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

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Faculty of Mechanical Engineering
Brno University of Technology

Defense of the PhD thesis
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2. State of the art review and analysis
3. Essence and goals of the PhD thesis
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Introduction - Grease product development

Global demand for energy-saving properties in order to reduce CO₂ emissions.

Requirement for grease development

1. High performance grease reducing bearing mechanical loss
2. Persuasive mechanisms of performance for customers

Mission

Clarifying the relationship between grease formulations and mechanical losses (bearing torque)
State of the art review and analysis

1. Bearing torque under grease lubrication

1.1 Thrust type

Seabra et al. decomposed a total friction torque into rolling torque and sliding torque.

Relevance; **Rolling torque: base oil viscosity**

- High viscosity $\Rightarrow$ High rolling torque

Limitation: thrust type bearing, commercial greases


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1. Bearing torque under grease lubrication

1.2 Radial type

Yokouchi et al. indicated relationship between bearing torque and yield stress of greases.

**High yield stress → Torque reduction**

**Due to grease channeling**

Limitation: one type thickener grease (Li-12OH-stearate)

2. Grease behaviors in a bearing

Venner et al. estimated the reduction of the grease film thickness in bearings by numerical simulations of grease flows.

The transition from flooded region to heavily starved contact

Bearings can be operated in not only flooded but also starved conditions.

Limitation: no direct information about relationship with bearing torque

3. Film thickness under grease lubrication

Cann et al. reported the behaviors of grease film thickness in EHL.

- Grease is pushed away with disk rotations.
- Under fully flooded condition, greases augment film thickness in slow speed.

Limitation: no direct information about relationship with bearing torque


Defense of the PhD thesis
4. Surface texturing for film thickness (oil lubrication)

Mourier et al. indicated shallow micro cavity can increase Film thickness under rolling/sliding condition.

Krupka et al. showed deep micro dents decrease film thickness but shallow micro dents increase.

Possibility of improvement of film thickness by surface texturing depending on the specific conditions in spite of non-conformal contacts

Limitation: no application to grease lubrication


Defense of the PhD thesis
State of the art review and analysis

**Bearing torque with grease**
- Thrust type
  - Seabra (Cousseau)
    - ✔ Rolling/Sliding torque factor
    - ✗ Only commercial grease
- Radial type
  - Yokouchi (Oikawa), Dong
  - ✔ High thickness in slow speed
  - ✗ Only 1 type Li thickener and base oil

**Main focus**

**Film thickness**
- Yokouchi
  -✔ Channeling effect
  - ✗ Only 1 type Li thickener
- Dong
  - ✔ High thickness in slow speed
  - ✗ Only 1 type Li thickener and base oil

**Loss Factors**
- Rheology
- Yield stress
- In bearing simulation
- Starved condition
- Chemical Analysis (IR)
- Surface texturing
- Track pattern

**Unknown parameters for Bearing torque**
- Venner
  - ✔ Film decay in operation
- Cann
  - ✔ Viscosity, thickener content effect
  - ✔ Thickener deposition on track
  - ✔ Urea thickener’s entrainment
- Mourier, Krupka
  -✔ Shallow cavity/dent increase the thickness
- Sugimura (Chen)
  -✔ Related to starvation

Defense of the PhD thesis
Essence and goals of the PhD thesis

1. Understanding of influence of grease formulation (focused on Li thickener) on radial ball bearing torque
2. Analysis of grease properties for clarification of lubrication mechanism
3. New approach as grease EHL film observation including surface texturing

New findings for future grease product development
Essence and goals of the PhD thesis

◎Study of the relationship between grease formulations and bearing torque

- Base oil
- Thickener

Grease formulation

- Rheology
- Thickener fiber structure
- Film thickness including surface texturing

Factor evaluation

Defense of the PhD thesis
Scientific questions and working hypotheses

Questions

● How do properties of grease influence on the radial ball bearing torque?
● Are there relations among the grease properties?

