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**STUDY OF CORRELATION BETWEEN GREASE  
FILM FORMULATIONS AND MECHANICAL LOSSES  
ON VARIOUS SURFACES**

**STUDIUM ZÁVISLOSTI MEZI SLOŽENÍM  
PLATICKÉHO MAZIVA A MECHANICKÝMI  
ZTRÁTAMI NA RŮZNÝCH PORVŠÍCH**

*Shortened version of PhD Thesis*

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# 1 INTRODUCTION

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 blend 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.

## 2 STATE OF THE ART

Please note that this document is a shortened version of the PhD thesis, the interested reader is referred to the full version of the thesis where following publications are described in a greater detail.

### 2.1 BEARING TORQUE UNDER GREASE LUBRICATION

The publications related to bearing torque can be roughly divided to thrust bearing and radial bearing types. Cousseau et al. [3, 5] investigated the influence of commercial greases on thrust bearing torque. 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. 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 was evaluated. Greases containing higher viscosity base oils 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 and the sliding torque was dependent on the specific film thickness with the bleed oil. That suggested that the sliding torque increased by higher friction coefficient and lower film thickness, especially related to contact replenishment and starvation. 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.

As studies on radial ball bearing torque, Oikawa et al. [8] investigated the lithium (Li) type thickener greases with different base oils. 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-grooved radial ball bearing 6305 were used and the initial torque and the steady-state torque were measured for the constant rotation speed. PAO and PAG-3 greases showed lower initial torques and the torque values stayed almost flat. On the contrary, the torque with POE grease significantly decreased at the initial stage of the duration before it became constant. 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.

## 2.2 EHL FILM THICKNESS UNDER GREASE LUBRICATION

Considering operating conditions of bearing, grease behaviors under EHL should be focused. Observation of film thickness formed by greases have been reported as representative analyses of grease behaviors in bearings.

Cann et al. [15, 16] showed that a grease is pushed away with disk rotations in the ball-on disk contact, different from oil. They used the greases 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 distorting the EHL film and augment the film thickness compared with the base oil. In this region, values in measurements fluctuate wildly. As speed increases, the behavior disappears and the thickness decreases and then climbed again. At higher speeds, the behavior is similar to conventional EHL film thickness of base oil. Film thickness increases with thickener content and base oil viscosity. 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 shear degradation effect was also studied by Kaneta et al. [21]. They investigated the film thicknesses for different types of urea greases. The thickness largely depends on thickener types and the thickener structures seem to influence on grease movements related to starvations. They showed the shear degradation suppresses starvation, but the film thicknesses of degraded greases were thinner than those of fresh greases especially at high temperature and speed. Cen et al. [23] stated that mechanically worked greases prepared in a roll stability tester showed lower film thickness than the fresh ones in slow speed. They also concluded that the thickener particles or fiber structure was degraded during mechanical aging and that led to smaller particles. They used at least 24 h for the degradation time in a roll stability tester.

Cann [24] used a ball-on-disk traction (MTM) device for greases under fully flooded and starved conditions. She used also the lithium 12-hydroxystearate thickener greases. The fully flooded friction values were typically low over the entire test period. Friction coefficient increased under starved conditions, reflecting increase of starvation of the contact as the lubricant was pushed out the track due to repeated overrolling.

### 2.3 OBSERVATION OF GREASE FLUIDITY

Non-uniformity of grease thickeners seems to have influence on grease film thickness behaviors. Publications focused on grease movements are shown as follows. Astrom et al. [25] added a small amount of molybdenum disulfide to Li greases in order to investigate the grease replenishment of an EHL contact using a ball-on-disk apparatus. At the outlet zone, where the gap between the ball and the glass disk diverges, the lubricant cavitates. The cavitation pattern looks like a tree stretching its branches to the rolling track. The thinner grease (lower Li soap content) gave coarser cavitation branches due to the difference in consistency.

Chen et al. [26] also investigated the grease flow around the conjunction and the flow pattern on the track of the disk were observed with CCD camera. 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). The features of grease track patterns changes with grease type and test conditions. 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 Herizian 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. Starvation and finger-loss occur at higher entrainment speeds with all the tested greases. The starvation speeds are lower than the finger loss speeds.

### 2.4 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 [27].

Wedeven [28] studied the influence of the dent debris on the EHL film in oil lubrication using an optical interferometry. The dent is deformed elastically associated to the central film thickness. As the central film thickness increases, the dent approaches its undeformed shape. A reduction in film thickness is confirmed at the leading edge and side of the dent.

Kaneta et al. [29] reported the influence of dents formed in the surfaces on the film thickness using optical interferometry technique, focused on the slide roll ratios. 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 $\mu$ m to 3 $\mu$ m and those of the width were from 50 $\mu$ m to 100 $\mu$ m. A mineral bright stock was used for the lubricating oil. The film thickness was observed using the optical interferometry technique. The main valuable of the experimental conditions was slide roll ratios ( $\Sigma = -1, 0, \text{ and } 1$ ). When the dent passing through the EHL

conjunction exists in the contact 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.

Mourier et al. [30] 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. 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. 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.

Krupka et al. [31, 32] investigated the effect of micro-dents of various depths on the film thickness considering slide roll ratio dependence. 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. 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.

### 3 SUMMARY AND CONCLUSION OF STATE OF THE ART

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 samples were composed of different base oil, thickener, and additives. In these samples, it could be difficult to evaluate the dependence of components. In addition, the results could contain the interaction among base oil, thickener, and additives.

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 similar. However, the influence of yield stress on the bearing torque is worth considering in terms of the grease channeling since Hatton [33] suggested the relationship of channeling and the bearing torque.

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. The effect of shear degradation on the grease film thickness has been reported by Kaneta et al. [21] and Cen et al. [23], therefore the influence on the bearing torque should be confirmed in this study. Since the shear degradation of the grease could occur in the bearing operation.

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. In addition, the bearing surfaces of balls and races have the localized asperity of hundreds of nanometers depth, although the averaged roughness is less than 100 nm. Considering grease film thickness behaviors, especially the thickener entrainment to the contact, the asperity of hundreds of nanometers depth could have a significant meaning. The values of film thickness increase caused by the thickener entrainment are also hundreds of nanometers. However, 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 dented surface.

Based on these literatures, grease formulation dependence or the important grease properties on the bearing torque have not been fully understood. In addition, the grease properties could correlate each other. The relationship should be verified in this PhD study.

## 4 AIM OF THESIS

The first objective of this research is to obtain the relationship between the radial ball bearing torque and grease formulations. The second objective is to understand the correlation of each grease parameter. 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, the bearing torque tendency was evaluated with Li type greases, considering base oil and thickener dependence. Analyses of the reason why each grease formulation provides the different bearing torque were conducted using comprehensive grease properties, such as rheological parameter and thickener structure, friction property, and behaviors including EHL films. Especially, EHL film thickness was measured by optical interferometry method with smooth and dented surfaces. Investigating grease behaviors on non-smooth surfaces and discussing the influence on the bearing torque were novel approaches in this field. The obtained findings could be significant knowledge for the development of advanced greases featuring energy-saving performance.

### 4.1 SCIENTIFIC QUESTIONS

- What properties of greases influence on the radial ball bearing torque?
- Are there relationship among the grease properties?

### 4.2 WORKING HYPOTHESES

- Rheological factor  
The literature [8] indicates greases with high yield stress have an influence on the reduction of bearing torque due to the grease channeling. The finding in the literature might be different depending on thickener types. Not only yield stress but also viscosity parameter will be evaluated in this study.
- 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 [34] also suggested the fiber structure influence on how easily grease is entrained to the contact area. The best thickener structure providing lower torque will be judged if it exists.
- Ability of film thickness and adaptability to surface conditions  
Higher grease film thickness seems to have a 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 types.
- Grease parameter correlation  
Except for relationship with the bearing torque, observed grease parameters could have correlate each other. For instance, the grease with higher film

thickness has specific thickener structure. Comparing the results of grease parameters, the relationship will be discussed.

## 5 MATERIALS AND METHODS

### 5.1 MATERIAL

#### 5.1.1 Lubricants

Model grease formulations for samples were selected, considering actual grease formulations for bearing lubrications. As hydrocarbon type base oils, mineral oils (API Group-I) and poly- $\alpha$ -olefin (PAO, API Group-IV) were used and these viscosity grade was controlled to VG32. The relatively low viscosity grade is based on the recent grease development trend with energy-saving properties.

The mineral oil is composed of paraffinic, naphthenic, and aromatic hydrocarbons. On the contrary, PAO is composed of only paraffinic hydrocarbons.

Used thickeners were three types of Li soaps. Single Li soap is Li-stearate or Li-12-hydroxy stearate. Li complex soap is a mixture of Li-12-hydroxy stearate and Li-azelate. Therefore, grease samples can be the combination of two types of base oils and three types of thickeners. However, in this study, the thickener dependence was mainly focused, therefore, the comparison of three types of Li thickeners with the mineral oil was conducted usually. As necessary, grease penetration dependence was also evaluated by selecting the thickener content.

