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Effect of Over Rolling Frequency on the Film Formation in Grease Lubricated EHD Contacts under Starved Conditions †

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Abstract: The service life of rolling bearings is significantly affected by the lubricating film formation in elastohydrodynamic (EHD) contacts. Grease lubricated EHD contacts show a film thickness decay from a characteristic rotational speed, which is referred to as starvation. Thus, the film thickness of grease lubricated contacts differs from that of oil lubricated contacts. However, the base oil properties under fully flooded conditions are commonly assumed to estimate the operating lifetime of grease lubricated bearings, which are usually not fully flooded. Hence, this assumption results in an overestimation of the film thickness for rotational speeds in the range of starvation, which can lead to uncertainties in the bearing design. At high rotational speeds, i.e., high over rolling frequencies, starvation is likely to occur, due to insufficient lubricant supply by replenishment behind the rolling element. Therefore, the focus of this contribution is to investigate the effect of over rolling frequency, and thus replenishment time, on the lubricating film formation in starved, grease lubricated EHD contacts. The film thickness measurements were performed on a ball-on-disc tribometer, which was extended by adding a second ball specimen in front of the measuring ball. By varying the angular distance between the two contacts, the lubricant displacement can be controlled, such that the effect of replenishment time on the film formation can be determined. These investigations should help to establish an advanced understanding of the mechanisms of grease lubrication, and encourage future work with a focus on developing a method to predict the film formation in grease lubricated EHD contacts.

Keywords: EHD contact; grease lubrication; starvation; replenishment; thickener layer

1. Introduction

Rolling bearings are commonly lubricated using oil or grease to separate the contacting surfaces and reduce friction and wear. Among operational conditions, such as temperature, rotational speed, or vibrations, the service life of rolling bearings significantly depends on the lubricating film thickness in elastohydrodynamic (EHD) contacts. In fully flooded applications, the lubricating film thickness is mainly determined by the rolling speed and the lubricant viscosity. If the lubricant supply is limited, a full film formation cannot be guaranteed for the entire range of rolling speeds. Thus, the film thickness decreases due to a lack of lubricant supply, which is referred to as starvation [1,2]. Grease lubricated rolling bearings are usually not fully flooded, so that starvation is likely to occur [3]. It is assumed, that the film formation in grease lubricated contacts is mainly determined by the bleed oil, which is released by the grease during operation [4]. Moreover, the film formation is affected by the grease thickener, which forms semi-solid layers on the contacting surfaces, or by free thickener particles entering the Hertzian contact zone within the bleed oil flow [3–7]. Thus, the film thickness of grease lubricated contacts differs from that of base oil lubricated contacts, as shown in Figure 1. The figure shows the schematic film formation for a fully flooded base oil lubricated contact and grease under starved lubrication. Measurement results presented in [8] show a similar behavior of the film formation using a ball-on-disc tribometer. Usually, in fully flooded oil lubricated contacts, the film thickness rises with increasing rolling speed. At low rolling speeds the film thickness of grease lubricated contacts is usually higher than that of the corresponding base oil [8–12]. This effect is induced by the grease thickener, which is deposited on the contacting surfaces and forms a layer leading to a higher film thickness at low rolling speeds [6,8,13–15]. Moreover, free thickener particles within the bleed oil flow can enter the contact area, which also leads to a higher film thickness [7,8,16,17]. At a characteristic rolling speed, grease lubricated contacts show a stagnation or even a film thickness decay with further increasing rolling speed [18]. Wilson [19] defines the onset of starvation, when the film thickness of the grease lubricated contact drops below the film thickness of the corresponding fully flooded base oil. This definition will be used in the following and the onset of starvation of the grease lubricated measurements is marked by a dashed line, as shown in Figure 1.

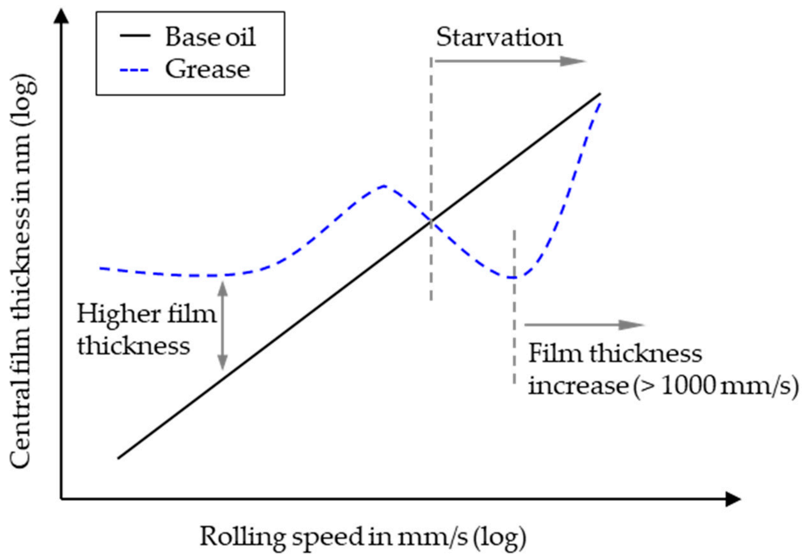

Figure 1. Film formation in fully flooded base oil and starved grease lubricated contacts.

However, for an estimation of the service lifetime of grease lubricated rolling bearings, a fully flooded bearing and the corresponding base oil viscosity are commonly assumed [20]. This assumption results in an overestimation of the lubricating film thickness for rotational speeds in the range of starvation, which can lead to uncertainties in the bearing design. If the contact is not fully flooded, the lubricant supply is mainly determined by lubricant replenishment near the contact zone [21]. The mechanisms leading to the onset of starvation due to insufficient replenishment are explained in Figure 2 [18]. By shearing the grease during operation, bleed oil is released by the side-lying grease bulks and flows into the formed track and is available for the lubrication of the EHD contact [22,23]. The bleed oil is displaced by the rolling element and replenishes behind it, after an over rolling. This mechanism is referred to as replenishment and is mainly driven by surface tension as well as capillary forces [24–26]. At low rolling speeds, the bleed oil can completely replenish behind the rolling element and is available for the lubrication at the next over rolling. With higher rolling speeds, the time for the oil to replenish before the next over rolling is limited by the over rolling frequency. Thus, the lubricant supply decreases with higher over rolling frequency, which results in a lower film thickness than under fully flooded lubrication [21,24–26].

