ABSTRACT
Three different lubricating greases and their bleed-oils and base oils were compared in terms of film thickness in a ball-on-disc test rig through optical interferometry. Film thickness measurements of all lubricants, under fully flooded conditions, followed EHL equations and showed that lubricating greases and the corresponding bleed-oils had similar film thickness values. Therefore, bleed oil properties might be used to predict film thickness in grease lubricated thrust ball bearings.

Friction torque measurements of thrust ball bearings were performed in a modified 4-Ball machine under a large range of entrainment speed. The friction torque measurements were used as input in the latest SKF friction torque model in order to predict the rolling and sliding friction torque components. It was assumed, based on the film thickness measurements, that grease lubrication is similar to oil-spot lubrication and it depends on the bleed-oil properties.

The results showed that grease formulation had a very significant influence on thrust ball bearing friction torque and operating temperature. The friction torque depends on the composition, viscosity and pressure-viscosity coefficient of the bleed-oils.

Keywords: grease, bleed-oil, friction torque, film thickness

INTRODUCTION
Influence of grease formulation on its rheological properties and tribological performance is unknown. Most of the published studies on grease behaviour in mechanical contacts are qualitative. To the authors’ knowledge, there are few existent models to predict grease film thickness and friction torque/friction coefficient that take the grease rheological properties into account (Kauzlarich & Greenwood, 1972), (Chapkov, Bair, Cann, & Lubrecht, 2007), (Wang & Yang, 2006). However, these models consider the properties of the fresh grease and its base oil properties, which is not always right. Cousseau et al. (Cousseau, et al., 201X) showed that grease bleed-oil can be substantially different from the grease base oil in terms of composition and properties, namely viscosity and pressure-viscosity coefficient. Besides that, it was shown that grease properties (and bleed-oil properties) change significantly in rolling bearings in the very beginning of the grease life (Cann, 2006), (Cann & Lubrecht, 2007), hence the grease tribological performance also changes.

Therefore, new models to predict grease behaviour in terms of friction and film thickness have to be developed considering bleed-oil properties and their changes with operating time. The bleed-oil is a simple way to take into account the grease formulation, because additives and...
thickener material might be contained in its composition (Cousseau, et al., 201X). Besides
that, the bleed-oil characterization is simple and faster in comparison with grease
characterization, and its variation with operating time is easily monitored.

The first step to reach this objective is the experimental evaluation of the grease and bleed-
oil performance; followed by a complete characterization of the bleed-oil to better
understanding of its behaviour in mechanical contacts.

Here it will be shown that fresh bleed-oil have similar performance than their corresponding
fresh grease in terms of film thickness, therefore the bleed-oil properties will be used to
calculate the bearing friction torque of grease lubricated ball bearings.

METHODS AND MATERIALS

Three lubricating greases and their base oils and bleed-oils were characterized. They were
compared in terms of viscosity, pressure-viscosity coefficient and film thickness.

The lubricating greases are named according to their formulation. LiM1 was formulated with
lithium thickener and mineral base oil; LiCaE was formulated with both, lithium and calcium
thickener and ester base oil; PPAO was formulated with polypropylene thickener, an
unknown elastomer co-thickener and PAO base oil. The additive package of this greases are
unknown. The ester based grease LiCaE passed the test for biodegradability (OECD 301F and
SS155470 class B) and eco-toxicity (OECG 202).

The bleed-oils were obtained according to the modified IP121 standard test method. The
refractive index of the lubricants was measured using an Abbot refractometer at ambient
temperature. Kinematic viscosity of the base oils and bleed-oils were measured in a MCR 301
rheometer with cone-plate geometry at 40 and 80ºC. The densities of the bleed-oils were
measured at 21ºC and the base oils density was provided by the manufacturer. The dynamic
viscosity was obtained with the equation C.4 and C.5 (Appendix C). The film thickness was
measured for all lubricants at 40, 60 and 80ºC under fully flooded condition, SRR=0 and
contact pressure of 0.5GPa. A complete description of the modified IP121 standard method
and the film thickness operating conditions were described in a previous work (Cousseau, et
al., 201X).

