The behaviour of grease in EHL contacts of ball bearings

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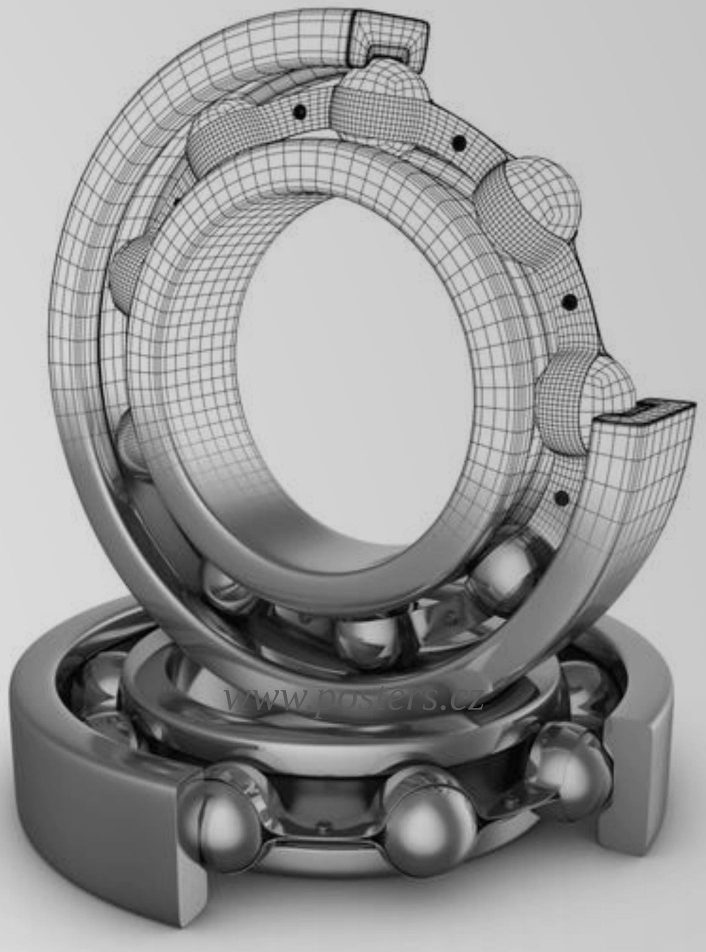
ÚSTAV
KONSTRUOVÁNÍ

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



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Deep groove ball bearings

Applications

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

Propertiess

- Low Cof. (0.001 to 0.005)
- 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**

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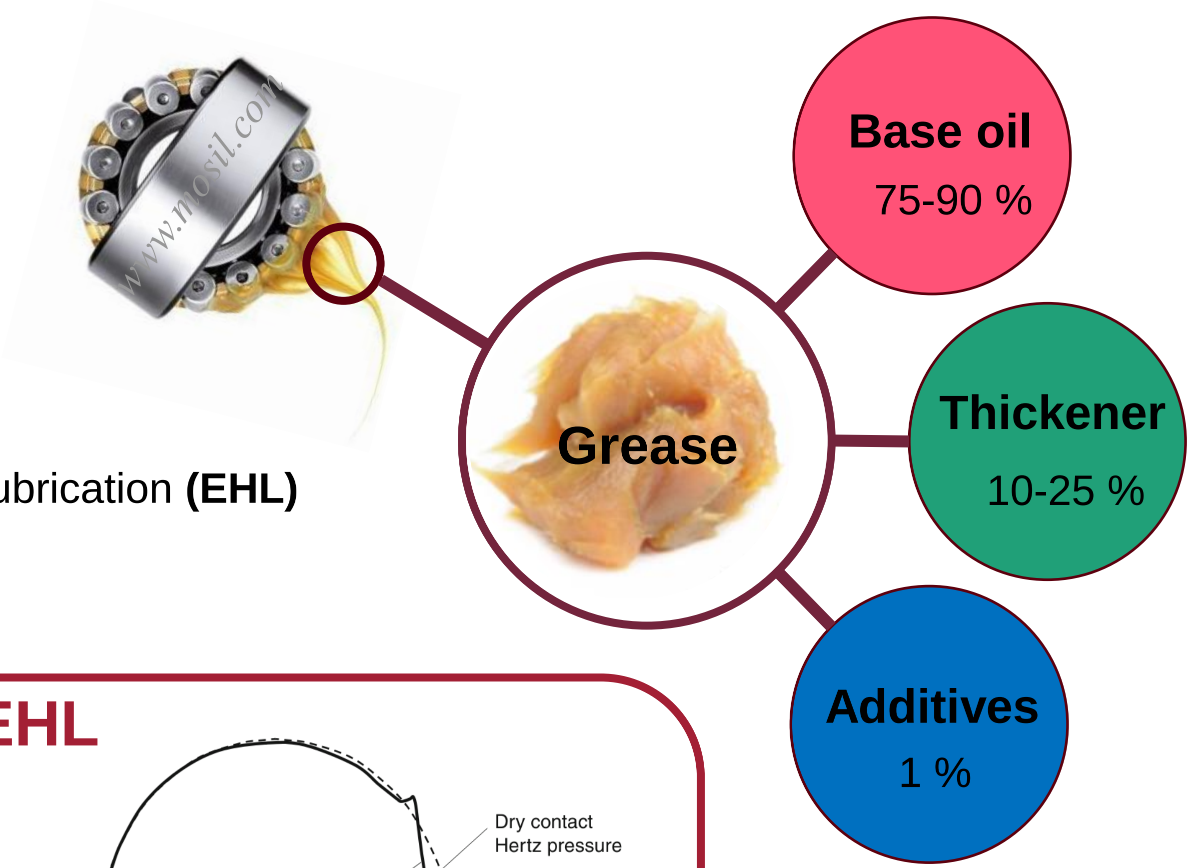
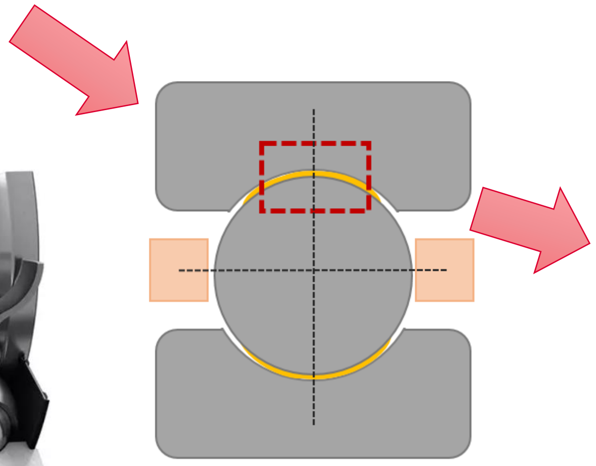
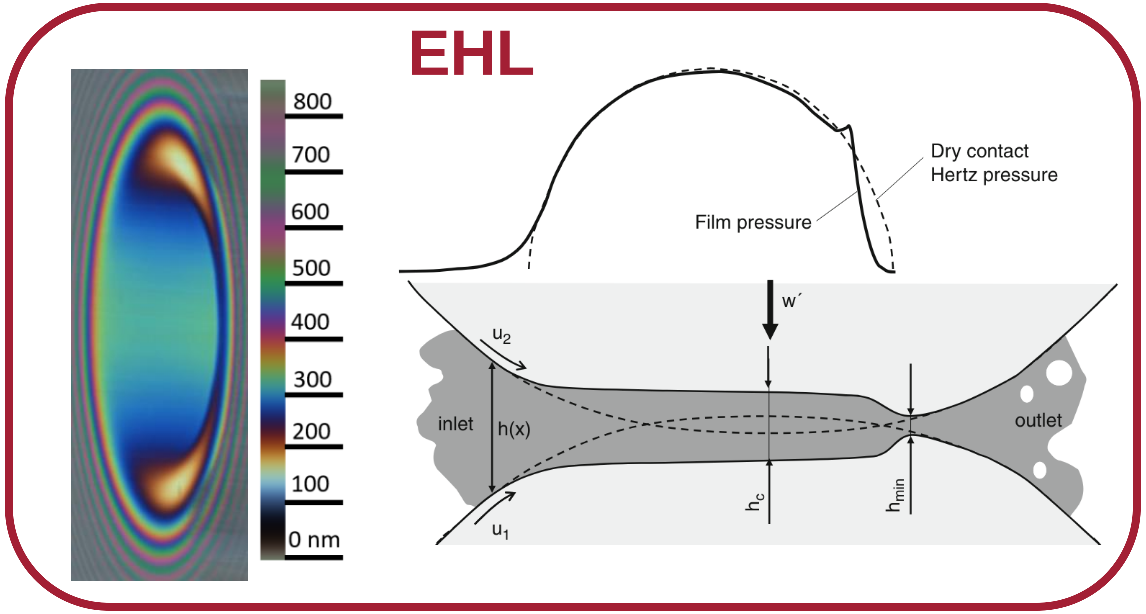
Lubrication of ball bearings