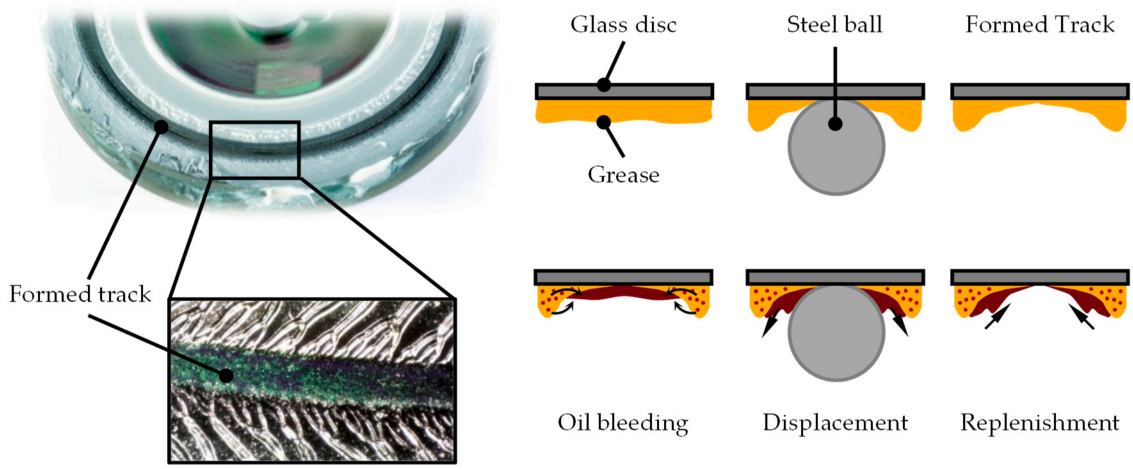

Figure 2. Model for grease lubrication in a ball-on-disc contact [18].

In further studies [26–30], the effect of oil replenishment on the film formation of oil lubricated EHD contacts under starved conditions was investigated using a ball-on-disc tribometer. According to the results of [28,29], replenishment time has a significant effect on the regeneration of the oil film in the rolling track, and thus on the lubricant supply, respectively the film formation. It was shown, that the lubricating film thickness decreases with shorter time intervals between two contacts due to insufficient replenishment. In order to investigate the correlation between the film thickness and the replenishment time in grease lubricated contacts under starved conditions, this study presents a method to control the over rolling frequency by adding a second ball specimen to the test rig. Thus, the over rolling frequency can be adjusted without changing the rotational speed, i.e., the entrainment speed, which would affect the film formation.

As indicated in Figure 1, the measurement results of grease lubricated EHD contacts presented in [8] show an increase in lubricating film thickness within the range of starvation at rolling speeds >1000 mm/s. It is assumed, that the increase of film thickness occurs either due to a recovery phase with increasing shear degradation [8,31,32] or due to centrifugal forces at high disc revolution speeds, which push the grease towards the contact area, and thus increase the lubricant supply [18]. Therefore, in this contribution, both the effect of over rolling frequency on the film formation and the mechanism leading to the increase of film thickness at high rolling speeds >1000 mm/s in starved EHD contacts is studied.

Moreover, it is generally assumed that the film thickness in grease lubricated EHD contacts is a build-up of layers of deposited thickener that forms on the contacting surfaces and bleed oil [6,8,13,15,21,32,33]. A schematic sketch of a grease lubricated contact is shown in Figure 3. The thickener is deposited on the surfaces of the ball and the disc and forms a semi-solid layer, which separates the surfaces [6,8]. Additionally, free thickener particles within the bleed oil flow lead to a higher film thickness, when entering the EHD contact [7,8,34].

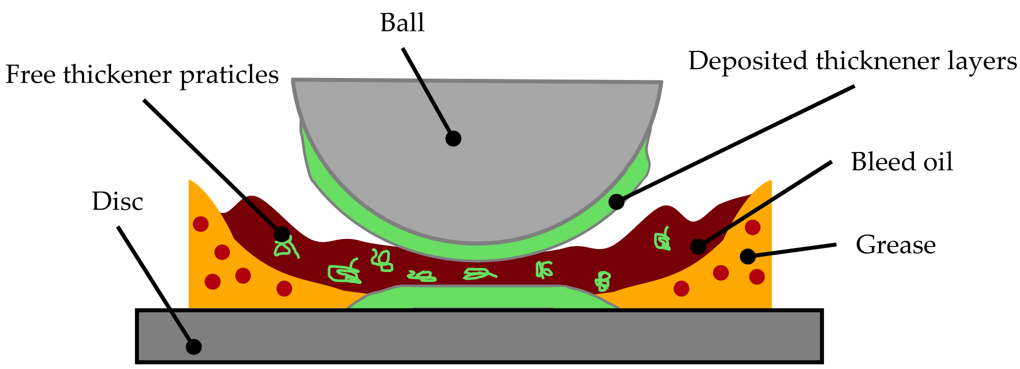

Figure 3. Model of contact lubrication by bleed oil and thickener material.

According to [4,13], the deposited thickener layers show a film thickness of approximately 20–60 nm at zero speed depending on the thickener type. Thus, it can be assumed that the lubricating film thickness is composed of semi-solid thickener layers on the contacting surfaces and a hydrodynamic part by the bleed oil. Therefore, the effect of the thickener layers on the film formation is also investigated in this contribution. The investigations in this study should help to establish an advanced understanding of the mechanisms of grease lubrication and encourage future work with a focus on a method to predict the film formation in grease lubricated EHD contacts.

2. Methods and Lubricants

The film thickness measurements were performed on a ball-on-disc tribometer EHD2 from PCS Instruments. In this work, the central film thickness of oil and grease lubricated EHD contacts were measured at 40 °C and 700 MPa. A polished steel ball with a diameter of 19.05 mm was loaded with 47 N against a glass disc, such that an EHD contact was formed. Each surface had a roughness of approximately R_a = 0.02 µm, so that the surfaces were completely separated during operation for a wide range of rolling speeds. Thus, it can be assumed that the measurements were not performed in a mixed lubrication regime. Both the disc and the ball were driven, and the circumferential speeds were chosen, such that no sliding occurred and pure rolling was applied. The lubricating film thickness was measured by the principle of interferometry, which is described in detail in [35]. Figure 4 shows a sketch of the tribometer with the principle function. For the measurements with grease in a starved lubrication regime, the grease is initially distributed on the disc before the measurement, using a grease distributer as described in [18]. The distributed grease film has approximately a thickness of 0.1 mm and a width of 23 mm. At all measurements, the ball was placed on a disc radius between 36 and 42 mm.