**Table 1** Lubricants compositions.

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

#### 5.1.2 Bearing

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

#### 5.1.3 Balls and indentation for dents

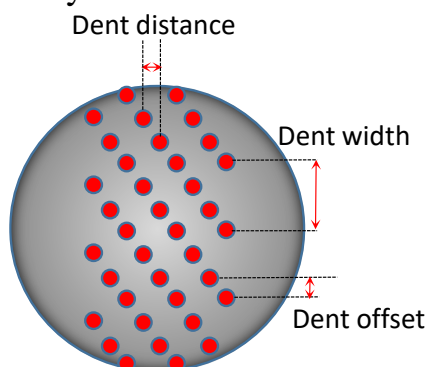
Balls for film thickness measurements were AISI 52100 steel balls with the diameter of 25.4 mm and the surface roughness (RMS) of about 15 nm. The elastic modulus and the Poisson's ratio of the steel ball were 210 GPa and 0.3, respectively.

For the investigation of the influence of the dented surface ball on the film thickness, dents were produced on steel balls using a modified Rockwell indenter. Tungsten carbide (WC) balls with diameters of 2.5, 1.6, and 1.27 mm were used as a tip of the indenter. The dent producing program was decided so that only one dent would enter the contact center as closely as possible in film thickness measurements, considering the Herzian contact diameter (440 $\mu$ m). The program is shown in Table 2 and the dent array image is shown in Fig. 5.1. The depth profiles were obtained by

3D optical interferometry method as shown in Table 3. Dent size images for each indenter are shown in Fig. 5.2. The dent depth deviation was large, for instance, the depth using 1.27 mm indenter ranged from 250 to 450 nm and the averaged value was about 360 nm. Therefore, the film thickness measurements on dents were conducted using averaged values for multiple dents as described in a following chapter. In order to evaluate the dent effect precisely, the depth profiles were identified for two particular dents created by the 1.27 mm indenter. Figure 5.3 shows the depth profiles of the targeted dents, referred as dent1 and dent2. The depths were 350 and 300 nm for dent1 and dent2, respectively.

**Table 2** Dent producing program.

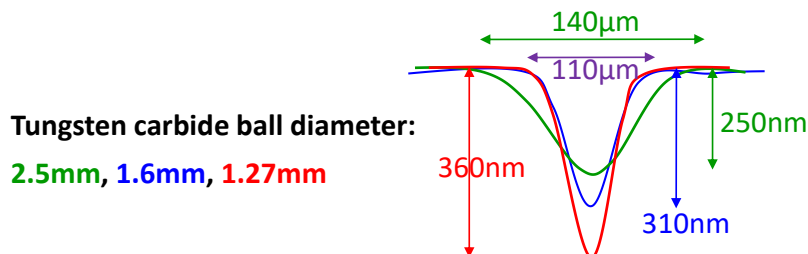
Dent width, $\mu\text{m}$	1200
Number of dents (rotating direction)	60
Dent distance, $\mu\text{m}$	150
Dent offset, $\mu\text{m}$	400
Number of arrays	9
Total number of dents	540



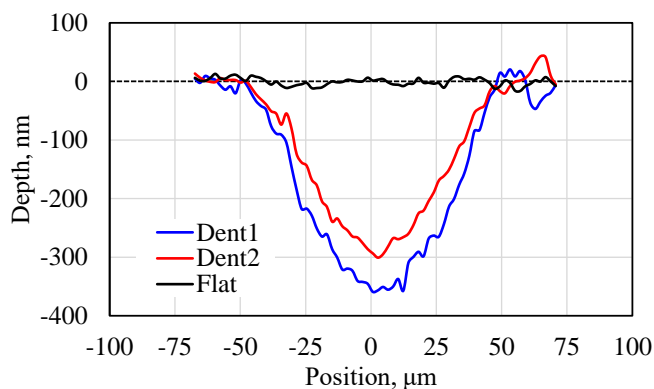
**Fig. 5.1** Image of dent arrays.

**Table 3** Dent profiles.

Diameter of indenter, mm	2.5	1.6	1.27
Width of dents (Averaged values), $\mu\text{m}$	120-160 (140)	110-130 (115)	100-110 (105)
Depth of dents (Averaged values), nm	130-360 (250)	250-400 (310)	250-450 (360)



**Fig. 5.2** Images of dents for different diameters of indenters.



**Fig. 5.3** Depth profiles of the dented steel ball for 1.27mm indenter.

## 5.2 BEARING TORQUE

In order to evaluate bearing friction torques caused by greases, bearing tests were conducted by using an original bearing friction torque testing machine as shown in Fig. 5.4. Radial and thrust loads can be applied to the bearing by weights and a coil spring, respectively, in the range of 10 N to 1000 N. Operating temperature can be controlled by air convection in the range of  $-50^{\circ}\text{C}$  to  $200^{\circ}\text{C}$ . Rotation speeds can vary from 200 rpm to 10000 rpm. Bearing torques are detected by a load cell through a wire fixed in the bearing housing in the range of 0 to 20 Nm.

For each measurement, a new 6204 bearing was used. The bearing was washed with white gasoline in order to remove the filled grease before a test grease was applied to the bearing. The bearing is filled with 2g of grease sample, approximately 35% of space volume of the bearing. Bearing seals were not used in this study in order to exclude the friction resistance of seals.

The inner race of bearing with the test grease was attached to a main shaft of the tester. After applying radial and thrust loads to the bearing in a housing, a wire was attached to the bearing housing in order to detect the bearing torque. The wire was also connected to a load cell. The temperature of bearing assembly was controlled in the chamber by air convection. After stabilizing the temperature in the chamber to  $25^{\circ}\text{C}$ , the main shaft was rotated at discrete speed in stepwise (200, 500, 1000, and 2000 rpm). The measurement time for each rotation speed was 10 minutes for screening the torque behaviors lubricated with each test grease. The tests were conducted 3 times since high deviations were observed depending on the grease thickener types. The bearing torque values at 2000 rpm were not stabilized in 10 minutes, therefore, the duration of 60 minutes was also tested only for 2000 rpm after stepwise speed increases from 200 to 1000 rpm. In addition, after finishing the 60 minutes measurement at 2000 rpm, the same test was proceeded in order to confirm the effect of grease channeling or grease distribution through the bearing operation. These test programs are shown in Table 4.

**Table 4** Operating conditions of bearing torque tests

Condition	Screening	Long duration	Repetition
Axial load, N	50		
Thrust load, N	50		
Rotation speed, rpm (Duration)	200(10min.) -500(10min.) -1000(10min.) -2000(10min.)	200(10min.) -500(10min.) -1000(10min.) -2000(60min.)	After 'long duration' test, 200(10min.) -500(10min.) -1000(10min.) -2000(60min.)
Temperature, $^{\circ}\text{C}$	25		



Fig. 5.4 Images of the bearing torque testing machine

### 5.3 RHEOLOGY

Measurements of the yield stress of grease were conducted with parallel-plate type of rheometer (HAAKE MARS III), using viscoelastic parameters. Diameter of the two plates was 25mm 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 0.01 to 100%. The yield stress is defined as the lowest shear stress when  $G''$  is greater than  $G'$ .

### 5.4 TRACTION PROPERTY

Traction coefficients were measured using a ball-on-disk tribometer, PCS Instruments Mini Traction Machine (MTM). An AISI 52100 steel ball with the diameter of 3/4 in. and the same material disk were selected as the standard specimen. The RMS roughness values of ball and disk were about 6 and 10 nm, respectively. The maximum Hertzian pressure was 0.65 GPa. A scoop was used for maintaining fully flooded conditions during the friction tests. A condition without the scoop was also evaluated. Tests were conducted at ambient temperature.

Assuming the rotation speed of inner race of the bearing during the torque tests, the bearing rotation speeds from 200 to 2000 rpm correspond to from 0.2 to 2 m/s. As a velocity dependence test, the traction coefficient transition of samples were observed with stepwise increase of velocity from 0.1 to 3 m/s, every 0.1 m/s. Following to the measurement of 3 m/s, the velocity decreased to 0.1 m/s in stepwise, every 0.1 m/s, conversely. As the slide roll ratio (SRR), 3% was selected considering the typical SRR range, around 3-5%, found in rolling bearings [35].

The SRR dependence was also evaluated for each bearing operation speed, from 0.2 to 2 m/s. The SRR was controlled from 0.1 to 100% in stepwise. These test conditions are summarized in Table 5.

