature to 130 °C). The test was then stopped and one pair of bearings saved for analysis.

The aim was to study the effect of the running time on the grease condition and distribution and to compare the condition at failure between the fail and non-fail test pairs. The results of the bearing life determinations are summarized in Fig. 1. The additized grease B gave a significantly longer life than grease A (100 to 700% increase depending on test condition). For both greases the L50 life decreased with increasing speed and temperature.

### Examination of Test Bearings

IR spectra were taken of the grease remaining in the bearing as it was dismantled. First, the shields were carefully removed. A visual assessment was made of the amount and condition of the grease present on both shields as the bearings were dismantled. Generally, the amount of grease present decreased with an increased running time and increasing severity of conditions. The degree of degradation also increased with running time. Most of the grease remaining in the bearing was on the shields and only trace amounts were observed close to the balls and raceways.

After the shields had been removed, the retaining tabs on the cage were lifted. One side of the cage was then removed, exposing the ball bearings, and it was then possible to pull out the second cage component. The material remaining in the cage pockets was examined under a low-power microscope. This appeared solid rather than viscous, although large differences did occur between samples. In some cases, brown rings of oxidized material were observed in the cage pockets, suggesting that this material was mobile when the bearing was running and had collected around the ball once the test was stopped. The cage pockets, of the failed bearings often had highly oxidized carbonized films. IR reflection spectra were taken from the different types of deposit in the cage pockets.

The inner raceway and balls were then knocked out and reflection spectra taken from the inner raceway. The lubricant remaining in the rolled track on the inner raceway was not continuous and the distribution, thickness, and appearance varied considerably both within the same raceway and between the different tests. The condition of the grease (after the initial running-in period) was such that the dismantling process would have had very little effect on lubricant distribution within the bearing. For the most part, the films were very thin and appeared highly viscous or solid at room temperature and there was no indication of smearing or removal during disassembly. Several different types of film were observed:

(a) Thin, smooth films of transparent material, which appeared to be a viscous fluid rather than grease. Interference colors were visible, suggesting a thickness of 300-1000 nm.
(b) Relatively thick islands of grease-like (rather than viscous) material.
(c) For longer test times, thick (~micron) ridges of dark brown material aligned transverse to the rolling direction. Again, this suggested that the material was mobile when the bearing was running and that it had gathered around the cage/balls once the test was stopped.
(d) Thin blue/brown films—possibly oxide layers.
(e) Black carbonized films in the failed samples.

### Table 2—Bearing Test Program. A Description of the R0F Test Rig Is Found in ISO 11010

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>Deep groove ball 6204</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cage Type</td>
<td>Steel</td>
</tr>
<tr>
<td>Outer Ring Temperature, °C</td>
<td>110, 120</td>
</tr>
<tr>
<td>Speed, rpm</td>
<td>10,000, 20,000</td>
</tr>
<tr>
<td>Rated/Applied Load, C/P</td>
<td>25</td>
</tr>
<tr>
<td>Time, Hours</td>
<td>40, 240, to failure</td>
</tr>
</tbody>
</table>

Fig. 1—Summary of R0F test results at 110 and 120 °C.
A photograph of a dismantled bearing and the IR sampling positions is shown in Fig. 2. The IR analysis was carried out on a Perkin Elmer Spectrum One FTIR equipped with a Multiscope FTIR microscope. This attachment allows the reflection spectra to be taken from small areas (100-150 $\mu$m diameter) of the lubricant film on the bearing surface. The microscope is focused using the visible optics and the specimen analysis area defined by a variable aperture. The inner raceway spectra were taken from the middle of the rolling track. IR spectra were taken over the full 4000-650 cm$^{-1}$ spectral range; however, most of the results shown in this paper are confined to 1900-700 cm$^{-1}$. This region includes absorbance bands from the thickener, the base oil, and the oxidation products.

