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Study on Factors Influencing Film Formation of Grease and Calculation Model for Grease Film Thickness

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Abstract: The grease film thickness was measured in fully flooded elastohydrodynamic lubrication, and the influence of rolling speed, load, consistency, base oil type and thickener type on grease film thickness was analyzed. A new calculation model for grease film thickness was established. The results show that the grease film thickness increases with the increasing rolling speed, and then levels off with the amount of thickener in the contact region reaching an equilibrium. The degree of grease film enhancement comparing to its base oil will depend on thickener type and consistency. The larger the atmospheric viscosity and pressure-viscosity coefficient of the base oil, the higher the film thickness of the greases with the same thickener. The grease film thicknesses with the same base oil and different thickeners are determined by the size of thickener particles at the same consistency or concentration. The larger the consistence of the grease, the larger the effective viscosity of the grease at the contact and the thicker the grease film thickness whose base oil has the same type and viscosity along with the same type of thickener. The calculated values by the new model are in good agreement with the measured values.

Keywords: grease; film-forming properties; film thickness; influence factor; EHD

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1. Introduction

As the most commonly used lubricant in current bearing equipment, grease with a lubricating and sealing effect can extend bearing maintenance intervals and reduce energy consumption. Generally, grease is a semi-solid composed of base oil, thickener and additives. Due to the presence of the thickener, its fluidity is lower than that of the corresponding base oil. As the film-forming process of greases is complex, the study of film-forming properties is usually achieved by measuring the film thickness of the grease.

Some studies showed that speed affected grease film formation [1–3]. Temperature also plays a decisive role in grease film formation [4]. Cen et al. [5] investigated the effects of speed and load on grease film thickness, where the effects of the speed and load were small. The grease composition plays an important role in the film-forming. The thickener is essential for the performance of greases [6–8]. The grease can form a thicker film at a low speed than the corresponding base oil [9–12], which indicates that the thickener fibers can enter the contact region and affect the film thickness. The film thickness variation pattern at speeds greater than the "transition speed" is consistent with the prediction by the Hamrock–Dowson formula in fully flooded elastohydrodynamic lubrication, while thickeners play an essential role at speeds less than the "transition speed" [13]. Kimura et al. [14] pointed out that the increase of grease film thickness at low speeds depended on the base oil and thickener. However, Kanazawa et al. [15] found that the grease film thickness at low speed was determined by the type of thickener while at high speed by the base oil. Bleeding oil also contributes to the film-forming properties. Saatchi et al. [16] pointed out a region surrounding the thickener particles, called the effective media, which was assumed to have completely immobilized the oil. Bleed oil was assumed to occur from the viscous flow of the unbound oil in a porous structure made of the effective media. It has been found that different NLGI grades and different grease components have different influences on grease film-forming [17]. Although the influence factors on the film formation were studied in many kinds of literature, these studies were limited to certain influence factors, the applicability of the research results drawn to other grease types and composition requires further validation.

In addition to the Hamrock–Dowson classical computing model proposed in the last century, certain developments and innovations have been made in recent years. Yin et al. [18] proposed an equation and procedure successfully applied to the calculation for the minimum oil film thickness in elastohydrodynamic lubrication. Zoelen et al. [19] established a model for predicting the variation of oil film thickness from the inlet region to the contact region in starved lubrication. Yang et al. [20] proposed a calculation formula of oil film thicknesses for beam interference grades exceeding zero. Xue et al. [21] used an iterative method to analyze grease film thickness and pressure distribution, and the effects on them by the load and entrainment velocity. Wang et al. [22] developed a numerical model to calculate the grease film thickness of smooth and rough surfaces, and compared the results with the base oils. So far, there has existed only film thickness formula for lubricating oils, such as the Hamrock–Dowson formula. The film thickness calculation for grease by solving the motion, continuity, surface elasticity and rheology equations simultaneously through numerical iteration, needs special software, and the accuracy of the calculation result is restricted by many factors. Until now, there was no formula for calculating the grease film thickness.

Despite grease film-forming has been studied in many papers, there is still ambiguity on the factors influencing the grease film-forming ability under fully flooded conditions, which inspired this study. In this paper, a grease film-forming experiment at room temperature was carried out and the grease film thickness was measured by employing a film thickness test rig to investigate the effect of various factors such as load, rolling speed, consistency, base oil type and thickener type on grease film thickness. In addition, the calculation models of film thickness for lithium greases and polyurea greases were established based on experimental data. The main objective of this paper is to lay the theoretical foundation for the study of grease film thickness and to provide primary data for grease formulation and bearing performance calculation.

2. Materials and Methods

2.1. Experimental Materials

Five greases without additives were used for the experiments, as shown in Table 1, where the base oils are poly alpha olefins (PAO) oil, ester oil and mineral oil, respectively, and the thickeners are lithium 12-Hydroxystearate as well as cyclohexylamine, octadecylamine and isocyanate. The viscosities of PAO, ester and mineral oil are 68 mm^2/s at 40 °C, as well as 10.06 mm^2/s, 9.72 mm^2/s, 9.53 mm^2/s at 100 °C, respectively. The pressure-viscosity coefficients of PAO oil, ester oil and mineral oil are 1.7×10^{-8} Pa^{-1}, 1.85×10^{-8} Pa^{-1} and 2.21×10^{-8} Pa^{-1}, respectively. A total of 4 consistencies for Grease 5 were selected, whose cone penetration values are 230, 250, 270 and 300 (0.1 mm), respectively.

2.2. Experimental Method

The grease film thickness measurements were performed on the test rig (EHD2), as shown in Figure 1. In this rig, a steel ball (diameter 19 mm, 52100 steel) is loaded against a chromium-coated glass disc with a spacer layer. The disc and ball are driven by separate electric motors, respectively. The performance of the rig is as follows:

1. The measuring accuracy can reach ±1 nm;
2. The spacer layer imaging method (SLIM) is used to observe the oil film-forming in the experiment process;
3. The maximum load is 50 N and the maximum contact pressure is 0.7 GPa for glass disc;

4. The maximum rolling speed is 4 m/s;
5. The temperature range: Ambient~150 °C;
6. The volume of the test sample was 120 mL.

