The behaviour of grease in EHL contacts of ball bearings

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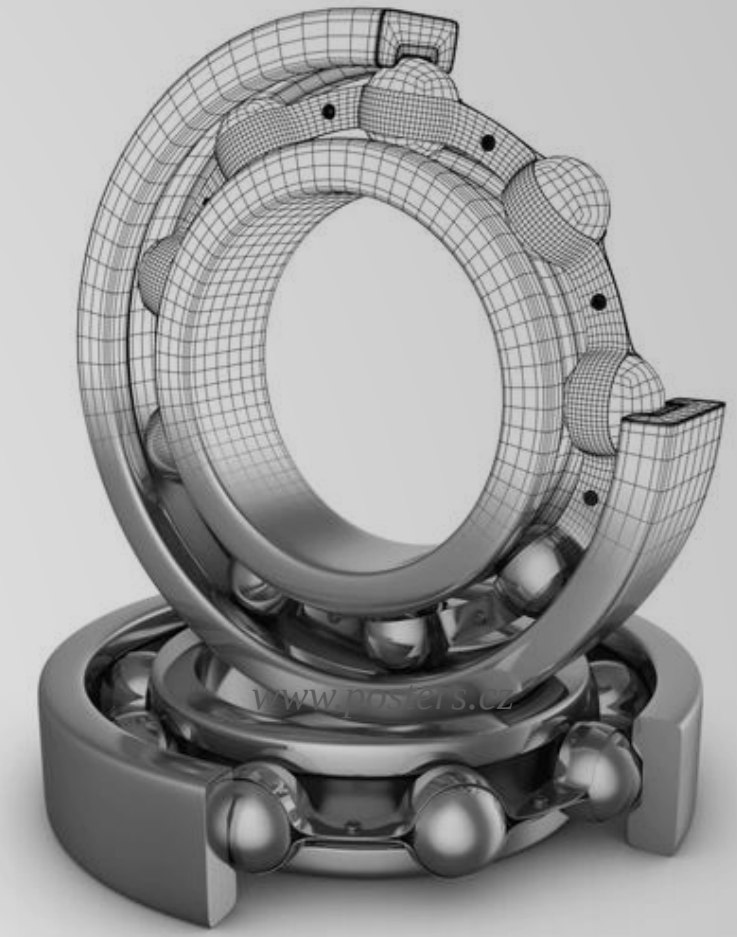
ÚSTAV
KONSTRUOVÁNÍ

- Introduction
  - Motivation
    - State of the art
      - Aim of thesis
      - Scientific questions and hypotheses
    - Materials and methods
  - Results
- Conclusion



Deep groove ball bearings

Applications

- Automotive
- Electric motors
- Aerospace
- Robotics
- Industrial machinery
- Conventional machines

Propertiess

- Low Cof.
- Low friction torque
- Versatile load capacity
- High-speed capability
- Long service life
- Simple and robust design

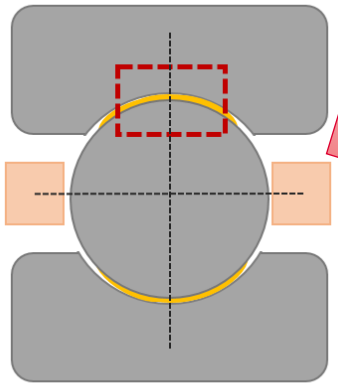
Numbers

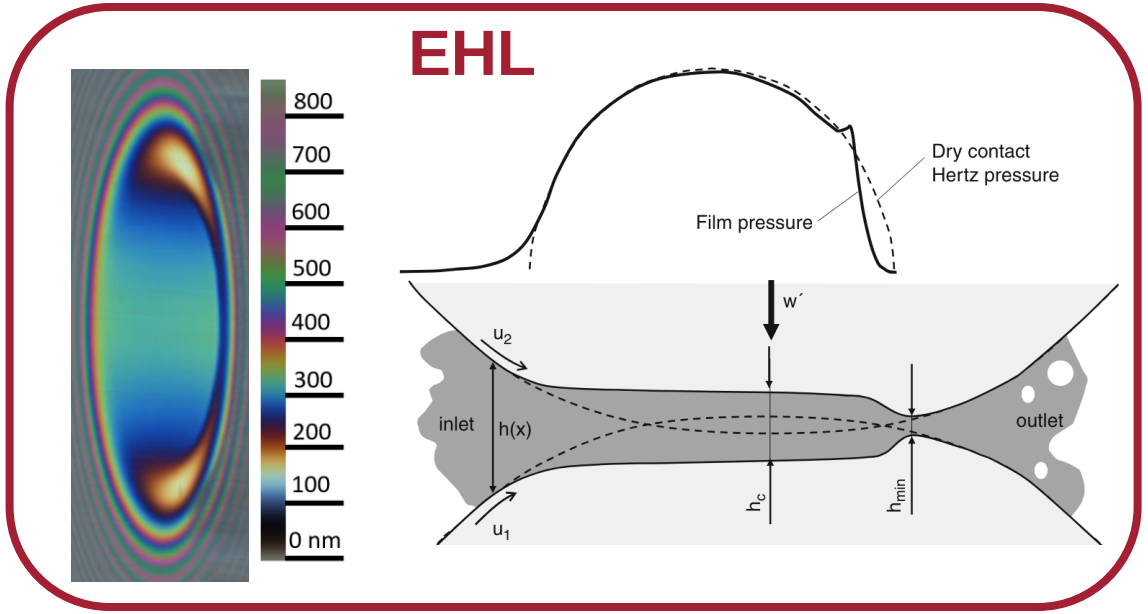
- **Production is around 20-30 billion pieces per year**
- **Approximately 500 billion pieces are currently in use**

Lubrication of ball bearings

- Base oil 75-90 %
- Thickener 10-25 %
- Additives 1 %

- Greases are the most widely used (90%) - **Lifetime fill**
- One of the most successful applications of elastohydrodynamic lubrication **(EHL)**

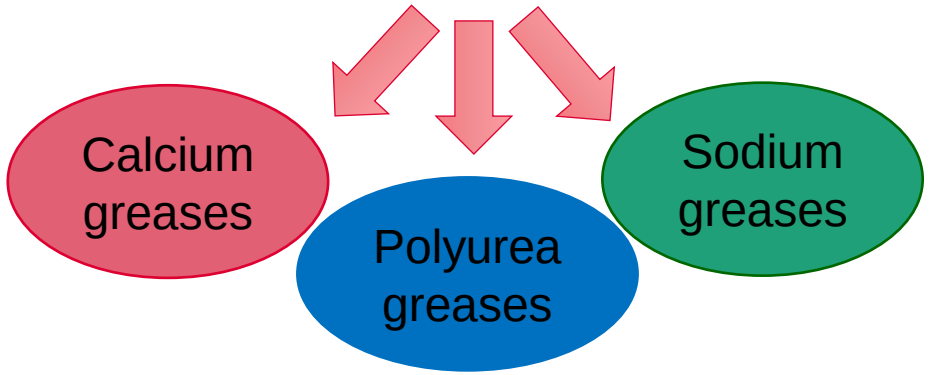




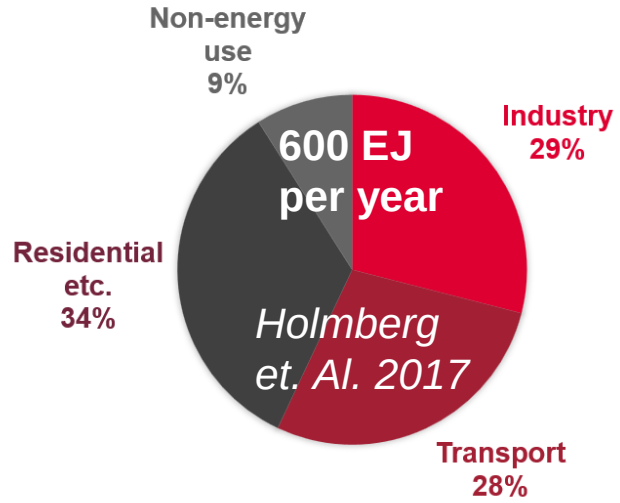
Larsson, R. (2013). EHL Film Thickness Behavior

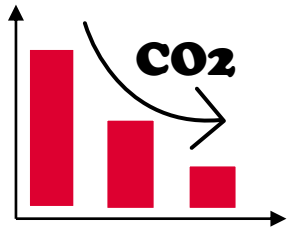
Motivation

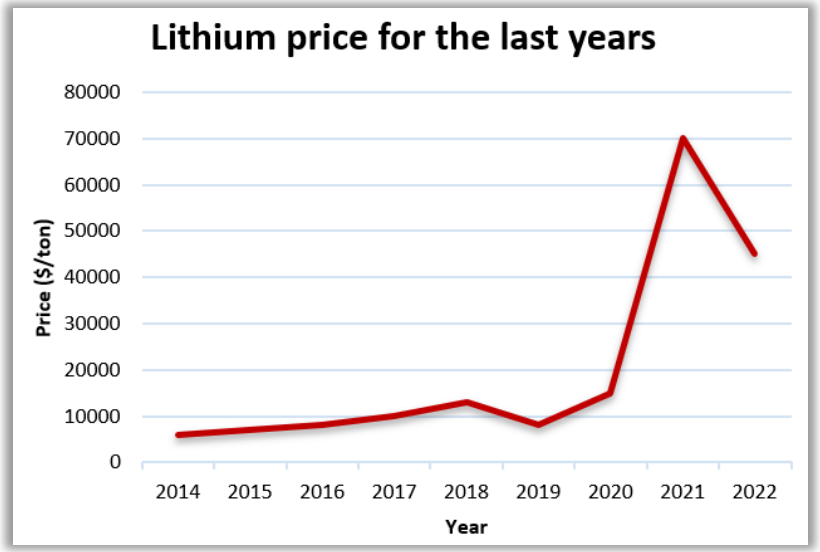
- 500 billion bearings represent one of the most frequent elements where frictional losses occur.
- Electromobility - higher lithium price (Uses almost 80% lithium-based greases)



Global energy consumption





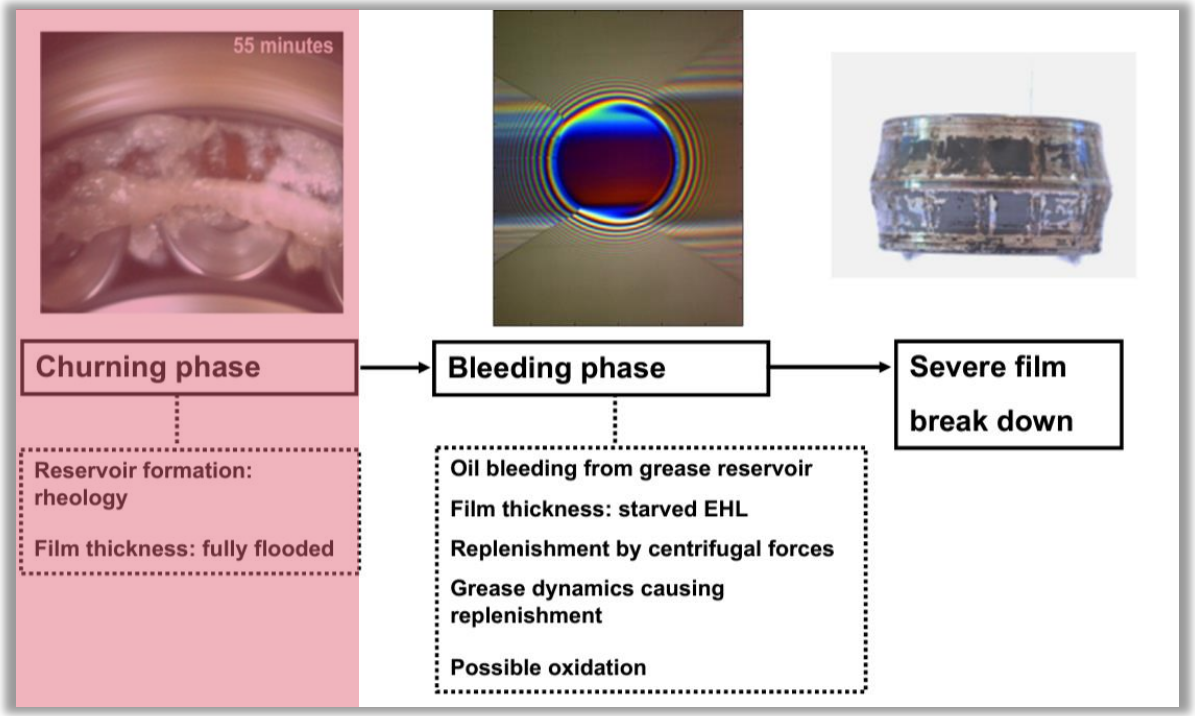


State of the art

Grease lubrication in ball bearings

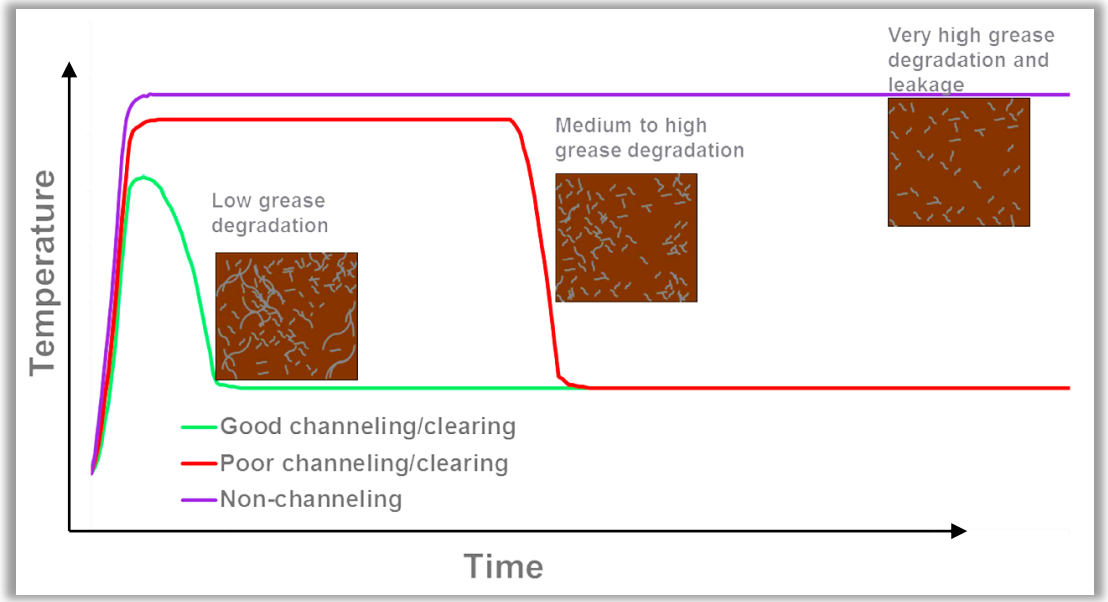
The lubrication phase

Lugt, P.M., (2016, Tribol. Int.)



The churning phase

Chatra, S., (2020, Tribol. Int).



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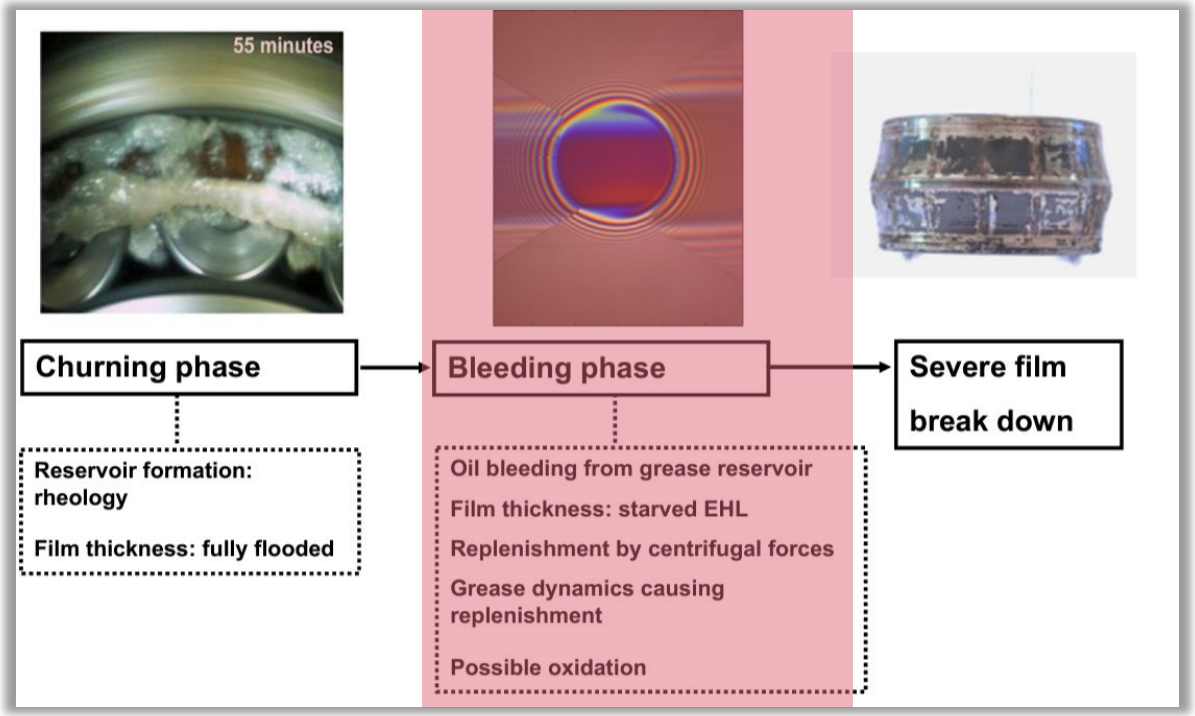
State of the art

Starved elastohydrodynamic lubricated contact

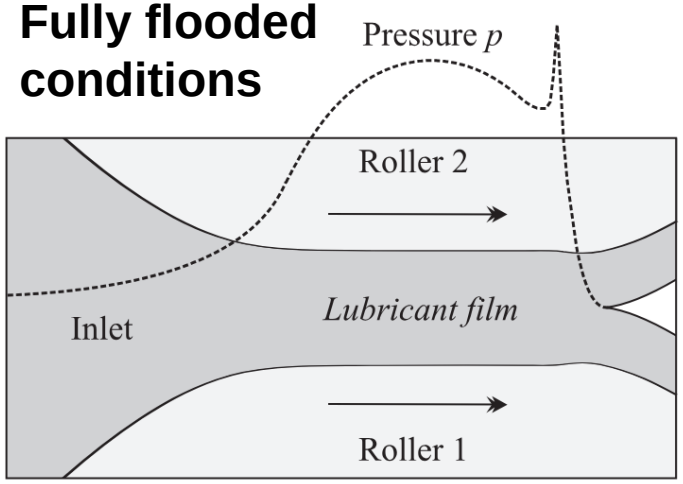
Hamrock (1977,J. Lubr. Tech).