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

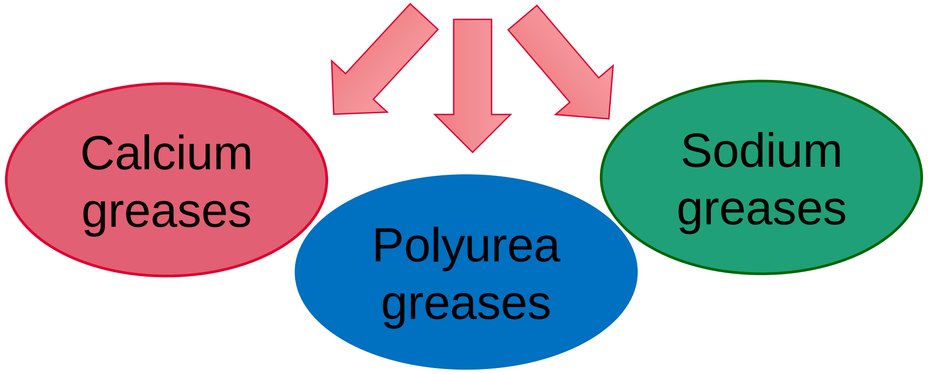




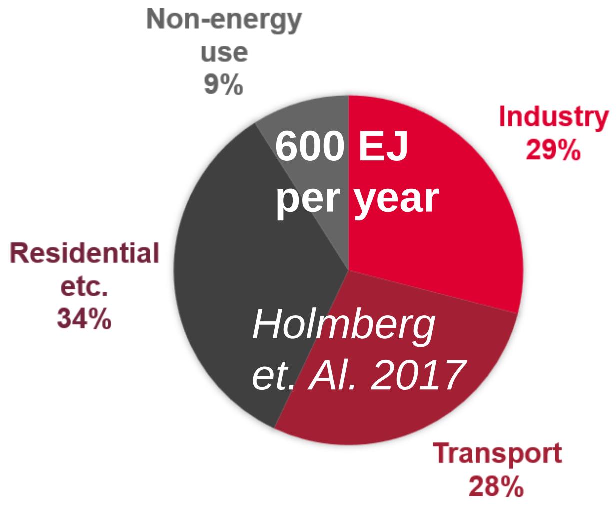
Larsson, R. (2013). EHL Film Thickness Behavior

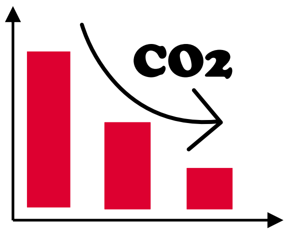
Motivation

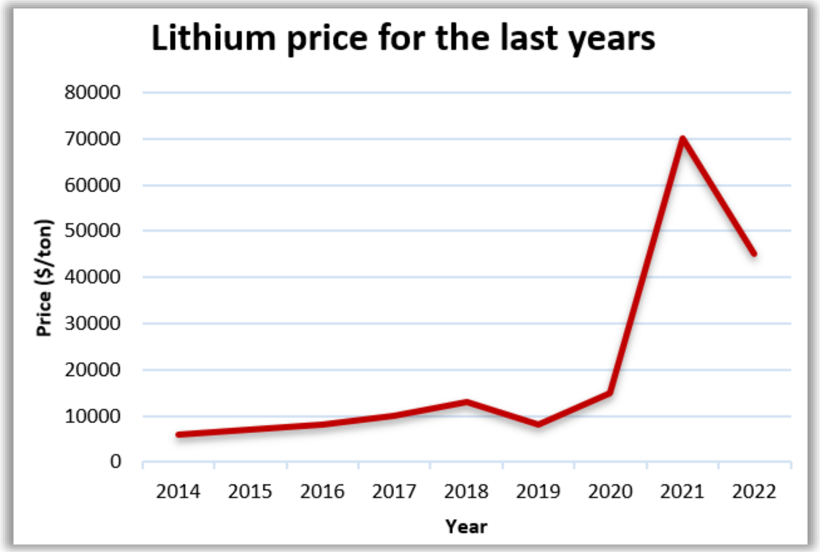
- 500 billion bearings represent one of the most frequent elements where frictional losses occur.
- Electromobility - higher lithium price (Uses almost 80% lithium-based greases)