Table 1. Grease composition and properties.

Type of Grease	Thickener	Base Oil	Cone Penetration (0.1 mm)	Concentration (Mass %)
Grease 1	Lithium 12-Hydroxystearate	PAO oil	270	11%
Grease 2	Lithium 12-Hydroxystearate	Ester oil	270	12%
Grease 3	Lithium 12-Hydroxystearate	Mineral oil	270	8%
Grease 4	Cyclohexylamine, octadecylamine and isocyanate	Mineral oil	270	9%
Grease 5	Cyclohexylamine, octadecylamine and isocyanate	PAO oil	230	13%
			250	12%
			270	11%
			300	9%

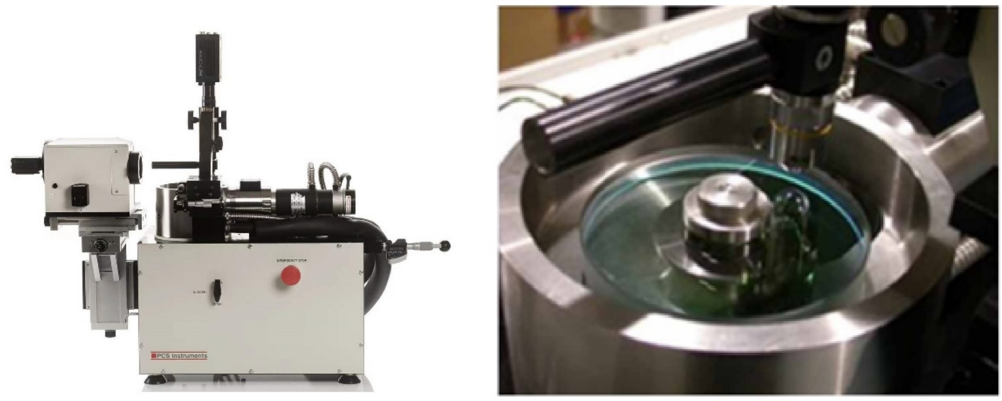


Figure 1. Film thickness test rig.

The film thickness was measured by the two-beam interference method, as shown in Figure 2. During the experiment, the steel ball comes into contact with a chrome-coated glass disc, forming a Hertz contact region by applying a load. Due to the half transmitting and half reflecting characteristic of the chromium metal film on the surface of the glass disc, the incident light is reflected at different locations. Part of the beam is reflected on the chrome film surface, named the reflected beam 1 in Figure 2, while the other part of the beam is reflected on the grease-filled steel ball surface, named reflected beam 2 in Figure 2. There is a distance between the two reflected beams, and this difference is the value of oil film thickness. Since the incident beam is monochromatic, the two reflected beams have the same frequency and interfere. The film thickness and shape in the contact region can be obtained through analyzing the collected interfering beams by the optical system.

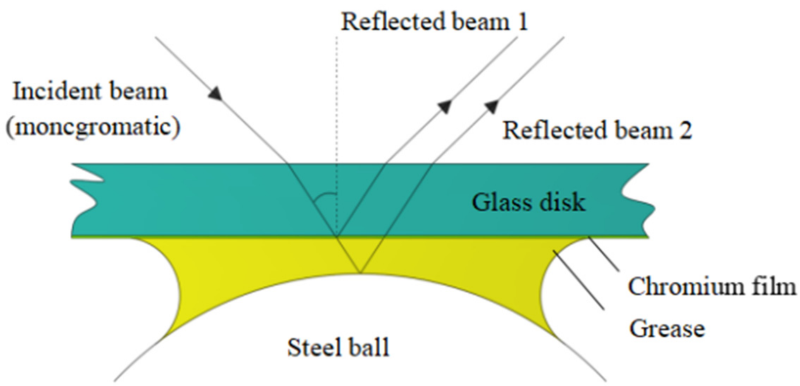


Figure 2. Two-beam interference principle.

In this paper, the film thickness measurements were carried out at the temperature of 25 °C in nominal pure rolling. Sixteen rolling speed parameters were selected: 0.25 m/s, 0.50 m/s, 0.75 m/s, 1.00 m/s, 1.25 m/s, 1.50 m/s, 1.75 m/s, 2.00 m/s, 2.25 m/s, 2.50 m/s, 2.75 m/s, 3.00 m/s, 3.25 m/s, 3.50 m/s, 3.75 m/s and 4.00 m/s. A total of 4 normal contact load parameters were selected: 10 N, 20 N, 30 N, and 40 N, and the corresponding contact pressures are 0.41 GPa, 0.52 GPa, 0.59 GPa and 0.65 GPa.

The disc used has a measured roughness value, R_q, of 10.0 nm, and the ball has a roughness value, R_q, of 15 nm, so the composite roughness is 18 nm. The minimum film thickness of base oils computed by the Hamrock–Dowson [23] formula is above 100 nm. Thus, the lambda ratio λ (ratio between film thickness and composite surface roughness R_q) was more than 5.6. The contact zone is in a state of full EHD lubrication. A small scoop was incorporated into the rig to channel the over-rolled grease back into the track so that a continuous grease supply was applied and no starvation could occur. Before each test, a thin layer of grease (approximately 0.5 mm) should be smeared on the glass disc and a small ball load was applied to the disc at a constant speed of 10 mm/s for 20 min in pure rolling conditions. This preliminary step was introduced to distribute the grease evenly over the contact area as well as to pre-shear the grease to ensure the same initial condition and obtain steady data for each test. The central film thickness was measured by increasing the rolling speed step by step on the test rig, and the film thicknesses of greases at different rolling speeds were measured three times and its average value was taken. After each test, the steel ball and glass disc were cleaned in toluene and isopropanol in an ultrasonic bath, and then air-dried before the next test.