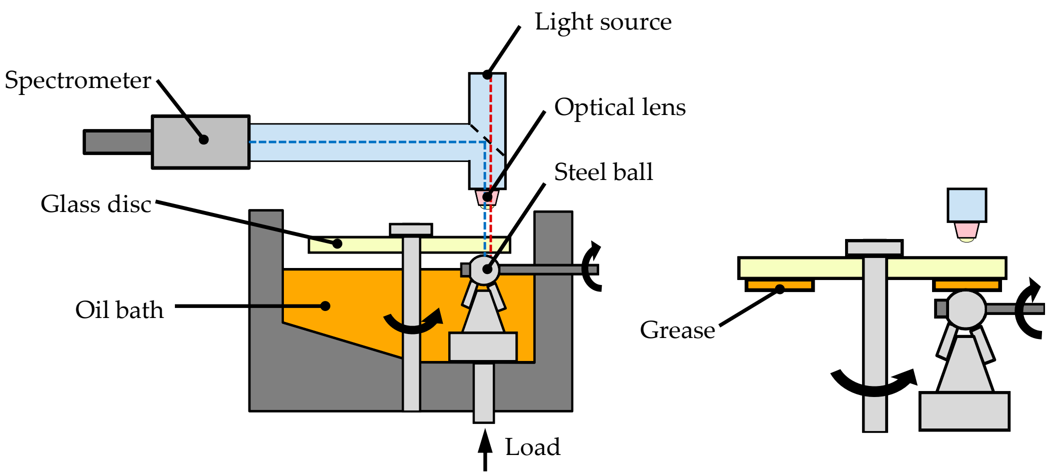

Figure 4. Functional sketch of the ball-on-disc tribometer for film thickness measurements.

The material properties of the glass disc and the steel balls used for the experiments are shown in Table 1.

Table 1. Material properties of the used specimens.

Parameter	Glass Disc	Steel Ball
Modulus of Elasticity	75 MPa	207 MPa
Poisson Ratio	0.22	0.29
Surface Roughness (R_a)	0.02 µm	0.02 µm

For the investigation of the lubricating film formation in dependence on the over rolling frequency, the ball-on-disc tribometer was extended by a second ball, which was positioned in front of the measuring ball. The second ball had the same geometrical as well as material properties as the measuring ball and was loaded with approx. 47 N against the disc, such that the same pressure of 700 MPa for both contacts was applied. It can be adjusted in between an angular range from 50° to 310°, as shown in Figure 5. To study the effect of lubricant displacement and replenishment time on the film formation, measurements were performed with the second ball at 50° and 180° angular positions. Thus, the extended test rig allowed changes to the over rolling frequency by holding the entrainment speed as well as the centrifugal forces constant due to a constant rotational speed of the disc.

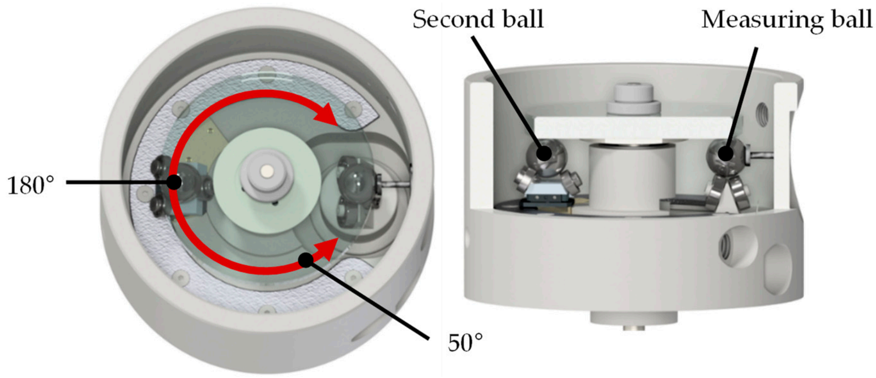

Figure 5. Ball-on-disc tribometer extended by a second ball specimen.

The examined grease was assigned to the consistency class NLGI 2 and did not contain additives. A polyalphaolefine (PAO) lithium complex grease was used for all grease measurements. As a reference and for the determination of the onset of starvation, fully flooded measurements using the corresponding base oil PAO were also performed. The lubricant properties of the examined lubricants are given in Table 2.

Table 2. Lubricant properties of the examined grease and base oil. PAO = polyalphaolefine.

Lubricant	Thickener Type	Thickener Content	Base Oil Type	Viscosity at 40 °C
Base Oil	–	–	PAO	98 mm^2/s
Grease	Lithium Complex	22 wt.%	PAO	98 mm^2/s

The measurements in this study were performed using two different measurement profiles. On the one hand, measurements at a constant rolling speed of 100 mm/s were performed and the film thickness is presented as a function of disc revolutions. On the other hand, measurements by increasing the rolling speed, as described in [18], were performed to identify the onset of starvation. All measurements were repeated to ensure reproducibility, and the mean values of three measurements are presented in the diagrams. In the case of measurements at constant rolling speed, the mean values were taken for interval steps of 30 measurement points. By measuring using the test setup with two ball specimens it is essential to ensure that both balls run on the same track radius. Therefore, the disc was examined directly after each measurement using a light microscope. Figure 6 shows an example of a track where both ball specimens ran on the same track radius (left) and an example where the track radius was slightly different (right). If both balls did not run on the same track, the results were rejected. The position of the second ball was then adjusted and the measurement was repeated. Following this procedure, ensures that both balls run on the same track radius.

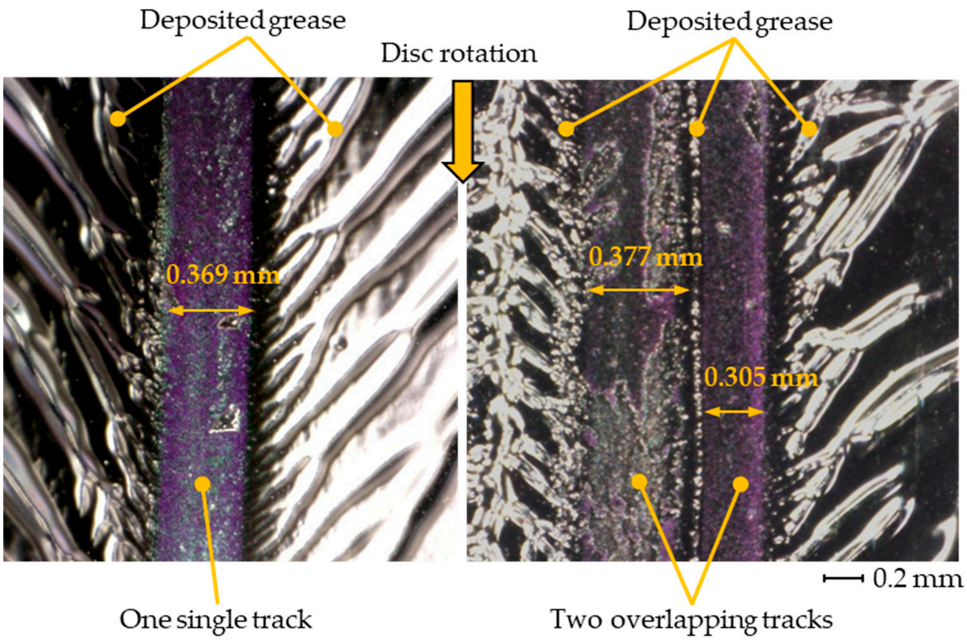

Figure 6. Recordings of matching tracks (**left**) and non-matching tracks (**right**).

