

Impact of Water on EHL Film Thickness of Lubricating Greases in Rolling Point Contacts

F. Cyriac^{1,2} · P. M. Lugt^{2,3} · R. Bosman² · C. H. Venner²

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Abstract This paper investigates the influence of water on the EHL film thickness of six commercial lubricating greases under fully flooded and starved conditions. Although grease can absorb large quantities of water, separation occurs due to pressure and shear, leading to free water. This does not have an impact on the film thickness under fully flooded conditions. However, water does have an effect on the film thickness under starved conditions where the differences are related to the change in oil bleed. In the presence of water, an increase in oil bleed was found for lithium, lithium complex and polyurea grease. These greases showed a reduction in the levels of starvation and, therefore, thicker films. Water contamination led to lower oil bleed for calcium sulfonate complex greases, which led to an increase in starvation, and therefore, thinner films compared to their uncontaminated counterparts.

Keywords EHL · Rolling element bearings · Grease · Film thickness

1 Introduction

The operational life of grease-lubricated rolling bearings strongly depends on the performance of the lubricating grease. Water is one of the most common contaminants in

grease/oil lubrication. Water may influence the rheology, chemistry and microstructure of the grease thereby adversely affecting its performance. The grease may soften or occasionally stiffen after absorbing water [1, 2].

The primary function of the grease is to form an elastohydrodynamic lubrication (EHL) film. It was shown earlier that the relative increase in the grease film thickness under fully flooded conditions, due to entrainment of the thickener is proportional to the ratio of thickener volume fraction and the size of the thickener particles [3]. In the absence of a suitable re-lubrication mechanism, the contact starves. The grease starvation was earlier found to be dependent on the thickener concentration, base oil viscosity, disk speed, temperature [4] and oil bleed [5]. Unfortunately, there is no compelling information on film forming capability of water contaminated greases. However, there is more known on EHL films for water in oil emulsions [6–11]. Hamaguchi et al. [6] showed the EHL film thickness in rolling contacts to be insensitive to the water concentration in liquid paraffin and mineral oil emulsions. On the contrary, Dalmaz [7] found higher film thicknesses for water in oil emulsions in pure rolling and no effect under pure sliding. Wan and Spikes [11] showed that a small amount of water in polyglycols and mono-glycols can reduce the pressure-viscosity coefficient and, therefore, the lubricant film thickness. A similar observation was found by Ratoi-Salagean and Spikes [10] for water in oil emulsions. Liu et al. [9] proposed a two-phase hydrodynamic film model for the thin films formed by water in oil emulsions, in line contacts, by taking into account the size of the dispersed water droplets.

In an earlier paper, the authors [1] studied the impact of water on the rheology of lubricating greases. The model greases represented the most commonly used thickener–oil systems that are used in rolling bearings. The same greases

✉ F. Cyriac
f.febincyriac@utwente.nl

¹ Materials Innovation Institute (M2i), 2600 GA Delft, The Netherlands

² University of Twente, 7500 AE Enschede, The Netherlands

³ SKF Engineering and Research Centre, P.O. Box 2350, 3430 DT Nieuwegein, The Netherlands

will be employed in this paper (Table 1). It was shown that the phenomenon of water and grease might lead to a complex rheological flow behavior. This determines the capability of the grease to form reservoirs in the rolling bearing from where grease bleeds oil to the contacts. The aim of the present paper is to understand how water influences the EHL film of these greases.

2 Materials and Methods

2.1 Tested Greases and Bled Oils

Six commercially available greases formulated with the most common thickeners and base oils were tested (Table 1). The maximum wt% of water absorption by the greases at room temperature is also shown in Table 1. The mixing of grease and de-ionized water was carried out using an in-house made grease worker [1]. The grease worker consisted of a 24 mm diameter plate with eight 2.5 mm diameter holes in a cylinder with a stroke of approximately 30 mm. The grease worker provided a thorough mixing of water and grease. All samples (greases with and without water) were similarly worked (1000 strokes). The saturation point of water in a given grease was obtained by observing with the ‘naked eye’ and/or a confocal microscope if any visible droplets were formed, indicating the presence of free water.