IR transmission spectra of the fresh greases are shown in Fig. 3; absorbance band position and assignments are summarized in Table 3. The spectra are plotted in absorbance units so that the height of the band correlates with the sample thickness and concentration of species. Peaks due to the thickener and base oil components are easily distinguished in this range. The main thickener bands are at 1580 and 1560 cm$^{-1}$ due to the asymmetric carboxylate stretch (Lin-Vien, et al. (12)). The bands at $\sim$1460 and 1377 cm$^{-1}$ are due to CH$_2$/CH$_3$ deformation vibrations, respectively, which are primarily from the base oil. The corresponding thickener CH$_2$ deformation occurs at 1454 cm$^{-1}$ and is often seen as a shoulder or doublet with the base oil peak. The height of the 1580 band relative to that at 1460 cm$^{-1}$ is a guide to the amount of lithium hydroxystearate thickener present. If there is a large increase, the soap CH$_2$ band (1454 cm$^{-1}$) becomes dominant and the base oil band (1460 cm$^{-1}$) is reduced to a shoulder. Thus, a shift in the position of this band is also evidence of a change in the thickener concentration.

<table>
<thead>
<tr>
<th>Grease A</th>
<th>Grease B</th>
<th>Base Oil</th>
<th>Soap</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1580</td>
<td>1580</td>
<td>—</td>
<td>1579</td>
<td>Asym. carboxylate COO$^-_1$</td>
</tr>
<tr>
<td>1560</td>
<td>1560</td>
<td>—</td>
<td>1561</td>
<td>Asym. carboxylate COO$^-_1$</td>
</tr>
<tr>
<td>1460</td>
<td>1460</td>
<td>1464</td>
<td>1454</td>
<td>CH$_2$ deformation</td>
</tr>
<tr>
<td>1377</td>
<td>1377</td>
<td>1377</td>
<td>1377</td>
<td>$-C$ (CH$_3$)$_2$ deformation</td>
</tr>
<tr>
<td>1306</td>
<td>1306</td>
<td>1306</td>
<td>1306</td>
<td>$-(CH_2)_n$ in-phase twist</td>
</tr>
<tr>
<td>1133</td>
<td>1133</td>
<td>—</td>
<td>1132</td>
<td>Carboxylate</td>
</tr>
<tr>
<td>—</td>
<td>1002</td>
<td>—</td>
<td>—</td>
<td>ZDDP additive P-O-C</td>
</tr>
<tr>
<td>722</td>
<td>722</td>
<td>724</td>
<td>722</td>
<td>$-(CH_2)_n$ in-phase rock</td>
</tr>
</tbody>
</table>

Table 3—Position of Main Absorbance Bands (in cm$^{-1}$) and Assignments for Test Greases and Components
IR Analysis of Bearing Samples

There were significant differences in the IR spectra taken from different parts of the bearing and an example is shown in Fig. 4. IR spectra are shown for the shield, the cage pocket, and the raceway films for a non-fail bearing. In most examples, the spectra were normalized to constant absorbance at ∼1460 cm\(^{-1}\). These results are typical of the grease condition found in the bearings. The shield sample is similar to the fresh grease. However, the inner raceway and cage pocket samples are heavily degraded. The IR spectra show thickener concentration changes (change in relative height of the 1580/1560 cm\(^{-1}\) bands) and the formation of new carbonyl species (at 1713, 1681, and 1600 cm\(^{-1}\)). The new carbonyl species are oxidation products from the base oil and the thickener. Thermal ageing tests have shown that the base oil gives three characteristic oxidation bands in this region at 1768 (shoulder), 1733 (shoulder), and 1713 cm\(^{-1}\). The corresponding thermal oxidation bands for the thickener occur at 1650-1600 cm\(^{-1}\). Clearly, the cage pocket and inner raceway lubricant has suffered far more extensive oxidation than the shield grease and the condition of the shield grease cannot be used as a guide to the degradation of the lubricant within the bearing. Each of the bearing regions is presented separately in the sections for the non-fail samples. The effects of failure on the lubricant condition are examined in another section of this paper.