Moreover, in this work, the thickness of the thickener layer was measured on the non-rotating disc after a grease measurement at constant rolling speed of 100 mm/s. The glass disc, which was used for the measurements, was coated at the bottom side by a silica layer, called spacer layer, to enable the ultra-thin film measurements [15]. For the investigation of the thickener layer, the thickness of the spacer layer must be determined on a clean and dry disc before the measurement. Therefore, six positions were marked around the measuring track on the disc with an angular distance of approximately 60°. The spacer layer thickness was determined using a clean and dry ball specimen measured at zero speed at the marked positions. Then, the grease was applied on the disc and a film thickness measurement at a constant speed of 100 mm/s was performed. Immediately after the measurement, the central film thickness was measured again at the marked positions at zero speed. By subtracting the film thickness of the spacer layer from the measured results at zero speed, the resulting thickener layer thickness between the contacting surfaces of the disc and the ball could be determined.

3. Results

In the following, the results of the film thickness measurements of grease lubricated EHD contacts are presented. First, the results of the film thickness measurements under grease and base oil lubrication are shown as a function of disc revolutions at constant rolling speed of 100 mm/s. Furthermore, the film thickness results of the thickener layer at zero speed are presented and correlated with the results of the film thickness measurements at constant rolling speed. Moreover, the results of the film thickness measurement with increasing rolling speed are presented to reveal the onset of starvation in dependence of the over rolling frequency. As described in the introduction, the onset of starvation is referred to the definition by Wilson [19].

3.1. Measurement Results at Constant Rolling Speed

The results of the film thickness measurements at a constant rolling speed of 100 mm/s using one ball specimen are shown in Figure 7. As described in Section 2, the mean values out of three measurements including standard deviation error bars are presented. The film thickness of the corresponding base oil under fully flooded lubrication is shown as a reference for the lubricating film thickness of the grease measurement. The measurement results show that during the first 500 disc revolutions, the film thickness increases and then decreases, due to the grease distribution on the disc. This initial behavior is characteristic for grease measurements, and is commonly referred to as a churning phase [21,32,34,36–40]. As soon as the grease is distributed uniformly on the disc, the film thickness reaches a constant level after 1000 disc revolutions. In this regime, a mean value of the film thickness of approximately 110 nm was measured, which is 25 nm higher than the film thickness of the base oil. As already discussed in Section 1, this increase in film thickness can be related to the thickener impact [21,36].

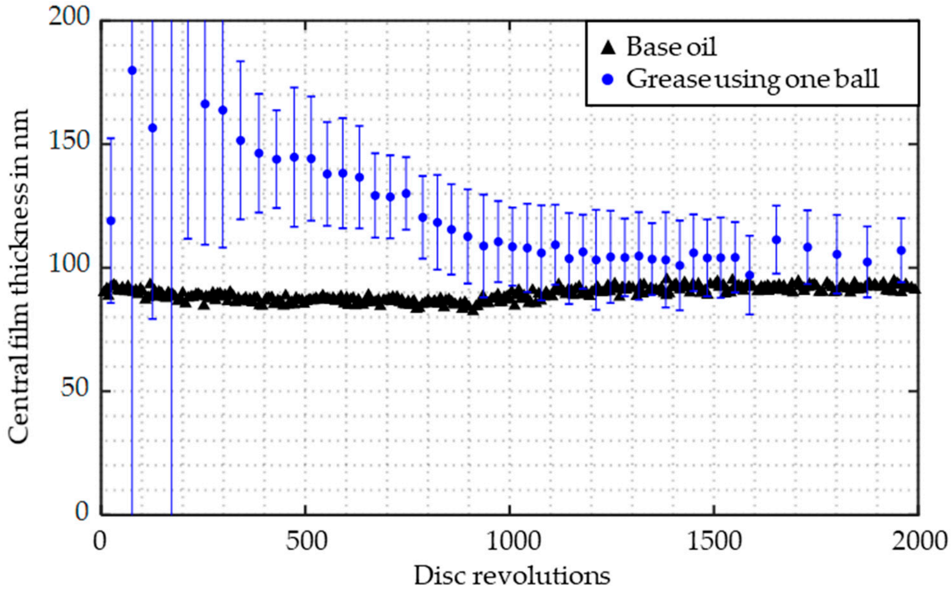

Figure 7. Film thickness of grease and base oil lubricated contacts at 100 mm/s.

To investigate the effect of the thickener on the film formation in grease lubricated contacts, the thickness of the thickener layer was determined, as described in Section 2, at zero speed after the measurement. As presented in Figure 8, the central film thickness was measured at six positions around the measuring track on the disc. The results show a distribution of the thickener layer in a range from approximately 33 to 47 nm with a mean value of approximately 40 nm around the track. The standard deviation indicates a distribution of the thickener layer around the disc with low scattering.

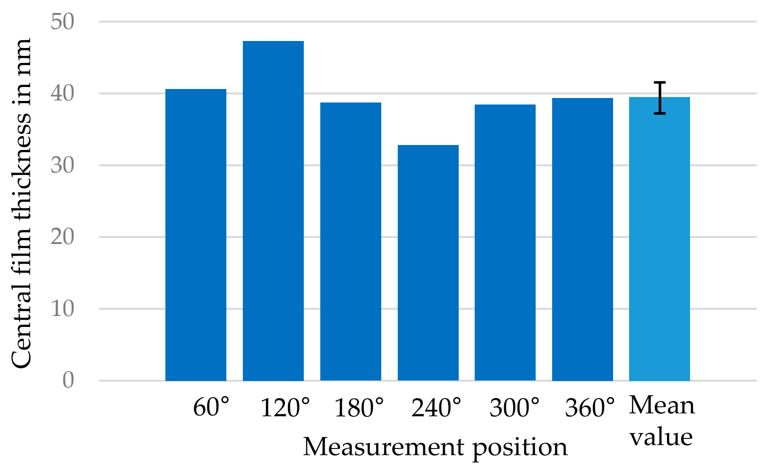

Figure 8. Thickener layer distribution on the disc at zero speed.

As shown in Figure 7, the mean value of the constant film thickness is approximately 110 nm when measuring with one ball at an over rolling frequency of 0.4 Hz. By applying the second ball, which displaces lubricant in the track, the film thickness reduces in a dependent manner with the angular distance. As presented in Figure 9, at an angular distance of 180° (0.8 Hz) the film thickness reduces to approximately 90 nm, and at an angular distance of 50° (3.0 Hz) the film thickness reaches a value of approximately 50 nm.