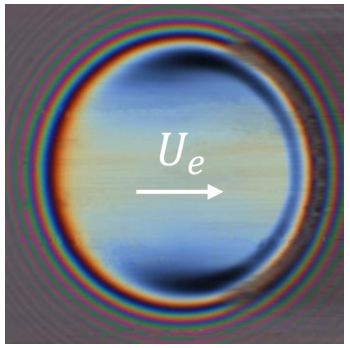
$$h_c = 2.69U^{0.67}G^{0.53}W^{-0.067}\left(1-0.61e^{-0.73k}\right)$$

$$h_{\min} = 3.63U^{0.68}G^{0.49}W^{-0.073}\left(1-0.61e^{-0.73k}\right)$$

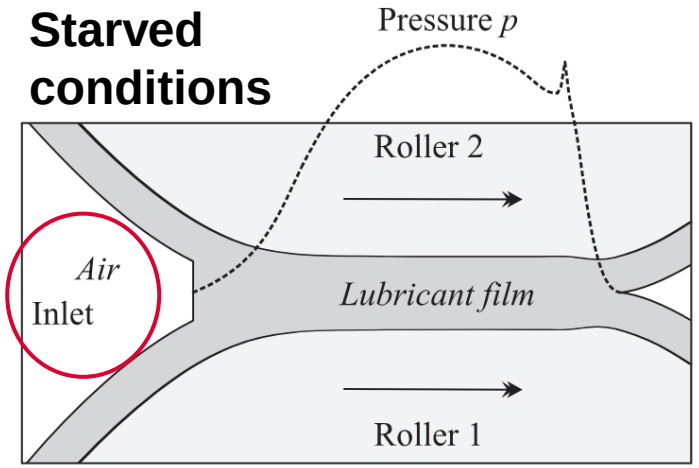


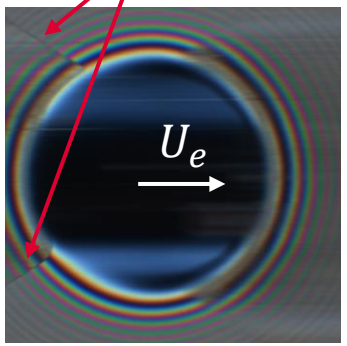
Fully flooded conditions

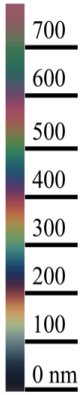




Starved conditions





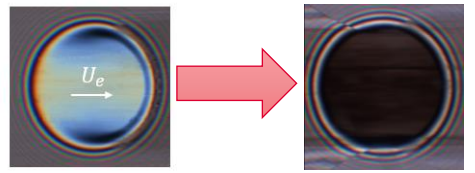


$$h_c^{\text{starv}} = h_c \cdot S$$

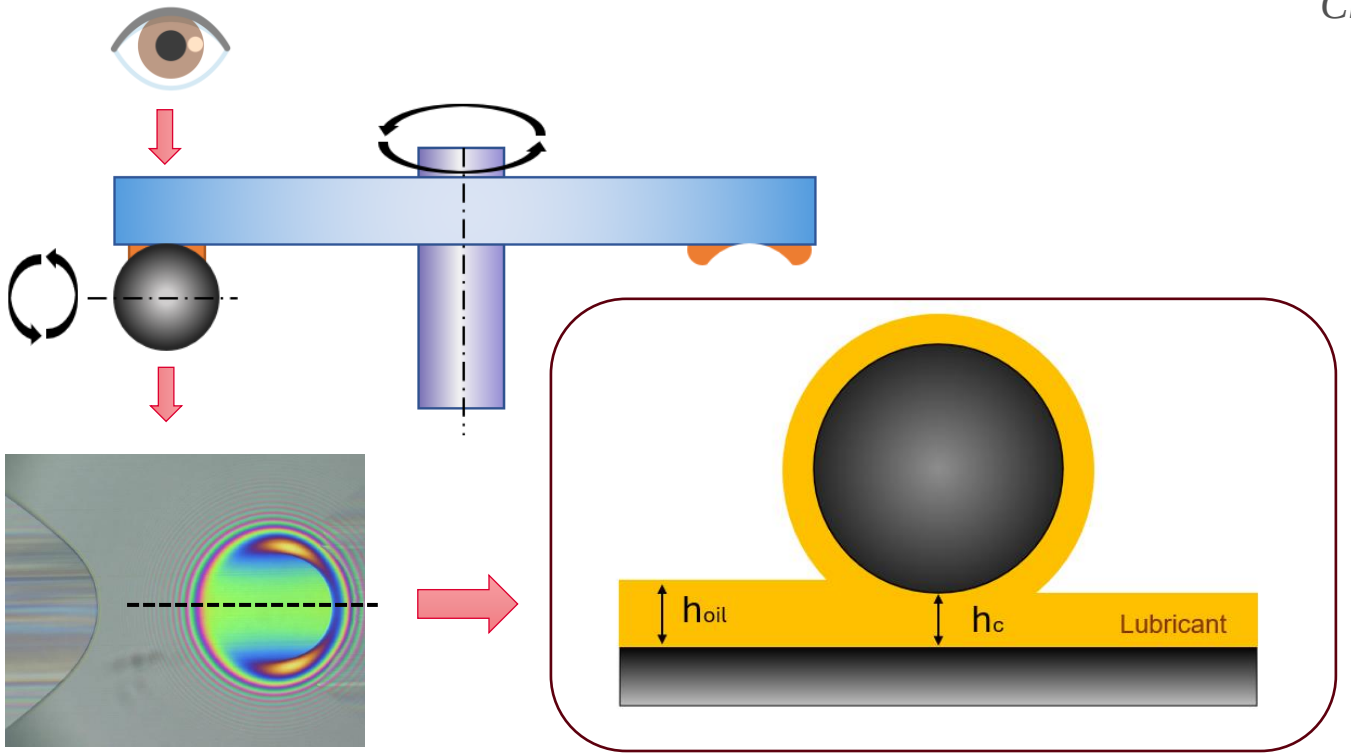
$$0 \le S \le 1$$

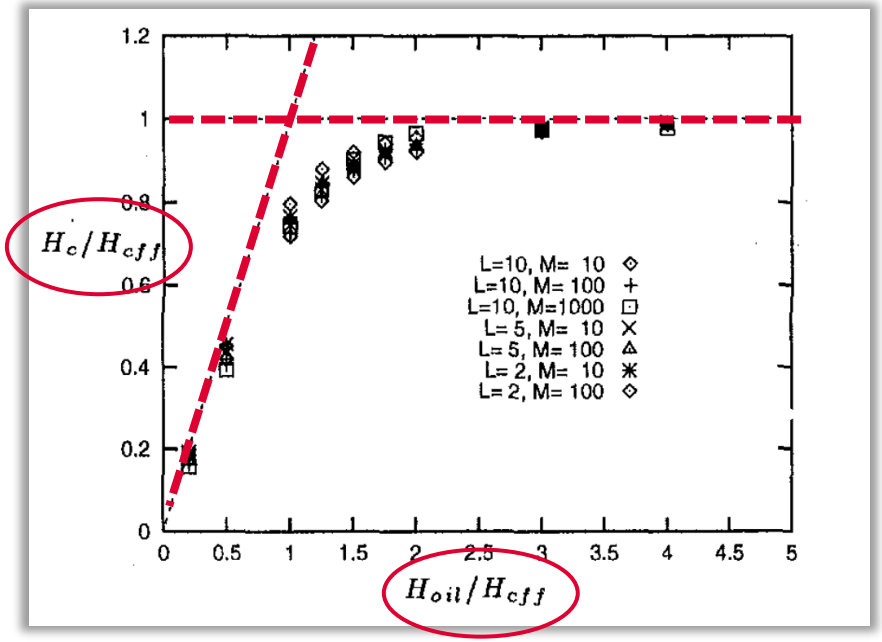
State of the art

Starved elastohydrodynamic lubricated contact



Chevalier (1998, J. Tribol.)

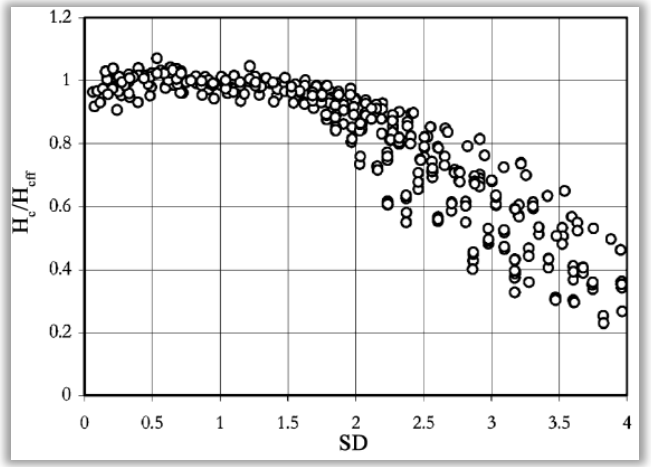




Cann (2004, Tribol. Int.)

$$SD = \frac{\eta_0 * u * a}{h_{oil\infty} * \sigma_s}$$

SD - Starvation degree
η_0 - Dynamic viscosity of the lubricant
u - Speed
a - width of the rolling path
σ_s - surface tension
$h_{oil\infty}$ - amount of lubricant near the contact



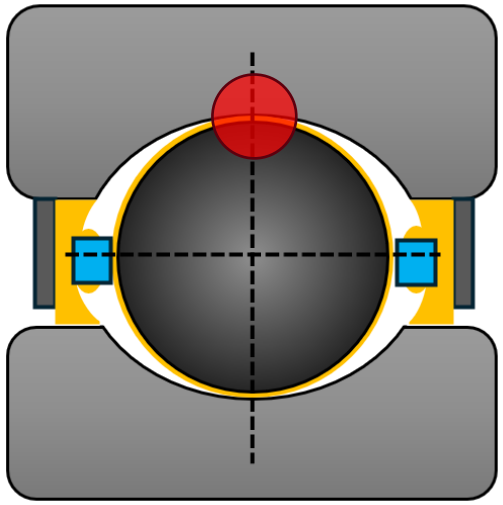
State of the art

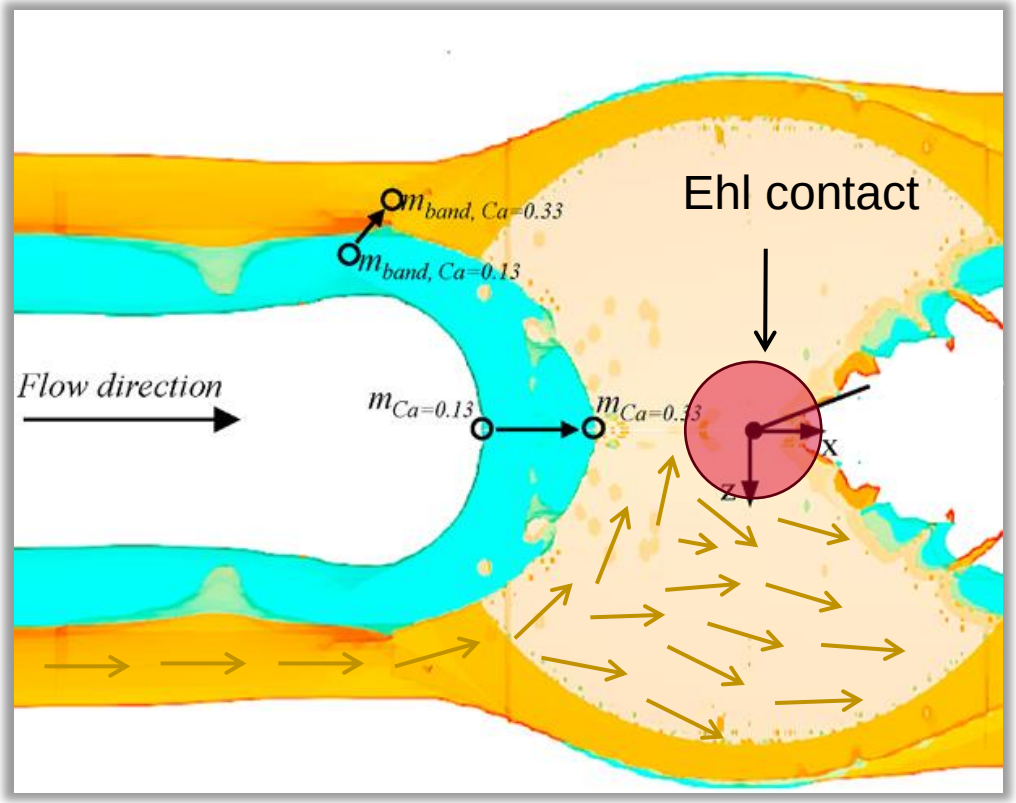
Replenishment mechanism

Zoelen, M. T.,. (2010. Tribol. Trans.)

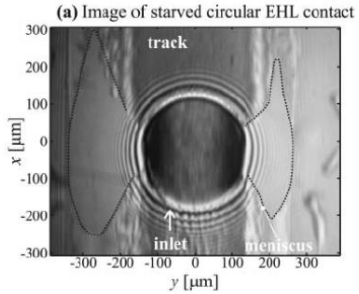
Replenishment before contact

Fischer. (2020. Tribol. Int.)

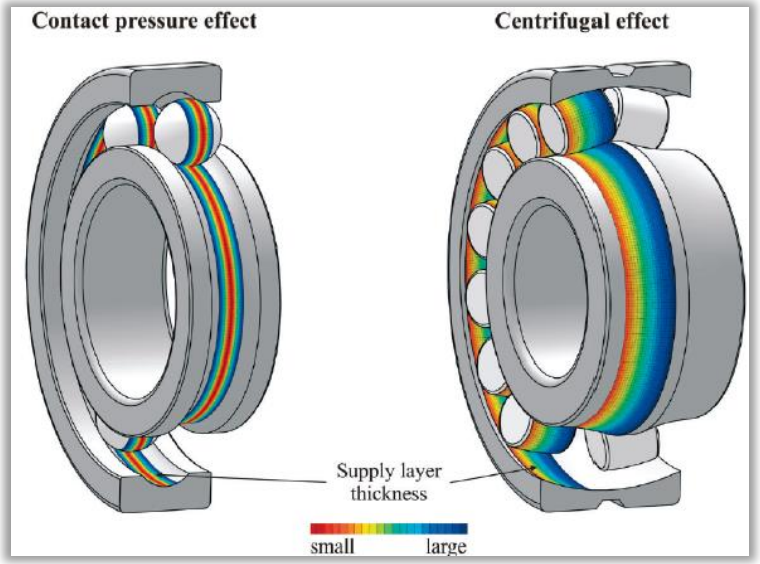


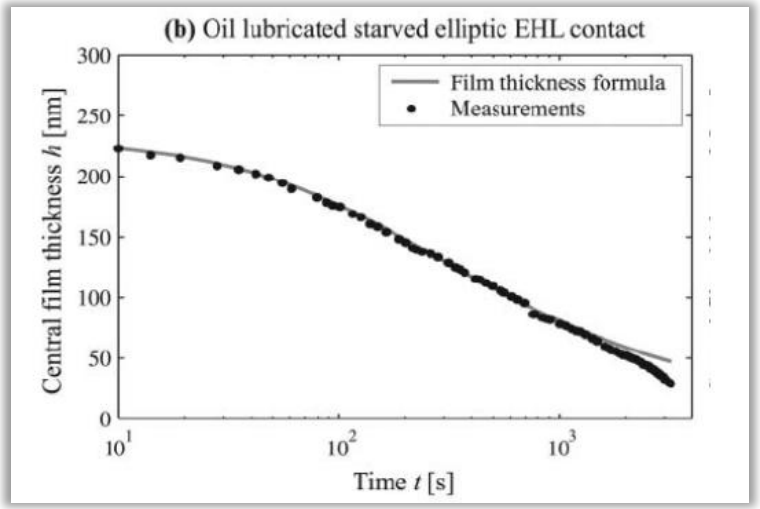


- Lubricant viscosity (rheology)
- Lubricant supply quantity
- Wettability
- Rolling speed
- Contact geometry



Replenishment out of contact

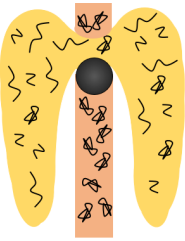




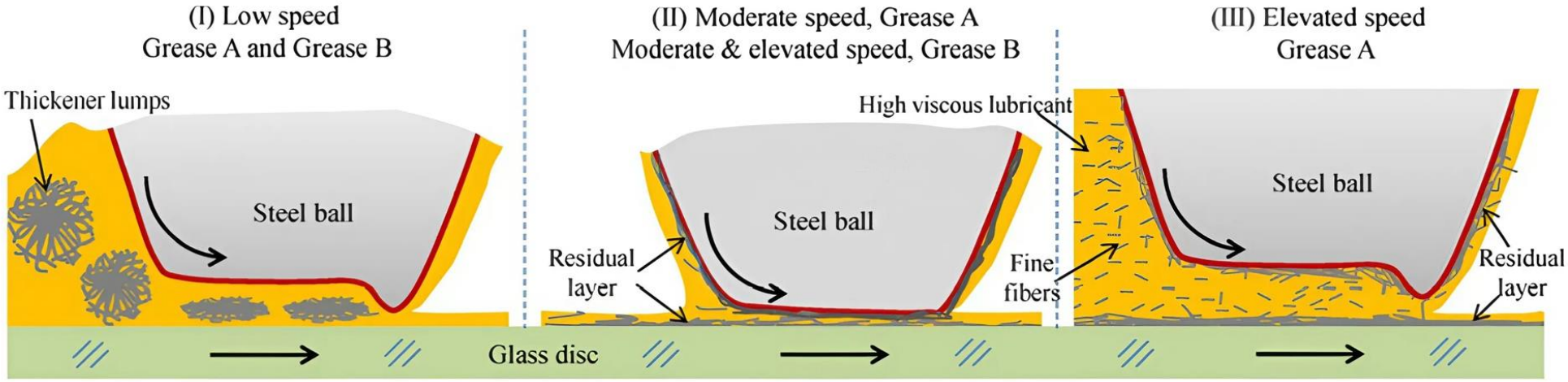
Zoelen, M. T.,. (2009. Tribol. Trans.)

State of the art

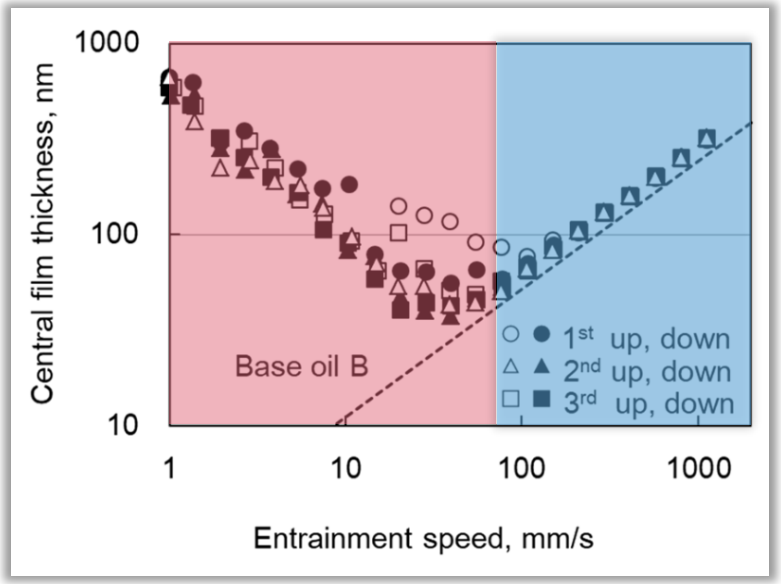
Thickner in EHL contact

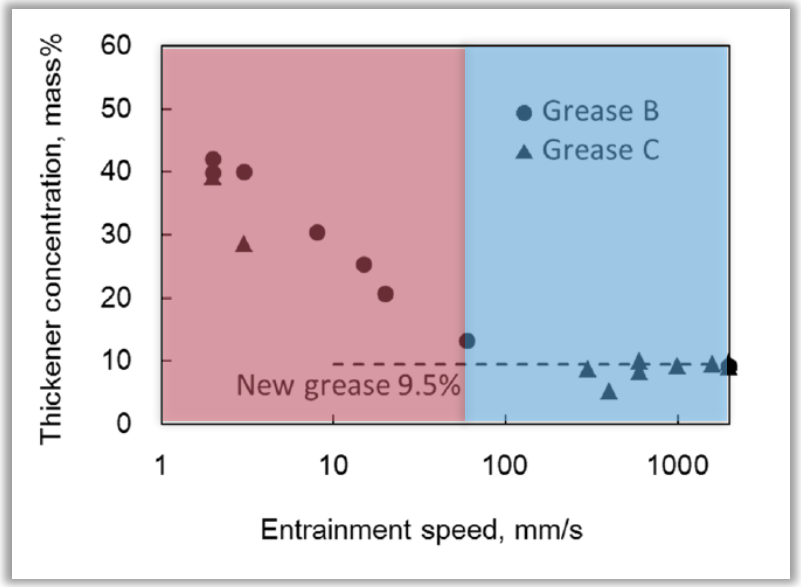


Li (2021, Friction)



Influence of speed



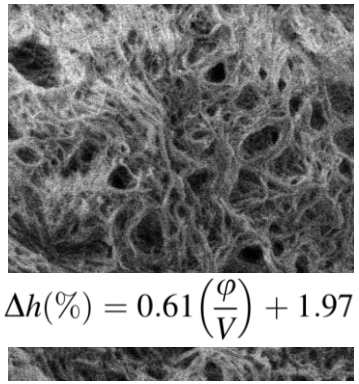


Kochi (2019, Tribology Letter)

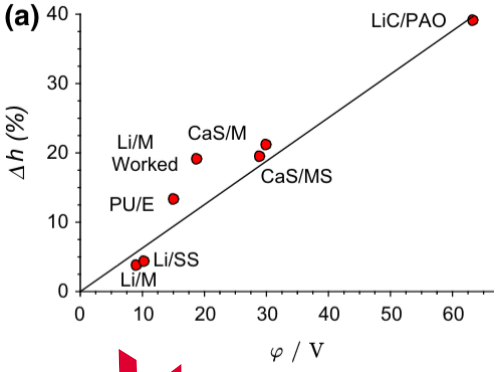
Cyriac (2015, Tribol. Lett.)

