On the prediction of the lubrication condition of grease sealing rotary shaft seals

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The so called “tear-in” tests were developed to evaluate a correlation between the tear-in of a grease dam in a tribological system and the lubricity of the grease. They were carried out with a rheometer as equivalent system and 23 greases. The grease sample was sheared in the gap between a rotating and a stationary plate with a linearly increasing shear rate. The motion of the grease within this gap was observed optically with a high-speed camera. In addition, the shear stress was measured and evaluated. The results of the tear-in tests correlate well with functional tests using a rotary shaft sealing system.

1 Introduction

Grease-lubricated systems require less design effort and less maintenance work than oil-lubricated system, as lifetime lubrication can be reached. Unlike oils, greases possess a flow point and rather remain at the applicated position instead of flowing away. Nonetheless, a seal is necessary as barrier to withhold the grease and its parts, as bled oil, inside and pollution particles outside the sealed system.

The seal is usually lubricated with the same grease as the other functional machine parts. Therefore, the grease might be optimised for other tribological systems whose requirements and loads can differ greatly from the seal. In the case of a grease-sealing system a failure of the sealing system doesn’t necessarily cause immediate leakage of larger fluid quantities - as it would be the case for oil-sealing systems. Nonetheless, a damaged seal can only limited withhold grease or bled oil inside and pollution particles outside the sealed system. As there exists neither a fluid pump nor a fluid filter, pollution particles will accumulate in the lubricating grease and disturb the tribological systems until the end of lifetime or until a complete fluid change. This is the reason why a damaged sealing system can lead to failures of the functional machine parts. Additionally, a damaged sealing system usually shows strong wear particles, revealing the damage to everybody around. By choosing a well-lubricating grease, these damages can be prevented.

Although starved lubrication is a common problem with grease-lubricated sealing systems [1, 2], grease-sealing rotary shaft seals are by far less researched than oil-sealing rotary shaft seals [3]. So, little is known about which property correlates with a good or bad lubricity of a grease in a rotary shaft sealing system. The tests of Sommer [4] showed, that a high shear viscosity often leads to starved lubrication. But he also pointed out the temperature dependence of the shear viscosity, that improves the lubrication at higher temperatures or velocities. Narten [5] observed starved lubrication at semifluid greases, indicating that the viscosity alone is not crucial for the lubricity of a grease. Basing on elastomer-ring/steel-disk test on a tribometer, [4] expected greases with a high dissipation factor to reach the hydrodynamic lubrication at smaller Gümbel numbers. Dürnegger [6] measured lower friction torques and lower temperatures for greases with a low base oil viscosity. Both, [4] and [5] couldn't confirm a correlation between oil-bleeding and lubrication condition. In the research project "Grease deficiency", the lubricity of 23 commercially available greases was tested [7]. Many properties of the 23 greases were analysed and correlated with each other [8, 9]. The results show no direct correlation between a single grease property and the lubricity of the grease. This fits with the observation of the former research. Nonetheless, some grease properties are likely to lead to a good or a bad lubricity. Greases with a low shear viscosity, a low consistency, a high oil separation and a low maximum force in tackiness measurements tend to lubricate well, without allowing the reverse to be concluded. These tendencies alone might not allow to choose a suitable grease, but they can give a hint on the grease-performance in the early development process. This can allow to pre-select greases with a good prognose, which reduces the test and/or maintenance effort.

This work aims to provide a more accurate method to predict the lubricity of a grease by fast measurements on a rheometer. Background of these "tear-in tests" are observations in different works at a tribometer [4, 10] and in the grease-filled gap of non-contact seals [11], that indicate a cracking of the grease in the gap. These tears separate the grease in several sections which no longer interact with each other. Whether this tearing correlates with starved lubrication was not analysed or known. For this work, the lubricity of 23 commercially available greases was first evaluated with a test and evaluation method [7] to rate the lubricity of the greases with a numeric score. Afterwards, the tearing was analysed on a rheometer with the help of a high-speed camera. In pre-tests it was first analysed, at which circumferential speeds and at which gap heights a tear-in occurs. Basing on this, test conditions were chosen and all greases were measured and evaluated using both, the measurement of the shear stress and the recordings of the high-speed camera.

2 Evaluation of the greases with test and evaluation method for rotary shaft sealing systems

A test and evaluation method [7, 9] was developed to evaluate the lubricity of the 23 analysed greases in a robust and reproducible way. The method also allows to compare the lubricity of different greases in a rotary shaft sealing system.