Working hypotheses

1. Rheological factor ⇒ Yield stress and/or viscosity
2. Thickener structure ⇒ Thickener fiber shape and size
3. Ability of film thickness and adaptability to surface conditions ⇒ Thicker film on both smooth and textured surfaces is better for torque reduction
4. Those factors correlate each other
## Research method

### 1. Grease samples

- Low viscosity grade oil
- Lithium type thickener : Considering recent trend of grease development

<table>
<thead>
<tr>
<th>Samples</th>
<th>L- (Li-Complex)</th>
<th>S1- (Single Li)</th>
<th>S2- (Single Li)</th>
<th>Base oil</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base oil</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>OilA: Mineral oil</strong> (API Group-I), Kinetic viscosity(40℃): 33.2 mm²/s, VI:107</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>OilB: Poly-α-olefin</strong> (API Group-IV), Kinetic viscosity(40℃): 30.6 mm²/s, VI:135</td>
</tr>
<tr>
<td><strong>Thickener</strong></td>
<td>12OH-stearic/</td>
<td>Stearic-Li</td>
<td>12OH-stearic-Li</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>azelaic-Li</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dropping point</strong></td>
<td>250 °C</td>
<td>200 °C</td>
<td>200 °C</td>
<td>-</td>
</tr>
</tbody>
</table>
Research method

2. Bearing torque (JXTG)
- Original frictional torque measuring rig for grease
- Rotation speed dependence for each grease
Bearing torque -screening-

<table>
<thead>
<tr>
<th>Grease</th>
<th>L-A</th>
<th>S1-A</th>
<th>S2-A</th>
<th>L-B</th>
<th>S1-B</th>
<th>S2-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base oil</td>
<td>Mineral oil (G-I), %</td>
<td>88</td>
<td>92</td>
<td>92</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Poly-α-olefin, %</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>88</td>
<td>92</td>
<td>92</td>
</tr>
<tr>
<td>Thickener</td>
<td>Li complex, %</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Li stearate, %</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Li-12OH-stearate, %</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>Penetration (60W)</td>
<td>265</td>
<td>293</td>
<td>359</td>
<td>311</td>
<td>305</td>
<td>341</td>
</tr>
</tbody>
</table>

Test condition

- Bearing: 6204 without seal
- Lubricant content: 2g
- Rotation speed: 200-500-1000-2000rpm
- Duration: 10 min. each
- Temperature: 25 ℃
- Thrust load: 50 N
- Radial load: 50 N
- Evaluation: Friction torque

L-A: the lowest torque high (2000 rpm) speed
S1-A: the lowest torque in low (200 rpm) speed
Bearing torque - long duration and repetition -

Long duration

Rotation torque of bearing, mN·m

0 20 40 60 80
Time, min.

0 5 10 15 20 25 30 35 40 45 50

L-A
S1-A
S2-A

200rpm
2000rpm
500rpm
1000rpm

Repetition

Rotation torque of bearing, mN·m

0 20 40 60 80
Time, min.

0 5 10 15 20 25 30 35 40 45 50

L-A repeated
S1-A repeated
S2-A repeated

200rpm
500rpm
1000rpm
2000rpm

Test condition

<table>
<thead>
<tr>
<th>Test condition</th>
<th>6204 without seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing</td>
<td>2g</td>
</tr>
<tr>
<td>Lubricant content</td>
<td>2g</td>
</tr>
<tr>
<td>Rotation speed,</td>
<td>200(10min.)</td>
</tr>
<tr>
<td>Duration</td>
<td>-500(10min.)</td>
</tr>
<tr>
<td></td>
<td>-1000(10min.)</td>
</tr>
<tr>
<td></td>
<td>-2000rpm(60min.)</td>
</tr>
<tr>
<td>Temperature</td>
<td>25 °C</td>
</tr>
</tbody>
</table>

L-A: Li-complex
S1-A: Single Li-Stearate
S2-A: Single Li-12OH-Stearate

The lowest torque of S1-A in low speed disappeared in repeated condition

→Grease property investigation
Rheology -Viscoelasticity-

**Test condition**
- **Plate diameter**: 25 mm
- **Frequency**: 1 Hz
- **Deformation**: 0.001-100%
- **Temperature**: 25 ℃

S1-A showed the highest yield stress. (Contrary to past reports)

Yield stress does not predict torque behavior for different thickener types.
**Thickener structures of thickeners observed by TEM**

<table>
<thead>
<tr>
<th>TEM</th>
<th>(Transmission Electron Microscope)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Extraction</td>
<td>Hexane</td>
</tr>
<tr>
<td>Acceleration voltage</td>
<td>20kV</td>
</tr>
<tr>
<td>Amplitude</td>
<td>$\times 10000$</td>
</tr>
</tbody>
</table>

**L-A:** thin and long fiber networks

**S1-A** and **S2-A:** thick and short fiber networks

Relationship with bearing torque is not confirmed.