Influence of fibre size

Percentage increase in film thickness:



$$\Delta h(\%) = 0.61\left(\frac{\varphi}{V}\right) + 1.97$$



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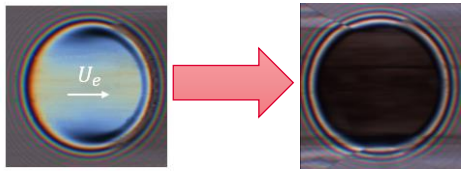
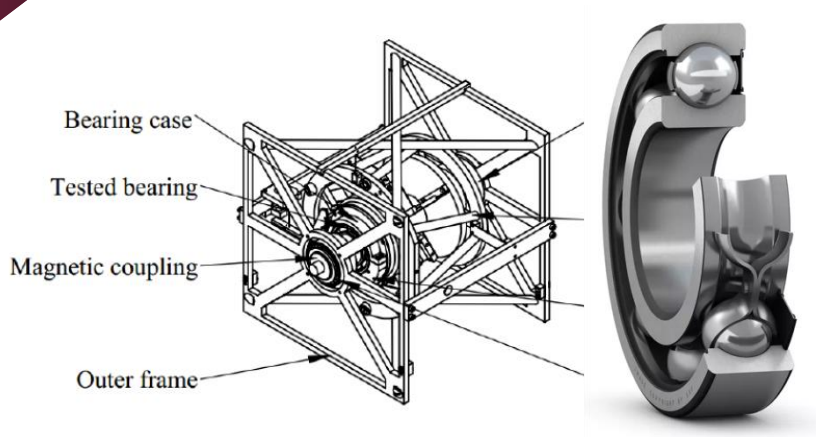
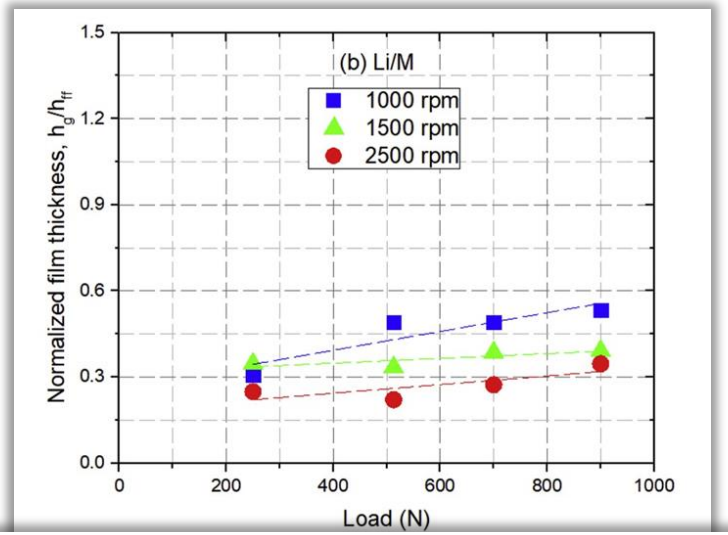
State of the art

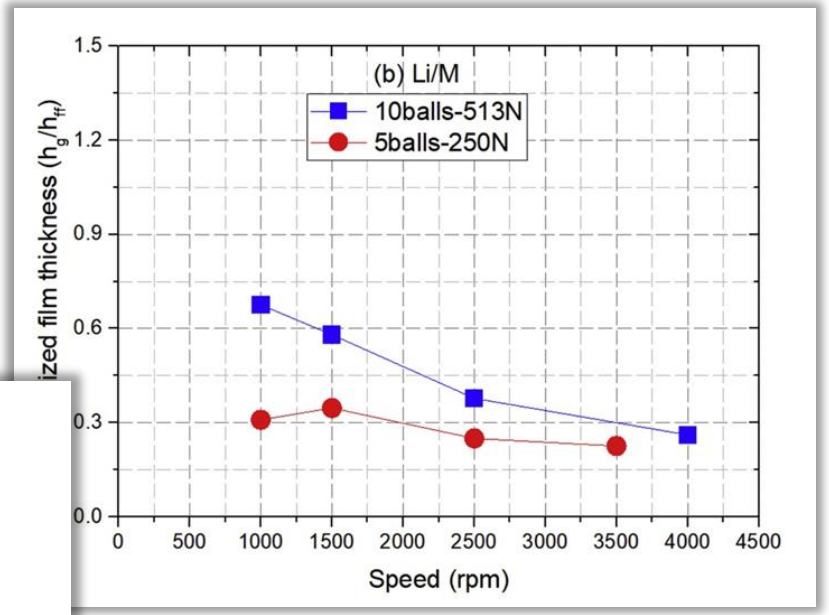
Film thickness in ball bearing

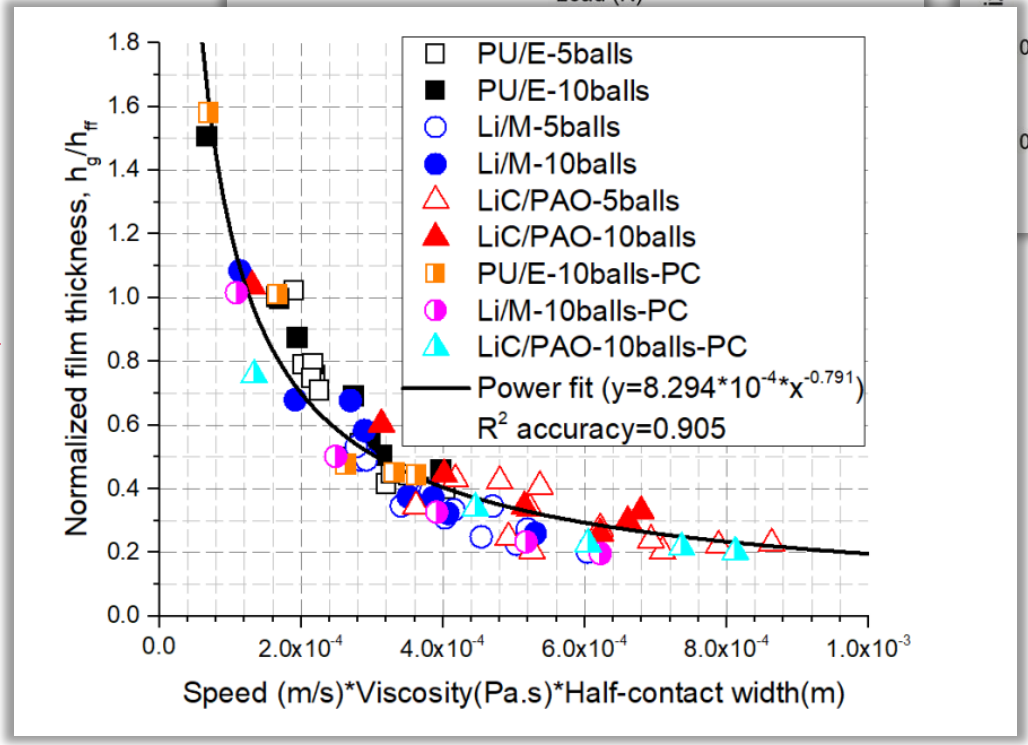




Cen (2019, Tribol. Int.)







Cen (2020, Tribol. Int.)

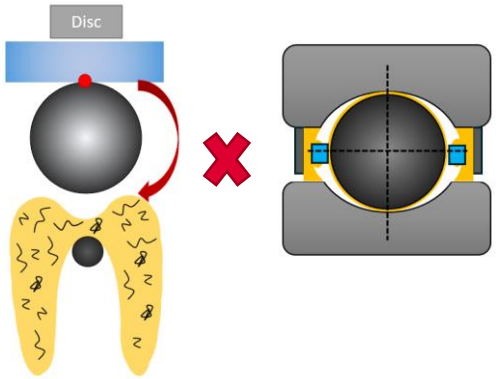
$$\frac{h_g}{h_{ff}} = 8.294 \times 10^{-4} \times (u\eta b)^{-0.791}$$

Speed x viscosity x half-contact

Gaps in current literature

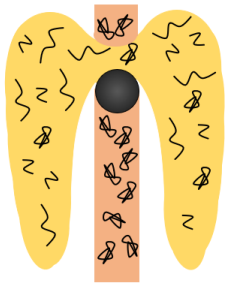
Conformity and film thickness

- Experimental studies limited to base oil
- Simplified contact geometries
- Mostly theoretical studies



Thickener and replenishment

- Only effect of speed and size of thickener fibres
- Experiments only under fully flooded conditions
- Simplified contact geometries



Ball bearing film thickness

- Tests conducted only at high speeds
- Limited number of grease samples (Lithium)
- Focus only on base oil

Aim of thesis

To clarify the behaviour of the individual grease components in the EHL contacts of a ball bearing and their contribution to the formation of the lubricating film.

Scientific questions

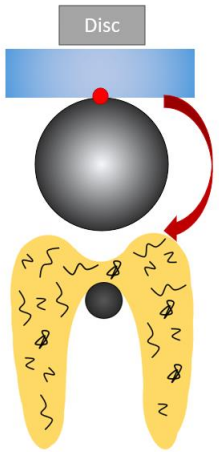
1. **What is the effect of conformity on grease replenishment around the contact and the level of starvation?**
2. **How does different replenishment affect the behaviour of the thickener in the EHL contact?**
3. **How does the thickener affect the lubrication film thickness in a deep groove ball bearing?**

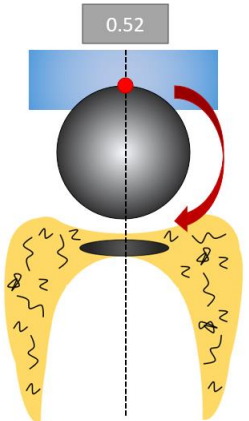
Hypotheses

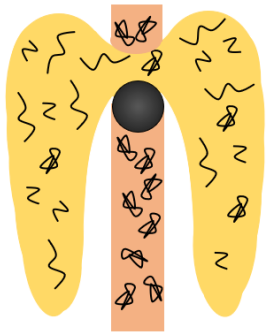
H1:

H2:

H6:

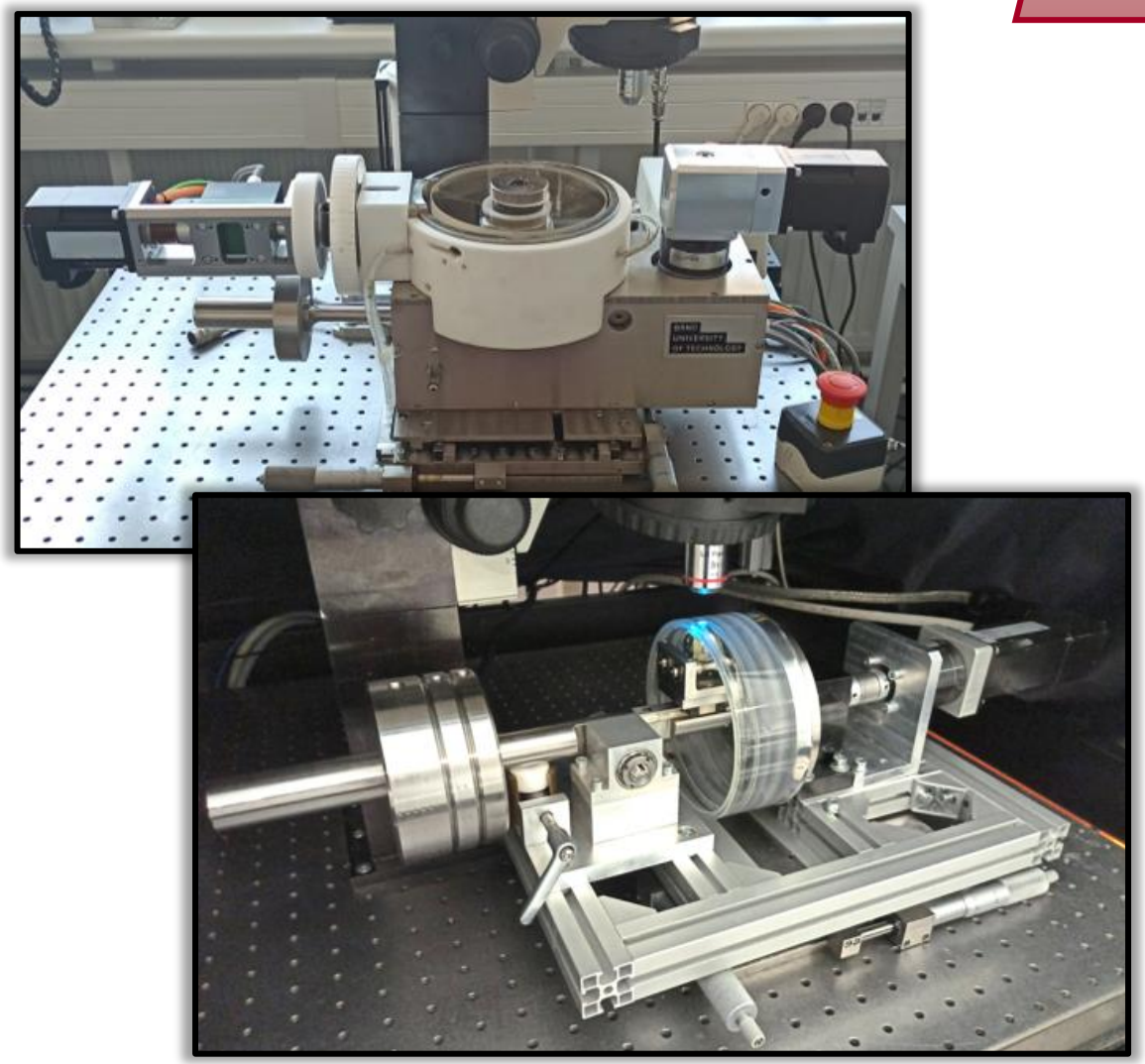




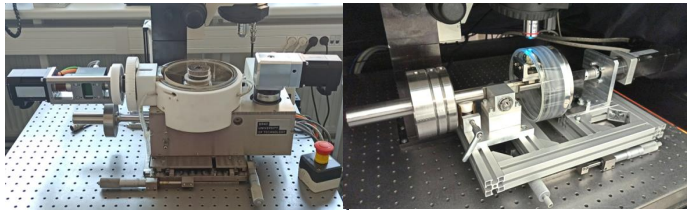


Experimental devices

Optical tribometers | Ball bearings

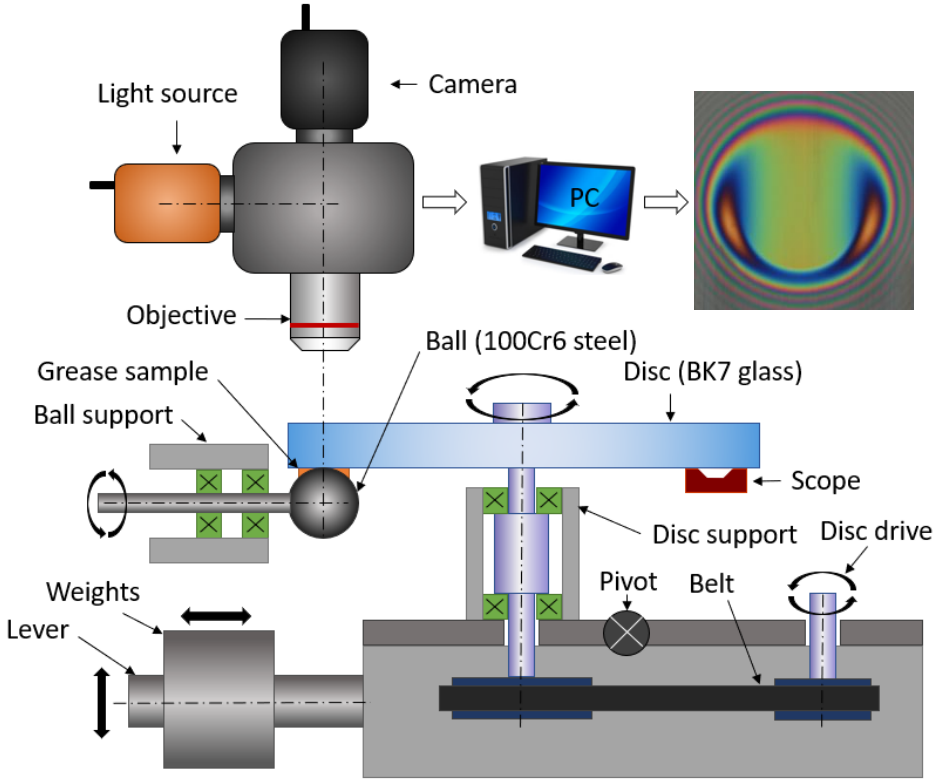


Optical tribometers



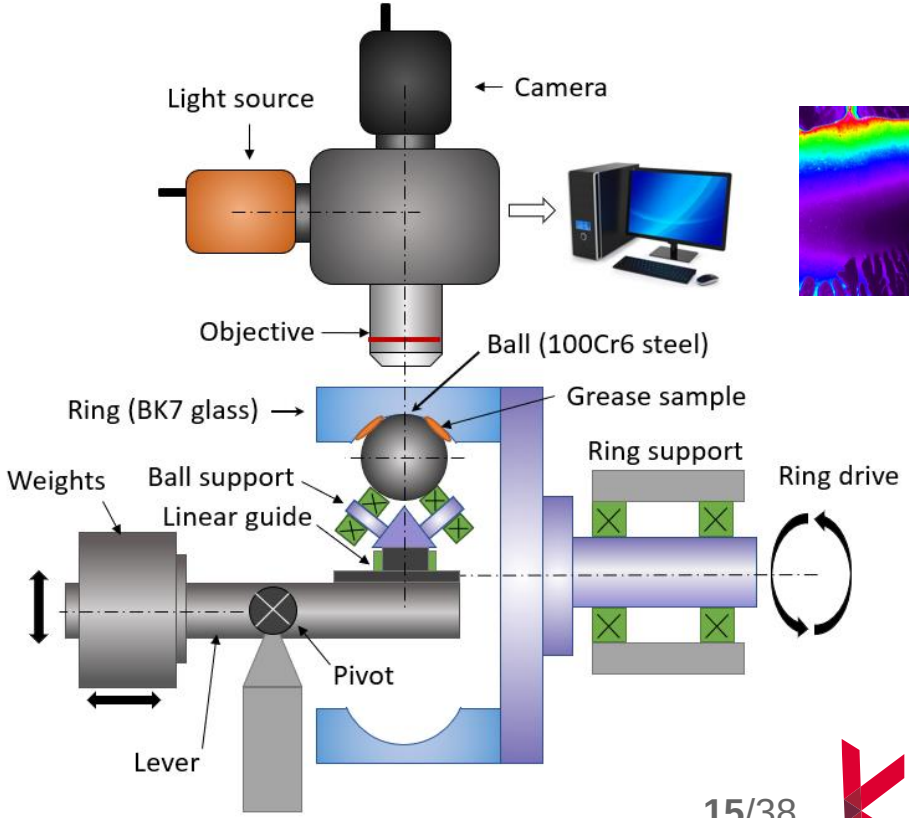
Ball-on-disc

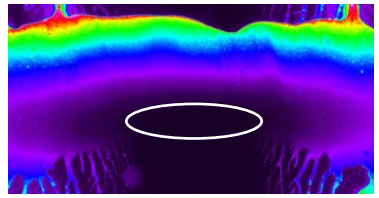
- Circular contact
- Artificial replenishment