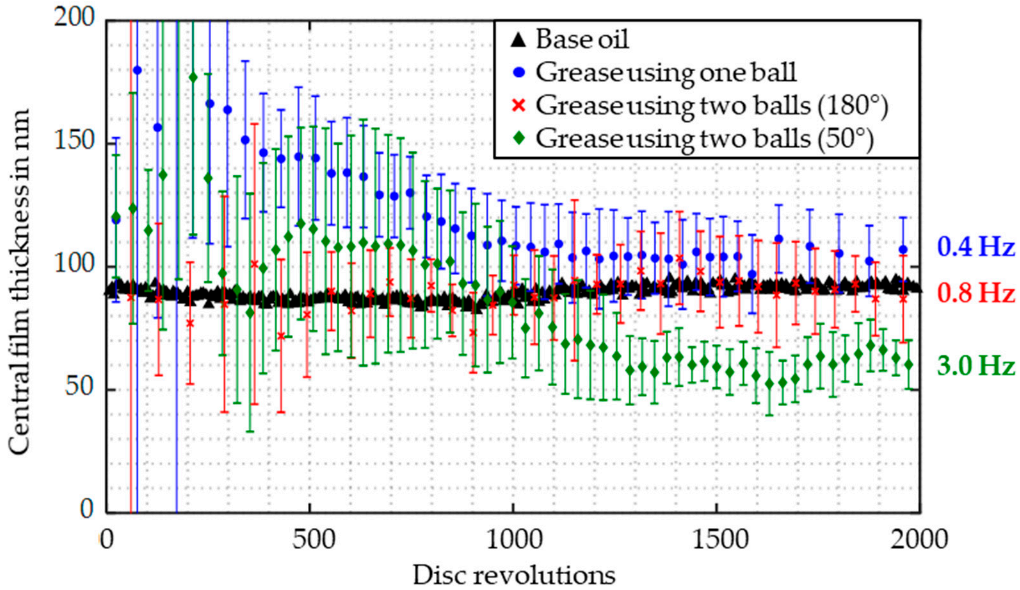

Figure 9. Film thickness at 100 mm/s using one and two ball specimens.

Considering the model in Figure 2, it can be assumed that the added ball displaces bleed oil, and thereby reduces the lubricant supply for the measuring ball. Hence, at an angular position of 50° close to the measuring ball, the high over rolling frequency of 3.0 Hz leads to a starved lubrication, since the film thickness drops below the fully flooded base oil level. However, when the second ball is positioned at 180° angular distance with an over rolling frequency of 0.8 Hz, the replenishment of the bleed oil is higher, such that the constant film thickness reaches a value of approximately 90 nm, which corresponds to the fully flooded base oil level.

3.2. Measurement Results at Increasing Rolling Speed

Measurements with increasing rolling speed were performed to investigate the dependence of the onset of starvation on the over rolling frequency. Using this type of measuring profile, the effect of increasing film thickness in the range of starvation at high rolling speeds >1000 mm/s can be clarified. Figure 10 shows the mean values of the results of the film thickness measurements with one and two balls showing the dependence on the rolling speed (left diagram) as well as the over rolling frequency (right diagram). To achieve a clear outline of the diagram, the standard deviation error bars are not presented in this figure. Compared to the base oil, the grease measurements do not show a linear increase of the film thickness over the whole range of rolling speeds as was shown in Figure 1. However, the film thickness using grease lubrication is significantly higher than the base oil film thickness at low rolling speeds <100 mm/s. From Figure 10 it can be seen, that the film thickness is generally lower when measuring with two ball specimens than using one ball. This leads to an earlier onset of starvation at 90 mm/s with two balls, in comparison to 180 mm/s with one ball. The right diagram in Figure 10 shows the same measurement results, however, the film thickness is shown as a function of the over rolling frequency. It can be seen that the lubricating film formation of both measurements with one and two balls up to 5.0 Hz as well as the onset of starvation at 0.8 Hz are in good agreement.

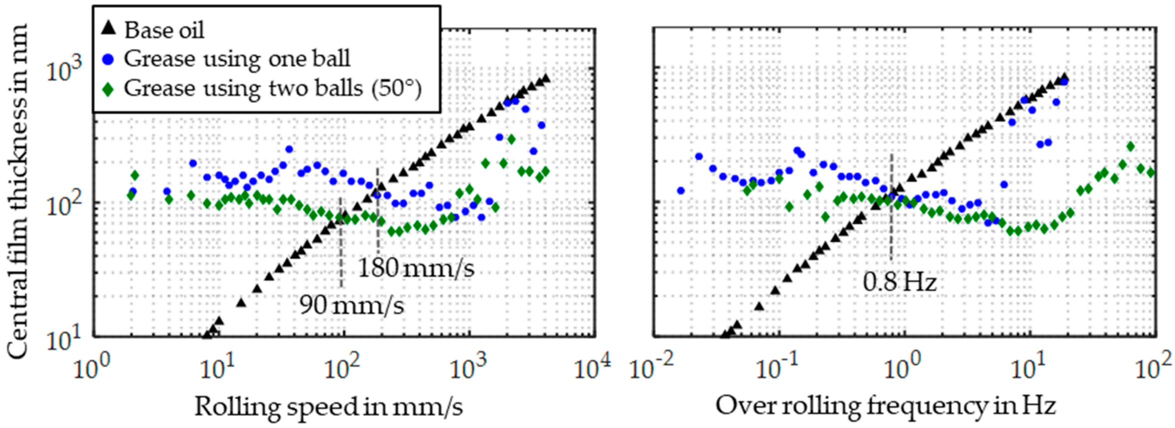

Figure 10. Film thicknesses at increasing speed and over rolling frequency.

At high rolling speeds, the lubricating film thickness for the configurations with one and two balls increases again. The increase starts for both measurement setups at approximately 1000 mm/s, as shown in Figure 10 in the left diagram. The results presented as a function of the over rolling frequency in the right diagram show different values for the increasing film thickness. Using one ball, the lubricating film thickness starts to increase at 5 Hz in contrast to the measurement with two balls at 10 Hz. These results indicate a dependence of film thickness increase on the rolling speed, and thus on centrifugal forces at high rolling speeds >1000 mm/s.

4. Discussion

The results of the film thickness measurements at constant rolling speed of 100 mm/s, presented in Figure 9, show a dependence of the lubricating film thickness on different angular positions of the second ball, hence on the over rolling frequency. A stepwise reduction of the resulting film thickness could be shown by a stepwise closer position of the second ball, due to higher over rolling frequencies. Related to the model presented in Figure 2, the replenishment time, i.e., the lubricant supply between the two balls, reduces with increasing over rolling frequency, which leads to a decrease of film thickness. These assumptions are confirmed by the results of the measurements with increasing rolling speed, which are presented in Figure 10. Measuring with two balls at an angular distance of 50° leads to an earlier onset of starvation in comparison to the measurements using one ball. Thus, it can also be assumed that the second ball displaces most of the bleed oil in the track at high over rolling frequencies. The presentation of the film thickness as a function of over rolling frequency shows, that the results of both measurements with one and two balls match and that the onset of starvation can be related to the same over rolling frequency. Thus, the over rolling frequency seems to be a significant parameter affecting the lubricating film formation.