Shield Lubricant

IR spectra for shield grease taken from a non-fail bearing are shown in Fig. 5. The main difference between the test samples is the extent of oxidation of the base oil, which was seen as new absorbance bands between 1700 and 1770 cm\(^{-1}\) (C=O) and at 1181/1121 cm\(^{-1}\) (C-O). Generally, the degree of oxidation increased with increasing running time. The 1713 absorbance is always associated with the 1181 and 1121 cm\(^{-1}\) bands, and an increase in OH absorbance at 3470 cm\(^{-1}\) also occurs. One explanation for these observations is that an α-hydroxyl ketone is the main oxidation product (Mortier and Orszulik (13)). The minor C=O bands at 1768 and 1735 cm\(^{-1}\) are assigned to δ-saturated lactone and ester or methoxyketone species, respectively (Lin-Vien, et al. (12)). These are typical products of the secondary oxidation phase of hydrocarbons (Mortier and Orszulik (13)). Polycondensation of the oxygenated species formed in the primary oxidation phase results in high-molecular-weight products that increase the oil viscosity and can lead to deposit formation (Mortier and Orszulik (13)). In the more heavily degraded samples, minor absorbance bands at 1600-1625 cm\(^{-1}\) were recorded, and these are attributed to a C=O of a carboxylic acid salt probably from the degraded thickener. Overall, the thickener concentration in the shield samples is similar to the fresh grease for the short-term tests but increases with running time due to the evaporation of the base oil.

Samples were taken from both shields from each bearing (see Fig. 2) and usually the condition of the grease was similar on either side of the bearing. However, in some cases significant differences were seen between the samples, as can be seen in Fig. 5. The degree of oxidation of the grease was related to the amount of the grease present. Generally, higher levels of oxidation were associated with lower grease coverage. The same pattern was seen in both failed and non-failed bearings of a test pair, suggesting that such asymmetry is due to the operating characteristics of the test device.

Cage Pocket Lubricant

The composition of the cage pocket lubricant changed as the test proceeded. After 40 h, the lubricant remaining in the cage pockets was similar to the fresh grease, although it had a higher
thickener concentration (Fig. 6, lower gray spectrum). This is seen in the increased intensity (relative to 1460 cm$^{-1}$) of the 1580 cm$^{-1}$ absorbance and CH$_2$ deformation shift to 1453 cm$^{-1}$. The base oil CH$_2$ deformation is reduced to a shoulder at 1460 cm$^{-1}$. After 240 h running (upper spectra), different types of film were noted and in some cases ridged “ring” deposits of brown material were formed. Spectrum 1 was taken from the clear area within the brown ring deposit, while Spectrum 2 was taken from the brown deposit itself. Clearly, there were very different levels of oxidation present. In Spectrum 2, intense bands are present at 1625-1600 and 1100-900 cm$^{-1}$, and these are indicative of new C=O and C-O species, respectively. The 1625 cm$^{-1}$ band tends to obscure the remaining carboxylate bands at 1580/1560 cm$^{-1}$.

The base oil oxidation bands (1768, 1733, and 1713 cm$^{-1}$) are relatively insignificant in the cage pocket spectra, indicating loss of base oil from the film. This might be due to the evaporation or

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**Fig. 5**—IR spectra for shield grease taken from either side of the same bearing. Grease B, 110°C, 20,000 rpm, 783 h.

**Fig. 6**—Comparison of cage pocket spectra for grease B after 40 and 240 h running, 110°C/10,000 rpm. Fresh grease B spectrum also shown.
the migration of the “free” base oil. Thermal oxidation of the hydroxystearate thickener gives a band at 1600-1625 cm⁻¹ attributed to the asymmetric C=O stretch of a carboxylic acid salt. The corresponding symmetric stretch absorbance occurs at 1410 cm⁻¹, which is also seen in Spectrum 2. The band at 1035 cm⁻¹ was also seen in inner raceway spectra, which was associated with a thin blue inorganic film.

