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The ROF+ methodology for grease life testing

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Abstract

Very often, the service life of grease lubricated rolling bearings is determined by the so called “grease life”. This can be tested on ROF test rigs, which have been available for this since more than 40 years. Recently, this technology has been updated and is now called ROF+. The ROF+ can be used as a reference for grease life/relubrication intervals or as a research tool. In this paper a description of the test rig and the test methodology will be given. Also the reliability of the rig will be described by means of a comparison of six test rigs. The test philosophy will be illustrated using the so-called “traffic light” and the “grease performance factor” concepts. The ROF+ goes beyond “standard grease life testing”. The rig is a most valuable tool in grease lubrication research due to its flexibility in varying load, speed, temperature and bearing type. This will be illustrated with some examples.

Introduction

Ideally, a rolling bearing would be lubricant free. However, this would cause high levels of friction and a very short life. A lubricant is generally applied in an attempt to develop a film between rolling elements and rings which accommodates for the shear which results from (micro) slip. When comparing oil with grease lubrication, the mechanisms for generating this film are essentially different. In the case of oil lubrication the film is mainly determined by the speed and oil viscosity and in most cases the prediction of the thickness of this film is straightforward using film thickness formula (e.g. Nijenbanning [1]). Generally oil is circulating through the bearing which refreshes the lubricant in the contacts and the active lubricant viscosity/chemistry will therefore not change very much in time.

In the case of grease lubrication this is different: no simple film thickness formulas exist, the lubricant on the track is less mobile, the grease in the bearing “ages” and the service life of the bearing is therefore very often determined by the life of the grease (called grease-life). This specifically applies to sealed bearings. If re-lubrication is possible the active grease may be replaced on a regular basis. So for both sealed and open bearings it is important to know the grease life: to calculate the service life of the bearing or for determining the re-lubrication intervals.

Due to the complexity of the grease lubrication mechanism it is not possible to predict grease life with calculations based on physical models only (as yet). Calculations are based on empirical models which are based on extensive testing (e.g. [2,3,4,5,6]).

The most common way of grease life testing is done by running a grease lubricated bearing until the grease is no longer able to lubricate the bearing. The point in time at which this happens may be a point of debate. Various criteria are used for this, the most common being the point in time where excessive vibrations occur, the temperature rises or when the bearing torque increases.

Today there are a number of grease life test methods which are either commonly used or have been standardized. For ball bearings the best known being the FE9 grease life test method (DIN 51 821), based on Angular Contact Ball Bearings and ROF based on Deep Groove Ball Bearings. For line contact bearings test rigs are also available (FE8, R2F, obsolete standard DIN 51 806) but these are mostly used for functional testing.

Due to the evolution of both bearing and grease technology the ROF test methods required an update. There is a trend for running grease lubricated bearings at higher temperatures and there is a need to test greases in a wide variety of bearing types. A re-design of the ROF has taken place which has led to the ROF+. This makes it possible to test grease for both ball and roller bearings and at high temperatures and also at various load conditions. In this paper both the rig and test methodology will be described. The paper will be concluded with some examples.

The grease lubrication mechanism

There are two successive phases in bearing grease lubrication: the churning phase and the bleeding phase. The churning phase starts immediately after starting the bearing with fresh grease. In this phase there is still a significant volume of grease in-between the rolling elements where it is flowing/churning until most of the grease is pushed to the side of the bearing. This phase is characterized by relative high levels of friction torque. During the bleeding phase, the grease has found its position in so-called reservoirs and small quantities of lubricant are transported into the running track by either bleeding or shear (Cann et al. [7]). The film thickness is determined by the available lubricant in front of the contacts (starved lubrication) and is therefore given by a feed and loss mechanism (Wikström and Jacobson [8]). Residual layers of thickener material may contribute to the development of the film, Cann [9].
The grease will change its physical and chemical properties in time, generally referred to as "aging" and the feed rate to the contacts will deteriorate leading to insufficient lubrication leading to "failure". Fortunately the process is not as simple and deterministic as described above. There are additional mechanisms that may cause occasional replenishment, which makes the deterioration process less dramatic [10]. Nevertheless, in grease lubricated bearings, the grease is often the weakest component, determining the service life. A more extensive description of the lubrication mechanism can be found in [11].