All the lubricant characteristics are presented in Table 1.

### Table 1 Uniaxial tension test results

<table>
<thead>
<tr>
<th>Designation</th>
<th>LiM1</th>
<th>LiCaE</th>
<th>PPAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base oil</td>
<td>Mineral</td>
<td>Ester</td>
<td>PAO Polypropylene</td>
</tr>
<tr>
<td>Thickener</td>
<td>Li</td>
<td>Li/Ca</td>
<td>-</td>
</tr>
<tr>
<td>Biodegradability</td>
<td>-</td>
<td>passed</td>
<td>-</td>
</tr>
<tr>
<td>Eco-Toxicity</td>
<td>-</td>
<td>passed</td>
<td>-</td>
</tr>
<tr>
<td>Grease properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLGI number</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Droppingpoint [ºC]</td>
<td>185</td>
<td>&gt;180</td>
<td>&gt;140</td>
</tr>
<tr>
<td>OperatingTemperature [ºC]</td>
<td>-20/+130</td>
<td>-30/+120</td>
<td>-35/+120</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.4965</td>
<td>1.4837</td>
<td>1.4892</td>
</tr>
<tr>
<td>Bleed-oilproperties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific gravity at 21ºC [g/cm³]</td>
<td>0.909</td>
<td>0.919</td>
<td>0.843</td>
</tr>
<tr>
<td>Viscosity at 40ºC [cSt]</td>
<td>192.1</td>
<td>95.43</td>
<td>528.83</td>
</tr>
<tr>
<td>Viscosity at 80ºC [cSt]</td>
<td>28.86</td>
<td>24.98</td>
<td>151.92</td>
</tr>
<tr>
<td>Refractive Index at 25ºC</td>
<td>1.4948</td>
<td>1.4744</td>
<td>1.4639</td>
</tr>
<tr>
<td>Base oil properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific gravity at 15ºC [g/cm³]</td>
<td>0.903</td>
<td>0.952</td>
<td>0.828</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Kinematic viscosity

Kinematic viscosity of base oils and bleed-oils were compared in terms of their relative difference, which is expressed by equation 1.

\[ \Delta \nu = \frac{\nu_{\text{bleed}} - \nu_{\text{base}}}{\nu_{\text{base}}} \times 100 \]  

Three different trends were observed when comparing the \( \Delta \nu \) of the lubricants at 40°C. LiCaE presented \( \Delta \nu = 0 \), indicating the base oil and bleed-oil have similar viscosity values. In the case of grease LiM1, the viscosity of the bleed-oil is 8% lower than the viscosity of the base oil (\( \Delta \nu = -8% \)), while in the case of the grease PPAO the viscosity of the bleed-oil is 1260% higher than the viscosity of the base oil (\( \Delta \nu = 1260\% \)).

Such difference is attributed to the grease formulation. In fact, the co-thickener and the additives may have large affinity with the oil, bleed out together with it during the static bleed oil test and generate a bleed-oil significantly different from the base oil. Furthermore, during the bleed oil test the thickener may pass through the mesh due to the imposed stress and temperature, thus thickening (or thinning) the bleed oil in comparison to the base oil. Therefore, the bleed-oil may contain additives and thickener/co-thickener material that are not present in the base oil, and their amount in the bleed-oil depends on grease formulation.

According to the manufacturer of the PPAO grease, the very high viscosity of its bleed-oil is mainly due to the co-thickener, which is an elastomer with high affinity with the base oil and therefore bleeds out with it during the bleed process. The small values of \( \Delta \nu \) of LiM1 and LiCaE are also assumed to be related with the grease formulation. These greases do not contain an elastomer as a co-thickener and the polymer molecules (viscosity improve additives), which is known to increase the oil viscosity, are lower in concentration when compared with the PPAO.

