

Brno University of Technology  
Vysoké učení technické v Brně

Faculty of Mechanical Engineering  
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Fakulta strojního inženýrství  
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Odbor Tribologie

# Study of correlation between grease film formations and mechanical losses on various surfaces

[Discourse on the Dissertation Thesis]

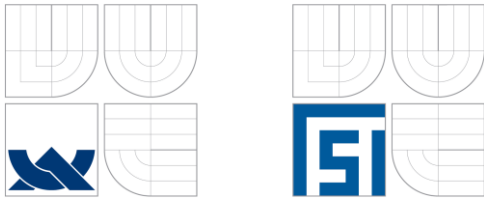
[Pojednání ke státní doktorské zkoušce]

Author: MEng. **Kazumi Sakai**  
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Brno 2016



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## **1 ABSTRACT**

Investigating the correlation between grease formulation and radial ball bearing torque and the lubrication mechanisms is the main objective of this thesis. First, thickener and base oil type dependence on bearing torque will be evaluated. Second, rheological parameters, thickener structures, and film thickness on smooth/textured surfaces will be examined. Based on obtained results, lubrication mechanisms will be proposed. Comprehensive grease formulation influence on radial ball bearing torque and analysis of film thickness on non-smooth surfaces for grease lubrication have not been reported. The expected findings could be significant knowledge for the development of advanced greases featuring energy-saving performance.

## 2 RESEARCH BACKGROUND

Use of lubricants featuring energy-saving property plays a significant role in reducing CO<sub>2</sub> emissions for prevention of the serious global warming. For instance, Holmberg et al. [1] have reported that 33% of fuel chemical energy is consumed by friction loss in the case of a passenger car driving at 60km/h. The impact is not small, therefore, not only liquid lubricants, such as motor oils and industrial lubricants, but also greases have been developed with improved energy-saving properties, such as low friction and torque properties. Greases are used for lubrication of more than 90% of rolling element bearings [2], therefore the industrial significance is high. Recently novel grease products effective in lowering energy consumption have been developed in some grease suppliers, but the detailed mechanisms have not been clarified. The mechanisms of the performance are quite important for not only the persuasion of customers but also further development of grease products. Therefore, the clarification of the influence of grease components on bearing torques is of crucial importance.

There are limited number of publications related to the bearing torque and grease components. In the study with the thrust ball bearings, Cousseau et al. [3, 4] reported commercial greases influence and they introduced a bearing friction model and decomposed a total friction torque into a rolling torque and a sliding torque. The rolling torque was high with greases containing higher viscosity base oils. While, the sliding torque was increased by greases with higher friction coefficient and lower film thickness. By investigating rheological parameters, it was shown that the rolling torque was dependent on the viscosity of the bleed oil and that the sliding torque depended on the specific film thickness with the bleed oil [5]. The following research by Goncalves et al. [6] was conducted for the polypropylene thickened greases. The rolling torque increased with increment of the bearing rotation speed, while the sliding torque decreased. In addition, the grease with large thickener content provided lower sliding torque. As the work on the cylindrical roller bearing, Wikstrom et al. [7] studied greases and operating parameters influences on bearing torques, especially focused on the low temperature region. Regarding grease parameters, base oil types and base oil viscosity were important factors, for instance, poly-alpha-olefin with superior viscosity index to naphthenes provided low starting torque.

For the study of radial ball bearing torque with greases, Oikawa et al. [8] suggested a relationship between the grease yield stress and the bearing torque. They used lithium (Li) type greases with different types of base oils and indicated a grease with higher yield stress caused the channeling in a bearing more easily, and that led to bearing torque reduction. Hokao et al. [9] reported a subsequent study, which indicated higher degree of dispersion of the thickener of the greases related to higher yield stress through the observation of thickener structures by using of AFM (Atomic Force Microscopy). Dong et al. [10] studied base oil viscosity dependence of Li type greases on radial ball bearing torque and the film thickness by using of the electrical potential method. It was confirmed that the grease forming higher film thickness reduced the bearing friction torque under the low bearing rotation speed due to higher viscosity base oil. Heyer et al. [11] measured the friction and the bearing torque for greases with different penetrations and temperatures using a modified low-temperature torque tester for ball bearings. The yield stress of greases influenced on the friction and the temperature effect for only one type grease was discussed for the

bearing torque. In the previous study, authors [12] investigated radial ball bearing torque with several types of greases with different types of base oils and thickeners. Higher film thickness formed the grease with thin and long thickener fiber structures reduced bearing torque. Also the tendency of thickener type corresponded to the grease flows observed by the fluorescence technique, Li complex type grease showed higher existence of lubricant in the inlet of EHL contact area.

Considering bearing operating conditions, the study of EHL under grease lubrication should be essential. Venner et al. [13, 14] estimated the central film thickness decay in ball and roller bearings by numerical simulations of grease flows. They observed that grease film thickness in a bearing decrease significantly and the bearing be operated under starved lubrication, therefore, film thickness under not only fully flooded but also starved conditions should be considered. Cann et al. [15] analyzed grease film thickness related rolling element bearings. Furthermore, Cann [16, 17] reported typical grease film thickness behaviors under fully flooded and starved conditions. Under fully flooded conditions and low speed area, grease thickener lumps pass through the contact and form greater film thickness than the base oil itself. Cousseau et al. [18] also indicated greases and bleed oils from the greases form similar film thicknesses under fully flooded conditions. Recently, it was reported that polymer thickened greases show also quite thick film thickness in low-medium speed range [19]. Laurentis et al. [20] compared the film thickness and friction coefficient of commercial greases for bearing. The friction was governed by base oil types in the high speed region and depended on the thickener type in the low speed region. Kaneta et al. [21] investigated the film thicknesses for different types of urea greases. The thickness largely depended on thickener types and the thickener structures seemed to influence on grease movements related to starvations. Cen et al. [22] observed the film thicknesses of greases in a full bearing by using a capacitance method and obtained a good correlation with the results of a single contact condition of optical interferometry method.

As mentioned above, the overview of researches related with bearing torque with grease lubrication are shown. In the next chapter, the detailed explanations for each research fields will be conducted.

### 3 STATE OF THE ART REVIEW

#### 3.1 Bearing torque under grease lubrication

The publications related to bearing torque can be roughly divided to thrust bearing and radial bearing types. Representative papers are introduced as follows.

**Cousseau, T., Graca, B., Campos, A., and Seabra, J.**, “Friction Torque in Grease Lubricated Thrust Ball Bearings,” *Tribology International*, 44, 2011, 523-531. [3]

**Cousseau, T., Graca, B. M., Campos, A. V., and Seabra, J. H. O.**, “Influence of Grease Rheology on Thrust Ball Bearings Friction Torque,” *Tribology International*, 46, 2012, 106-113. [5]

Thrust ball bearings lubricated with several commercial greases were tested on a modified Four-Ball Machine, where the Four-Ball arrangement was replaced by a bearing assembly (Fig.1). A rolling bearing friction torque model was introduced and decomposed a total friction torque into a rolling torque and a sliding torque. The relationship each torque and grease parameters such as rheology and film thickness were evaluated.

#### Results

The measured values of the bearing friction torque are plotted against the bearing rotational speed in Fig.2. Also, the SKF rolling bearing friction torque model (Eq.1) was introduced for the calculation of the ratios of rolling and sliding torque for total friction torque (Fig. 2). Greases containing higher viscosity base oils (MG1 and MG2) generated higher rolling torque.

They also studied the influence of grease rheological parameter and proposed that the rolling torque was dependent on the viscosity of the bleed oil of the grease (Fig.3 left) and the sliding torque was dependent on the specific film thickness with the bleed oil (Fig. 3 right). That suggested that the sliding torque increased by higher friction coefficient and lower film thickness, especially related to contact replenishment and starvation.

$$M_{\text{total}} = \underbrace{\varphi_{\text{ish}} \varphi_{\text{rs}} (G_{\text{rr}} (vn)^{0.6})}_{M_{\text{r}}} + \underbrace{(G_{\text{sl}} (\mu_{\text{sl}}))}_{M_{\text{sl}}} + \underbrace{(V_M K_{\text{ball}} d_m^5 n^2)}_{M_{\text{drag}}} + \underbrace{(K_{\text{S1}} d_s^{\beta} + K_{\text{S2}})}_{M_{\text{seal}}} \quad (1)$$

#### Conclusions

The bearing rolling torque is mainly dependent on the viscosity of the bleed oil and on the replenishment of the contact. The bearing sliding torque is mainly dependent on the specific film thickness of the ball-race contact and on the base oil type.

Even though the studies are related to thrust bearing type, they used the model to decompose the total friction torque into the rolling and the sliding ones, and suggested a trade-off relationship in reducing the both torque. Since using lowered viscosity base oil for a grease could reduce the rolling torque, however, that might increase the sliding torque due to lower film thickness and higher friction coefficient. In addition, they indicated that the essence of the bearing torque with greases exist on the bleeding oil of the grease not grease itself.

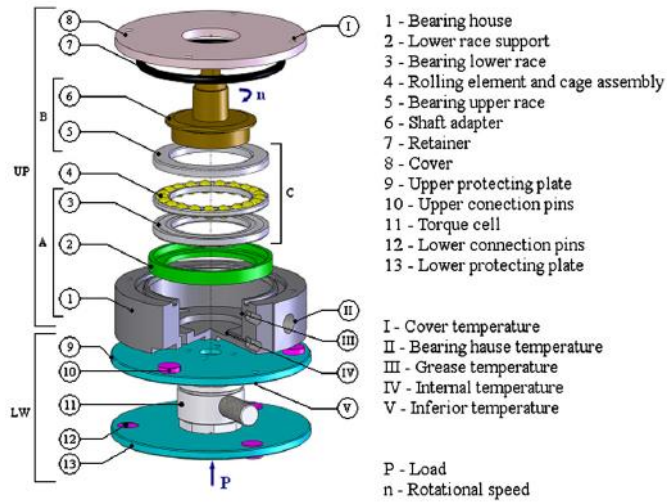


Fig. 1 Schematic view of the rolling bearing assembly with torque cell [3]

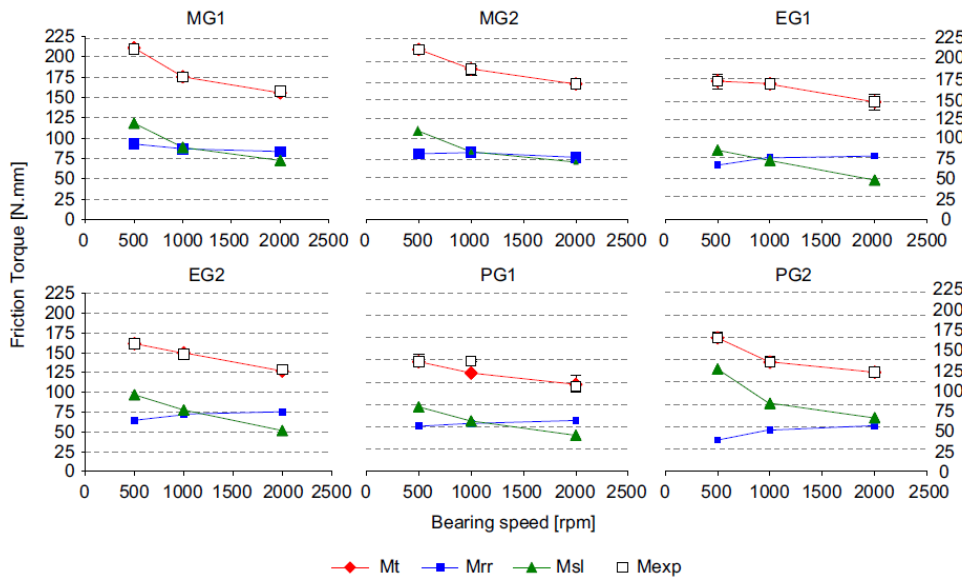


Fig. 2 Experimental torque ( $M_{exp}$ ), rolling ( $M_{rr}$ ), sliding ( $M_{sl}$ ) and total torque ( $M_t$ ) calculated vs. rotational speed [3]

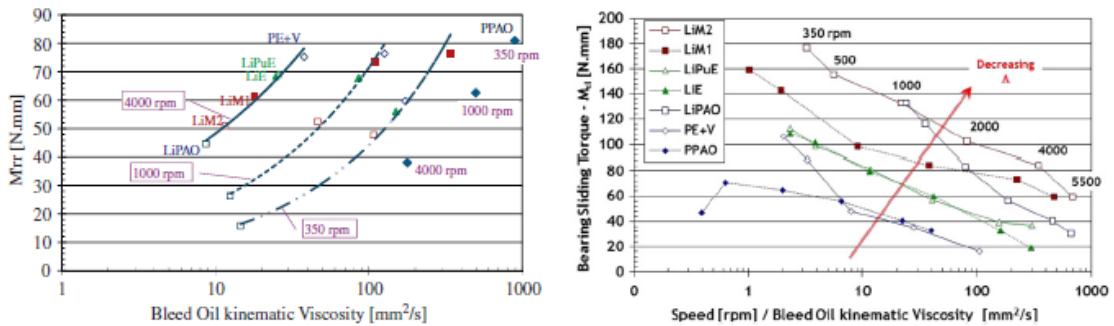


Fig. 3 (left) Bearing rolling torque vs. bleed oil viscosity [5].

Fig. 3 (right) Bearing sliding torque vs. speed / bleed oil viscosity [5].

**Oikawa, E., Inami, N., Hokao, M., Yokouchi, A., and Sugimura, J.,** “Bearing Torque Characteristics of Lithium Soap Greases with Some Synthetic Base Oils,” *Proc IMechE Part J: J Engineering Tribology*, 226, 6, 2012, 575-583. [8]

**Hokao, M., Inami, N., Watabe, E., Yokouchi, A., and Sugimura, J.,** “A Study of the Structure Formed by Thickeners of Greases Using Atomic Force Microscope,” *Tribology Online*, 8, 1, 2013, 76-82. [9]

As studies on radial ball bearing torque, the lithium (Li) type thickener greases with different base oils were used. The influence of rheological properties such as yield stress on the torque characteristics were evaluated. For the investigation of the correlation of the yield stress of the greases and other parameters, the thickener structures of greases were tested using atomic force microscope (AFM).

### Results

Test greases were composed of lithium 12-hydroxystearate thickener and five types of base oils of poly alpha olefin (PAO), carbonate ester (COE), polyol ester (POE), and two types of poly alkylene glycol (PAG) with the same range of viscosity. Deep-groove radial ball bearing 6305 were used and the initial torque and the steady-state torque were measured for the constant rotation speed. As shown in Fig. 4 left, PAO and PAG-3 greases showed lower initial torques and the torques stayed almost flat. On the contrary, the torque with POE grease significantly decreased at the initial stage of duration before it became constant. The torque decrease from initial torque is plotted in Fig.4 right. It shows that the grease with higher yield stress shows larger torque decrease and that the grease with higher yield stress tends to show channeling, which is effective in torque reduction.

The thickener structures of greases were observed by AFM (Fig. 5 left). As the parameters for AFM images, size, shape, number, density, and distribution were evaluated. The density and distribution related to the grease yield stress. In addition, the factor of grease dispersion showed good correlation with the yield stress (Fig. 5 right).

### Conclusions

The greases with higher yield stress tend to show channeling, and provide lower steady-state torque, because these greases are not easily entrained contact area. The greases with lower yield stress tend to show churning and maintain high steady-state torque, because a large volume of grease is remained balls and races. AFM images for lithium soap greases indicated greases with a larger value of the degree of dispersion have higher yield stress.