3. Results and Discussion

3.1. Results

3.1.1. Effect of Rolling Speed and Normal Load on Grease Film Thickness

Figures 3–5 show the film thicknesses of Grease 1, Grease 2, Grease 3 and their base oils versus rolling speed under fully flooded lubrication. The grease film thickness increases with the increase in rolling speeds under the constant normal contact load, but the growth rate of grease film thickness decreases with the increasing rolling speeds. It also can be seen that the grease film thickness decreases with the increasing normal contact loads when the rolling speed is constant. Even if the load increases exponentially, the grease film thickness changes slightly. When the rolling speed is 4 m/s and the normal contact load is 10 N and 40 N, the maximum and minimum values of grease film thickness were obtained, as shown in Figure 6. The maximum/minimum film thicknesses of Grease 1, Grease 2 and Grease 3 are 1105.5 nm/972.3 nm, 1176.4 nm/1021 nm, and 1225.9 nm/ 991.2 nm, respectively.

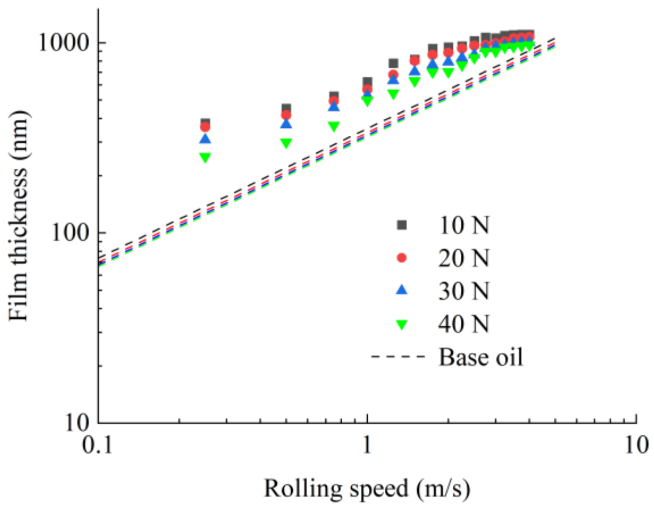


Figure 3. Film thickness of Grease 1 versus rolling speed under different loads.

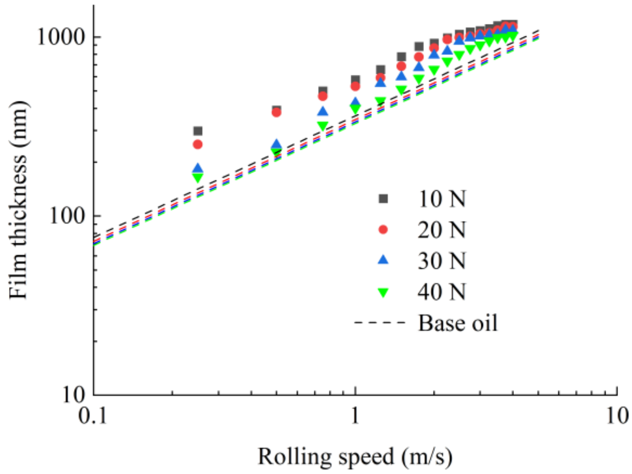


Figure 4. Film thickness of Grease 2 versus rolling speed under different loads.

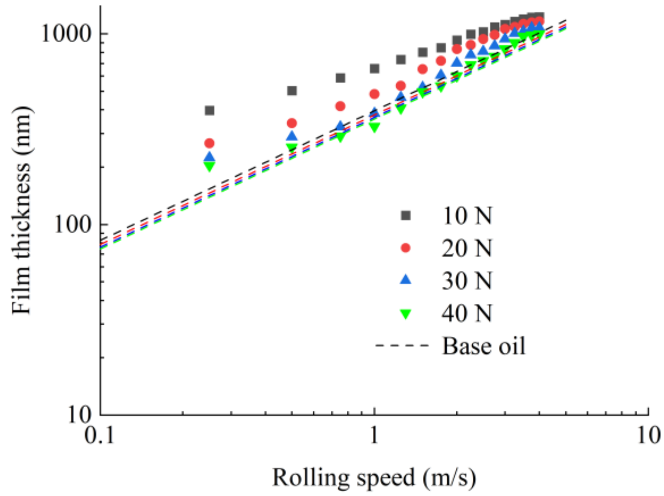


Figure 5. Film thickness of Grease 3 versus rolling speed under different loads.

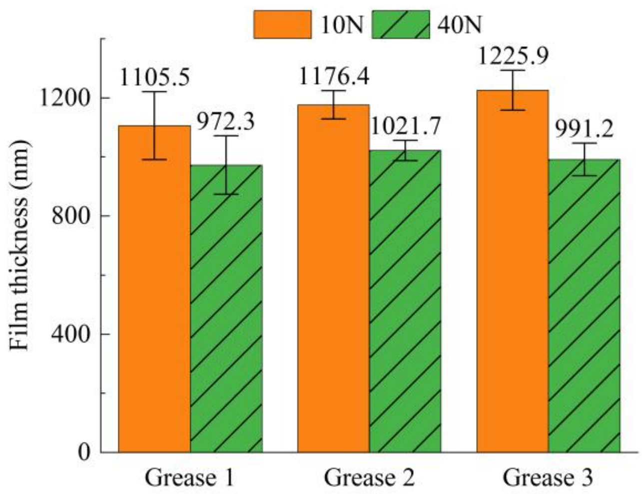


Figure 6. Maximum and minimum film thickness of Grease 1, 2 and 3.

3.1.2. The Effect of Consistency on Grease Film Thickness

The consistency can be expressed in cone penetration and grease grade number. The cone penetration indicates the deformability of the grease under low shear rate conditions. The higher the cone penetration of grease, the softer the grease will be, the less consistency it will be, and the more likely it will deform and flow. For Grease 5, four consistencies (cone penetration of 230, 250, 270 and 300 (0.1 mm)) were selected for preparation.