The heavily oxidized material usually occurs as a brown ring, suggesting that it is fluid when the bearing was running. Once motion had stopped, this collected around the ball where it sat in the cage pocket forming a high viscosity deposit as the bearing cooled. The clear material within the ring at the bottom of the cage pocket (Spectrum 1) was very similar to the fresh grease although there was a higher concentration of the thickener present. In this case, there is only minor oxidation of the thickener and the base oil. The very clear difference in the degradation of the films within the same cage pocket is interesting. A number of tentative conclusions have been drawn from these observations. Firstly, the clear material within the ring deposit is not actively involved in the lubrication process, although the base oil has been lost through the evaporation of volatile species. Secondly, the “ring” material is the active lubricant and it is mobile at the running temperature of the bearing. It has suffered additional degradation of the thickener through shearing in the cage/ball conjunction or the presence of wear debris. Thus, the active lubricant in the ball/cage region is heavily degraded lubricant containing a high proportion of thickener. The spectra shown in Fig. 6 were taken from a non-fail bearing after 240 h, which is very early in its life cycle (L₅₀ for this condition was >2500 h). The spectra represent the condition of the lubricant under normal operation. In some of the cases examined, a low thickener concentration was noted in the cage pocket film. This appeared to be associated with the higher speed tests (Fig. 4).

**Inner Raceway**

The inner raceway films were usually transparent with isolated areas of thicker film. The appearance of the thick film regions depended on the test condition and could be either patchy deposits of grease-like material (short-term tests) or dark ridges transverse to the rolling directions.

IR spectra taken from the 40-h test with greases A and B showed that the films contained both the thickener and the base oil in similar proportions to the fresh bulk grease (Fig. 7). The ZDDP 1002 cm⁻¹ peak is also evident for grease B.

At longer test times with grease B (240 h, 110°C, 10,000 rpm) the inner raceway lubricant was not evenly distributed but appeared as a thin transparent film with intermittent ridges of darker material transverse to the rolling direction. The ridges have much higher thickener content, typically 20-25% more than the fresh grease (see Fig. 8, Spectrum 1). The effect of increased severity of the test conditions (120°C, 20,000 rpm) at a similar test time (240–250 h) is seen in Spectrum 2. The grease is severely degraded and both base oil oxidation (1713 cm⁻¹) and thickener degradation (1598 cm⁻¹) peaks are present.

From the limited number of test samples available, it appeared that the higher speed samples had a lower thickener content. It is possible that at the higher rotation speed the thickener is ejected from the track.

Thus, depending on the test condition and the running time, the inner raceway films contained a number of components and these included the thickener and the base oil, the oxidized base oil.

![Fig. 7—IR spectra from the inner raceway for bearings grease A and grease B. 40 h, 10,000 rpm/110°C.](image-url)
Fig. 8—IR spectra from ridge film areas on the inner raceway non-fail bearings grease B. Spectrum 1, 10,000 rpm, 110°C, 240 h. Spectrum 2, 20,000 rpm, 120°C, 250 h.

Fig. 9—IR spectra for failed bearing, 110°C, 20,000 rpm, grease B 783 h.

Grease Condition at Failure

The effect of failure on the grease condition was also examined. In Fig. 9, IR spectra from the shield, the cage pocket, and the inner raceway are shown for grease B for a bearing that failed after 783 h. The grease coverage on the shields varied on either side of the bearing and this is reflected in the oxidation level seen in the IR spectra. The lower coverage shield shows a far higher oxidation level. The corresponding non-fail bearing spectra are shown in Fig. 5 wherein a similar effect is seen. This pattern would suggest that the bearing was running hotter on one side, resulting in loss of grease from the shield. Both the thickener and the base oil are present in the spectrum; the main degradation band...
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Fig. 10—Comparison of IR reflection spectra of the inner raceway films at failure for grease A, 110°C.

at 1713 cm\(^{-1}\) is due to the oxidation of the base oil. The thickener concentration (relative to the normalized CH band at 1460 cm\(^{-1}\)) is much higher in shield 2, indicating the base oil evaporation. The IR spectra from the inner raceway and the cage pocket are very similar and show significant oxidation of both the base oil (1713 cm\(^{-1}\)) and the thickener (\(\sim1600\) cm\(^{-1}\)). The thickener concentration is very high in both spectra, again suggesting loss of the base oil.

