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The influence of bearing grease composition on friction in rolling/sliding concentrated contacts

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ABSTRACT

This paper presents new results examining the relationship between bearing grease composition and rolling-sliding friction in lubricated contacts. Friction coefficient and lubricating film thickness of a series of commercially available bearing greases and their bled oils were measured in laboratory tribometers. Test greases were selected to cover a wide spectrum of thickener and base oil types, and base oil viscosities. The trends in measured friction coefficients were analysed in relation to grease composition in an attempt to establish the relative influence of individual grease components on friction. Two distinct operating regions with markedly different friction behaviour are identified for each grease. At relatively high speeds the greases behave approximately as their bled/base oils, while in the low speed region the frictional response is very dependent on their thickener type and properties of the lubricating film. Low viscosity, synthetic base oil seems to offer efficiency advantages in the high speed region regardless of thickener used, while the choice of thickener type is significant under low speed conditions.

1. Introduction

More than 90% of rolling element bearings are grease lubricated [1]. Consequently, improved understanding and optimisation of grease frictional performance can offer an important way of reducing power losses in rolling bearings. As most machines utilise multiple rolling bearings, this in turn offers one of the most pervasive ways of improving the overall efficiency of mechanical systems with associated savings in energy and carbon emissions. Currently, there exist broad guidelines for the selection of bearing greases, based on extensive laboratory analysis and observations from the field, suggesting generalised selection rules to fulfil the application conditions. However, at present there is a lack of detailed understanding of the role of individual grease components in determining friction response under different bearing operating conditions. Without this knowledge it is impossible to develop a scientific framework for choosing grease for a specific application, or to formulate new low-friction greases.

Grease is a two-phase lubricant composed of a thickener physically dispersed in base oil. It is typically made from 85% base oil, 10% thickener, plus additives ($\sim$5%) [2]. When a stress is applied to grease, both the thickener fibres and the oil will resist deformation, opposing elastic and viscous forces respectively [3]. The elasticity characteristic prevents the grease from leaking, while its fluidity is essential for the grease to lubricate the contact. Lubricating base oils exhibit non-Newtonian behaviour at high shear rates and pressures [4], while greases show this behaviour even at the lowest shear rates, due to their bi-phasic structure. The base oil, thickener and additives system in typical greases is obviously a far more complex rheological system than a simple base oil, so it is difficult to ascribe lubricant film formation and thus bearing frictional behaviour to a single grease component. The composition and properties of the lubricating film are likely to depend on both the grease properties (base oil and thickener type, additives, rheology) and operating conditions (speed, temperature and bearing design). There are a number of models for grease lubrication of bearings. The most widely accepted one is that the film-forming lubricant is 'bled' oil released from the thickener matrix [5] due to shearing. In this model the thickener does not play an active role in the lubrication process. However, more recent work has challenged this model [6], and moreover there is considerable evidence from examination of bearing lubricant films that the thickener does participate in the lubrication process [7], although this does depend on the bearing design [8].

There is very little published work on friction mechanisms in grease lubricated contacts. A selection of studies focus on the effect of operating conditions, such as degradation time [9], high [10] or low [11,12] temperature. Others have attempted to explain grease friction through rheometry [13,14]. Only a few have explored the effect of grease chemical composition on its friction

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behaviour, on a thrust ball bearing [15,16], four-ball machine [17] and ball-on-disc machine [6]. Some of these studies have shown the importance of the base oil in grease formulation, with low viscosity and low pressure–viscosity oils suggested as a preferred choice for low friction in EHL conditions [15]. Furthermore, thickener type [6], composition and texture [17] have also been shown to affect friction, with some thickeners able to reduce friction, particularly under boundary and high temperature conditions [10]. However, it is clear that grease frictional behaviour cannot entirely be ascribed to one single component of grease, but rather it is determined by the interaction between all grease elements, which in turn strongly depends on the specific operating conditions [16].

At present, the literature is missing a comprehensive investigation on the influence of grease composition on friction in concentrated EHL contacts operating under conditions pertinent to rolling bearings. In contrast, there is considerable work on grease EHL film thickness behaviour [4]. Film thickness and friction are clearly related, and therefore, combined film thickness and friction analysis may help to explain some of the mechanisms of grease friction and suggest potential ways of improving frictional performance of bearing greases.

This study aims to provide understanding of the role of the different grease components in determining friction and film thickness in non-conformal contacts pertinent to rolling bearings. As the focus of the research was lubricant composition rather than bearing factors, standard laboratory tests were used to measure friction coefficient and film thickness. The intention was to simulate the conditions (slide-roll ratio, contact pressure, temperature, speed, materials) in the contact between the rolling elements and the raceway of a bearing.

One of the fundamental factors determining lubrication and film formation with greases is the lubricant supply to the inlet of the contact [18]. Grease has a yield stress and, unless it is compelled by an external force, will not readily flow back into the raceway after it has been displaced by passage of a rolling element, resulting in onset of lubricant starvation, potential film thickness reduction and surface damage [19]. Greased rolling bearings often operate in starved lubrication conditions [1], although these depend on operating, design and grease composition factors. In order to eliminate this critical variable, which greatly affects the repeatability of laboratory experiments, the tests described in this work were carried out in fully flooded conditions.

2. Methodology and analysis

A number of commercially available greases, chosen to represent a wide range of real bearing applications and operating conditions, and therefore made of various base oil/thickener systems, were tested. The study was not limited to nominally low friction greases, but intentionally covered greases of widely dissimilar compositions and bearing applications in order to identify significant trends in frictional behaviour. In an attempt to isolate the influence of thickener and oil, the performance of bled oils obtained from each grease was also studied. Additionally, film thickness measurements were carried out to aid the interpretation of the friction data.