Figure 7 shows the variation of the film thickness of Grease 5 versus rolling speed and consistency at a load of 10 N. As the cone penetration increases (the consistency decreases), the film thickness of the grease decreases. When the load is 20 N, 30 N and 40 N, the rule of the variation of grease film thickness versus rolling speed and consistency is similar. When the rolling speed is the same, the smaller the consistence of the grease, the smaller the grease film thickness, which indicates that the thickener is involved in the oil film-forming. Figure 8 shows the maximum and minimum values of grease film thickness for different loads and consistencies at a rolling speed of 4 m/s. When the loads are 20 N, 30 N and 40 N, the maximum values of grease film thickness all appear at the cone penetration of 230 (0.1 mm), and the values are 1213 nm, 1155 nm and 1124 nm, respectively, while the minimum values of grease film thickness all appear at the cone penetration of 300 (0.1 mm), the values are 928 nm, 847 nm and 856.6 nm, respectively.

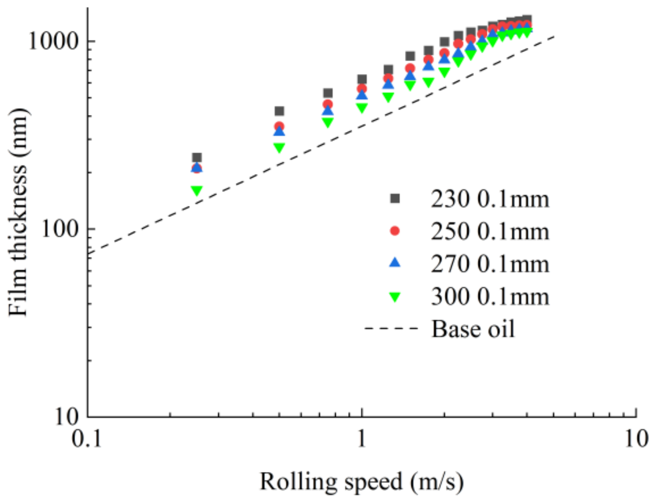


Figure 7. Grease film thickness versus speed for different cone penetrations at a load of 10 N.

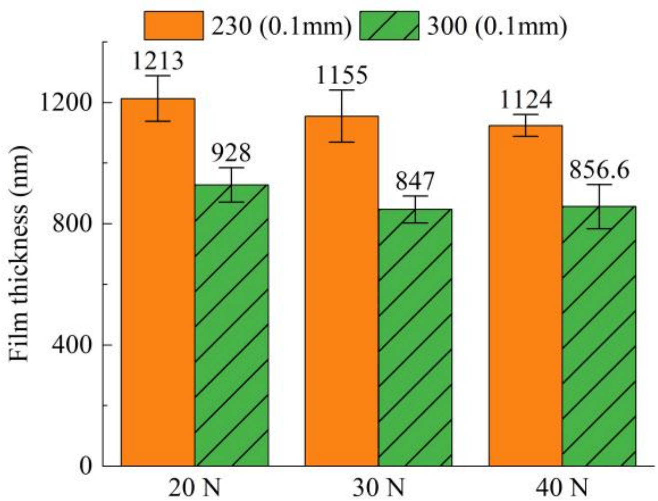


Figure 8. Maximum and minimum film thickness of grease at different loads and consistencies.

3.1.3. The Effect of Base Oil Type on Grease Film Thickness

Grease 1, Grease 2 and Grease 3 have the same thickener, all of which are lithium 12-hydroxystearate, and the base oils are PAO oil, ester oil and mineral oil, respectively. The film thicknesses of these three greases versus rolling speed under the same working conditions are shown in Figure 9. It can be found that the film thickness of Grease 3 is the largest, followed by Grease 2, and the smallest is Grease 1 when the rolling speed is the same, which means that grease with a base oil of mineral oil forms the largest film thickness, followed by ester oil and the smallest by PAO oil. The three grease film thicknesses are larger than those of their base oils.

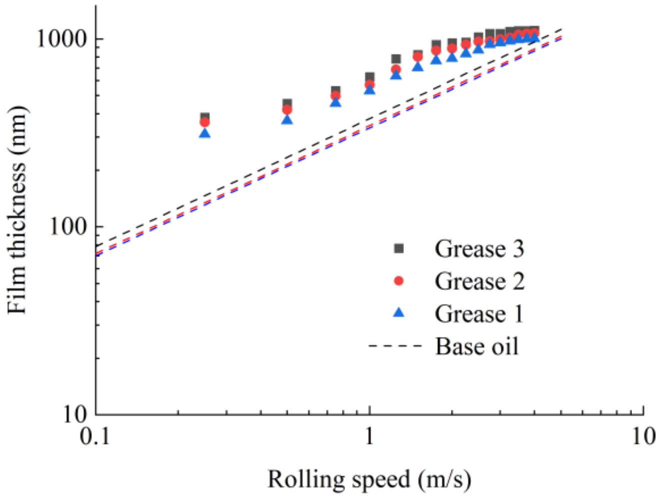


Figure 9. Influence of base oil type on grease film thickness.

3.1.4. The Effect of Thickener Type on Grease Film Thickness

The base oil for both Grease 3 and Grease 4 is mineral oil, and the thickeners of Grease 3 and Grease 4 are lithium 12-hydroxystearate, cyclohexylamine and octadecylamine, respectively. Figure 10 shows the film thickness of Grease 3 and Grease 4 versus rolling speed at a load of 20 N. The oil film-forming properties of greases with different thickeners vary considerably. As shown in Figure 10b, the film thickness difference between the two greases gradually increases during the gradual increase in rolling speeds. When the rolling speed is 4 m/s, the difference between the two film thicknesses is the greatest. At the same rolling speed, the film thickness of Grease 4 is larger than that of Grease 3. In other words, when the base oil is the same, the film thickness of polyurea grease is higher than that of lithium grease. The thickener has a more significant effect on the film-forming ability of grease, which indicates that thickener also enters the contact region to participate in the composition of the grease film.