The test and evaluation method consists of a 24-hour test run on a frictional torque test rig followed by a detailed analysis of the used seal, shaft and grease. Before the test, a ring of $1\ \mathrm{ml}$ grease is applied around the shaft with a diameter of $50\ \mathrm{mm}$. Afterwards the rotary shaft seal is pushed over the grease ring with its fluid side ahead, so that the grease ring is located directly at the fluid side of the sealing lip. A pyrometer measures the temperature on the air side close to the sealing contact. The seal holder is mounted on an aerostatic bearing and is supported by a load cell so that the frictional torque can be measured.

The 24-hour test run consists of an 8-hour test cycle which is repeated three times and includes eight 1-hour periods with circumferential velocities between $0.15\ \mathrm{m/s}$ and $5.5\ \mathrm{m/s}$ and a standstill period. Each grease was tested at least one time in each direction of rotation. Every test run was evaluated with eight criteria, which showed a good correlation with starved lubrication [9]:

- Temperature fluctuation (qualitative)
- Friction torque fluctuation (qualitative)
- Abrasion particles (qualitative)
- Grease: visual impression (qualitative)
- Sealing edge: wear width (quantitative)
- Wear track: visual impression (qualitative)
- Wear track: depth (quantitative)
- Wear track: width (quantitative)

Each criterion was rated with a grade from 1 (very good) to 5 (very bad), so that all quantitative and qualitative criteria of a test run could be averaged to a test-run-score. By averaging all test-run-scores for each grease, an overall grease score was determined for each grease. The overall grease scores are shown in the qualitative evaluation of the tear-in tests in Figure 7, section 6.5. A more detailed description of the test and evaluation method and the results obtained can be found in [7, 9].

3 Analysed Greases

For this work 23 greases were tested (Grease 1 – Grease 23). The greases have an NLGI grade between under the classification (<000) and 2-3. All are commercially available greases with different kinds and amounts of thickener, base oils and additives. While this makes it difficult to trace the lubricity back to single grease properties, the evaluation becomes independent of individual grease properties and thus generally valid. The results of the tests can therefore be applied to a wide range of greases. The 23 greases have eight different thickeners, Figure 1.

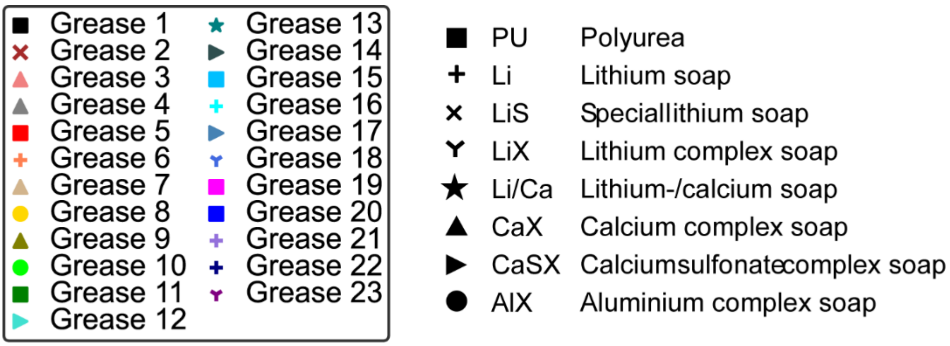

Figure 1: Symbols and thickeners of the greases

4 Test setup

The tear-in tests were conducted on a rheometer MCR 302 of the company Anton Paar Germany GmbH with a parallel plate setup with a diameter of 25 mm for both plates. The tests were conducted at $25\,°\mathrm{C}$ and the grease in the gap between the plates was observed with a high-speed camera CR3000x2 of the company Optronis GmbH, Figure 2. Before the test, the zero gap of the rheometer was determined at $25\,°\mathrm{C}$ and the grease was trimmed and tempered at the test gap height.