The bled oils were extracted from the greases by using a centrifuge—Heraeus Biofuge 17RS. The centrifugation was carried out by loading grease samples into a filter with a mesh size of 10 μm . The dynamic oil separation was performed at a temperature of approximately 37–40 °C at a centrifugal acceleration of 360 g.

2.2 Film Thickness Measurements

Film thickness measurements were performed with a ball on flat-disk test apparatus with optical interferometry [3, 10] (PCS Instruments Ltd) for bled oils and greases. The testing conditions are shown in Table 2.

Central film thickness measurements were taken under fully flooded conditions for greases with maximum wt% water and without water. To ensure fully flooded conditions, a grease scoop was used for re-distributing and re-directing the grease back onto the rolling track. Nevertheless, the film thickness was found to decrease with time, so to maintain a sufficient and stable film, the fresh grease was fed manually into the contact at each speed increment. Starved film thickness measurements were performed by placing a single charge of the lubricant onto the rolling track of the glass disk. The measurements were taken for 1000 disk revolutions or until the film thickness had dropped below 10 nm. The measurements were taken for greases with maximum wt% water, 10 wt% and without water.

The testing conditions for fully flooded and starved film thickness measurements are shown in Table 2. The tests were carried out twice to check the repeatability, and the film thickness results that are shown here are an average of two measurements.

2.3 Oil Bleed Measurements

The oil bleed was obtained using the static bleed oil test DIN 51817/IP 121. The test is performed by placing a known quantity of grease on the cone-shaped woven wire cloth and loading it with a dead weight of 100 g for 168 h at 40 °C. The amount of oil separated (S_{oil}) is calculated by

Table 1 Important properties and maximum wt% water absorbed by the greases

Grease	NLGI	Thickener	Thickener concentration [3]	Base oil	Viscosity of base oil (mm^2/s) (40/100 °C)	Consistency (60 Strokes, 0.1 mm)	Max wt% water [1]
CaS/MS	1–2	Calcium sulfonate complex	26	Synthetic (PAO)/mineral	80/8.6	300	80
CaS/M	2	Calcium sulfonate complex	27	Mineral oil	420/26.5	275	80
Li/M	3	Lithium	15	Mineral oil	99.9/10	207	10
Li/SS	2	Lithium	17	Mineral oil (semi-synthetic)	41.9/7.5	270	10
LiC/PAO	2–3	Lithium complex	20	Synthetic PAO	191/22	255	30
PU/E	2–3	Polyurea	26	Synthetic ester	70/9.4	283	80

Table 2 Ball on flat disk: geometry and testing conditions

Geometry	Radius (mm)	Roughness (Rq) (nm)	Elastic modulus (GPa)	Poisson ratio
Ball	9.53	6.5	210	0.29
Disk	50	<10	60	0.18
Regime	Load (N)	P_{\max} (GPa)	Speed (m/s)	Temperature (°C)
Fully flooded	20	0.74	0.02–1	25, 50 and 75
Starved	20	0.74	0.25	25 and 40

$$S_{\text{oil}} = \frac{m}{M} \times 100, \quad (1)$$

where M is the mass of the grease placed on the wire cloth and m is the mass of the oil obtained from the test.

3 Results

3.1 Fully Flooded Film Thickness

The elastohydrodynamic central film thickness for the greases and corresponding bled oils, as a function of rolling speed on log–log scales is shown in Fig. 1. In the range of studied speeds, the central film thickness was found to increase with a slope of ≈ 0.62 – 0.71 , which is in accordance with the film thickness equations from Hamrock and Dowson [12] for fully flooded conditions. In many cases, the grease films were found to be higher than their corresponding bled oils, which are ascribed to the presence of thickener material influencing the effective viscosity of the lubricant in the contact [3, 13, 14].

