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Impact of grease churning on grease leakage, oil bleeding and grease rheology

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ABSTRACT

Grease performance is strongly determined by the properties and quantity of the grease after the churning phase in which grease reservoirs are formed. During this churning phase, macroscopic flow takes place, leading to drag forces dissipating energy in the grease, generating heat and causing thermo-mechanical degradation. The impact of grease churning on grease properties such as oil bleed, leakage and rheology was studied using bearing experiments and a roll stability tester. Grease leakage increased whereas oil bleeding capacity and tackiness decreased with increased churning intensity, measured as temperature-corrected energy density.

1. Introduction

Grease is the preferred lubricant for rolling bearing lubrication due to many advantages like inherent sealing, no leakage under normal conditions, and lower friction (at higher speeds) [1].

Before the start of the bearing operation, grease is usually located in-between the rolling elements. As soon as rotation starts, grease starts to flow. A portion of the grease flows next to the running track and stays there due to the grease consistency, and another portion flows inside the bearing, ending up on the cage bars. If the bearing is overfilled, this phase will not be reached as high drag forces will result in overheating and seals may detach from the bearing. Therefore, for sealed/shielded bearings, as a rule of thumb, only 30–50% of the free volume should be filled with grease. For very high-speed applications, this quantity may be reduced to 20% [2,3]. At some point, the grease becomes semi-stationary, forming grease reservoirs from where bleed takes place.

Grease lubrication process in bearings running under constant controlled conditions can be roughly divided into two phases, the churning phase and the bleeding phase [4]. During the churning phase, the balls in a running bearing form a channel of grease. This process is called "channeling". Next, the raceways are cleared of grease, after which the churning phase is finished [5]. The process of forming the channel and clearing the raceway may take from an hour to 24 hours or longer, depending on the percentage of filling, operating conditions, bearing geometry, and the rheological properties of the grease. During this phase, grease can degrade heavily on the running tracks [6]. The film thickness in this phase may vary depending on the rheological properties of the grease. However, fully flooded conditions prevail wherein both the thickener and base oil enter the contact [7,9]. The formed grease reservoirs on the cage bars/pockets and shields/seals may contribute to the process of lubrication by supplying base oil to the contacts via a mechanism called bleeding [8]. This phase is therefore called "the bleeding phase". The grease in the reservoirs e.g., on the shields, cage bars and bearing shoulders bleeds oil to the contacts driven by capillary forces, surface tension and centrifugal forces [10]. Currently, there is no complete consensus on grease lubrication mechanism. Lansdown and Gupta [11] showed that the entire grease was involved in the process of lubrication in a ball bearing experiment. Contrary to this, Dalmaz and Nantua [12] showed that only the base oil provided the lubricating film. Some authors [13,14] showed that initially, the thickener contributed to the film thickness but in a later phase, only the base oil formed the film. The latter was confirmed by Saita [15], who showed that a film developed by thickener and base oil lasted only for a short period followed by a film generated by base oil only.

During the process of channeling in the churning phase, grease is pushed forward and sideways from the swept volume to the unswept volume of the bearing [4]. The grease that moves to the unswept area may flow back again into the swept area until the process of clearing is finished [5]. The duration of the process varies. The high drag forces lead to high temperatures. The combination of high temperature and shear results in thermo-mechanical degradation [17–20].

The length of the churning phase and therefore clearing behavior can be obtained from the temperature profile [16]. The process of clearing can be distinguished into two behavioral categories [5]: good/peak-type clearing behavior in which grease undergoes a short churning period and poor/plateau-type clearing behavior in which grease experiences a long churning period. Churning duration has an impact on grease aging.

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Table 1
Properties of the greases used in the experiments.

Grease Name	LM2L	LM3L	LM3C	LCP 2.5 C
Thickener Type	Lithium	Lithium	Lithium	Lithium Complex
Thickener (%)	10.75	13.9	–	–
NLGI grade	2	3	3	2.5
Base oil type	Mineral	Mineral	Mineral	PAO
Viscosity at 40 °C (mm^2/s)	100	100	98.8	200
Viscosity at 100 °C (mm^2/s)	10	10	10	25
Dropping Point (°C)	204	205	191	280
Density (g/cm^3)	0.9	0.9	0.9	< 1
Churning Type[5]	Good/ Peak-type	Poor/ Plateau-type	Good/ Peak-type	Poor/ Plateau-type

A good clearing grease undergoes a short churning period, resulting in less grease degradation, whereas a poor clearing grease undergoes a longer churning period, resulting in more severe grease degradation [5]. We have recently refined this classification by using temperature-corrected dissipated energy rather than churning time [5]. Along with this severe grease degradation, a bearing with poor clearing grease runs at a higher temperature for a long period. During this period, a small amount of anti-oxidants present in the grease may be consumed. This long churning process impacts the grease performance via changes in rheology and bleed properties [5]. In applications like grease lubricated rolling bearings, the mechanical degradation of thickener fibers during the churning phase reduces the grease consistency. The lowered consistency, measured as a rheological property, e.g., yield stress, and increase in temperature results in grease leakage and an increase in oil bleeding rate which impact the lubricating effectiveness of grease in a bearing [21,22]. Grease is pushed out of the bearing by pressures induced by ball or cage motion and centrifugal forces. The flow properties change due to thermo-mechanical degradation [23].

Significant and rapid mechanical degradation happens with increased shear rate and shear stress on grease [24]. The focus of this study is to understand the impact of thermo-mechanical degradation during the churning phase on grease leakage, oil bleed rate, and rheological properties like yield stress and tackiness in ball bearings running at constant speed/load, on a horizontal shaft, and in the absence of vibrations.

2. Materials and methods

2.1. Grease samples

Four different greases were studied. The grease properties are listed in Table 1. Two greases (LM2L and LM3L) were manufactured in the SKF laboratory following the method described by Nolan et. al. [25], varying the thickener concentration and manufacturing process. The other two greases (LM3C and LCP 2.5 C) are commercially available.

2.2. Bearing test rig

Bearing tests were performed with 6204–2Z/C3 Deep Groove Ball Bearings (DGBB) in the R0F+ test rig [26]. The bearings were sealed with non-contacting seals, referred to as “shields”. The details about the test procedure can be found in our earlier paper, reference [16]. A test is run using a single shaft with two ‘test bearings’ and two `support bearings’. 30% of each bearing’s free volume was filled with grease. The operating conditions were speed: 15,000 rpm; radial load: 150 N. The bearings ran under self-induced temperatures which were measured on the outer rings of the bearings.

2.3. Grease leakage

2.3.1. Grease leakage for single bearing experiments

Grease lubricated rolling bearings undergo two different phases in the lubrication process: the churning phase and the bleed phase. During the churning phase, the entire grease flows and there is more grease leakage than during the bleed phase wherein the grease is semi-stationary. In this study, grease leakage tests were performed on two greases: LM2L and LM3L. The leakage was determined by measuring the weight of a bearing before and after the test. The leakage was then calculated as

$$L_t = \left(\left(\frac{m_0 - \; m_t}{m_0} \right) \times 100 \right) \tag{1}$$

where

L_t is the leakage of grease from the bearing at time t.

m_0 is the initial grease mass in the bearing.

m_t is the grease mass in the bearing at time t.