2.1. Test lubricants

Table 1 lists properties for all test greases used in the study. Typical bearing applications where these greases are employed are also specified. Grease naming nomenclature, shown in column 1, reflects the grease composition; for example ‘LiMi’ indicates a lithium thickener grease with mineral base oil. As is evident these greases cover a wide spectrum of chemical, physical and rheological properties. Base oils range from mineral to PAO, ester and mixed mineral/synthetic oils, while the thickeners include lithium, lithium complex, polyurea and calcium sulphonate complex. Four greases are based on lithium 12-hydroxystearate, and one is a lithium complex thickened grease. This is broadly representative of the global market of lubricating greases, 70% of which are currently based on lithium soaps [20]. Two of the selected greases, LiEs and LiPAO, are categorised as ‘low friction’ greases. In addition to the data in Table 1, bled oil was also obtained from each grease by centrifugation, and its friction behaviour tested for comparison.

2.2. Experimental equipment and procedure

Friction and film thickness were measured in separate experiments on ball-on-disc tribometers to characterise the properties of the lubricating films over a range of entrainment speeds and temperatures. Repeatability of results was confirmed by conducting every friction and film thickness test for each grease and test condition at least twice.

The MTM (Mini Traction Machine) rig was employed for the friction tests. This rig uses a ball-on-disc configuration, illustrated schematically in Fig. 1(a), where both ball and disc specimens are made of AISI 52100 standard bearing steel. The ball and disc are held in a temperature-controlled steel enclosure, and are driven independently so that a range of speeds and slide-roll ratios can be obtained. The test rig has been previously used to measure friction in grease lubrication [9,6]. Friction tests consisted of 4 measurement steps. In the first step a small ball load was applied on the disc, at a constant speed of 5 mm s^{-1}, for 5 min and in pure rolling conditions. This preliminary step was introduced with the purpose of pre-shearing the grease, equivalently to common protocols used to examine greases flow and viscoelasticity in a rheometer [21], and ensuring the same initial condition for each test. The friction data were then obtained in 3 consecutive speed-sweep steps, where the speed was increased from 10 mm s^{-1} to 1000 mm s^{-1} to generate Stribeck-like curves. This procedure allowed the monitoring of the step repeatability within the same test, and the analysis of the effect of time dependency on the friction coefficient evolution after each step. Friction tests were carried out at 40 °C,

Table 1
List of test greases.

Grease	Oil	Thickener	Oil viscosity @ 40 °C [cSt]	Oil viscosity @ 100 °C [cSt]	Application
LiMi	Mineral	Lithium	74	8.5	Reference grease
LiMi2	Mineral	Lithium	200	16	High load extreme pressure
LiEs	Ester	Lithium	25.1	4.9	Low friction
LiPAO	PAO	Lithium	18	4.5	Low friction
LiCPAO	PAO	Lithium complex	191	42	Wide temp range
PoEs	Ester	Polyurea	70	9.5	High temp
CaSMi	Mineral	Calcium sulphonate complex	420	26.5	Heavy duty high temp
CaSMix	Mixed mineral/ synthetic	Calcium sulphonate complex	80	8.6	Heavy duty low temp

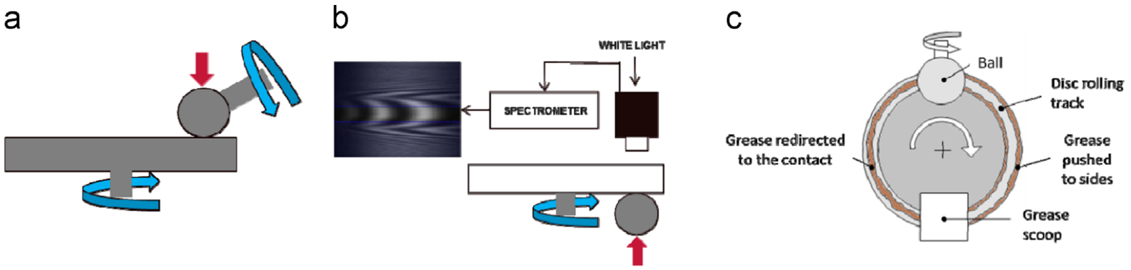

Fig. 1. Schematic representation of friction (a) and film thickness (b) tests setup, and grease scoop (c).

Table 2
Friction and film thickness test conditions.

Test	Friction	Film thickness
Test specimens	52100 steel disc; 19.05 mm diameter AISI 52100 steel ball	Chromium coated glass disc with spacer layer; 19.05 mm diameter AISI 52100 steel ball
Composite roughness Rq [nm]	18.5	< 10
Maximum Hertzian pressure [GPa]	0.96	0.52
Temperatures [°C]	40, 60 and 80	40
Slide/roll ratio [%]	10	0
Entrainment speed range [mm s^{-1}]	10–1000	5–1000

60 °C and 80 °C. The same test profile was used to study the behaviour of the bled oils. The repeatability of the friction results for all test greases within the specified range of conditions was excellent. Nevertheless, all friction results in this paper are plotted as an average of two last Stribeck steps of each test and its repeat.

Film thickness measurements were made using a thin-film optical interferometry rig [18,22] illustrated schematically in Fig. 1 (b). This also uses a ball-on-disc geometry, but in this case the upper disc surface is made of glass to allow optical interferometry measurements. The film thickness testing procedure consisted of 3 steps, where the first step is equivalent to that in friction tests and its role is to ensure consistent conditions in each test. The film thickness measurements were taken during the following Stribeck steps, where the speed was first increased from 5 mm s^{-1} to 1000 mm s^{-1} and then decreased back to 5 mm s^{-1}. As was the case for the friction measurements, the film thickness results in this paper are plotted as an average of speed decrease steps of each test and its repeat.

The film thickness tests were run at 40 °C only.

The test profile and conditions for the friction and film thickness measurements are summarised in Table 2. Prior to commencing each test, all specimens were cleaned in toluene and isopropanol in an ultrasonic bath, and then air dried prior to assembly.