**Table 5** Operating conditions of traction tests

Condition		Velocity dependence	Slide roll ratio dependence
Specimen	Ball	AISI52100, $\phi 3/4$ in	
	Disk	AISI52100	
Maximum Hertzian pressure, GPa		0.65	
Velocity, m/s		0.1→3.0→0.1	0.2, 0.5, 1, 2 (constant)
Duration, sec.		15 each	15 each
Slide roll ratio, %		3	0→100
Temperature, °C		25	

## 5.5 FILM THICKNESS

Grease and oil film thicknesses were measured by using the colorimetric interferometry technique [36]. The film thickness formed between a glass disk and a steel ball was observed as shown in Fig. 5.5 as a schematic image. The contact images were captured by a digital camera. The film thickness calculation from the interferograms is based on colorimetric analysis using color matching algorithm and CIELAB color film thickness calibration.

The detail of the steel ball was described in 5.1.3. BK7 glass disk with optically smooth surface was used. The elastic modulus and the Poisson's ratio of the glass disk were 81 GPa and 0.208, respectively. 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 used load for film thickness measurements were 27N and the maximum Hertzian pressure of the contact was 0.43GPa for the smooth ball-on-disk contact. The load was 54N and the maximum Hertzian pressure was 0.54GPa for the dented ball on the smooth glass disk contact. A v-shaped scoop was used for pushing the grease at the side trace back to the running track in order to maintain fully flooded conditions. The film thickness observations were conducted with the velocity from 0.01 to 1m/s under nominally pure rolling conditions and 22°C. The disk was driven and the ball was followed for the smooth ball-on-disk contact. The

ball was driven and the disk was followed for the dented ball on the smooth glass disk contact. The observed film thickness using greases was fluctuated due to the entrainment of thickener particles, therefore the averaged thickness values of central circle areas with a diameter of 100  $\mu\text{m}$  were selected for central film thickness. In addition, the central film thickness values were averaged from the results of 5 captured images for the smooth surface contact. Following to the measurement from 0.01 to 1 m/s (acceleration), the film observation was continued from 1 to 0.01m/s (deceleration). For the dented surface, the central film thickness was also measured on smooth areas, not dented areas for comparison. Focused on the dent1 and dent2 as shown in Fig. 5.3, the highest thickness values observed on the dents were selected for the film thickness on dents.

In order to observe the grease film thickness decay under starved conditions, film thickness measurements without the scoop were conducted for the smooth surface contact. The contact images were captured with the velocity increase by 0.024 m/s every 30 seconds.

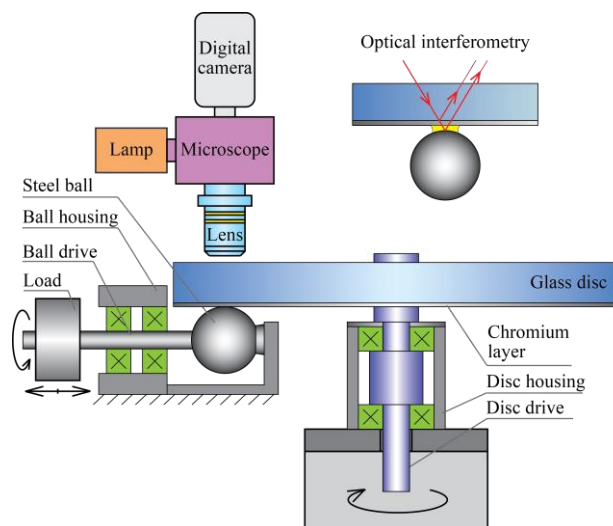


Fig. 5.5 Schematic image of film thickness measurement

## 5.6 TRACK PATTERN

After the film thickness measurements at each velocity under fully flooded conditions between the smooth surfaces, the grease flow patterns created at the downstream of the contact on the disk were observed. As well as the film thickness measurements, observation was conducted from 0.01 to 1 m/s (acceleration), subsequently from 1 m/s to 0.01m/s (deceleration).

## 5.7 INTERPRETATION OF OBTAINED RESULTS

The dependence of thickener and base oil types on the bearing torque were obtained through the process described in 5.1 and 5.2. The causes of the difference are also analyzed through 5.3 to 5.6. Based on the hypotheses described in 4.2, the correlation between bearing torque values and each parameter was discussed. In addition, the relationship among grease properties except for the bearing torque

property was also evaluated. The lubrication mechanisms were proposed based on the discussion.

## 6 RESULTS

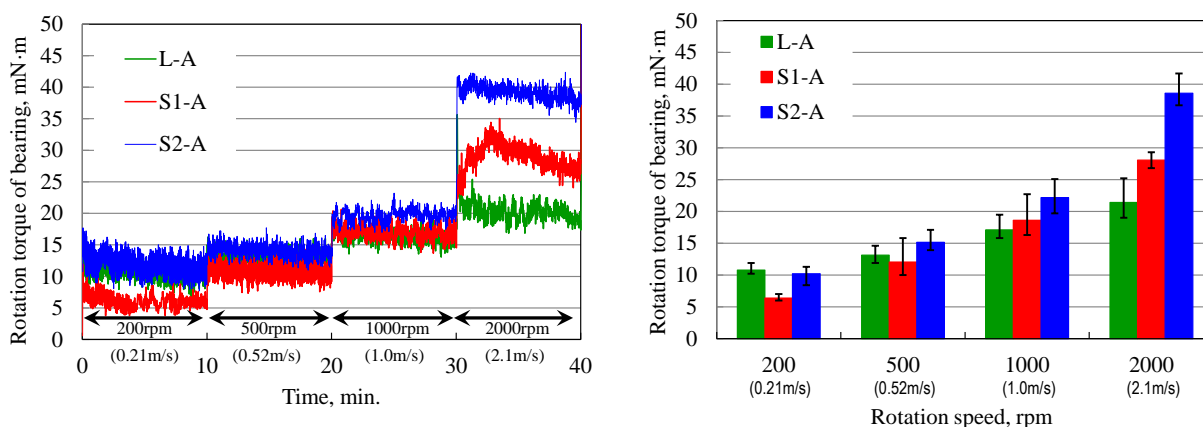
### 6.1 BEARING TORQUE

Bearing torque behaviors were investigated for the six model greases as shown in Table 6. The greases are the combination of two types of base oil and three types of Li thickeners. In this shortened version, only mineral oil based greases were discussed.

The bearing torque was examined by using ‘Screening’ condition as described in Table 4. Figure 6.1 left shows the speed dependence of bearing friction torques for greases with mineral oil. The velocity value of the inner race of the bearing for each bearing rotation speed was indicated in brackets, such as 200 rpm (0.21 m/s). The torque values for all the samples increased with increment of the bearing rotation speed. L-A indicated the minimal torque increase with the rotation speed increase. In contrast, the torque increase of S2-A was remarkably large. In the low rotation speed range of 200 rpm, S1-A provided the lowest torque, while L-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. Figure 6.1 right shows the averaged torque values including deviations for each rotation speed. Each torque value was the averaged torque value during 30 seconds at the end of each duration of each rotation speed. There can be found some deviations, but the rank showing lower torque values did not change.

**Table 6** Sample greases

Grease	L-A	S1-A	S2-A	OilA	L-B	S1-B	S2-B	OilB
Mineral oil (G-I), %	88	92	92	100	-	-	-	-
Poly- $\alpha$ -olefin (PAO), %	-	-	-	-	88	92	92	100
Li complex thickener, %	12	-	-	-	12	-	-	-
Li stearate, %	-	8	-	-	-	8	-	-
Li-12OH-stearate, %	-	-	8	-	-	-	8	-
Penetration (60W)	265	293	359	-	311	305	341	-



**Fig. 6.1** Speed dependence of bearing torque with mineral oil based greases under the ‘Screening’ condition.

In order to investigate the effect of the long duration test, the same test program was continued after finishing the ‘Long duration’ test. Figure 6.2 shows the bearing

torque behaviors under the ‘Repetition’ condition. The bearing torque values were more stabilized compared with Fig. 6.1 left. The most of fluctuations about S1-A and S2-A disappeared. In contrast, L-A still showed lower bearing torque. In the ‘Repetition’ test, the tendency showing lower torque at high rotation speed unchanged. Considering the slow rotation speed of 200 rpm, the tendency was not the same. Figure 6.2 right shows the averaged torque values for each rotation speed. The values were selected during 30 seconds at the end of each duration of each rotation speed. The grease rank showing the lower torque were unchanged except for the condition of 200 rpm. Although the difference is small, S1-A showed the lowest bearing torque in Fig. 6.1. However, the predominance of S1-A diminished in the ‘Repetition’ condition. The bearing torque values at 200 rpm in the ‘Repetition’ condition were almost the same among the three greases. For the understanding the cause of the difference of bearing torque behaviors for greases, greases properties were measured as follows.