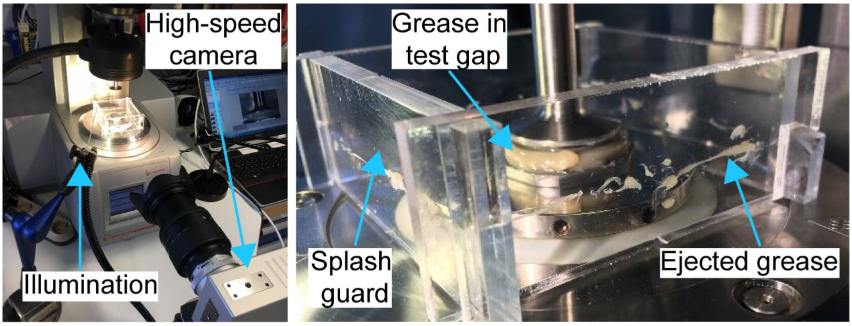

Figure 2: Test setup, Rheometer with illumination, high-speed camera, splash guard (left), splash guard after test (right)

5 Test procedure

Pre-tests showed, that tearing indeed occurs in a parallel plate setup on a rheometer and not only in tribometer tests or within contactless seals. The tearing can be replicated with a constantly accelerated rotation of the upper plate. This is of advantage, since the tearing can happen at different shear stresses for different greases. For the following tear-in tests the gap height was set at $h = 2.00\ \mathrm{mm}$, since this gap height lies in the order of magnitude of the depot zone between the fluid side of the sealing lip and the shaft [9, 12]. The upper plate is accelerated from 0 to $3000\ \mathrm{rpm}$ in $t = 60\ \mathrm{s}$. For each grease at least three tear-in tests were conducted, from which at least one was observed and evaluated with the high-speed camera.

6 Qualitative evaluation of tear-in tests

The tear-in tests were evaluated in two steps: First, the measured shear stress was evaluated qualitatively together with the recorded film sequences. This gives an overview of the general movements of and the differences between the greases. On this basis, the tear-in tests were evaluated quantitatively in a second step, using the measured shear stress over the rotational speed.

The qualitative evaluation showed, that the tear-in behaviour of the greases can be categorised into four groups. In the following, records from the high-speed camera and the corresponding shear stress record of a typical grease are shown as example for each group. In addition, the shear stress records of two further measurements with the same grease are shown in order to illustrate the fluctuations between the measurements.

6.1 Group 1

Exemplary for group 1, Figure 3 shows the records of the high-speed camera of Grease 7. The record times (a-f) are marked in the corresponding shear stress record. Immediately after the start of the tear-in test (a), the grease sample forms a helical constriction (b). Once the constriction is built, the grease sample shows no more peculiarities. Later, the grease sample starts to constrict and the grease accumulates more and more at the upper rotating plate and is pushed outwards over the edge of the plate by the centrifugal force (c). This results in a growing constriction in the lower area of the grease sample, which reduces the effectively sheared grease volume, so that the shear stress begins to decrease. The grease bulge on the upper plate is moved upwards over the plate edge (d), while the constriction in the grease growths. Finally, the centrifugal force further accelerates the grease on the upper plate until the binding forces of the grease are overcome. The upward movement of the grease bulge stops and the grease begins to spin out steadily (e). The grease spins out (f) until the gap is almost empty and only a narrow bridge of grease connects the centre of the two plates. The shear stress reaches a low level and doesn't increase again as there is no grease close that could be drawn back into the gap.

In the shear stress record, the constrictions at the beginning (b) express themselves in small fluctuations in the shear stress measurement, before the shear stress rises linearly with the increasing rotational speed. When the grease begins to accumulate on the upper plate, the shear stress first decreases (c-d) and drops strongly, when the grease is finally spun out (e-f). As the gap empties further, the shear stress approaches a low constant level, caused by a rest of grease that remains in the gap.

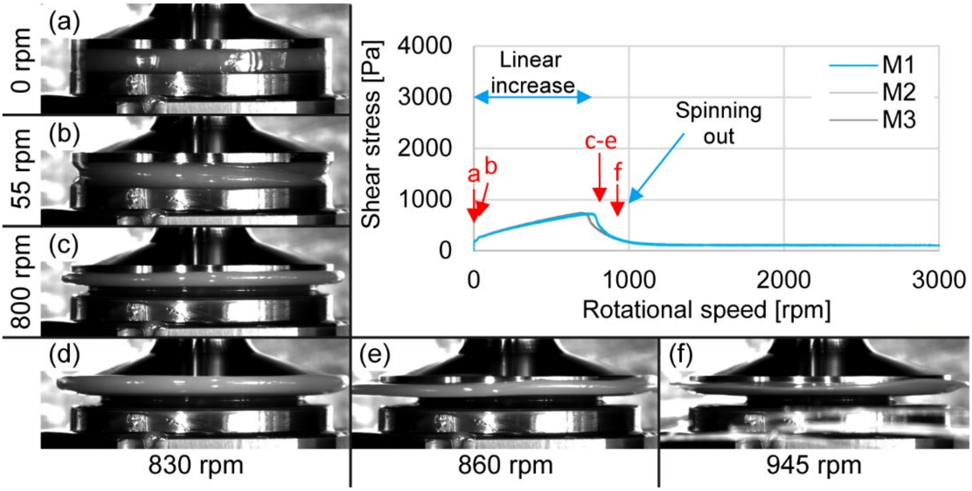

Figure 3: Tear-in test: records of high-speed camera and shear stress of Grease 7, group 1