In order to maintain a continued supply of lubricant to the contact, a small scoop was positioned in front of the inlet to channel grease back into the track in both friction and film thickness tests as illustrated in Fig. 1(c). This ensured that the contact zone was fully flooded with lubricant over the entire speed range. In the bled oils friction tests this was unnecessary, as in this case the fully flooded conditions were simply achieved by filling the pot where the disc is attached, up to its contact surface.

The film thickness and friction measurements were made on separate instruments with different slide-roll ratios, materials and loads. The presence of moderate sliding has been shown to have negligible influence on grease film thickness in EHL contacts under fully flooded conditions [23]. Therefore, only the influences of differing load and material elastic properties need to be accounted for. Given the EHD theory, these are minimal, but have nevertheless been accounted for using the Hamrock–Dowson EHL film thickness equation [24] leading to the following relationship:

$$\frac{h_{\mathrm{MTM}}}{h_{EHD}} = \left(\frac{E'_{EHD}}{E'_{MTM}}\right)^{0.073} * \left(\frac{W_{EHD}}{W_{MTM}}\right)^{0.067} = \sim 0.92$$

where h is the central film thickness, E' the reduced Young's modulus, W the load, and the suffixes MTM and EHD refer to the friction and film thickness tests respectively. This factor was used to project the film thickness measurements from the EHD rig onto the MTM rig, making it possible to create single plots relating the film thickness and friction trends in grease lubricated contacts.

Finally, whenever measured grease film thicknesses is compared with the corresponding base oil values in this study, the latter was also estimated using the Hamrock-Dowson film thickness formula [24]. In these calculations, the base oil kinematic viscosities were those provided by suppliers and shown in Table 1, while the density was assumed to be 850 kg m^{-3} for all base oils since no exact figures were available. The pressure–viscosity coefficients were calculated using a procedure described by Khonsari and Booser [25].

3. Results

3.1. Grease friction coefficient results

Recorded Stribeck curves for all tested greases are shown in Fig. 2(a)–(c) at 40 °C, 60 °C and 80 °C respectively. The most striking feature of Fig. 2 is the very different frictional behaviour of the tested greases: at low speeds the friction values cover a range of almost one order of magnitude, from below 0.01 to almost 0.09. Clearly, the grease friction versus speed curve at low speeds differs from the shape of a typical Stribeck curve of an oil [26]. Focussing on the low speed region of the plots, all lithium based greases LiMi, LiMi2, LiEs, LiPAO and LiCPAO display an 'inverse-Stribeck' behaviour [6], i.e. relatively low friction in the low speed region, in contrast to what is commonly found in base oils which exhibit higher friction in the low speed boundary and mixed regimes. As the speed increases, LiMi2 shows constantly increasing friction while for LiMi, LiEs, LiPAO and LiCPAO the friction coefficient rises with speed, up to a local maximum (the curve 'bump'), after which it starts descending. This behaviour only appears at 60 °C in LiEs and LiCPAO. The 'bump' moves to higher speed with increasing temperatures. On the contrary, in the calcium sulphonate complex greases CaSMi and CaSMix, and to a lesser extent the polyurea grease PoEs, the maximum friction coefficient value is found at the lowest speed at all temperatures, and monotonically decreases as the speed is increased producing a Stribeck curve typical of a lubricating oil. At sufficiently high speed the friction coefficient becomes 'steady state', and the speed at which this steady friction is reached for each grease increases with temperature.

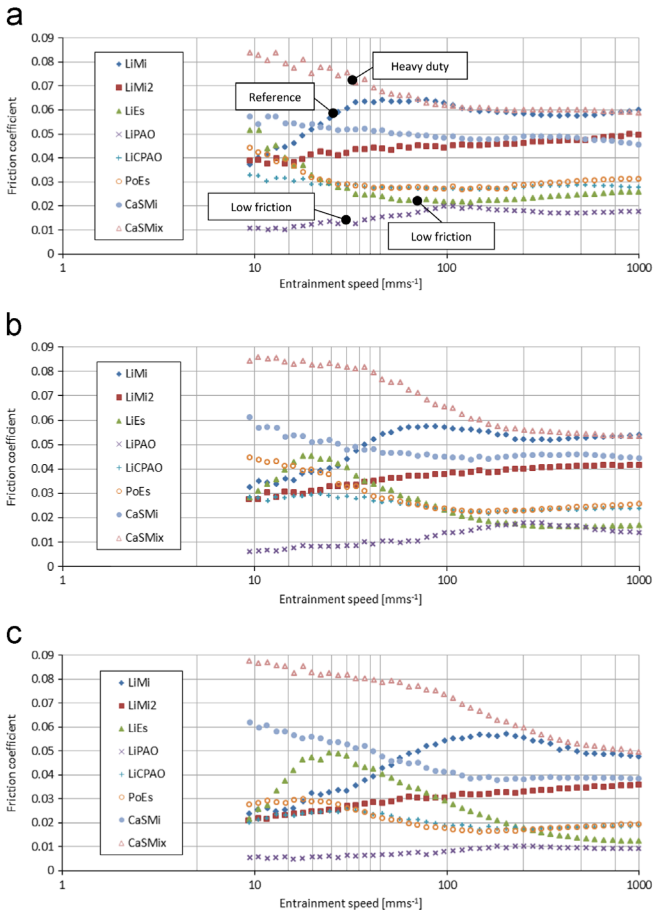

Fig. 2. Friction coefficient against entrainment speed at (a) 40 °C, (b) 60 °C and (c) 80 °C.