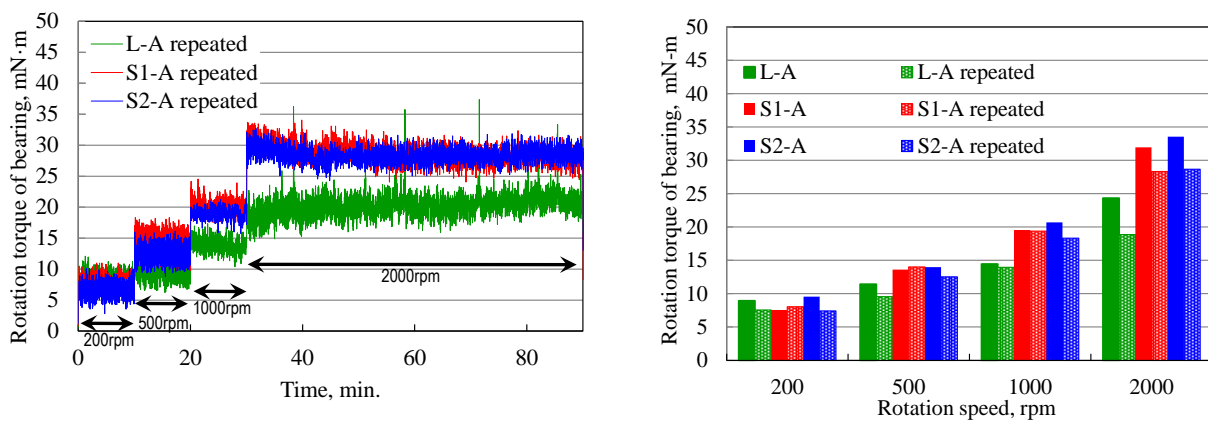


Fig. 6.2 Influence of repetition tests on the bearing torque values for each rotation speed.

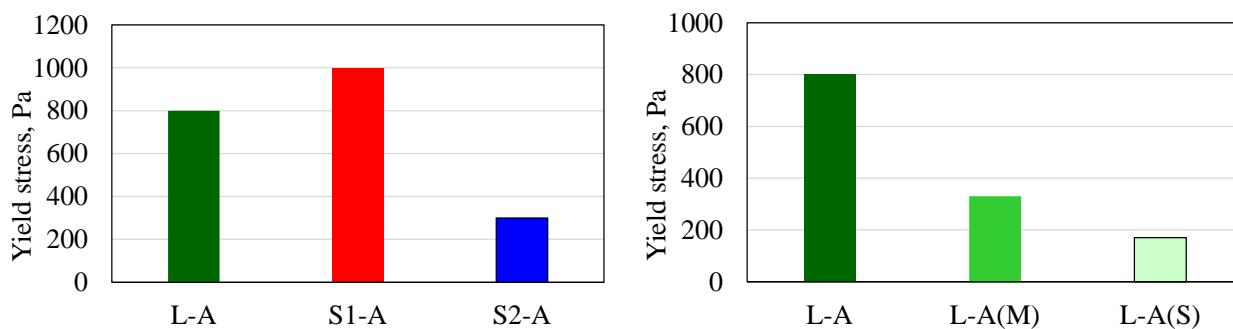
## 6.2 RHEOLOGICAL PARAMETER

As mentioned in 5.3, 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. 6.3. S1-A showed the highest yield stress. Oikawa et al. [8] reported the grease with higher yield stress causes channeling easily and suggested that the grease with higher yield stress causes torque reduction high speed rotation speed (1800rpm, 6305 deep grooved radial ball bearing). However, such behavior of S1-A was not observed in this study as referred in 6.1. One of the reasons can be the different thickener types. In Oikawa’s study, the greases with the same Li-OHSt thickener were used. Regarding the same type thickener, L-A (Li-complex) type greases with the different thickener content were also investigated as listed in Table 7. The penetration (hardness) of greases depends on the thickener content. Figure 6.3 right compares the yield stress of different thickener contents. The harder grease showed the higher yield stress. Considering channeling effect of greases, it is easy to imagine that harder grease can cause channeling more easily. Therefore, the result is

reasonable, however, for grease with different thickener types, the interpretation becomes more complicated.

**Table 7** Additional sample greases

Grease	L-A	L-A(M)	L-A(S)
Mineral oil (G-I), %	88	90	92
Li complex thickener, %	12	10	8
Penetration (60W)	265	289	360

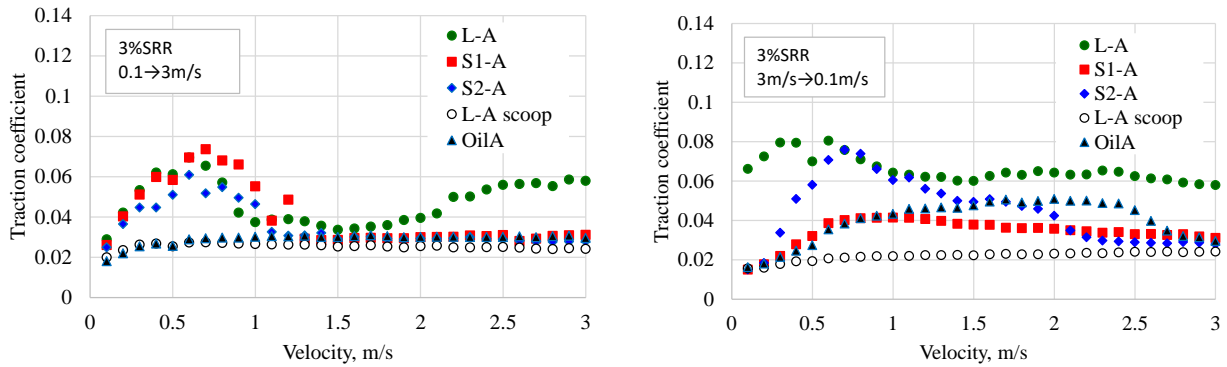


**Fig. 6.3** Yield stress of greases

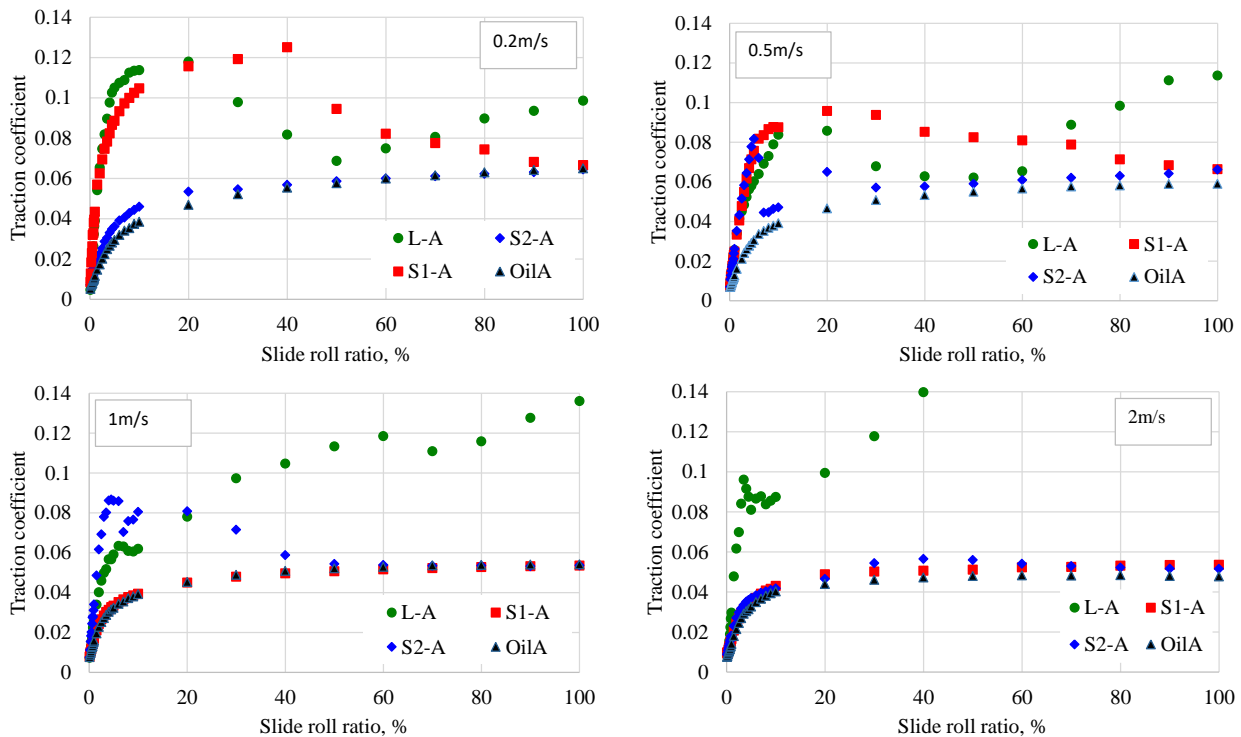
### 6.3 TRACTION PROPERTY

The traction property was investigated using a MTM device. Figure 6.4 compares the velocity dependence of the traction coefficients of the greases and their base oil with 3% of SRR. Without a scoop for maintaining fully flooded conditions, three greases showed the temporary traction increase and with increasing the velocity. The traction increased again at high velocity for only L-A. S1-A and S2-A kept the lower constant traction values at the high velocity region. The base oil used for the greases (OilA) showed the almost constant traction values through the all velocity. The values were close to the traction values of S1-A and S2-A at the high velocity region. In addition, the effect of the scoop was also confirmed for L-A. L-A with the scoop showed the stable traction coefficients close to the base oil. This result suggests that the traction properties of the grease depends on the base oil at least under fully flooded conditions. The increase of the traction values compared with the base oil could be related to the lack of the lubricant at the contact area. Berthe et al. [37] studied the lubricant starvation using a MTM device and reported that the increase of traction coefficients is caused by the lack of lubricants due to the high velocity or the long duration of tests under limited volume of lubricants. In this study, the temporary traction increase for all the greases at low velocity region could be the running-in process of the greases because all the samples showed the behavior commonly. After that, S1-A and S2-A can supply the lubricant (only oil or grease itself) to the contact, therefore the traction values approach those of the base oil. On the contrary, L-A is not able to provide the lubricant to the contact at high velocity region, therefore the traction increases. This phenomenon could be related