Global energy consumption



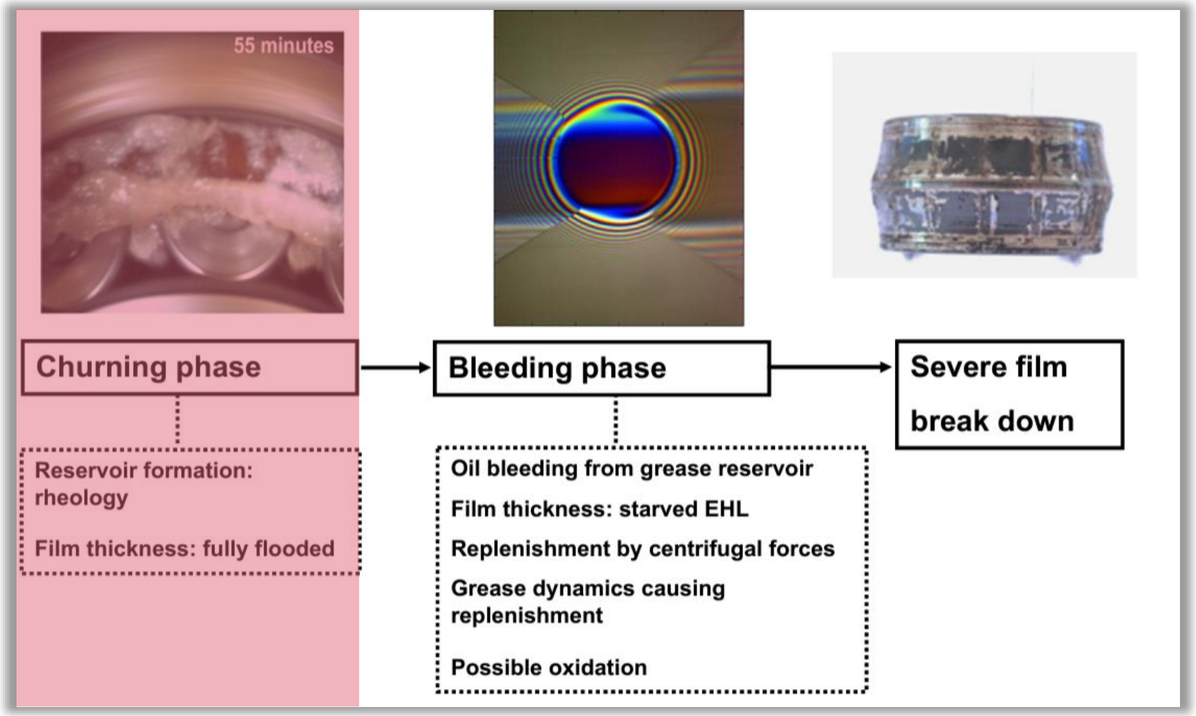




Grease lubrication in ball bearings

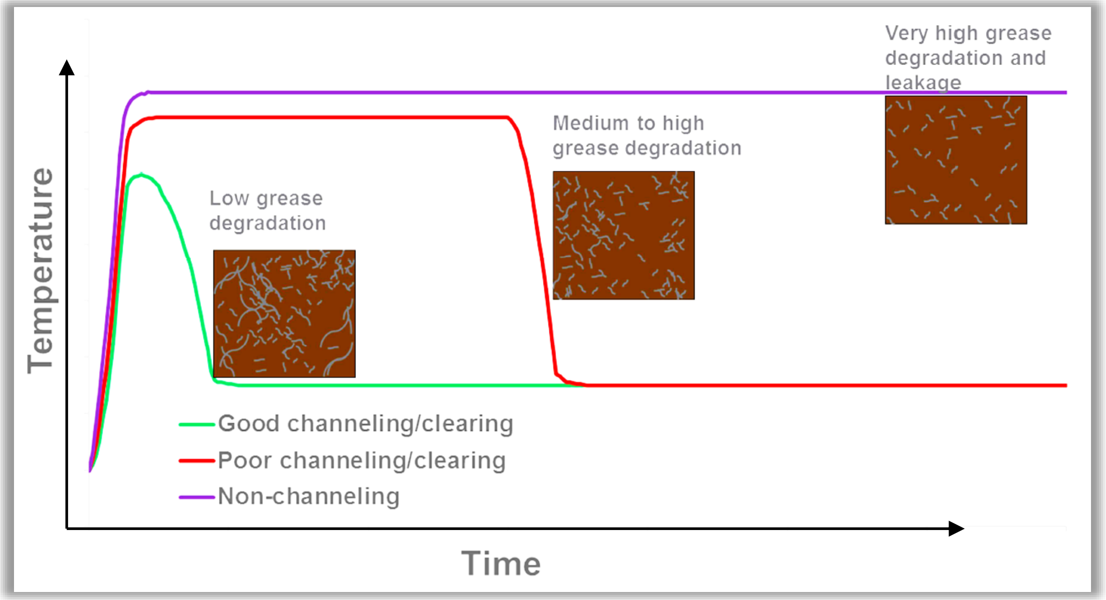
The lubrication phase

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



The churning phase

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

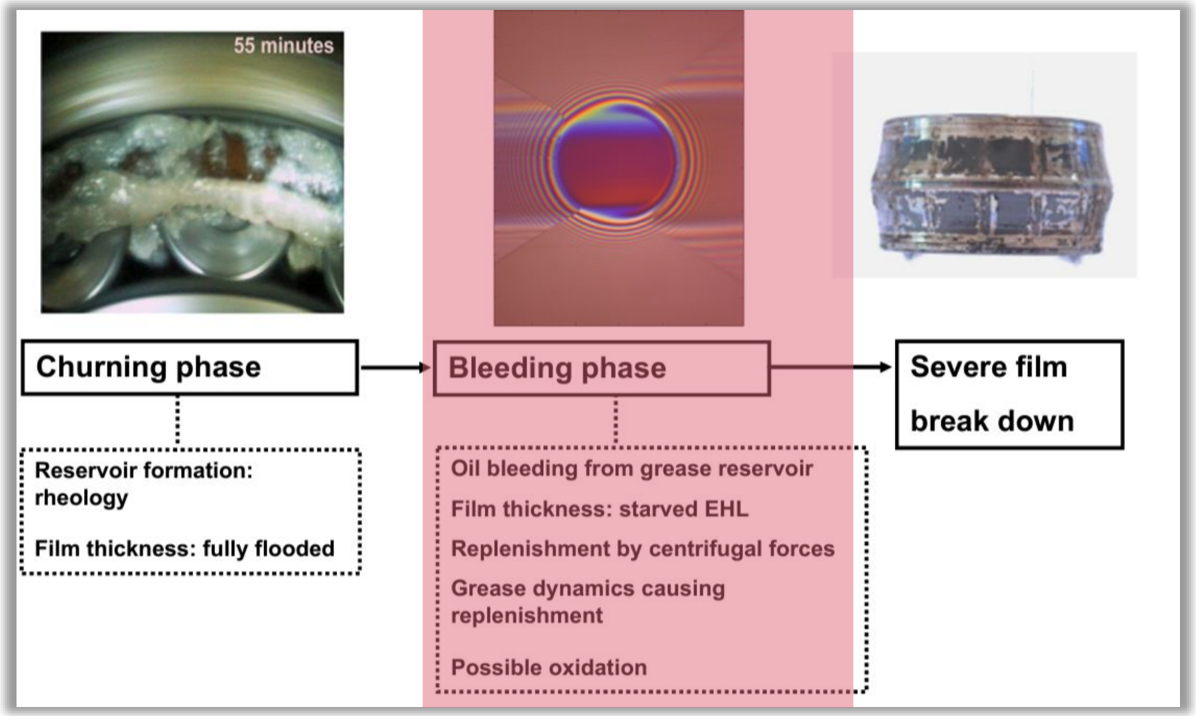


Starved elastohydrodynamic lubricated contact

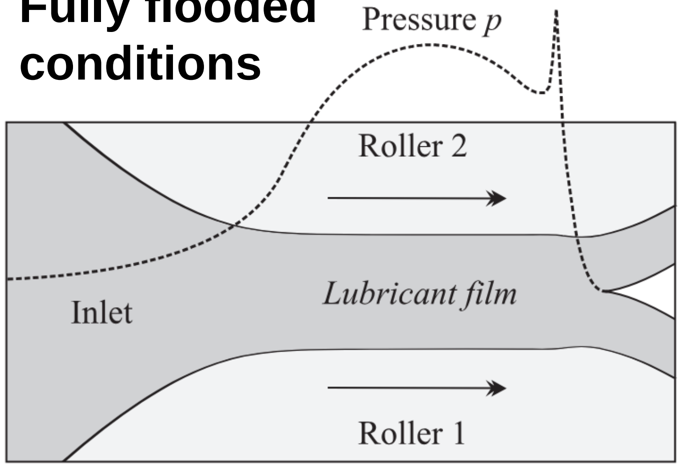
Hamrock (1977,J. Lubr. Tech).

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

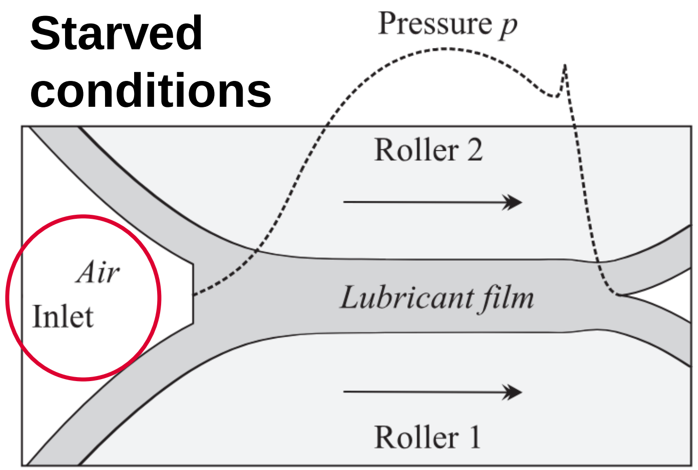
$$h_{\min} = 3.63U^{0.68}G^{0.49}W^{-0.073}\left(1 - 0.61e^{-0.73k}\right)$$

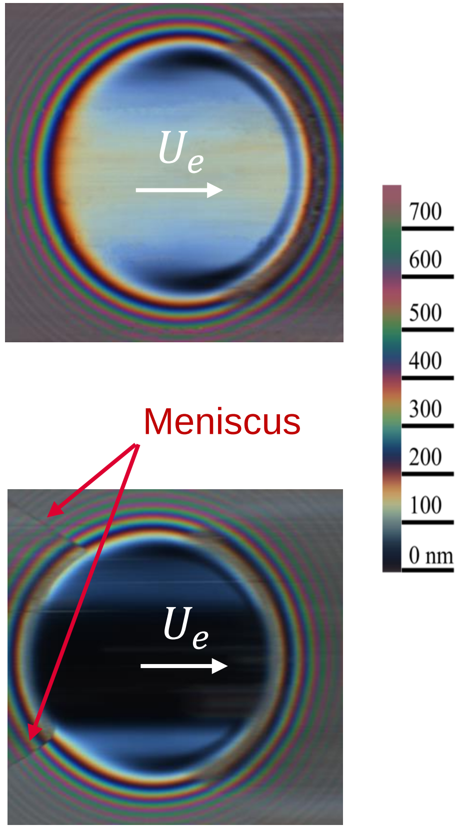


Fully flooded conditions



Starved conditions





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

$$0 \leq S \leq 1$$

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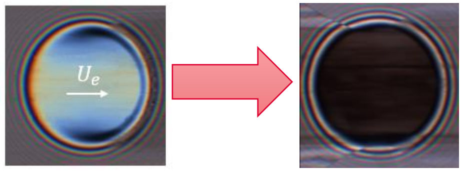
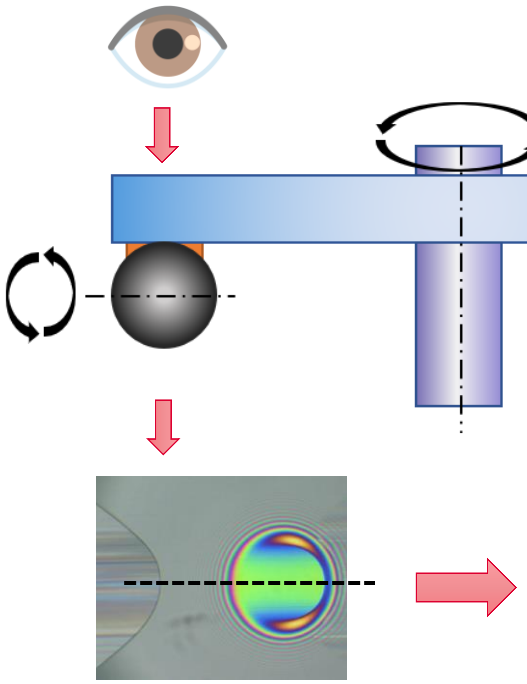
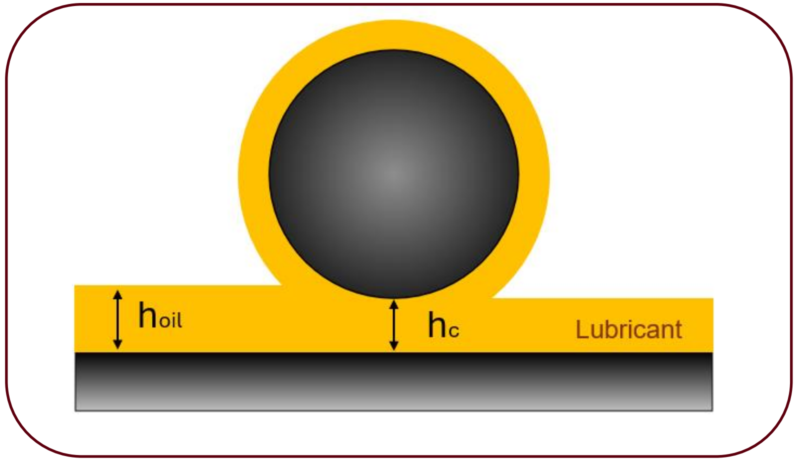
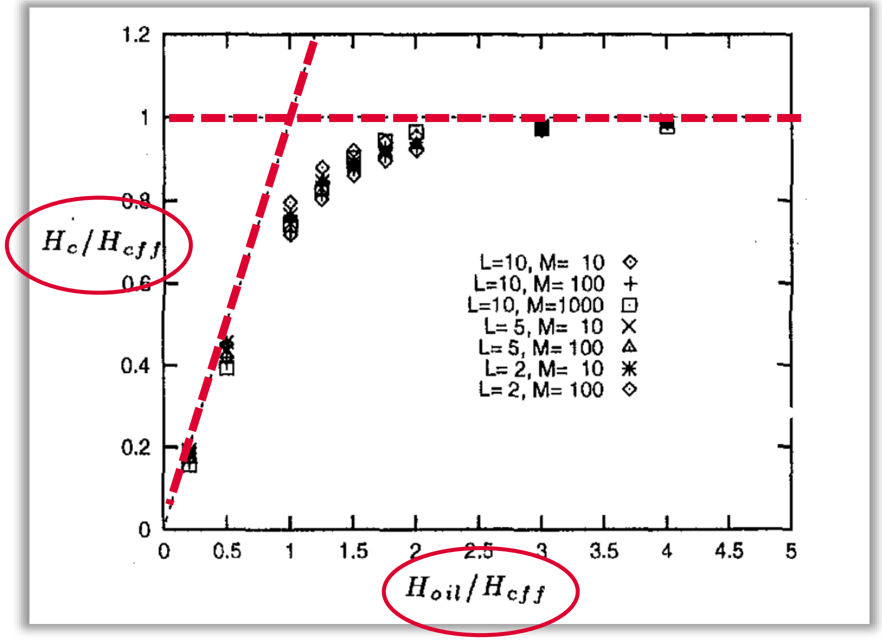
Starved elastohydrodynamic lubricated contact



Chevalier (1998, J. Tribol.)



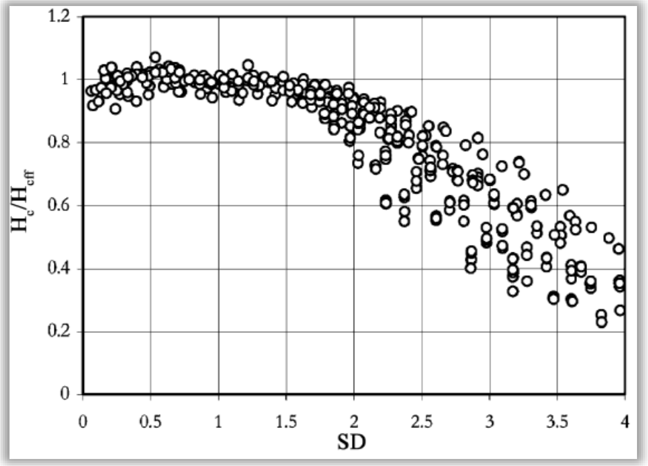




Cann (2004, Tribol. Int.)