Oikawa et al. proposed the yield stress of greases as an important factor for radial ball bearing torque. They emphasize the rheological parameter or the movement of grease itself, different from the bleed oil of greases as Seabra et al. proposed. However, the effect of the yield stress should be considered in different types of thickeners.

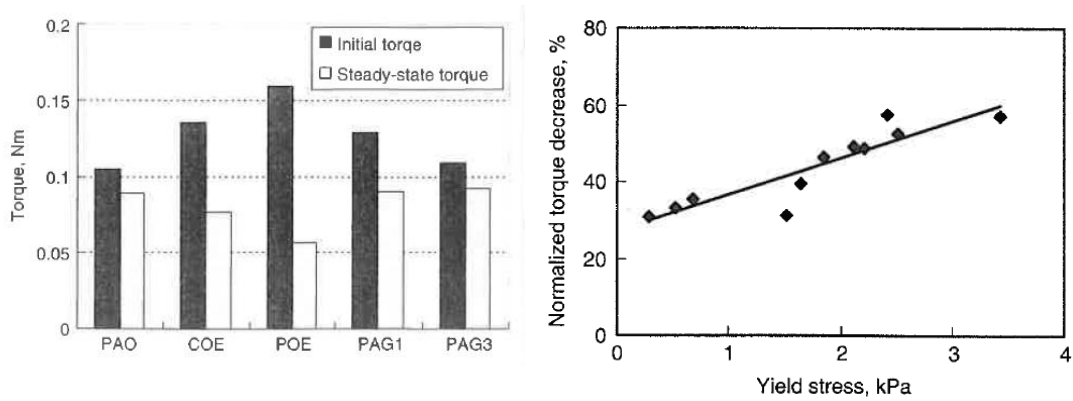


Fig. 4 (left) Initial torque and steady-state torque of tested greases [8]

Fig. 4 (right) Relationship between yield stress and torque decrease [8]

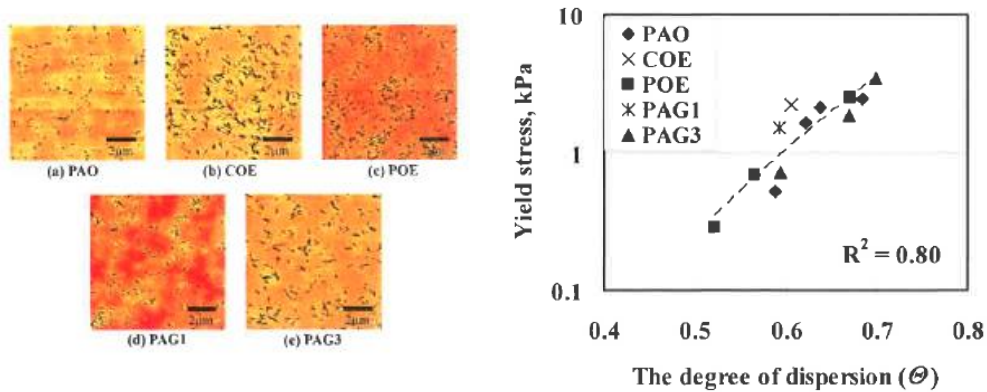


Fig. 5 (left) AFM images of the greases with different type of base oil [9]

Fig. 5 (right) Relationship between the degree of dispersion and yield stress [9]

**Dong, D., Komoriya, T., Endo, T., and Kimura, Y.,** “Formation of EHL Film with Grease in Ball Bearings at Low Speeds,” *Journal of Japanese Society of Tribologist*, 57, 8, 2012, 568-574 (in Japanese). [10]

The dependence of base oil viscosity of Li type greases on film thickness were measured by the electrical potential method. The correlation with the radial deep-grooved ball bearing friction torque were confirmed with simultaneous monitoring of film thickness and bearing torque.

## Results

6204 radial deep grooved ball bearings were used for measurements. Figure 6 left shows the schematic image of measuring film thickness by the electrical potential method and measuring bearing friction torque. The tested grease composed of lithium 12-hydroxystearate thickener and PAO with different viscosity.

Figure 6 right shows that higher film thickness provided by the grease with higher viscosity oil under slow bearing rotation speed decrease the bearing friction torque. Under higher rotation speed range, the torque for each grease was similar. The results suggests that thick grease film thickness under slow rotation speed prevent metal contacts and reduce the sliding resistance.

## Conclusions

Thick grease film thickness under slow rotation speed was confirmed by electrical potential method, and the results correspond to the results from optical interferometry method. The thick film thickness of greases is attributed to the viscosity increase under the slow rotation speed. The thick film thickness prevents metal contacts in the bearing and reduces friction torque.

Dong et al. indicated higher film thickness under slow bearing rotation lower friction torque. This is a reasonable finding but should be confirmed in different types of base oils and thickeners.

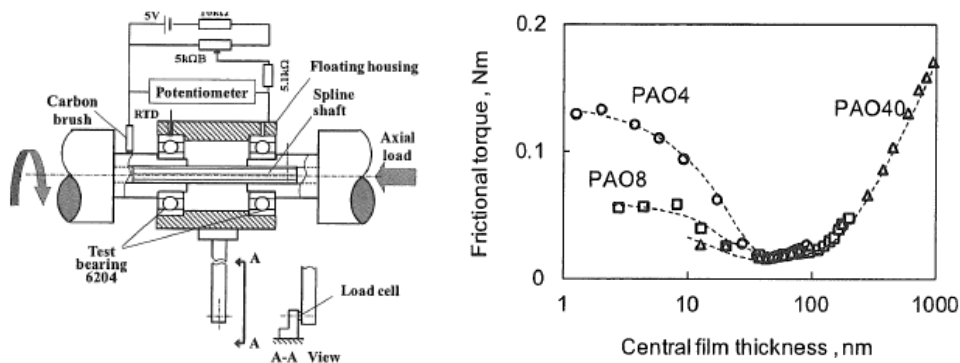


Fig. 6 (left) Schematic diagram of experimental apparatus [10]

Fig. 6 (right) Variation of frictional torque with film thickness [10]

**Sakai, K., Tokumo, Y., Ayame, Y., Shitara, Y., Tanaka, H., and Sugimura, J.,** "Effect of Formulation of Li Greases on Their Flow and Ball bearing Torque," *Tribology Online*, 11, 2, 2016, 168-173. [12]

The effect of base oil type and thickener type on radial ball bearing torque were evaluated for Li type greases. For the clarification of the cause of the torque difference among greases, rheological parameters and film thickness were measured. The fluorescence technique was introduced for the observation of grease flow behaviors around EHL contact area.

## Results

The tested greases composed of mineral oil or PAO for the base oils, Li complex or single Li soap for the thickeners, and pyrene for the fluorescence dye. The bearing friction torque behaviors under grease lubrication for each bearing rotation speed are shown in Fig. 7 left. Grease-A (mineral oil and Li complex) showed the lowest torque especially under higher rotation speed. After the measurement of the film thickness for each grease, it seemed that grease with higher

film thickness related to the lower bearing torque as shown in Fig.7 right. In addition, grease flow behaviors were observed by fluorescence technique. Grease-A (Li-complex) showed the higher lubricant existence in the EHL inlet area under dynamic conditions compared with Grease-B (single Li soap), as shown in Fig. 8. The reason might exist on the thickener fiber structure. In other words, thin and long fibers of Li complex enable the grease to be entrained to the contact vicinity.

**Conclusions**

The present results suggest that the bearing torque depended on the grease base oil and thickener types. Grease film thickness and around EHL region seem important. The fluorescence observation demonstrated that Grease-A, G-I base oil and Li-complex thickener, which provides lower bearing torque, showed higher film thickness and superior flow behavior especially in the inlet of EHL region. The thin and long fiber structure of Li-complex thickener contributed to the improvement of film thickness and flow behaviors as the grease was entrained into the contact area.

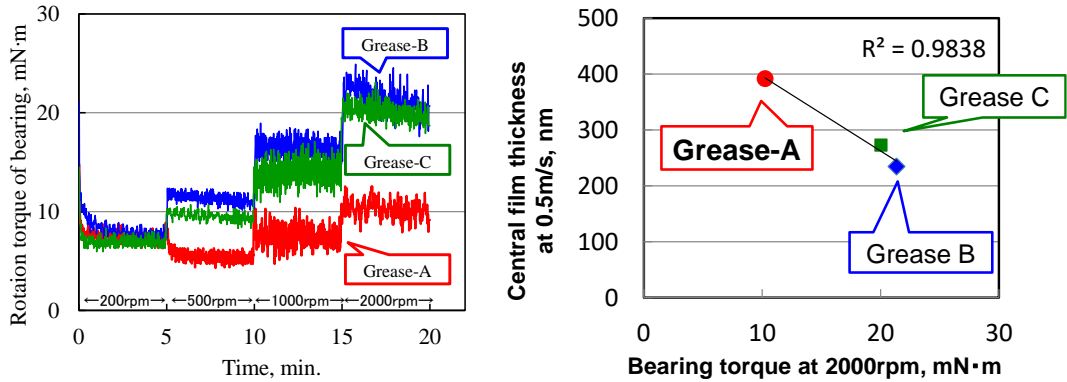


Fig. 7 (left) Friction torques of ball bearings using greases [12]

Fig. 7 (right) Relationship between the bearing torque and grease film thickness

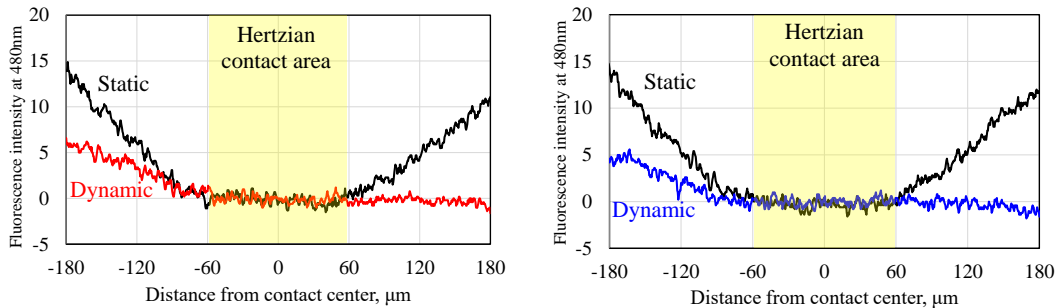


Fig. 8 (left) Line profile of fluorescence (Li-complex type grease) [12]

Fig. 8 (right) Line profile of fluorescence (single Li soap grease) [12]

### 3.2 Grease behaviors in bearings

In order to understand the grease influence on the bearing torque, grease behaviors in bearings are also important. As approaches of grease film thickness evaluation in bearings, numerical simulation and experimental measurement are introduced here.

**Venner, C. H., van Zoelen, M. T., and Lugt, P. M.**, “Thin Layer Flow and Film Decay Modeling for Grease Lubricated Rolling Bearings,” *Tribology International*, 47, 2012, 175-187. [13]

**van Zoelen, M. T., Venner, C. H., and Lugt, P. M.**, “The Prediction of Contact Pressure–Induced Film Thickness Decay in Starved Lubricated Rolling Bearings,” *Tribology Transactions*, 53, 2010, 831-841. [14]

In order to understand the grease behaviors in bearings, a theoretical prediction model for film thickness in a bearing has been developed. The film thickness decay related to the starvation phenomenon for each conditions was evaluated.

#### Results

Interferometric images of the full contact region are shown associated with the decay (Fig. 9). The images show the characteristic butterfly shape of the flooded region characterizing a heavily starved contact. The analyses for a 22317 spherical roller bearing and a 209 deep groove ball bearing were compared in Table 1 and the film thickness distribution is shown in Fig. 10. The decay time depended on the bearing speed; the higher the speed, the longer the decay time. The predicted decay time for the spherical bearing was larger than for the ball bearing. The influence of the bearing radial load was found to be small.

#### Conclusions

The model predicts that layer thickness decay periods are far shorter than the operation periods of bearings commonly found in practice. The results show that a bearing cannot sustain an adequate layer of base oil on the running track unless significant replenishment takes place.

Therefore, not only fully flooded condition but also starved one should be considered in order to understand the bearing torque under grease lubrication.

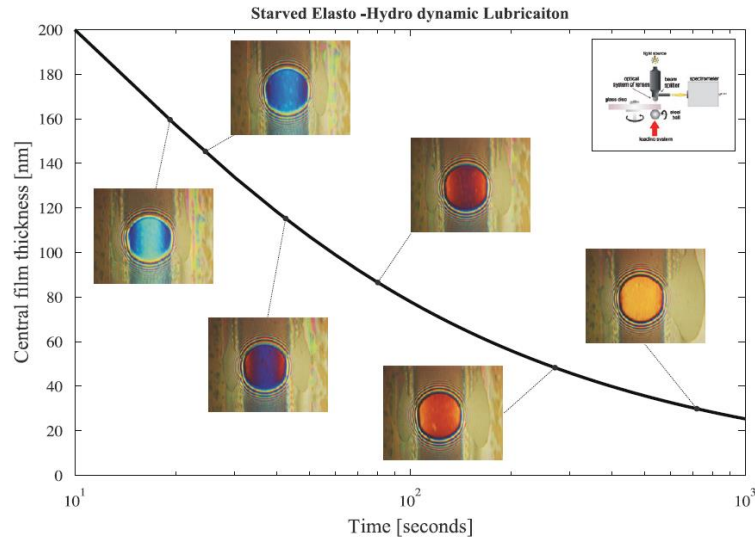


Fig. 9 Central film thickness decay in a starved circular EHL contact as a function of time [13].

Table 1 Parameters and central film thickness decay times for the deep groove ball bearing 209 and the spherical roller bearing 22317 [14]

Case Number:	Spherical Roller Bearing 22317					Deep Groove Ball Bearing 209					Unit	
	1	2	3	4	5	6	7	8	9	10		
Radial load	$F_r$	10	10	10	5	2.5	10	10	10	5	2.5	kN
Rotational speed raceway	$\Omega_i$	750	1,500	3,000	3,000	3,000	1,500	3,000	6,000	6,000	6,000	rpm
Contact speed	$u_m$	2.56	5.11	10.2	10.2	10.2	2.46	4.91	9.82	9.82	9.82	m/s
Centrifugal load	$F_c$	5.52	22.1	88.3	88.3	88.3	0.27	1.09	4.34	4.34	4.34	N
Maximum static load	$F_{max}$	4.98	4.98	4.98	2.82	1.62	5.07	5.07	5.07	2.59	1.34	kN
Load distribution factor	$\epsilon$	0.16	0.16	0.16	0.12	0.09	0.44	0.44	0.44	0.41	0.38	—
Maximum Hertzian pressure, $F = F_{max}$	$p_h$	1.23	1.23	1.23	1.02	0.85	3.21	3.21	3.21	2.57	2.06	GPa
Max. half length inner raceway contact	$a$	0.220	0.220	0.220	0.182	0.151	0.285	0.285	0.285	0.228	0.183	mm
Max. half width inner raceway contact	$b$	8.80	8.80	8.80	7.29	6.06	2.64	2.64	2.64	2.12	1.70	mm
Fully flooded central film thickness inner raceway, $\psi=0$	$h_{off}$	122	194	309	321	333	92	147	234	245	256	nm
Decay time	$t_{cr}$	1.8	2.7	4.1	4.0	3.8	0.057	0.086	0.127	0.118	0.110	h

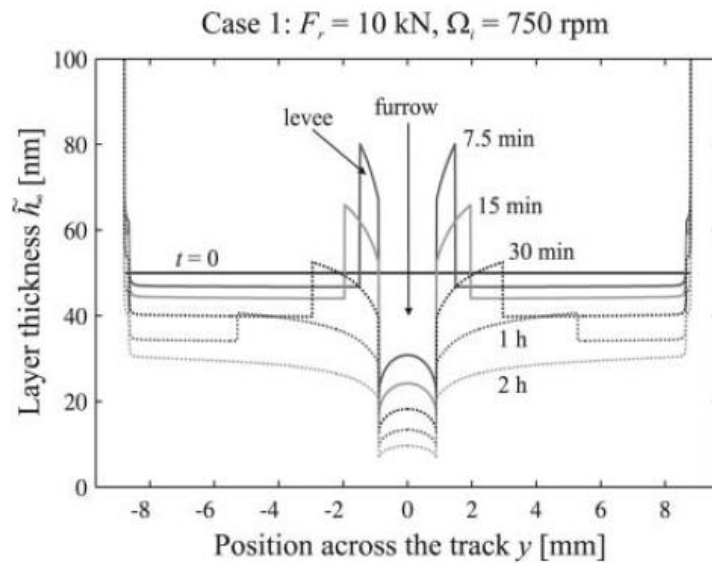


Fig. 10 Layer thickness distribution for spherical roller bearing 22317 [14].