Moreover, the results of the measurements at constant rolling speed allow conclusions regarding the effect of the thickener on the film formation. Comparing the measured thickness of the thickener layer at zero speed with the results of the film thickness measurements, a correlation can be observed between the film thickness of the thickener layer and the film formation during operation. Figure 11 emphasizes that the film thickness of the grease lubricated contact at 100 mm/s using one ball is approximately 25 nm higher than the corresponding base oil film thickness. Assuming a sufficient lubricant supply at a low over rolling frequency of 0.4 Hz and considering the results of the measurements at zero speed, shown in Figure 8, the higher film thickness is likely to occur due to a deposited thickener layer. Using the test setup with the second ball at an angular position of 50°, the residual film thickness does not reach a zero level, although a zero-film thickness would be expected due to displacement of bleed oil and insufficient replenishment at a high over rolling frequency of 3.0 Hz. However, a residual film thickness of approximately 40–60 nm is reached; and thus it can be concluded that the thickener layer supports the separation of the surfaces although most of the bleed oil in the track is displaced. The assumption of the formation of a thickener layer, which supports the film thickness, is in accordance with the literature [6,8,13,15,21,23,32].

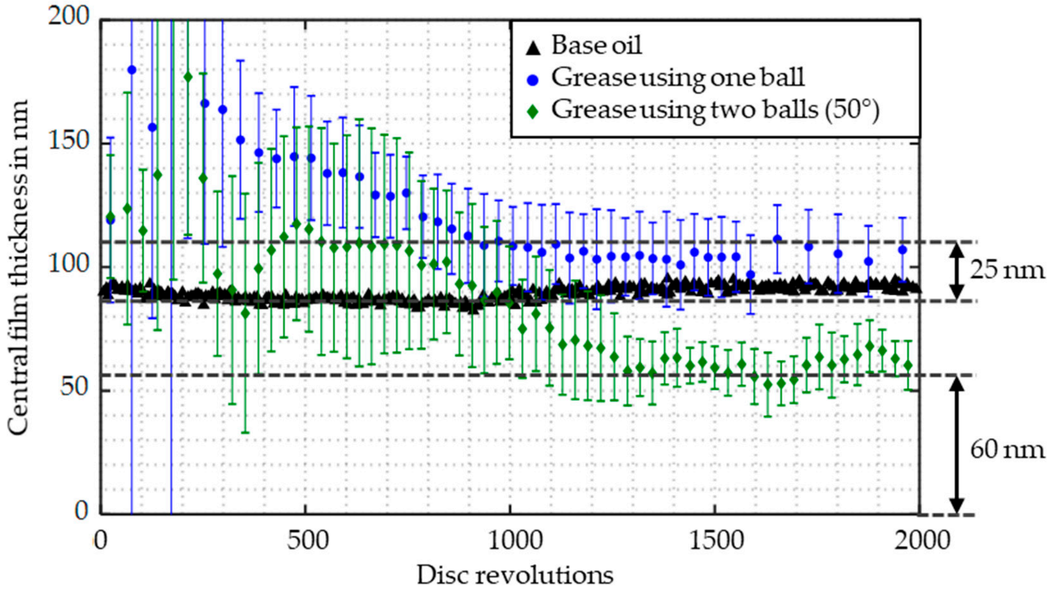

Figure 11. Thickener effect on the film formation using one and two ball specimens.

To ensure that the residual film thickness can be related to a thickener layer at the surfaces, the film thickness measurement at zero speed was repeated. This time the ball specimen was cleaned, such that the thickener layer on the ball surface was removed. The clean and dry ball was installed again and the film thickness measurement at zero speed was repeated. Figure 12 shows that the film thickness of the thickener layer reduces by half to nearly 20 nm. Therefore, it is assumed that the thickener layer forms on both surfaces in equal parts and supports the film formation in grease lubricated contacts even in the range of starvation, when most of the bleed oil is displaced.

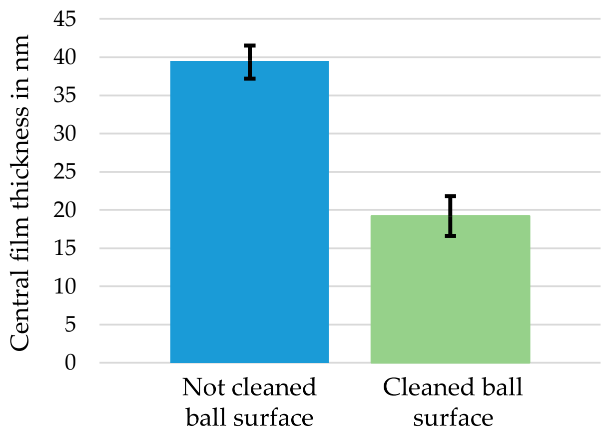

Figure 12. Reduction of film thickness after cleaning the ball specimen.

Furthermore, it can be seen from Figure 10 that even at high rolling speeds, i.e., high over rolling frequencies, the lubricating film thickness does not drop towards a zero level but remains on a nearly constant level higher than approximately 60 nm. If most of the bleed oil is displaced due to high over rolling frequencies up to 10 Hz, it can be concluded that the deposited thickener layers still provide a separation of the surfaces. In the absence of bleed oil, the film thickness appears to be independent of the rolling speed at pure rolling. A similar observation of this effect is described in [4].

Figure 10 also shows the increase of film thickness at high rolling speeds >1000 mm/s in the range of starvation. As discussed in the introduction, this increase can either occur in a recovery phase due to shear degradation of the grease [8,31,32] or due to centrifugal forces as proposed in [18]. If the increase is related to shear degradation, it would be dependent on the number of contacts by the rolling elements. This implies a faster shear degradation using two balls, since the number of contacts is doubled in comparison to a measurement using one ball. A faster shear degradation would lead to an early onset of the recovery phase, when measuring with two balls. Thus, the increase in film thickness would be expected at lower rolling speeds than measuring with one ball. However, as shown in Figure 10, the increase in film thickness occurs at a similar rolling speed (left diagram) and is independent of the over rolling frequency (right diagram). This indicates, that centrifugal forces become dominant at rolling speeds >1000 mm/s and push the side lying grease into the contact area, which leads to an increase in lubricant supply and film thickness in the range of starvation.

Based on the assumption that the replenishment of bleed oil significantly affects the film formation and especially the onset of starvation, the investigation of the replenishment time can be useful to determine the lubricant supply. Therefore, the replenishment time for oil lubricated contacts under starved conditions has already been investigated by several authors [26,28,29]. The diagram in Figure 13 shows the dependence of the film thickness on the replenishment time to emphasize the correlation of the flow behavior of the investigated lubricant. The onset of starvation can be determined at 1.25 s, which is equal to 0.8 Hz as shown in Figure 10. Thus, the minimum time that is necessary for a reflow ensuring a sufficient lubricant supply, such that no starvation occurs, can be determined from Figure 13 to be >2.0 s. These results are in accordance with results for oil lubricated contacts under starved lubrication presented in [29].