Film thickness measurements

Figure 1 presents the central film thickness measurements (markers) for different entrainment speeds and temperatures for the lubricating greases, base oils and bleed-oils under fully flooded conditions. The predicted film thickness values (lines) were calculated with equation A.1 and the bleed oil properties. The main observations of these figures are:

- Lubricating greases obeyed the EHL rules, i.e., the film thickness increased with the entrainment speed at a rate of around \( U^{0.67} \), such as predicted by most of the film thickness equations.
- Lubricating greases and their bleed-oils generated similar film thickness values, which are significantly higher than the ones obtained with the base oils.
- The film thickness difference between bleed-oil and base oil increased with temperature.

From the observations above it is possible to conclude that grease film thickness may be predicted with equations developed for lubricating oils ((Chittenden, Dowson, Dunn,
&Taylor, 1985), (Hamrock, Schimid, & Jacobson, Fundamentals of fluid film lubrication, 2004)) if the bleed-oil properties (viscosity and pressure-viscosity) are used. Based on this fact, bleed-oil properties will be calculated using the same rules applied to lubricating oils, and these properties will be used as input in the latest friction torque model developed by SKF(SKF General Catalogue 6000EN, 2005).

Figure 1 – Film thickness versus entrainmentspeed of alltestedlubricant in fullyfloodedconditions at 40, 60 and 80ºC: measuredvalues (markers) and theoreticalvalues (lines)

**Friction Torque Measurements**
Friction torque measurements were carried out in a modified Four-Ball Machine with thrust ball bearings 51107 for the three tested greases. A description of the test rig and test procedure is described by Cousseau et al.(Cousseau, Graça, Campos, & Seabra, Experimental measuring procedure for the friction torque in rolling bearings, 2010). All the bearing tests were running under self-induced temperature conditions, with load of 7000N (P₀≈1.8GPa) and rotational speed varying from 100 to 5500rpm. Figure 2 shows the friction torque values and the operating temperature versus the rotational speed.

Friction torque and operating temperatures are in close agreement. The LiM1 grease has the highest friction torque and operating temperature and the PPAO has the lowest friction torque and operating temperature, while LiCaE has its values in between the LiM1 and PPAO greases.

At 2000rpm, the friction torque and the operating temperature of the grease MG1 were 153.9Nmm and 65.25ºC, while the corresponding values for grease PPAO were 95.13Nmm and 56.28ºC, that is, 38.19% and 13.75% lower, respectively.
ANALYTICAL RESULTS

Pressure-viscosity coefficient

Several authors have proposed equations to predict the pressure-viscosity coefficient: Gold et al. (Gold, Schmidt, Dicke, Loos, & Assmann, 2001), So and Klaus (B. So & Klaus, 1980), Fein (Fein, 1992), among others. The values predicted by these equations, however, show very large differences (> 95%) whatever the base oil considered. This situation, together with the fact that high pressure rheological measurements are difficult and expensive, led to the extrapolation of the pressure-viscosity coefficient from film thickness measurements. Recently, Van Leeuwen (Leeuwen, 2009) compared accurate film thickness measurements with the values predicted by the central film thickness equations proposed by Hamrock et al. (Hamrock & S. R. Schmid, Fundamentals of fluid films lubrication, 2004); a correlation of $R^2 > 97\%$ was found. The same method was used here and the obtained pressure-viscosity coefficient values are presented in Table 2. The film thickness equation used to predict the $\alpha$-value is presented at the appendix A (Eq. A.1).