**Cen, H., Lugt, P. M., and Morales-Espejel, G.,** “On the Film Thickness of Grease-Lubricated Contacts at Low Speeds,” *Tribology transactions*, 57, 2014, 668-678. [22]

**Morales-Espejel, G. E., Lugt, P. M., Pasaribu, H. R., and Cen, H.,** “Film Thickness in Grease Lubricated Slow Rotating Rolling Bearings,” *Tribology International*, 74, 2014, 7-19. [23]

Film thickness measurements in grease lubrication were conducted for different greases. Not only the optical interferometry technique but also electrical capacitance method using rotating bearing (Fig. 12) in fully flooded condition were used.

**Results**

Grease film thickness results measured using optical interferometry technique showed substantially thicker film thickness respect to its base oil in fully flooded and low speed conditions. At higher speeds, the film thickness versus speed relation follows the conventional EHL behavior. Two greases were selected to be tested in a full bearing tester. By using dimensionless film thickness parameter, the film thickness behaviors corresponded in both the full bearing tester and the optical interferometry tester.

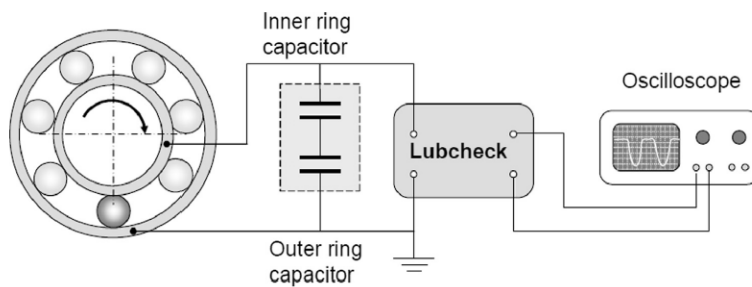


Fig. 11 Illustration of the full bearing tester [22]

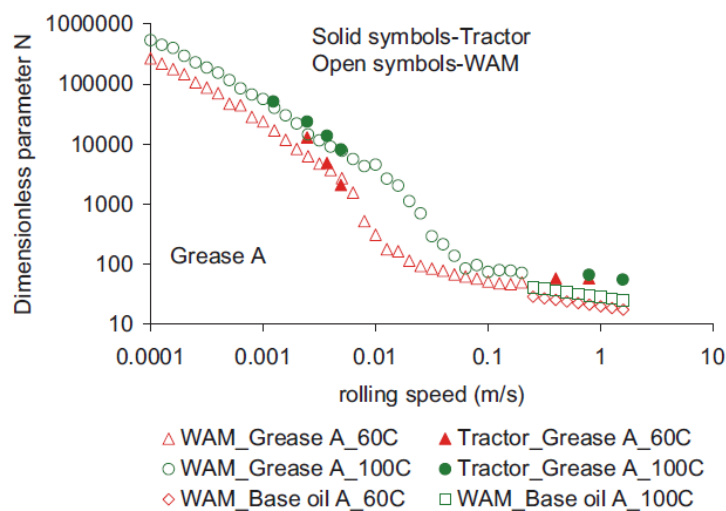


Fig. 12 Dimensionless film thickness parameter N comparison for Grease A [22]

## Conclusion

The full bearing using greases results confirmed the V-shaped curve for the relationship between film thickness and speed. The grease film thickness at higher speeds can be predicted using base oil properties. A dimensionless film thickness parameter was introduced to compare the results from a single contact and full bearing test.

### 3.3 EHL Film thickness under grease lubrication

Considering operating conditions of bearing, grease behaviors under EHL should be focused as shown above literatures. Observation of film thickness formed by greases have been reported as representative analyses of grease behaviors in bearings. The lubricating conditions are roughly divided into two, fully flooded and starved. The grease typical behavior was studied by Cann as follows. Also, the behaviors of grease bleed oil is introduced in this section.

**Cann, P., and Lubrecht, A. A.**, “An Analysis of the Mechanisms of Grease Lubrication in Rolling Element Bearings,” *Lubrication Science*, 11-3, 1999, 227-245. [15]

**Cann, P.**, “Starved Grease Lubrication of Rolling Contacts,” *Tribology Transactions*, 42, 4, 1999, 867-873. [16]

In a ball-on-disk contact, a grease is pushed away with disk rotations, different from oil (Fig. 13 left). The influence of the operating conditions and grease parameters on the film thickness in starved conditions.

## Results

Tested greases were composed of paraffinic mineral oils and lithium 12-hydroxystearate thickener. The dependence of base oil viscosity, thickener content, and operating conditions were evaluated. Film thickness was measured using optical interferometry technique. Under fully flooded condition and lower rolling speed, grease thickener lumps pass through the contacts and augment the film thickness compared with the base oil (Fig. 13 right). In this region, measurements fluctuate wildly. As speed increases, the thickness decreases and then climbed again. At higher speeds, the behavior is similar to conventional EHL film thickness of base oil.

Under starved condition, the film thickness decay was observed through disk rotations. The degree of starvation increases with increasing base oil viscosity, thickener content, and rolling speed. The difference between fully flooded and starvation decreases with increasing temperature (Fig. 14).

## Conclusions

1. Fully flooded results: Film thickness increases with thickener content and base oil viscosity. At low rolling speeds thickener lumps pass through the contact distorting the EHL film. At higher speeds, the behavior disappeared and approached to the base oil film thickness.
2. Starvation results: The degree of starvation increases with increasing base oil viscosity, thickener content (decreasing oil bleed), and rolling speed. It decreases with increasing temperature.

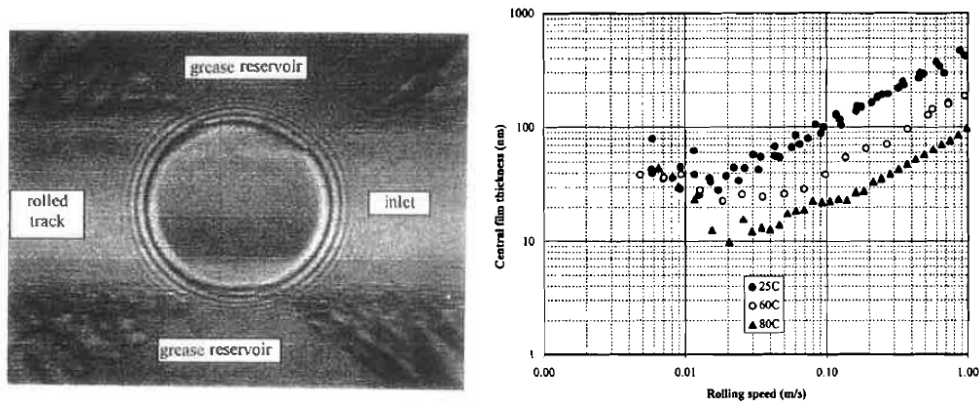


Fig. 13 (left) Photograph of a starved grease lubricated contact [15]  
 Fig. 13 (right) Comparison of fully flooded film thickness results at different temperatures for 5% 30 cSt greases [16]

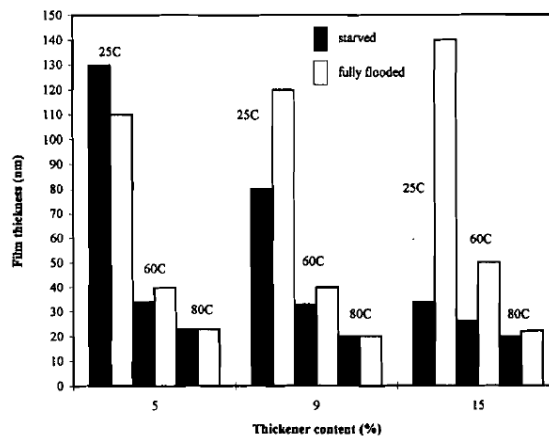


Fig. 14 Comparison of starved and fully flooded film thickness for a grease [16]

Cousseau, T., Bjorling, M., Graca, B., Campos, A., Seabra, J., and Larsson, R., "Film Thickness in a Ball-on-Disk Contact Lubricated with Greases, Bleed Oils and Base Oils," *Tribology International*, 53, 2012, 53-60. [18]

Different type greases and their bleed oils were compared in terms of film thickness in a ball-on-disk test rig through optical interferometry under fully flooded conditions. The theoretical values calculated according to Hamrock's equation for base oil and bleed oil were compared to experimental values.

### Results

Film thickness were observed by using optical interferometry method under fully flooded conditions and in higher speed range. Three tested greases were composed of different base oils (mineral oil, ester, and PAO) and different thickeners (Li, Li/Ca, and polypropylene).

Greases and their bleed oils showed higher film thickness compared with their base oils (Fig. 15). Most greases and the corresponding bleed oils generate similar film thickness values. However, the film thickness differences between base

oils and bleed oils depended on their types, especially, PAO + polypropylene thickener grease showed large difference.

### Conclusions

Greases and the corresponding bleed oils generate similar film thickness values under fully flooded conditions, and their values are higher than their base oils. The difference is assigned to the thickener type and concentration, base oil viscosity, additive package, and so on.

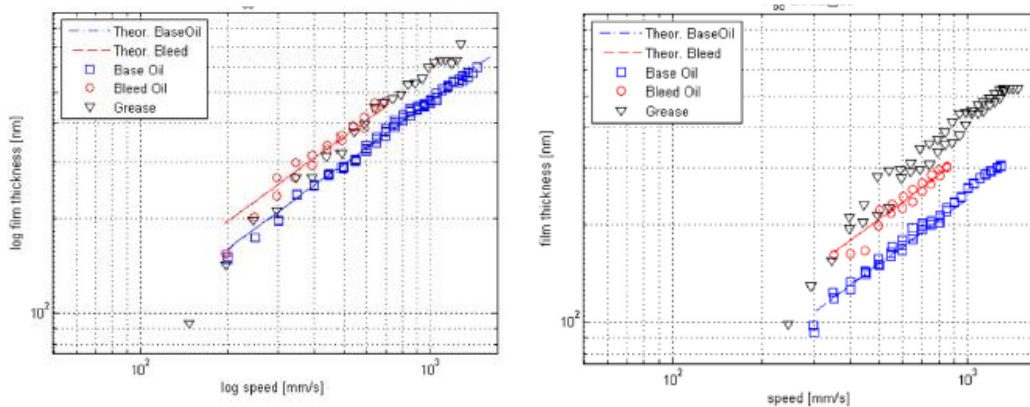


Fig. 15 (left) Film thickness for lithium thickener type grease at 60°C [18]

Fig. 15 (right) Film thickness for lithium/calcium thickener type grease at 60°C [18]

### 3.4 Chemical analysis of grease film thickness

The studies of EHL film analysis have been reported and the information could be important for bearing lubrications. The representative approach is the observation by microscopic FT-IR (Fourier Transform Infrared Spectroscopy) technique as follows.

**Cann, P. M.**, “Grease Lubrication of Rolling Element Bearings – Role of the Grease Thickener,” *Lubrication Science*, 19, 2007, 183-196. [24]

The contribution of grease thickener to lubricant film formation was examined. Lubricant film thickness and friction were measured different grease thickener types in a bearing simulation device. The thickener deposition was confirmed by IR analysis.

### Results

After the friction tests using MTM (Mini-Traction Machine) device, IR analysis of lubricant films in the rolled track on the MTM disk was performed. The greases tested for IR analysis were model LiXM grease (Mineral oil and Li complex thickener) and commercial CaSul grease (unknown base oil and calcium sulphonate thickener). Grease formed thick lubrication film at high temperature or low speeds and improved lubrication. The thickener influenced oil release indirectly and augmented the film thickness. Film related thickeners appeared to be a deposited solid layer, 40-100nm thickness (Fig.16). IR spectra shows that the film in track contains a much high thickener content as shown by the relative intensity of peaks at

1580 and 1560  $\text{cm}^{-1}$  associated with the carboxylate asymmetric stretch vibration (Fig. 17).

### Conclusions

Thickener augments the EHL film thickness. The film physically deposited 'solid' layer (40-100nm) can maintain surface separation when the surfaces are stationary. IR spectroscopic analysis has indicated a high thickener concentration.

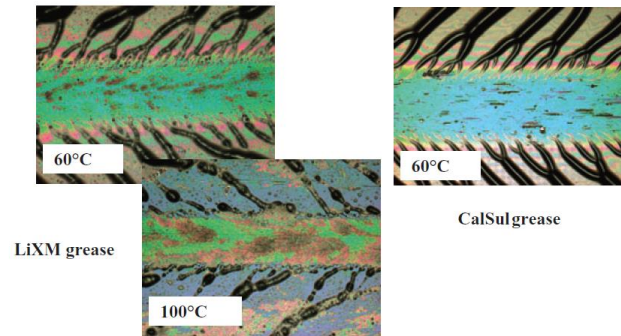


Fig. 16 Microphotographs taken from the rolled track on the glass disc for model (LiXM) and commercial (CaSul) greases [24].

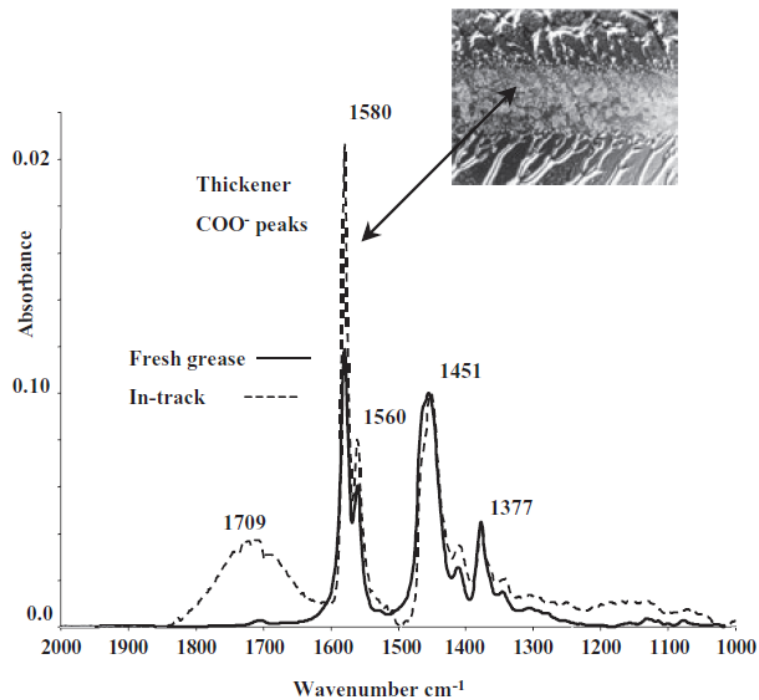


Fig. 17 Infrared spectra for fresh grease and from the film in the rolled track for LiXM grease [24].