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

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



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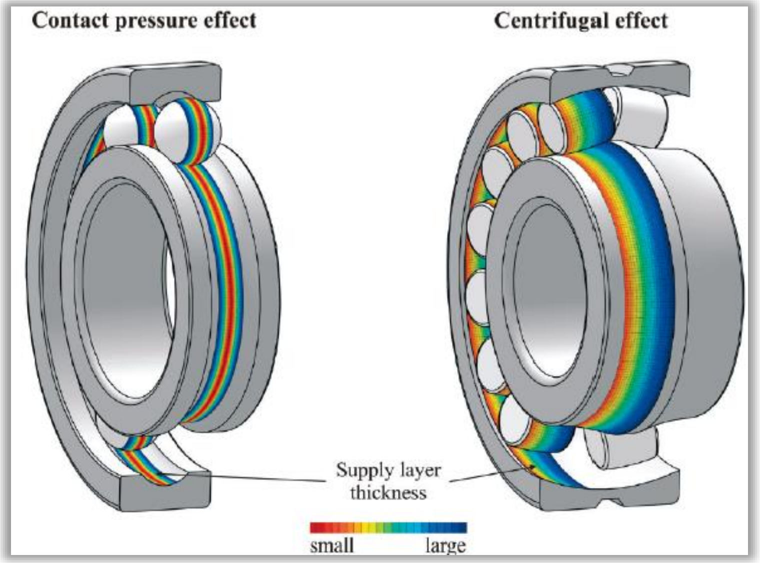
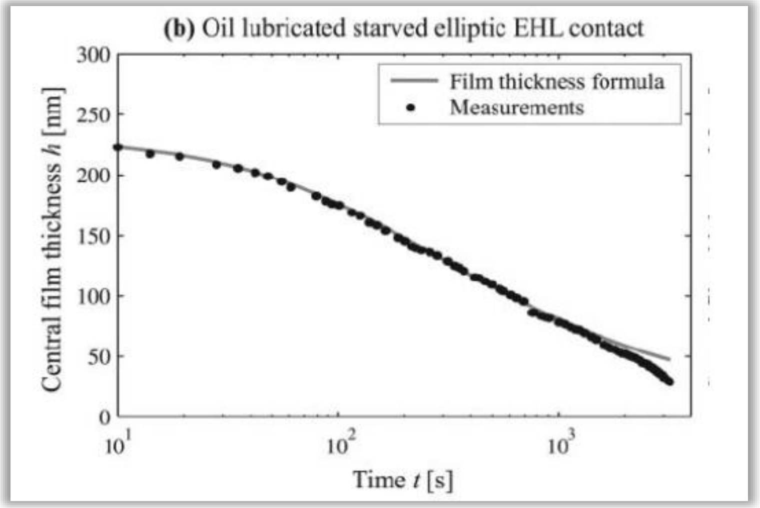
Replenishment mechanism

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

Replenishment out of contact

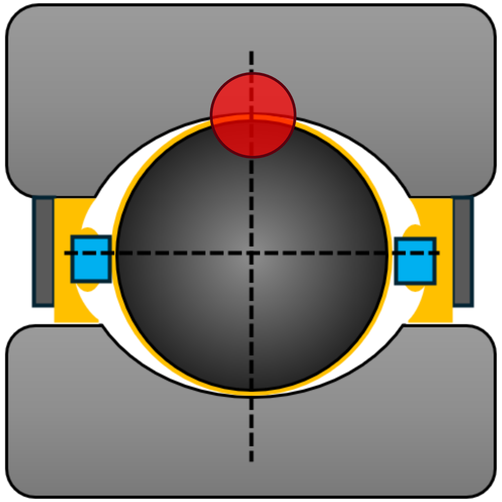


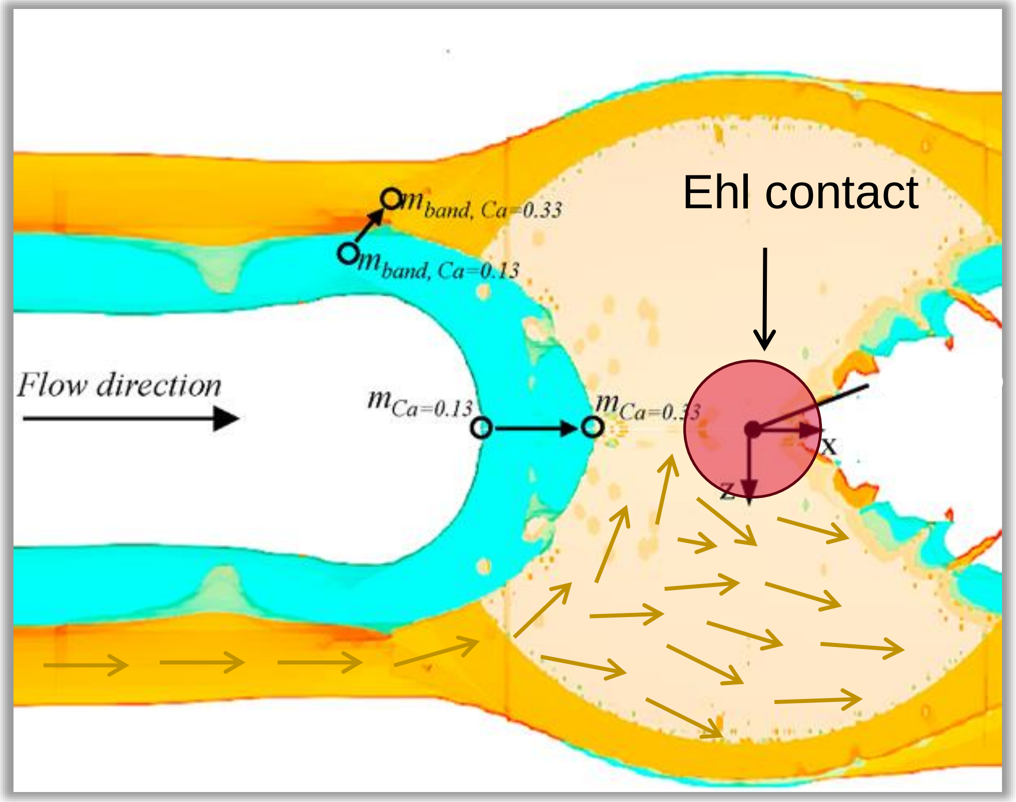


Zoelen, M. T.,. (2009. Tribol. Trans.)

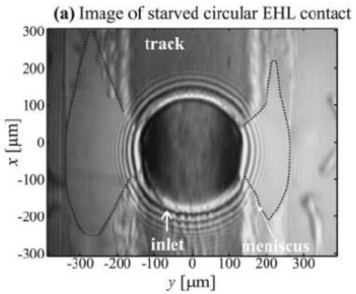
Replenishment before contact

Fischer. (2020. Tribol. Int.)



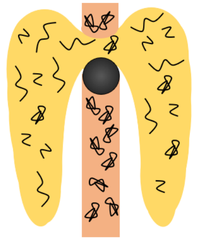


- Lubricant viscosity (rheology)
- Lubricant supply quantity
- Wettability
- Rolling speed
- Contact geometry