<table>
<thead>
<tr>
<th>Base oil</th>
<th>LiM1</th>
<th>LiCaE</th>
<th>PPAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 40°C</td>
<td>28.4</td>
<td>16.1</td>
<td>22.0</td>
</tr>
<tr>
<td>@ 60°C</td>
<td>26.7</td>
<td>13.5</td>
<td>16.2</td>
</tr>
<tr>
<td>@ 80°C</td>
<td>20.8</td>
<td>11.2</td>
<td>12.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bleed-oil</th>
<th>LiM1</th>
<th>LiCaE</th>
<th>PPAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>@ 40°C</td>
<td>42.1</td>
<td>27.9</td>
<td>2.41</td>
</tr>
<tr>
<td>@ 60°C</td>
<td>36.8</td>
<td>24.3</td>
<td>2.17</td>
</tr>
<tr>
<td>@ 80°C</td>
<td>35.9</td>
<td>20.9</td>
<td>2.61</td>
</tr>
</tbody>
</table>

The pressure-viscosity coefficient of base oils and bleed-oils are substantially different. While the bleed-oils of the lithium greases (LiM1 and LiCaE) have pressure-viscosity coefficient up to 86% higher than the base oils, the PPAO bleed-oil has a pressure-viscosity coefficient up to 89% lower than the base oil. According to the grease manufacturer the same elastomer that increased the PPAO bleed-oil viscosity (see Table 1) to improve its film formation ability, reduces significantly its pressure-viscosity coefficient to reduce the COF (See Table 2). The influence of polymer molecules on pressure-viscosity reduction has already been published by Novak et al. (Novak & Winer, 1986). However the influence of lithium and calcium thickeners and the additive package on the $\alpha$-value is unknown.
Rolling and Sliding Friction Torques
The SKF friction torque model was correlated with the experimental torque values to determine the rolling (Mrr) and sliding (Msl) bearing torque. The equations and constants for grease or oil-spot lubrication are exactly the same. It indicates that the SKF model, most likely assumes that grease lubrication is governed by the oil released from the grease during operation and therefore, the equations and constants considering oil-spot lubrication and the bleed-oil properties were used in this work. The SKF model for oil-spot lubrication is described in the Appendix B.

ASTM D341 was used to describe the dependency of the kinematic viscosity with the temperature and Roelands’ equation was chosen to determine the dependency of the pressure-viscosity coefficient with the temperature at the convergent (see appendix C). The measured and calculated kinematic viscosity and pressure-viscosity coefficient of the bleed-oils are presented in Figure 3.

![Figure 3 - Y-axis: Calculated kinematic viscosity (continuous line with not filled markers); Calculated pressure viscosity (dotted lines with not filled markers); Measured kinematic viscosity (filled markers). Measured pressure-viscosity coefficient (filled markers). X-axis: Operating temperature.](image)

Figure 3 shows the calculated rolling and sliding friction torque. The kinematic viscosity presented in Figure 3 is used as input in the model, however the pressure viscosity is not considered in the SKF model, which is known to be wrong.

![Figure 4 - Thrustball bearing rolling torque (left) and sliding torque (right) versus therotational speed.](image)

The rolling and sliding torque depend on the lubrication regime. The lubrication regime can be calculated by equation 2 or 3, where the latest is found at the SKF general catalogue (SKF...
General Catalogue 6000EN, 2005). The results obtained with both equations are presented in Figure 5.

$$\Lambda = \frac{H_{oc}}{\sigma}$$  \hspace{1cm} (2)  \hspace{1cm} K = \frac{V}{V_i} \times 100$$  \hspace{1cm} (3)

![Figure 5 – Specific film thickness $\Lambda$ (left) and viscosity ratio $K$ (right) versus rotational speed](image)

Large differences are observed when the two models are compared. The one with better agreement with the rolling torque is the viscosity ratio $K$. This is because both of these equations do not take into account the $\alpha$-value (see Eq. B.1 and Eq. 3).

The rolling torque depends mainly on the bleed-oil viscosity (consequently the viscosity ratio $K$). The highest the viscosity, the highest is the rolling torque. However, if the viscosity is too high at the operating temperature and high speeds, the inlet shear heating ($\phi_{ish}$) and the replenishment factor ($\phi_{rs}$) become very significant, reducing significantly the rolling torque. The lithium greases (LiM1 and LiCaE) were not very influenced by these factors ($\phi_{ish}$, $\phi_{rs}$), and therefore the same trends were observed between the Mrr and $K$. However, the PPAO rolling torque is reduced up to 6.5 times due to $\phi_{ish}$ and $\phi_{rs}$, while the maximum reduction of the lithium greases was only 1.37.