**Cann, P. M. and Spikes, H. A.**, “In Lubro Studies of Lubricants in EHD Contacts Using FTIR Absorption Spectroscopy,” *Tribology Transactions*. 34, 2, 1991, 248-256. [25]

**Hoshi, Y., Takiwatari, K., Nanao, H., Yashiro, H., and Mori, S.**, “In Situ Observation of EHL Films of Greases by a Micro Infrared Spectroscopy,” *Journal of Japanese Society of Tribologist*, 60, 2, 2015, 153-159(in Japanese). [26]

Cann et al. reported IR spectra observation from within and around an operating EHD contact. Hoshi et al. studied the distribution of each absorbance peak for different thickener type greases using steel ball / silicon disk tribometer. Silicon disk enabled to observe the lower wave length area ( $< 2000\text{cm}^{-1}$ ), such as C=O stretch vibration. Thickener behaviors in and around EHL contact area were compared.

### Results

In situ observation of EHL film by micro IR analysis was conducted using a ball-on-disk tribometer. The ball was steel and the disk was single crystal silicon. In contrast, conventional sapphire disk absorbs the wavelength less than  $2000\text{cm}^{-1}$ , therefore, only higher wavelength, such as C-H, N-H, and O-H vibrations can be observed. Silicon disk transmits wavelength less than  $2000\text{cm}^{-1}$ , and enables to observe C=O vibration. Tested greases were Li grease (Li stearate thickener) and urea grease (Aromatic diurea thickener) using PAO base oil commonly.

Fig. 18 compares IR spectra of each grease from the inlet to the center of EHL contact area. C-H absorbance (base oil) decreases in the center of contact area. C=O absorbance (thickener) of Li grease decreases similarly, however that of urea grease remains. N-H absorbance (urea thickener) also keeps the intensity in the center of contact area. Therefore, in the EHL contact areas, thickener concentration of Li type grease decreased but that of urea type grease increased as illustrated in Fig. 19.

### Conclusions

Microscopic FT-IR analysis on EHL contact area under grease lubrications shows that thickener concentration of Li grease decreases in the contact area and that the concentration of urea grease increases there. The boundary film formed by urea thickener builds the lubrication film under urea grease lubrication.

Hoshi et al. indicated that how easily the thickener can enter the contact area depend on thickener types. The behaviors of thickeners under EHL could affect the bearing torque.

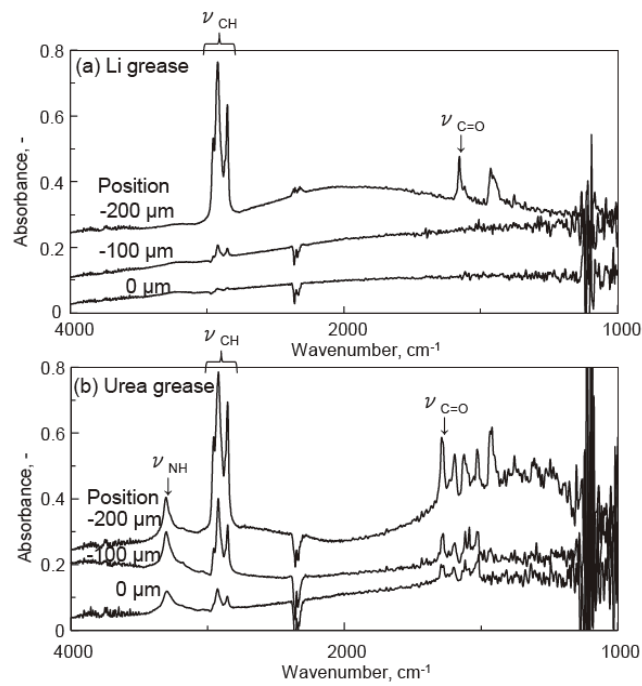


Fig. 18 Typical IR spectra of EHL film of Li grease and urea grease [26]

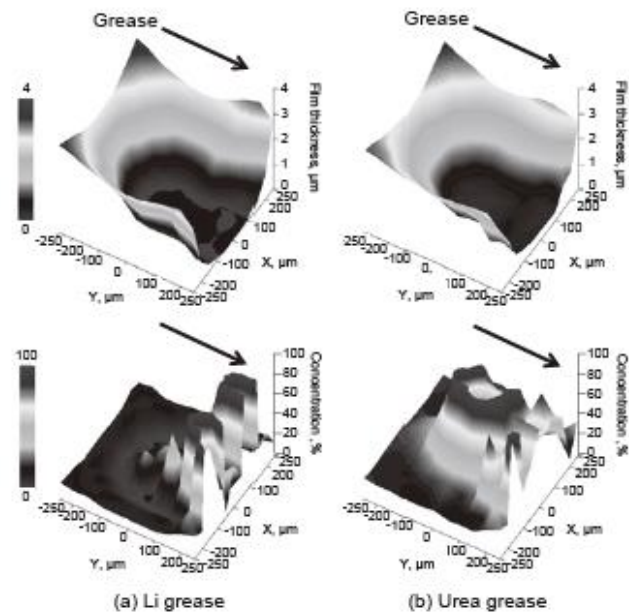


Fig. 19 3D images of film thickness and thickener concentration [26]

### 3.5 Observation of grease fluidity

Non-uniformity of grease thickeners seem to have influence on grease film thickness behaviors. Publications focused on grease movements are shown as follows.

**Chen, J., Tanaka, H., and Sugimura, J.**, “Experimental Study of Starvation and Flow Behavior in Grease-Lubricated EHD Contact,” *Tribology Online*, 10, 1, 2015, 48-55. [27]

The relationship between starvation and flow behavior in grease lubricated EHL contact was investigated. The EHL film thickness was determined by the optical interferometry method, and the grease flow around the conjunction and the flow pattern on the track of the disk were observed with CCD camera.

#### Results

Grease flow behaviors were observed by ball-on-disk tribometer. The sample greases were Li greases (Lithium 12-hydroxystearate thickener and PAO or POE base oils) and urea grease (diurea thickener and POE base oil). For fully flooded conditions, a pair of scoop was used. For starvation conditions, the scoop was not used.

Typical grease flow pattern is shown in Fig. 20. The finger interval  $\lambda$  is defined as the average interval measured perpendicular to the average tilt angle at a position 4 to 5 times the Hertzian contact radius apart from the center of the track. The interval decreased with the increase of entrainment speed. The finger like patterns disappeared at high speeds in starved conditions. However, the starvation phenomena, defined as the speed when the film thickness dropped from the theoretical film thickness values of the base oils, occurred before the finger-loss.

#### Conclusions

The features of grease track patterns changes with grease type and test conditions. The average interval between fingers decreases with increasing entrainment speed. Starvation and finger-loss occur at higher entrainment speeds with all the tested greases. The starvation speeds are lower than the finger loss speeds.

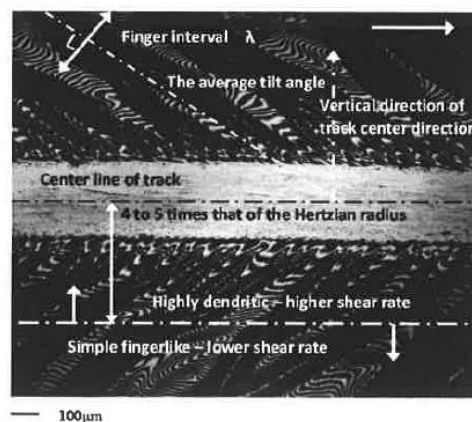


Fig. 20 Definition of finger interval in downstream image [27]

**Yokouchi, A., Hokao, M., and Sugimura, J.,** “Effect of Soap Fiber Structure on Boundary Lubrication of Lithium Soap Greases,” *Tribology Online*, 6, 4, 2011, 219-225. [28]

The influence of fiber length of lithium-soap thickener greases on friction under boundary lubrication conditions using a ball-on-disk sliding tester.

### Results

Two types of greases with different soap fiber lengths were used. One is with short fibers E03S (0.4 $\mu\text{m}$ ) and the other is with longer fibers E03L (10 $\mu\text{m}$ ) as shown in Fig. 21. The thickener was lithium 12-hydroxystearate and the base oil was ester type (E03). The friction tests were performed using ball-on-disk tester.

The friction coefficients for the greases were lower than that of E03 base oil. The E03L with longer fibers showed lower friction coefficients compared with E03S (Fig. 22). The friction tests under partially grease coated conditions also showed lower friction coefficient of E03L. That indicates the difference in the capability of the two greases to be entrained at the contact. From the rheological tests, E03L showed lower viscosity and yield stress, therefore, that suggests the better entrainment capability of longer fiber thickener.

### Conclusions

The greases tested showed a lower friction coefficient than that with the base oil alone. The grease with longer soap fibers had a lower friction coefficient than the grease with shorter fibers. The partial coat tests revealed that the cause of the better boundary lubrication of the grease with longer fibers was its higher capability to be entrained into the conjunction than the grease with shorter fibers. It was suggested the better entrainment capability of the grease with longer fibers was caused by its lower viscosity and lower yield stress.

In addition to these study, Oikawa et al. [8] stated a grease channeling phenomenon correlates to the yield stress as referred. Such grease fluidity could relate to bearing torque behaviors.

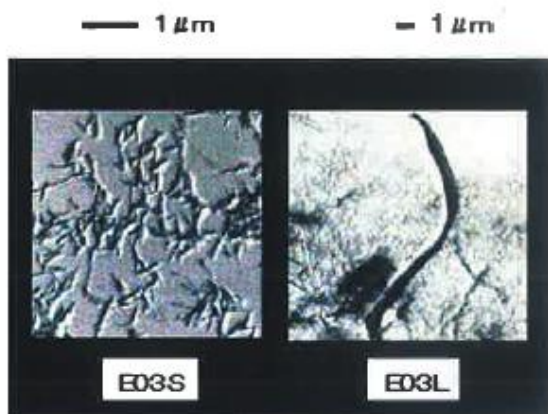


Fig. 21 Soap fibers of the greases [28]

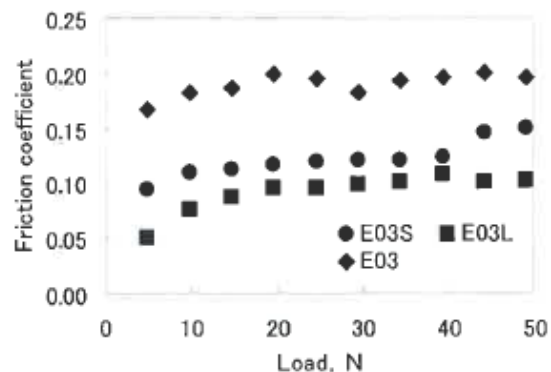


Fig. 22 Results of sliding tests [28]

### 3.6 Surface texturing for film thickness

Surface texturing effect for oil lubrication and non-conformal contacts is not basically beneficial. Due to the fluctuation of pressure and film thickness around the texture, even the lubrication film breakdown, it reduces the rolling contact fatigue life [29]. Considering the possibility that the non-uniformity of greases influences on the texture, the publications of positive texturing effects are shown as follows.

**Kaneta, M., Kanada, T., and Nishikawa, H.**, “Optical Interferometric Observations of the Effects of a Moving Dent on Point Contact EHL,” *In: Elastohydrodynamics - '96 Fundamentals and Applications in Lubrication and Traction. Tribology Series* 32. 1997, 69-79. [30]

The influence of dents formed in the surfaces on the film thickness were evaluated using optical interferometry technique, focused on the slide roll ratios.

#### Results

A dent was produced onto one part of the smooth ball surface ( $R_a$ : 5nm) with a spherical cemented carbide tool. The values of the dent depth were from  $0.5\mu\text{m}$  to  $3\mu\text{m}$  and those of the width were from  $50\mu\text{m}$  to  $100\mu\text{m}$ . A mineral bright stock was used for the lubricating oil. The film thickness were observed using the optical interferometry technique. The main valuable of the experimental conditions was slide roll ratios ( $\Sigma = -1, 0, \text{ and } 1$ ). The slide roll ratio dependence on the film thickness are shown in Fig. 23. The main findings are summarized as follows.

#### Conclusions

When the dent passing through the EHL conjunction exists as the in the inlet region under  $\Sigma > 0$ , a local reduction in film thickness occurs at downstream of the dent. Under pure rolling condition ( $\Sigma = 0$ ), the film reduction occurs at the leading and trailing edge. Under the condition of  $\Sigma < 0$ , the film reduction occurs at the trailing edge. The oil within the dent is emitted to the downstream or upstream when the dent is slower or faster than moving surfaces, respectively.

In cases of  $\Sigma \neq 0$ , the depth of the dent decreases as the dent enters the contact area.

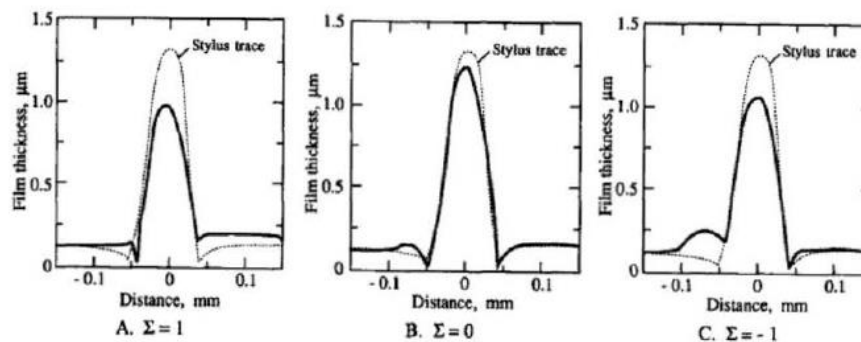


Fig.23 Midplane film profile in the direction of motion [30]

**Mourier, L., Mazuyer, D., Lubrecht, A. A., and Donnet, C.,** “Transient Increase of Film Thickness in Micro-Textured EHL Contacts,” *Tribology International*, 39, 2006, 1745-1756. [31]

**Krupka, I. and Hartl, M.,** “Thin-Film Lubrication of Dented Surfaces,” *Tribology Transactions*, 50, 2007, 448-496. [32]

**Krupka, I. and Hartl, M.,** “The Effect of Surface Texturing on Very Thin Film EHD Lubricated Contacts,” *Tribology Transactions*, 52, 2009, 21-28. [33]

Mourier et al. analyzed the transient change of film thickness induced by circular micro-cavities passing through an EHL point contact. The experiments were conducted by actual observation and numerical simulation under rolling/sliding conditions. Krupka et al. investigated the effect of micro-dents of various depths on the film thickness considering slide roll ratio dependence.

### Results

Micro-cavities were produced using LST (Laser Surface Texturing) method with ultra-short laser pulse. The micro-cavities with various diameters (20-120 $\mu\text{m}$ ) and depths (0.2-100 $\mu\text{m}$ ) were produced on steel balls. Film thickness was observed using the optical interferometry technique under rolling/sliding ( $\Sigma = -0.5$ ) conditions. In the case of deep micro-cavity (0.7 $\mu\text{m}$ ), film thickness reduced compared with the smooth surface case. In contrast, a shallower micro cavity (0.4 $\mu\text{m}$ ) increased film thickness near the leading edge on the cavity as shown in Fig. 24 left.