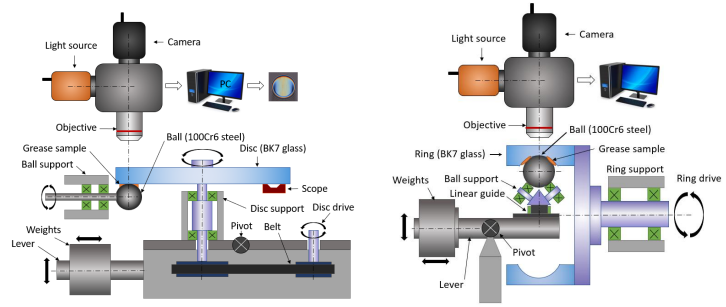
Ball-on-ring

- Eliptical contact (Real comformity)
- Natural replenishment



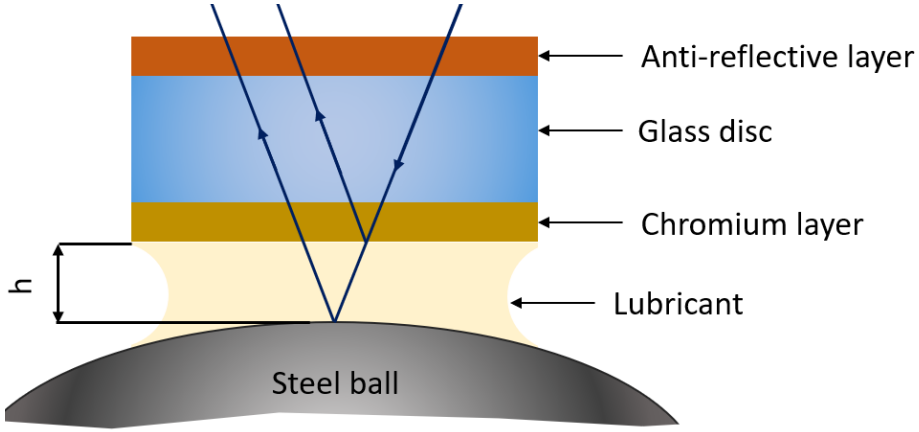


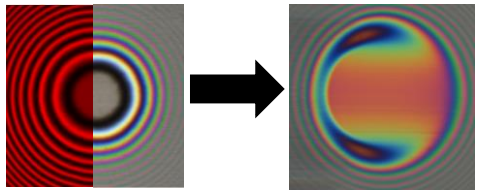
Optical methods



Thin film colorimetric interferometry

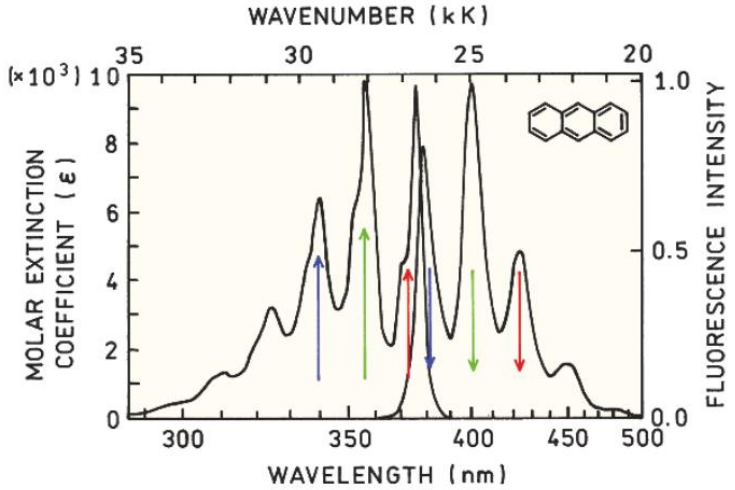
- Distance between surfaces
- Range 0-900 nm

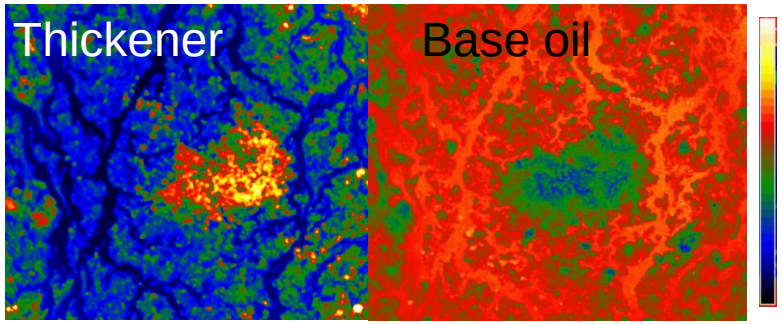


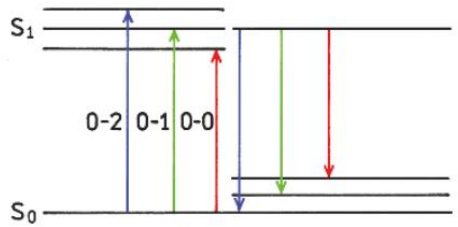


LED induced fluorescence microscopy

- Fluorescent light intesity
- Range 0-0.05 nm
- Multi-component dyeing







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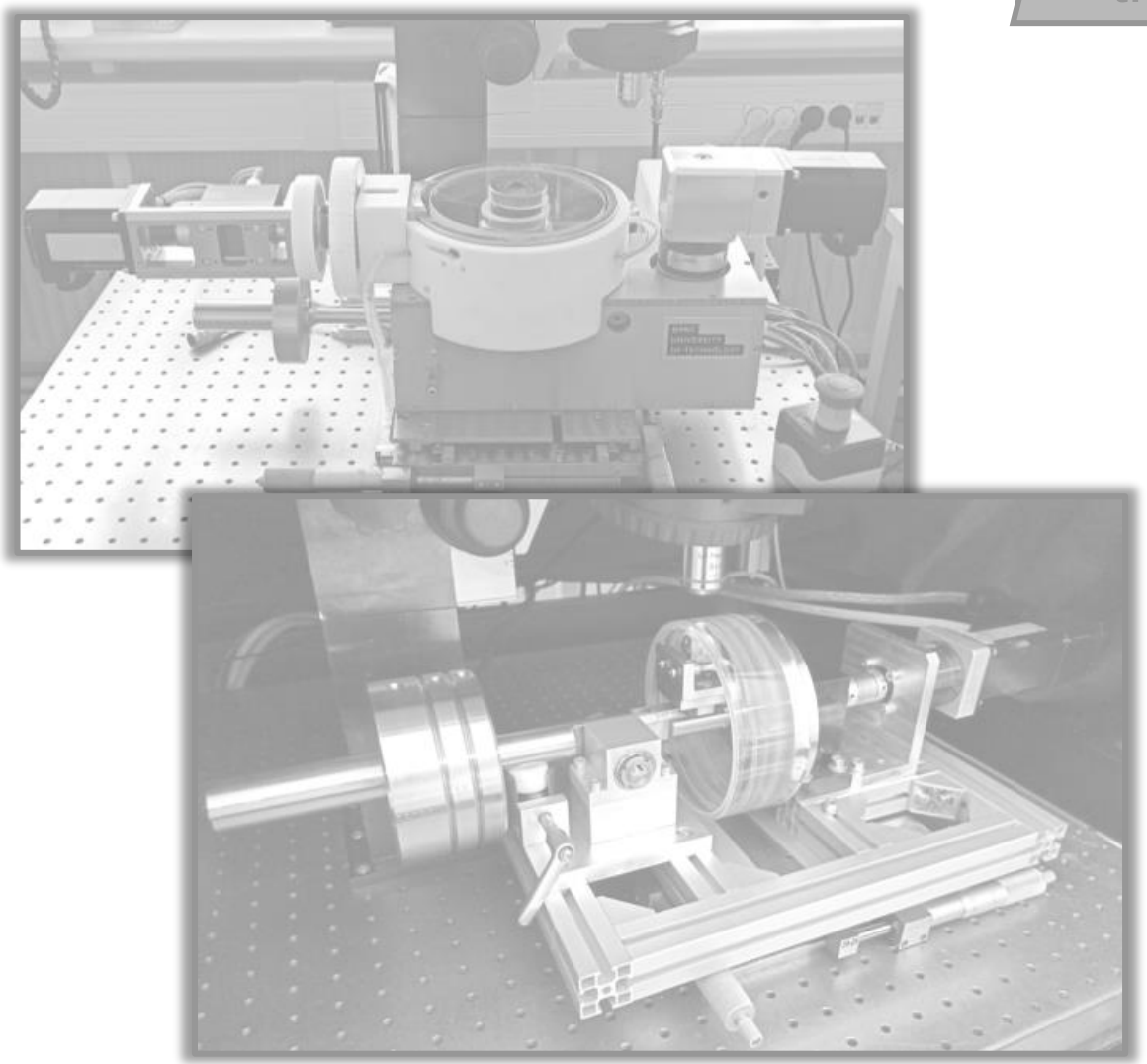
Optical tribometers | Ball bearings



Ball bearing test rig

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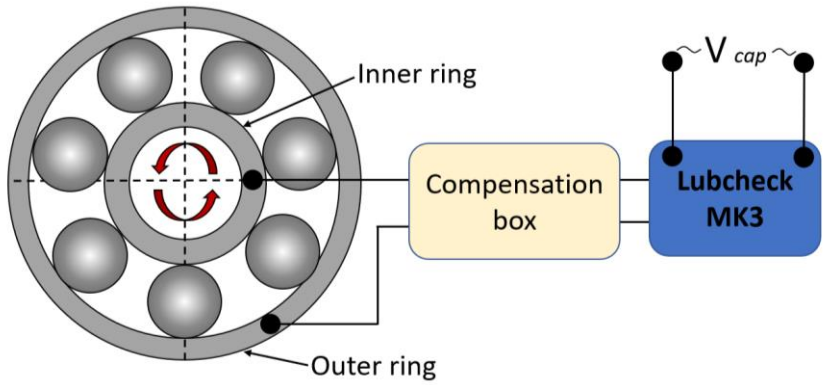
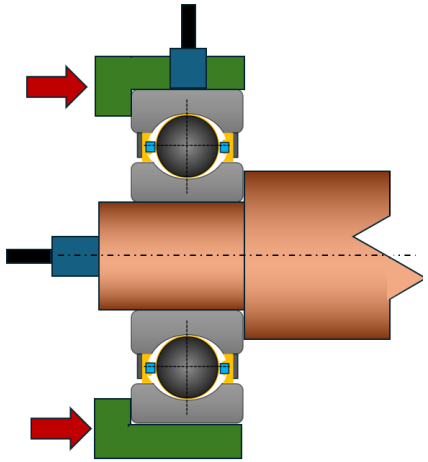
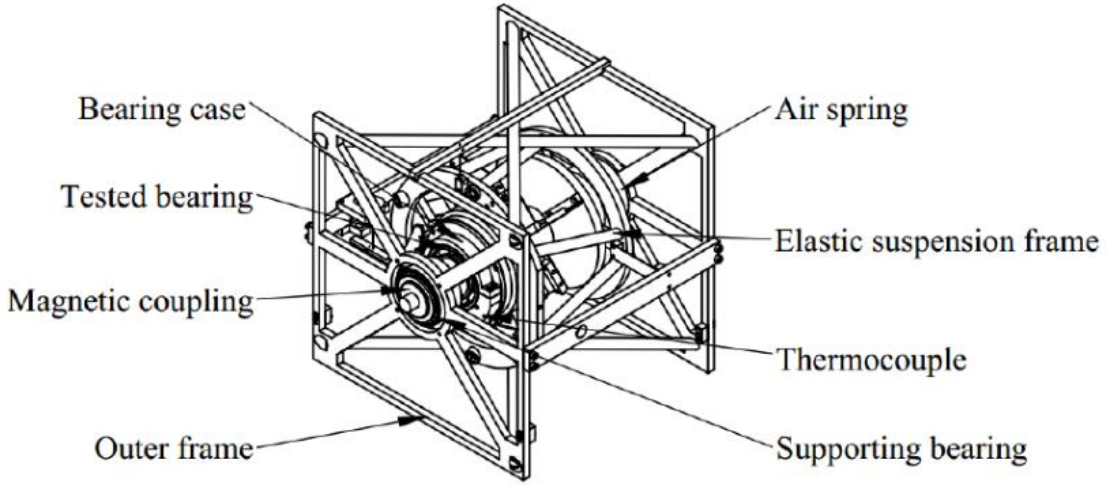
SKF University Technology Centre for Grease Lubrication

- Electrical capacitance method (Lubcheck Mk3)
- Lubcheck converts bearing capacity to output voltage (Average film thickness between the inner and outer ring)

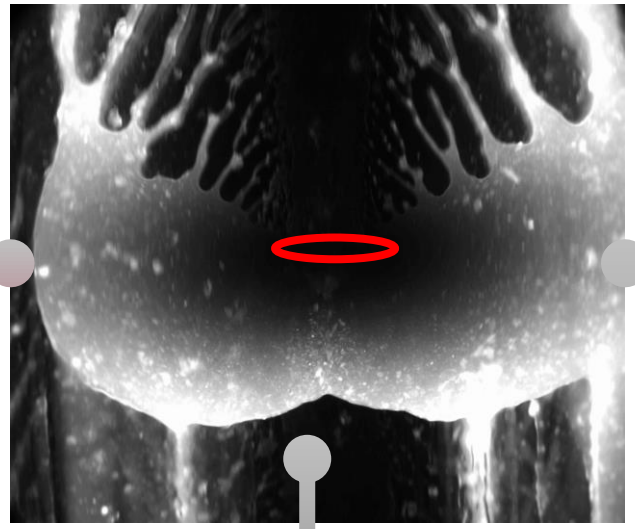




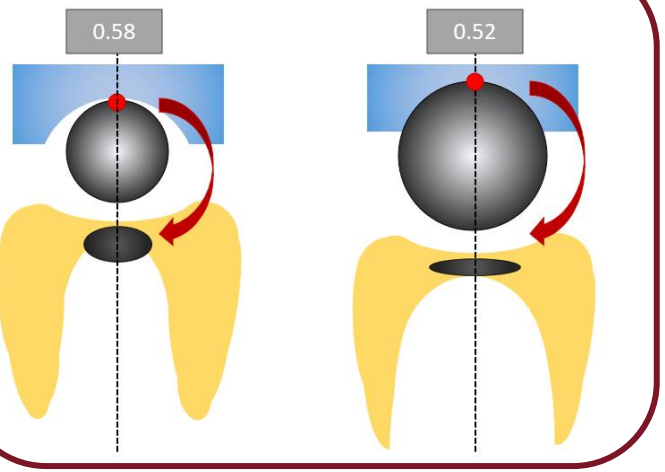


$$C_{Hertz} = \frac{1}{\frac{1}{C_{inner}} + \frac{1}{C_{outer}}} + C_{Backround}$$

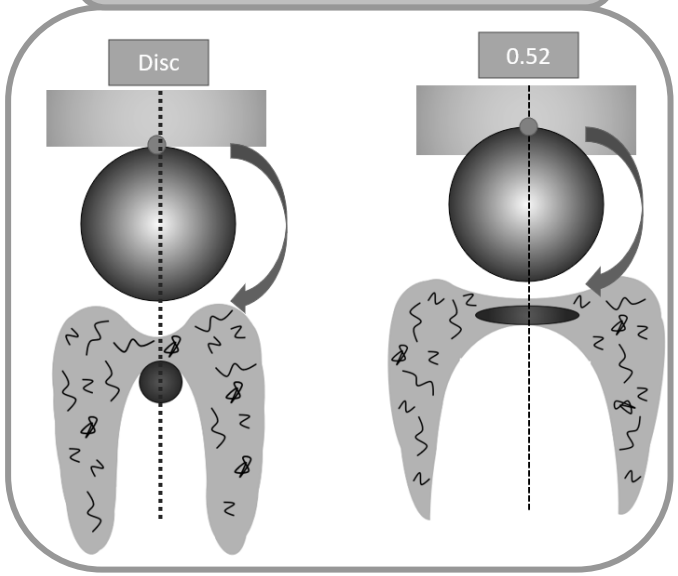
Cen (2019, Tribol. Int.)



Conformity and film thickness



Thickener and replenishment



Ball bearing film thickness

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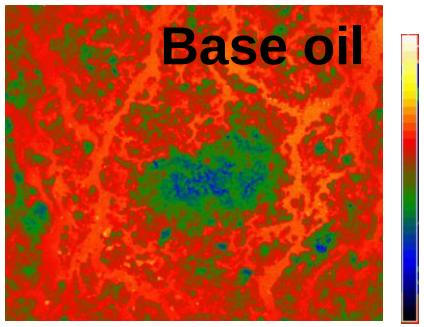
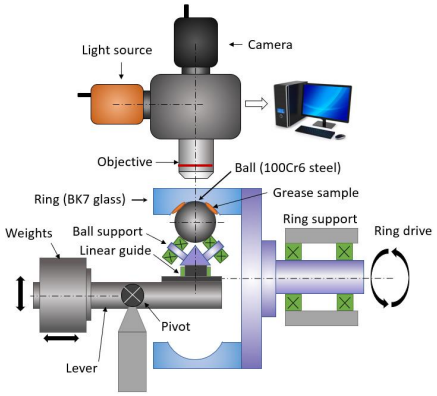
Ball bearing conformity





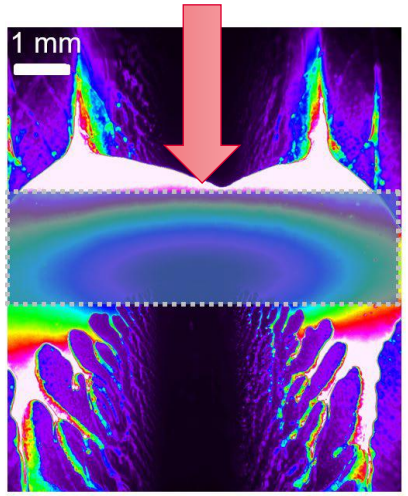
Does the amount of lubricant at the contact or the capillary force have more influence?

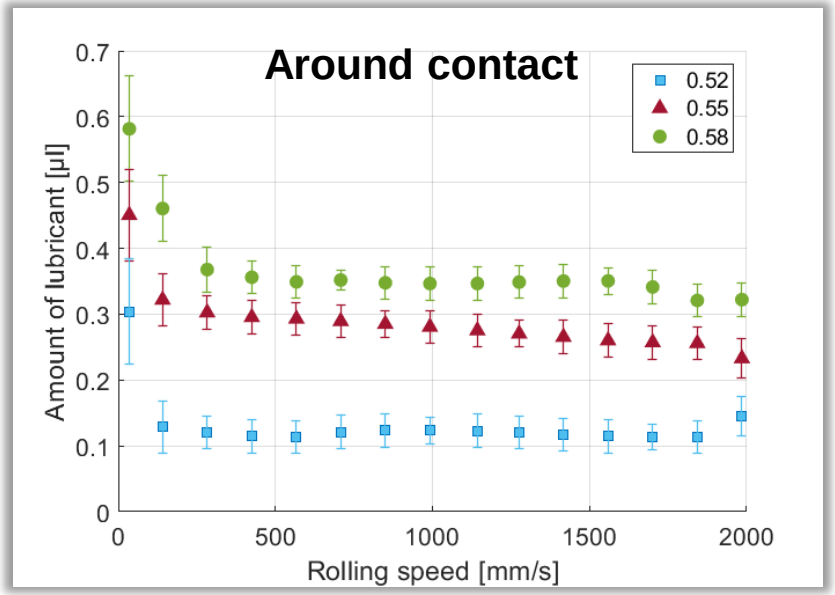
Information from the literature:

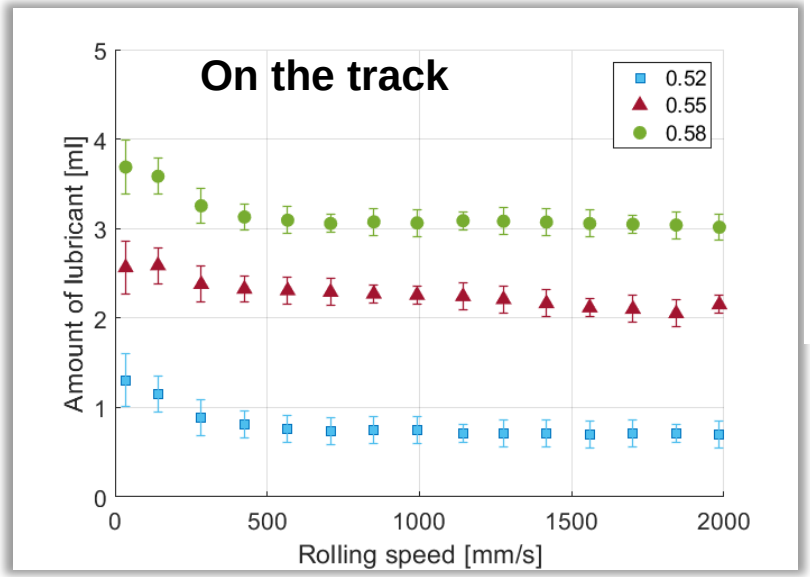
- More lubricant before contact means more film thickness
- Greater capillary force causes more efficient inlet replenishment

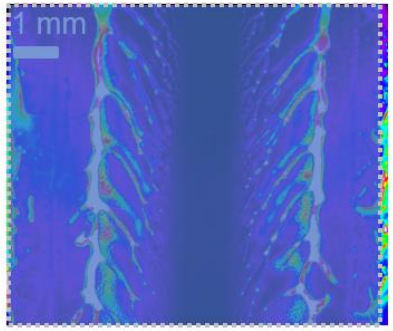
	Ball diameter	Conformity (f)	Ellipticity of contact
●	25.4	**0.52**	8.4
●	23.8	**0.55**	4.5
●	22.2	**0.58**	3.3