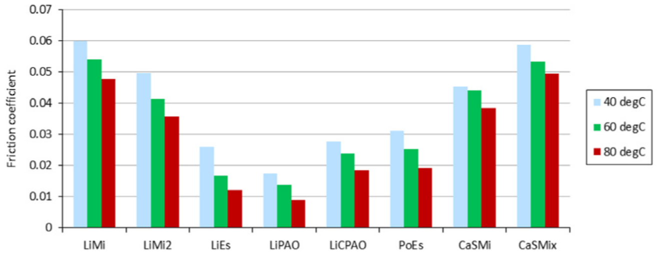

Fig. 3. Temperature influence on friction coefficient measured at 1000 mm s^{-1}.

It is interesting to compare the behaviour of the two low friction greases, LiEs and LiPAO. LiPAO clearly displays the lowest friction coefficient throughout the whole speed range, while LiEs only reaches a relatively low friction coefficient at high speeds. At lower speeds LiEs actually has higher friction than some standard greases.

In order to further investigate the effect of temperature on friction, Fig. 3 shows a bar chart of friction coefficient at the three temperatures and at a fixed speed of 1000 mm s^{-1}. This speed is sufficiently high for all the greases to develop a full EHL film (i.e. $\Lambda > 3$, where Λ is the specific film thickness estimated as the ratio of calculated central base oil film thickness to composite RMS roughness). It should be noted that Λ is based on the central film thickness, instead of the more commonly used minimum film thickness, because, unlike oil films, grease films do not always exhibit clearly identifiable minimum film regions, particularly at low speeds. Clearly, an increase in temperature leads to a decrease in friction for each individual grease, suggesting that the base oil viscosity of each grease drives its frictional behaviour under these conditions. However, the effect of temperature on friction is much less obvious at lower speeds. Fig. 5 shows the equivalent bar chart for friction measured at 50 mm s^{-1}. It is apparent that at this lower speed, friction can either decrease with temperature, as for LiMi or LiMi2, be unaffected as in the case of CaSMi, or even increase with temperature as in LiEs and CaSMix.

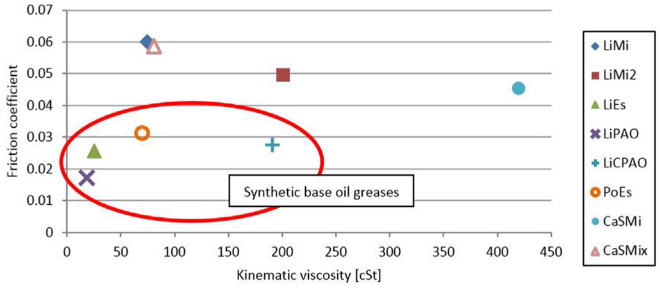

Fig. 4. Friction coefficient of test greases at 1000 mm s^{-1} against kinematic viscosity of base oils.

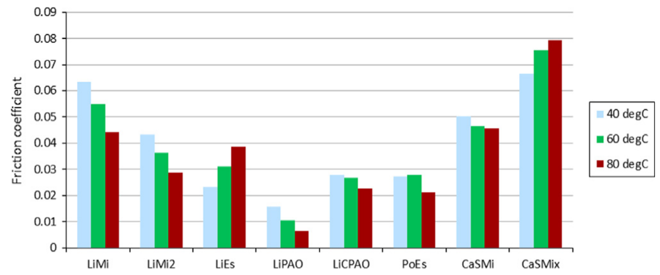

Fig. 5. Temperature influence on friction coefficient at 50 mm s^{-1}.

To further investigate the correlation between the base oil viscosities and measured friction across all greases, Fig. 4 plots friction coefficient measured at 1000 mm s^{-1} (i.e. $\Lambda > 3$) and 40 °C against the base oil kinematic viscosity. Although no clear correlation is found, the lowest friction coefficient values are displayed by the synthetic base oil greases LiEs, LiPAO, PoEs and LiCPAO, as indicated in Fig. 4.

3.2. Bled oil friction coefficient results

The bled oil friction behaviour was investigated in an attempt to establish the relative influence of thickener and base oil. The bled oils may be different from the base oils, as they could contain additives and thickener particles [16], but the base oils of this wide range of commercial greases are not easily available. However, the comparison between the friction behaviour of LiPAO bled and base oils (the only one available to this study) showed minor differences, only evident at the lowest speeds.

Only selected results are shown in this section, chosen to cover the general trends observed when comparing performance of test greases and their respective bled oils. The friction coefficient of LiPAO is plotted in Fig. 6 together with its bled oil at (a) 40 °C, (b) 60 °C and (c) 80 °C. It is apparent that LiPAO friction is much lower than that of its bled oil in the low speed region. However, as the speed increases, a point is reached from where on the friction curves are close to identical. It is also apparent that the exact speed where this occurs corresponds to conditions of mixed lubrication based on the bled oil, where friction is still decreasing with speed, and therefore this may be partly responsible for the appearance of the 'bump' in the grease friction curve. This speed also increases with temperature, i.e. the 'inverse-Stribeck' behaviour of LiPAO at low speed is extended up to higher speed when temperature is increased. The same behaviour was observed in all