Micro-dents were produced by indentation of the ball surface with Rockwell indenter. The depth ranged from 0.23 to 1.02  $\mu\text{m}$ . The deep micro dents on the ball decrease the film thickness but shallow micro dents increased the film thickness depending on the rolling/sliding conditions, especially negative slide roll ratio (Fig. 24 right).

### Conclusions

Under rolling/sliding conditions, deep cavity give a local decrease of the lubricant layer, and a significant increase in lubricant film thickness is induced by a shallow micro-cavity.

An increase in the lubricant film thickness has been observed upstream of the trailing edge of the micro-dent when the slide roll ratio is negative. For the positive slide roll ratio, the presence of the micro-dent reduce the film thickness located downstream of the leading edge.

Mourier and Krupka et al. found out the improvement of film thickness depending on the specific conditions in spite of the non-conformal contacts. Applications for grease lubrication has not been reported, and the behaviors could be different by the non-uniformity of greases.

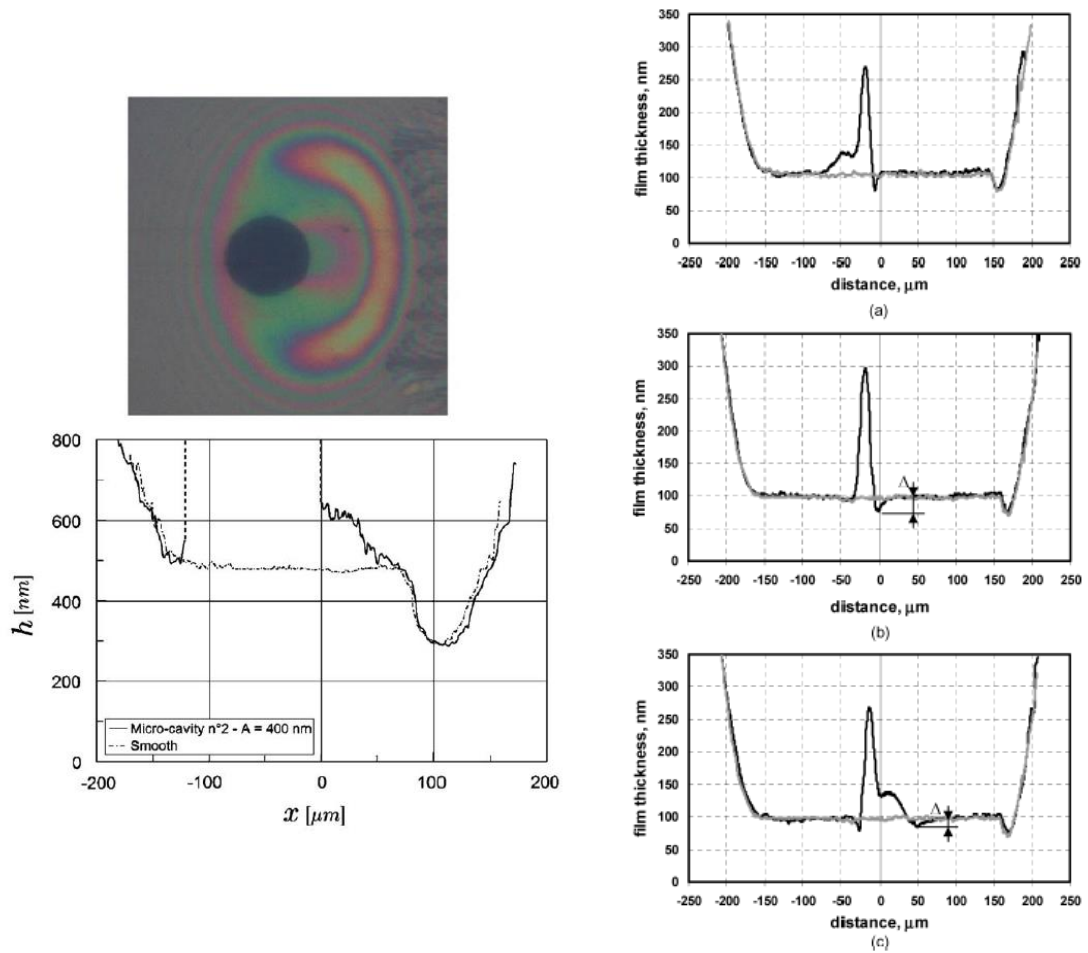


Fig. 24 (left) Transient increase of film thickness induced by a shallow micro-cavity under rolling-sliding [31]

Fig. 24 (right) Film thickness profiles depicting the effect of shallow micro-dent on lubrication film for  $\Sigma = -0.5$ (a), 0(b), and 0.5(c) [33]

## **4 ANALYSIS, INTERPRETATION AND EVALUATION OF FINDINGS OBTAINED FROM CRITICAL REVIEW**

As described above, there are some literatures about grease formulation and bearing torque and its lubrication, the relationship is illustrated on next page. However, each study includes unknown areas.

Cousseau et al. [3, 5] indicated their findings about greases and thrust bearing torque. It is not clear to be applicable to radial ball bearings. The sample greases are based on commercial ones, therefore the results could contain the interaction among base oil, thickener, and additives. The influence cannot be ignored.

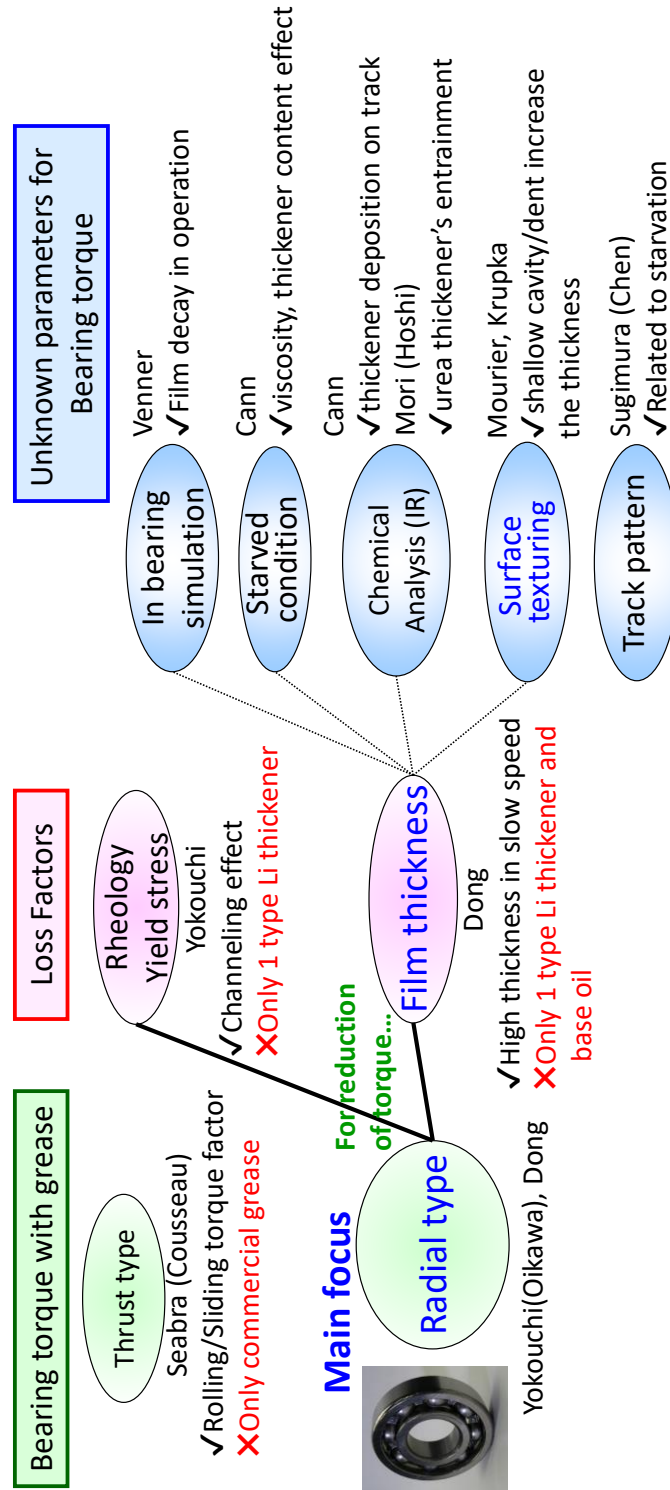
Oikawa et al. [8] and Dong et al. [10] reported influence of Li greases on radial ball bearing torque. Their thickeners are limited to Li-12-hydroxy stearate, and the tendency for the different thickener type of greases are not necessarily the same.

Venner et al. [13-14] simulated grease behaviors in bearing, and Cann et al. [15-16] reported grease film thickness under fully flooded and starved conditions, however, the relationship between those findings and bearing torque has not been clear.

Chemical analysis of grease film [24-26] and grease flows [27] could be significant factors determining bearing torque. In other words, grease rheological parameters, EHL films, and grease flows are necessary to understand the bearing torque under grease lubrications. In that meaning, recently the authors [12] proposed a lubrication mechanism about bearing torque by using of fluorescence observation of grease flows, but that was limited grease formulations.

In addition to these factors, surface influence to film thickness should be introduced in this research. The non-uniformity of greases due to mixture of oil and thickener could affect film thickness on non-smooth surfaces. A study of grease film thickness considering various surface conditions has not been reported. If the grease behaviors of film thickness are different from oil and there is some dependence for grease formulations, it will be a new subject to be discussed for considering the relationship between bearing torque and grease formulations. For instance, specific type of grease might form higher film thickness on textured surface, otherwise, all type of grease might decrease film thickness and the negative influence might be reduced in some type of grease.

For the PhD project, the effect of grease formulation on bearing torque will be considered through the combination of bearing torque measurement and each factor for a wide variety of greases. The bearing type is set to radial ball bearings for the versatility. The rotation torque of a radial ball bearing will be measured in grease lubrication. The samples are model greases composed of different types of base oils and thickeners in order to study the influence of these types. To clarify the cause of the difference among bearing torques with different formulated greases, each factor will be evaluated. For instance, the grease rheological parameters will be determined by viscosity and viscoelasticity measurement. The structure of grease thickener fibers will be observed by an electron microscope. Film formation properties for each grease will be compared by optical interferometry method considering smooth and textured surfaces.



## **5 ESSENCE AND GOALS OF THE PHD THESIS**

The general objective of this research is to obtain the relationship between the bearing torque and grease formulations. The bearing torque in grease lubrication definitely correlates to several parameters as described above, and these parameters also interact each other. However, the detailed mechanism of how the components of greases simultaneously influence the bearing torque has not been fully understood.

In this research, radial ball bearing torque tendency will be evaluated with various type of greases, considering base oil and thickener type dependence. Analyses of the reason why each grease formulation provides the different bearing torque will be conducted by comprehensive grease properties, such as rheological parameter and thickener structure, and behaviors including EHL films. Especially, EHL film thickness will be measured by optical interferometry method with smooth and textured surfaces. Investigating grease behaviors on non-smooth surfaces and discussing the influence on the bearing torque will be novel approach in this field. The obtained findings could be significant knowledge for the development of advanced greases featuring energy-saving performance.

## **6 SCIENTIFIC QUESTION AND WORKING HYPOTHESIS**

### **Scientific question:**

What properties of greases affect the radial ball bearing torque?  
Are there relationship among the properties?

### **Working hypothesis:**

#### 1. Rheological factor

As described in the literature [8], high yield stress of greases could have influence on the reduction of bearing torque. The finding in the literature might be different in thickener types, therefore the tendency will be confirmed. Not only yield stress but also viscosity parameter will be evaluated for understanding correlations.

#### 2. Thickener structure

Authors [12] indicated the thin and long thickener fiber structure lead to higher film thickness and superior grease fluidity in the inlet of contact area. Yokouchi [28] also suggested the fiber structure affect how easily grease is entrained to the contact area. The tendency will be confirmed and whether the structure change depending on base oil types will be investigated.

#### 3. Ability of film thickness and adaptability to surface conditions

Higher grease film thickness seems to have relationship with the lower bearing torque according to Dong [10] and authors [12] study. It should be verified whether the tendency is applicable in the different thickener and base oil types.

A study on grease film thickness on non-smooth surface has not been reported. If a grease can form higher film thickness on textured surface, it could mean the higher adaptability to the surface conditions or higher fluidity as a grease. It should be confirmed whether the difference of the film forming properties of greases relate to the bearing torque properties.

## 7 METHOD

### 7.1 Material

#### 7.1.1 Lubricants

Samples will be basically model grease formulations, considering actual grease formulations for bearing lubrications. Hydrocarbon type base oil (API Group-I, III, and IV) and ester type base oil will be used and these viscosity grade is controlled to VG32. The relatively low viscosity grade is based on recent grease development trend with energy-saving properties.

Group-I is mineral oil composed of paraffinic, naphthenic, and aromatic hydrocarbons. Group-III is also mineral oil, highly refined paraffinic hydrocarbons. On the contrary, Group IV is poly-alpha-olefin (PAO), therefore, composed of only paraffinic hydrocarbons.

Thickeners are two kinds of Li soap; single Li soap / Li complex soap. Single Li soap is Li-stearate or Li-12-hydroxy stearate, and Li complex soap is a mixture of Li-12-hydroxy stearate and Li-azelate. Therefore, grease samples will be the combination of four types of base oils and three types of thickeners. At first, each type base oil will be used for each grease sample, as necessary, a mixture of base oils will be tested for reflecting actual grease formulations.

Table 2 Lubricants compositions

Samples	Li-complex grease	Single Li grease 1	Single Li grease 2	Base Oil
Base oil	Mineral oil(G-I, G-III), PAO(G-IV), Ester			
Thickener	12OH-stearic/azelaic-Li	Stearic-Li	12OH-stearic-Li	-
Dropping point	250°C	200°C	200°C	-

#### 7.1.2 Bearing

As the bearing for measurement of bearing torque, a conventional type of bearing, 6204 deep groove ball bearing is used. The outer and inner diameters are 47 and 20 mm, respectively.

#### 7.1.3 Balls

Balls for film thickness measurements are AISI 52100 steel balls with the diameter of 25.4 mm and the surface roughness (RMS) of about 10 nm. For the investigation of textured surface, dents will be produced by a ball indenter. The depth will be controlled at from several hundreds of nanometer up to 1µm.

## 7.2 Bearing torque

In order to evaluate bearing friction torques caused by greases, bearing tests will be conducted by using an original bearing friction torque testing machine (Fig. 25). 6204 bearing is filled with grease sample (2g) without sealing. Bearing torques are detected by a wire fixed in a bearing housing case and load cell when a main shaft attached with inner race of a bearing rolls at some rotation speed. Bearing friction torques are measured with each grease for five minutes each at several speeds (200, 500, 1000, and 2000rpm, continuously). Radial and axial loads are both 50N and the operating temperature was 25°C. Repeatability will be confirmed by 2 or 3 operations.

In addition, about this testing machine, detective torque is up to 20Nm, rotation speed is up to 10000rpm, and temperature can be controlled from -50°C to 200°C.