As shown by the example of Grease 7, the tear-in tests of group 1 show a continuous, nearly linear increase of the shear stress, which suggests a mostly constant sheared grease volume. At a grease-individual rotational speed, the grease begins to constrict and to accumulate on the upper plate, bevor it is spun out of the gap. The latter is shown by a sudden drop of the shear stress in the measurement.

6.2 Group 2

Figure 4 shows the records of the high-speed camera of Grease 15 as well as the corresponding measurement of the shear stress as example for the greases of group 2. After the start (a) only a small part of the grease in the upper region of the gap is deformed and sheared, whereas the majority of the grease remains without movement, at first (b). Short after, the whole grease sample rotates with the upper plate without being mixed with itself. At the edge of the gap, a small accumulation of grease emerges, which is visible on the right side in (c). The accumulation is pressed out of the gap, but it remains on the upper plate without interfering with the grease in the gap. In the test gap, large sections are no longer filled with grease and a strong constriction forms in the lower area of the gap (d). At $365\,\mathrm{rpm}$, the grease accumulation has been completely pushed out of the gap and only participates at the shearing as a nearby obstacle. The grease on the upper plate is almost completely separated from the grease on the lower plate by a deep tear (e). Briefly, a part of the grease accumulation is drawn back into the gap, causing the tear to partially close (f). As a result, more grease participates at the shear again.

The shear stress of Grease 15 decreases nearly continuously over the test, this decrease is interrupted time and again by small, flat climbs, when a tear closes or the grease inside the gap interferes with the grease outside the gap for a small time. There is never much grease drawn back into the gap, that's why there is no sudden, strong increase of the shear rate. Instead, the sheared grease volume in the gap decreases over the test time, and so does the shear stress.

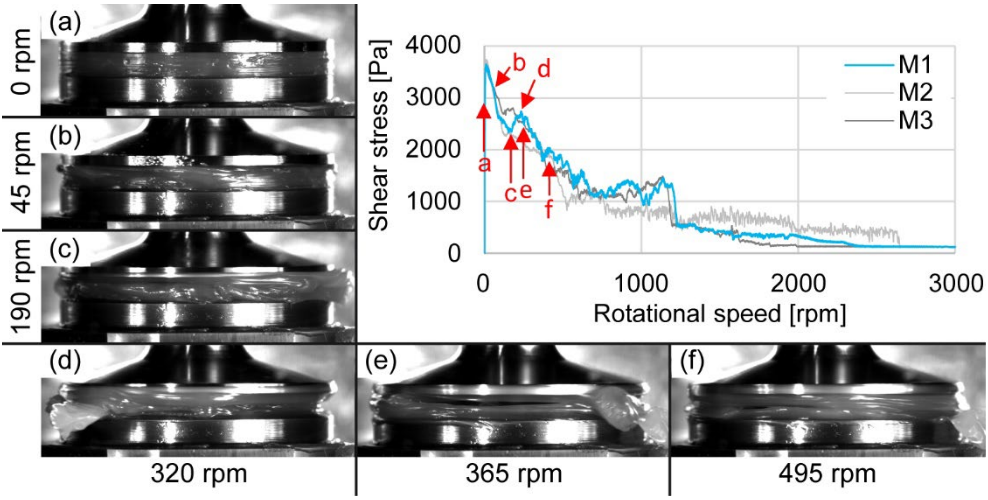

Figure 4: Tear-in test: records of high-speed camera and shear stress of Grease 15, group 2

In contrast to group 1, the greases of group 2 don't spin out of the gap. Instead, starting very early in the tear-in test, parts of the grease are moved out of the gap, but remain close to the gap. By that, there's left space in the test gap so that deep tears or constrictions can build in the remaining grease sample. The displaced grease is hardly drawn back into the gap afterwards.