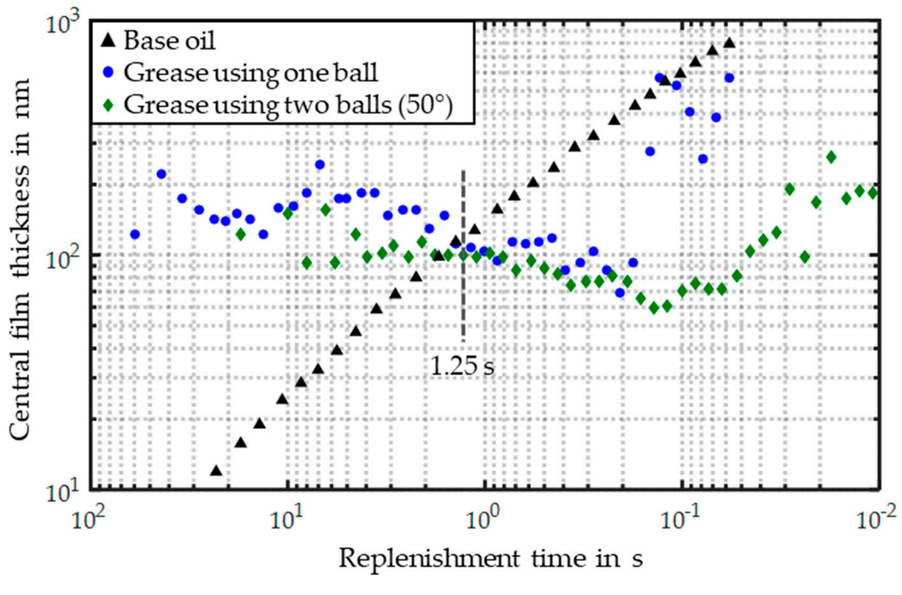

Figure 13. Film thickness as a function of replenishment time.

However, since the replenishment time is dependent on the lubricant flow, it varies with different lubricants and lubricant properties [21,30,41]. Moreover, some studies [33,41,42] show that the replenishment time does not only depend on the over rolling frequencies, but additionally on operating conditions, such as vibrations or centrifugal forces in radial bearings as well as the wettability of the lubricant on different surfaces, e.g., in the presence of deposited thickener layers on the surfaces. Future work should consider these aspects when investigating the lubricant supply of oil or grease lubricated EHD contacts under starved conditions.

5. Conclusions

In this study, the effect of the over rolling frequency on the lubricating film formation was investigated. Therefore, a ball-on-disc tribometer was extended by a second ball specimen, which was added in front of the measuring ball to increase the over rolling frequency in a dependent manner with the angular distance. Using this test setup, the displacement and replenishment of the lubricant can be controlled. The main results are summarized as follows:

- The film thickness at a constant rolling speed of 100 mm/s could be stepwise-reduced by a closer position of the second ball to the measuring ball. Thus, the presented model in Figure 2 could be confirmed. It can be pointed out that the film formation in grease lubricated EHD contacts under starved conditions depends on the lubricant supply, which is reduced by a higher over rolling frequency.
- Since the film thickness was not reduced towards a zero-level using a setup with the second ball, even at high over rolling frequencies >3.0 Hz, it is concluded that the residual film thickness of approximately 40–60 nm is formed by a deposited thickener layer on the surfaces. The presence of a semi-solid thickener layer at the rolling track could be verified by measurement results at zero speed, which is in accordance to published studies [6,8,13,15,21,23,32].
- Moreover, the film thickness does not drop below approximately 60 nm, even when increasing the rolling speed and thereby the over rolling frequency up to 10 Hz using the setup with two ball specimens. From these results, it can be concluded that even in the range of starvation, the thickener layer is present and separates the contacting surfaces.
- Using the test setup with the second ball, the effect of replenishment on the film formation with dependence on the over rolling frequency, i.e., replenishment time, could be emphasized. It has been shown that the lubricating film formation as well as the onset of starvation depends on the over rolling frequency, i.e., replenishment time. Additionally, it can be emphasized that the minimum time for a reflow ensuring a sufficient lubricant supply can be determined to be approximately >2.0 s for the investigated grease, which is in accordance with results for oil lubricated contacts under starved conditions in [29].
- Moreover, with these measurement results it could be shown, that an increase in film thickness at speeds >1000 mm/s does not refer to a recovery phase due to shear degradation. It can be pointed out that centrifugal forces become dominant at high rotational speeds and push the grease on the disc into the contact area, which leads to an increase in film thickness.

Author Contributions: D.F. and H.M. wrote the article, designed and performed the experiments, and analyzed the data. G.J. and A.S. supervised the work, discussed the basic design of experiments, and provided suggestions for the final discussion.

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References

1. Wedeven, L.D.; Evans, D.; Cameron, A. Optical analysis of ball bearing starvation. *J. Lubr. Technol.* **1971**, *93*, 349–361. [CrossRef]
2. Kauzlarich, J.J.; Greenwood, J.A. Elastohydrodynamic lubrication with herschel-bulkley model greases. *ASLE Trans.* **1972**, *15*, 269–277. [CrossRef]
3. Lugt, P.M. A review on grease lubrication in rolling bearings. *Tribol. Trans.* **2009**, *52*, 470–480. [CrossRef]