Initially, tests were run till churning finished, which is confirmed by the temperature profile dropping and reaching a steady state. The test was stopped immediately after churning finished, and bearings were taken out without opening them of the test equipment. The exteriors of the bearings were cleaned with soft absorbent paper, and the weights were measured again. The weight drop is believed to be caused by grease leakage during the churning period (Equation-1). The same bearings were re-installed on the test equipment and the test was continued with the same test conditions. In this step, there was no new churning period and the temperature profile remained in its previously attained steady state from the beginning of this step. After 24 h of running, the test was stopped again and grease leakage was estimated as described previously. The same bearings were re-installed on the test equipment and the test continued. The measurements were repeated again at 48 h and 72 h run intervals.

2.3.2. Grease leakage during multiple bearing tests

As in the single bearing tests, the bearing weights before and after the test were used to determine grease leakage. Here, the leakage tests were carried out for a pre-defined time. A few tests were stopped while churning was still ongoing. In the other tests, churning was allowed to finish before stopping. In both cases, the churning state was indicated by the corresponding temperature profile.

2.4. Grease rheology measurements

The rheology of the grease was measured using a strain-controlled DHR2 rheometer manufactured by TA instruments, with a smooth finished plate-plate geometry (plate diameter of 25 mm).

2.4.1. Tackiness

Grease tackiness is the ability of grease to stick to metal surfaces. To measure tackiness, a small grease quantity (~0.25 g) was loaded between the plates, and excess grease was trimmed away using a micro spatula after reaching an offset of 0.0125 mm from the selected gap setting of 500 μm. Then pre-shear was performed for 30 s at a shear rate of 10 s^{-1}. Next, the rheometer was left idle for 900 s to relax the normal force. Before starting the experiments, the axial force was manually set to zero. Tackiness was measured at the churning temperature (125 ℃ for LM3L, 110 ℃ for LM2L and LM3C, and 150 ℃ for LCP 2.5 C) by measuring the axial force (N) as a “Pull-off force” while increasing the gap height until a value of 5000 μm is attained. Tackiness is defined here as the maximum peak value of the axial pulling force. The average deviation from the mean tackiness value was less than 10%.

2.4.2. Yield stress measurements

The yield stress was measured following the method developed by

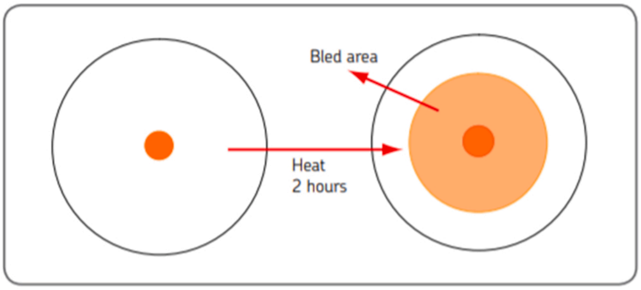


Fig. 1. Schematic representation of oil bleed measurement.

Cyriac et al. [27]. A small quantity of grease sample was applied on the stationary lower plate and excess grease sample was trimmed away when the top plate reached the pre-set gap of 525 mm. At the desired temperature, a pre-shear of 100 s^{-1} was applied for 60 s followed by a 30-minute equilibration period. Subsequently, the oscillation sweep measurement was started at the constant frequency of 1 Hz between the controlled strain of 0.001–1000%. Measurement was repeated three times on each sample. The average deviation from the mean yield stress value was less than 10%.

2.5. Roll Stability Test (RST)

The "Roll Stability Tester" (RST) was used to artificially age the grease samples, as described in our earlier article [5]. In this test, a closed cylinder containing a heavy roller and 50 g of grease rotates in an oven at the churning temperature T_{ch} (for LM3L, T_{ch} is 125 °C; for LM2L and LM3C, T_{ch} is 110 °C; and for LCP 2.5 C, T_{ch} is 150 °C). The duration of the tests varied, and an oil bleed measurement was performed after each test showing the evolution of oil bleed versus time in the RST test. In our earlier study [5], we determined the RST run duration that will obtain the same level of aging as in a real bearing operation by comparing the yield stresses of greases taken from bearing tests with those from RST samples. Following our findings from that work, the duration of the RST test in this study is different from the bearing churning time.

2.6. Oil bleeding capacity measurements

The volumes of greases obtained from post-bearing tests were so small that none of the standardized bleed tests could be used to measure the oil bleed rate. Therefore the SKF MaPro test [27] was used. In this oil bleeding test, a fixed volume of grease is placed on a piece of blotter paper for 2 h, heated at 60 °C (approximating the temperature obtained in the bearing experiments during the bleed phase) to release the base oil from the grease, creating an oil stain on the paper; see Fig. 1. The stain surface area of the fresh grease (equation-2) and the stain surface area of the grease collected from the aged grease in RST (equation-3) are calculated. The stain surface area, which will be hereafter called 'bled area', gives a measure of the grease's bleed capacity. The bled area difference (B_{AD}) between the used and fresh samples, which measures the change in bleed capacity, is calculated via equation-4. All bleed measurements were repeated four times and the average values used for calculations [27].

$$Bleed_{AvFresh} = \pi/4 \times \left(D^2_{AvFresh} - 100\right) \quad (2)$$

$$Bleed_{AvUsed} = \pi/4 \times \left(D^2_{AvUsed} - 100\right) \quad (3)$$

$$B_{AD} = 100 \times \left(\frac{Bleed_{AvUsed} - Bleed_{AvFresh}}{Bleed_{AvFresh}}\right) \quad (4)$$

where,

$Bleed_{AvFresh}$ is the average bled area from the fresh sample;.

$D_{AvFresh}$ is the average bled area diameter (in mm) from 4 measurements of fresh grease;.

$Bleed_{AvUsed}$ is the average bled area from the used sample;.

D_{AvUsed} is the average bled area diameter (in mm) from 4 measurements of used grease;.

B_{AD} is the relative bled area difference between the used and fresh samples.

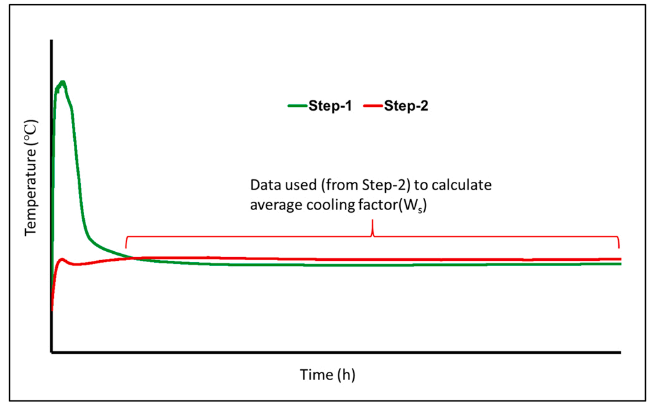


Fig. 2. Schematic representation of experimental curves for the temperature-corrected energy density calculation. The cooling factor is calculated using the increase in temperature that results from heat generation by EHL friction only, i.e., during the bleeding phase.