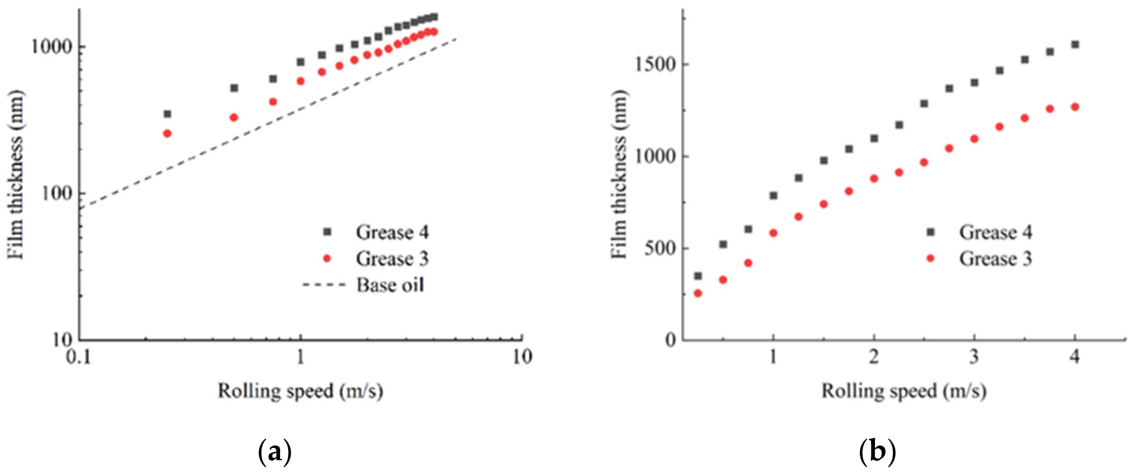


Figure 10. Effect of thickener type on grease film thickness (**a**) logarithmic coordinate system (**b**) linear coordinate system.

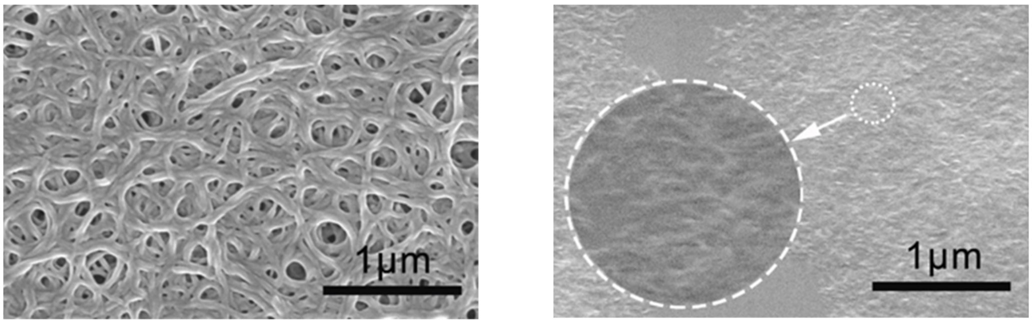
3.2. Discussion

Early studies show that the film thickness of grease is slightly larger but practically follows the H–D formula for its base oil in the high-speed region in fully flooded elastohydrodynamic lubrication. When the speed decreases, the thickness deviates from the formula and shows a marked increase, called the low-speed region. This general behavior results in the characteristic "V-shaped" film thickness versus speed curve for greases [3,15,24]. The speed at the inversion point of the "V" is called the "transition speed" [25]. The "transition speed" was affected by the thickener type and the test temperature [15].

The grease film measurement in this paper belong to the high-speed region. As seen from Figures 3–5 that grease forms a higher film thickness compared to its base oil in fully flooded lubrication. The EHD contact is probably not only lubricated by the bleed oil, but also by parts of the thickener entering the contact and causing a higher film thickness [12,26]. The degree of film enhancement compared to the base oil will depend on the thickener type and concentration [7]. When the rolling speed is less than 3 m/s, grease film thickness follows the H–D formula for its base oil, similar to the results of the above literature [3,15,24,25], and then the film thickness growth of the grease decreases and approaches to a fixed value. In most of the previous literature [3,15,24,25], the study on the grease film thickness versus rolling speed was only limited to the rolling speed of less than 3 m/s. Changes in grease film thickness beyond 3 m/s have been not studied. The growth rate gradually decreases, and then approaches to a fixed value when the rolling speed is beyond 3 m/s, which may be because when the grease film thickness increases to a specific value, a steady pressure develops in the contact area. At this point, the contact region is filled with enough thickener, so that no more thickener can enter the region and the variation of grease film thickness remains almost unchanged with a further increase in speed. It again shows that grease film thickness in the high-speed region is determined not only by bleed oil but also by thickener, though the bleed oil plays a major role. Another research objective in this paper is to establish the calculation formula of grease film thickness. Previous studies have shown that the grease film in the low-speed region is characterized by chaos and irregularity. Therefore, only the grease film thickness in the high-speed region was investigated in this paper. The literature [15] shows that the transition speeds of diurea-thickened grease and lithium-thickened greases were 120 mm/s and 30 mm/s, respectively, at 25 °C. Therefore, the rolling speeds selected in this paper are greater than 0.25 m/s.