6.3 Group 3

Figure 5 shows the records of the high-speed camera of Grease 18 as example for group 3 and the corresponding measurement record of the shear stress. A short time after the start (a), the entire volume of grease is involved in shearing (b). This becomes clearly visible by the helix that is formed over the entire grease sample. Soon afterwards, a tear emerges (c, right side of the gap), which is enabled by lot of grease that is pushed out of the gap (d, right side of the gap) leaving space for the tear. The grease outside the gap is moved to the front (e), where it stays for the rest of the high-speed record as well as the deep tear (f).

The shear stress record reflects the movements of the grease by increasing at first (a-b) and decreasing after the tear builds up. The grease on the upper plate is mostly separated from the grease on the lower plate by the tear, but the small fluctuations in the measurement record (b-f) show, that sometimes the two grease parts interact with each other when a co-rotating grease bulge collides with the stationary grease on the lower plate. As a result, the measurement record of Grease 1 fluctuates slightly and shows no strictly linear record. At (g), so much grease is drawn back into the gap, that it causes several significant but short increases in the shear stress (after the end of the recording of the high-speed camera). After these jumps, the previous shear stress curve is continued.

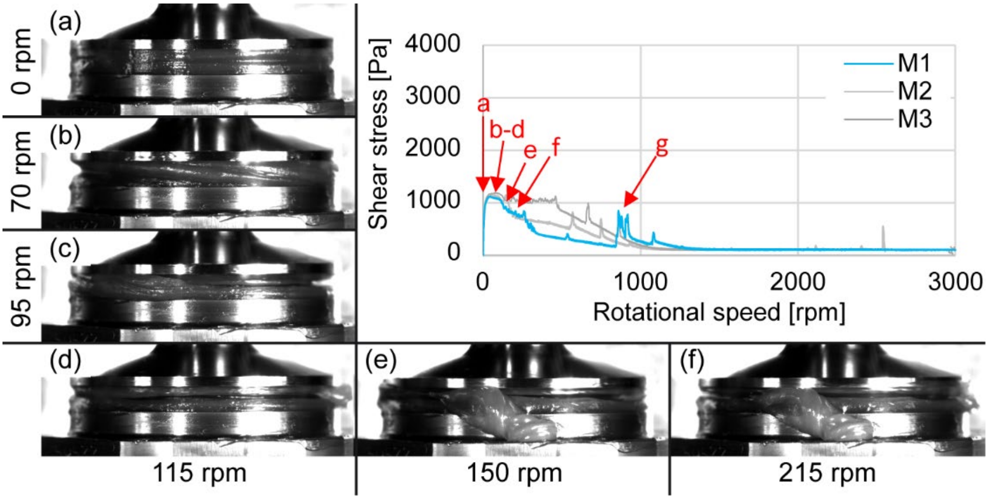

Figure 5: Tear-in test: records of high-speed camera and shear stress of Grease 18, group 3

As exemplary seen for Grease 18, big parts of the greases of group 3 move rapidly out of the test gap, but they remain in the vicinity of the gap. Parts of the grease samples are, in contrast to group 2, drawn back into the gap for short periods of time. This is reflected in abrupt increases in shear stress, as marked (g) in Figure 5. However, the drawn back grease is quickly displaced again, so that the increases in shear stress are not permanent and sometimes only manifest themselves as short peaks or fluctuations in the measurement record.

6.4 Group 4

Figure 6 shows the records of the high-speed camera and the shear stress record of Grease 5 as example for group 4. Shortly after the start (a), all the grease is involved in the shearing (b). The grease sample immediately shows a coarse helix form. A large part of the grease is then (c) pushed out of the test gap, reducing the sheared volume. The large volume of grease pushed out has created a deep tear, which is recognisable in the right upper part of the grease in the gap (d). This tear separates the grease in a rotating part on the upper plate and a stationary part on and around the lower plate. As the grease either rotates with the upper plate or remains stationary on the lower plate, there is almost no shearing of grease. After two thirds of the test (e), the lower part of the grease is drawn back into the gap by a vortex (f). In the following, it remains in the test gap and participates in the shear for a long time.

The shear stress record reflects the shearing of most of the grease at the beginning by a first increase of the shear stress. The pushed-out grease then limits this initial increase and results in a decreasing shear stress (a-d). After the forming of the tear, the separated grease causes only a very small measured shear stress. Deflections in the measured shear stress originate from random contacts of the grease adhering to the top with the grease on and next to the lower plate (d-e). The vortex and the drawn back grease in the gap indicate themselves by a strong increase of shear stress (e-f), which results in a permanent rise of the shear stress. This indicates, that the grease participates in the shearing for the rest of the test.