The traffic light concept

The life of the grease is obviously determined by the quality of the grease. However, it is also determined by the design and quality of the bearing. For engineering purposes, in the bearing manufacturers' catalogues the bearing geometry complexity is generally reduced to a mean diameter reflecting the pitch diameter. The bearing speed is given by the product of rotational speed and mean diameter, ndm, which can be regarded as an estimate of the rolling element or cage speed. Very roughly, the grease life can be written as $\ln L \propto (nd_m)^{-1}$ at a certain temperature and the temperature dependence as $\ln L \propto T^{-1}$. The temperature dependence will not come as a surprise: grease life shows Arrhenius behavior, typically used to describe first order chemical reactions but also quite similar to the change of viscosity with temperature.

All this only applies in the temperature range for which the grease has been designed. This temperature range is determined by what is called the "Low Temperature Performance Limit" (LTPL) and the "High Temperature Performance Limit". Within this range the bearing may be operated for longer times and grease life is predictable. Exceeding these temperatures is allowed but with a penalty on grease life (Smith and Wilson [12]). At no time the dropping point temperature should be reached. This concept is also called the "traffic light concept" [2] as depicted in figure 1.

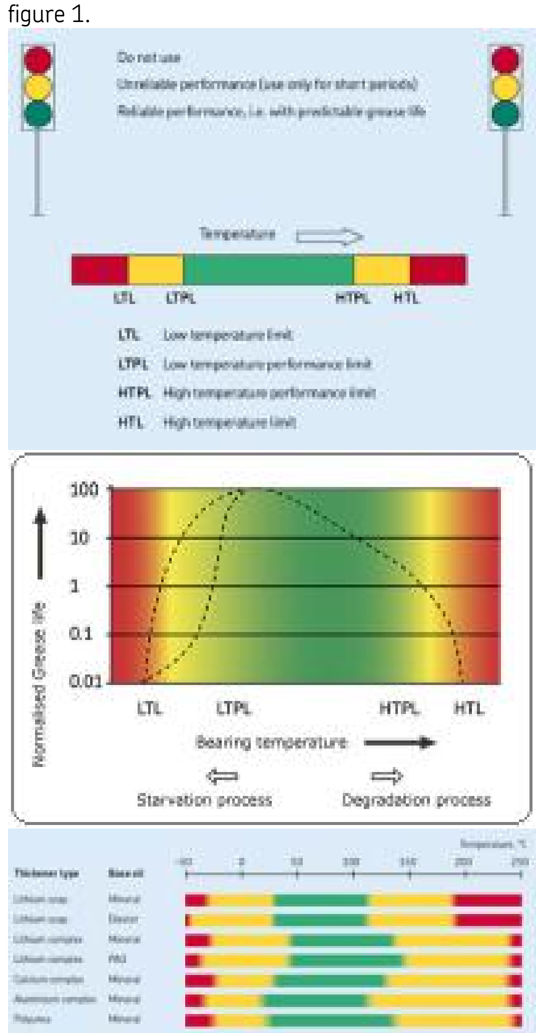


Figure 1. Traffic light concept [2].

The ROF+ machine is used to determine the HTPL of a grease by measuring the grease life L up to the temperatures where $\ln L \propto T^{-1}$ no longer applies.

Bearing factors, lubrication of line contact bearings

According to all major bearing manufacturers' catalogues some bearing types are "easier" to lubricate than others where ball bearings are the "easiest" to lubricate. This is reflected into so-called "bearing factors". These factors should be considered as a rule of thumb though. Comparing is difficult because, in general, ball bearings require different greases than roller bearings, e.g. greases for roller bearings should have a higher bleed rate, Kühl [13]. The ROF+ has been designed to make it possible to test greases for a wide variety of bearing types: Deep Groove Ball Bearings (DGBB), Angular Contact Ball Bearings (ACBB), Tapered Roller Bearings (TRB), and Spherical Roller Bearings (SRB).