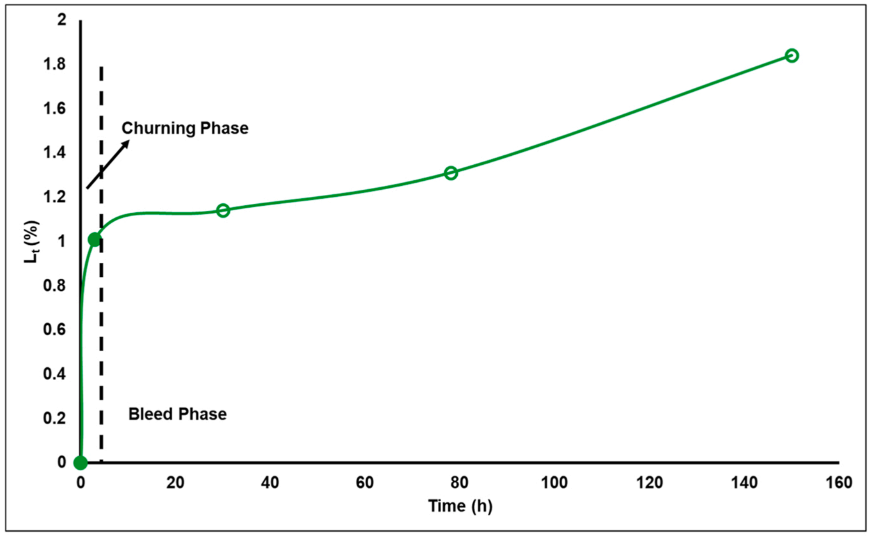
2.7. The temperature-corrected energy density concept

In reference [5], we showed that the length of the churning phase is related to the imposed/dissipated energy on/in the grease. This energy was estimated by integrating the measured temperature change during the churning phase. In reference [5], we also distinguished the process of churning into two phases: the channeling and clearing phases. Most of the grease is pushed to the sides in the channeling phase, whereas a small amount is pushed to the sides during the clearing phase. The clearing phase is the longer of the two. In both phases, the bearing is lubricated under fully flooded conditions. Starved lubrication occurs during the bleed phase. Energy consumption during the bleed phase originates from the frictional losses in the Elasto-Hydrodynamic Lubrication (EHL) contacts and hence, this is called EHL friction. During churning, the imposed energy is a function of both EHL sliding/rolling friction and churning friction (friction due to drag losses, also known as viscous dissipation by drag).

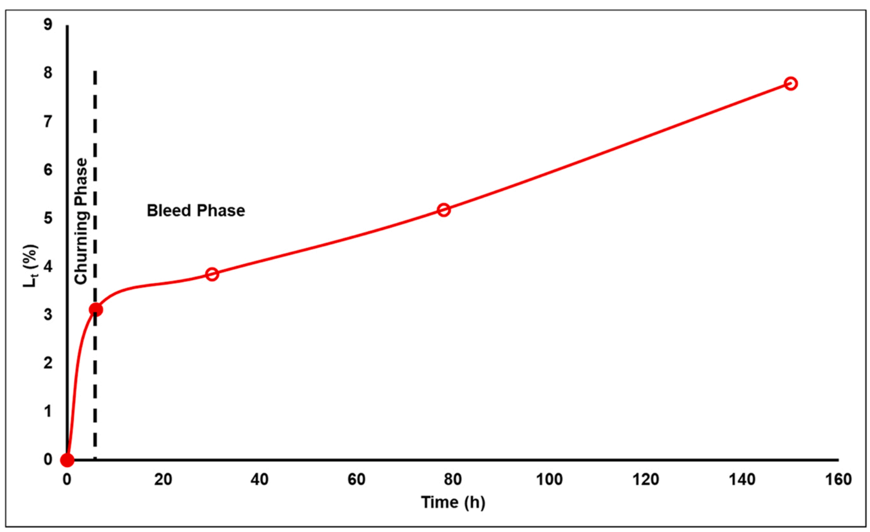
Evaluating the mechanical energy imposed (or work done on the grease) by churning only requires subtracting the EHL energy from the total energy during both the churning and bleeding phases. To achieve this experimentally, we performed experiments in a two-step process (Fig. 2).

In step 1 (green curve in Fig. 2), all bearings ran with fresh grease (including test and support bearings) for about 45 h under the same conditions (15,000 rpm and 150 N of radial load) as other experiments in this paper. During these 45 h run, all greases finished the high-temperature churning phase over a period ranging from 1 to 8 h and ran for the rest of the test duration in the bleeding phase at a lower stationary temperature (Fig. 2). After 45 h, the experiment was stopped and the bearings allowed to return to room temperature without dismantling them from the test equipment.

In step 2, the same bearings were restarted with the same conditions (15,000 rpm and 150 N radial load) again for 45 h. Here, the bearings did not have an additional churning phase; the peak temperature was approximately equal to the stationary temperature of the bleed phase (the steady-state region) in step 1. The energy imposed during step 2 is caused by EHL friction only. The imposed energy (or work done) on the



(a)



(b)

Fig. 3. **:** Grease leakage (%) versus time (h) for single bearing. (a) LM2L; (b) LM3L. The first two points (closed markers) in each plot are from the churning period and the other three points (open markers) are measured in the bleed phase.

grease during churning is then the difference between the total energy imposed during step 1 and the (EHL) energy imposed during step 2. Methods to accurately calculate—for practical purposes—the energy imposed or work done on grease in a bearing during bearing operation are currently unavailable. This energy is the time integral of the product of generated friction torque and rotational speed. The speed can be measured easily but accurate measurement of frictional torque at high speed is currently unachievable. Hence, we estimate energy from the measured temperature signal via the thermal energy balance. The increase in running bearing temperature (from the initial ambient temperature) occurs primarily via heat generation which is given by the bearing's power loss. The temperature change is given by [28].

$$\Delta T = \frac{P}{W_s} \tag{5}$$

where P is the bearing power loss (W); W_s is the average cooling factor (J/s ℃). For every combination of bearing and grease, only one average cooling factor is needed. W_s is calculated using the steady-state temperature during step 2 (the highlighted region in Fig. 2) for which the power loss P is readily evaluated, considering EHL friction, as

$$P_{step2} = 1.05 \times 10^{-4} M^{'} n \tag{6}$$

where M' is the friction torque of the bearing (Nmm) and n is the rotational speed (rpm). The friction torque is given by the equations in the SKF rolling bearing catalogue [28]:

$$M^{'} = (\varnothing ish \times \varnothing rs \times Mrr + Msl) \times 10 \tag{7}$$

$$M^{'} = \left(\varnothing ish \times \varnothing rs \times Grr(vn)^{0.6} + Gsl \times \mu sl\right) \tag{8}$$

$$M^{'} = \frac{1}{1 + 1.84 \times 10^{-9}(ndm)^{1.28}\nu^{0.64}} \times \frac{1}{e^{\left[K_{rs} \times vn(d+D) \times \frac{\sqrt{K_z}}{2(d-D)}\right]}} \times G_{rr}(vn)^{0.6} + G_{sl} \times \mu_{sl} \tag{9}$$

$$M^{'} = G_{rr} \times n^{0.6} \times \frac{1}{1 + 1.84 \times 10^{-9(ndm)^{1.28}\nu^{0.64}}} \times \frac{1}{e^{\left[K_{rs} \times vn(d+D) \times \frac{\sqrt{K_z}}{2(d-D)}\right]}} \tag{10}$$

where.