**Table:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>L-A:</td>
<td>Li-complex</td>
</tr>
<tr>
<td>S1-A:</td>
<td>Single Li-Stearate</td>
</tr>
<tr>
<td>S2-A:</td>
<td>Single Li-12OH-Stearate</td>
</tr>
</tbody>
</table>
Traction coefficient - velocity dependence -

Without scoop, temporary traction increase

L-A showed traction increase at high speed.

With scoop, the traction is the same to base oil.

Traction increase of L-A could be due to lack of lubricants (channeling in bearing)

**MTM**

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Specimen</th>
<th>Test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ball</td>
<td>Steel φ19.05 mm</td>
</tr>
<tr>
<td></td>
<td>Disk</td>
<td>Steel</td>
</tr>
<tr>
<td>Mean Hertzian pressure</td>
<td></td>
<td>430 MPa (10N)</td>
</tr>
<tr>
<td>Velocity</td>
<td></td>
<td>0.1-3-0.1 m/s</td>
</tr>
<tr>
<td>Slide roll ratio</td>
<td></td>
<td>3 %</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>25 ℃</td>
</tr>
<tr>
<td>Grease supply</td>
<td></td>
<td>V-shaped scoop</td>
</tr>
</tbody>
</table>

**Sample**

<table>
<thead>
<tr>
<th>Sample</th>
<th>L-A</th>
<th>S1-A</th>
<th>S2-A</th>
<th>OilA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base oil</td>
<td>88</td>
<td>92</td>
<td>92</td>
<td>100</td>
</tr>
<tr>
<td>Thickener</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li complex</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Li stearate</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Li-12OH-stearate</td>
<td>-</td>
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</tbody>
</table>
Film thickness and indentation

Film thickness

- Colorimetric interferometry technique
- Smooth / dented steel ball on glass disk
- Fully-flooded / starved condition

Target depth: 200-400nm depth

→Tungsten carbide (WC) ball indentation

Diameter: 2.5mm, 1.6mm, 1.27mm
Fully flooded condition - smooth, acceleration -

L-A and S2-A showed thick film thickness in slow speed.

Grease film thicknesses close to base oil in high speed.

Thickener particles entrainment increased film thickness in slow speed.

Test condition

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ball</th>
<th>Steel φ25.4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk</td>
<td></td>
<td>Cr-coated glass</td>
</tr>
<tr>
<td>Mean Hertzian pressure</td>
<td>290 MPa</td>
<td></td>
</tr>
<tr>
<td>Hertzian contact diameter</td>
<td>348 μm</td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>0.01-1 m/s</td>
<td></td>
</tr>
<tr>
<td>Slide roll ratio</td>
<td>0 % (nominally)</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>23 ℃</td>
<td></td>
</tr>
<tr>
<td>Grease supply</td>
<td>V-shaped scoop</td>
<td></td>
</tr>
</tbody>
</table>

L-A: Li-complex
S1-A: Single Li-Stearate
S2-A: Single Li-12OH-Stearate
**Fully flooded condition - smooth, deceleration -**

Film thicknesses unchanged in high speed.

Film augmenting effect decreased in slow speed.

**Test condition**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Test condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball</td>
<td>Steel φ25.4 mm</td>
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<tr>
<td>Velocity</td>
<td>0.01-1 m/s</td>
</tr>
<tr>
<td>Slide roll ratio</td>
<td>0 % (nominally)</td>
</tr>
<tr>
<td>Temperature</td>
<td>23 °C</td>
</tr>
<tr>
<td>Grease supply</td>
<td>V-shaped scoop</td>
</tr>
</tbody>
</table>

Thickener particles effect decreased

Thickener particles could be influenced by high speed condition.
**Track patterns of downstream (0.025 m/s)**

**Acceleration**

- Lubricant flow

**Deceleration**

- Lubricant flow

Side "fingers" sharpened after high velocity conditions for L-A, S2-A

The fingers of S1-A were not clear
Starved conditions

Velocity increased by 0.024 m/s every 30 sec. without grease supply

Film thickness decay of S1-A occurred in low velocity.

The tendency that thickener particles of S1-A are not dragged into the contact area might cause early starvation without grease supply.
Bearing surface profile

Asperity of hundreds of nanometer exists on the real bearing surfaces.