The sliding torque depends mainly on the pressure-viscosity coefficient when $K>2$ and the additive package when $K<2$. It is in agreement with the pressure-viscosity coefficients obtained from the film thickness measurements.

**CONCLUSIONS**

The mechanism of grease lubrication can be simplified considering oil-spot lubrication once lubricating greases release some oil during operation, and this oil (bleed-oil) lubricates the contact. Such theory/assumption was already claimed for several authors (Booser & Wilcock, 1953), (Wikström & Höglund, 1996) and it has been used in the latest SKF friction torque model (SKF General Catalogue 6000EN, 2005). This model takes into account the base oil properties. However, the large differences observed between base oil and bleed-oil properties and the similarity between the film thickness values of lubricating greases and their bleed-oils indicate that it would be more suitable to use the bleed oil properties. It gets rise to a new and very simple approach to predict grease film thickness and friction torque. However, the bleed rate under usual bearing operating conditions is not well known and its influence on the lubrication mechanism is dominant, and therefore, has to be investigated.
APPENDIX A – Film thickness

The Hamrock et al. centre film thickness equations are described as follow.

\[ H_{oc} = 1.345 \cdot R_s \cdot U^{-0.67} \cdot W^{0.53} \cdot \omega^{-0.067} \cdot C_0 \] (A.1)

\[ U = \frac{\eta_0 \cdot (U_1 + U_2)}{2 \cdot R_s \cdot E^2} \] (A.2)

\[ W = \frac{2 \cdot F_N}{R_s^2 \cdot E^2} \] (A.3)

\[ G = 2 \cdot \alpha \cdot E^* \] (A.4)

\[ C_0 = 1 - 0.61 \cdot e^{\left(-0.752 \left(\frac{R_s}{R_c}\right)^{0.64}\right)} \]

APPENDIX B – SKF Friction Torque Model

The SKF friction torque model is described below for thrust ball bearings 51107 and oil-spot lubrication. The total friction torque (Mt) is given by the sum of the rolling (Mrr') and the sliding torque (Msl).

\[ M_t = \left[ \varphi_{sl} \cdot \varphi_{rr} \cdot G_{rr} \cdot (\nu \cdot n)^{0.6} \right] + \left[ G_{sl} \cdot \mu_{sl} \right] \] (B.1)

\[ G_{rr} = R_s \cdot d_m^{1.83} \cdot F_a^{0.54} \] (B.2)

\[ G_{sl} = S_1 \cdot d_m^{0.05} \cdot F_a^{4/3} \] (B.3)

\[ \mu_{sl} = \varphi_{bl} \cdot \mu_{bl} + (1 - \varphi_{bl}) \cdot \mu_{EHL} \] (B.4)

\[ \varphi_{bl} = \frac{1}{e^{2.6 \cdot 10^{-3} (n \nu)^{1/4} d_m}} \] (B.5)

\[ \varphi_{slh} = \frac{1}{1 + 1.84 \times 10^{-5} \left(n \cdot d_m\right)^{1.28} \nu^{0.64}} \] (B.6)

\[ \varphi_{rr} = \frac{1}{\exp \left[k_{rr} \cdot \nu \cdot n \cdot (d + D) \sqrt{\frac{K_z}{2(D - d)}}\right]} \] (B.7)
APPENDIX C – viscosity and pressure-viscosity coefficient

ASTM D341 was chosen as the description of the kinematic viscosity with the temperature.

$$\log\log(\nu + a) = n - m\log(T)$$  \hspace{1cm} (C.1)

It follows from Eq. (C.1) that 2 kinematic viscosity measurements are enough to calculate the viscosity at a given temperature, once it is known that the constant $a=0.70$.