4. Cann, P.M.; Spikes, H.A. Film thickness measurements of lubrication greases under normally starved conditions. *NLGI Spokesm.* **1992**, *56*, 21–27.
5. Scarlett, N.A. Use of Grease in Rolling Bearings. *Proc. Inst. Mech. Eng.* **1967**, *182*, 585–624. [CrossRef]
6. Cann, P.M.E. Understanding grease lubrication. *Tribol. Ser.* **1996**, *31*, 573–581. [CrossRef]
7. Cann, P.M. Starved grease lubrication of rolling contacts. *Tribol. Trans.* **1999**, *42*, 867–873. [CrossRef]
8. Vengudusamy, B.; Kuhn, M.; Rankl, M.; Spallek, R. Film forming behavior of greases under starved and fully flooded EHL conditions. *Tribol. Trans.* **2016**, *59*, 62–71. [CrossRef]
9. Couronné, I.; Vergne, P.; Mazuyer, D.; Truong-Dinh, N.; Girodin, D. Effects of grease composition and structure on film thickness in rolling contact. *Tribol. Trans.* **2003**, *46*, 31–36. [CrossRef]
10. Kaneta, M.; Ogata, T.; Takubo, Y.; Naka, M. Effects of a thickener structure on grease elastohydrodynamic lubrication films. *Proc. Inst. Mech. Eng.* **2000**, *214*, 327–336. [CrossRef]
11. Kimura, Y.; Endo, T.; Dong, D. EHL with Grease at Low Speeds. In *Advanced Tribology*; Luo, J., Meng, Y., Shao, T., Zhao, Q., Eds.; Springer: Berlin/Heidelberg, Germany, 2009; pp. 15–19.
12. Cyriac, F.; Lugt, P.M.; Bosman, R.; Padberg, C.J.; Venner, C.H. Effect of thickener particle geometry and concentration on the grease EHL film thickness at medium speeds. *Tribol. Lett.* **2016**, *61*, 1–13. [CrossRef]
13. Cann, P.M. Grease lubrication of rolling element bearings—Role of the grease thickener. *Lubr. Sci.* **2007**, *19*, 183–196. [CrossRef]
14. Morales-Espejel, G.E.; Lugt, P.M.; Pasaribu, H.R.; Cen, H. Film thickness in grease lubricated slow rotating rolling bearings. *Tribol. Int.* **2014**, *74*, 7–19. [CrossRef]
15. Chen, J.; Tanaka, H.; Sugimura, J. Experimental study of starvation and flow behavior in grease-lubricated EHD contact. *Tribol. Online* **2015**, *10*, 48–55. [CrossRef]
16. Cann, P.M.E. Thin-film grease lubrication. *Proc. Inst. Mech. Eng. Conf.* **1999**, *213*, 405–416. [CrossRef]
17. Cen, H.; Lugt, P.M.; Morales-Espejel, G. On the film thickness of grease-lubricated contacts at low speeds. *Tribol. Trans.* **2014**, *57*, 668–678. [CrossRef]
18. Fischer, D.; Jacobs, G.; Stratmann, A.; Burghardt, G. Effect of base oil type in grease composition on the lubricating film formation in EHD contacts. *Lubricants* **2018**, *6*, 32. [CrossRef]
19. Wilson, A.R. The Relative Thickness of Grease and Oil Films in Rolling Bearings. *Proc. Inst. Mech. Eng.* **1979**, *193*, 185–192. [CrossRef]
20. International Organization for Standardization. *Rolling Bearings—Dynamic Load Ratings and Rating Life (ISO 281:2007)*; DIN ISO 281:2010-10; ISO: Geneva, Switzerland, 2007.
21. Cann, P.M. Starvation and reflow in a grease-lubricated elastohydrodynamic contact. *Tribol. Trans.* **1996**, *39*, 698–704. [CrossRef]
22. Baker, A. Grease bleeding—A factor in ball bearing performance. *NLGI Spokesm.* **1958**, *22*, 271–277.
23. Hurley, S.; Cann, P.M. IR spectroscopic analysis of grease lubricant films in rolling contacts. *Tribol. Ser.* **1999**, *36*, 589–600. [CrossRef]
24. Cann, P.M.; Chevalier, F.; Lubrecht, A.A. Track depletion and replenishment in a grease lubricated point contact: A quantitative analysis. *Tribol. Ser.* **1997**, *32*, 405–413. [CrossRef]
25. Chiu, Y.P. An analysis and prediction of lubricant film starvation in rolling contact systems. *ASLE Trans.* **1974**, *17*, 22–35. [CrossRef]
26. Jacod, B.; Pubilier, F.; Cann, P.M.; Lubrecht, A.A. An analysis of track replenishment mechanisms in the starved regime. *Tribol. Ser.* **1999**, *36*, 483–492. [CrossRef]
27. Pemberton, J.; Cameron, A. A mechanism of fluid replenishment in elastohydrodynamic contacts. *Wear* **1976**, *37*, 184–190. [CrossRef]
28. Kostal, D.; Sperka, P.; Svoboda, P.; Krupka, I.; Hartl, M. Experimental observation of elastohydrodynamically lubricated contacts replenishment. *MM Sci. J.* **2015**, *3*, 640–644. [CrossRef]
29. Kostal, D.; Sperka, P.; Svoboda, P.; Krupka, I.; Hartl, M. Influence of lubricant inlet film thickness on elastohydrodynamically lubricated contact starvation. *J. Tribol.* **2017**, *139*, 1–6. [CrossRef]
30. Huang, L.; Guo, D.; Shizhu, W. Film thickness decay and replenishment in point contact lubricated with different greases. *Tribol. Int.* **2016**, *93*, 620–627. [CrossRef]
31. Mérieux, J.-S.; Hurley, S.; Lubrecht, A.A.; Cann, P.M. Shear-degradation of grease and base oil availability in starved EHL lubrication. *Tribol. Ser.* **2000**, *38*, 581–588. [CrossRef]
32. Lubrecht, T.; Mazuyer, D.; Cann, P. Starved elastohydrodynamic lubrication theory: Application to emulsions and greases. *C. R. Acad. Sci. Ser. IV Phys.* **2001**, *2*, 717–728. [CrossRef]

33. Huang, L.; Guo, D.; Liu, X.; Xie, G.; Wan, G.T.Y.; Wen, S. Effects of nano thickener deposited film on the behaviour of starvation and replenishment of lubricating greases. *Friction* **2016**, *4*, 313–323. [CrossRef]
34. Lugt, P.M. *Grease Lubrication in Rolling Bearings*; John Wiley & Sons, Ltd.: Chichester, UK, 2013; ISBN 978-1-118-35391-2.
35. Johnston, G.J.; Wayte, R.; Spikes, H.A. The measurement and study of very thin lubricant films in concentrated contacts. *Tribol. Trans.* **1991**, *34*, 187–194. [CrossRef]
36. Cousseau, T.; Björling, M.; Graça, B.; Campos, A.; Seabra, J.; Larsson, R. Film thickness in a ball-on-disc contact lubricated with greases, bleed oils and base oils. *Tribol. Int.* **2012**, *53*, 53–60. [CrossRef]
37. Åström, H.; Isaksson, O.; Höglund, E. Video recordings of an EHD point contact lubricated with grease. *Tribol. Int.* **1991**, *24*, 179–184. [CrossRef]
38. Åström, H.; Östensen, J.O.; Höglund, E. Lubricating grease replenishment in an elastohydrodynamic point contact. *J. Tribol.* **1993**, *115*, 501–506. [CrossRef]
39. Gonçalves, D.; Campos, A.; Seabra, J. An Experimental Study on Starved Grease Lubricated Contacts. *Lubricants* **2018**, *6*, 82. [CrossRef]
40. Svoboda, P.; Kostal, D.; Kunak, J.; Krupka, I. Study of grease behaviour in starved elastohydrodynamically lubricated contact. *MM Sci. J.* **2014**, *2*, 465–469. [CrossRef]
41. Cann, P.M.; Damiens, B.; Lubrecht, A.A. The transition between fully flooded and starved regimes in EHL. *Tribol. Int.* **2004**, *37*, 859–864. [CrossRef]
42. Li, X.M.; Guo, F.; Wong, P.L.; Zhao, Y. Regulation of lubricant supply by wettability gradient in rolling EHL contacts. *Tribol. Inte.* **2018**, *120*, 565–574. [CrossRef]