The picture that emerges from this work is that base oil oxidation and evaporation loss occur in the grease on the shields; however, this plays little direct role in the failure process. Grease degradation in the cage pocket and raceway regions is more complex and the condition at failure varies with the test condition and time. This can be seen in Fig. 10, which compares the inner raceway spectra from the bearings that failed after 1784 (10,000 rpm) and 186 (20,000 rpm) h. These tests were with grease A at 110°C. The 10,000 rpm sample shows an intense base oil oxidation band at 1713 cm\(^{-1}\) and a thickener oxidation band at \(\sim1600\) cm\(^{-1}\). In contrast, the 20,000 rpm sample shows relatively little base oil oxidation. There is no consistency between the degree of the oxidation/degradation found after failure for the different samples. The 1784-h bearing was able to operate successfully with far greater levels of base oil oxidation as shown by the intense 1713 cm\(^{-1}\) peak. It was observed that if a test had failed relatively early there was a large difference between the failed and non-fail samples. In long-term tests the spectra were very similar.

**DISCUSSION**

**Grease Condition and Distribution**

The IR analysis has shown that the composition of the grease film depends on the position within the bearing and the test condition (speed/duration). To summarize these findings:

(a) Shield lubricant
Most of the grease remaining in the bearing is on the shields. Oxidation of the base oil is the main degradation mechanism, as severe oxidation of the thickener does not occur even at failure. This would imply that the shields are at a significantly lower temperature than the inside of the bearing or that shearing or the presence of metallic debris contributes to thickener degradation. It is also evident from the comparison of the bearing test pair that most of the shield grease degradation occurs during normal operation rather than at failure. Volatile base oil components are lost from the shield sample as the amount of grease present decreases with running time.

In many cases there was plenty of grease remaining on the shields, even for the failed samples, suggesting that this region does not provide an active “reservoir” supplying the lubricant to the track. Degradation and loss of this grease is, therefore, not a necessary precursor to failure. The thickener concentration for short-term operation remains similar to that of the fresh grease. For prolonged test times, severe oxidation/evaporation of the base oil occurs leaving a thin residual varnish layer.

One further observation is that there is no correlation between the oxidation condition (as assessed by IR analysis) of the shield grease and the onset of failure.

(b) Cage pocket
The composition depends on the running time and the test condition. A clear difference is seen between the 10,000 and 20,000 rpm samples. At the lower speed, “ring” deposits are formed of oxidized material, which have a high thickener concentration, suggesting that the degradation of the grease has occurred in the cage pocket/ball shear region. The base oil is lost from this material, leaving an oxidized, thickener-rich film.
At the higher speed, a reduction in the thickener content is observed and the ring formation is not so evident. It is possible that at the higher rotation speed, the thickener is rapidly removed or shear degraded; however, there was little evidence of an oxidized thickener in the sample spectra.

(c) Inner raceway

The films were relatively thin (micron) and patchy, with very little bulk grease present even after 40 h running. In the early stages, both the thickener and the base oil are deposited in the roller track as a thin continuous layer. As the test time increases, this film is sheared/thermally degraded, giving a viscous liquid that would be mobile at the operating temperature. Under severe test conditions, both the base oil and the thickener are oxidized. The 10,000 rpm samples appeared to have a higher thickener content compared to the 20,000 rpm test due to ejection of the thickener from the track at the higher speed.

At failure, the oxidation of both the base oil and the thickener occurs and often there is a relatively higher concentration of the thickener present, again indicating a loss of the base oil. The exceptions to these observations occurred in tests with grease A, where failure occurred relatively quickly. In this case, the raceway films were not heavily oxidized and there was no indication of base oil evaporation/loss. This would suggest that under these conditions the lubrication failure mechanism is different.

**Lubrication Mechanism and Failure**

One of the conclusions from the R2F(M) study (Cann, et al. (11)) was that the base oil was released from the shield grease by the shearing action of the cage and this lubricated the roller tracks. It was noticeable that in these bearings there was free oil present both in the cage pockets and on the outside of the bearing. Significant amounts of free oil were not observed for the R0F bearings. This would suggest that the design and operation of the R2F(M) ensures the continued release of the base oil from the shield grease and thus the provision of the raceway lubricant. Thus, the basic lubrication mechanism in the R2F(M) bearing is the oil release/reflow, although there is evidence of thickener deposition in the early stages of the test.