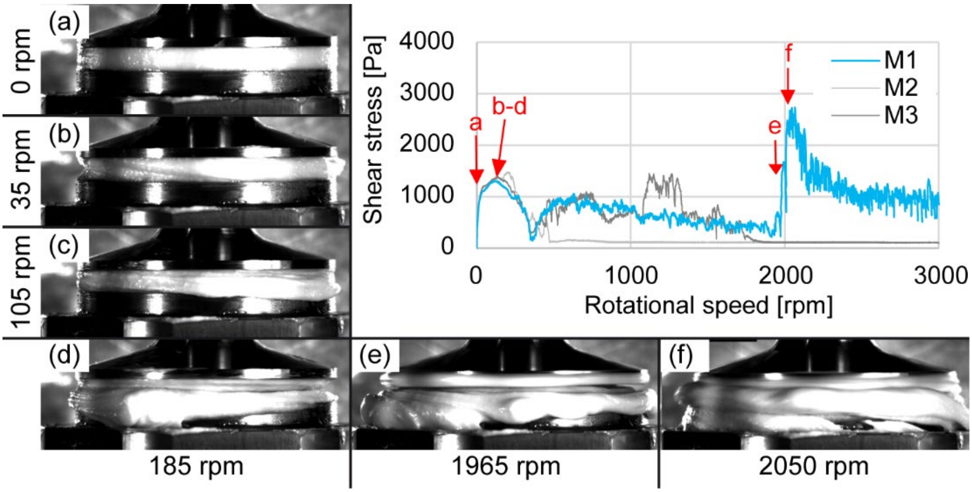

Figure 6: Tear-in test: records of high-speed camera and shear stress of Grease 5, group 4

As exemplary pictured for Grease 5, a large part of the group 4 greases is pressed over the edge of the test gap at the beginning of the test. This pressed-out grease is later drawn back into the gap by a "grease vortex". As a result, the grease again participates almost completely in the shearing, which causes the shear stress to increase abruptly. In contrast to the beginning of the measurement and to the greases of group 3, the grease is not immediately pressed out of the test gap again. Instead, it participates at the shearing over a longer period of time, so that the shear stress remains at the high level. The pull-in occurs preferably in the last two thirds of the measurement. The jump in the measurement record can be so strong that the shear stress is above the original shear stress level at the beginning of the measurement.

6.5 Conclusion of qualitative evaluation

The qualitative grouping of the greases can be reduced to the following main points:

- Group 1: smooth shear stress record, grease spins out instead of tearing in
- Group 2: grease is moved out of the gap, it stays close but outside the gap
- Group 3: grease is moved out of the gap; short shear stress peaks indicate that the grease is briefly being drawn back into the gap
- Group 4: grease is moved out of the gap and later drawn back into the gap for a long period of time

Many greases show a similar shear stress over the repeated measurements. So, it can be assumed, that a regular behaviour is present here. Some greases on the other hand show a behaviour that appears highly irregular and random due to parts of the grease sample being pushed out and pulled back into the gap or being swirled around. Especially with these greases, the individual measurement records can differ significantly, as it is visible for Grease 18 in Figure 5 and for Grease 5 in Figure 6. Therefore, repeat measurements should be carried out to obtain an overview of the tear-in behaviour of the grease.

The grouping of the measurement records on the basis of qualitative criteria is not always uncontroversial nor exhaustive, as the Greases 3 and 21 cannot be assigned to the four defined groups. Moreover, the repeated measurements do not necessarily show a similar behaviour. Nevertheless, a subsequent comparison of the grouping with the grease performance in the sealing system (chapter 2) shows a good correlation: Four of the six poorly rated greases were assigned to group 4, while conversely no very good and only a few relatively well rated greases have been classified in group 4, see Figure 7. The remaining two poorly rated greases are found in group 3. In both groups, 3 and 4, the grease is pressed out of the gap instead of being thrown out. It thus remains in the vicinity of the gap and is drawn back into it - either in the short term (group 3) or in the long term (group 4). In this process, it shows a flow behaviour that appears partially random.