Description of the ROF+ test rig

The ROF+ test rig is an upgrade of the ROF test rig which had been in operation for more than 40 years. ROF stands for **R**ig with size **O** (small) for **F**ett (Swedish word for "Grease"). Although the ROF is an excellent tool for grease qualification testing, there was a need for flexibility in operating conditions and bearing types to accommodate for the increasing demands on grease performance and to be able to use the rig as a research tool.

Figure 2. The ROF+ set-up: five units, where each unit contains two test bearings.

In the new ROF+ all input parameters (speed, radial load, axial load and temperature) are continuously variable. Signals such as temperature but also motor and heater power can be monitored online and stored for post-processing. This gives much more information about the time and cause of failure.

The SKF ROF+ grease testing machine essentially consists of two parts (see figures 2 and 3):
a mechanical test unit and a PC with control and evaluation software. The mechanical unit contains five cast-iron housings. Each housing contains two test bearings, mounted on a shaft; the total number of test bearings is ten. Various test bearings can be used. In order to fill the bearings with different greases, the shields for DGBB are delivered separately. The shaft is rotated by a frequency controlled electrical motor.
The cast-iron housing contains two test bearings heating elements, where temperature probes check and calculate the test temperature. For control and evaluation, a PC with the new ROF+ software is used.

Figure 3. ROF+ test unit.

In each unit the grease is tested in ten bearings under preprogrammed temperature, speed and loading conditions. The test parameters can be easily set via the control and evaluation software.
The speed is variable between 5 000 and 25 000 rpm and is constant during the test cycle. The test temperature can vary from room temperature up to 230 °C.
The radial load (Fr) is 50 ... 900 N/bearing.
The axial load (Fa) is 100 ... 1 100 N/bearing.
Fa/Fr is adjustable pneumatically and constant during one specific test cycle out of maximal 20 test cycles.
The test bearings 6204, 6203, 6202, 608 (DGBB), NU 204 (CRB), 7204 (ACBB), 30304 (TRB) and 22220 (SRB) are standard bearings, partly with separate shields.
As a standard, heating elements and bearings speed are switched on simultaneously. The temperature at each bearing is individually controlled by means of a thermocouple. When the test-temperature increases beyond preprogrammed limits, the unit involved will be switched off automatically (Sudden Death Test). The other units will continue running.

Weibull statistics and Sudden Death testing

Rolling bearing life, whether fatigue or grease, in a population of identical bearings, is a random variable, which is generally described using a Weibull distribution [14,15]. The application to rolling bearing testing has been described in e.g. Harris [16]. In this paper a summary dedicated to ROF(+) will be given.
The basic relationship between the life probability of survival and the time of operation is

$$L_p = \eta \left(\ln \frac{100}{100-p} \right)^{1/\beta}, \qquad (1)$$

where Lp is the expected life at a given reliability 100-p, p is the percentile of failures, η is the scale parameter and β is the shape parameter (also referred to as the "Weibull slope").

By using the so-called maximum likelihood method the Weibull parameters η and β can be determined using *n*, the number of units tested (*n=5*) and *r*, the number of failures (*r=5*) failing at time t_i:

$$\frac{1}{\hat{\beta}} + \frac{\sum_{i=1}^{n} \ln t_i}{r} - \frac{\sum_{i=1}^{n} t_i^{\hat{\beta}} \ln t_i}{\sum_{i=1}^{n} t_i^{\hat{\beta}}} = 0 \qquad (2)$$

$$\hat{\eta} = \left(\frac{1}{r} \sum_{i=1}^{n} t_i^{\hat{\beta}} \right)^{1/\hat{\beta}} \qquad (3)$$

For grease life, the shape parameter β is generally higher than for bearing (fatigue) life, typically β=2.3 (Huiskamp [17]), whereas for bearing fatigue life about 1.1 (Harris [16]) .