Observed area

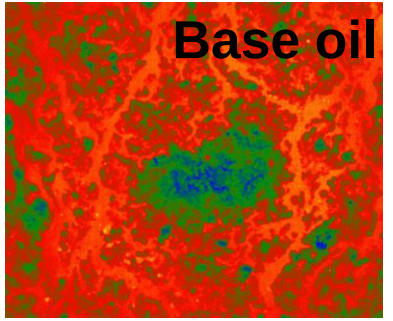






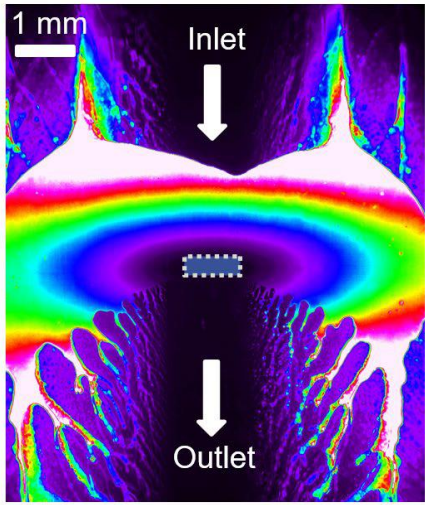


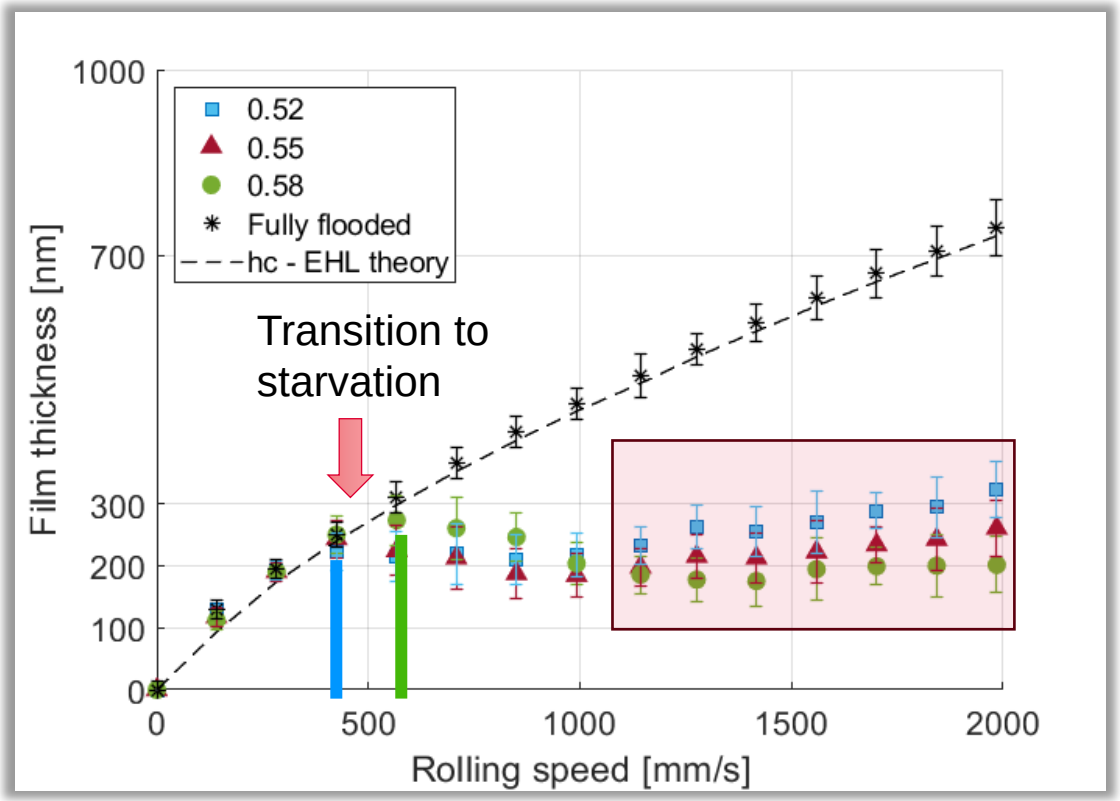
Ball bearing conformity

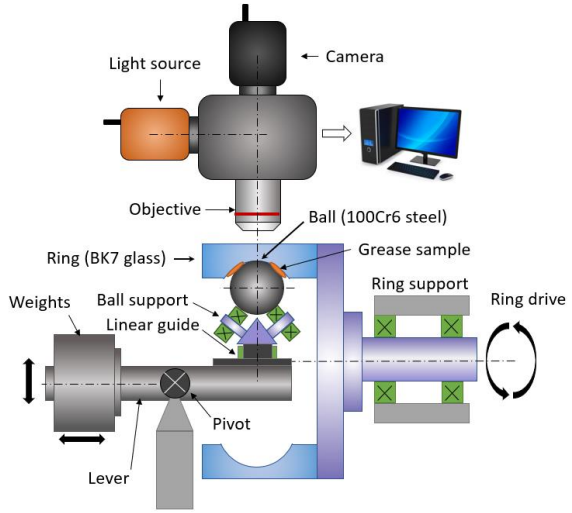


Influence of the amount of lubricant and speed?

(1.) Hertzian area







Ball diameter	Conformity (f)	Ellipticity of contact
25.4	**0.52**	8.4
23.8	**0.55**	4.5
22.2	**0.58**	3.3

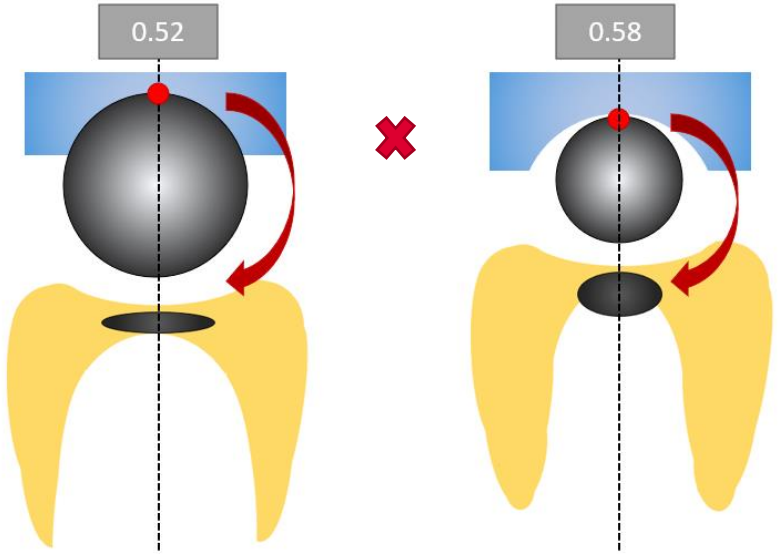
Ball bearing conformity

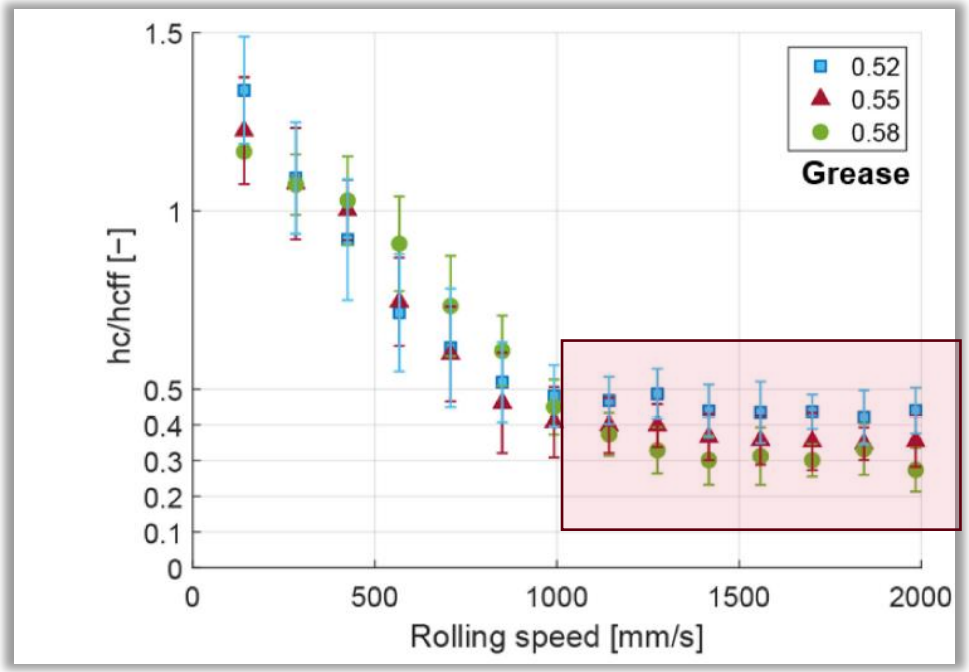
More conformal contacts:

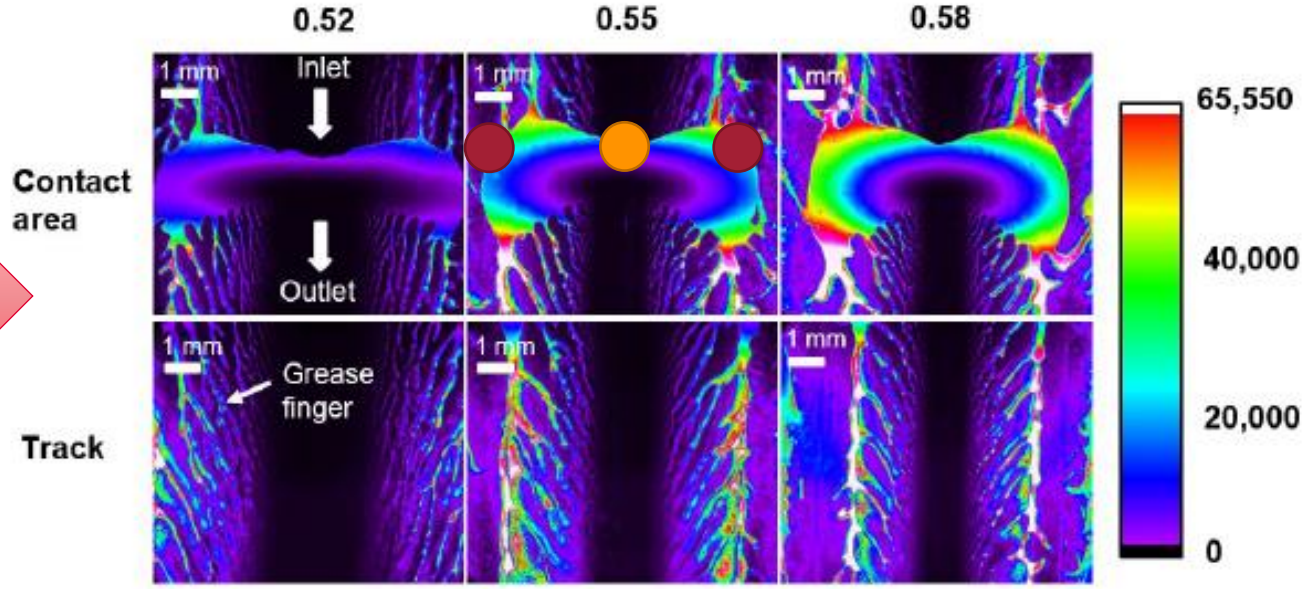
Less lubricant around the contact (RESERVOIRS)

Greater ability to prevent starvation

Narrower gaps create better conditions for meniscus formation







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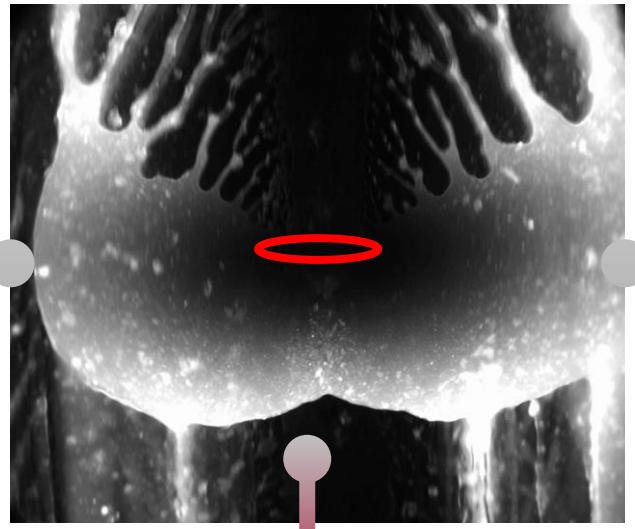
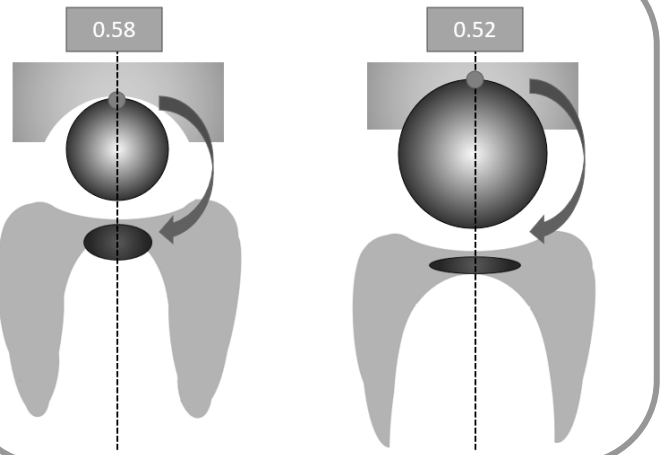
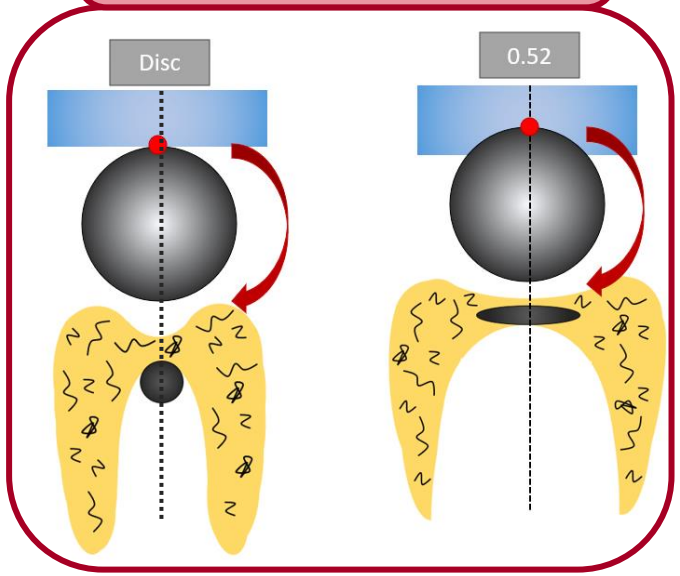


Conformity and film thickness



Thickener and replenishment



Ball bearing film thickness

Effect of thickener in EHL contact

How does the different replenishment affect the behaviour of the thickener in the EHL contact?

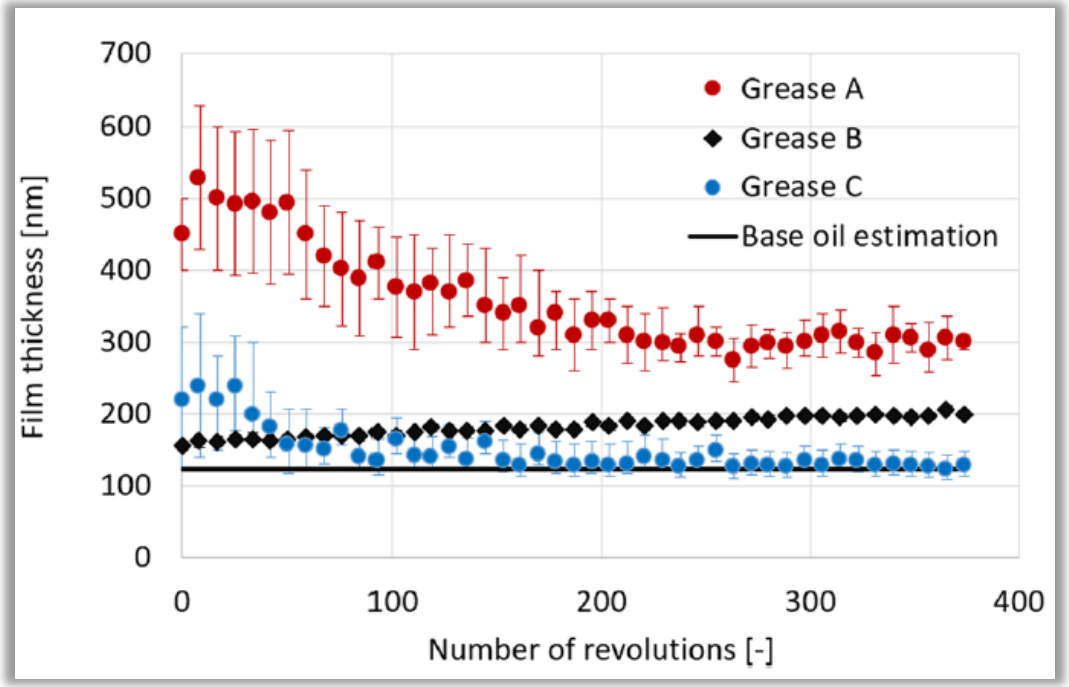
Samples

- Alicyclic di-urea-normal thickener (A)
- Alicyclic di-urea-fine thickener (B)
- Lithium complex (C)

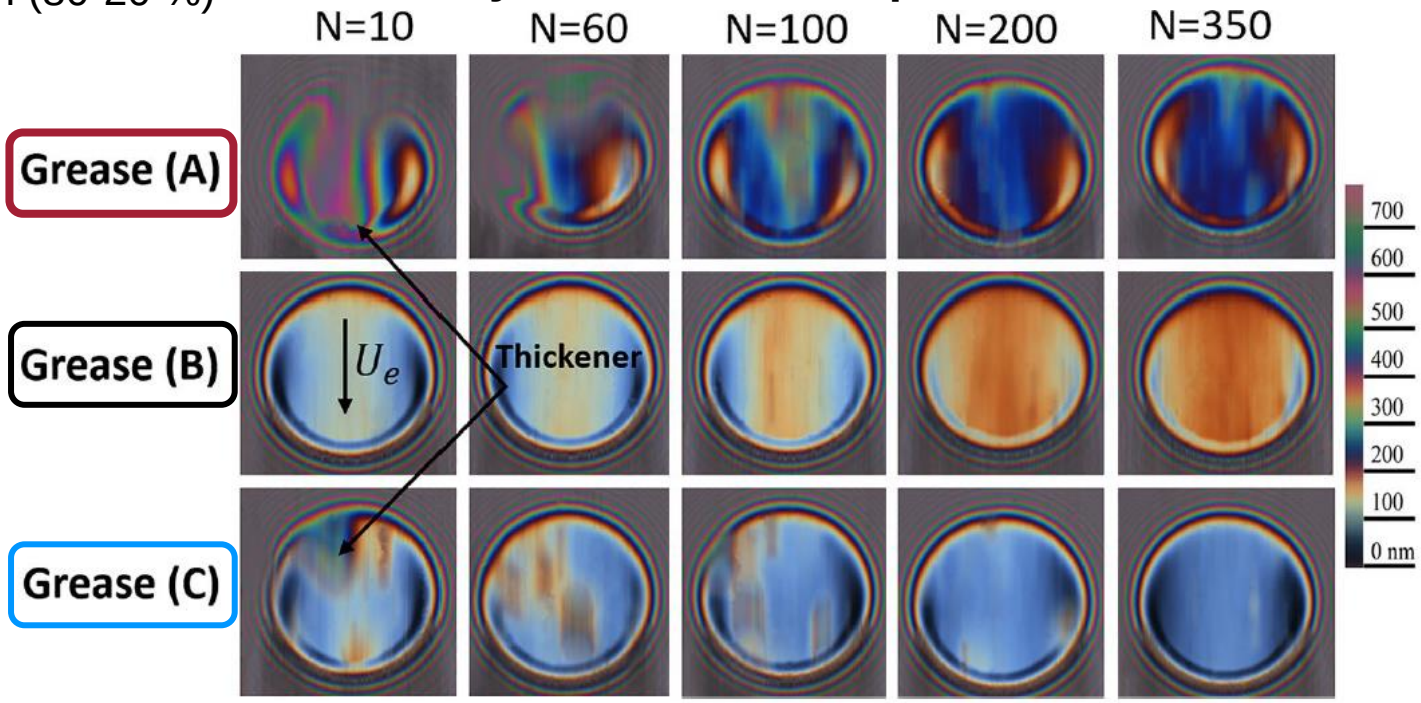
Same base oil

Information from the literature:

- Concentration of thickener varies with speed - Low speeds (0-50mm/s)
- At higher speeds the original thickener representation (80-20 %)