to the channeling in the bearing operation at high rotation speed. The traction measurements were continued under deceleration conditions as shown in Fig. 6.4 right. The traction behavior of L-A with scoop was similar to that in acceleration condition. In contrast, the other greases and base oil showed higher traction coefficients compared with Fig. 6.4 left. These traction increase could be the lack of the lubricant to the contact because the lubricant was pushed away at the high velocity conditions in former experiments. This result of the higher traction coefficients of L-A also indicates that L-A is easy to be pushed away from the contact.



**Fig. 6.4** Velocity dependence on traction property (left: acceleration, right: deceleration)



**Fig. 6.5** Slide roll ratio dependence on traction property

The tests of the velocity dependence of the traction property without the scoop conditions seems to reflect the grease movement at the contact. SRR dependence was also investigated in order to confirm the grease movements. Considering the

velocity of the inner race of the bearing at the bearing torque tests, the velocity was selected as 0.2, 0.5, 1, and 2 m/s, corresponding to the 200, 500, 1000, and 2000 rpm, respectively. Figures 6.5 compares the SRR dependence of the greases and the base oil at 0.2, 0.5, 1, 2 m/s, respectively. OilA showed the typical traction curve for each velocity condition. The temporary traction increase was observed for the greases occasionally, similar to the velocity dependence as shown in Fig. 6.4. As the overall tendency, with increasing SRR, L-A showed the traction increase at high SRR conditions following to the temporary traction increase at low SRR and the decrease of the traction (only for low velocity conditions). The traction increase was significant at higher velocity conditions. Conversely, S1-A and S2-A showed the lower traction coefficients which are close to those of the OilA at high SRR conditions. These findings are similar to the velocity dependence results, therefore, it is suggested that L-A is easy to be pushed away from the contact at high SRR condition, compared with S1-A and S2-A. These phenomenon could be related to the bearing torque results at high rotation speed. That will be discussed in the discussion section.

## **6.4 FILM THICKNESS FOR SMOOTH SURFACES**

### **6.4.1 Film thickness under fully flooded conditions**

Figure 6.6 left compares the central film thicknesses for greases and base oil under fully flooded conditions with ‘acceleration’ velocity. Regarding the low velocity region, greases with L-A and S2-A formed thick film thicknesses compared with those formed by the base oil itself since the thickener particle entrainment to the contacts occurred as shown in Fig. 6.7 left, observed interferometry images at 0.025 m/s. The thickness values between L-A and S2-A were similar. In contrast, film thickness values formed by S1-A were close to those of the base oil. At high velocity region, the dependence of thickener types on the film thicknesses turned to be less significant, although all the greases formed thicker films than the base oil to some extent.

The central film thicknesses with the velocity condition of ‘deceleration’ are plotted in Fig. 6.6 right. At higher speed range of more than 0.3 m/s, all the greases gave almost the same thicknesses compared with the condition of ‘acceleration’. However, the thicknesses for the two greases, L-A and S2-A, apparently decreased in low speed range. Figure 6.7 right also illustrates the interferometry images at 0.025 m/s with the velocity condition of ‘deceleration’. The thickener entrainments dramatically diminished about L-A and S2-A. This entrainment changes influenced on the film thickness values especially at low speed. In contrast, OilA and S1-A showed no difference of film thicknesses between the 2 conditions.

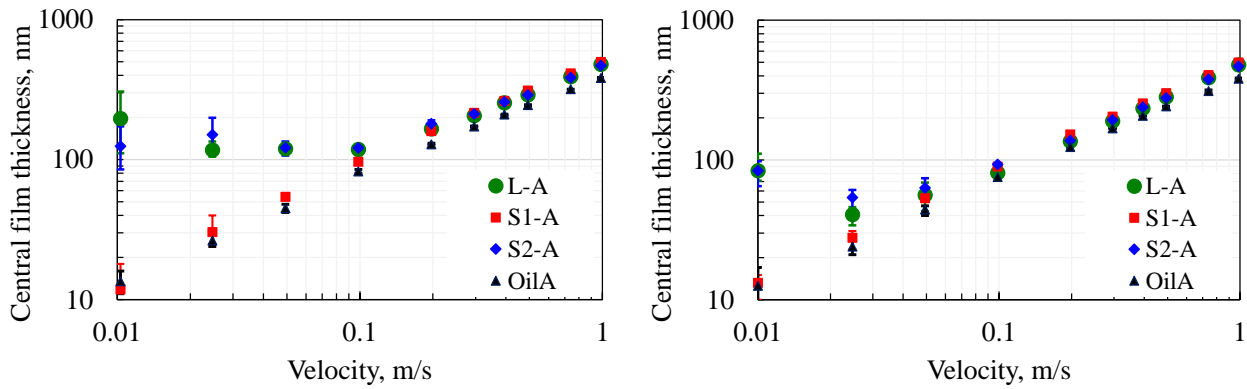


Fig. 6.6 Central film thickness under fully flooded condition (left: acceleration, right: deceleration)

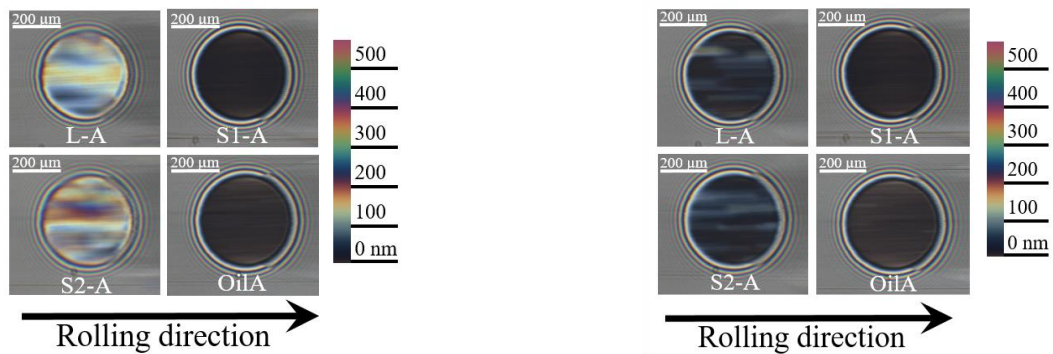
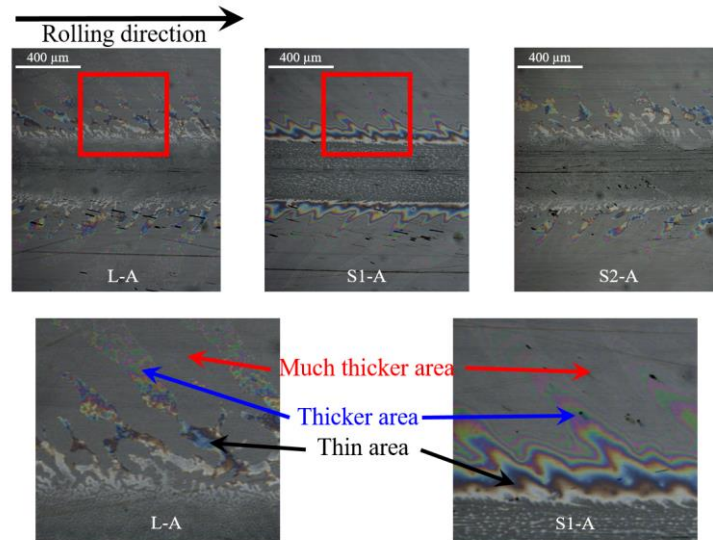


Fig. 6.7 Interferometry images at 0.025m/s (left: acceleration, right: deceleration)