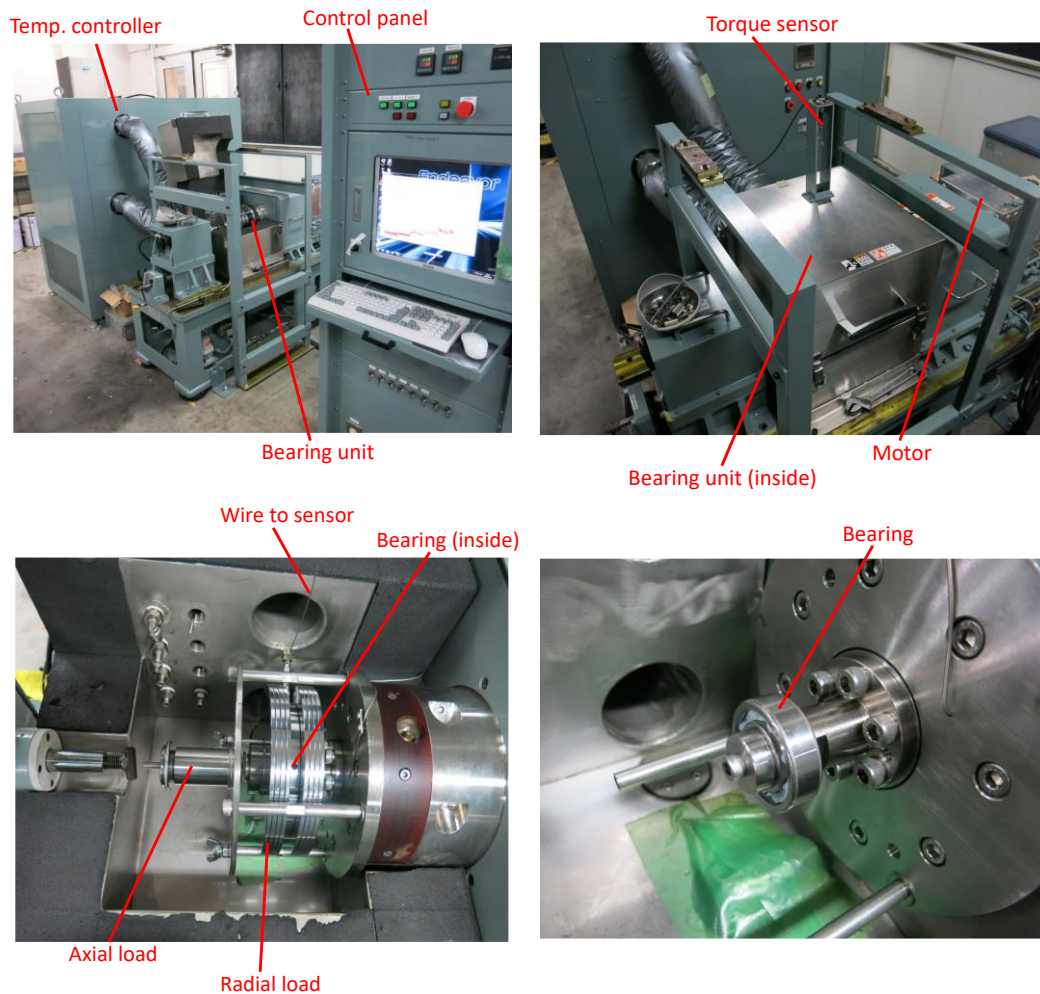


Fig. 25 Images of the bearing torque testing machine

### 7.3 Rheology

Grease viscosity and yield stress will be evaluated for the relationship with bearing torque properties for comparison to past report [8]. The apparent viscosity of each of the greases at a shear rate of  $0.1\text{-}2000\text{s}^{-1}$  will be determined by using a cone-plate type of rotational viscometer (HAAKE Viscometer550). The cone is 20 mm in diameter and has an angle of 1 degree. Measurements of the yield stress of grease will be conducted with parallel-plate type of rheometer (TA Instrument ARES), using viscoelastic parameters. Diameter of the two plates was 20mm and the frequency is 1Hz. The storage modulus ( $G'$ ), the loss modulus ( $G''$ ), and shear stress will be measured while the deformation is controlled from  $7 \times 10^{-5}$  to 6. The yield stress is defined as the lowest shear stress when  $G''$  is greater than  $G'$  (Fig. 26).

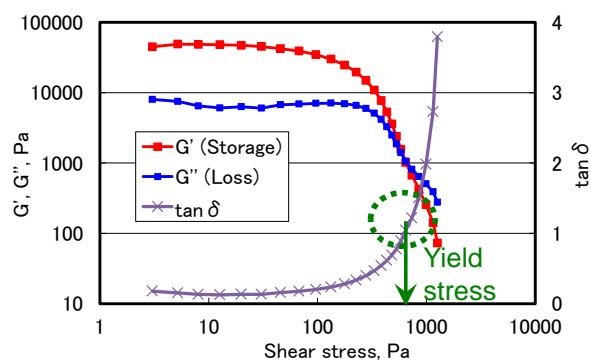


Fig. 26 Viscoelasticity of a grease

### 7.4 Grease structure

Grease thickener fiber structures (Fig. 27) will be observed by TEM (Transmission Electron Microscope) in order to investigate influence of the structures on the bearing torque and other properties. Oil component is removed by n-hexane solvent, and the residual thickener components are observed by TEM (JEOL JEM-2010). Acceleration voltage was 200kV.

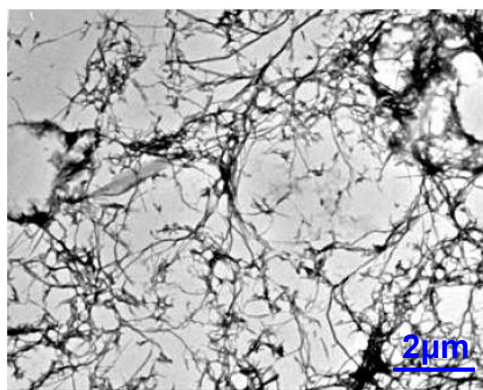


Fig. 27 Thickener fiber image of a grease

## 7.5 Film thickness

Grease and oil film thickness will be measured by using the colorimetric interferometry technique [34]. Film thickness formed between a glass disk and a steel ball (AISI 52100) will be observed as shown in Fig. 28. The bottom surface of the glass disk is coated with a thin and reflective chromium layer, and the top of that is coated with antireflective layer. The maximum Hertzian pressure will be about 430MPa. A scoop is used for pushing the grease at the side trace back to the running track under fully flooded condition. The film thickness measurement will be conducted with the velocity from 0.01 to 1m/s. Film thickness between these smooth surfaces for each sample will be compared to the bearing torque properties.

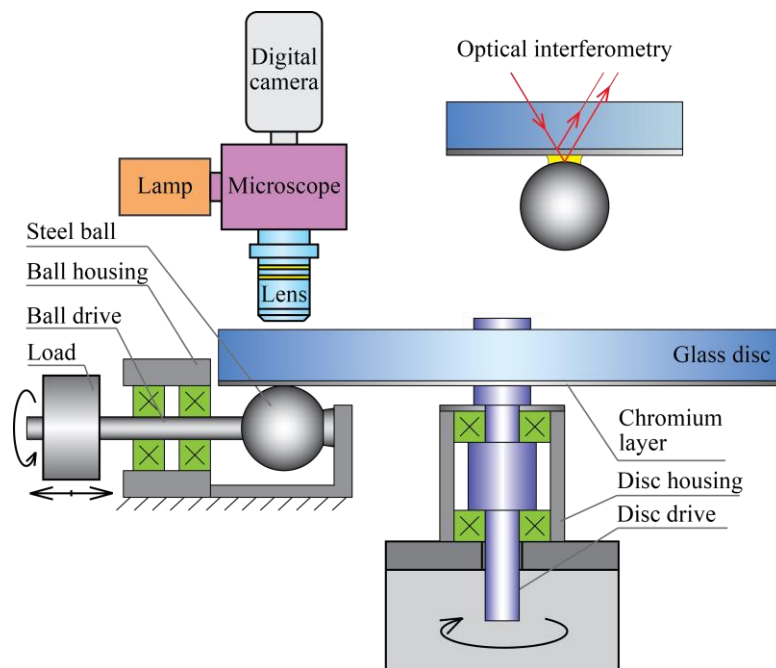


Fig. 28 Schematic image of film thickness measurement

In addition, surface texturing effects on the film thickness will be evaluated by using balls with dented surfaces. Dents will be produced by a ball indenter and the dependence of the depth on the film thickness for each sample will be investigated. The depth will be controlled at from several hundreds of nanometer up to  $1\mu\text{m}$ , considering the positive effect reported in the references [32-33]. Since the grease behaviors could be different from the reports. The tendency for each sample toward non-smooth surfaces and the correlation with the bearing torque will be investigated.

## 7.6 Interpretation of obtained results

The dependence of thickener and base oil types on bearing torque will be obtained through 7.1 to 7.2. The cause of the difference will be analyzed through 7.3 to 7.5. If a remarkable correlation between bearing torque values and each parameter is obtained, the parameter could be significant in bearing torque property. Furthermore, discussing the significant parameter with other properties could be understanding of the grease lubrication mechanism in radial ball bearings.

## 8 CURRENT STATE OF THESIS

### 8.1 Relationship between bearing torque and smooth surface

Before investigating the influence of surface texturing effects on the grease film thickness, the properties of bearing torque, rheological parameters, and film thickness for smooth surfaces were studied. Based on the obtained results, provisional lubrication mechanism is discussed.

#### 8.1.1 Lubricants

Tested greases used in the present study are limited to six types, the combination of two types of base oils (G-I and PAO) and three types of Li thickeners. The component of each grease and some properties are listed in Table 3 and 4.

Table 3 Sample greases

Grease	A	B	C	D	E	F
Mineral oil (G-I), %	88	92	92	-	-	-
Poly- $\alpha$ -olefin (G-IV), %	-	-	-	88	92	92
Li complex thickener, %	12	-	-	12	-	-
Li stearate, %	-	8	-	-	8	-
Li-12OH-stearate, %	-	-	8	-	-	8
Penetration (60W)	265	293	359	311	305	341

Table 4 Base oil property

Base oil		G-I	PAO
Kinetic viscosity, mm <sup>2</sup> /s	40C	33.2	30.6
	100C	5.6	5.8
Viscosity index		107	135
Hydrocarbon group, % (n-d-M method)	Paraffinic	67	100
	Naphthenic	28	0
	Aromatic	5	0

#### 8.1.2 Bearing torque

Figures 29 and 30 show the speed dependence of bearing friction torques for greases with G-I and PAO base oils, respectively. The torque values for all the samples increased with increment of the bearing rotation speed. Grease A (G-I base oil + Li-complex) indicated the minimal torque increase with the rotation speed increase. In contrast, those torque increase of Grease C and F with Li-OHSt were remarkably large. In the low rotation speed range, Grease B provided the lowest torque, while Grease A showed the lowest value in the high speed range. This inversion of the grease providing lower torque depending on bearing rotation speed suggests the lubricating condition change due to the rotation speed. Comparing the result of the previous work [12], the lower torque for Grease A with a combination of G-I base oil and Li-complex in the high rotation speed range was similar, even if the test rigs for the measurement of bearing torque were not identical. In the present study, the torque behaviors among grease types in the low rotation speed range have become clear, while the difference of the torque values in the low speed range could

not be distinguished in the previous study. That may be attributed to the radial and thrust loading condition on the bearing.

Regarding the base oil type dependence, the difference between Grease B and E with Li-St was small, that can be applicable to Grease C and F with Li-OHSt. According to the results of Wikstrom et al. [7], PAO base oil provided the lower running torque compared with the mineral (Naphthenic) oil for Li-OHSt greases and cylindrical roller bearings at 100rpm. In the present study, the comparison between Grease C and F at the rotation speed of 200rpm seems relatively close to the past result, and actually Grease F with PAO base oil showed lower bearing torque than Grease C with mineral (paraffinic) oil. However, the relationship appears to change depending on the rotation speeds. On the contrary, the difference between Grease A and D with Li-complex was quite large, especially in the high speed range. The influence of the affinity between base oil and thickener could be significant in Li-complex greases, therefore the base oil dependence on the bearing torque was larger in Li-complex greases. For the understanding the cause of the difference of bearing torque behaviors for greases, greases properties were measured as follows.

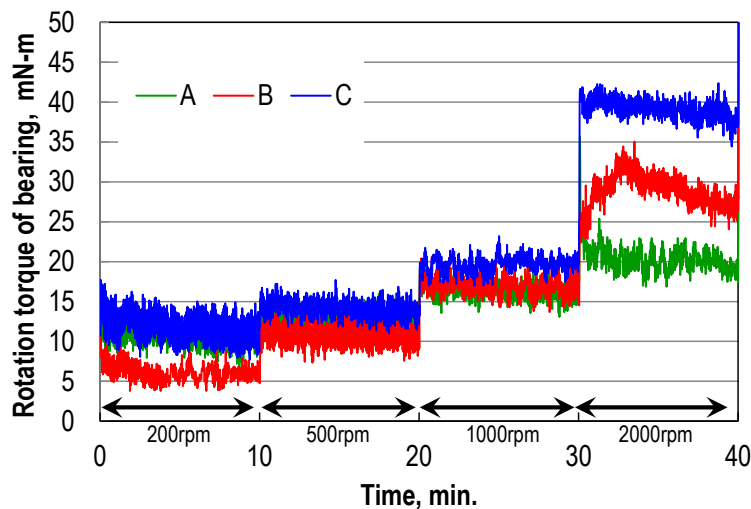


Fig. 29 Speed dependence of bearing torque with greases (G-I base oil)

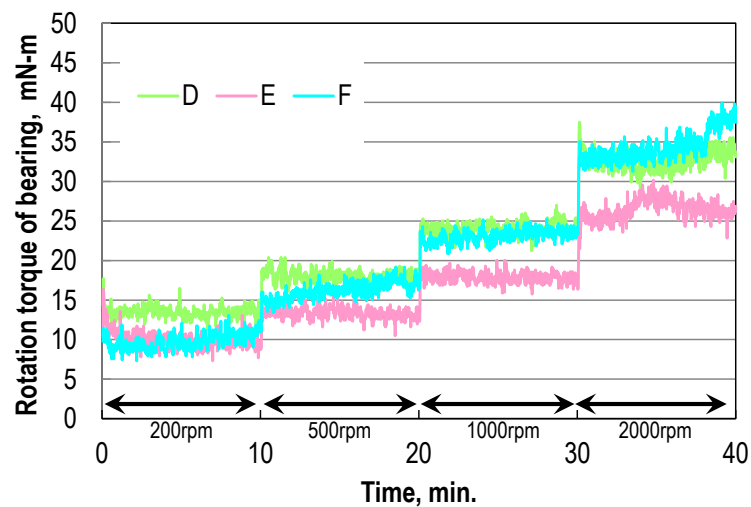


Fig. 30 Speed dependence of bearing torque with greases (PAO base oil)

### 8.1.3 Rheological parameters

The shear rate dependence of apparent viscosity for grease samples with G-I and PAO base oils were shown in Figs. 31 and 32, respectively. The viscosities of Grease C and F with Li-OHSt were relatively lower than those of other thickener type greases. In addition, Grease A and D with Li-complex showed higher viscosities in all speed range. Comparing base oil types, the viscosities of greases with PAO base oil were lower than those with G-I base oil. Therefore, it could be stated that thickener dependence is dominant for the apparent viscosity of the greases, rather than base oil.

The viscoelastic parameter of Grease D is shown in Fig. 33. The yield stress is defined as the lowest shear stress when  $\tan \delta (= G''/G')$  is greater than one, and the yield stresses of greases are summarized in Fig. 34. Comparing the bearing torque results, Grease A with the highest yield stress seems to have some correlation in the lowest bearing torque in the higher speed range and this tendency corresponds to the past report of Oikawa et al. [8]. However, the relationship about bearing torque in the lower speed range cannot be found. In addition, Oikawa et al. pointed out that high yield stress greases related high apparent viscosity at low shear rate. The tendency generally can be applicable to the present study, such as Grease A with the highest yield stress (Fig.34) showed the highest apparent viscosity (Fig. 31) and Grease F did the lowest yield stress (Fig.34) and lowest apparent viscosity (Fig.32). At least, the bearing torque in the high rotation speed range, the bulk grease movement including channeling appears to be an important factor.