The fully flooded film thickness of water contaminated greases was found to be almost independent of water (Fig. 1). This applies to all greases and all applied temperatures. Even though water was found not to influence the film thickness under fully flooded conditions, it disturbed the formation of the ‘butterfly-shaped’ lubricant reservoir [15], usually observed for grease- and oil-lubricated contacts (Fig. 2). This was due to the formation of water patches within the lubricant reservoir on the sides of the track. The ‘free water’—water that was expelled from the contact under pressure and shear was found to flow around or at the tail of the contact (Fig. 2).

3.2 Starved Film Thickness

Starved film thickness measurements as a function of the number of disk revolutions for water contaminated and uncontaminated greases are shown in Fig. 3, 4, 5 and 6.

The impact of water on the film thickness of calcium sulfonate complex grease is already observed after a few disk revolutions. For CaS/M, a substantial reduction in film

thickness was observed with 80 % water, at a lower temperature (Fig. 3). The contact severely starved, reaching a film thickness below 10 nm after 575 revolutions. In this case, the measurements were stopped after 575 revolutions to prevent surface damage. For uncontaminated grease, the film thickness stabilized after 150 revolutions. For 10 % water, the CaS/M grease showed again a decrease in film thickness but not as severe as for 80 % water. At a higher temperature, a stable film thickness occurred after 300 disk revolutions for water contaminated and uncontaminated grease samples. However, also at this higher temperature, the film thickness was lower than for the uncontaminated grease. Surprisingly, the film did not collapse with 80 % water now.

CaS/MS exhibited hardly any starvation at a higher temperature. At lower temperature, the starvation rate was smaller than for the mineral oil-based calcium sulfonate complex grease and no sign of film collapse was observed with 80 % water.

Contrary to calcium sulfonate complex greases, for the same concentration of water, an increase in film thickness was exhibited by the lithium grease with a semi-synthetic base oil (Li/SS) (Fig. 4). At a higher temperature, a collapse in film thickness is displayed by water contaminated Li/SS grease after 500 disk revolutions. Another important observation is the absence of film thickness decay and regeneration for water contaminated Li/SS grease, which is otherwise observed for its uncontaminated counterpart, at a lower temperature. Unlike Li/SS, no significant distinction in film thickness can be seen for Li/M with and without water. Nevertheless, irrespective of the temperature, water was found to slightly delay the transition from mild to severe starvation (Fig. 4).

In the case of LiC/PAO, irrespective of the temperature, an equilibrium film thickness was observed after 200 disk revolutions for uncontaminated and water contaminated grease samples (Fig. 5). Similar to lithium greases, an increase in film thickness can be seen for this grease in the presence of water.

Similar to lithium and lithium complex greases, an increase in film thickness is exhibited by the studied polyurea grease with water (Fig. 6). However, for 10 %