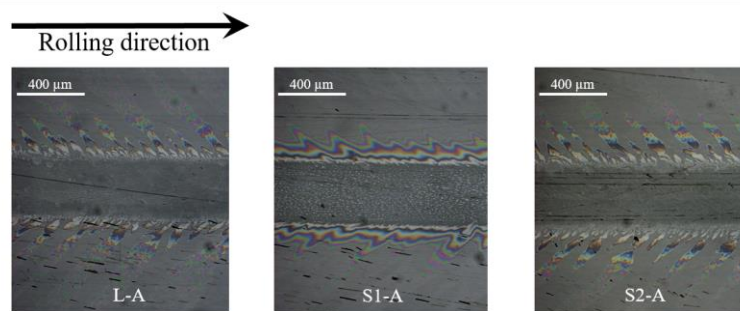
### 6.4.2 Track pattern

Flow patterns created on the disk during film thickness measurements under fully flooded conditions were also investigated. Figure 6.8 compares the patterns at the low velocity of 0.025m/s without high speed history ('acceleration' condition). These images show the contact track in the center and the flow patterns on both sides of the track. It was reported that the finger-like patterns are formed by the outlet cavity [25, 26], and the patterns were dependent on the thickener types in this study. Both L-A and S2-A showed flow patterns stretching to the track. In contrast, the pattern formed by S1-A did not reach to the track. This difference can be recognized more clearly in the magnified images of L-A and S1-A. The color of the images is relevant to the thickness of the grease to some extent, like Fig. 6.7. However, it should be noted that the value of the thickness is not precise, because the interference is not related between the steel ball and the glass disk but between the air and the disk. Although the interference colors do not show adequate quantitative values, it can be stated that brown and dark blue show thinner film (shown in black arrows) and green and purple show thicker film (shown in blue arrows), and no colors (or grey) show much thicker film (shown in red arrows). For instance, in the flow pattern of the side track of L-A, there can be found that thick area without colors and thin area with some colors repeat alternately. The thick area without colors distributed to the near side of the track. In the case of the S1-A, the edge of the track was surrounded by the thin area such as brown color. These difference could relate to the film thickness behaviors.

As well as the film thickness measurements in order to understand the influence of the high speed history, the flow patterns were compared in the speed of 0.025 m/s with the velocity condition of ‘deceleration’ as show in Fig. 6.9. The flow pattern on the side track formed by S1-A was almost the same to the one observed under the ‘acceleration’ condition as shown in Fig. 6.8. In the cases of L-A and S2-A, the flow patterns after high speed condition became more distinct compared with those in Fig. 6.8. These pattern changes indicate the correlation with the film thickness changes observed in Fig. 6.6.



**Fig. 6.8** Grease flow patterns at the downstream of the contact at 0.025m/s (acceleration) and magnified images of the zone shown in red rectangles



**Fig. 6.9** Grease flow patterns at the downstream of the contact at 0.025m/s (deceleration)

### 6.4.3 Film thickness under starved conditions

Figure 6.10 shows the grease film thickness transition with the velocity increase without a scoop under starved conditions. The film thickness values for all the greases showed the transition to starvation between 0.2 and 0.5 m/s. In the low speed range just before the film thickness drops, the film thickness values were similar to those under fully flooded conditions as shown in Fig. 6.6. The grease film thickness transition related to the starvation corresponded to the former research [17]. The film decay of S1-A occurred early in 0.2 m/s, and that of S2-A did latest in more than 0.3 m/s. The interferograms of the contacts for each grease were

illustrated in Fig. 6.11 at 0.25 m/s. S1-A shows the typical starvation image with the visible meniscus. Conversely, L-A and S2-A did not reach the starvation and kept substantial film thicknesses in spite of the approach of the meniscus to the contacts. Comparing L-A and L-A(S) (with the higher worked penetration), the film decay occurred relatively late in L-A(S), therefore, it suggests that the softer grease can contribute to the higher lubricant replenishment.

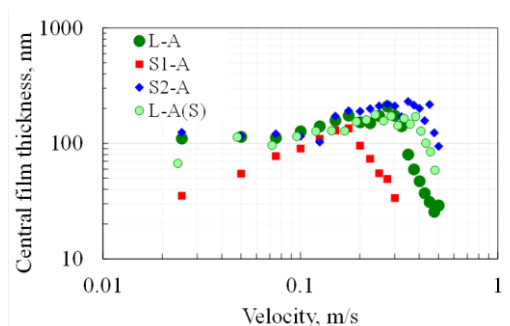


Fig. 6.10 Central film thickness of greases under starved condition

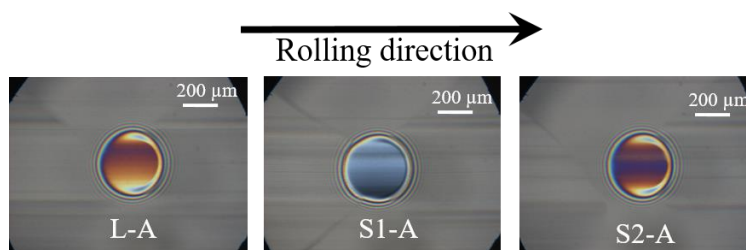
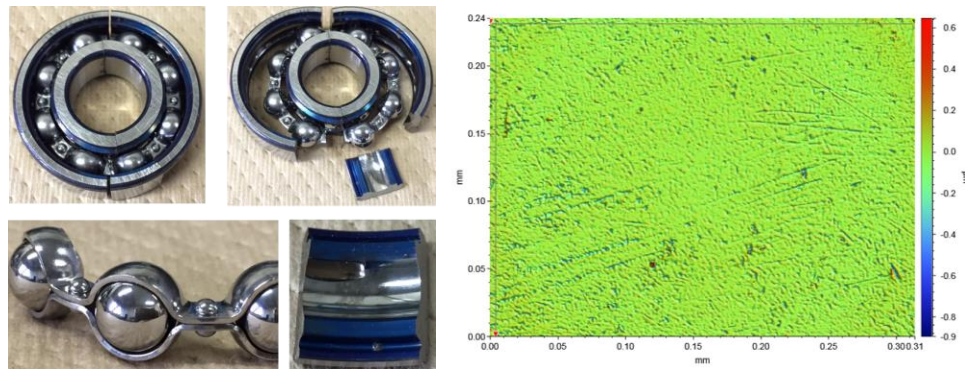


Fig. 6.11 Interferometry images at 0.25m/s (starved conditions)

## 6.5 FILM THICKNESS FOR DENTED SURFACES

### 6.5.1 Surface profiles of bearing

Surface profiles of the bearing used in the bearing torque tests were determined by 3D optical interferometry in order to compare the real asperity of the bearing surfaces and the dented surfaces produced in this study. A 6204 bearing was cut for the observation of the surfaces of each bearing part as shown in Fig. 6.12 left and the surface profile of the bearing ball is illustrated in Fig. 6.12 right. The RMS roughness values of 6204 bearing ball, outer race, and inner race were about 25, 20, and 27 nm, respectively. However, from the profiles the asperities of hundreds of nanometers were observed on all the bearing surfaces. Therefore, it is valuable to consider the influence of dents of a few hundreds of nanometer depth (see Table 3) on the film thickness in this study although the aspect ratios of the asperity of the real bearing and the dents produced in this study are not the same.

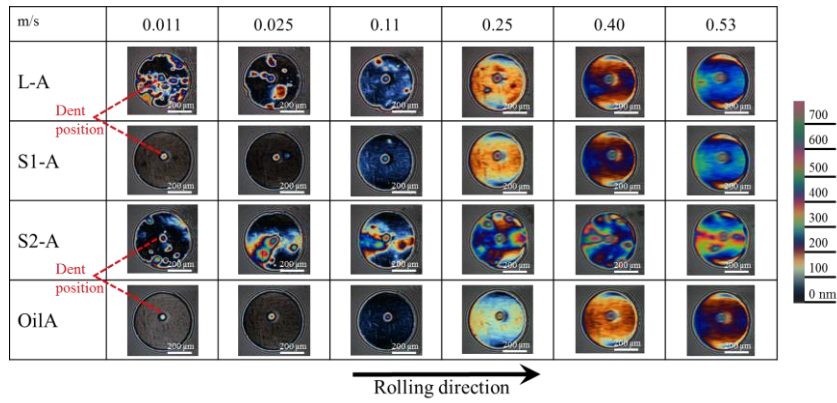


**Fig. 6.12** 6204 bearing and the surface profile of a ball of the bearing

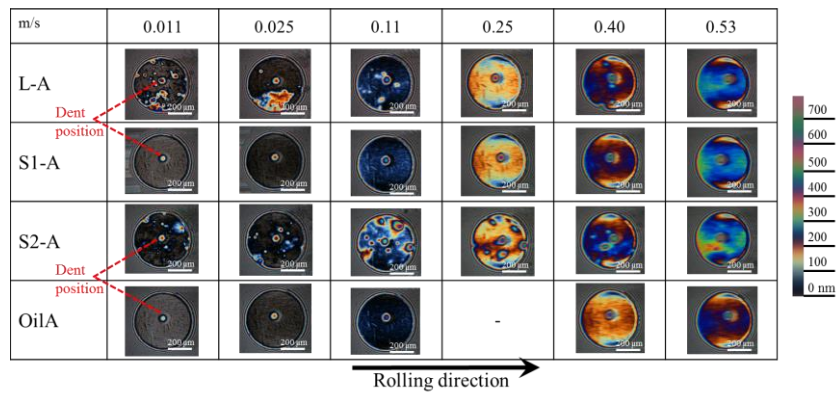
### 6.5.2 Film thickness under fully flooded conditions

The effect of the dent size on the film thickness was investigated for the greases and the base oil. Figures 6.13 and 6.14 shows the representative interferometry images when the dented ball produced by the WC indenter with a diameter of 1.27 mm was used. The images were captured when the dents of the ball approached the center of the contact.