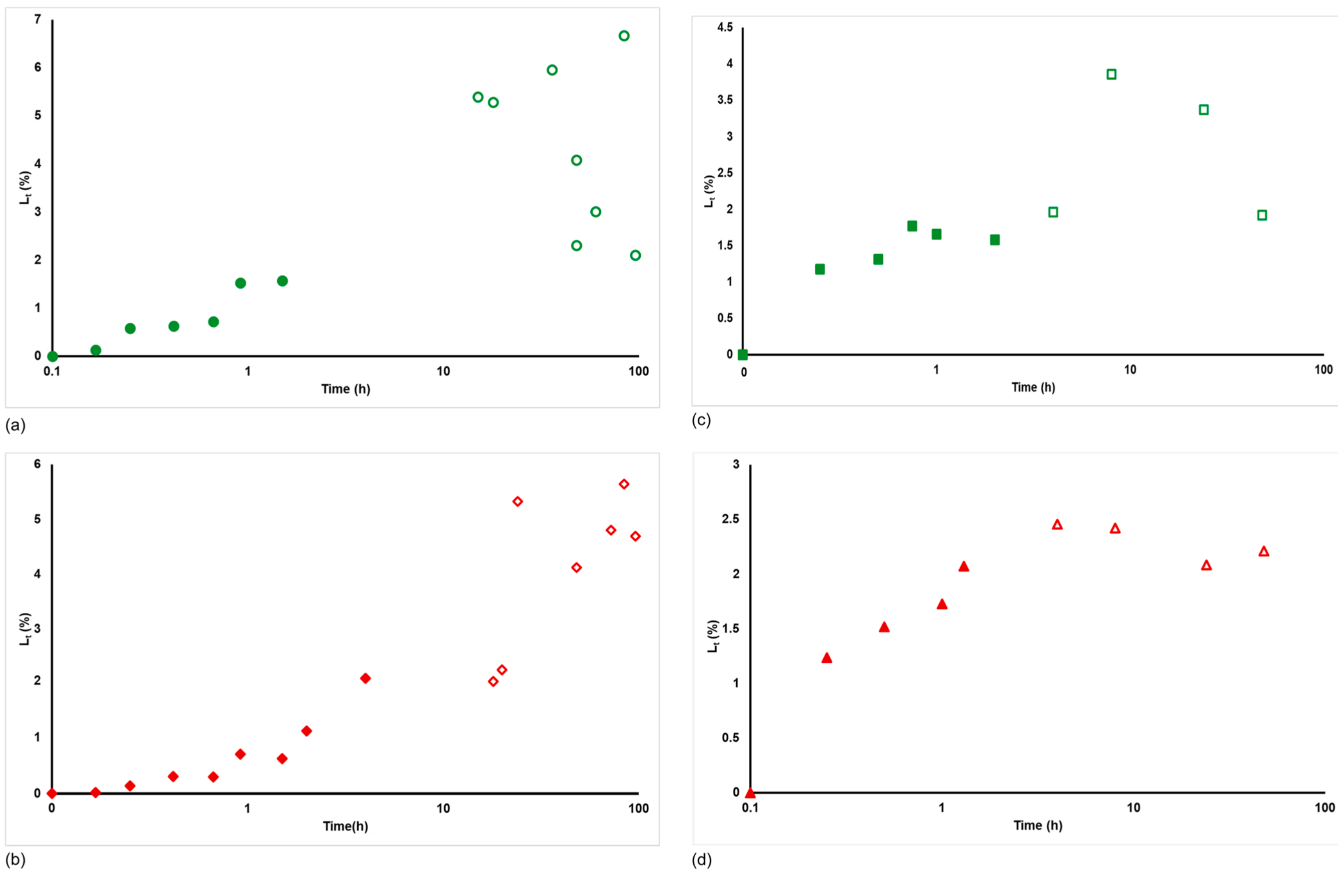


Fig. 4. : Grease leakage versus time (on a semi-log scale). (a) LM2L; (b) LM3L; (c) LM3C; (d)LCP 2.5 C. The closed symbols represent measurements during the churning phase whereas open symbols refer to measurements done in the bleed phase. The green marker represents the greases with good/peak-type churning behavior and the red marker represents the greases with poor/plateau-type churning behavior. Note: Other than in Fig. 3 every point is a separate test.

$\O_{ish}$ is the inlet shear heating reduction factor.

$\O_{rs}$ is the kinematic replenishment/starvation reduction factor.

M_{rr} is the rolling frictional moment (Nmm).

M_{sl} is sliding frictional moment (Nmm).

ν is the kinematic viscosity of base oil at operating temperature, calculated using Walther's equation [29].

n is the rotational speed (rpm).

μ_{sl} is the sliding friction coefficient, it is 0.05.

d is the bearing inner diameter (20 mm).

D is the bearing outer diameter (47 mm).

d_m is the mean diameter of the bearing.

K_{rs} is the replenishment or starvation constant, for greases K_{rs}=6 × 10^{-8}.

K_z is the bearing type related geometric constant; for Deep Groove Ball Bearing (DGBB), $K_z = 3.1$.

G_{rr} is the variable defined by the equation ($G_{rr} = R_1 \; d_m^{1.96} F_r^{0.54}$) for the axial load of zero Newton.

R_1 is the geometry constant, $R_1 = 3.9 \times 10^{-7}$ for 6204 bearings.

F_r is the radial force applied in Newton.

G_{sl} is the variable defined by the equation ($G_{sl} = S_1 d_m^{-0.26} F_r^{5/3}$) for the axial load of zero Newton.

S_1 is the geometry constant; S_1=3.23 × 10^{-3} for 6204 bearings.

Combining the cooling factor W_s obtained from step 2 (red curve in Fig. 2) and the temperature profile in step 1 (green curve in Fig. 2), the power during step 1 is evaluated from Eq. (1) as $P_{step1} = W_S \Delta T_{step1}$. Then the churning power is the difference between the total power in step 1 and the EHL power in step 2, that is, $P_{chu} = P_{step\ 1} - P_{step\ 2}$. The mechanical degradation process is accelerated by heat. The churning power is corrected for temperature by multiplying P_{chu} with a factor C_T obtained via the Arrhenius equation:

$$C_T = 2^{\left(\frac{T - T_0}{T_A}\right)} \tag{11}$$

where T is the measured temperature and T_0 = 40 °C is the reference temperature. Eq. [11] normalizes all the churning powers calculated for the various experiments to the same reference temperature and accounts for secondary thermal effects. This approach is commonly used for calculating grease life [2,25] where the Arrhenius temperature T_A= 15 °C.

The accumulated churning energy E is the corrected power integrated over time:

$$E = \int_0^{t_{chu}} C_T P_{chu} \mathrm{d}t \tag{12}$$

where P_{chu} is the power dissipated in the grease by churning and t is the churning time; the test starts at $t = 0$ and t_{chu} is the churning duration. The temperature-corrected energy density during churning, in J/mm^3, is calculated by dividing the churning energy (Eq. (12)) by the grease volume in the bearing V_g:

$$E_V = \frac{E}{V_g} \tag{13}$$

The effect of leakage on the change in V_g is neglected here since it does not change more than 5% during churning.