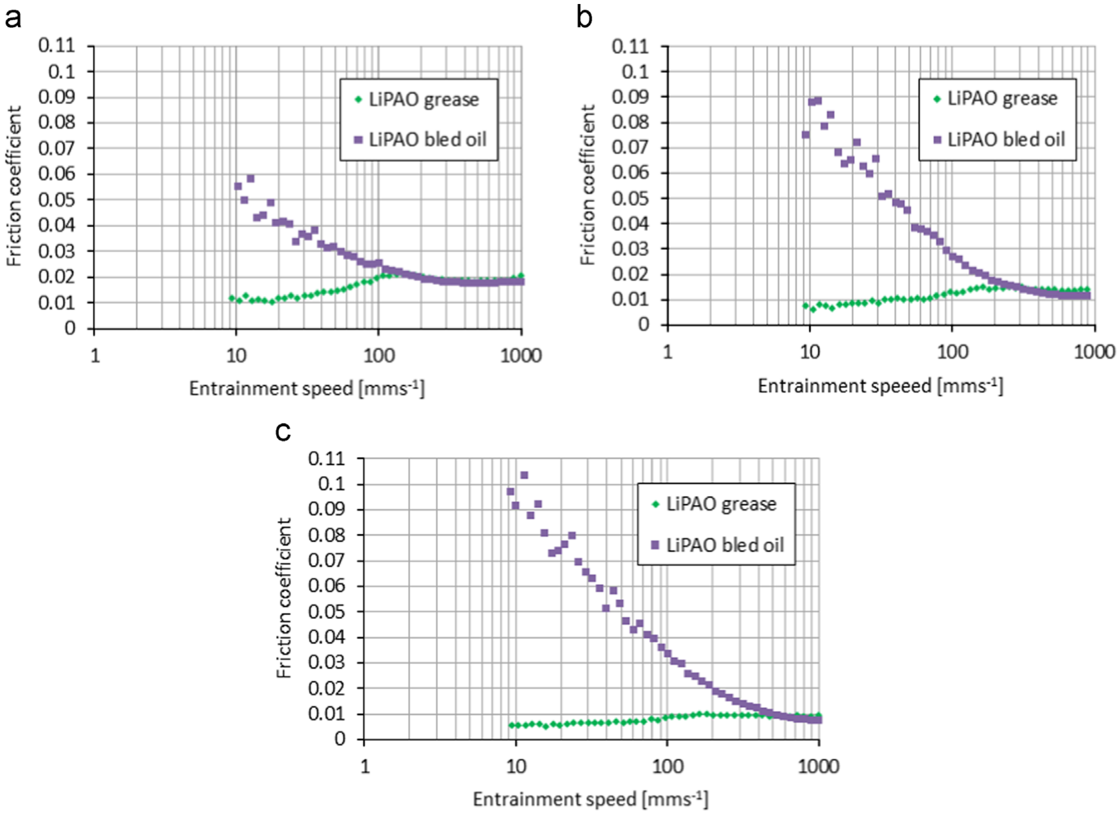

Fig. 6. Friction coefficient of LiPAO and its bled oil at (a) 40 °C, (b) 60 °C and (c) 80 °C.

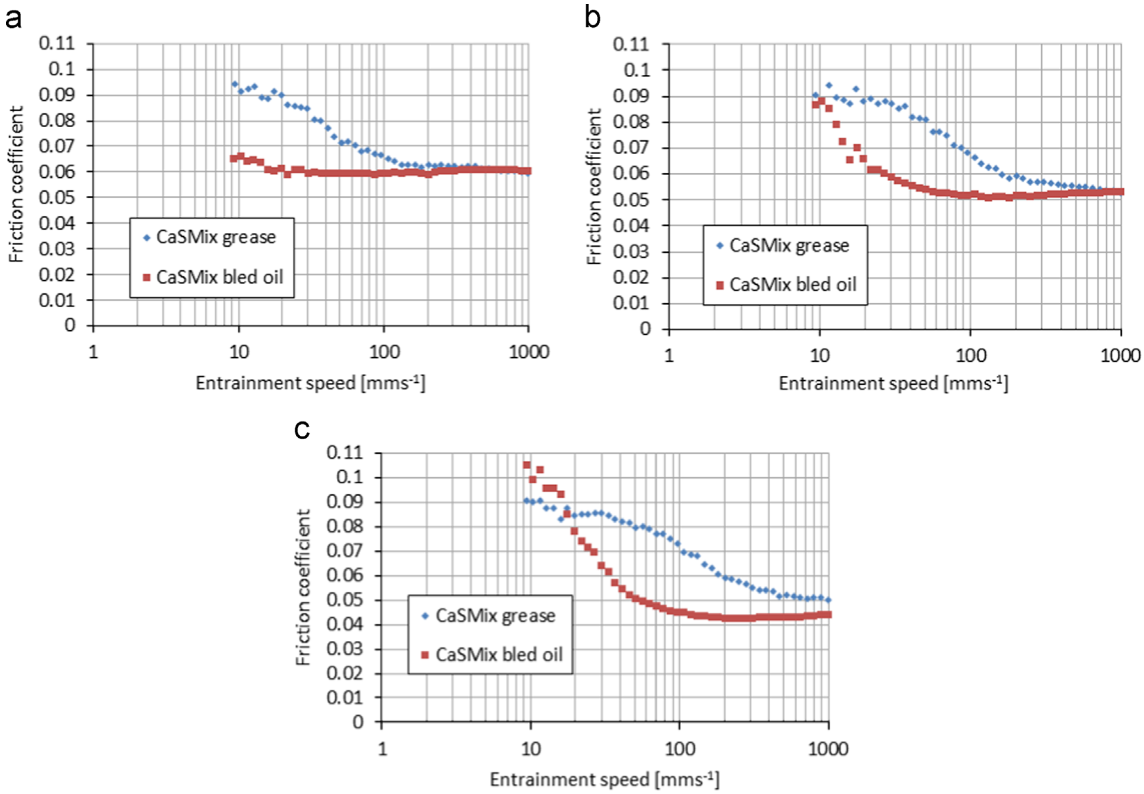

Fig. 7. Friction coefficient of CaSMix and its bled oil at 40 °C, 60 °C and 80 °C.

other lithium thickened greases as well as the polyurea grease. These greases also showed a decrease in the friction coefficient with increasing temperature at the lowest speeds.

Both calcium sulphonate complex greases showed a contrasting behaviour to that of lithium and polyurea greases described above. To illustrate this, CaSMix and its bled oil friction coefficients are plotted in Fig. 7 at (a) 40 °C, (b) 60 °C and (c) 80 °C. While at the lowest speed CaSMix friction seems to be unaffected by test temperature, it is evident that this grease gives a much higher friction than its bled oil in the low speed region, with relative difference in friction becoming larger at higher temperatures. The transition speed after which grease and oil exhibit the same friction is again identified. As was the case for lithium greases, this speed increases with temperature, but in the case of calcium sulphonate complex greases this effect appears more pronounced, so that at the highest temperature of 80 °C the grease and bled oil friction curves do not even start merging within the range of test speeds shown.