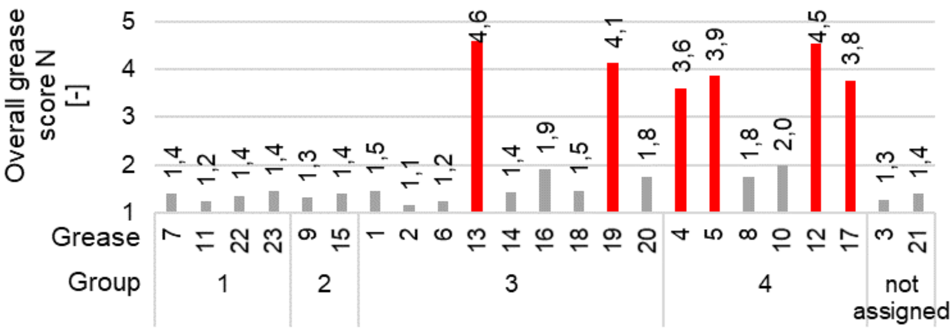

Figure 7: Tear-in test: comparison of overall grease score and qualitative evaluation

7 Quantitative evaluation of tear-in tests

The next step is to convert the qualitative evaluation of the measurement records into a quantitative. The aim is to automatically identify those greases that show a strong or long-term increase in shear stress as a result of grease being drawn back into the gap.

For the further evaluation, the measurement record is first smoothed by forming a moving average over every n-th of the measurement shear stress values $\tau(n)$. This results in a smoothed measurement value $\bar{\tau}(n)$ for each measurement value $\tau(n)$. The moving average is formed on the basis of the previous $\frac{Z}{2}$ and the following $\frac{Z}{2}$ measured values as well as the current measured value, so that the average $\bar{\tau}(n)$ consists of $Z+1$ values:

$$\bar{\tau}(n) = \sum_{k=n-\frac{Z}{2}}^{n+\frac{Z}{2}} \frac{\tau(k)}{Z+1} \tag{1}$$

A measurement record consists of 3000 measurement points, so that a measurement value is recorded every $0.02\ \mathrm{s}$ or every $1\ \mathrm{rpm}$. For the first and last $\frac{Z}{2}$ values, the average consists of up to $\frac{Z}{2}$ less values. Subsequently, the mean values $\bar{\tau}(n)$ are subtracted point by point from the measured values $\tau(n)$, the residual values form the fluctuation function $s(n)$ of the measured values:

$$s(n) = \tau(n) - \bar{\tau}(n) \tag{2}$$

Figure 8 exemplary shows the measurement curve $\tau(n)$, the mean curve $\bar{\tau}(n)$ and the fluctuation function $s(n)$ of Grease 5.

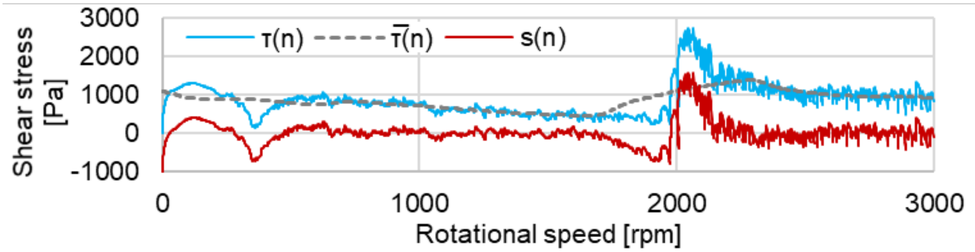

Figure 8: Tear-in test of Grease 5, measurement record of shear stress $\tau(n)$, mean curve $\bar{\tau}(n)$, fluctuation function $s(n)$

The definition of a threshold $\hat{s}$ allows to detect particularly large jumps in the measured shear stress. The fluctuation occurrence of the measured shear stress can be expressed via the jump count A that counts the values for which applies $s(n) > \hat{s}$. By correlating the overall grease score N with the jump count A of the single tear-in tests, the mean length Z and the threshold $\hat{s}$ were estimated to $Z = 600$ and $\hat{s} = 250\ \mathrm{Pa}$. With these values a coefficient of determination of $R^2 = 0{,}541$ can be reached for the correlation between the single tear-in tests and the overall grease score N of the greases. The values of $Z = 600$ ($\triangleq 12\ \mathrm{s}$ or $600\ \mathrm{rpm}$) and $\hat{s} = 250\ \mathrm{Pa}$

appear to be very high. However, the high threshold $\hat{s}$ confirms the observation from the qualitative evaluation that large jumps in particular correlate with starved lubrication. Since the smoothing function adapts only slowly to the increased level with a large mean length, the high mean length Z emphasizes both: short, strong jumps and longer jumps with an increased level. Corresponding to the qualitative and the quantitative evaluation, those greases with a quickly dropping shear stress while the grease remains in the vicinity of the gap are particularly critical. Later in the test, this grease is drawn back into the test gap at higher speeds and participates in the rotation again, partly for a longer time.