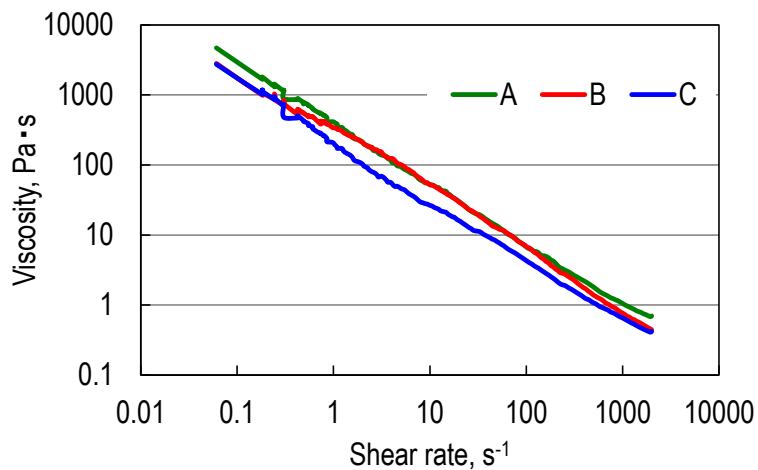


Fig. 31 Apparent viscosity of greases (G-I base oil)

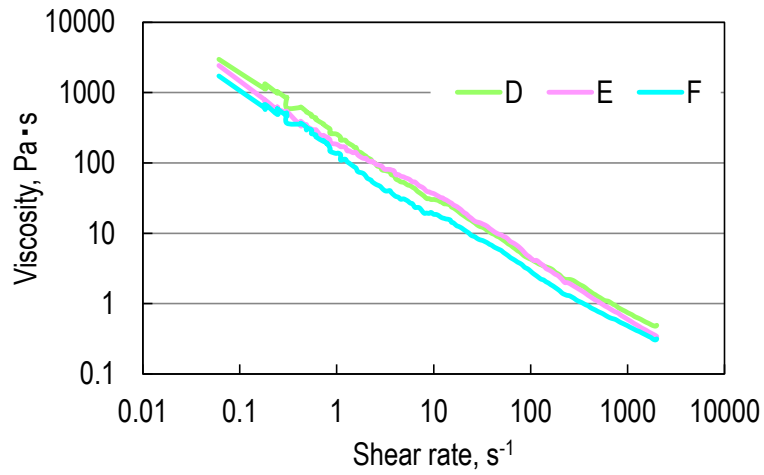


Fig. 32 Apparent viscosity of greases (PAO base oil)

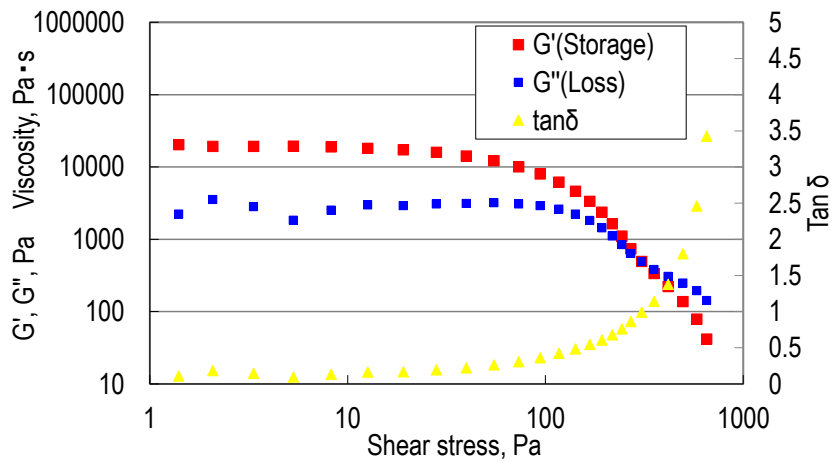


Fig. 33 Viscoelasticity of Grease D

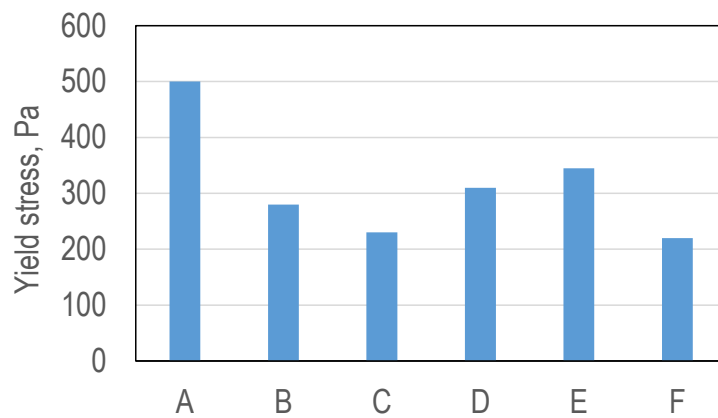


Fig. 34 Yield stress of greases

#### 8.1.4 Film thickness

The central film thickness for each lubricant were observed using the colorimetric interferometry technique. Figures 35 and 36 compare the thickener type dependence for samples with G-I and PAO base oils, respectively. Regarding the low velocity region, greases with Li-complex (Grease A and D) and Li-OHSt (Grease C and F) formed thick film thickness compared with the base oils itself, and the thickness values between two thickeners were similar, such as Grease A and C. In contrast, film thicknesses with Li-St thickened greases were similar to those of the base oils. In the previous study [12], the tendency that higher film thickness of Grease A and thin film of Grease B were observed, however, the reliability of lower speed range (very thin film formation) was not high. In the present study, the grease behaviors in the low speed range could be revealed as follows.

Typical captured images in film thickness observations under the velocity of 0.01m/s are shown in Fig. 37. Li-complex and Li-OHSt thickeners seem to have great influence on the film thickness under low velocity region similar to past reports [16-17], but Li-St thickener does not appear to enter the EHL contact area. The difference could be attributed to the chemical structure of thickeners. For instance, high polar hydroxyl groups of aliphatic chains in Li-complex and Li-OHSt could have higher affinity for the metal surface, since the surfaces should be in metal oxide state and have polarity, and promote the entrainment of greases into the contact area. Hoshi et al. [26] observed grease EHL film thickness by using micro infrared spectroscopy and reported the concentrations of the thickeners in the contact area decreased in Li thickener (Li-St) and increased in urea type thickener. The chemical structure of the urea thickener was aromatic diurea, high polarity thickener due to the urea groups and the aromatic hydrocarbons. Therefore, it can be considered that higher polarity thickener is easy to be entrained to the contact area. In addition, the point that Li-St was difficult to be entrained to the contact area corresponds to the present study.

Under high velocity region, the dependency of thicker types on the film thicknesses was not so significant. However, all greases formed thicker films than the base oils. Regarding base oil types, G-I base oil formed thicker film thickness than PAO. The difference seems to be kept in grease film thickness. Above results regarding film thicknesses indicate that thickener dependence be larger in low velocity region and negligible in high velocity region and that base oil dependence be limited.

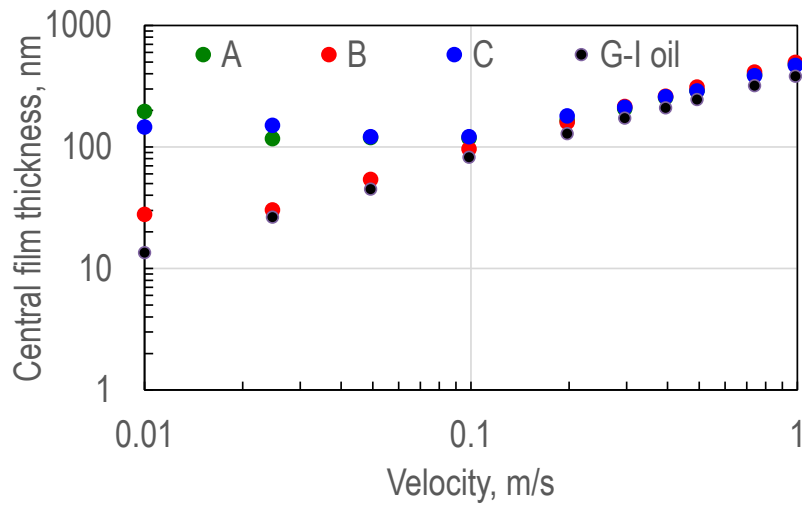


Fig. 35 Central film thickness of G-I base oil samples

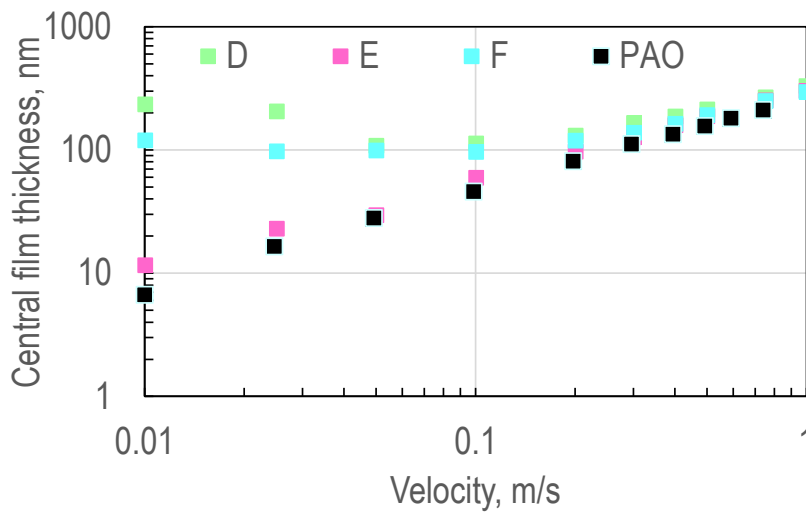


Fig. 36 Central film thickness of PAO base oil samples

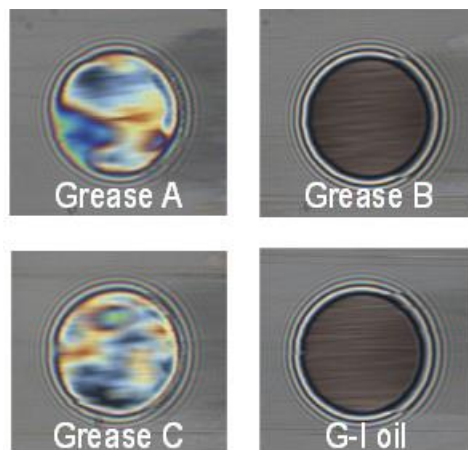


Fig. 37 Interferometry images under 0.01m/s

### 8.1.5 Correlation between bearing torque and grease parameters

Bearing torque behaviors for sample greases will be considered dividing into low and high bearing rotation speeds. Grease B showed the lowest bearing torque under low rotation speed. As an outstanding parameter of Grease B, the thin film thickness under low velocity region. Figure 38 compares the rotation torque for each grease at 200rpm (averaged values in the last 30 seconds of each measurement) and the film thicknesses under 0.025m/s as low rotation speed range. A correlation with two parameters can be recognized to some extent, namely, greases formed thinner film thickness under low speed region provided lower bearing friction torque under low rotation speed range. That indicates thick film thickness is not always effective in lowering bearing torque. Additionally, there could not be found any relationship between bearing torque under low speed region and other parameters such as yield stress, apparent viscosity, and film thickness under high speed region. These results suggest that higher film thickness under low speed region due to the entrainment of thickeners into the contact area increase the bearing friction torque under low speed range. The tendency contradicts to the past report [10], since it reported the higher film thickness of the grease with high viscosity base oil under low speed range reduced friction torque. In addition, the fact that there is no relationship with yield stress indicates that the grease channeling does not occur or the influence of the channeling be negligible in the low rotation speed region.

Considering bearing torques under high rotation speed range, Grease A provided the lowest bearing friction torque. The representative parameter of Grease A is the highest yield stress. The relationship between the yield stress and the rotation torques at 2000rpm for each grease is exhibited in Fig. 39. Greases with the higher yield stress seem to lower the bearing torque under high rotation speed range. This tendency corresponds to the past findings [8]. Furthermore, unlike the low speed range behaviors, grease channeling influence could be significant in this condition. It suggests that the grease behaviors change depending on the rotation speed condition. Regarding other parameters, the relationships with the viscosity under high shear rate and the penetration are shown in Figs. 40 and 41. These parameters also appear to have some correlations with the bearing torque under the high rotation speed. The tendency that higher viscosity and low penetration greases provide the low bearing torque might indicate that the importance of grease structures. It is considered that the higher thickening ability of the thickener contributes to the formation of hard and viscous greases. The feature could enhance the yield stress of the grease and lead to the channeling state in the bearing. Hokao et al. [9] stated that the higher yield stress be brought about by the high dispersion of the thickener, therefore, it has some correspondence in terms of grease structure.