3.3. EHD film thickness results

To aid the interpretation of the friction results, the grease film thickness was measured over the same speed range.

The film thickness results for (a) LiPAO, (b) LiEs and (c) CaSMix greases are displayed in Fig. 8 as a representative selection of all film measurements made. For comparison, the theoretical film thickness values for all corresponding base oils are also shown. A thicker film at low speed, when compared to the base oils, was observed for all greases, but important differences in behaviour are evident. LiPAO shows the highest film thickness of all the test greases, despite having the lowest base oil viscosity. It has the highest film thickness at the lowest speed of 10 mm s^{-1}, where it is more than 5000% larger than that of the corresponding base oil. As the speed increases, the film reduces and the minimum is reached at a speed of about 300 mm s^{-1}, after which the film thickness starts to increase again. LiPAO film thickness remains higher than that of its base oil over the whole speed range tested here. LiEs grease film thickness is much lower than that of the LiPAO grease at all speeds. The general trends are the same, with LiEs grease film thickness being much greater than that of its base oil at low speeds, and gradually reducing as the speed is increased. However, in LiEs the speed of transition into the EHL-like behaviour that may be expected from its base oil alone is already reached at around 10 mm s^{-1}. This 'V shaped' film thickness versus speed curve has been observed in earlier grease studies [27,23]. In contrast to the lithium based greases, CaSMix film thickness does not exhibit the 'V-shape' behaviour. Instead, its film thickness constantly increases with speed within the test speed range. Similar behaviour was observed with the other calcium sulphonate complex grease, CaSMi, tested here. Once again the grease film thickness is higher than that expected from the corresponding base oil in the low speed range, below about 200 mm s^{-1}.

3.4. Correlation between friction coefficient and film thickness

The relationship between the film thickness and friction was investigated by focussing on the two extreme cases of CasMix and LiPAO greases, having the highest and lowest friction coefficients respectively.

Measured values of film thickness and friction for CaSMix grease and its bled oil are both plotted against the entrainment speed in Fig. 9(a). A similar plot for LiPAO is shown in Fig. 9(b). The two dashed horizontal lines mark the approximate boundaries between the three lubrication regimes: full film ($\Lambda > 3$), mixed ($1 < \Lambda < 3$) and boundary lubrication ($\Lambda < 1$). Clear parallels

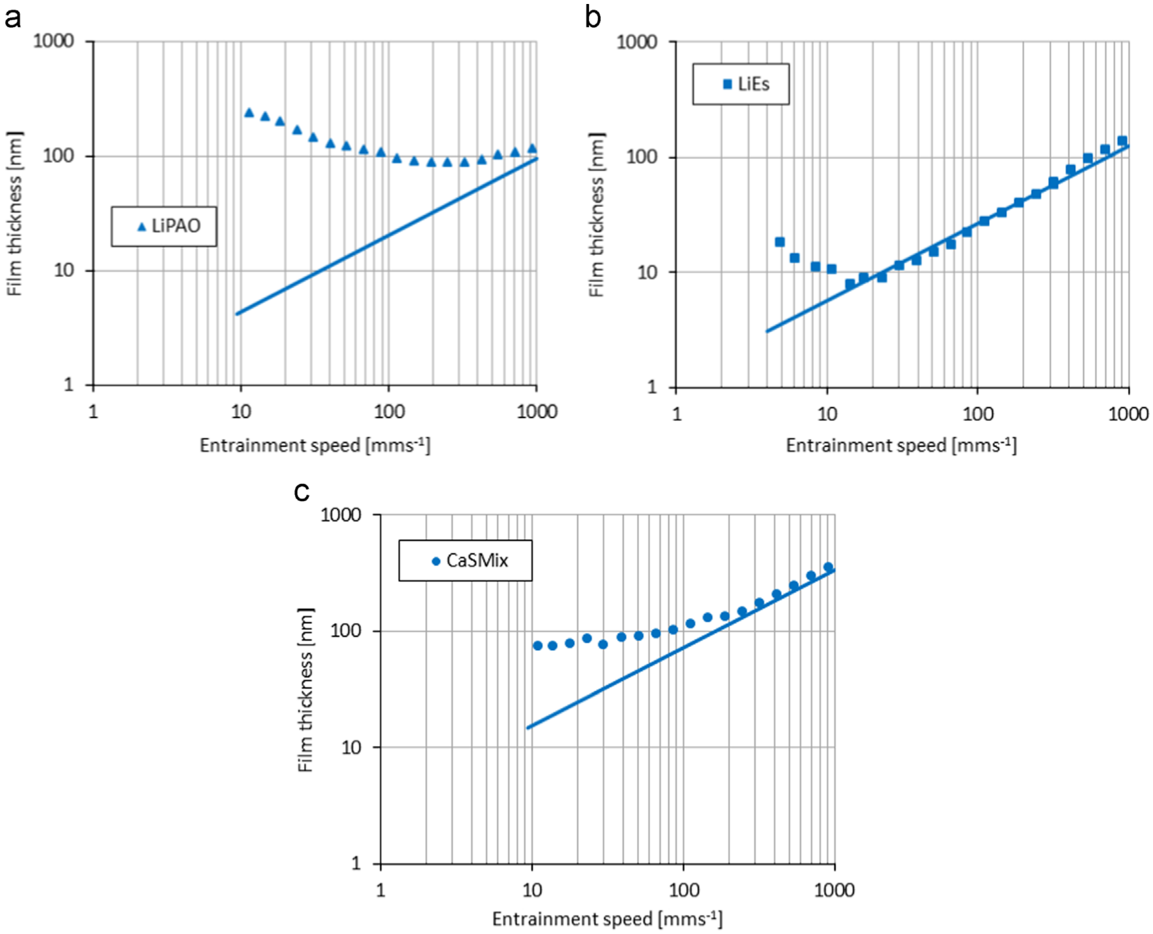

Fig. 8. LiPAO (a), LiEs (b) and CaSMix (c) film thickness and base oil film thickness prediction (solid line) plotted against entrainment speed.