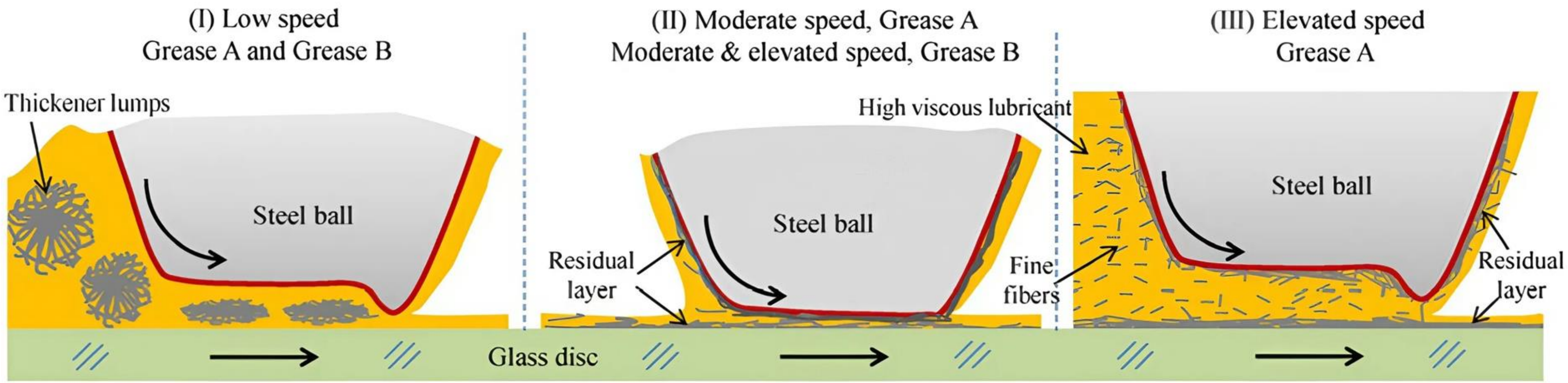


State of the art

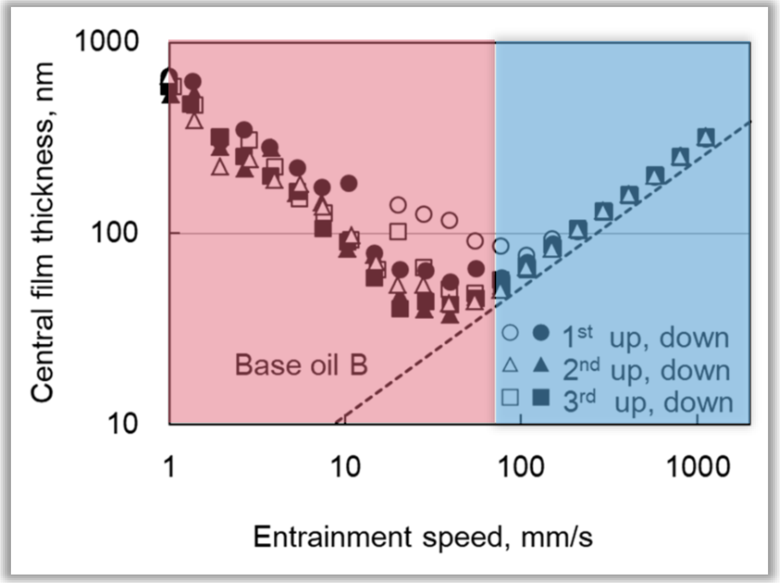
Thickner in EHL contact

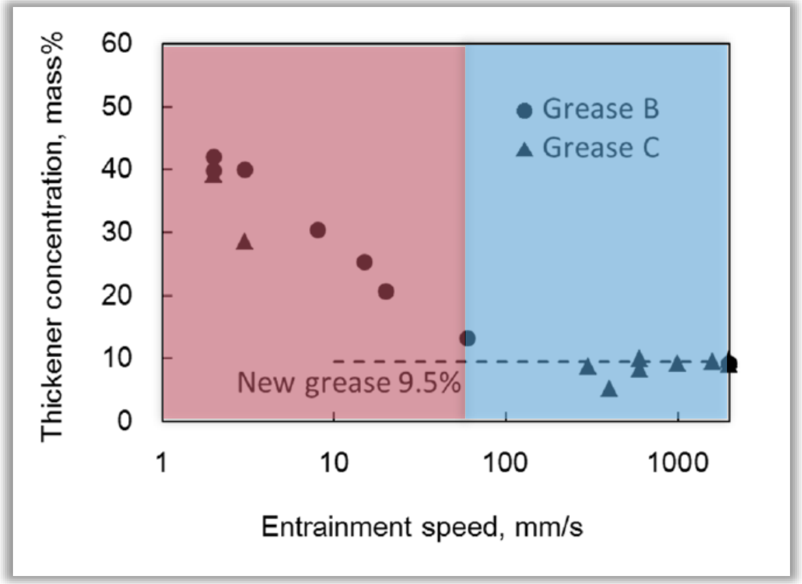


Li (2021, Friction)



Influence of speed



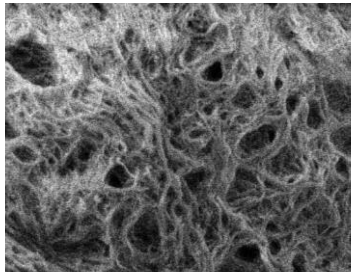


Kochi (2019, Tribology Letter)

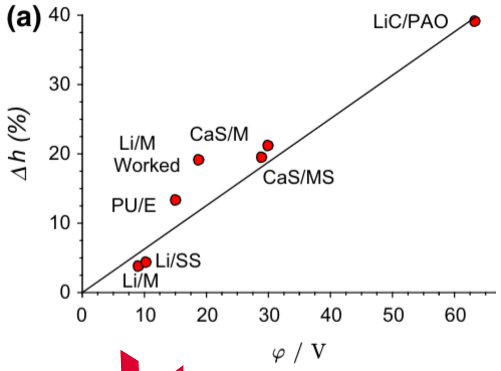
Cyriac (2015, Tribol. Lett.)

Influence of fibre size

Percentage increase in film thickness:



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



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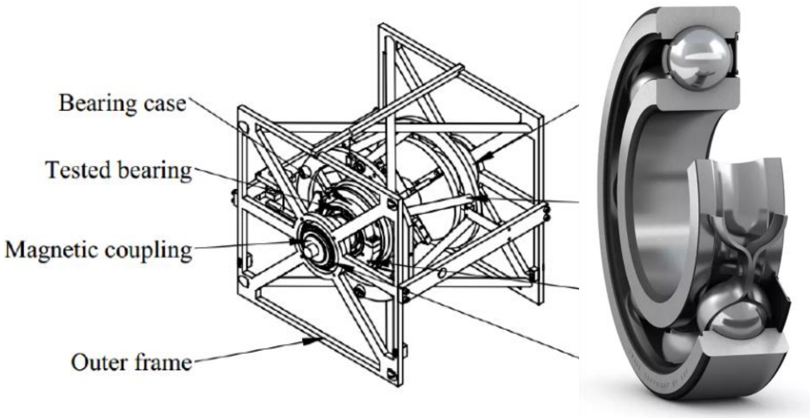
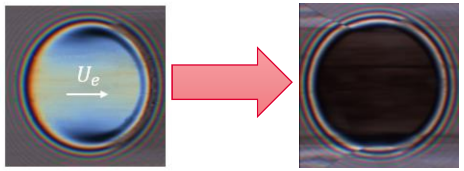
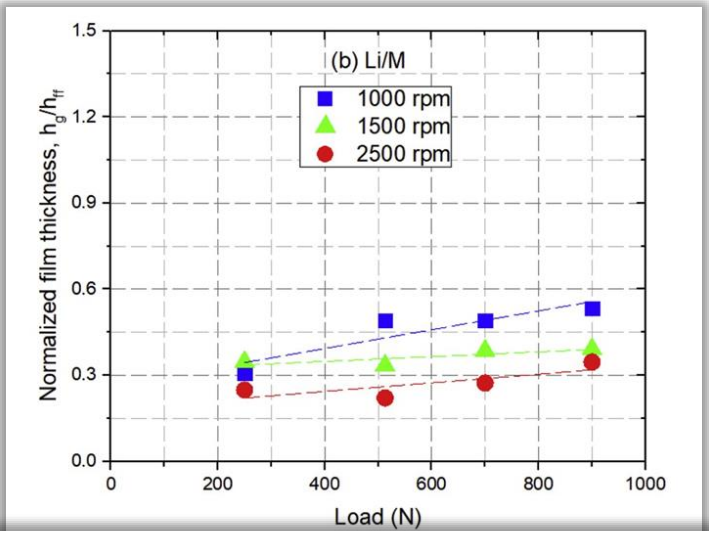
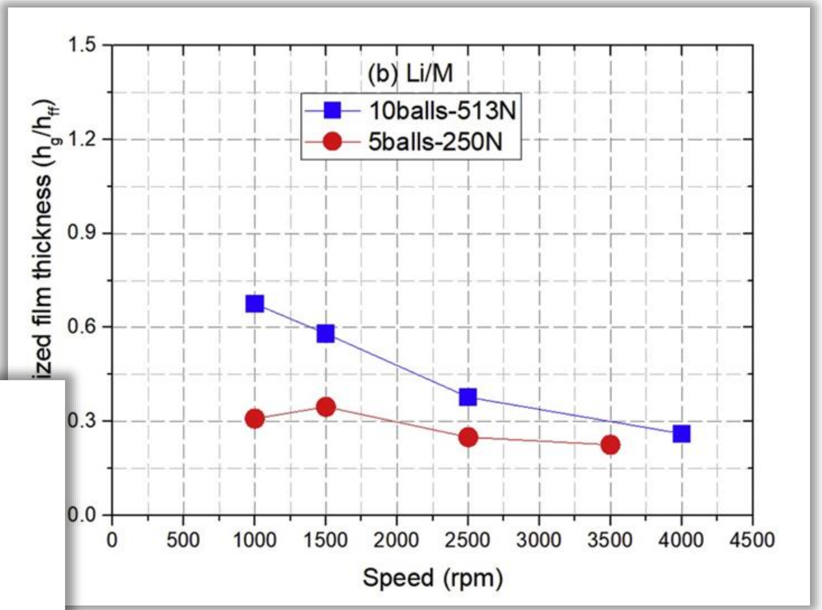
Film thickness in ball bearing

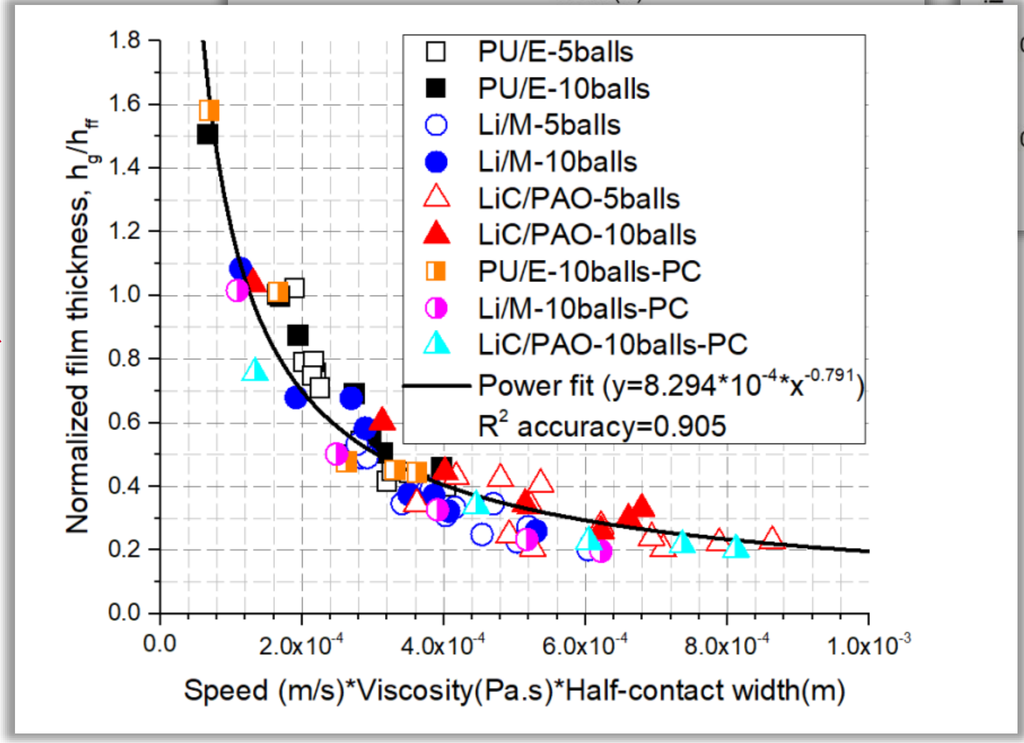


Cen (2019, Tribol. Int.)