A large number of samples are required to make an accurate estimate of the Weibull parameters.
This is costly and time consuming. Therefore a balance needs to be made between accuracy and costs. A good balance is found in the ROF+ machines where five failures may be obtained at the end of the test. Mean or median values and 90 % confidence intervals for the Weibull parameters can be calculated, which can be translated into median/mean values and confidence intervals for the life percentiles.

Generally L_{50} (the time at which 50 % of the bearing population has failed) is used as a measure for grease life. By taking L_{50}, the smallest confidence interval is obtained, Andersson [18]. If a higher reliability is required, more bearings need to be tested, either by using more machines or by testing sequential.

According to McCool [19], the median unbiased value for β can be estimated as

$$\beta'' = \hat{\beta} / v_{0.5} \qquad (4)$$

With vp is a pivotal function. A second pivotal function up is introduced to calculate point and life estimates, McCool [19]. Here p is the percentile.

$$L_{50}'' = \hat{L}_{50} \exp\left[-\frac{u_{0.50}(p=50)}{\beta''} \right] \qquad (5)$$

These pivotal functions are calculated using Monte Carlo simulations using a very large number of samples. Extensive tables for these pivotal functions can be found in the literature. For this paper it suffices to give four values only: $v_{0.05}$ =0.67, $v_{0.95}$ =2.89, $v_{0.5}$ =1.24 and $u_{0.05}$=-1.24, $u_{0.95}$=0.65,$u_{0.5}$= -0.12. The 90 % confidence intervals can be calculated using:

$$\hat{L}_{50} \exp\left(-\frac{u_{0.95}}{\beta''} \right) < L_{50} < \hat{L}_{50} \exp\left(-\frac{u_{0.05}}{\beta''} \right) \qquad (6)$$

and

$$\frac{\hat{\beta}}{v_{0.95}} < \beta < \frac{\hat{\beta}}{v_{0.05}} \qquad (7)$$

On the ROF+ machine the bearings are tested *in pairs*. As soon as one of the two bearings in a unit has failed the unit is stopped. The information of the un-failed bearing can well be used in the analysis. After all, the grease in this bearing will have a life that is longer than that of the grease in the failed bearing. This test strategy is generally referred to as "Sudden Death Testing" and is used to reduce the test time and increase the precision (it decreases the values of u in equation 6). This is clearly a strong advantage of the ROF+ machine.
Again equation (3) can be used to calculate the estimate of the scale parameter η, with $r=l$ and $n=2l$ so that in the sum each value of t_i appears twice. This means that the corrected scale parameter now reads:

$$\eta' = \eta \cdot 2^{1/\beta} \qquad (4)$$

Example/illustration

This can be illustrated using the test data from a typical ROF test from table/figure 5 which had individual failures at 278, 347, 396, 646 and 737 hours (test ROF1). Using equations 2 and 3 this gives $\hat{\beta} = 2.98$ and $\hat{\eta} = 541.2$ hours.
Equation (1) gives the percentile life for the failed population L_{50}:
$\hat{L}_{50} = \hat{\eta}\,(\ln 2)^{1/\beta} = 478$ hours.
The bearings were running in pairs where only one of the bearings had failed, so by using equation (4) the corrected scale parameter reads:
$\eta' = 541.2 \cdot 2^{1/2.98} = 683$ hours and therefore the corrected life reads $L_{50}' = 603$ hours.
Equation (4) is used to calculate the median unbiased value for the shape parameter:
$\beta'' = 2.98 / 1.24 = 2.4$
and equation (5) for the median unbiased 50 % percentile life:

$$L_{50}'' = 603 \exp\left[-\frac{-0.12}{2.4} \right] = 634\ hours$$

The 90 % confidence intervals for L_{50} and β can be calculated with equations (6) and (7).

$$604 \exp\left(-\frac{0.81}{2.98} \right) < L_{50} < 604 \exp\left(-\frac{1.54}{2.98} \right)$$

so:
$460 < L_{50} < 1011$ hours.
With the ROF+ machine also software is provided that automates these calculations and makes it possible to easily calculate other life percentiles (such as L_{01}, L_{10}, etc). Note that the values for the pivotal functions given above are only valid in the case of five failures. In the case of less failures (the

test is stopped earlier) different numbers should be used. However, this is included in the software.