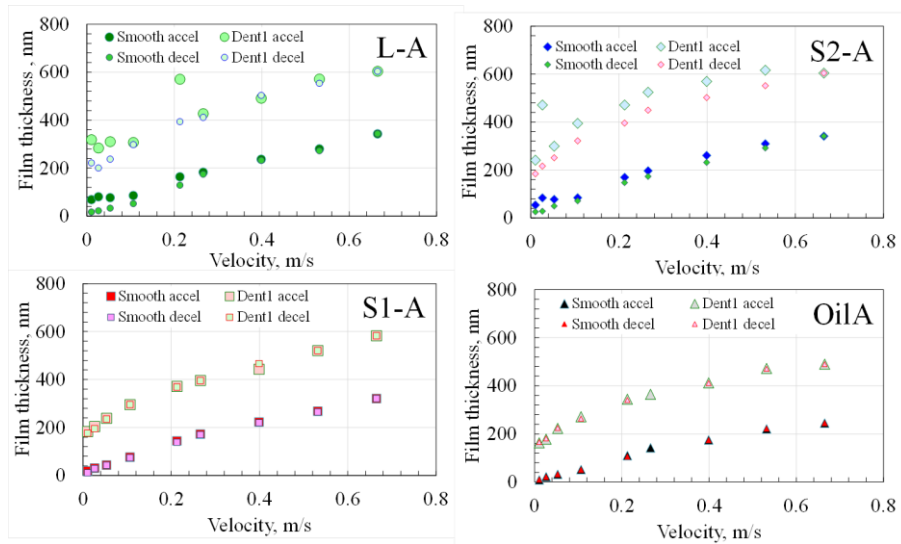
The film thicknesses on the dents were higher than those on the smooth area. The film decrease at the downstream of the dents was also observed, corresponding to the previous study in oil lubrication [28, 30, 31]. In this study, the thickener entrainments to the contact were found in the case of L-A and S2-A, not only in smooth areas but also in dented areas. There can be found the tendency that the thickener particles of S2-A were dragged into the dents more frequently than those of L-A. The entrainment was rarely observed for S1-A. For the thickener entrainment, the film decrease at the downstream of the particles was not observed in these interferometry images. The values of the central film thickness on smooth areas and the thickness on dents were shown in Fig. 6.15. ‘Accel’ and ‘decel’ mean the conditions of ‘acceleration’ and ‘deceleration’, respectively. The values of the film thickness were the averaged values calculated from 5 captured images since the values fluctuated especially at low speeds. Under the ‘acceleration’ conditions, L-A and S2-A showed much higher film thickness on dents occasionally, not always. That increase depends on the random entrainments of the thickener to the dents. However, the most of film increases on the dents in L-A and S2-A disappeared under the ‘deceleration’ condition. The tendency is similar to the results for smooth surfaces contacts as shown in Fig. 6.6. S1-A and the base oil did not show such ‘inconsistency’ on the film thickness for dented surfaces, because the thickener entrainments to the dents did not occur. The differences between smooth and dented areas were almost the same in S1-A and the base oil. The difference values are also close to the case of L-A and S2-A under the ‘deceleration’ condition. That suggests that grease film behavior on dents is similar to oil behavior if the thickener does not enter the dent.



**Fig. 6.13** Interferometry images on the dented surface produced by the indenter of 1.27mm (dent1, acceleration)



**Fig. 6.14** Interferometry images on the dented surface produced by the indenter of 1.27mm (dent1, deceleration)



**Fig. 6.15** Film thickness of central smooth and dented areas under fully flooded conditions (indenter of 1.27mm)

## 7 DISCUSSION

The results obtained in 6.1 indicate that the rank showing the lower bearing torque be influenced by the bearing rotation conditions.

In the low rotation speed region of 200 rpm, S1-A with Li-St showed the lower bearing torque. This tendency could correlate to the film thickness behaviors at low speeds. Li-St thickened grease forms thinner film thickness similar to the base oil and that Li-complex and Li-OHSt thickened greases form thicker film thickness at low speed. This difference is attributed to the thickener particle entrainment to the contact. This particle entrainment could disturb the smooth rotation in bearings and cause the higher bearing torque at low rotation speed conditions.

The thickener chemical structures could be one of the reasons of thickener entrainment to the contact. For instance, high polar 12-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.

As another finding on the bearing torque in low speed conditions, the effect of the ‘repetition’ is shown in Fig. 6.2. The bearing torque of each grease at 200 rpm under the ‘repetition’ condition was almost the same. These phenomena seem to correspond to the film thickness behaviors at low speeds under ‘deceleration’ conditions. Figures 6.6 and 6.7 suggest that the film augmenting effects of L-A and S2-A diminish after high speed conditions. The film thickness decrease at low speed after high speed condition can relate to the torque decrease of L-A and S2-A at 200 rpm after long duration tests.

The results described in 6.1 indicate the consistent lower bearing torques with L-A at 2000 rpm. As another correlation factor of the bearing torque in high speed conditions, the traction coefficients behavior of greases without the scoop can be raised rather than grease yield stress. As described in 6.3, L-A showed the tendency of traction coefficient increase at high velocity or SRR conditions compared with S1-A and S2-A. This increase could be due to the lack of the lubricant to the contact because the lubricant was pushed away during the disk rotation. This traction behavior of L-A without the scoop could be an indicator of the channeling of greases.

The obtained results in this study are summarized in Table 10 regardless of the relationship with the bearing torque. Regarding the typical grease like behaviors about the film thickness of Li-complex and Li-OHSt, The main reason could exist on the thickener particle entrainment to the contact area. The thickener entrainment influences not only the film thickness but also the flow patterns. Li-complex and Li-OHSt thickened greases showed flow patterns at the side track of downstream of the contact. The images that thick area without colors distributes to the near side of the track as shown in Fig. 6.8 could be attributed to the thickener entrainments to the contacts. In Fig. 6.8, the large sized thickener particles pass through the contact to the side track, therefore the patterns are not so homogenized. After high speed condition, the thickener particles turn to be small and the flow pattern formed by

particles passing through the contact to the side track becomes clear as shown in Fig. 6.9.

For the film thickness measurement under starved conditions without using a scoop, the Li-St thickened grease caused the quick starvation as shown in Fig. 6.10. One of the reasons could be that the Li-St thickener is not dragged into the contact. Without thickener entrainments, the lubricant replenishment to the contact reduces. In addition, the Li-OHSt thickened S2-A caused later starvation. Worked penetrations of S2-A and L-A(S) are almost the same, therefore the cause of difference should be the thickener type. L-A and S2-A with different thickeners have shown almost the same behaviors such as thick film thickness in slow speeds, similar flow patterns at the side of the track, and the influence of the high speed conditions on the film thickness and the flow patterns. The difference between the two greases can be observed in the film thickness formed between a dented ball and a glass disk.

The thickener entrainment to the contact area between a dented ball and a glass disk was observed in L-A and S2-A as well as between the smooth surfaces in order to understand thickener dependence on the particle entrainment to the dent. The thickener particles of the two greases sometimes existed on the dent positions, however the tendency of the greases was different. The thickener particles of L-A entered both smooth and dented areas independently. It was often observed that the thickener particles of S2-A existed near the dent areas. As a result, it was frequently observed that the thicknesses on the dents were higher in S2-A rather than in L-A. In addition, considering the result of the film thickness decay as shown in Fig. 6.10, the easier entrainment of S2-A to the contact and dents could bring the higher replenishment effect and postpone the starvation.

Although there is not complete evidence, it is possible that one of the causes of the difference is the chemical structure of the thickeners. Li-complex consists of Li-12-hydroxy stearate and Li-azelate, on the contrary Li-OHSt is composed of only Li-12-hydroxy stearate. The ratio of the 12-hydroxyl groups of aliphatic chain is higher in S2-A compared with L-A, and that difference could influence the thickener entrainment to the dented area. The higher polarity of S2-A thickener could be effective in introduction to the dented area. In other words, it can be considered that higher polarity thickener is easy to be entrained to the contact area.