Fully flooded under speed 100 mm/s



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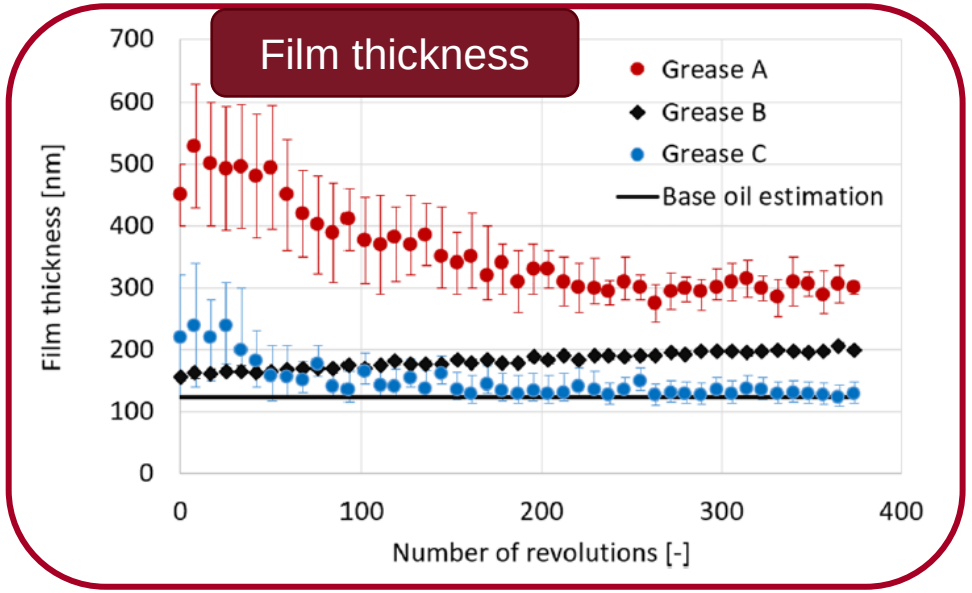
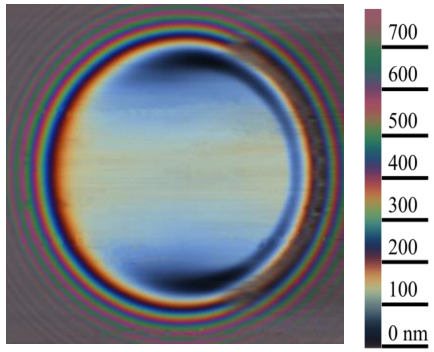
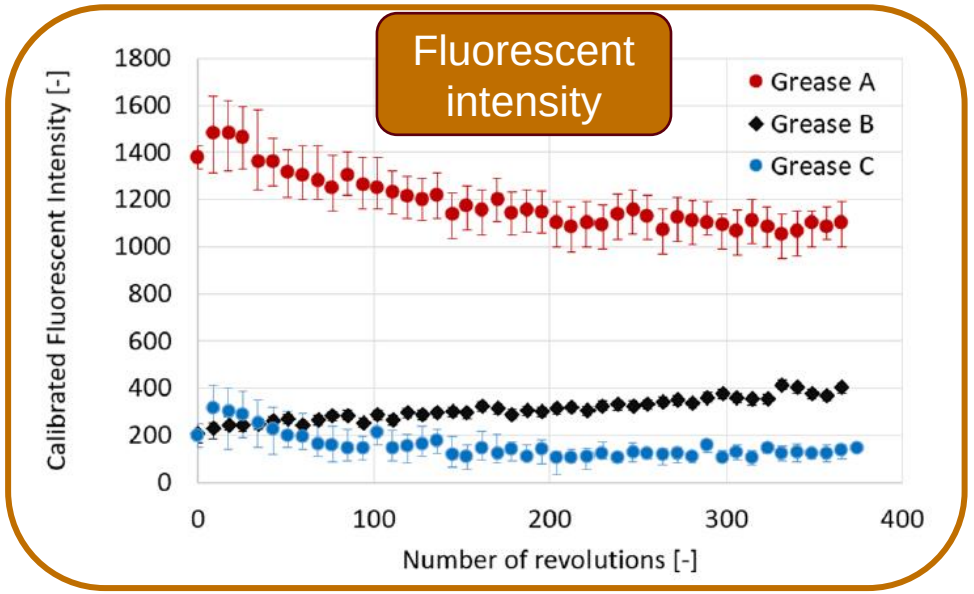
Effect of thickener in EHL contact

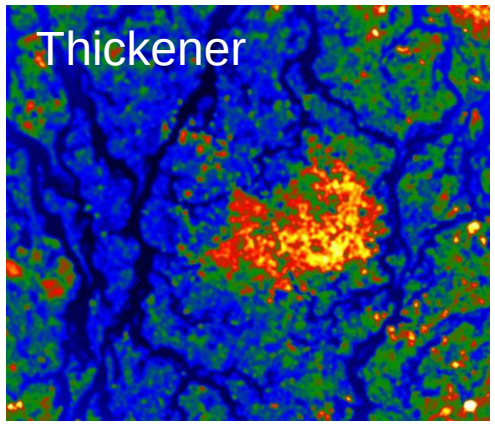
Effect of type and structure of the thickener?

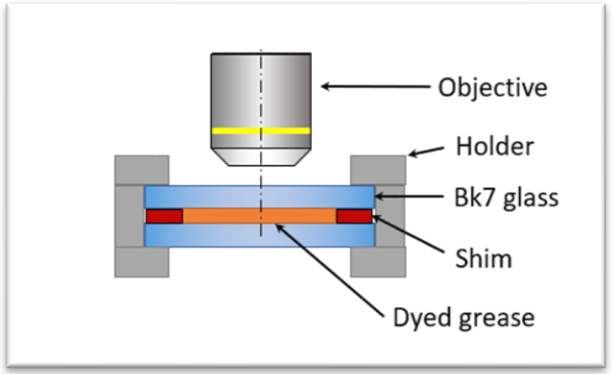
Fully flooded under speed 100 mm/s.











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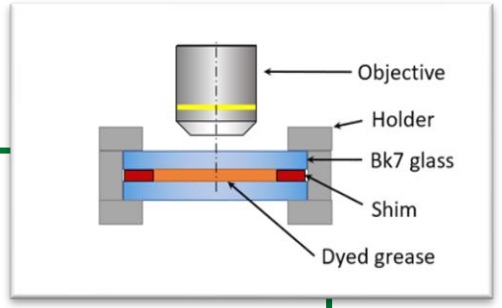
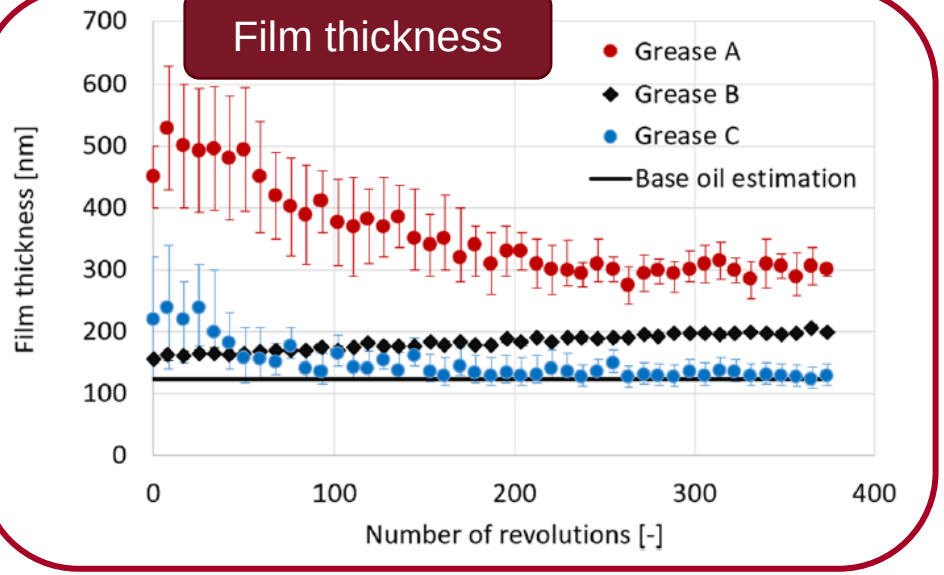
Effect of thickener in EHL contact

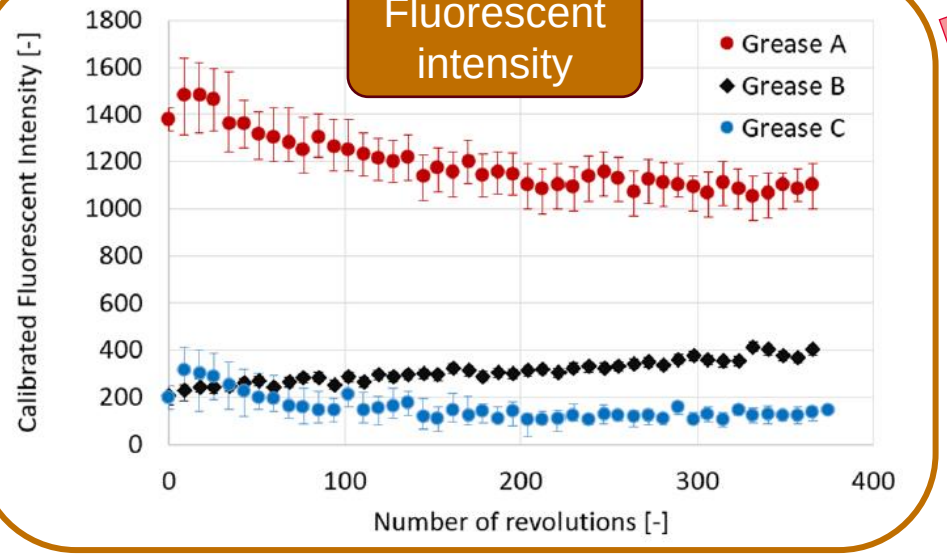
Effect of type and structure of the thickener?



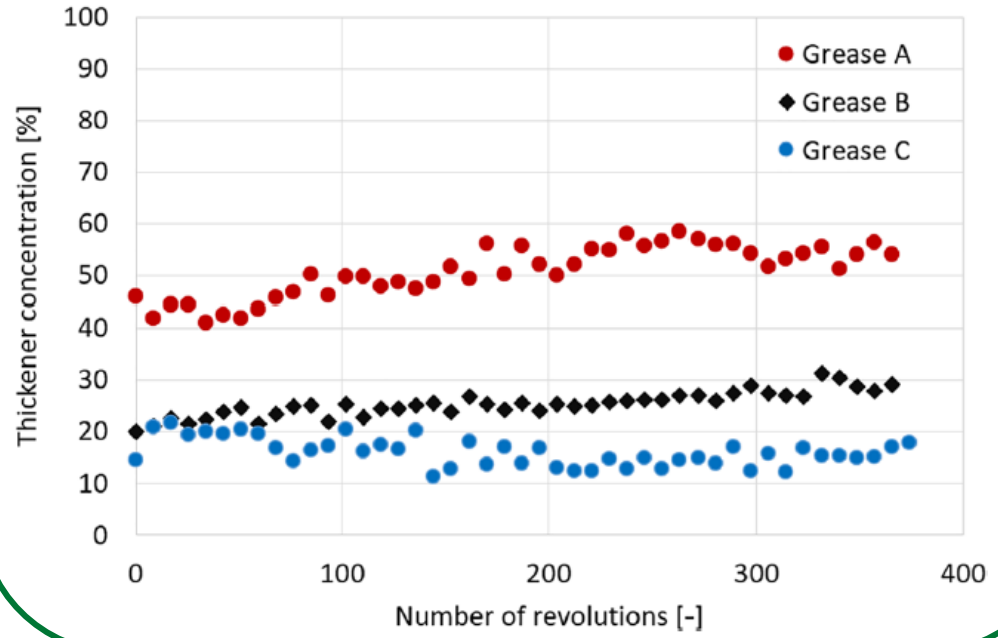
Film thickness



Fluorescent intensity



Thickener concetration



- **Lithium grease** has the original thickener representation after time
- **Alicyclic di-urea grease (A-B)** has a concentration increase over time

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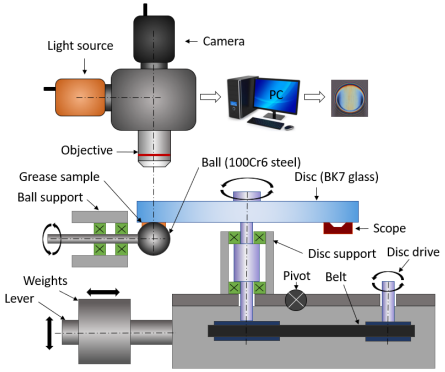
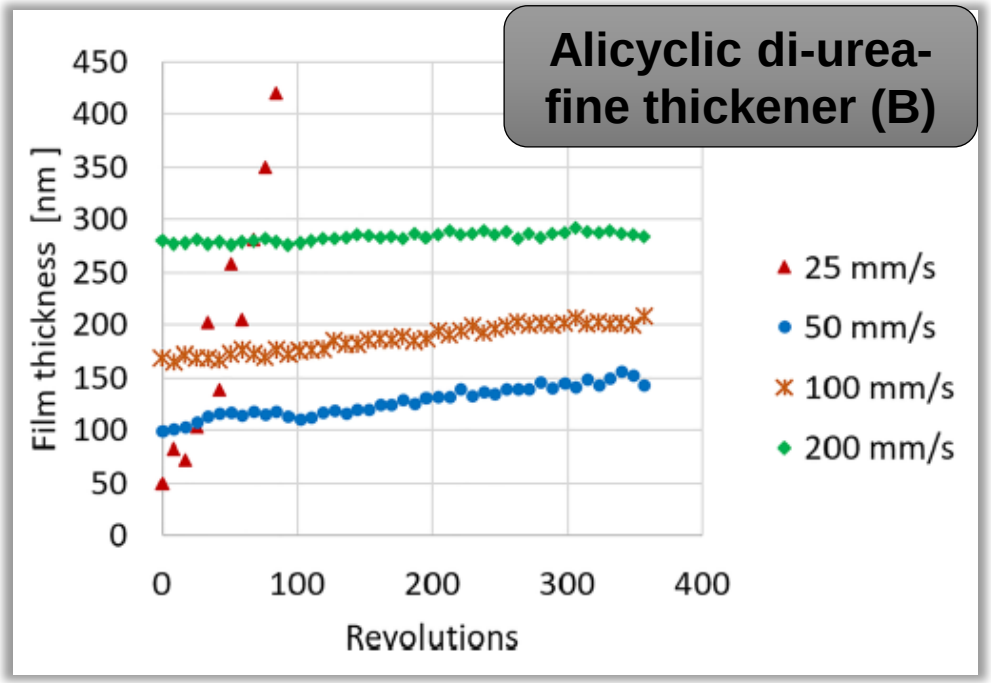
Effect of thickener in EHL contact

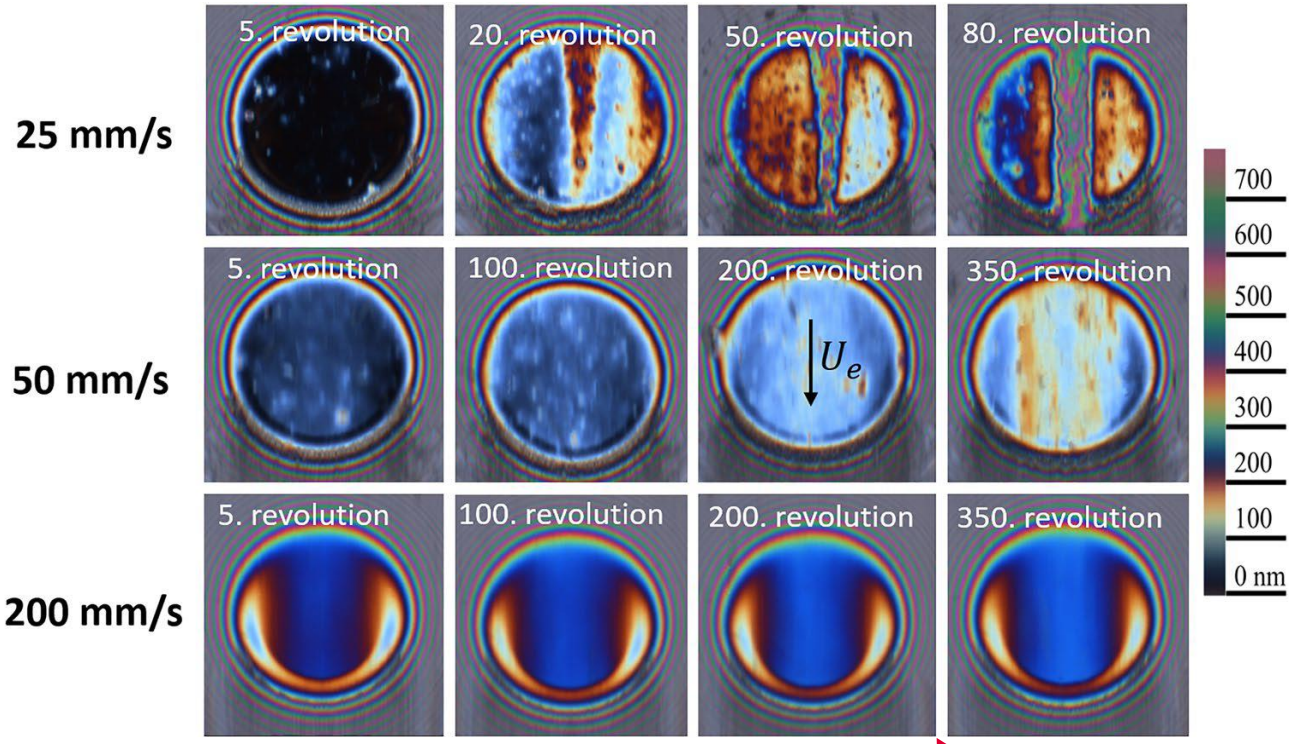
And effect of speed?



- Higher speed - less influence on film thickness
- Concentration growth due to the growth of the layer on the track **(Built-up effect)**

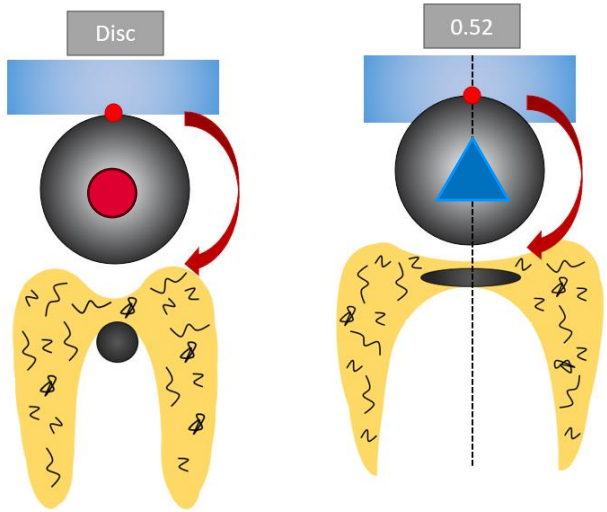


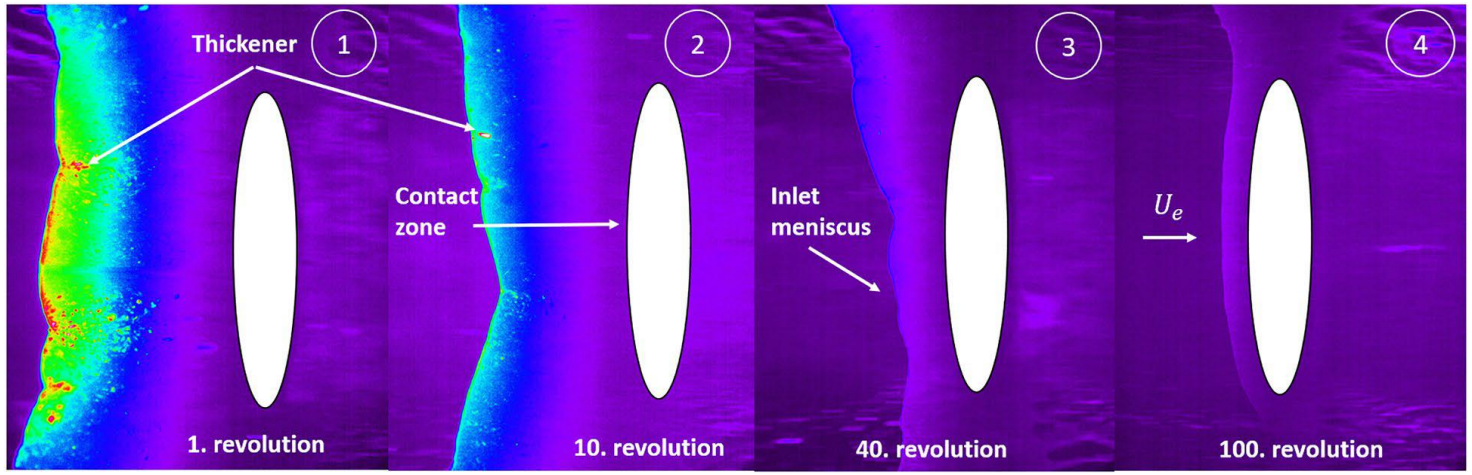
Defferent speed and same distance



Effect of thickener in EHL contact

Alicyclic di-urea-fine thickener (B)