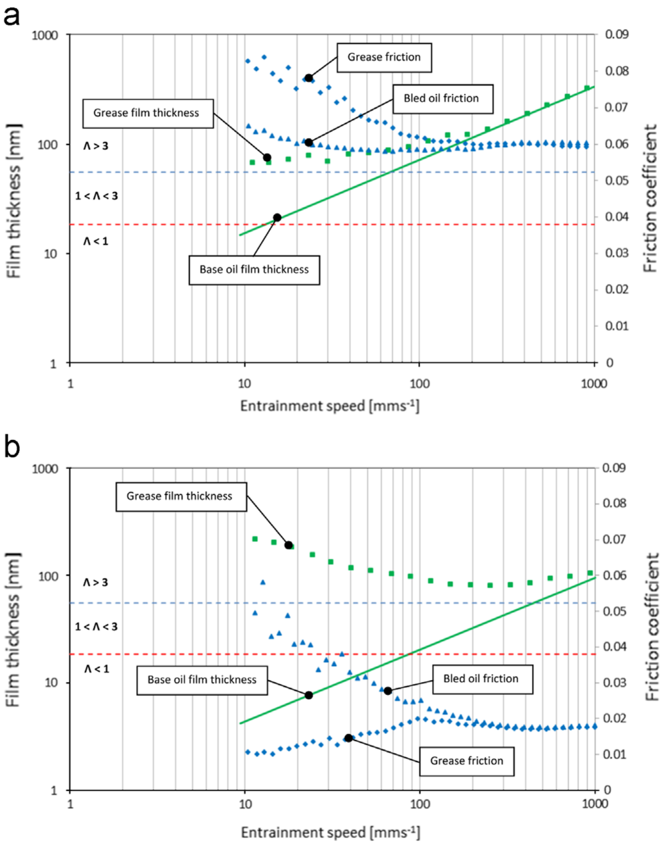

Fig. 9. Correlation of friction and film thickness for CaSMix (a) and LiPAO (b) and their base and bled oils.

between friction and film thickness behaviour for CaSMix grease are evident in Fig. 9(a). Both friction and film thickness curves for grease and bled/base oil start overlapping at the same entrainment speed of about 200 mm s^{-1}. The CaSMix grease forms a film that is thick enough for the surfaces to be fully separated even at lowest speeds, unlike its base oil. However, the region where grease produces this relatively thick film coincides with the region where grease friction is significantly higher than that of the bled oil. This clearly suggests that the composition and morphology of the thick film at low speeds is responsible for the higher friction.

A somewhat contrasting behaviour of LiPAO grease is evident in Fig. 9(b). The grease film thickness is again high enough, even at low speeds and despite the very low viscosity of its base oil, to keep the contact in the full film regime throughout the whole speed range. However, unlike CaSMix grease, the abnormally thick grease film at low speeds results in friction coefficient that is much lower than that of the bled oil within the same low speed range. Furthermore, the film thickness and friction curves for grease and bled oil now do not overlap at the same entrainment speed unlike for CaSMix grease. Instead, at the speed where the grease and bled oil friction curves start to merge (250 mm s^{-1}), LiPAO film thickness is still much higher than that of its base oil. Interestingly, although still higher than for base oil, the grease film thickness goes through an inflexion point at this speed, suggesting a change in the grease lubrication mechanism.

4. Discussion

The results presented in this paper suggest that under fully flooded conditions greases exhibit two distinct operating regions in terms of friction and film thickness.

Firstly, at sufficiently high entrainment speeds the friction and film thickness behaviour of studied greases is generally determined by the properties of their base oils. Figs. 6–9 all show that in this region greases behave the same as what may be expected of their bled/base oil, and therefore the standard EHL theories can be used to predict grease film thickness and traction. For example, the log–log film thickness-speed plots in Fig. 8(b) and (c) follow a straight line in this region, with a slope of approximately 0.7 in accordance with EHL theory. In this region the friction coefficient decreases with increasing test temperature, and therefore decreasing oil viscosity (Fig. 3), as may be expected since the properties of any given oil play the dominant role here.

Furthermore, the results also show that the absolute value of grease friction in this region cannot be related to the base oil viscosity alone, but that the specific base oil type plays a major role, with synthetic oils providing the lowest friction coefficients (Fig. 4). This is in agreement with earlier work on friction in oil lubrication [28,29]. Greases made with low viscosity synthetic base oil may be expected to provide low friction in the high speed region. Indeed, the two low friction greases tested here, LiEs and LiPAO, are made with very low viscosity synthetic base oils. It should be noted that although such a composition may not ensure low friction under different operating conditions, as discussed below, reduced friction in this high speed region can provide the most significant contribution to the reduction of overall machine power losses.

Secondly, in the low speed region, the grease friction and film thickness behaviour diverges from that of its base oil. This indicates that the contribution of grease thickener becomes significant under these conditions. This conclusion is further supported by the fact that greases generally show two types of behaviour in this region, dependent on the type of thickener present. With this in mind, the tested range of greases can be broadly divided into two groups: lithium and polyurea based greases and calcium sulphonate complex greases. All test greases show a thicker film at low speed compared to their base oils. This behaviour could be associated to either a residual, speed independent film deposited within the rolling track [18], a dynamic accumulation of thickener material entrained in the contact at low speed, or a combination of both. However, clear differences between the two groups of greases in terms of friction and film build-up mechanism are apparent:

- The lithium and polyurea greases display a 'V shaped' film thickness curve: below the transition speed their film thickness increases as the speed decreases. In this case the relative improvement in film thickness at low speeds is much more significant, with up to 500 times thicker films than with corresponding base oils. These thick films also produce lower friction than in the corresponding base oils at low speeds, resulting in 'inverse-Stribeck' behaviour. Friction in the low speed region is affected by temperature, with higher temperatures (lower base oil viscosities) leading to lower friction.