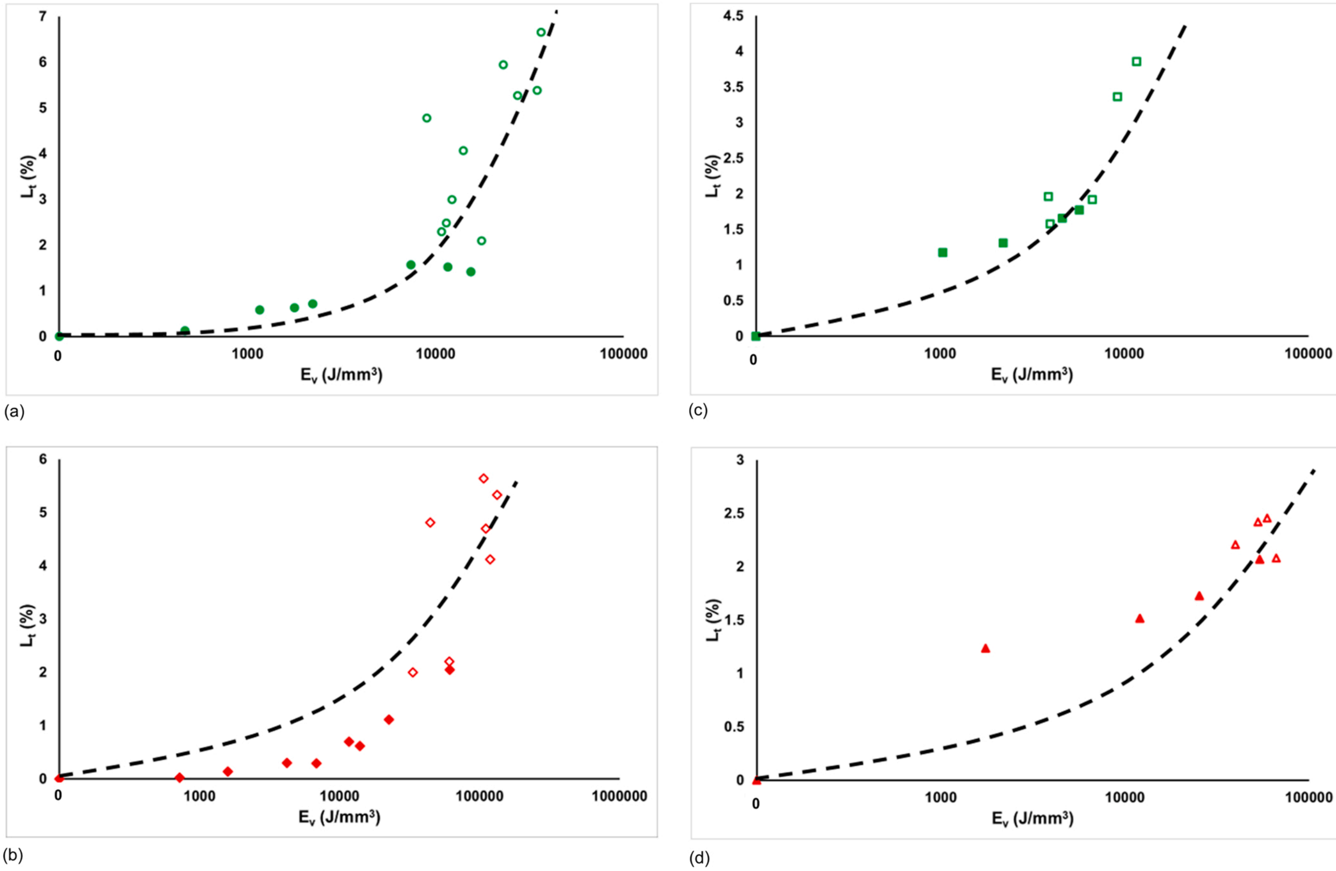


Fig. 5. **:** Grease leakage (%) versus accumulated churning temperature corrected energy density E_v. (a) LM2L; (b) LM3L; (c)LM3C; (d) LCP 2.5 C. The closed symbols represent measurements at different stages of the churning phase whereas open symbols refer to measurements done at different stages of the bleed phase (after churning is completed). The green markers denote greases with good/peak-type behavior and the red markers the greases with poor/plateau-type behavior. Note: the dashed lines are observed trends and not curve fits.

3. Results

3.1. Grease leakage for single and multiple bearing tests

Grease leakage is the measured grease mass loss from the bearing after a test, calculated in this study as described in Section 2.3. The results in Fig. 3 show that leakage primarily occurs during churning. Leakage during the bleed phase is very small and may be caused by the loss of base oil produced by grease bleed, or by the grease itself leaking out.

Fig. 4 presents grease leakage vs time (on a logarithmic scale) for all four greases tested.

The results in Fig. 4 show that for a good/peak-type churning grease (Fig. 4a and c), leakage is quite small (note that each point in Fig. 4 is a separate test). By contrast, for poor/plateau-type churning grease (Fig. 4b and d), leakage continuously increases in time during churning. As mentioned previously [5], it is extremely difficult to precisely reproduce/repeat grease-lubricated bearing experiments/measurements due to the highly chaotic character of grease flow and its dependence on the initial conditions (grease filling, etc.). The length of the churning phase, the friction torque, and the self-induced temperature will vary. All four plots show significant scatter for the bleed phase measurements. Time is therefore not the sole determinant of grease leakage.

Fig. 5 shows that grease leakage is a function of the effective temperature-corrected energy density input E_v on the grease during the churning period. Leakage is more adequately quantified by the temperature-corrected energy density than by time. Irrespective of the grease churning behavior/type, grease leakage increased with increasing E_v. This energy density by drag (viscous) losses does not increase much further after the churning phase. Grease degradation continues during the bleed phase but at a much lower rate than during the churning phase.

3.2. Grease tackiness in bearings

Grease tackiness was measured on samples that were taken from bearings before, during, and after churning. The results are shown in Fig. 6. The fresh LM2L grease (Fig. 6a) had a low initial tackiness which increased immediately after bearing operation commenced. The increased tackiness stayed constant during and after the churning period. Fresh LM3L (Fig. 6b) grease also had a low initial tackiness value. Similar to LM2L, the tackiness of LM3L grease started to increase as soon as the bearing started to run. It stayed constant for a very long period but started to decrease at the end of the churning phase; in the bleeding phase, measured tackiness was low compared to that during the churning phase. Fresh LM3C grease (Fig. 6c) had a high initial tackiness, which started to decrease very quickly once the bearing started running. It stayed constant during the churning phase but stepwise decreased during the transition from churning to bleeding. All measurements done in the bleed phase gave the same tackiness value even though all the grease samples experienced different churning energy densities. Fresh LCP 2.5 C grease (Fig. 6d) had a low initial tackiness and similar to LM2L and LM3L, its tackiness started to increase from the beginning of bearing operation. This increase continued until the end of the churning process. Samples of LCP 2.5 C, which had entered into the bleed phase showed values of tackiness similar to other greases. Similar to LM3C, all measurements done in the bleed phase gave the