The properties of the bleed oils differ hardly from those of the base oils in the high-speed regions [12], so the grease film thickness can be mainly determined by its base oil. Figure 9 indicated the influence of base oil type on the grease film thickness, and there is a slightly difference in grease film thickness whose thickeners are the same. Gunsel [27] pointed out that the larger the atmospheric viscosity and pressure-viscosity coefficient, the higher the oil film thickness in fully flooded elastohydrodynamic lubrication. The atmospheric viscosities of the three base oils used in this paper are same. The pressure-viscosity coefficients of PAO oil, ester oil and mineral oil are $1.7 \times 10^{-8}\ P_a{}^{-1}$, $1.85 \times 10^{-8}\ P_a{}^{-1}$ and $2.21 \times 10^{-8}\ P_a{}^{-1}$, respectively. Therefore, the film thickness of mineral oil is the largest, followed by ester oil, and the smallest is PAO oil. The pressure-viscosity coefficients of the three base oils are close, so the oil film thickness is also close. The film thickness of Grease 3 is the largest, followed by Grease 2, and the smallest is Grease 1 as shown in Figure 9, which results from the film thickness of mineral oil being the largest, followed by ester oil, and the smallest is PAO oil.

The influence of thickener type on the grease film thickness can be revealed in Figure 10, the grease film thicknesses with the same base oil and different thickener are different. Cann [28] assumed that grease film thickness might consist of a part formed by elastohydrodynamic action and a part formed by residual layers formed by the thickener, and the residual film thickness was about 30–60 nm. Figure 10 shows that the film thicknesses of Grease 3 at 2 m/s and 4 m/s are 879.07 nm and 1609.01 nm, respectively, and the film thicknesses of Grease 4 at 2 m/s and 4 m/s are 1098.84 nm and 1268.9 nm, respectively. The thicknesses of the base oil at 2 m/s and 4 m/s are 602.22 nm and 964.84 nm, respectively. The minimum difference between the two grease film thicknesses and the base oil thickness is more than 276 nm. Therefore, the enhancement in the film thickness of grease is not dependent on the residual film deposited on the ball and disc, but on the thickener entering in the contact region. Cyriac [26] also concluded that the films in the high-speed region were so thick that the effect could not be ascribed to the formation of a boundary layer, but the increase in viscosity of a fluid containing thickener particles. When the thickener consistencies of greases are same, the smaller the thickener particles, the more thickener particles enter into the contact to increase the grease film thickness. Since the fiber skeleton of Grease 4 (mineral oil-polyurea grease) is smaller than that of Grease 3 (mineral oil-lithium grease), as shown in Figure 11, which results in a much higher thickener content in the contact region and a thicker film of Grease 4 than that of Grease 3.



(**a**) (**b**)

Figure 11. Microstructure of (**a**) Grease 3 and (**b**) Grease 4 by SEM (scanning electron microscopy).

It can be found from Figure 7 that the larger the consistency or concentration of thickeners (the smaller the cone penetration), the thicker the grease film thickness whose base oil has the same type and viscosity along with the same type of thickener. The reason is that the larger the consistency of the grease (the more the content of the thickener), the larger the effective viscosity of the grease at the contact and the thicker the grease film thickness formed.

4. Calculation Model for Grease Film Thickness

4.1. Mathematical Model

Analysis of the experimental data reveals that the grease film thickness H may be expressed as an exponential function of rolling speed V:

$$H = (\alpha + \beta V)\mathrm{e}^{-\mu V} + \delta \tag{1}$$

where H is the grease film thickness, V is the rolling speed at the contact point of the ball and disc specimens, α, β, μ and δ are undetermined parameters. The least-square regression analysis is used to compute coefficients α, β, μ and δ. The least-square method refers to finding a $\Phi(X_i)$ that minimizes $\sum_{i=1}^{n}[F(X_i) - \Phi(X_i)]^2$ to obtain the coefficients α, β, μ and δ.

Given a set of values V_i (i = 1, 2, 3, . . . , n) and the measured grease film thicknesses H_i. Compute an estimated value H_i^* for each V_i by Equation (1). The deviation between the estimated value and the measured value is $\varepsilon_i = H_i - H_i^*$, and the sum of squares of deviations Q is as follows:

$$Q = \sum_{i=1}^{n}(H_i - H_i^*)^2 = \sum_{i=1}^{n}\left\{H_i - \left[(\alpha + \beta V_i)e^{-\mu V_i} + \delta\right]\right\}^2 \tag{2}$$

To minimize Q, a set of α, β, μ and δ should be found to minimize the value of Q (α, β, μ and δ). Respectively, setting the derivation of Q for α, β, μ and δ equal to zero will yield the following equations:

$$\begin{cases} \sum_{i=1}^{n}\left[(\alpha+\beta V_i)e^{-\mu V_i}+\delta-H_i\right]e^{-\mu V_i}=0 \\ \sum_{i=1}^{n}\left[(\alpha+\beta V_i)e^{-\mu V_i}+\delta-H_i\right]V_i e^{-\mu V_i}=0 \\ \sum_{i=1}^{n}\left[(\alpha+\beta V_i)e^{-\mu V_i}+\delta-H_i\right](\alpha+\beta V_i)V_i e^{-\mu V_i}=0 \\ \sum_{i=1}^{n}\left[(\alpha+\beta V_i)e^{-\mu V_i}+\delta-H_i\right]=0 \end{cases} \quad (3)$$

Each optimum solution of the coefficients α, β, μ and δ can be obtained by a computer program used to solve Equation (3) at any given operating conditions.

For convenience in application, three dimensionless parameters, which include operating conditions, W, V, and material properties, η_0, E^*, R, G, can be assumed as follows.

Dimensionless load:

$$\overline{W}=W/\left(E^*R^2\right) \quad (4)$$

Dimensionless speed:

$$\overline{V}=\eta_0 V/(E^*R) \quad (5)$$

Dimensionless consistency:

$$\overline{G}=G/R \quad (6)$$

where E^* is the equivalent elastic modulus of ball and disc; R is the radius of equivalent curvature of ball and disc; η_0 is the atmospheric viscosity of base oil. W, V and G are contact load, rolling speed and grease cone penetration, respectively.