Influence of 3 types of dents on film thickness were investigated.

Defense of the PhD thesis
### Fully flooded conditions -dented, sharp-

#### Acceleration dent1

<table>
<thead>
<tr>
<th>m/s</th>
<th>0.011</th>
<th>0.025</th>
<th>0.11</th>
<th>0.25</th>
<th>0.40</th>
<th>0.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-A</td>
<td><img src="L-A.png" alt="Image" /></td>
<td><img src="L-A.png" alt="Image" /></td>
<td><img src="L-A.png" alt="Image" /></td>
<td><img src="L-A.png" alt="Image" /></td>
<td><img src="L-A.png" alt="Image" /></td>
<td><img src="L-A.png" alt="Image" /></td>
</tr>
<tr>
<td>S1-A</td>
<td><img src="S1-A.png" alt="Image" /></td>
<td><img src="S1-A.png" alt="Image" /></td>
<td><img src="S1-A.png" alt="Image" /></td>
<td><img src="S1-A.png" alt="Image" /></td>
<td><img src="S1-A.png" alt="Image" /></td>
<td><img src="S1-A.png" alt="Image" /></td>
</tr>
<tr>
<td>S2-A</td>
<td><img src="S2-A.png" alt="Image" /></td>
<td><img src="S2-A.png" alt="Image" /></td>
<td><img src="S2-A.png" alt="Image" /></td>
<td><img src="S2-A.png" alt="Image" /></td>
<td><img src="S2-A.png" alt="Image" /></td>
<td><img src="S2-A.png" alt="Image" /></td>
</tr>
<tr>
<td>OilA</td>
<td><img src="OilA.png" alt="Image" /></td>
<td><img src="OilA.png" alt="Image" /></td>
<td><img src="OilA.png" alt="Image" /></td>
<td><img src="OilA.png" alt="Image" /></td>
<td><img src="OilA.png" alt="Image" /></td>
<td><img src="OilA.png" alt="Image" /></td>
</tr>
</tbody>
</table>

- **L-A**: Thickener particles were entrained.
- **S1-A**: Thickener particles were not entrained.
- **S2-A**: Thickener particles were entrained and some particles accompanied with dents.

---

Defense of the PhD thesis
Fully flooded conditions -dented, sharp-

**Deceleration dent1**

<table>
<thead>
<tr>
<th>m/s</th>
<th>0.011</th>
<th>0.025</th>
<th>0.11</th>
<th>0.25</th>
<th>0.40</th>
<th>0.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-A</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>S1-A</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>S2-A</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td>OilA</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
<td><img src="image21.png" alt="Image" /></td>
<td><img src="image22.png" alt="Image" /></td>
<td><img src="image23.png" alt="Image" /></td>
<td><img src="image24.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Rolling direction

- L-A, S2-A: Particle entrainments diminished.

Defense of the PhD thesis
Fully flooded conditions - dented, sharp -

S2-A:
Thickener particle entrainment was more frequent.

L-A, S2-A:
Thickener particle entrainments diminished in deceleration condition.
Fully flooded condition - Rolled grease, smooth -

L-AR: modified L-A rolled by ceramic roller in order to make finer particles

Film thickness in slow speed were close to base oil.

Interferograms

High film thickness of grease in slow speed was due to big thickener particles.

<table>
<thead>
<tr>
<th>Sample</th>
<th>L-A</th>
<th>L-AR</th>
<th>OilA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base oil</td>
<td>88</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>Thickener</td>
<td>12</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Li complex, %</td>
<td>88</td>
<td>88</td>
<td>100</td>
</tr>
<tr>
<td>Li stearate, %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Li-12OH-stearate, %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Penetration (60W)</td>
<td>265</td>
<td>250</td>
<td>-</td>
</tr>
</tbody>
</table>

Defence of the PhD thesis
Discussion

Relation with bearing torque in low speed (200rpm)

- Film thickness in slow speed
  → NOT particle entrainments caused smooth rotation?
- 3 greases showed the same bearing torque in slow speed on repeated bearing tests
  → Suggestion of thickener particles breakdown

After high speed condition

Bearing operation?