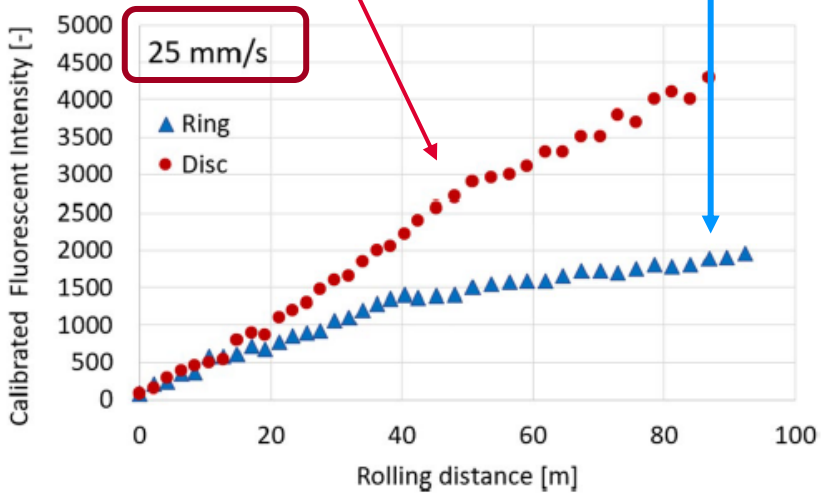


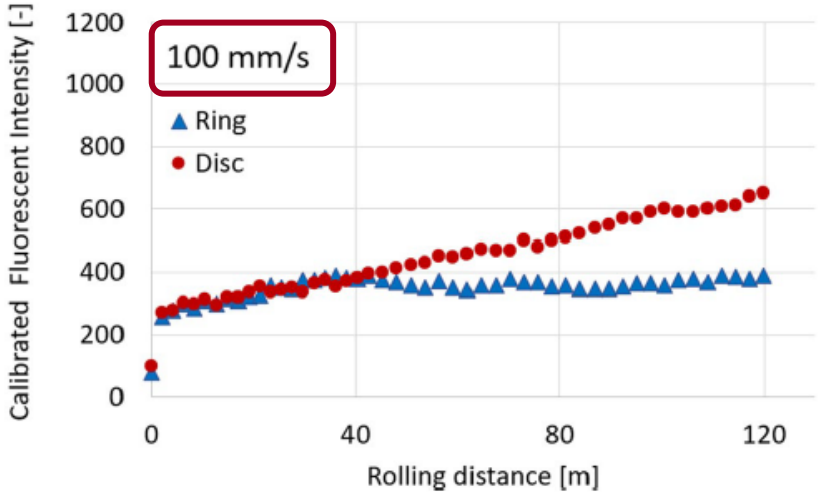
Artificial replenishment

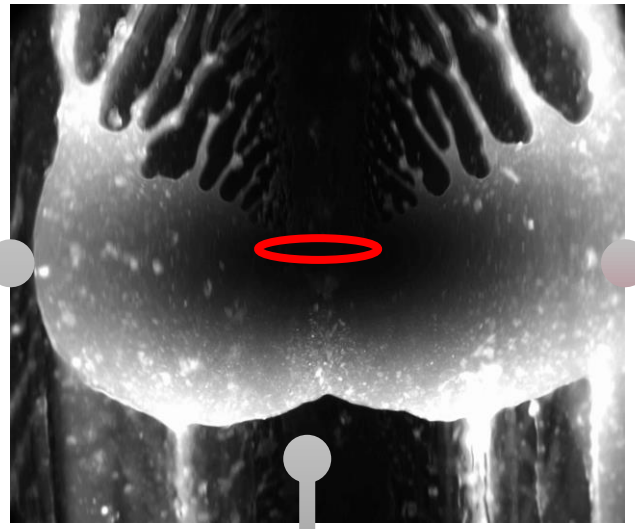
Natural replenishment

Higher speed => less influence on built-up of thickener

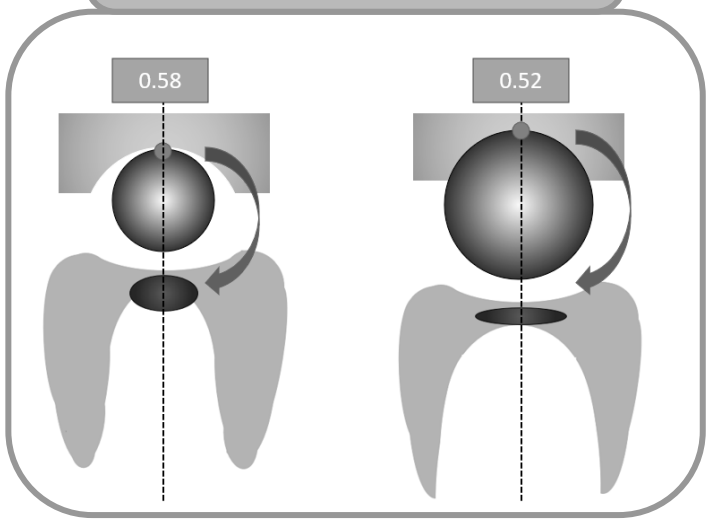
Natural replenishment=> less amount lubricant around



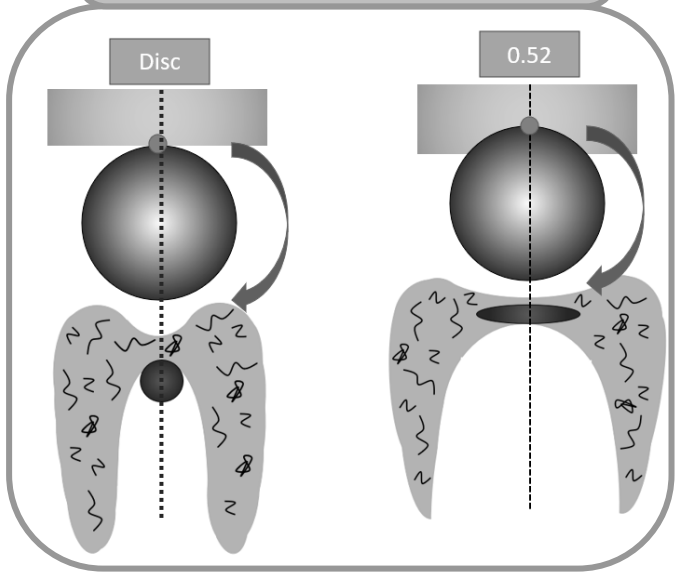




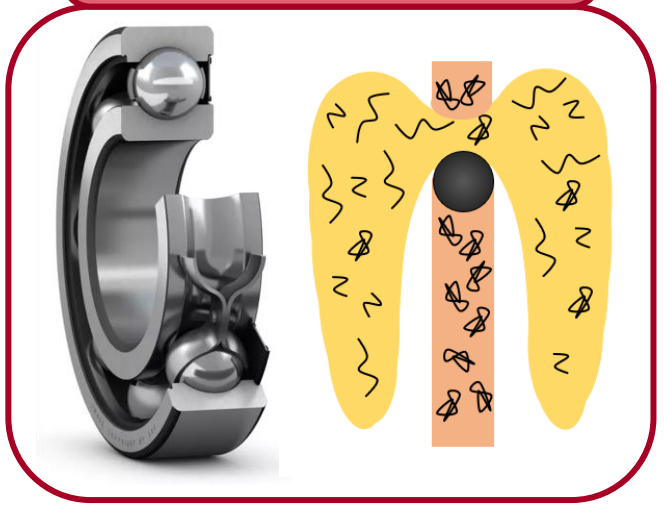
Conformity and film thickness



Thickener and replenishment



Ball bearing film thickness



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Ball bearing film thickness

How the thickener affects the lubrication film thickness in a deep groove ball bearing?

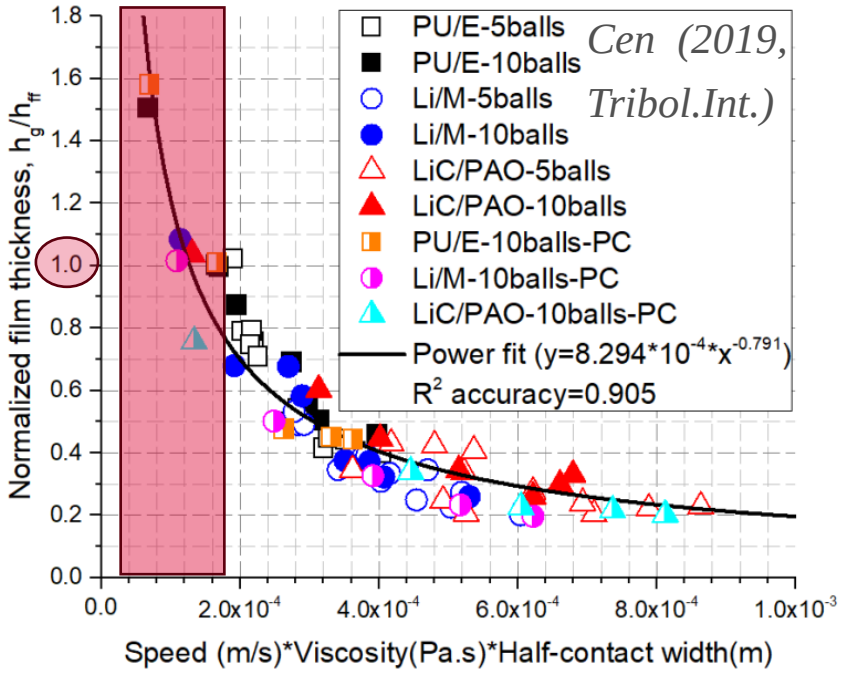
Information from the literature:

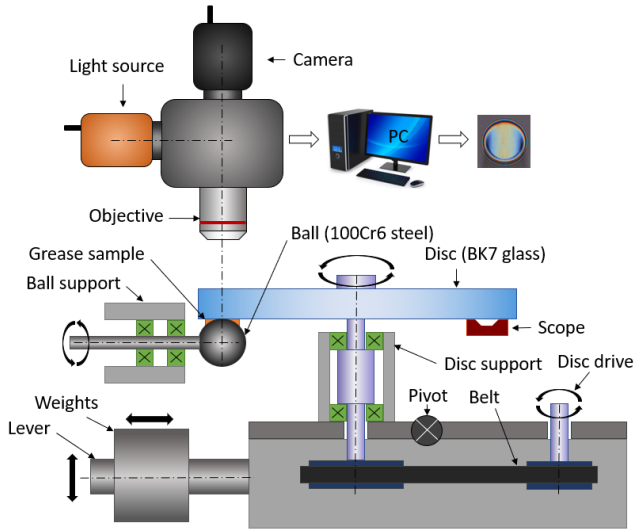
- The film thickness in the bearing is **not dependent on the thickener**
- In the case of urea greases, a larger residual thickener layer is formed

Samples

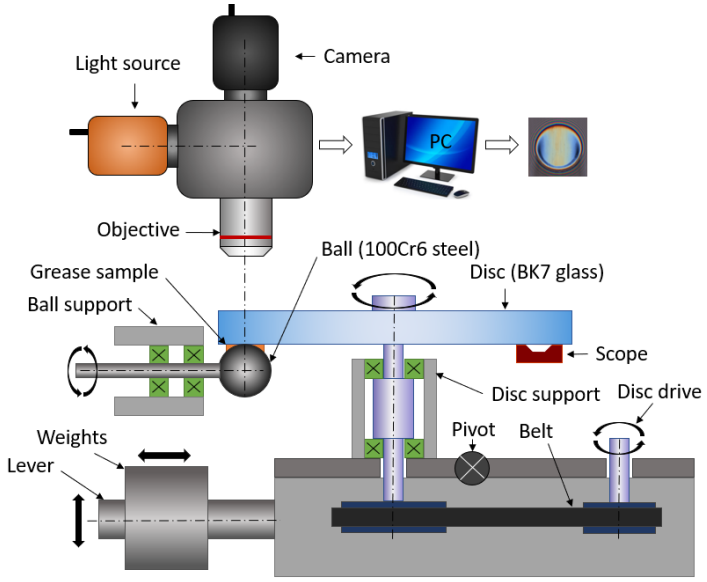
- **Alicyclic** di-urea-normal thickener
- **Lithium complex**
- **Aliphatic** di-urea-fine thickener

Same base oil

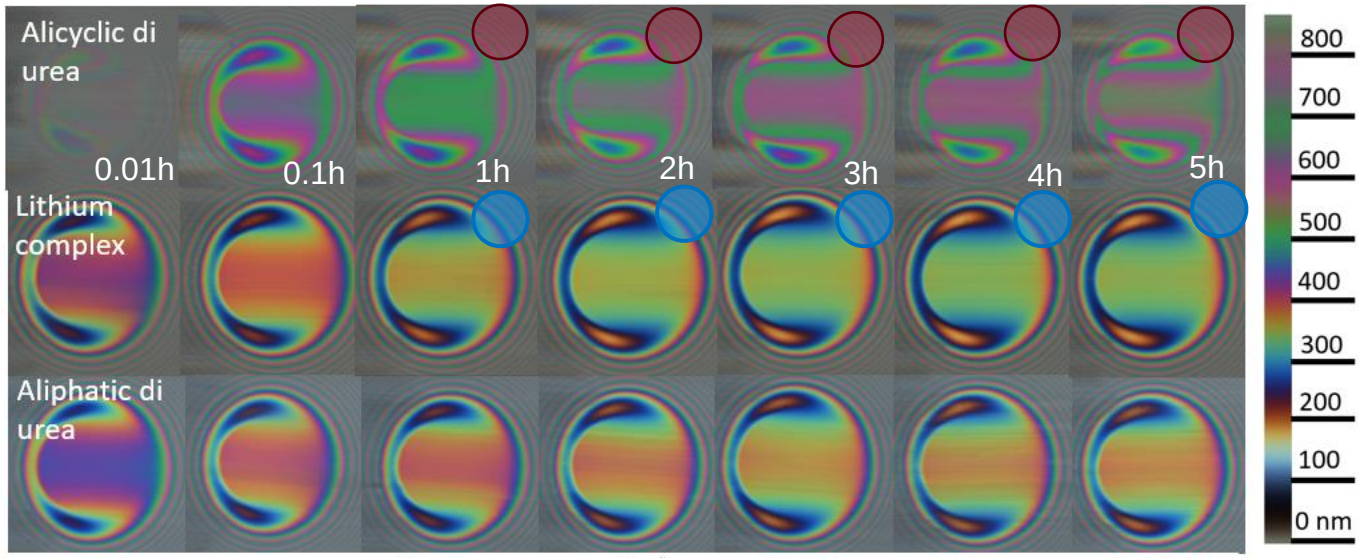




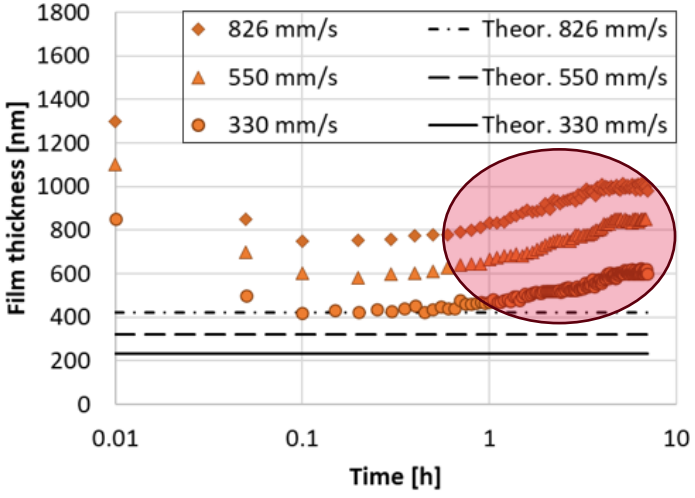
Ball bearing film thickness



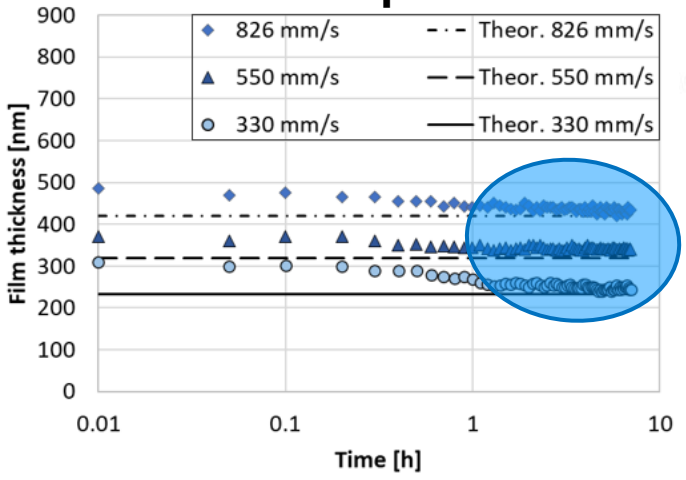
Constant speed 550 mm/s under fully flooded conditions