- In the case of calcium sulphonate complex greases, the film thickness settles at a constant value as the entrainment speed is reduced. These greases give higher friction than their bled oils in the low speed region. At the lowest speeds, the level of friction does not seem to be affected by temperature, but as the speed increases towards the 'transition' speed, higher temperatures produce higher friction, in contrast to lithium and polyurea based greases.

It should be noted that these results were obtained using fresh greases, and their behaviour might change after many working hours in a real bearing due to mechanical and thermal degradation [30,7,31].

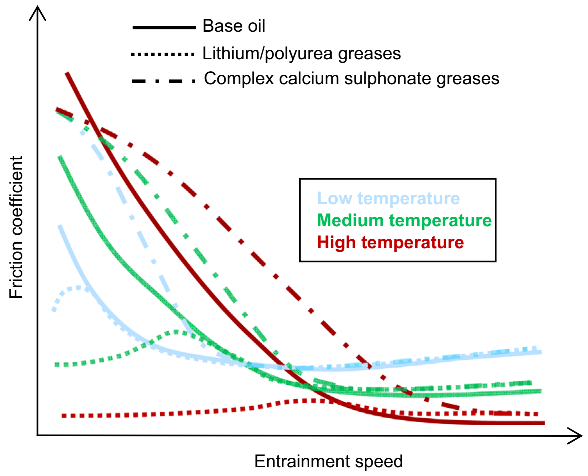

Fig. 10. Friction coefficient with base oil viscosity for lithium/polyurea and calcium sulphonate complex greases.

A schematic representation of the main trends discussed above is shown schematically in Fig. 10.

Since in the current tests the low speed film thickness with both groups of greases described above was generally sufficient to ensure full film regime (Fig. 9), these results point to the fact that factors other than simple Λ ratio govern grease friction at low speeds. Indeed, even when grease is able to move the contact from mixed to full film lubrication regime, the friction may actually increase, as is observed with calcium sulphonate greases. The results therefore suggest that in addition to any influence of Λ ratio, it is the actual nature of the thick grease film that governs the friction at low speeds. The opposite behaviour of the two sets of greases in terms of low speed friction at different temperatures further supports the postulate that their low speed films are of very different nature. The nature of these films is not yet fully understood, but some of the basic properties of significance include roughness, morphology, viscosity and mechanical and chemical properties. Further research into these aspects is being conducted in an attempt to fully explain the mechanisms of grease friction in the low speed region. However, since it is known that the morphological microstructure of lithium and calcium sulphonate complex greases is very different, it is perhaps not entirely surprising that these two sets of greases give dissimilar friction results. Lithium thickener is described as typically consisting of entangled fibres [32,33], while calcium sulphonate complex thickener is a fine dispersion of spherical and agglomerated particles [33]. If thickener material, in the form of soap particles, is able to deposit on the contact surfaces and form a speed-independent residual layer [34], the friction coefficient at low speed, when little oil is available inside the contact, may be expected to in some way depend on thickener morphology.

Given the wide range of greases tested here, current results go some way in indicating potential composition of a low friction grease. Based on the observed results with lubricants tested here, low friction in the high speed region can be achieved by using certain synthetic base oils of low viscosity. For most machines, this high speed region is the one that determines the overall power losses, so ensuring low friction here is of primary concern. The low speed region may be less important in terms of overall energy losses, but the grease here must ensure that lubricant films are thick enough to protect the surfaces from coming into direct contact. This is particularly important when using low viscosity base oils which, without correct choice of other grease components, may quickly result in boundary lubrication as speed is reduced. Based on current results, many greases are able to form such thick films, but lithium and polyurea greases seem to offer further advantage of low friction even at these low speeds.

5. Conclusions

The friction and film thickness behaviour of a series of fully formulated greases, covering a wide range of different base oils and thickeners, was studied on ball-on-disc tribometers. Markedly different friction behaviour is observed for different greases, and this is attributed to their different compositions. By also studying the behaviour of corresponding base and bled oils under the same conditions it has been possible to establish some of the relative influences of individual grease components on friction. All studied greases exhibit two operating regions: the relatively high entrainment speed region where they closely follow the Stribeck-like friction and EHL-like film thickness behaviour of their base oils, and the low speed region where grease friction and film thickness are determined by the combined effect of thickener and oil type. Furthermore the following observations are made:

- In the high speed region, friction is governed by base oil viscosity and base oil type. For a given viscosity, friction is lower in the synthetic base oil greases and for a given oil type, friction reduces with higher temperature (and therefore lower viscosity).
- In the low speed region, all tested greases are able to form a thicker film than their corresponding base oils. However, the film build-up behaviour differs markedly from grease to grease depending on thickener type. With decreasing speed, the film thickness appears to reach a constant value in calcium sulphonate complex greases, while in lithium and polyurea greases the film thickness increases. The corresponding friction behaviour also varies depending on grease composition: lithium and polyurea greases exhibit friction coefficients that are lower than those of their base oils, and reduce with temperature, while calcium sulphonate complex greases produce friction that is higher than that of their base oils and increases with temperature. Given that all greases are able to form thick enough films to ensure full-film conditions even at these low speeds, these observations indicate that at low speed grease friction is governed by the complex nature of the formed protective films rather than simply the Λ ratio and base oil properties.

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