Test strategy

The test bearings are thoroughly cleaned and filled with grease. The filling rate may vary but a standard filling would be 1.4 gram for a 6204-2Z bearing corresponding to 30 % of the free space in the bearing for a standard Li-grease. The bearings are manually rotated clock and anti-clock wise for a few revolutions to ensure a proper distribution of the grease in the bearing. A choice on running-in needs to be made and may be recommendable for speeds exceeding 15 000 rpm for ball bearings. In general the bearings are kept at a constant temperature for which the heating elements are only switched on at the start of the test. This means that the bearings will run at a relatively low temperature during some first minutes. However, at this phase, the churning of the grease will generate heat and shorten the time needed to reach the test temperature. The bearings will run until the grease is no longer able to provide sufficient lubrication, which is measured through an increase of temperature or unacceptable increase in motor torque. The temperature increase criteria for ball bearings is 10 °C and for line contact bearings 20 °C, the reason being that roller bearings are more susceptible to heat generation during the churning phase which will increase the probability of an overshoot in temperature here which would cause the machine to stop before reaching the bleeding phase.

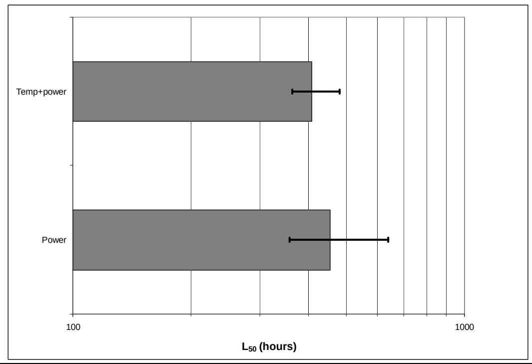
Often grease life is so long that unacceptable test times will arise. A generally applied way to shorten this is to increase the test temperature and extrapolate to the required temperature using Arrhenius' law or several tests done at various temperatures. This is justified as long as testing is done in the green zone. Another way would be to increase the speed. This is only acceptable in the domain in which $\ln L \propto \left(n \cdot d_m\right)^{-1}$ applies. Great care should be taken here. It is most important that failures will not have occurred in the churning phase (especially for extrapolation test results to lower speeds). All-in-all one may say that a sufficiently long test times is always required, say, longer than 500 hours. This is an important aspect when planning for tests.

Reliability of the R0F+ test rig

The reliability of the R0F+ test rig may be determined from a comparison to the earlier version R0F and to other R0F+ test rigs. A main difference is the stop-criteria that is/are used: temperature or/and motor power.

Stop criteria based on temperature and on torque

As mentioned above, the end of grease life is determined by the point in time where the grease is no longer able to lubricate the bearing. This manifests itself by a drastic increase in friction torque and by heat development that is higher than that of the external heaters resulting in a temperature that is higher than the pre-set temperature level. Two tests on R0F+ test rigs using SRBs have been done to compare the stop criteria. In one test, motor power was the only criterion, in the other test the temperature. The results are shown below in table/figure 4:



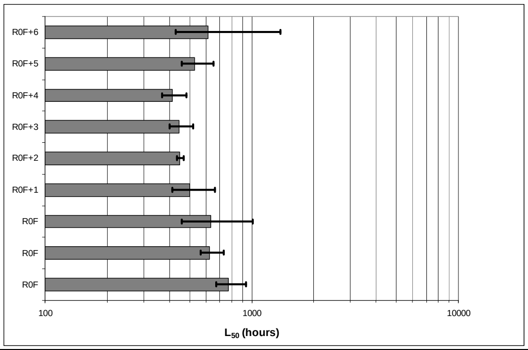
Criterion	L_{50}	L_{50} Confidence intervals		β
		5%	95%	
Power	454	358	639	3.27
Temp+power	407	363	479	6.83

Table/figure 4. Impact of stop criteria on grease life for R0F+. The tested grease is a Li-soap with mineral base oil grease. 22205E bearing, Fr= 900 N; n=5600 rpm and T=130 °C.