**Table 8** Summary of the results

Supply	Surface	Property	Li-complex	Li-OHSt	Li-St
Flooded	Smooth	Thickness	Thick in slow speed Influenced by high speed history		Close to base oil No change after high speed
		Flow pattern	Finger patterns on side track Sharpened by high speed history		No fingers in high speed
		Film decay	Late starvation		Quick starvation
Flooded	Dented	Particle entrainment	Occurred	Frequently occurred	Not occurred

## 8 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 present thesis deals with the dependence of the base oil and the Li thickener types of model greases on the bearing torque behaviors. Grease parameters such as rheology and thickener fiber structure and film thickness including surface texturing and track patterns were investigated in order to understand the relationship with the bearing torque behaviors. Especially, the effect of surface texturing on the grease film thickness had not been investigated yet.

According to the bearing torque results, the grease rank showing lower bearing torques differed by depending on the bearing operating conditions. S1-A (mineral oil and Li-St thickener) provided the lowest bearing torque at low speed condition, and L-A (mineral oil and Li-complex thickener) reduced the bearing torque at high speed condition. Grease parameters were investigated focused on the thickener dependence.

For the low speed conditions of the bearing, the film thickness behaviors seem to correlate to the bearing torque behaviors. Grease thickener entrainments to the contacts (Li-complex and Li-OHSt) build up the film thickness at low speed conditions, however, that could cause the increase of the torque in the bearing since the thickener fibers or particles might prevent smooth rotations of bearing balls. This idea is also supported by the bearing tests under ‘repetition’ conditions. After operations at high speed conditions, the bearing torques with Li-complex and Li-OHSt thickened greases at low speed condition reduced compared with the first operations and the torque values were almost the same to the Li-St thickened grease. In addition, the film augmenting effect of Li-complex and Li-OHSt diminished in the film thickness measurements with ‘deceleration’ conditions. The reason should be that grease thickener particles are broken into small fragments during the high speed conditions. The film thickness and bearing torque behaviors at low speed conditions seem correlate each other.

At high speed conditions for the bearing operation, the grease channeling could be the important factor for the bearing torque. Instead of the yield stress, the traction coefficient behaviors of greases without grease supply could be a standard showing the grease channeling. Li-complex thickened grease (L-A) showed the obvious traction increase at high velocity or SRR conditions compared with other Li type thickeners. This traction increase could be the lack of the lubricant to the contact because the lubricant was pushed away at the high velocity or SRR conditions. This traction behavior of L-A without the grease supply could be an indicator of the channeling of greases.

Except for the bearing torque relationship, there can be found some correlations among the grease properties. The grease thickener entrainments to the contact influence on not only film thickness but also the flow patterns created at the

downstream of the contact. The definite track patterns were observed for Li-complex and Li-OHSt thickened greases with particle entrainments. The patterns are also influenced by the speed history. At low speed conditions, the large sized thickener particles pass through the contact to the side track, therefore the patterns are not so homogenized. In the high speed condition, the thickener particles are broken into small particles. After that, the flow pattern formed by finer particles passing through the contact to the side track becomes clear. In contrast, track patterns were not observed clearly for Li-St thickened grease without thickener entrainment to the contact. This phenomenon could correlate to the starvation behaviors. The Li-St thickened grease caused the quick starvation. Not thickener entrainments to the contact could reduce the lubricant replenishment to the contact.

Between the Li-complex and Li-OHSt thickened greases, the difference can be confirmed on the film thickness behaviors on dented surfaces. The thickener particles of the two greases sometimes existed on the dent positions, however, it was often observed that the thickener particles of S2-A existed near the dent areas compared with L-A. The easier entrainment of S2-A to the contact and dents could bring the higher replenishment effect and postpone the starvation. It is possible that one of the causes of the difference is the chemical structure of the thickeners. Li-complex consists of Li-12-hydroxy stearate and Li-azelate, on the contrary Li-OHSt is composed of only Li-12-hydroxy stearate. High polar 12-hydroxyl groups of aliphatic chains could have higher affinity for the metal surface, since the surfaces should have some polarity, and promote the entrainment of greases into the contact area. The higher polarity of S2-A thickener could be effective in introduction to the dented area. On the contrary, the Li-St thickener is not entrained to the contact due to lower polarity, therefore the thickness building up effect is limited and the film thickness behavior is similar to the base oil.

In association with the scientific questions and the working hypotheses, the findings from this thesis can be concluded as follows.

- Rheological factor

The yield stress can occasionally be an indicator of reducing the bearing torque at high speed when the same type thickener greases are used. The tendency cannot be applicable for different thickener greases. Regarding the grease channeling, the traction increase behaviors without grease supply could correlate the bearing torque behaviors at high speed conditions. The apparent viscosity itself cannot predict the bearing torque behaviors. (Hypothesis was partially confirmed)

- Thickener structure (discussed in full PhD thesis)

Thickener fiber structures were measured by TEM observation. The fibers of Li-complex were thinner and longer, in contrast the fibers of Li-St and Li-OHSt were thicker and shorter. Greases with the similar thickener structure showed different torque behaviors. In addition, film thickness behaviors were also different between

the greases. The fiber structures do not reflect the bearing torque behaviors. (Hypothesis was falsified)

- Ability of film thickness and adaptability to surface conditions

Greases with Li-complex and Li-OHSt thickener showed higher film thickness especially at low speed. Contrary to expectations, the two type greases showed higher bearing torques at low speed conditions. The film thickness behavior of the Li-St thickened grease was similar to the base oil. The Li-St grease showed lower bearing torque at low speed. Regarding the film thickness behaviors on dented surfaces, Li-OHSt showed higher adaptability to the surface condition. However, the effect does not correlate with the torque behaviors. In contrast, the adaptability could be effective for grease replenishment to the contact. In addition, at high speed conditions, the dependence of the thickener types on the film thickness turns to be negligible and close to the base oils. Therefore, the correlation with the bearing torque at high speeds is weak. (Hypothesis was falsified)

- Grease parameter correlation

Grease thickener entrainments influence on some grease properties, for instance, the film building up effect at low speeds, the formation of track patterns at the downstream of the contact, and the delay of the starvations. The behaviors of the film thickness and the track patterns were linked including the high speed history. The starvation is also related with the film thickness formation especially on dented surfaces, in other words, Li-OHSt thickened grease showed higher film thickness on the dented areas and the later starvation. (Hypothesis was confirmed)

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## **ABSTRACT**

In this dissertation thesis, radial ball bearing torque tendency was evaluated with Li type greases, considering base oil and thickener dependence. Analyses of the reason why each grease formulation provides the different bearing torque were conducted considering comprehensive grease properties, such as rheological parameter and thickener structure and friction and film thickness behaviors of EHL films. Observation of EHL film thickness measured by colorimetric interferometry has enabled detailed insight into the behavior of grease within smooth and dented surfaces. Investigating grease film thickness behaviors on non-smooth surfaces and discussing the influence on the bearing torque were novel approaches in this field. It was found that the film thickness behaviors seem to have a relationship with bearing torque at low rotation speeds and the yield stress and traction behaviors correlated with the bearing torque values at high rotation speed conditions. It was observed that the grease thickener entrainments to the contact areas influence on the film thickness at low speed and track pattern formations at the downstream of the contact areas, and starvation behaviors. The reason of the thickener entrainments exists on the chemical structure of thickeners. The high polarity of the hydroxyl group of the thickener promotes the entrainments to the contact surfaces. On the dented surfaces, the grease with the highest polarity showed the frequent entrainments to the dent areas. The obtained findings could be significant knowledge for the development of advanced greases featuring energy-saving performance of machine parts.

## **ABSTRAKT**

Tato disertační práce se zaměřuje na studium závislosti mezi reakčním momentem ložiska mazaného plastickým mazivem s lithným mýdlem a vlastnostmi maziva, jako například tloušťka vytvářeného mazacího filmu, jeho reologie, struktura zpevňovadla, trakční vlastnosti či vliv topografie povrchu. Typ maziva poskytujícího nižší odpor závisí na podmínkách provozu ložiska, zejména rychlosti. Chování mazacího filmu za nízkých rychlostí má vliv na reakční moment ložiska v nízkých rychlostech. Mez toku a trakční chování koreluje s momentem ložiska za vysokých rychlostí. Schopnost zpevňovadla vstupovat do kontaktu má vliv na tloušťku filmu, vzhled kavitační oblasti na výstupu kontaktu a chování hladovění. Důvod vstupu zpevňovadla do kontaktu je jeho chemická struktura. Vysoká polárnost hydroxylových sloučenin zpevňovadla podporuje jeho vtažení kontaktními povrchy. Mazivo s nejvyšší polaritou prokázalo na površích obsahujících denty nejčastější vstup do prostoru dentů. Na základě předchozích pozorování je navržen popis principu mechanismu mazání.