In the R0F bearing there is very little free oil available and the cage pocket and roller track contain a far higher proportion of the thickener. From examination of the bearings, there was little evidence of continued supply of grease from the shield to the cage pocket/raceway region. Thick films of grease were present on the shields even after extended test times or failure. It is possible therefore that in the R0F bearings the grease is supplied in the first few hours of running, whereas in the R2F the supply continues for a much longer period. In the R2F tests, the thickener was degraded/oxidized grease that contained a significant proportion of the thickener. This material was fluidic at the operating temperature and would have provided efficient replenishment of the contact zone, thus ensuring lubricant film formation.

One of the observations from this work is that the products of the base oil and thickener oxidation/degradation reactions can be distinguished in the IR spectra. Static thermal ageing studies have shown that grease degradation in these tests is dominated by base oil oxidation (IR peaks at 1700-1780 cm\(^{-1}\)). However, the presence of metallic debris was found to accelerate thickener degradation (IR peaks at 1650-1600 cm\(^{-1}\)). The identification of thickener oxidation bands in the cage and raceway spectra suggests that wear debris was present and this had promoted thickener oxidation. In bearings that failed after a long running time, the raceway/cage pocket spectra are dominated by base oil oxidation. In this case, very similar results were obtained from the failed and non-failed bearings, suggesting that the ultimate grease life (where there are no other contributing factors; for example, cage wear/debris formation) had been reached. Under more severe conditions, in bearings that failed after a relatively short running time, the raceway/cage pocket spectra exhibited much greater thickener degradation (see Fig. 9). In this case it might be the thickener degradation rather than the base oil oxidation that determined the lubrication life. The increased severity of the test condition would favor the formation of wear debris, particularly in the cage pocket region. Thus, under more severe operating conditions, it is the anti-wear/boundary additives that will contribute the most to increased grease life.

One of the questions that arises from this study is the nature of the lubrication failure in these tests and whether this changes depending on the running condition. Komatsuzaki, et al. (6) identified the loss of base oil due to the evaporation of the oxidized species as the critical factor in determining failure. However, in tests with grease A where the bearing failed relatively early there was little evidence of oxidation of either the base oil or the thickener. It seems unlikely that failure in this case was due to an inability of the raceway lubricant to maintain a film. Grease A gives a reduced life at high speeds and temperatures and this could reflect the poorer boundary lubrication performance of the grease under these conditions. In longer term tests, the loss of the base oil had occurred and this was usually associated with oxidation of the base oil and the thickener. It is likely, therefore, that the contributing factors that determine failure differ depending on the test condition and it is not possible to identify a single mechanism. Thus, base oil oxidation, thickener degradation, and antiwear/boundary properties will all play a role depending on the test condition.

**CONCLUSIONS**

The aim of this paper was to examine the mechanisms of lubrication failure in rolling element bearings. A series of R0F bearing tests have been run with additized and non-additized greases. The additive package increased L\(_50\) life by 100-700% depending on test condition. Post-test the distribution and condition of the lubricant in the bearing was assessed. The chemical composition was determined by IR spectroscopy. The conclusions are as follows:

1. Grease distribution:
   - Most of the bulk grease is present on the shields; the amount decreases with time.
   - Thin films of degraded grease are present on the inner raceway and cage pocket.
2. Grease degradation—depends on the position and hence local conditions:
Oil degradation in R0F bearing tests involves:

- Oxidation and evaporation of base oil occurs during normal operation throughout the bearing.
- Under more severe conditions, the (cage/raceway) oxidation of the thickener occurs.
- IR analysis of the shield grease does not provide a guide to the lubrication condition of the bearing.

3. After an initial running-in period, the “active” lubricant is heavily degraded grease:
   - Contains oxidized species from the base oil and the thickener.
   - The thickener plays an important role in the lubrication process.

4. R0F lubrication mechanisms:
   - Grease on the shields does not provide a long-term lubricant reservoir.
   - Degradation of the grease in the ball/cage and the ball raceway region is necessary to generate a mobile lubricant for track replenishment.

5. Failure mechanism depends on the test condition:
   - Tests that fail very quickly are due to poor boundary lubrication performance or cage failure.
   - Long-term failure is due to a reduction in the amount/mobility of the raceway lubricant.

REFERENCES