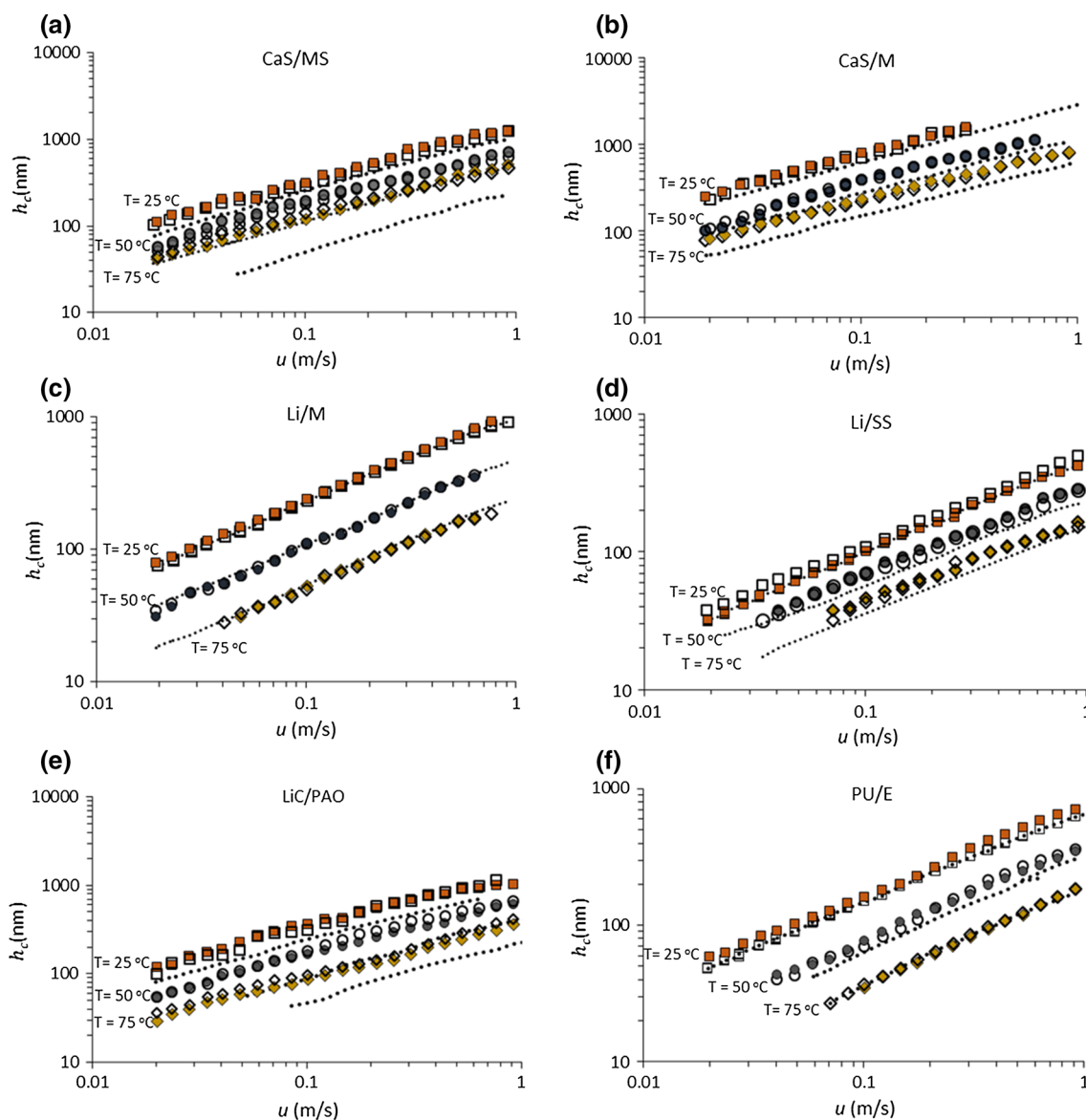


Fig. 1 Central film thickness versus rolling speed for the greases and bled oils at different temperatures. *Filled symbols* film thickness for non-contaminated greases, *unfilled symbols* film thickness for greases with maximum wt% water, *dotted line* film thickness for bled oils

water, the influence was found to be limited to a few disk revolutions, above which the film thickness was found to be comparable to that of uncontaminated grease.

3.3 Static Oil Separation

The DIN 51817/IP 121 test method was used to measure the ability of a grease to separate oil under static condition, subjected to a very small static pressure. The percentage change in oil bleed in the presence of water is calculated by

$$\Delta S(\%) = \frac{s_{oil/w} - s_{oil}}{s_{oil}} \times 100, \tag{2}$$

where $s_{oil/w}$ is the oil bleed for greases with 10 wt% water and s_{oil} is the oil bleed for non-contaminated grease.