The pressure-viscosity coefficient, according to Gold et al. is obtained from

$$\alpha = \frac{\ln \eta(T,0.2\text{GPa}) - \ln \eta(T,P_{\text{atm}})}{0.2 \text{ GPa}}$$  \hspace{1cm} (C.1)

In the context of the Roelands’ equation

$$\ln \frac{\eta}{\eta_0} = (\ln \eta_0 + 9.67) \cdot \left\{ \left( \frac{T-138}{T_0-138} \right)^{S_0} \cdot \left( 1 + \frac{p}{0.196} \right)^Z - 1 \right\}$$  \hspace{1cm} (C.2)

this becomes

$$\alpha = \frac{(\ln \eta + 9.67)(2.0204+Z-1)}{0.2 \text{ GPa}}$$  \hspace{1cm} (C.3)

Then, from the definition of kinematic viscosity, one can obtain the dynamic viscosity from:

$$\eta = \rho \nu$$  \hspace{1cm} (C.4)

Where $\rho = \rho(T_0) \cdot \left( 1 - \frac{T-T_0}{1250} \right)$  \hspace{1cm} (C.5)

For the determination of the $Z$ material parameter, at least one measurement of the dynamic viscosity at non-atmospheric pressure would be needed or, alternatively, at least one measured value of pressure-viscosity coefficient. Therefore, the 3 pressure-viscosity coefficients (see Table 2) calculated through the film thickness measurements for all lubricating greases were used here. The average of the three $Z$ values is presented in Table C.1. Those values were used at equation C.3 to obtain the variation of the pressure-viscosity coefficient with the temperature.

<table>
<thead>
<tr>
<th>Material parameter $Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Z</td>
</tr>
</tbody>
</table>

APPENDIX D – List of symbols

- $C_0$: ellipticity influence parameter [-]
- $d_{m}$: bearing mean diameter [mm]
- $E^*$: equivalent young’s modulus [GPa]
- $F_{N,A}$: normal/axial force [N]
- $G$: material parameter [-]
- $G_{fr/d}$: factor that depends on the bearing type, bearing mean diameter and applied load [-]
- $H_0$: centre film thickness [$\mu$m]
- $K$: viscosity ratio [-]
- $K_z$: bearing type related geometry [3.8]
- $K_{RS}$: Replenishment/starvation constant [$6.10^{-8}$ for grease and oil-spot lubrication]
M_{rr} rolling friction torque [N.mm]
M_{sl} sliding friction torque [N.mm]
M_t total bearing friction torque [N.mm]
M_{exp} bearing friction torque measured experimentally [N.mm]
n rotational speed [rpm]
n_m_a lubricant parameters for viscosity calculation [a=0.7]
p pressure in the convergent [considered 0.2GPa]
Z material parameter of Roeland´s equation [-]
R_x equivalent radius [mm]
R_1 geometry constant of rolling frictional moment \[8.446 \times 10^{-7}\]
S1 geometry constant of sliding frictional moment \[0.0101\]
T temperature [ºC]
T_0 reference temperature [ºC]
U speed parameter [-]
U_{1,2} Speed of body 1 and 2 [m/s]
W load parameter [-]
Λ specific film thickness [µm]
α pressure-viscosity coefficient [GPa⁻¹]
η dynamic viscosity at the operating temperature [mPa/s]
η_0 dynamic viscosity at the reference temperature [mPa/s]
ρ density [g/cm³]
φ_{ish} inlet shear heating reduction factor [-]
φ_{rs} kinematic replenishment/starvation reduction factor [-]
φ_{bl} weighting factor for the sliding frictional moment [-]
σ composed roughness [µm]
µ_{bl} coefficient depending on the additive package in the lubricant [-]
µ_{EHD} friction coefficient in full film conditions [-]
µ_{sl} sliding friction coefficient [-]
ν kinematic viscosity at the operating temperature [mm²/s]
ν_0 kinematic viscosity at reference temperature [mm²/s]

ACKNOWLEDGEMENTS

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