Cen (2020, Tribol. Int.)

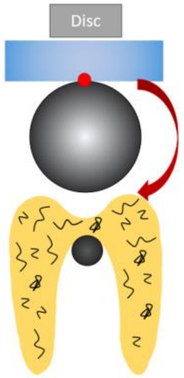
$$\frac{h_g}{h_{ff}} = 8.294 \times 10^{-4} \times (u\eta b)^{-0.791}$$

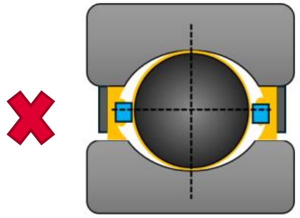
Speed x viscosity x half-contact

Gaps in current literature

Conformity and film thickness

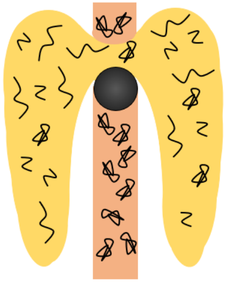
- Experimental studies limited to base oil
- Simplified contact geometries
- Mostly theoretical studies





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

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

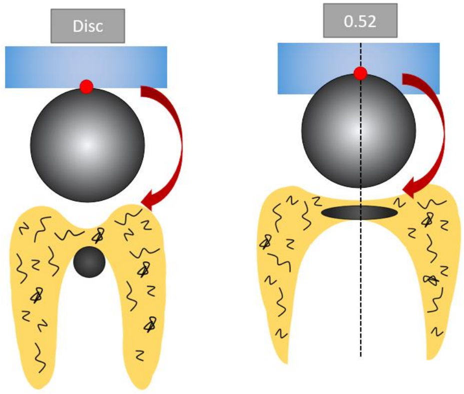
1. **What is the effect of conformity on grease replenishment around the contact and the level of starvation?**
2. **How does different replenishment affect the behaviour of the thickener in the EHL contact?**
3. **How does the thickener affect the lubrication film thickness in a deep groove ball bearing?**

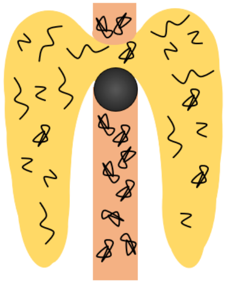
Hypotheses

H1:

H2:

H6:





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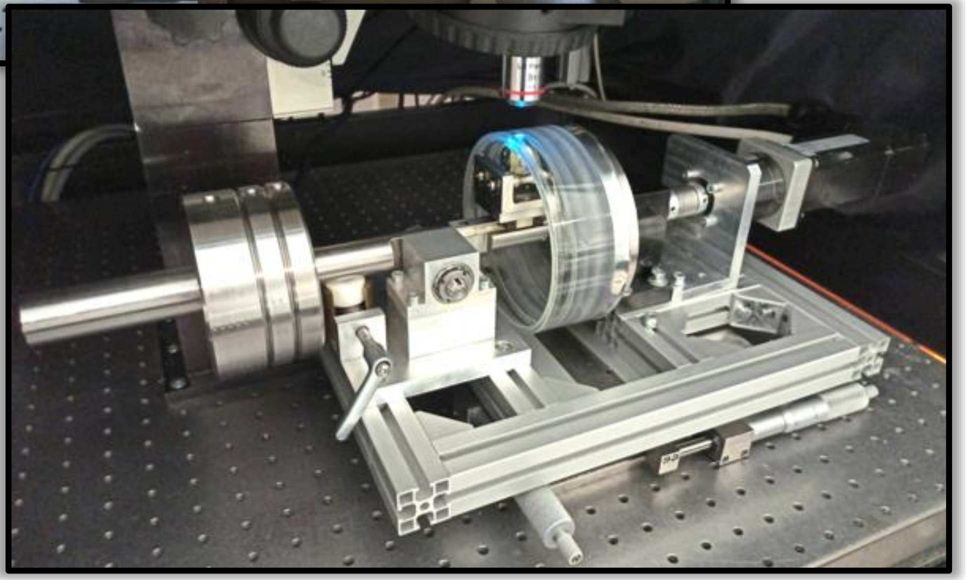
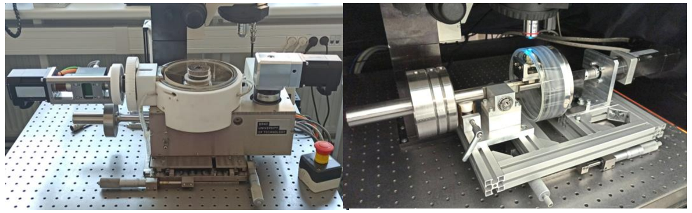
Experimental devices