For lithium grease, α, β, μ and δ are expressed by the exponential functions of $\overline{W}$ and $\overline{V}$.

$$\alpha=A_0\overline{W}^{A_1}\overline{V}^{A_2} \quad (7)$$

$$\beta=B_0\overline{W}^{B_1}\overline{V}^{B_2} \quad (8)$$

$$\mu=C_0\overline{W}^{C_1}\overline{V}^{C_2} \quad (9)$$

$$\delta=D_0\overline{W}^{D_1}\overline{V}^{D_2} \quad (10)$$

For polyurea grease of different consistencies, α, β, μ and δ are expressed as the exponential functions of $\overline{W}$, $\overline{V}$ and $\overline{G}$.

$$\alpha=A_0\overline{W}^{A_1}\overline{V}^{A_2}\overline{G}^{A_3} \quad (11)$$

$$\beta=B_0\overline{W}^{B_1}\overline{V}^{B_2}\overline{G}^{B_3} \quad (12)$$

$$\mu=C_0\overline{W}^{C_1}\overline{V}^{C_2}\overline{G}^{C_3} \quad (13)$$

$$\delta=D_0\overline{W}^{D_1}\overline{V}^{D_2}\overline{G}^{D_3} \quad (14)$$

According to the values of α, β, μ and δ under different test conditions of lithium grease and polyurea grease, the values of the regression coefficients can be obtained through Equations (7)–(14). The results are shown in Tables 2 and 3.

Table 2. Regression coefficients for lithium grease.

α	β	μ	δ
A_0: 2.2698×10^{-11}	B_0: 1.2613×10^{-12}	C_0: -2.0530×10^{-9}	D_0: 3.5269×10^{-8}
A_1: 9.1593×10^{-6}	B_1: 1.0021×10^{-4}	C_1: 8.2771×10^{-4}	D_1: 1.7401×10^{-3}
A_2: -2.63×10^{-2}	B_2: -2.46×10^{-2}	C_2: -2.72×10^{-2}	D_2: -3.47×10^{-2}

Table 3. Regression coefficients for polyurea greases of different consistencies.

α	β	μ	δ
A_0: -4.5269×10^{-11} A_1: 2.5547×10^{-4} A_2: -0.5028 A_3: -2.9881×10^{-2}	B_0: 1.6603×10^{-12} B_2: 1.4218×10^{-4} B_2: -0.4626 B_3: -3.9442×10^{-2}	C_0: 3.2045×10^{-8} C_1: 9.9042×10^{-5} C_2: -0.4548 C_3: -3.1540×10^{-2}	D_0: 4.0610×10^{-8} D_1: 1.0156×10^{-4} D_2: -0.4791 D_3: -2.7927×10^{-2}

4.2. The Film Thickness Calculation Model for Two Greases

According to the above method, the model for calculating the film thickness of lithium grease is as follows:

$$H = (\alpha + \beta V)e^{-\mu V} + \delta \quad (15)$$

$$\alpha = 2.2698 \times 10^{-11} \times \overline{W}^{9.1592\times10^{-6}} \times \overline{V}^{-2.63\times10^{-2}} \quad (16)$$

$$\beta = 1.2613 \times 10^{-12} \times \overline{W}^{1.0021\times10^{-4}} \times \overline{V}^{-2.46\times10^{-2}} \quad (17)$$

$$\mu = -2.0530 \times 10^{-9} \times \overline{W}^{8.2771\times10^{-4}} \times \overline{V}^{-2.72\times10^{-2}} \quad (18)$$

$$\delta = 3.5269 \times 10^{-8} \times \overline{W}^{1.7401\times10^{-3}} \times \overline{V}^{-3.47\times10^{-2}} \quad (19)$$

The model for calculating the film thickness of polyurea greases of different consistencies is as follows:

$$H = (\alpha + \beta V)e^{-\mu V} + \delta \quad (20)$$

$$\alpha = -4.5269 \times 10^{-11} \times \overline{W}^{2.5547\times10^{-4}} \times \overline{V}^{-0.5028} \times \overline{G}^{-2.9881\times10^{-2}} \quad (21)$$

$$\beta = 1.6603 \times 10^{-12} \times \overline{W}^{1.4218\times10^{-4}} \times \overline{V}^{-0.4626} \times \overline{G}^{-3.9442\times10^{-2}} \quad (22)$$

$$\mu = 3.2045 \times 10^{-8} \times \overline{W}^{9.9042\times10^{-5}} \times \overline{V}^{-0.4548} \times \overline{G}^{-3.154010^{-2}} \quad (23)$$

$$\delta = 4.0610 \times 10^{-8} \times \overline{W}^{1.0156\times10^{-4}} \times \overline{V}^{-0.4791} \times \overline{G}^{-2.7927\times10^{-2}} \quad (24)$$

4.3. Verifying Calculation Model

As shown in Figures 12–15, the points represent the measured values, the solid lines represent the calculated values by the model, and the dotted lines represent the base oil film thickness predicted by the Hamrock–Dowson formula. The measured and calculated values of film thicknesses for Grease 1 and 4 are compared in Figures 12 and 13, respectively. Figures 14 and 15 show the measured and calculated film thicknesses of

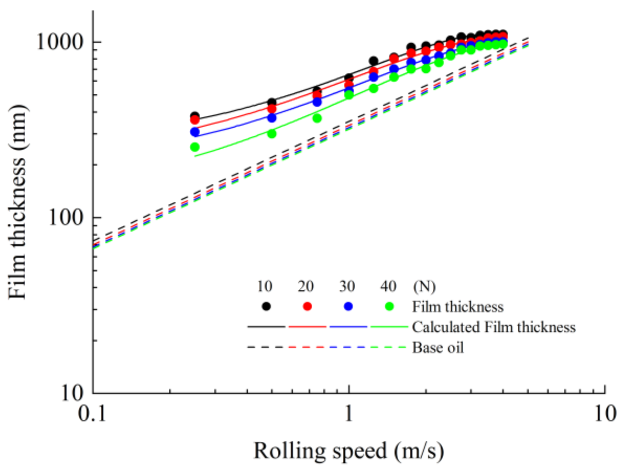


Figure 12. Measured and calculated film thickness for Grease 1.