Table/figure 4 clearly shows that both temperature and motor torque increase can be used as a stop criterion. An argument to increase the number of stop criteria is that this could make them more definite, increase the Weibull slope and therefore decrease the 90 % confidence intervals.

Reliability of the test rigs

In order to investigate the reliability of the test rigs six R0F+ batteries have been run with an NLGI 2, Li-complex grease with ester base oil. The standard 6204-2Z bearings were run at 10 000 rpm and at 150 °C. The test results are shown in table/figure 5.

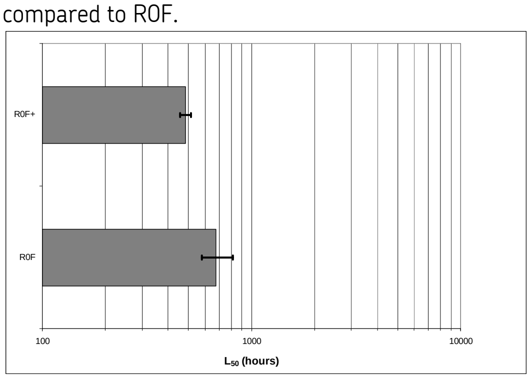


	L_{50}	L_{50} Confidence intervals		β
		5%	95%	
R0F3	772	675	937	5.7
R0F2	625	566	731	9.2
R0F1	635	460	1 011	2.4
R0F+1	502	414	663	4.0
R0F+2	448	434	470	24
R0F+3	445	400	520	7.2
R0F+4	412	369	482	7.1
R0F+5	530	460	651	5.4
R0F+6	615	428	1 375	2.3

Table/figure 5: Test results showing the reliability of the R0F+ test rigs

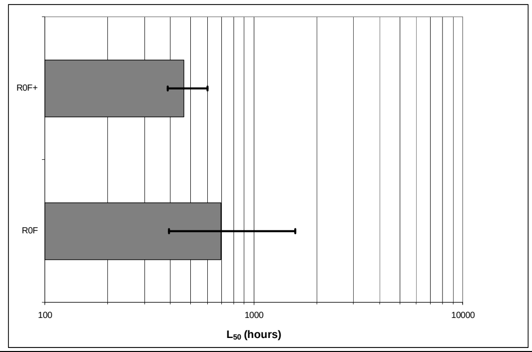
The 90% confidence levels overlap and clearly no significant difference can be observed in L_{50}.

A more accurate comparison could be made by increasing the number of tests bearings. By assuming that all test-units are identical the 60 bearings tested on the R0F+ can be treated as a single test population and the same can be done for the 30 bearings tested on the R0F. Figure/table 6 shows the result of the Weibull analysis for this. Indeed, the 90% confidence intervals are very small now. The R0F+ gives a slightly shorter L_{50} and a higher value for β, compared to R0F.



	L_{50}	L_{50} Confidence intervals		β
R0F	679	577	815	2.8
R0F+	483	456	514	5.2

Table/figure 6: Weibull evaluation using 60 R0F+ bearings and 30 R0F bearings, to compare the R0F+ with R0F.



	L_{50}	L Confidence intervals		β
CRB		5%	95%	
R0F	696	394	1586	1.4
R0F+	463	388	600	4.3

Table/figure 7: CRB tests : Diurea grease with mineral base oil. NJ 204 ECP, Fr=200 N radial load, n=15 000 rpm, T=150 °C.

Table/figure 7 shows a comparison between the R0F and R0F+ for Cylindrical Roller Bearings (note that special measures needed to take place to load the R0F with 200 N). The results are not significantly different, although similar to DGBB, again for R0F+ the L_{50} is lower and the β higher.