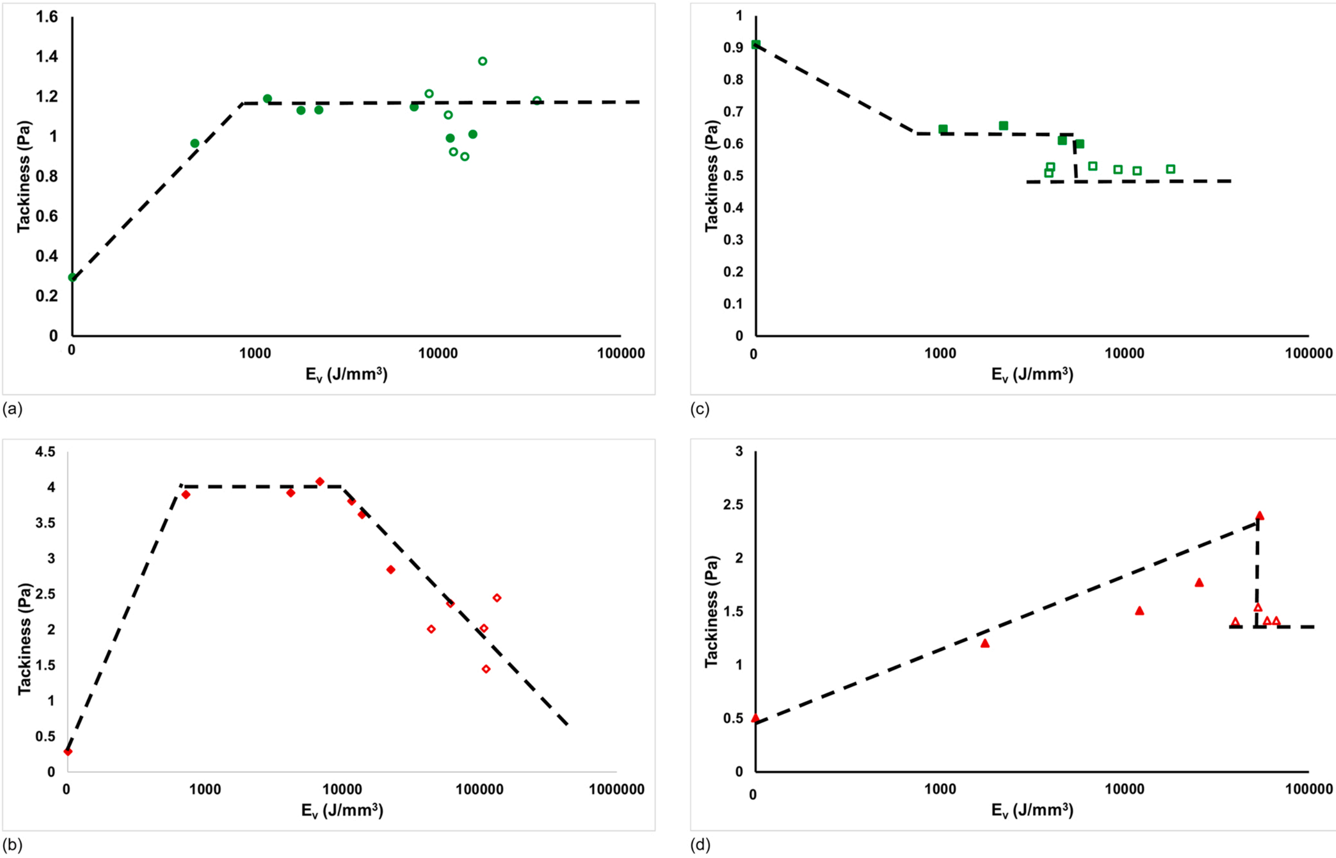


Fig. 6. Tackiness during (closed marker) and after (open marker) churning process in bearing; (a) LM2L; (b) LM3L; (c) LM3C; (d) LCP 2.5 C. The closed symbols represent measurements at different stages of the churning phase whereas open symbols refer to measurements done at different stages of the bleed phase (after churning is completed). The green marker represents the greases with good/peak-type behavior and the red marker represents the greases with poor/plateau-type behavior. Note: the dashed line is a trend line and not a curve fit.

same tackiness value even though all samples experienced different churning energy densities.

From Fig. 6a-d, it is evident that there is no critical tackiness for the end of the churning phase. All the used greases, irrespective of their churning type (peak or plateau), have different tackiness values at the end of the churning phase. For 2 of the 4 greases, all measurements done in the bleed phase gave the same tackiness value although all samples experienced different churning energy densities, which would indicate that there could be a critical temperature-corrected energy density at which tackiness would instantaneously drop, marking the transition from churning to bleed. However, this does not apply to the other greases. This suggests that tackiness is not the property that consistently defines churning behavior.

3.3. Oil bleeding capacity measurements in the RST

Fig. 7 shows the results of the oil bleeding capacity measurements (using the bled area difference B_{AD}) for different grease samples aged for different durations in the Roll Stability Tester (RST). To compare with the bearing tests, Fig. 7 also shows the expected transition from churning to bleeding. The label “Also in bearings” refers to aging that would also happen in bearings (this time duration was determined in our earlier paper [5] by comparing the rheological properties from samples taken from the RST and the bearings). The label “Only in RST” refers to aging in an RST that goes beyond aging that would happen in a bearing during the churning phase. There is no clearing process in the RST and therefore, aging in the RST proceeds beyond the point where this would stop in a bearing. For all greases, irrespective of the churning type, oil bleeding capacities progressively increased in the RST during the simulated churning period. For the good/peak-churning type greases (Fig. 7a and c), the oil bleeding capacities started to decrease from their maximum just before or at the end of the simulated churning phase. By contrast, for the poor/plateau-churning type greases (Fig. 7b and d), oil bleeding capacities initially increased but started to decrease well before the end of the churning phase, reaching a very low value at the end of churning. This is attributed to the long churning duration and therefore more severe grease degradation.

There is a similarity between the change in yield stress and bleed capacity (Fig. 8). Both can be explained using the concept of “grease microstructural flexibility”. In our earlier study [5], we explained the evolution of yield stress in the roll stability tester from the change in grease microstructure as measured with the AFM. The yield stress decreased in the beginning due to a change in the grease microstructure but without breaking the fibers. The microstructural change during this period is attributed to the movement of grease fibers within the microstructure, without breaking. The increased yield stress (Fig. 8) after the initial decrease is attributed to the degradation of longer grease thickener fibers into more medium-sized and short fragments. Later, the yield stress again started to decrease and AFM visualization [5] showed that this happens due to the formation of smaller thickener fragments. At one stage, all the thickener fibers are degraded into small and fine particles resulting in very low yield stress. This leads to an increase in oil bleeding capacity due to more breakdown of grease microstructure. This was evident in all the greases tested (Fig. 8a-d) in this work, irrespective of churning type behavior. For the LCP 2.5 C grease (Fig. 7d), the oil bleeding capacity (via bled area difference B_{AD}) is very high just after the end of the churning period, attributed to its severe microstructure degradation during churning.