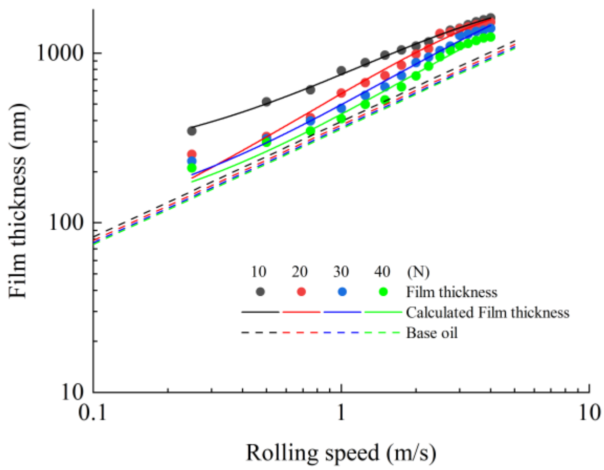


Figure 13. Measured and calculated film thickness for Grease 4.

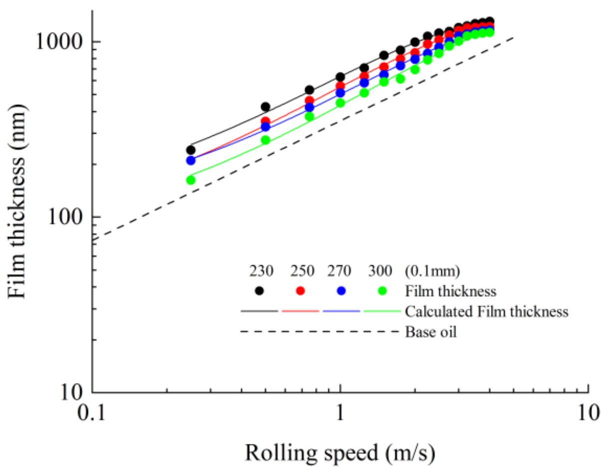


Figure 14. Comparison of measured and calculated film thickness of Grease 5 for different consistencies at 10 N load.

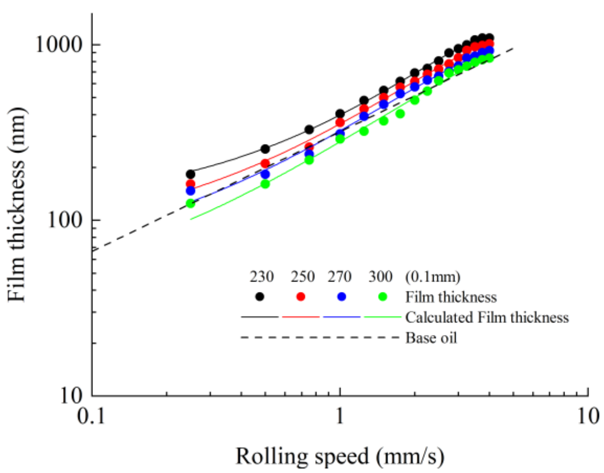


Figure 15. Comparison of measured and calculated film thickness of Grease 5 for different consistencies at 40 N load.

Grease 5 at 10 N and 40 N for different consistencies. It can be seen that the errors between the measured data and the values predicted by the formulae (15)–(24) are very small. Thus, the calculation model of grease film thickness presented has a high calculation accuracy. In addition, as shown from the Figures that the calculation model of grease film thickness presented in this paper is more appropriate to predict the grease film thickness in comparison with the base oil film thickness predicted by the Hamrock–Dowson formula.

However, it must be remembered that the model of grease film thickness presented in this paper simply represents a correlation and does not provide any physical significance for regression coefficients. The regression coefficients obtained by experiments are different for different greases. Presenting this correlation is simply to generate a method that may be easily and quickly used to compute grease film thickness in rolling bearing. The numerical simplicity of the model makes it easily adaptable to a sophisticated computer program.

5. Conclusions

In this paper, the influence of rolling speed, load, consistence, base oil type and thickener type on grease film thickness was investigated and a new calculation model of grease film thickness was established. The following conclusions are drawn:

(1) The degree of film enhancement comparing to its base oil in fully flooded lubrication will depend on thickener type and consistency (or concentration);
(2) In the high-speed region (above 0.25 m/s), when the rolling speed is less than 3 m/s, the grease film thickness increases with increasing rolling speed. The growth rate gradually decreases, then approaches to a fixed value when the rolling speed is beyond 3 m/s, which may be because at this point, the contact region is filled with enough thickener, and no more thickener can enter the region and the variation of grease film thickness remains almost unchanged with a further increase in speed;
(3) The lithium-based grease with mineral oil forms the largest film thickness, followed by ester oil and the smallest by PAO oil. The larger the atmospheric viscosity and pressure-viscosity coefficient of the base oil, the higher the film thickness of the greases with the same thickener;
(4) The grease film thicknesses with the same base oil and different thickeners are determined by the size of thickener particles at the same consistency or concentration. The fiber skeleton of mineral oil-polyurea grease is smaller than that of mineral oil-lithium grease, which results in a thicker film of mineral oil-polyurea grease than that of mineral oil-lithium grease;
(5) The larger the consistency or concentration of thickeners (the smaller the cone penetration), the thicker the grease film thickness whose base oil has the same type and viscosity along with the same type of thickener. The reason is that the greater the consistency of the grease (the more the content of the thickener), the greater the effective viscosity of the grease at the contact and the thicker the grease film thickness;
(6) A new calculation model for grease film thickness is proposed, which considers the influence factors such as working conditions, grease type and consistency. The calculation model has a high calculation accuracy and applicability to predict the grease film thickness compared to the base oil film thickness predicted by the Hamrock–Dowson formula.

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