The Grease Performance Factor concept and R0F+

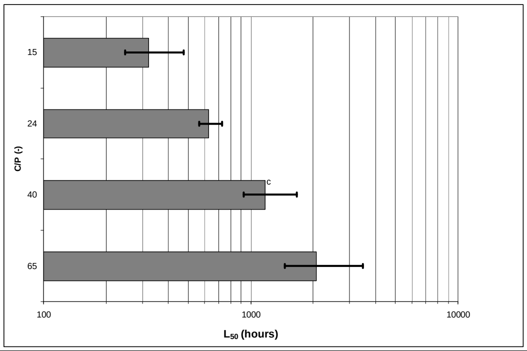
For the prediction of grease life the bearing manufacturers have published grease life diagrams for engineering purposes. These diagrams are bearing specific but not grease specific. Terms like “good quality Li-grease” are used without specifying the exact formulation or giving the performance of different greases. For the qualification of specific greases the so-called “Grease Performance Concept (GPF)” for deep groove ball bearings has been introduced by Huiskamp [17]. A grease is tested on the R0F/R0F+ and compared to a “good quality Li-grease”. If GPF>1 then this particular grease outperforms the standard grease on the R0F/R0F+.

Examples:

Impact of load on grease life for DGBB

To illustrate the flexibility of the R0F+ test rig briefly, a study on the impact of load on grease life is shown in figure/table 8. Again 6204-2Z bearings where used, running at 15 000 rpm and 130 °C.

The lubricant was a standard Li-soap mineral oil grease and the (pure radial) bearing load varied from Fr=208 to Fr=900N, corresponding to C/P=65 down to C/P=15.



C/P	L_{50}	L_{50} Confidence intervals		β
		5%	95%	
65	2080	1456	3478	2.2
40	1176	922	1669	3.2
24	625	564	726	7.5
15	322	247	475	2.9

Figure/table 8. Impact of load on grease life as measured on the ROF+.

Impact on speed on grease life for DGBB

Another test parameter which can be varied in the ROF+ test methodology is the speed. The range in speed is from 3 500 up to 25 000 rpm.
Historically typical electric motor bearing applications are running at about 300 000 nd_m corresponding to about 10 000 rpm, which has become a standard test speed. However, for industrial applications the speed is often higher with a speed range from 300 000 up to about 800 000 nd_m, sometimes in combination with higher temperatures. Both parameters can be tested *with limited test time* by subjecting lubricants first to normal speed (10 000 rpm) and relatively high temperature (170 °C) test conditions, and next to higher speed and lower temperature, i.e. in general at 20 000 rpm and 140 °C. The results are shown in table 9.

Grease Oil type	Temperature [°C]	Speed [rpm]	L_{50} (hours)	GPF
A = Ester	170 140	10 000 20 000	895 503	3.3 3.8
B = Ester	170 140	10 000 20 000	3 760 400	13.3 3.0
C = SHC+ADE	170 140	10 000 20 000	1 020 1 740	3.6 13.3
D = mineral+SHC	170 140	10 000 20 000	683 1 480	2.5 11.1

Table 9. Polyurea high temperature greases tested on the ROF.

Note that these types of tests can be performed with both the ROF and the ROF+ test rigs. The results show that the greases C and D have high speed lubrication potential, as expressed in increased GPF values.

Conclusions

In grease lubricated bearings the life of the grease very often limits the service life of the bearing. Grease life is a function of the quality of the grease and of the bearing. Both can be tested on the ROF+. The test methodology typically applies to medium speeds and higher temperatures. A wide variety of bearing types can be tested.
For grease life the spread in life is smaller than for bearing life (Weibull slope is larger) which reduces the need to test a very large population of bearings. The test population is large enough to do a statistical analysis of the results and the concept of two test bearings per shaft (so 5x2 bearings) increases the precision and reduces the required test time.

The methodology can be applied to measure the grease performance (grease life performance concept) and to measure the domains in which the grease can successfully be used.

A comparison between ROF and ROF+ shows that ROF+ testing may result in slightly shorter lives with a smaller spread in life.

The method provides an efficient way of testing lubricating grease on its durability and reliability. It can be used as a standard test. However, thanks to its flexibility, the test method is most effective for research purposes as well.

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