Optical tribometers

Ball bearings

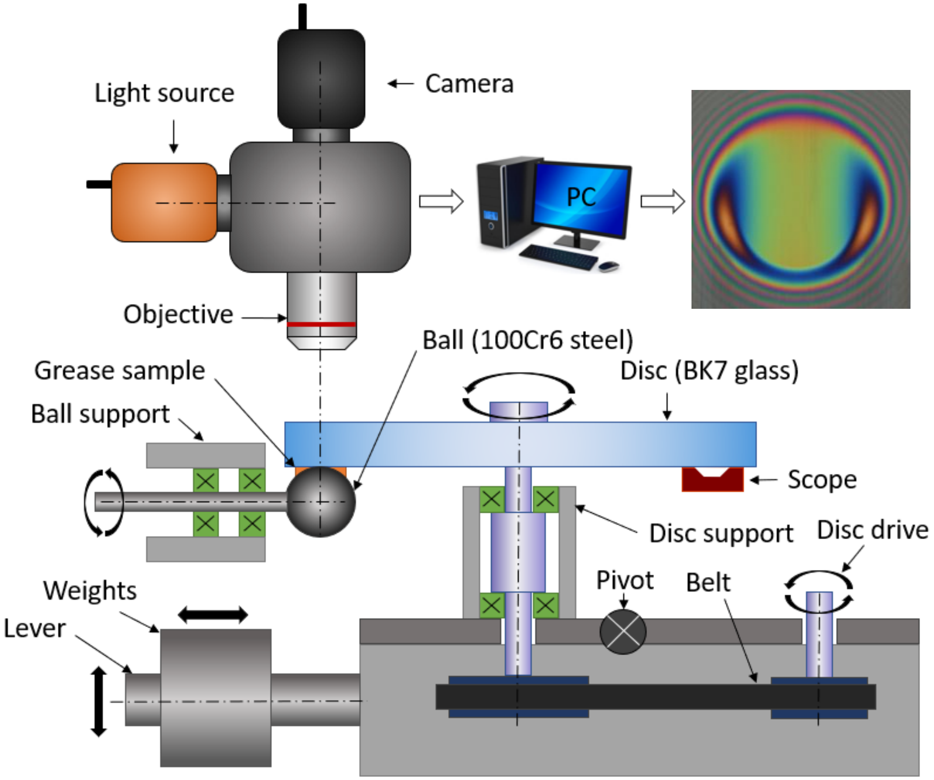


Optical tribometers



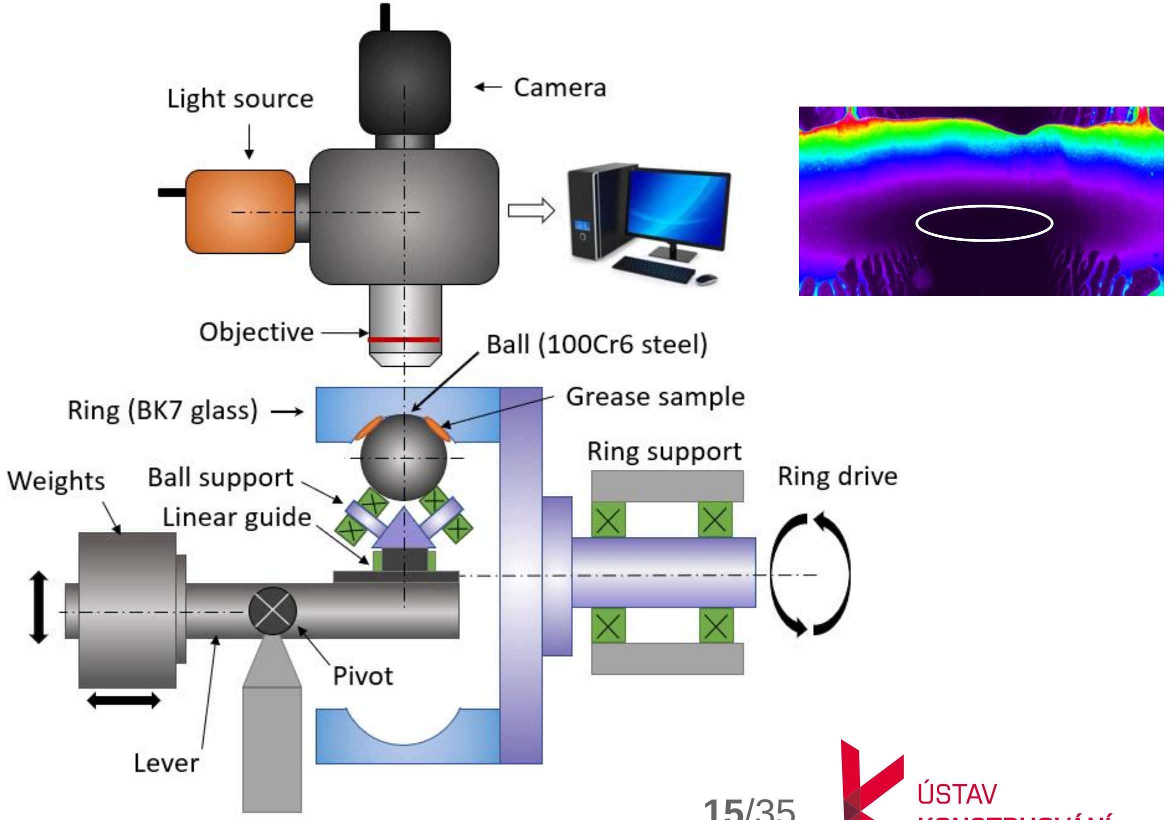
Ball-on-disc

- Circular contact
- Artificial replenishment

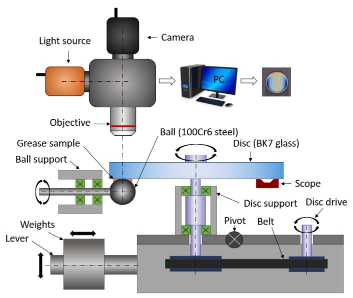


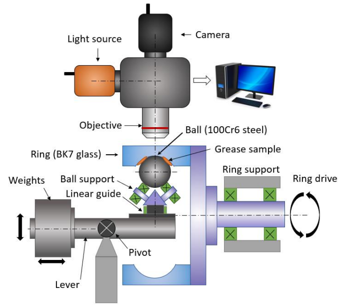
Ball-on-ring

- Eliptical contact (Real comformity)
- Natural replenishment



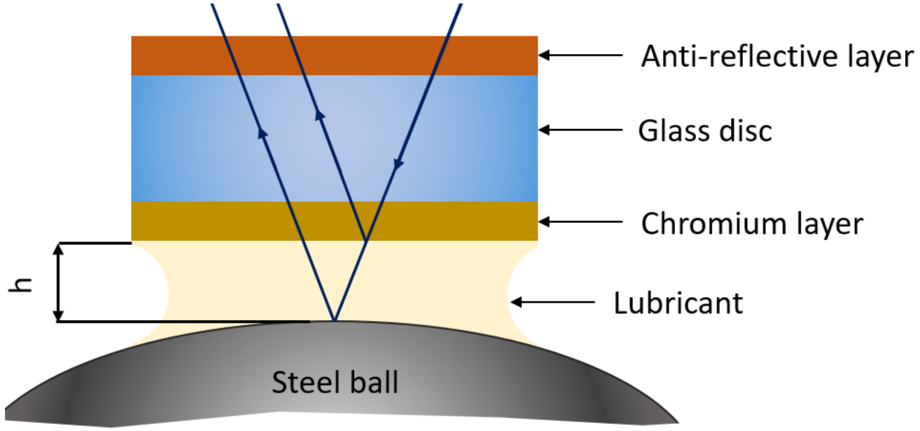
Optical methods

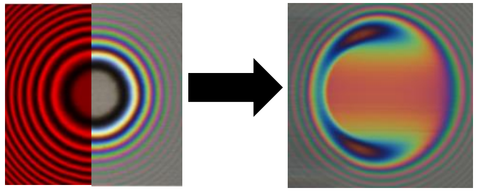




Thin film colorimetric interferometry

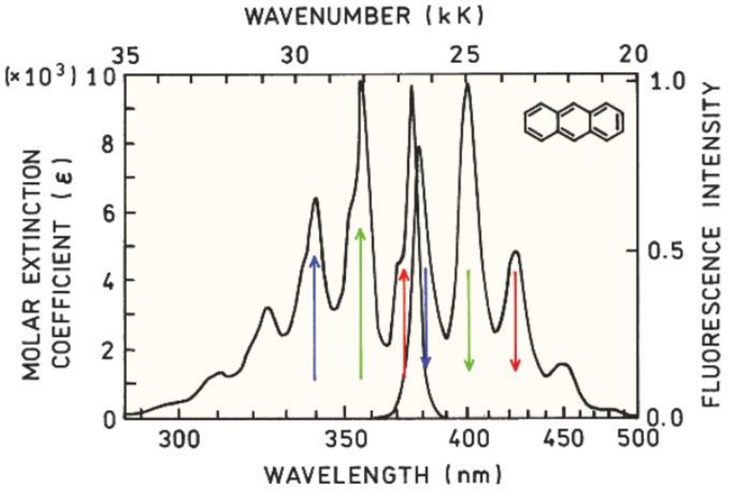
- Distance between surfaces
- Range 0-900 nm

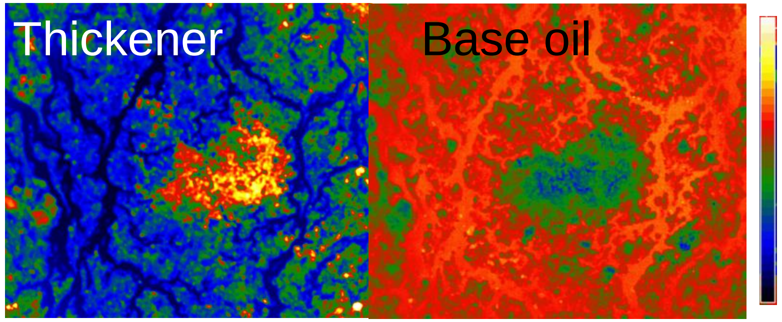


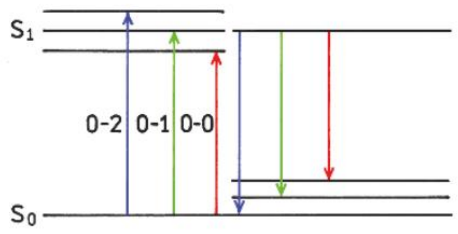


LED induced fluorescence microscopy

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







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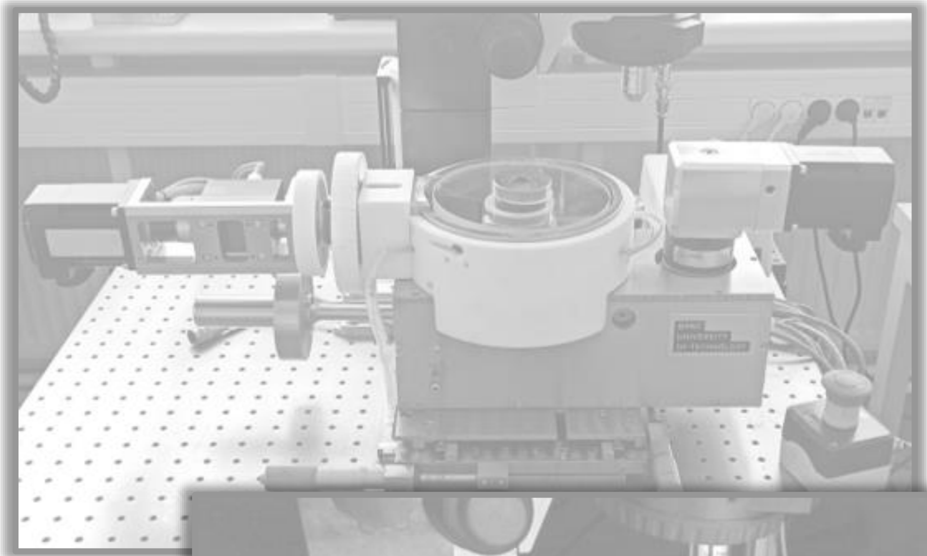
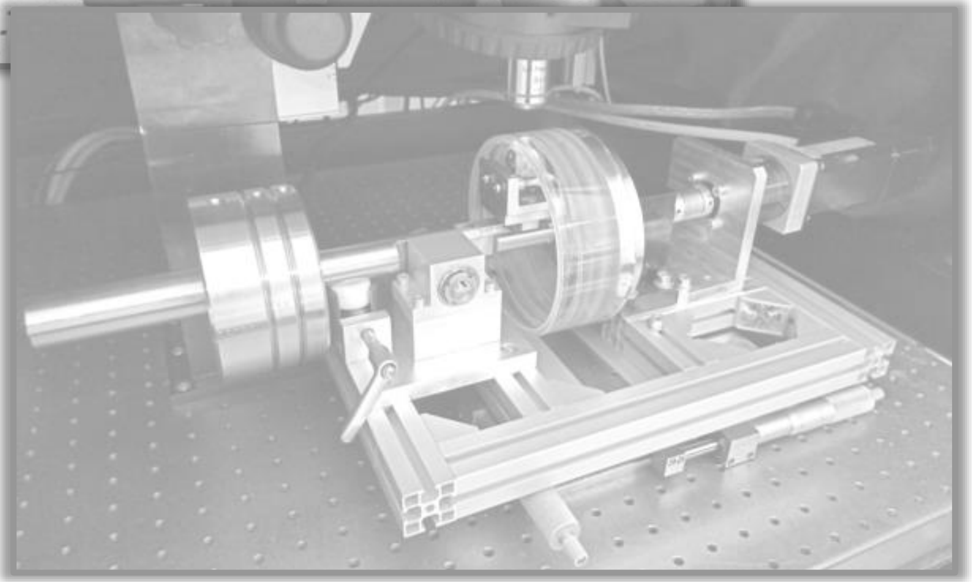
Experimental devices