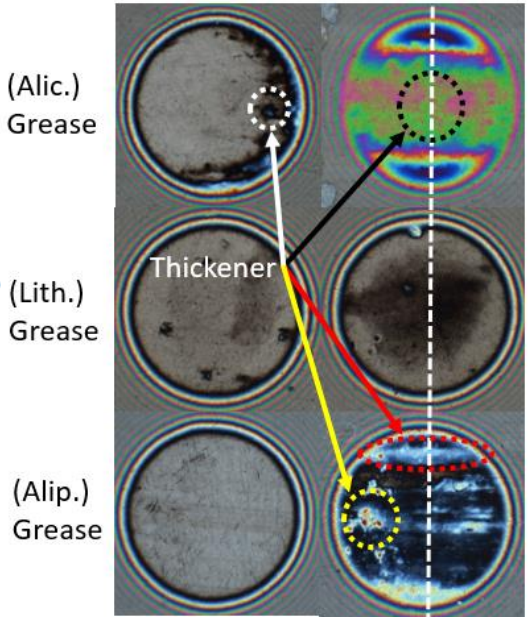


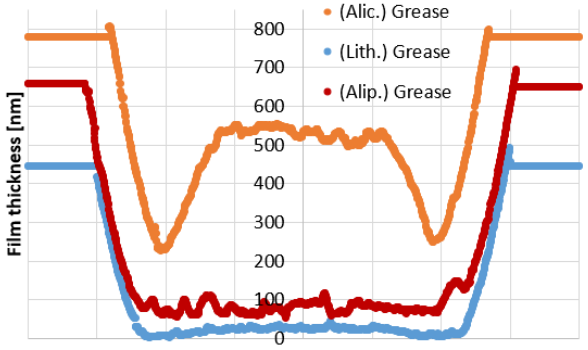
Alicyclic di-urea



Lithium complex

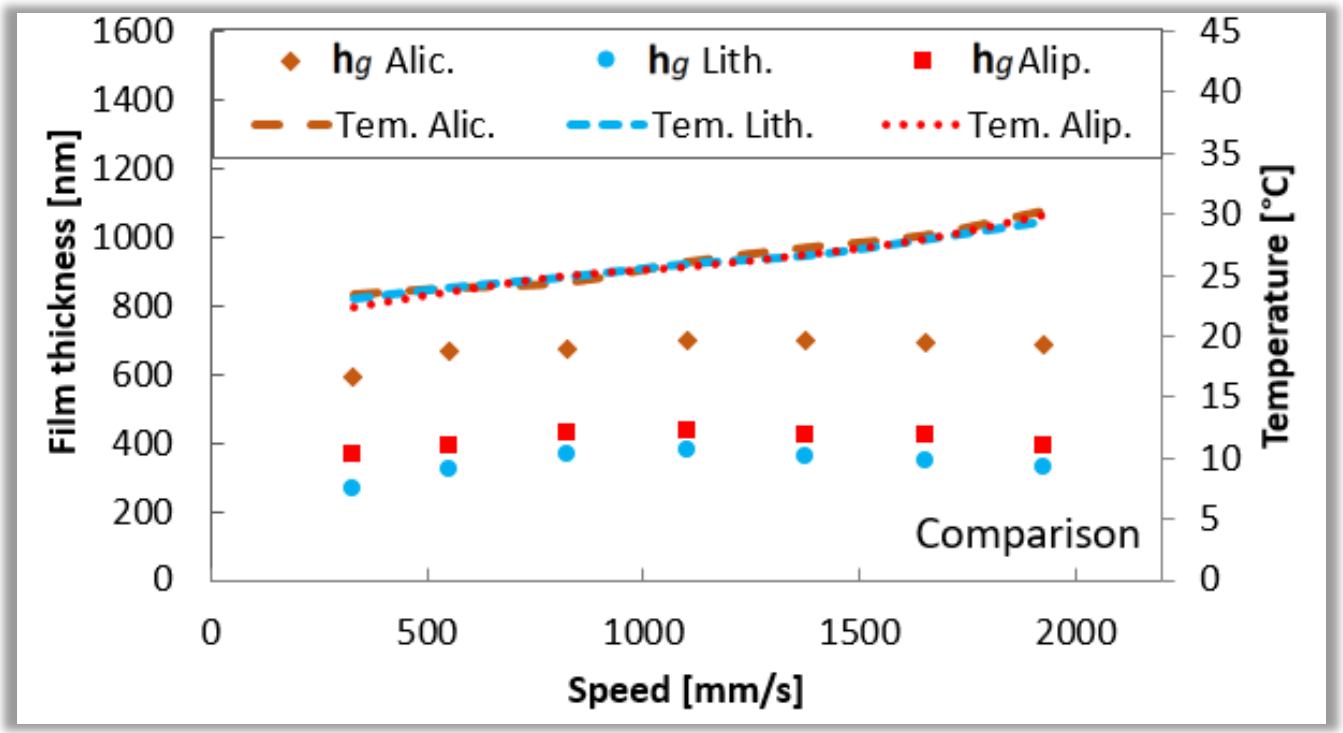


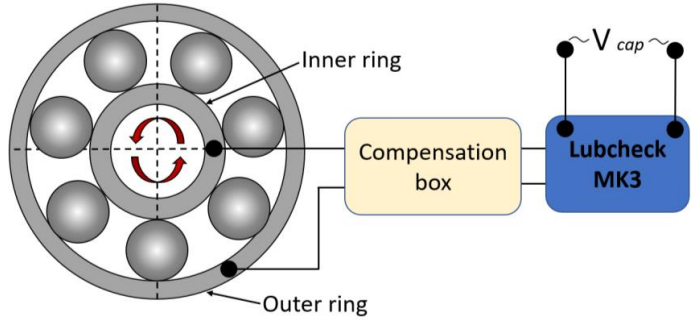


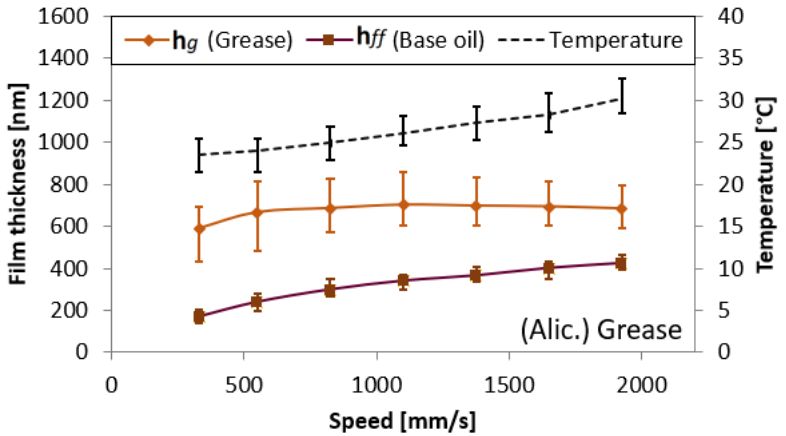


Ball bearing film thickness

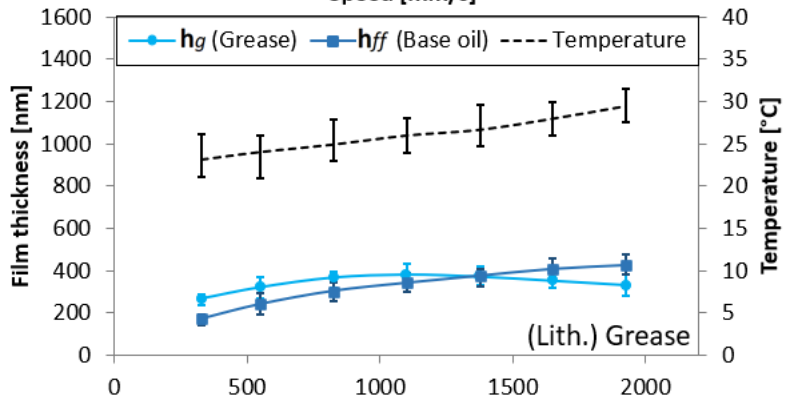
- The difference between film thickness.
- Minimum difference in bearing operating temperature.





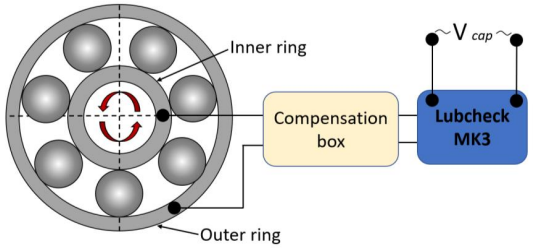


Alicyclic di urea



Lithium complex

Ball bearing film thickness

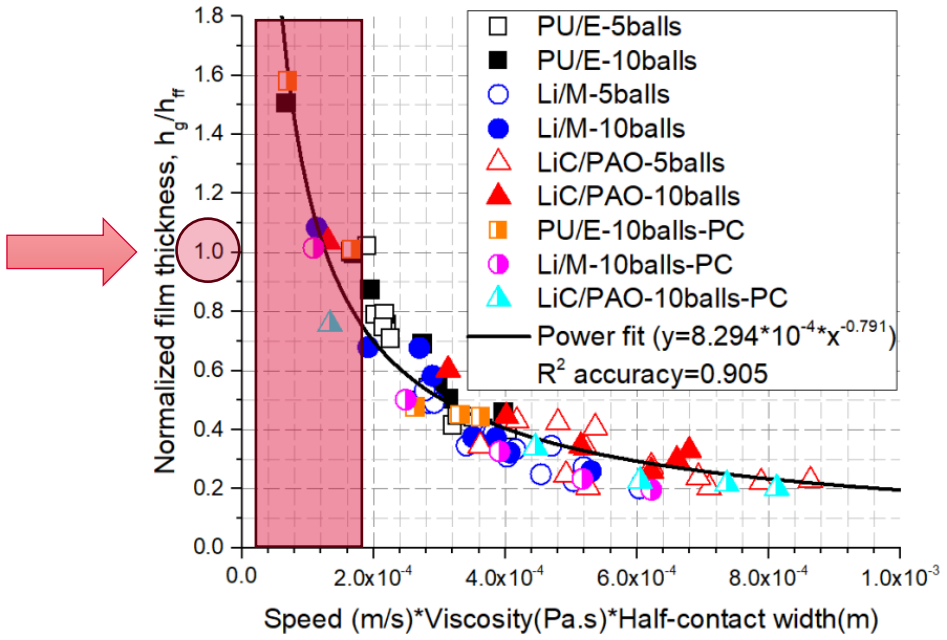


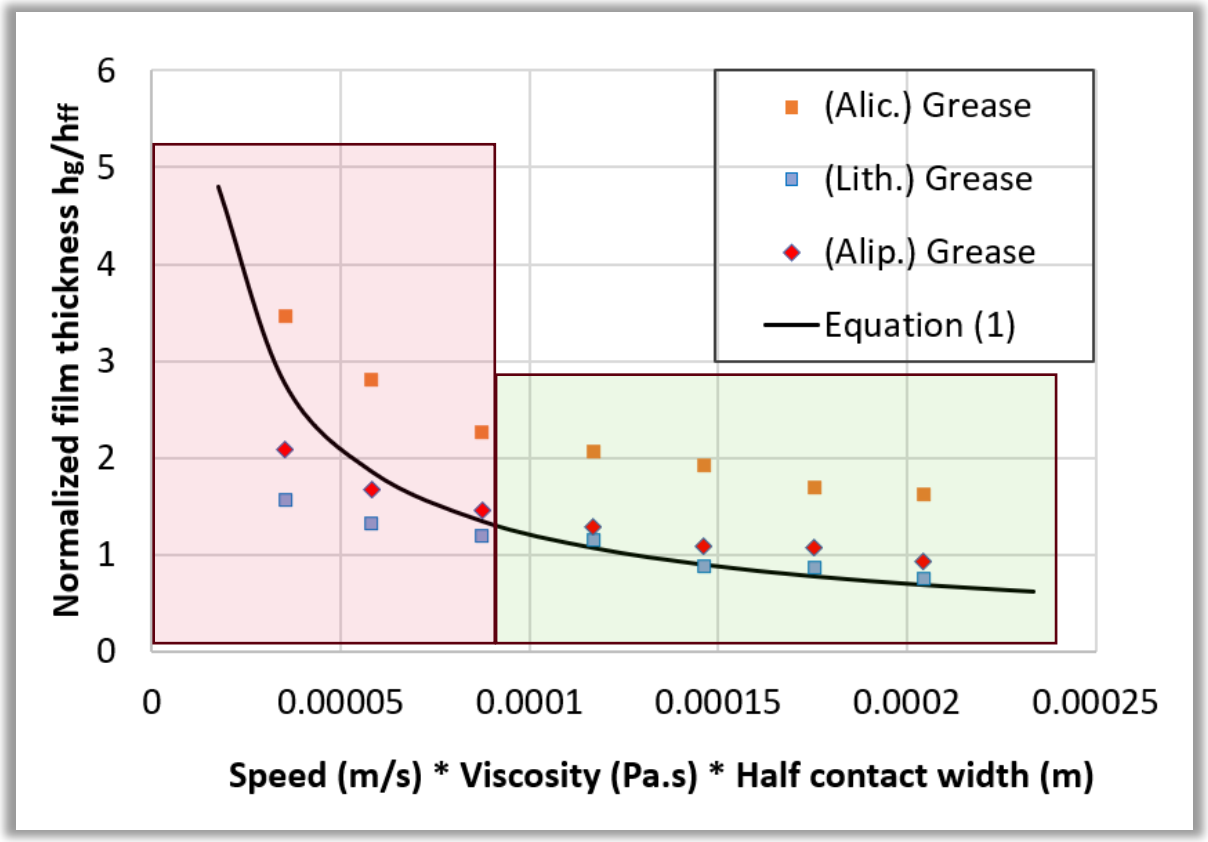
Deviation in the area of very low speeds

At higher speeds agreement with theory

Alicyclic di-urea

Same curve shape, but offset





$$\frac{h_g}{h_{ff}} = 8.294 \times 10^{-4} \times (u\eta b)^{-0.791}$$

Conclusions of the PhD thesis

Conformity and film thickness

- More conformal contacts produce less lubricant in the surrounding area, but the stronger capillary effect can better prevent contact starvation at higher speeds.

Thickener and replenishment

- The concentration of thickener in the EHL contact changes even at higher speeds, but it depends on the type of thickener.
- An increase in thickener concentration is associated with an increase in the residual layer on the contact surfaces. This growth is slower at higher speeds as well as with more limited lubricant in the surrounding area.

Ball bearing film thickness

- At very low speeds, the film thickness in the ball bearing is also affected by the thickener. Residual layer growth occurs on the surfaces where the thickness can increase by several hundred nanometres.

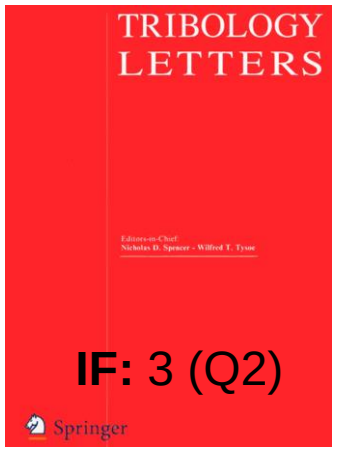
Thesis layout

Verification of findings in real bearings

Behaviour in EHL point contacts

Dyeing of grease components

Observation of the grease constituents in EHL contacts by fluorescence microscopy



IF: 3 (Q2)

Effect of contact conformity on grease lubrication

lubricants

IF: 3.1 (Q2)

Thickener behaviour in rolling EHL lubrication contacts

IF: 3 (Q2)

Experimental Study of the Effect of Thickener on the Film Thickness in the Contacts of a Grease-Lubricated Ball Bearing at Low Speed

IF: 2:5 (Q2)

2022 **2025**

Thesis layout

journals with impact factor

Kostál, D.; **Okál, M.;** Frýza, J.; Křupka, I.; Hartl, M. Novel in-situ observation of the grease constituents in elastohydrodynamic contacts by fluorescence microscopy, Tribol. Lett. 2022

Okal, M., Kostal, D., Sperka, P., Krupka, I., Hartl, M., Effect of Contact Conformity on Grease Lubrication. Lubricants 2022; 10. https://doi.org/10.3390/lubricants10110289.

Okal, M., Kostal, D., Sakai, K., Krupka, I., Hartl, M., Thickener Behaviour in Rolling Elastohydrodynamic Lubrication Contacts. Tribol. Lett. 2024; 72. https://doi.org/10.1007/s11249-024-01874-0.

Okal, M., Kostal, Osara, J., Lugt, P., Krupka, I., Hartl, M., "Experimental Study of the Effect of Thickener on the Film Thickness in the Contacts of a Grease-Lubricated Ball Bearing at Low Speed," Tribol. Trans. 2025.

conference abstracts

Kostál, D.; **Okál, M.;** Křupka, I.; Hartl, M. From single contact devices to rolling bearing simulator. World Tribology Conference, 2022, Lyon, France.

Okal, M., Kostal, D., Krupka, I., Hartl, M., Grease replensihment behaviour on the ball-on-ring tribometr. World Tribology Conference, 2022, Lyon, France.

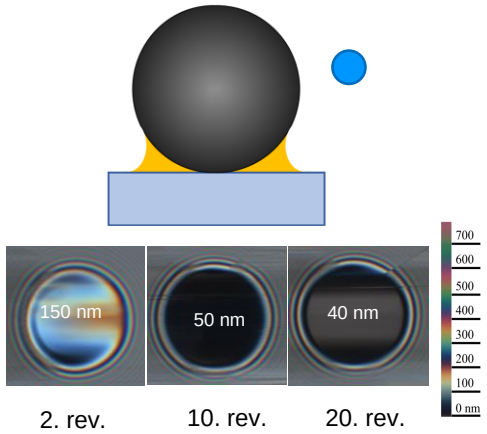
Kostál, D.; **Okál, M.;** Křupka, I.; Hartl, M. Grease constituents observation with the use of the fluorescent microscopy. International Tribology Conference, 2023, Fukuoka, Japan.

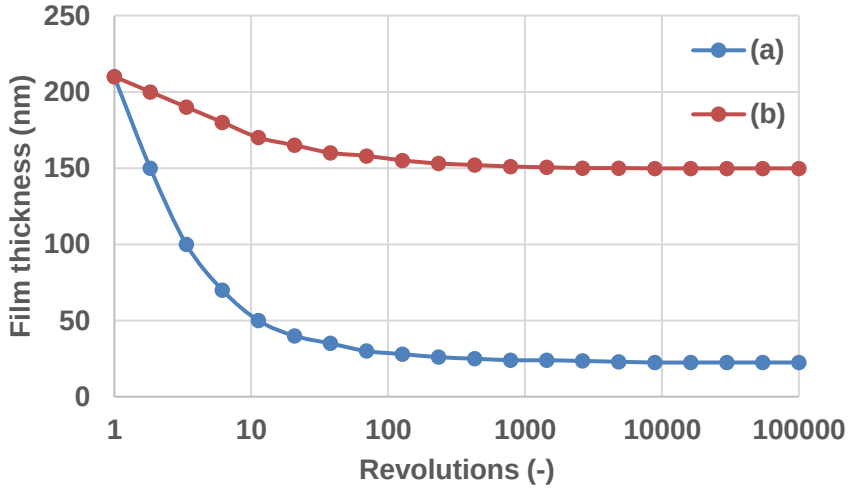
Okal, M., Kostal, D., Krupka, I., Hartl, M., Behaviour of grease thickener in and around the EHD contact. International Tribology Conference, 2023, Fukuoka, Japan.

Novelty

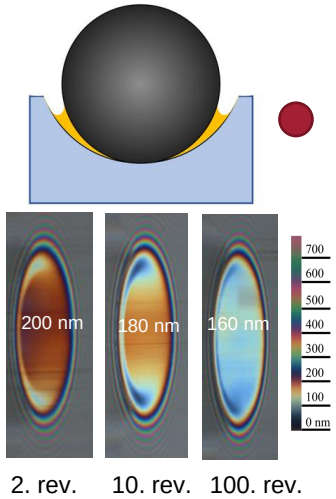
A new method for experimental study of greases in EHL contacts:

A) Low-comformity EHL contact - (Traditional method) – shows a rapid decrease in thickness with each subsequent revolution, indicating much lower film thickness than in real applications.



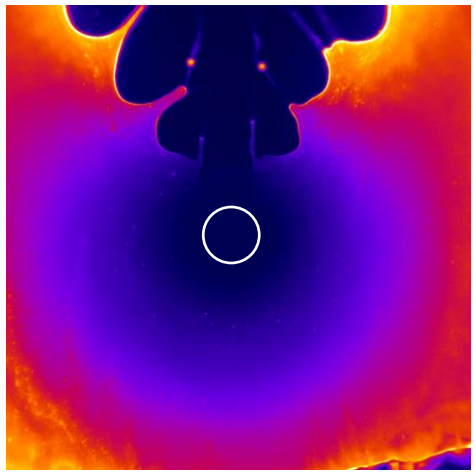


B) High-comformity EHL contact - (New method) produces a much thicker and more stable film thickness over a long duration of the experiment, approaching real application conditions.

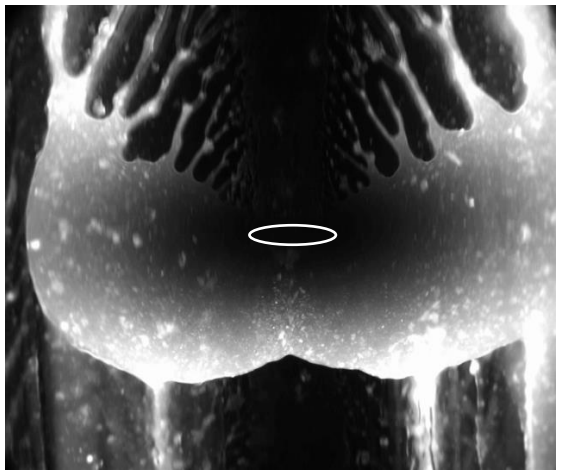


Applications of results

Traditional method



New method



Testing of greases under conditions closely resembling real-world applications allows for more accurate performance assessment and supports the development of new grease formulations.

Joint research

Study of grease film thickness and flow observation in and around of contact area

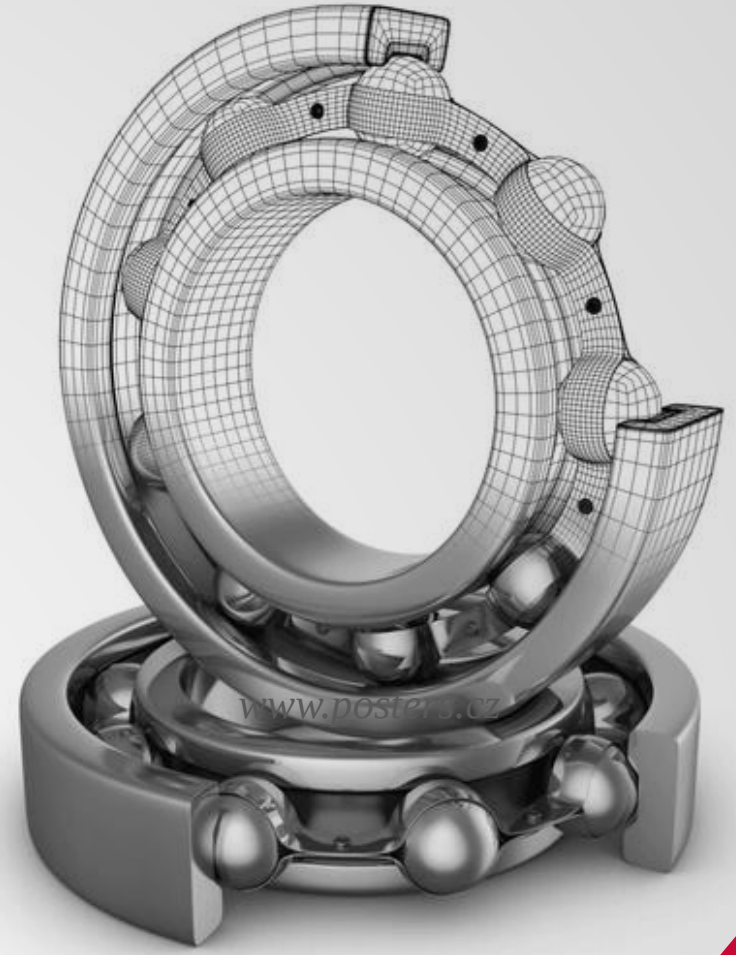
ENEOS

ENEOS

Grease R&D Group, Lubricants R&D Dept., Lubricants company
ENEOS Corporation

ENEOS Group Japan's Premier Energy and Materials Corporate Group

THANK YOU FOR YOUR ATTENTION



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AND **INDUSTRIAL DESIGN**

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