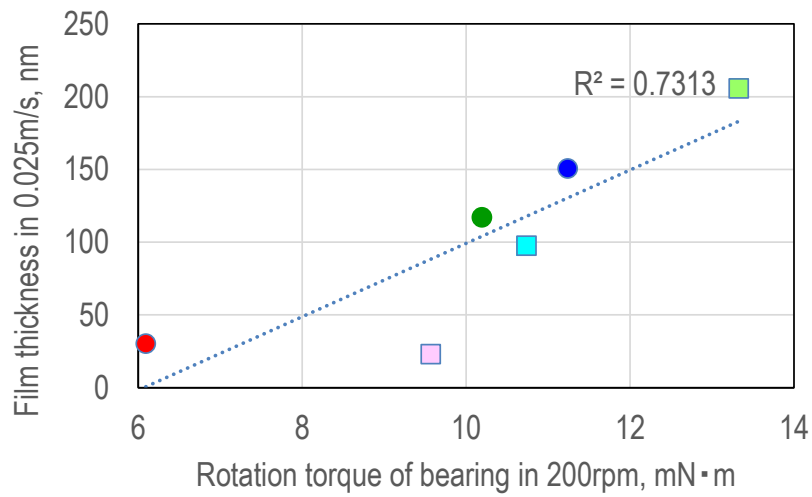


Fig. 38 Relationship bearing torque under low speed region and film thickness

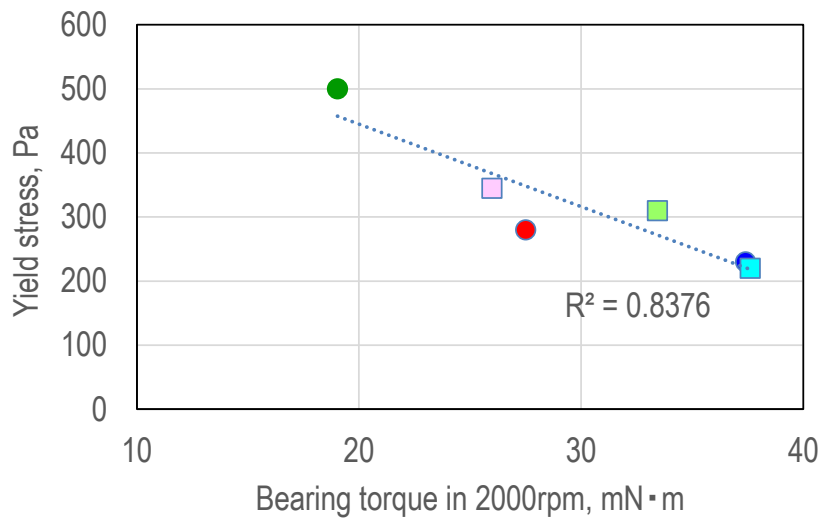


Fig. 39 Relationship bearing torque under high speed region and yield stress

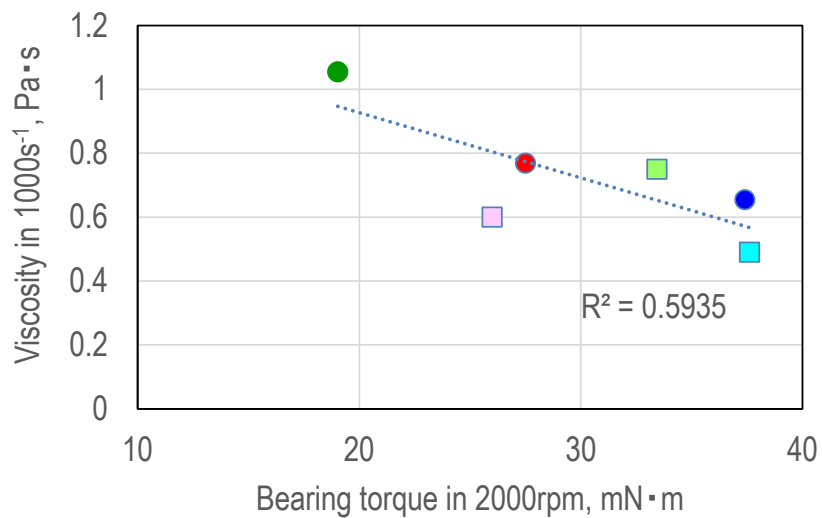


Fig. 40 Relationship bearing torque and viscosity under high speed region

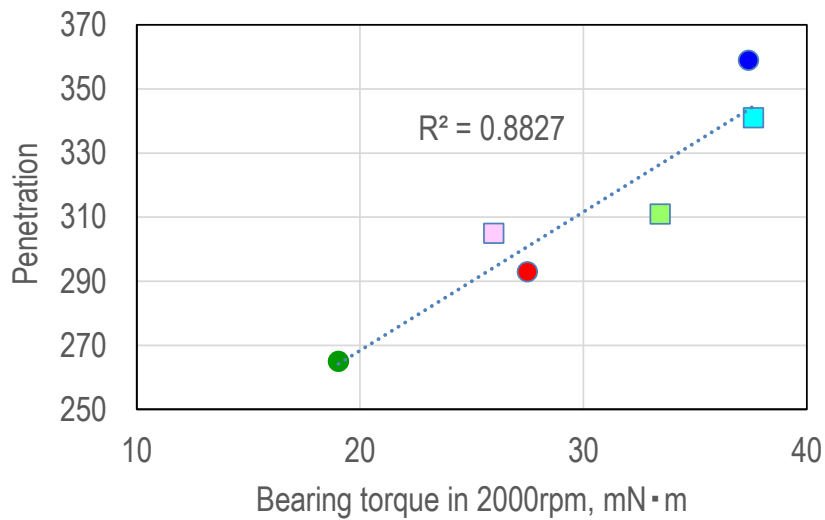


Fig. 41 Relationship bearing torque under high speed region and penetration

### 8.1.6 Provisional lubrication mechanisms

Based on the finding in the present study, lubrication mechanisms related to the bearing torque with greases are proposed in Fig. 42. Under low bearing rotation speed, it is considered that grease channeling effect is negligible and that the film thickness formed under the low speed range is a dominant factor. In those conditions, grease thickener fibers play important roles in increase of the film thickness. However, that film augment effect of thickeners could result in increase of the bearing torque, for instance, the fibers might prevent smooth rotations of bearing balls. A thickener, Li-St, which does not enter the contact surface provides lower bearing torque in this condition. Furthermore, considering the thickener fibers movements in the contact area, the surface roughness effect should not be ignored, while film thicknesses were measured on smooth surfaces in the present study. The value of the surface roughness of the bearing could be close to the size of thickener fibers, and the interaction may be occur. Therefore, the relationship between the grease film thickness including thickener fiber movement and the surface roughness of the contact areas will be investigated in the future work.

On the contrary, under the high rotation speed region, greases lubricate in the channeling state. In other words, greases with higher yield stress are easily pushed away from the track of the balls in the bearing. Reducing the redundant greases lowers the viscosity resistance in the bearing. The yield stress could also have some relationship with grease viscosity and penetration, because these parameters relate to thickening ability of grease thickeners.

In order to develop greases featuring reduction of bearing torque, it seems to be essential to select thickener and base oils considering the bearing operating conditions, since the important factors for reducing bearing torque could change depending on the conditions.

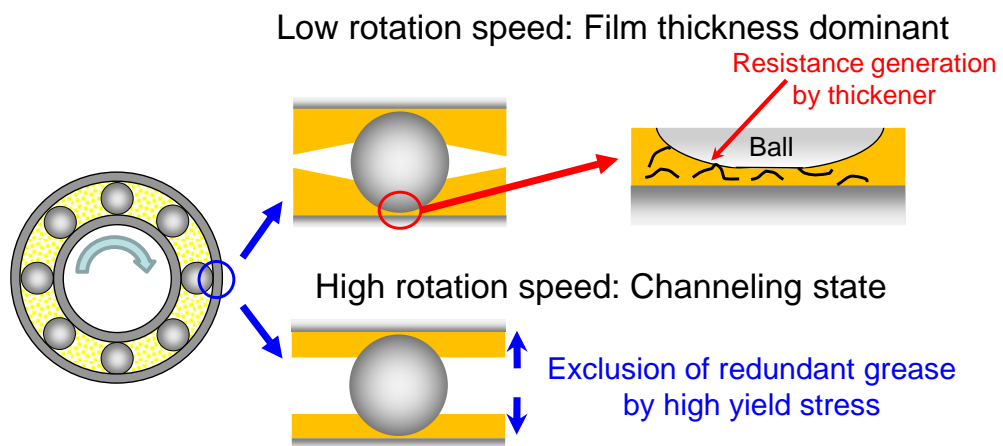


Fig. 42 Lubrication mechanism depending on velocity conditions

## 9 CONCLUSIONS

Most rolling element bearings are lubricated with greases. Not only the improvement of energy-saving properties by means of lowering bearing torque with appropriate grease formulations but also the clarification of the mechanism of grease lubrications is also essential for the future development of greases.

The dependence of the base oil and the thickener types of model greases will be determined by each parameter such as rheology, thickener fiber structure, film thickness. Especially, the effect of surface texturing on the grease film thickness and the relationship with the bearing torque have not been investigated yet. These approaches will bring new findings to grease lubrication mechanisms of radial ball bearings. Not limited in such industrial findings, revealing the relationship among each parameter could contribute to deep understanding of grease lubrication.

According to the present results, under the low and high rotation speed ranges, Grease B (G-I base oil and Li-St thickener) and Grease A (G-I base oil and Li-complex thickener) provided lower friction torque, respectively. The order of superior greases in reducing bearing torque differed by depending on the operating conditions. After analyzing the rheological parameters and film thickness behaviors for smooth surfaces of sample greases, important factors for reducing torque also seem to be different depending on the conditions. For the low rotation speed region, the grease forming thinner film thickness without entrainment of thickeners into the contact area seems promising. In contrast, hard and viscous greases as represented by high yield stress and viscosity and low penetration led to lower torque. These findings suggest that grease behaviors in bearings change depending on the operating condition.

These results are ready to be submitted to the Tribology International.

For future work, the relationship between the grease film thickness including thickener fiber movement and the surface roughness of the contact areas will be investigated in order to understand the grease lubrication mechanisms deeply.

## 10 REFERENCES

- [1] Holmberg, K., Andersson, P., and Erdemir, A., “Global Energy Consumption Due to Friction in Passenger Cars,” *Tribology International*, 47, 2012, 221-234.
- [2] Lugt, P. M., “A Review on Grease Lubrication in Rolling Bearings,” *Tribology Transactions*, 52, 2009, 470-480.
- [3] Cousseau, T., Graca, B., Campos, A., and Seabra, J., “Friction Torque in Grease Lubricated Thrust Ball Bearings,” *Tribology International*, 44, 2011, 523-531.
- [4] Cousseau, T., Graca, B., Campos, A., and Seabra, J., “Experimental Measuring Procedure for the Friction Torque in Rolling Bearings,” *Lubrication Science*, 22, 2010, 133-147.
- [5] Cousseau, T., Graca, B. M., Campos, A. V., and Seabra, J. H. O., “Influence of Grease Rheology on Thrust Ball Bearings Friction Torque,” *Tribology International*, 46, 2012, 106-113.
- [6] Goncalves, D., Pinho, S., Graca, B., Campos, A., and Seabra, J., “Friction Torque in Thrust Ball Bearings Lubricated with Polymer Greases of Different Thickeners Content,” *Tribology International*, 96, 2016, 87-96.
- [7] Wikstrom, V. and Hoglund, E., “Starting and Steady-State Friction Torque of Grease-Lubricated Rolling Element Bearings at Low temperatures—Part I: A Parameter Study,” *Tribology Transactions*, 39, 3, 1996, 517-526.
- [8] Oikawa, E., Inami, N., Hokao, M., Yokouchi, A., and Sugimura, J., “Bearing Torque Characteristics of Lithium Soap Greases with Some Synthetic Base Oils,” *Proc IMechE Part J: J Engineering Tribology*, 226, 6, 2012, 575-583.
- [9] Hokao, M., Inami, N., Watabe, E., Yokouchi, A., and Sugimura, J., “A Study of the Structure Formed by Thickeners of Greases Using Atomic Force Microscope,” *Tribology Online*, 8, 1, 2013, 76-82.
- [10] Dong, D., Komoriya, T., Endo, T., and Kimura, Y., “Formation of EHL Film with Grease in Ball Bearings at Low Speeds,” *Journal of Japanese Society of Tribologist*, 57, 8, 2012, 568-574 (in Japanese).
- [11] Heyer, P. and Lauger, J., “Correlation between Friction and Flow of Lubricating Greases in a New Tribometer Device,” *Lubrication Science*, 21, 2009, 253-268.
- [12] Sakai, K., Tokumo, Y., Ayame, Y., Shitara, Y., Tanaka, H., and Sugimura, J., “Effect of Formulation of Li Greases on Their Flow and Ball bearing Torque,” *Tribology Online*, 11, 2, 2016, 168-173.
- [13] Venner, C. H., van Zoelen, M. T., and Lugt, P. M., “Thin Layer Flow and Film Decay Modeling for Grease Lubricated Rolling Bearings,” *Tribology International*, 47, 2012, 175-187.
- [14] van Zoelen, M. T., Venner, C. H., and Lugt, P. M., “The Prediction of Contact Pressure-Induced Film Thickness Decay in Starved Lubricated Rolling Bearings,” *Tribology Transactions*, 53, 2010, 831-841.
- [15] Cann, P., and Lubrecht, A. A., “An Analysis of the Mechanisms of Grease Lubrication in Rolling Element Bearings,” *Lubrication Science*, 11-3, 1999, 227-245.
- [16] Cann, P., “Starved Grease Lubrication of Rolling Contacts,” *Tribology Transactions*, 42, 4, 1999, 867-873.
- [17] Lubrecht, T., Mazuyer, D., and Cann, P., “Starved Elastohydrodynamic Lubrication Theory: Application to Emulsions and Greases,” *Comptes Rendus De L Academie Des Sciences Serie IV Physique Astrophysique*, 2, 5, 2001, 717-728.

- [18] Cousseau, T., Bjorling, M., Graca, B., Campos, A., Seabra, J., and Larsson, R., "Film Thickness in a Ball-on-Disc Contact Lubricated with Greases, Bleed Oils and Base Oils," *Tribology International*, 53, 2012, 53-60.
- [19] Goncalves, D., Graca, B., Campos, A. V., Seabra, J., Leckner, J., and Westbroek, R., "On the Film Thickness Behavior of Polymer Greases at Low and High Speeds," *Tribology International*, 90, 2015, 435-444.
- [20] Laurentis, N. D., Kadiric, A., Lugt, P., and Cann, P., "The Influence of Bearing Grease Composition on Friction in Rolling/Sliding Concentrated Contacts," *Tribology International*, 94, 2016, 624-632.
- [21] Kaneta, M., Ogata, T., Takubo, Y., and Naka, M., "Effects of a Thickener Structure on Grease Elastohydrodynamic Lubrication Films," *Proc IMechE Part J: J Engineering Tribology*, 214, 4, 2000, 327-336.
- [22] Cen, H., Lugt, P. M., and Morales-Espejel, G., "On the Film Thickness of Grease-Lubricated Contacts at Low Speeds," *Tribology transactions*, 57, 2014, 668-678.
- [23] Morales-Espejel, G. E., Lugt, P. M., Pasaribu, H. R., and Cen, H., "Film Thickness in Grease Lubricated Slow Rotating Rolling Bearings," *Tribology International*, 74, 2014, 7-19.
- [24] Cann, P. M., "Grease Lubrication of Rolling Element Bearings – Role of the Grease Thickener," *Lubrication Science*, 19, 2007, 183-196.
- [25] Cann, P. M. and Spikes, H. A., "In Lubro Studies of Lubricants in EHD Contacts Using FTIR Absorption Spectroscopy," *Tribology Transactions*. 34, 2, 1991, 248-256.
- [26] Hoshi, Y., Takiwatari, K., Nanao, H., Yashiro, H., and Mori, S., "In Situ Observation of EHL Films of Greases by a Micro Infrared Spectroscopy," *Journal of Japanese Society of Tribologist*, 60, 2, 2015, 153-159(in Japanese).
- [27] Chen, J., Tanaka, H., and Sugimura, J., "Experimental Study of Starvation and Flow Behavior in Grease-Lubricated EHD Contact," *Tribology Online*, 10, 1, 2015, 48-55.
- [28] Yokouchi, A., Hokao, M., and Sugimura, J., "Effect of Soap Fiber Structure on Boundary Lubrication of Lithium Soap Greases," *Tribology Online*, 6, 4, 2011, 219-225.
- [29] Chang, L., Jackson, A., and Webster, M. N., "Effects of 3-D Surface-Topography on the EHL Film Thickness and Film Breakdown," *Tribology Transactions*, 37, 1994, 435-444.
- [30] Kaneta, M., Kanada, T., and Nishikawa, H., "Optical Interferometric Observations of the Effects of a Moving Dent on Point Contact EHL," *In: Elastohydrodynamics - '96 Fundamentals and Applications in Lubrication and Traction. Tribology Series 32*. 1997, 69-79.
- [31] Mourier, L., Mazuyer, D., Lubrecht, A. A., and Donnet, C., "Transient Increase of Film Thickness in Micro-Textured EHL Contacts," *Tribology International*, 39, 2006, 1745-1756.
- [32] Krupka, I. and Hartl, M., "Thin-Film Lubrication of Dented Surfaces," *Tribology Transactions*, 50, 2007, 448-496.
- [33] Krupka, I. and Hartl, M., "The Effect of Surface Texturing on Very Thin Film EHD Lubricated Contacts," *Tribology Transactions*, 52, 2009, 21-28.

- [34] Hartl, M., Krupka, I., Poliscuk, R., Liska, M., Molimard, J., Querry, M., and Vergne, P., "Thin Film Colorimetric Interferometry," *Tribology Transactions*, 44, 2001, 270-276.