Table 3 shows that all greases showed an increase in oil bleed except for the calcium sulfonate greases where the oil bleed decreased in the presence of water. A similar observation was done by Leckner [16]. Calcium sulfonate complex greases can form reverse micelles in the presence of water [16]. Increase in particle agglomeration and increase in attractive potential between the micelles in the presence of water [17] might have resulted in a decrease of oil bleed for calcium sulfonate complex greases. On the contrary, an increase in oil bleed for the other greases can

Fig. 2 Influence of water on the lubricant reservoir for a representative grease at $T = 25\text{ }^{\circ}\text{C}$

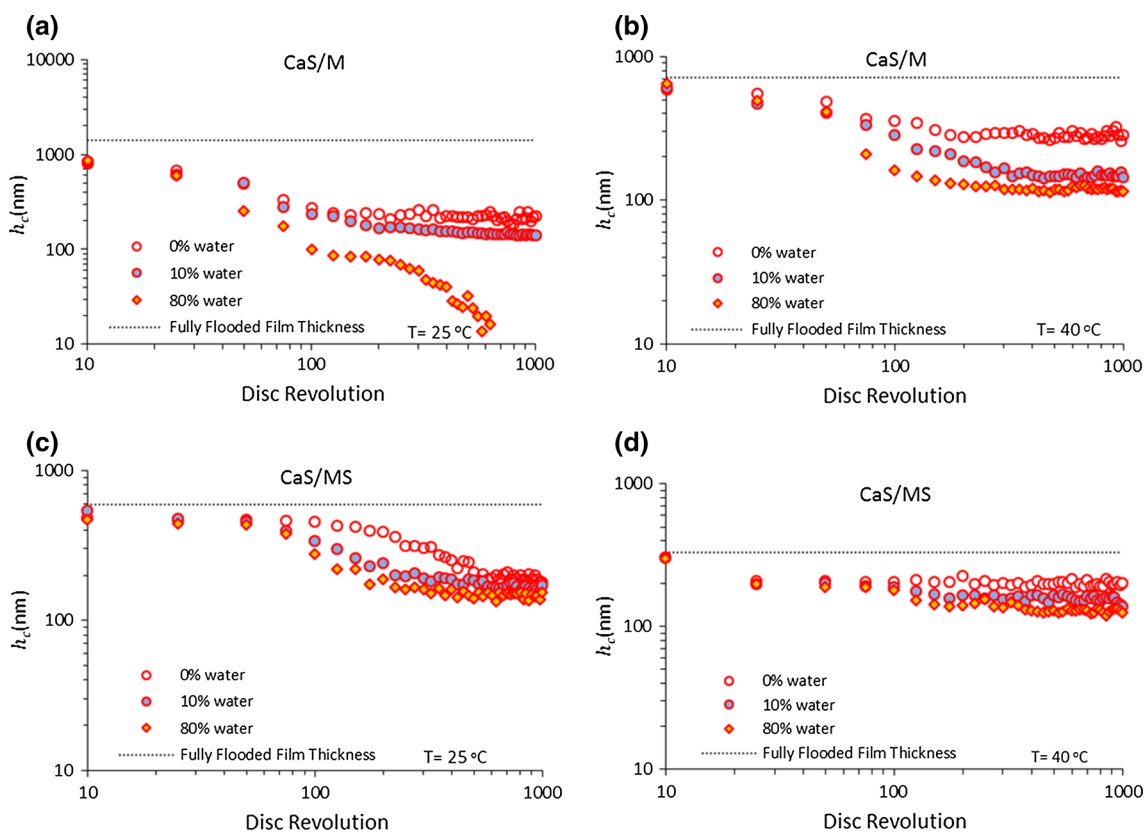
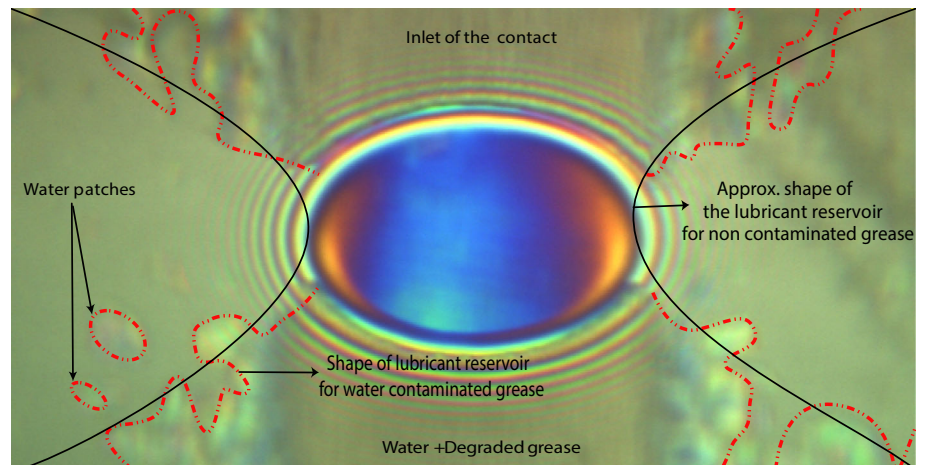