L-A: Li-complex
S1-A: Single Li-Stearate
S2-A: Single Li-12OH-Stearate

Defense of the PhD thesis
Discussion

Relation with bearing torque in high speed (2000rpm)

- Grease channeling should be related.
  - Not always related to yield stress of greases, different from past report
  - Traction coefficient behaviors without grease supply indicates grease channeling of Li-complex grease.

Defense of the PhD thesis
Discussion - mechanisms

Low rotation speed
Effect of thickener particles entrainment
= 200rpm

Resistance generation by thickener
(L-A and S2-A)

High rotation speed
Exclusion of redundant grease is effective.
= 2000rpm

L-A: Li-complex
S1-A: Single Li-Stearate
S2-A: Single Li-12OH-Stearate

Defense of the PhD thesis
## Discussion - Tendency of grease thickener type

<table>
<thead>
<tr>
<th>Supply</th>
<th>Surface Property</th>
<th>Li-complex</th>
<th>Li-12OH-stearate</th>
<th>Li stearate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flooded Smooth Thickness</td>
<td>Thick in slow speed Influenced by high speed history</td>
<td>Close to base oil No change after high speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooded Smooth Flow pattern</td>
<td>Finger patterns on side track Sharpened by high speed history</td>
<td>No fingers in high speed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starved Film decay</td>
<td>Late starvation</td>
<td>Quick starvation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooded Dented Particle entrainment</td>
<td>Occurred</td>
<td>Frequently occurred</td>
<td>Not occurred</td>
<td></td>
</tr>
</tbody>
</table>

The cause of difference between L-A/S2-A and S1-A is on whether the thickener particles are dragged into contacts??
### Chemical structures of thickeners

<table>
<thead>
<tr>
<th></th>
<th>Structure</th>
<th>+</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>L-A:</strong> Li-complex</td>
<td><img src="structure1.png" alt="Structure" /></td>
<td>Li-OH</td>
</tr>
<tr>
<td><strong>S1-A:</strong> Single Li-Stearate</td>
<td><img src="structure2.png" alt="Structure" /></td>
<td>Li-OH</td>
</tr>
<tr>
<td><strong>S2-A:</strong> Single Li-12OH-Stearate</td>
<td><img src="structure3.png" alt="Structure" /></td>
<td>Li-OH</td>
</tr>
</tbody>
</table>

(12-)Hydroxyl groups bonded to carbon chains could influence on particle entrainments.
Discussion - mechanisms

- Thickeners are entrained independently
  - L-A: Li-complex
  - S1-A: Single Li-Stearate
  - S2-A: Single Li-12OH-Stearate

- Thickeners are entrained to dents

- Thickeners easy to enter contact surfaces
  - S1-A
  - S2-A

- Thickeners are broken into the small fragments
  - S2-A

- Thickeners are not dragged into contact surfaces
  - L-A

Thickeners are entrained independently.

Contact area

Glass

Ball

Defense of the PhD thesis
**Discussion - mechanisms**

- **L-A, S2-A**
  - Track pattern
  - Side finger patterns

- **S1-A**
  - No side fingers
  - Quick starvation?

**Thickener entrainment forms finger patterns**

**Defense of the PhD thesis**

**Symbols:**
- L-A: Li-complex
- S1-A: Single Li-Stearate
- S2-A: Single Li-12OH-Stearate
Conclusions

1. Relation with bearing torque at **low speed**
   ⇒ Thin **film thickness** without particle entrainment is effective in torque reduction

2. Relation with bearing torque at **high speed**
   ⇒ Grease channeling represented by **yield stress** and **traction** behaviors is effective

3. Thickener **entrainments** to the contacts
   ⇒ Film **thickness increase**, **track pattern formation**, **starvation delay**

4. Thickener entrainments to the **dents**
   ⇒ Promotion by thickener with **higher polarity**
List of publications


List of publications -conference abstracts-

- SAKAI, K., D. KOSTAL, Y. SHITARA, M. KANETA, I. KRUPKA and M. HARTL. Effects of Li Grease Components on Radial Ball Bearing Torque and the Grease Properties. 72nd STLE Annual Meeting & Exhibition. 2017, Atlanta, USA.
- SAKAI, K., Y. TOKUMO, Y. AYAME, Y. SHITARA, H. TANAKA and J. SUGIMURA. Effect of Formulation of Li Greases on Their Flow and Ball Bearing Torque. 7th International Tribology Conference Tokyo 2015 -ITC Tokyo 2015. 2015, Tokyo, Japan.
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