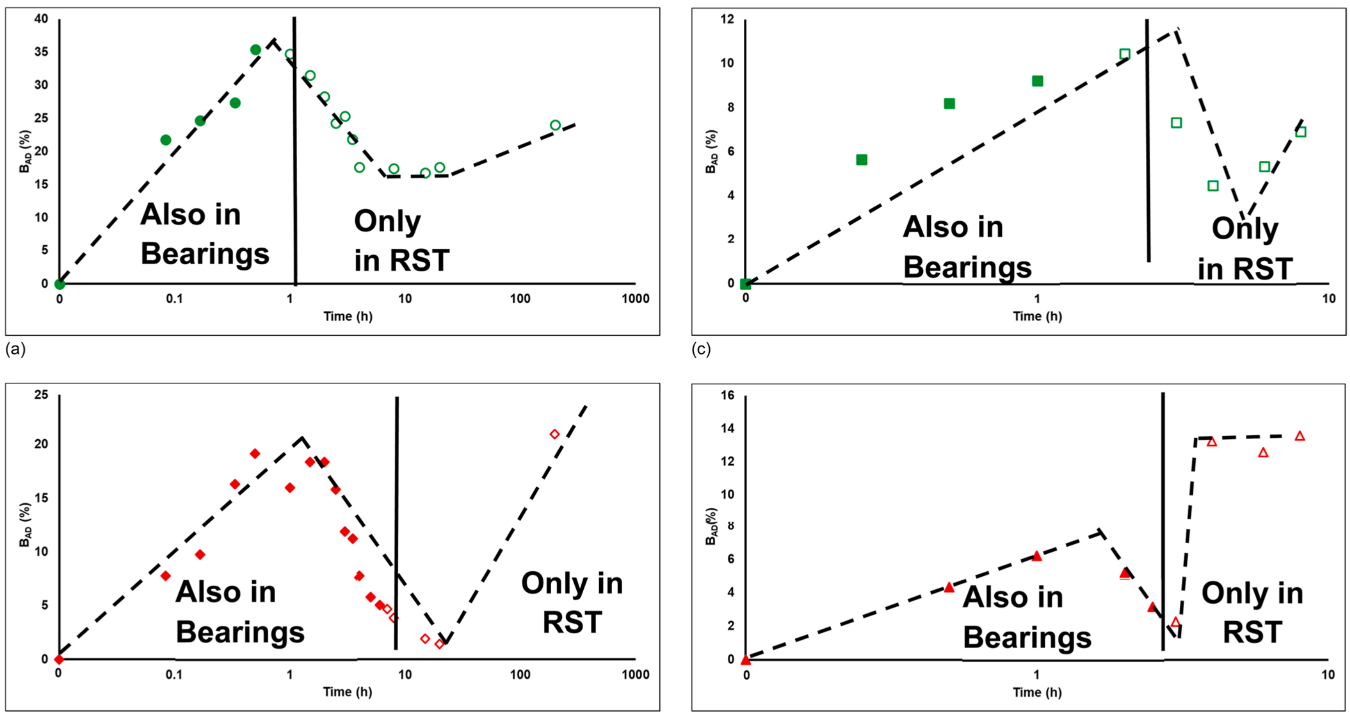


Fig. 7. Changes in oil bleeding capacities, measured as the difference B_{AD} in bled areas, during (closed markers) and after (open markers) the churning phase. (a) LM2L; (b) LM3L; (c) LM3C; (d) LCP 2.5 C. The closed symbols represent measurements during the churning phase whereas open symbols refer to measurements done in the bleed phase. The green marker represents the greases with good/peak-type behavior and the red marker represents the greases with poor/plateau-type behavior. Note: The dashed line is a trend line and not a curve fit.

4. Discussion

In grease lubricated rolling bearings, the lubrication process can be roughly divided into two phases: the churning phase and the bleeding phase. During the first few minutes of the churning phase, the rolling elements push most of the grease away from the "swept area" into the "unswept area" forming a grease channel. Therefore, this process is called "channeling". After channeling, continuous bearing operation "clears" the remaining grease on the tracks; this phase which takes several hours is therefore called the "clearing phase".

During both channeling and clearing, macroscopic grease flow takes place and the bearing frictional torque is dominated by drag losses leading to relatively high temperature. High shear in combination with high temperature leads to grease degradation during this phase, which takes only up to a few hours compared to the much longer grease life. Once churning is over, starved lubrication will prevail and minimize macroscopic flow of grease, leading to low friction and therefore low bearing temperature. Note that there may still be creep flow and "events" that will shear some grease. However, the overall grease flow rates will be very low during this post-churning phase and the specific degradation rate will hence also be very low. Much of the total degradation will therefore happen during the churning phase. This degradation will have an impact on the lubrication properties and performance of the grease. After all, the end of this (churning) phase is the start of the very long bleeding phase. These start conditions will give the total volume of grease in the bearing and the "quality" of the reservoirs, measured using the yield stress, tackiness, and bleed capacity.

Long grease life that leads to long bearing service life is obtained by having grease that bleeds for a long period. In our earlier study [16], many bearing experiments were performed to characterize and understand grease churning behavior and corresponding grease properties. With the temperature profile, greases were categorized into a good/peak-type, with a short churning period, and a poor/plateau-type with a long churning period. In reference [5], we showed that the difference in churning behavior may be ascribed to "microstructure flexibility", i.e. the ability of a grease to change its rheological properties without breaking down its thickener fibers. Greases with better microstructure flexibility are of the good/peak-type whereas greases that show fiber breakdown during churning show a poor/plateau-type grease behavior.

Grease degradation or aging impacts its properties and causes grease leakage, which will reduce grease life and grease performance in a bearing. As shown in Fig. 5, grease leakage is related to the imposed temperature-corrected energy density (E_V) irrespective of the churning behavior type. Grease leakage increases with increasing E_V. Furthermore, it is shown that the amount of grease leakage is also related to the grease's intrinsic properties, irrespective of the churning type. Low values of E_V show less leakage than high values of E_V. Once churning ends, the rate of grease leakage decreases, and leakage is then primarily caused by leakage of bled oil (Fig. 3).

Grease reservoirs are formed during churning. During the subsequent bleeding phase, lubricant supply to the contacts happens primarily due to oil bleeding. The rate of oil bleeding has a large impact on the durability of the grease (long-life properties). It is evident from Fig. 7 that grease bleeding capacity is adversely impacted during churning. In the initial period, irrespective of the churning behavior, the oil bleed capacity increases. However, after the initial period of increase, oil bleed capacity drastically decreases. This decrease is more severe for greases which have long churning durations or higher E_V.

In reference [5], we showed that grease aging in the RST leads to increased yield stress. All the greases irrespective of the churning behavior showed increased oil bleeding capacity and correspondingly decreased yield stress during the early hours of aging in RST. However, in a bearing application with a good/peak-type churning grease where E_v is low, degradation of the grease is minimal. Hence, such grease will maintain a healthy level of oil bleeding capacity and provide adequate bearing lubrication.