Fig. 3 Starved film thickness for calcium sulfonate greases at 25 and 40 °C

be due to the reduction in particle interactive forces in the presence of water.

To ensure that the bled oil from water contaminated grease did not contain water, a qualitative analysis was performed using Fourier transform infrared spectroscopy (FTIR). These measurements were taken under absorption mode using Bruker FT-IR TENSOR 27 apparatus [3].

4 Discussion

The greases were found to absorb considerable quantities of water. As lubricating oils have limited water absorptivity [18], absorption of high concentrations of water by the greases can be attributed to their polar thickeners and additives [1]. During the mixing of water and grease, water may be adsorbed at the surface of the thickener particles

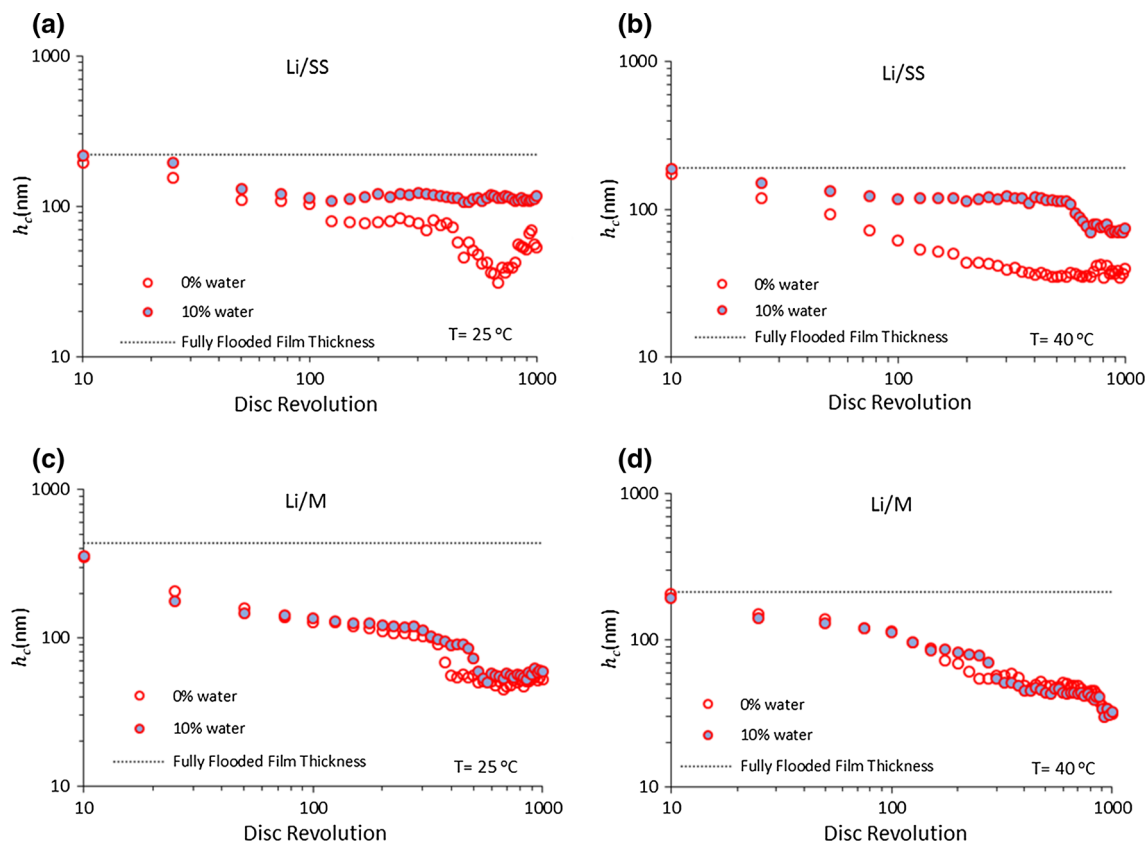


Fig. 4 Starved film thickness for lithium greases at 25 and 40 °C

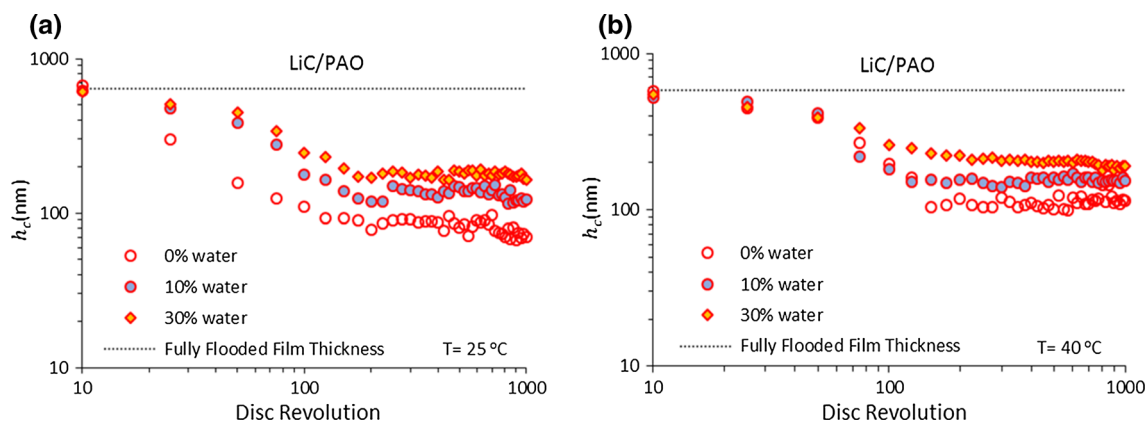


Fig. 5 Starved film thickness for lithium complex grease at 25 and 40 °C

and may form micro emulsions in the oil, presumably stabilized by additives with surfactant properties [16].

Water hardly influenced the film thickness of the greases, under fully flooded conditions. It should be noted that the greases were very different in thickener and base oil type and had different rheological properties and change in rheological properties by adding water [1]. However, the change in rheological properties was found not to influence the film thickness under fully flooded conditions. This is in

agreement with our earlier work [3]. It is likely that the grease–water mixture tends to undergo a phase separation leading to ‘free water’ and oil by the high shear and pressure at the vicinity of the contact. Unlike oil, water hardly builds up a film due to its zero pressure-viscosity coefficient [19]. So the ‘free water’ formed due to phase separation will be pushed out and will migrate to the low shear rate region of the flow field. The free water was clearly visible in the measurements and was indeed found