The tear-in tests were also evaluated with methods different from the jump count [9]. However, the correlations of the overall grease score with the maximum variation $Max(s_n)$ or with the integrated fluctuation curve $\sum s_n$ (separately for $s_n > 0$, $s_n < 0$ and $|s_n|$) show a maximum of $R^2 = 0.438$. They are therefore less suitable to predict the lubricity of a grease in the sealing system than the presented jump count.

8 Transfer to the sealing system

For the sealing system, this means that especially those greases tend to starved lubrication which show the following behaviour in the tear-in tests at the rheometer:

- a large part of the grease is displaced after a short time, so that only a small part of the grease participates in the shearing, **and**
- in the further course, grease that was not previously involved in the lubrication is drawn back into the gap. Thereby, the shear stress abruptly increases strongly and, in some cases, permanently.

This could also apply to the depot zone next to the sealing gap. There, the grease could either form a homogeneous volume or is separated in parts that participate in the shearing and lubrication or not. First video records of the fluid side of single grease-lubricated sealing systems strengthen this assumption [9].

Correspondingly, the tearing behaviour of greases that tend to starved lubrication is characterised by a flow that appears random. Depending on how the grease was pressed out of the gap and comes into contact with the remaining, moving grease, it repeatedly participates in the shear or not. Correspondingly, the measurement records of the individual tests do not always show uniform behaviour with clear assignment to one of the qualitatively formed groups. It therefore makes sense to carry out several measurements to investigate the tear-in behaviour and to consider the results as a whole. By averaging the jump count of at least three tear-in tests for each grease, the correlation of the jump count A with the overall grease score rises to $R^2 = 0.645$ for all greases and up to $R^2 = 0.837$ within the Ca-thickener group. For the PU-thickener group the correlation decreases to $R^2 = 0.339$. This decrease of the coefficient of determination can also be seen for other grease properties, as is shown in [8, 9]. All correlations are shown in Figure 9.

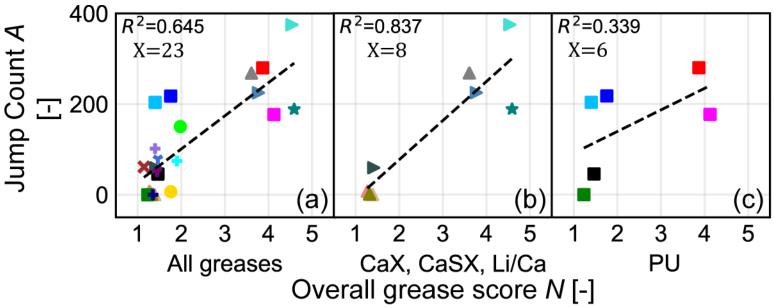

Figure 9: Correlation of the overall grease score N with the averaged jump count A for (a) all greases, (b) the greases of the Ca-thickener group and (c) the PU-thickened greases. X gives the number of correlated greases

9 Summary and conclusion

To achieve a reliable sealing function, the sealing lip of a rotary shaft seal must be sufficiently lubricated. Often, a grease-sealing seal is lubricated with a grease optimised for other tribological systems. Grease-lubricated rotary shaft seals frequently show starved lubrication and sealing system failure. This could be avoided by predicting the lubricity of a grease and pre-selecting greases, that better lubricate the sealing lip. The presented “tear-in” tests provides such a method.

The tear-in tests were performed with 23 greases. Their results were compared with functional tests using a rotary shaft sealing system. It was found that most greases with poor lubricity move out of and back into the gap between the parallel plates and form deep tears. This leads to large fluctuations in the measured shear stress. A quantitative evaluation of these fluctuations via the so called “jump count” correlates very well with the lubricity of the greases in the sealing system, especially when evaluating within one thickener group. Therefore, the tear-in tests can predict the lubricity of a grease and allow a pre-selection of suitable greases to prevent starved lubrication and sealing system failure.

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FKM Forschung im VDMA

11 Nomenclature

Variable	*Description*	*Unit*
A	Jump count	[-]
h	Gap height	[mm]
ϑ	Temperature	[°C]
R^2	Coefficient of determination	[-]
$s(n)$	Fluctuation curve	[Pa]
$\hat{s}$	Threshold	[Pa]
t	Test time	[s]
$\tau(n)$	Measured shear stress curve	[Pa]
$\bar{\tau}(n)$	Mean curve of the shear stress	[Pa]
Z	Mean length	[-]

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