Poor/plateau-type churning greases, that show high values of E_v,

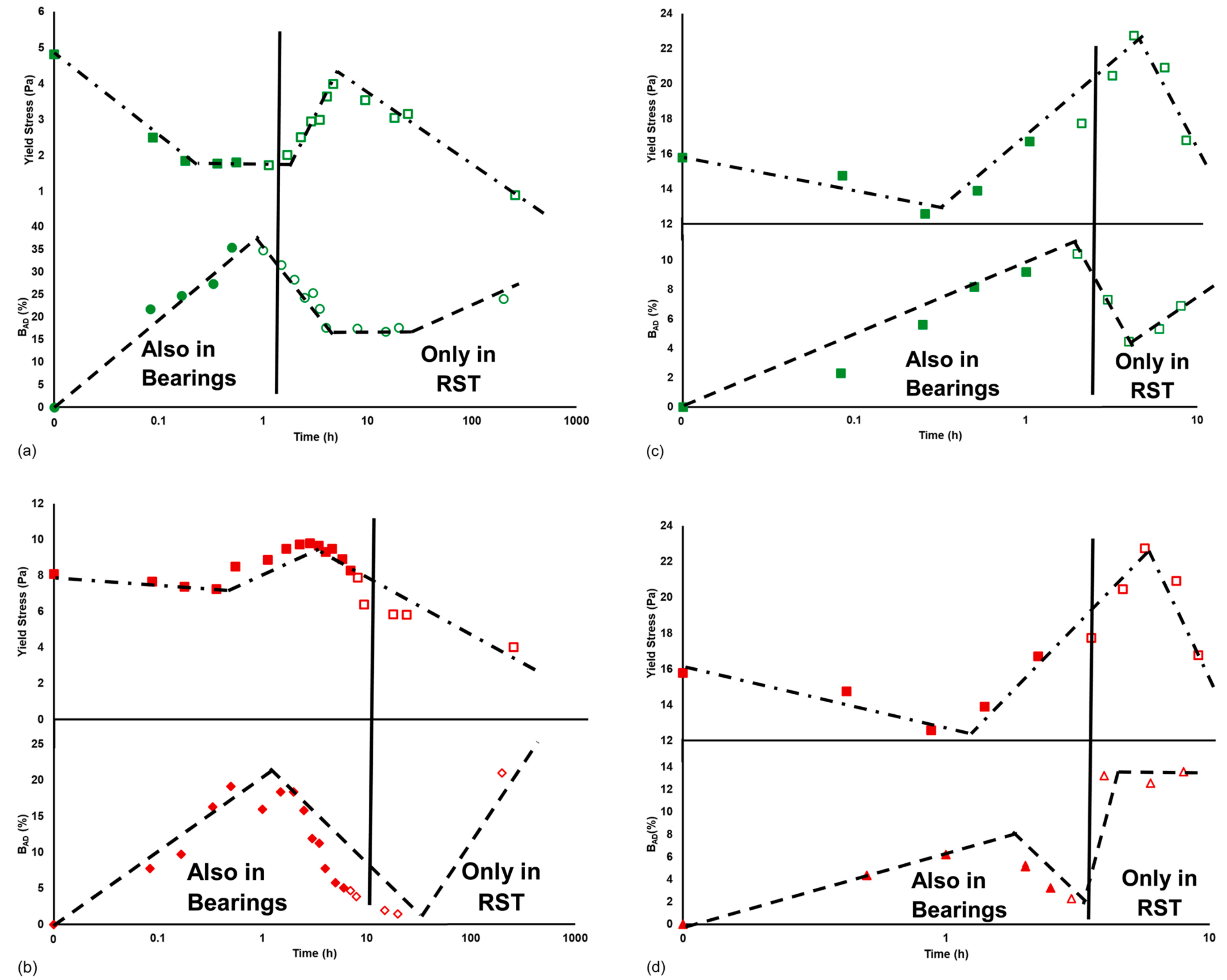


Fig. 8. Comparison of the bled area difference B_{AD} (which defines bleed capacity change) and yield stress at the churning temperature, measured during (closed markers) and after (open markers) the churning phase; (a) LM2L; (b) LM3L; (c) LM3C; (d) LCP 2.5 C. Measurements on grease samples taken from the Roll Stability Test. Note: The dashed line is a trend line and not a curve fit.

undergo severe microstructure degradation represented by low/decreased yield stress (Fig. 8b & 8d). These greases end their churning periods with low oil bleeding capacities. This will not immediately have an impact on the film thickness in the early stage of the bleed phase [30]; however, it will have an impact in the long run and therefore on grease life. If we translate these results into a bearing application, for the good/peak-type churning greases with low E_V (Fig. 8a & 8c), the churning phase has little impact on the decrease of oil bleeding capacities during the bleed phase. However, for poor/plateau-type churning greases with very high E_V, the resulting high level of degradation has a significant impact on the oil bleeding capacities (Fig. 8b & 8d). This suggests that in a running bearing, as the imposed temperature-corrected energy density (from the bearing to the grease) increases during churning, the grease bleed capacity further decreases.

Grease reservoirs are formed by grease adhering to the metal surfaces of the cage bar, bearing shoulders, and shields. The ability of grease to attach to these metallic surfaces depends on the tackiness of the grease, which is the combination of adhesion and cohesion properties of the grease. During the churning process, tackiness changed (Fig. 6). It is evident that there is no universal critical tackiness characterizing the churning phase, indicating that tackiness is not a consistent grease churning behavior-defining property.

For good/peak-type churning greases with large total E_V, tackiness changed during the churning process. However, this change happened in a short period or with very low input of temperature-corrected energy density (E_V). After the churning process, the tackiness was almost constant. Also, for poor/plateau-type churning grease, during the process of churning, tackiness increased. The increase in tackiness progressed longer and with higher dissipated energy density E_V. This continuous energy dissipation E_V resulted in grease degradation and thus the reduction in the tackiness. The reduction in tackiness may impact the stickiness of the grease to the metallic surfaces in the long run and may contribute to the grease dynamism—wherein a small portion of grease falls back into the contacts and results in friction and temperature rise due to the micro channeling. These processes/events may happen regularly due to decreased tackiness in the aged greases. This will contribute negatively to the grease life.

Higher grease degradation also results in the reduction in grease tackiness at the end of the churning phase. It is not completely clear what a good level of tackiness is for long-term lubrication. However, one of the hypotheses is that the reservoir cannot be maintained if grease tackiness is too low. The grease will not stick to the seals/shields and/or bearing steel surface but will fall back into the swept region during the long-running of the bearing. This creates a short period of churning with increased temperature during the bleed phase. This further increases the grease aging and decreases the potential grease performance. This topic needs further detailed work for better understanding and may be included in our future study.

For better lubrication performance in a rolling bearing application and long grease life, it is essential for grease to maintain a good bleeding ability, tackiness, and have minimum grease leakage. A high churning temperature-corrected energy density leads to a high level of grease aging/degradation. This results in increased grease leakage, decreased oil bleeding capacity and tackiness at the end of the churning period, adversely impacting grease lubrication and grease life.

5. Conclusion

Grease leakage in the initial bearing operation is not random but is a function of the imposed temperature corrected energy density to the grease during the churning process. The type of churning behavior has an impact on the grease aging because good/peak-type churning grease will only need a low level of temperature corrected energy density to finish the churning period and therefore will not show much degradation, whereas a poor/plateau-type churning grease will undergo more work (imposed temperature corrected energy density) to finish the churning period. A poor/plateau type will therefore show more grease degradation.

A small level of grease aging will lead to an increase in oil bleeding capacity. However, beyond a certain level of aging, grease bleed capacity reduces again. For a good/peak-type grease, this point will not be reached, leading to higher bleeding ability after the churning phase. The poor/plateau type grease shows so much degradation that the bleed capacity is very poor at the end of the churning phase. This may lead to early bearing failures.

The overall conclusion is that a good/peak-type grease provides better grease performance (leakage and bleed) in a rolling bearing application, and that degradation can be quantified using a temperature-corrected dissipated energy density concept. We have presented an engineering approach to this which could be further improved by applying more fundamental thermodynamics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Statement of originality

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As corresponding author, I Sathwik Chatra Kalsanka Ramakrishna, hereby confirm on behalf of all authors that:

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Yours Sincerely,

Sathwik Chatra Kalsanka Ramakrishna.

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