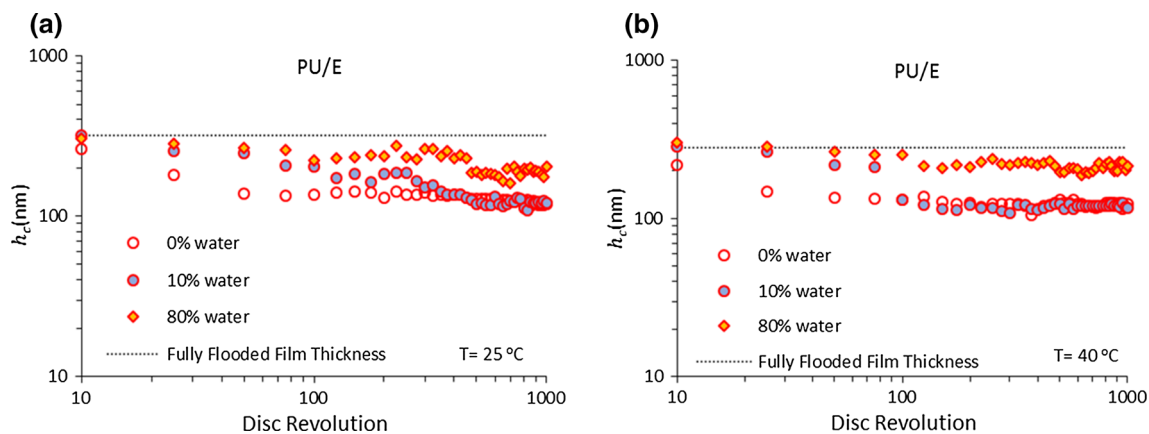


Fig. 6 Starved film thickness for polyurea grease at 25 and 40 °C

Table 3 Percentage change in oil bleed, ΔS (%) obtained using IP 121 and at $T = 40$ °C, for uncontaminated and water contaminated greases

Grease	s_{oil} (0 % water)	$s_{oil/w}$ (with 10 wt% water)	ΔS (%)
CaS/MS	2.09	0.28	-87
CaS/M	1.22	0.24	-80
Li/M	0.43	0.68	58
Li/SS	4.12	8.37	103
LiC/PAO	1.31	2.25	72
PU/E	3.80	4.83	27

to flow around the contact. This water did not have an effect on the fully flooded film thickness for any of the greases. So even for water contaminated grease samples, the film thickness is given by the base oil viscosity corrected with the effect of thickener particle entrainment [3].

Contrary to the fully flooded results, water exerted a profound influence on the film thickness in the starved regime. Contact replenishment takes place by grease and oil flow. Free oil is formed by oil separation also called “bleeding” [20]. A high oil bleed will therefore lead to an enhanced contact replenishment. It is shown here that such a correlation indeed exists. In the case that oil bleed was reduced by the presence of water, such as for the CaS/M and CaS/MS greases, thinner films were found. On the other hand, an increase in oil bleed is observed for lithium, lithium complex and polyurea grease in the presence of water. Simultaneously ‘free water’ will also be formed during over rolling. However, it does not contribute to the film thickness and will flow around the contact. Other factors that have an effect on replenishment in single contacts are differences in surface tension/wetting, differences in bulk viscosity or differences in grease softening by aging caused by shear close to the contact. It was shown earlier that the viscous flow causing replenishment is so

slow that it plays only a minor role. The same applies to the smoothening/flattening of the lubricant ridges behind the contact by surface tension. Grease aging by shear leading to very soft grease may have a significant effect and would also lead to a higher oil bleed. This has not been investigated here. However, the effect of water on oil bleed on fresh grease was already so apparent that this is the most likely cause for the differences in film thickness that were observed here under starved lubrication.

5 Conclusions

The fully flooded EHL film thickness of the studied greases with and without water was found to be almost equal. The working of grease by shear and pressure caused water separation from the grease forming free water. The free water was found to disturb the formation of the ‘butterfly-shaped’ lubricant reservoir, usually observed for grease- and oil-lubricated contacts.

Even though the water was found not to influence the film buildup under fully flooded conditions, it exerted a significant influence under starved conditions. Water contaminated calcium sulfonate greases gave thinner films, whereas lithium, lithium complex, and polyurea greases gave thicker films compared to their uncontaminated counterparts. It is shown that the change in film building ability of the studied greases in starved lubrication and in the presence of water is most likely related to their change in oil bleed.

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