Optical tribometers

Ball bearings





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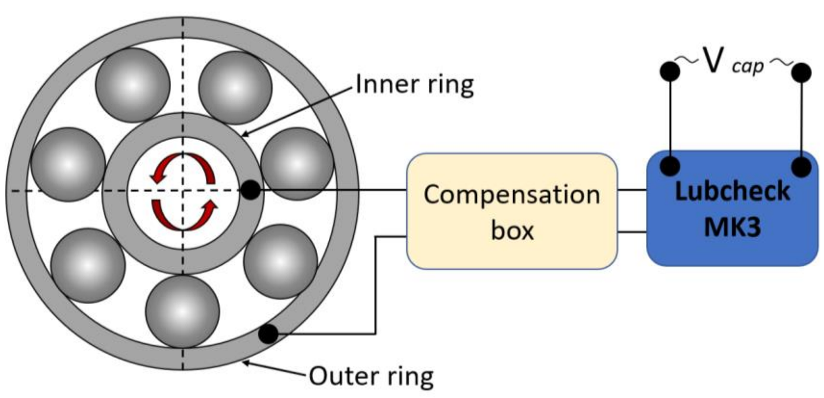
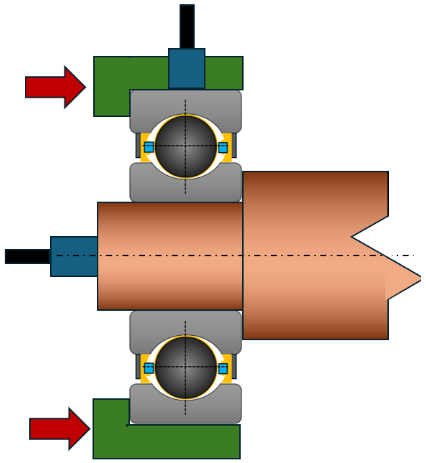
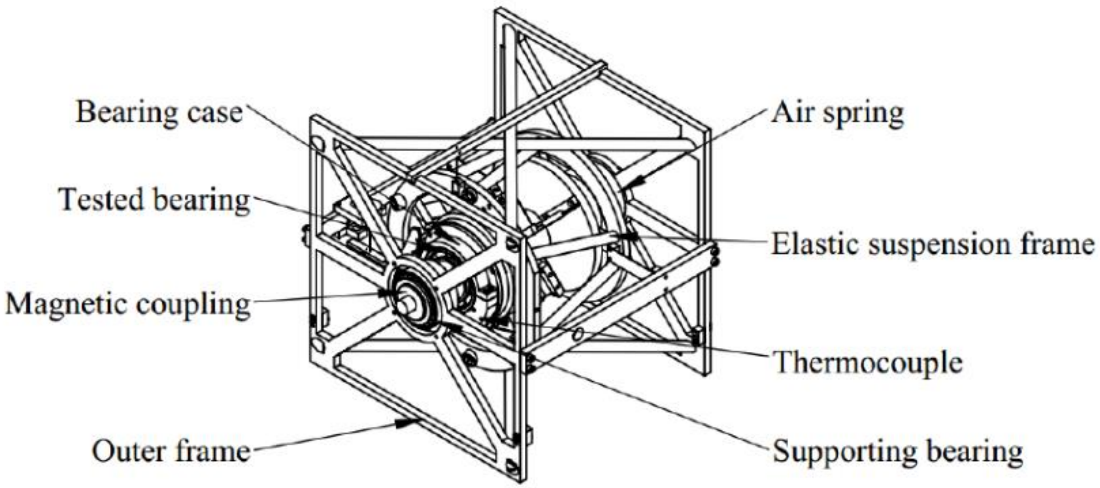
Ball bearing test rig

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

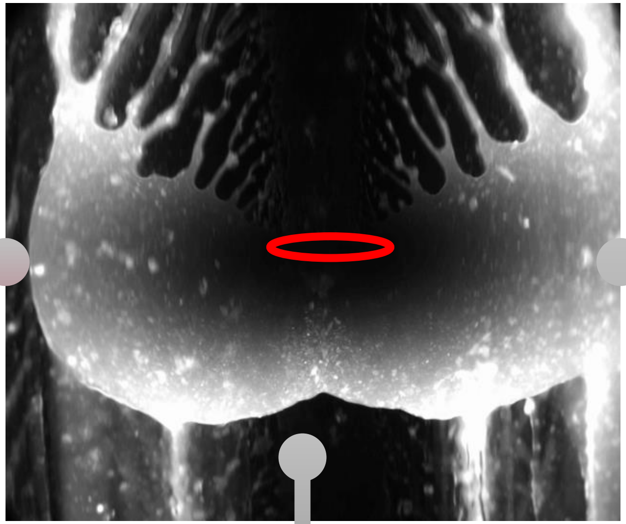


$$C_{Hertz} = \frac{1}{\frac{1}{C_{inner}} + \frac{1}{C_{outer}}} + C_{Backround}$$

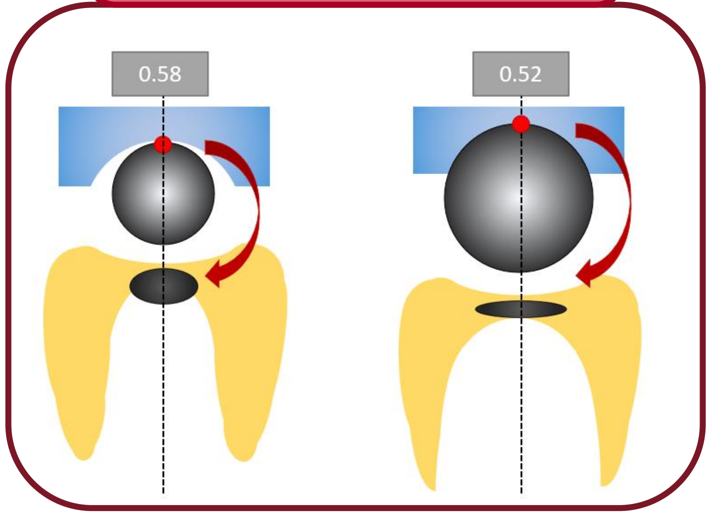




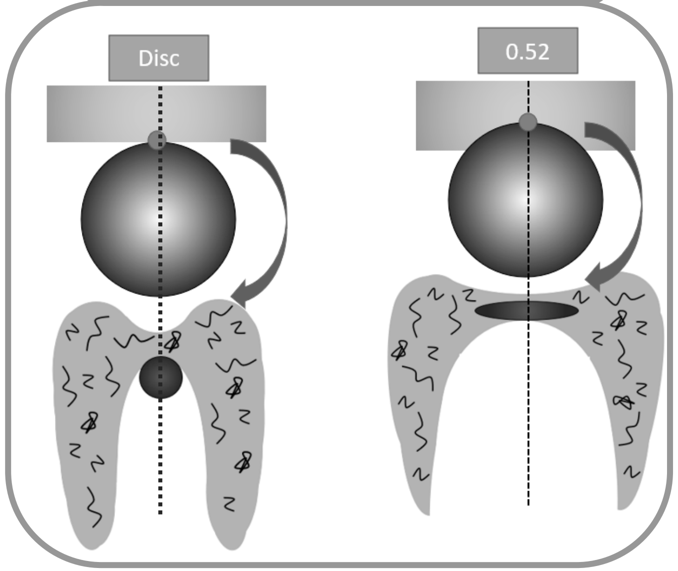
Cen (2019, Tribol. Int.)



Conformity and film thickness



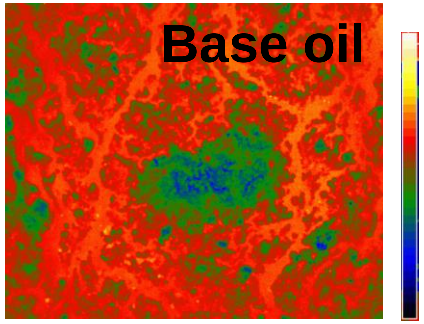
Thickener and replenishment

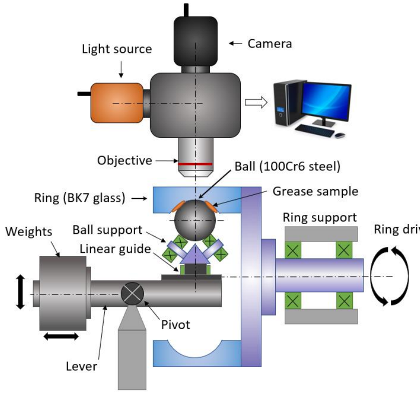


Ball bearing film thickness

Results

Ball bearing conformity





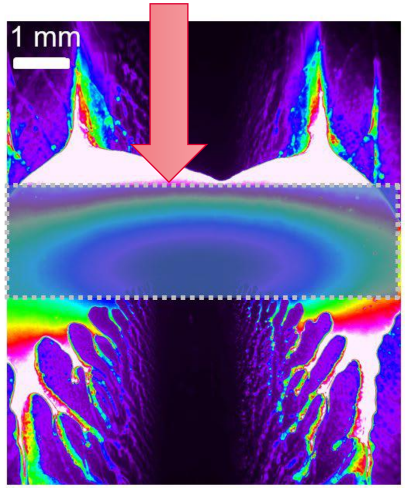
Does the amount of lubricant at the contact or the capillary force have more influence?

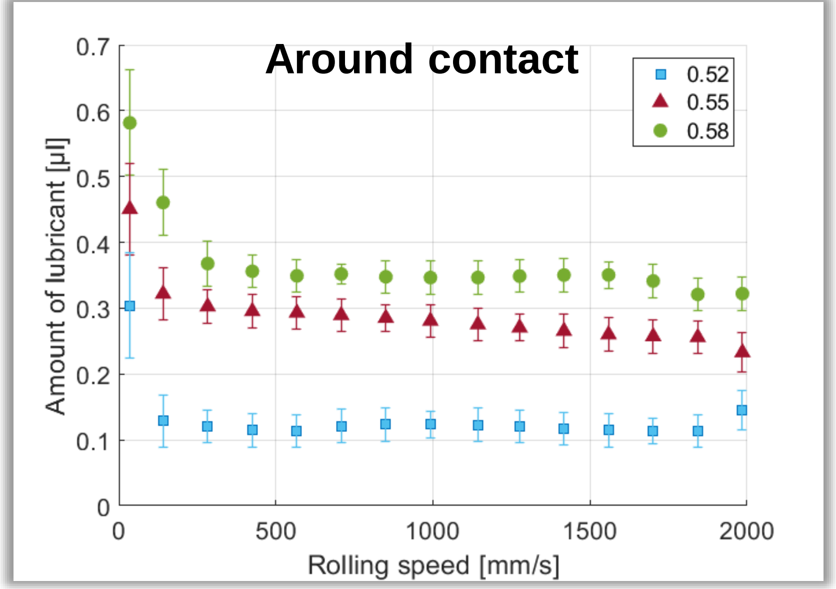
Information from the literature:

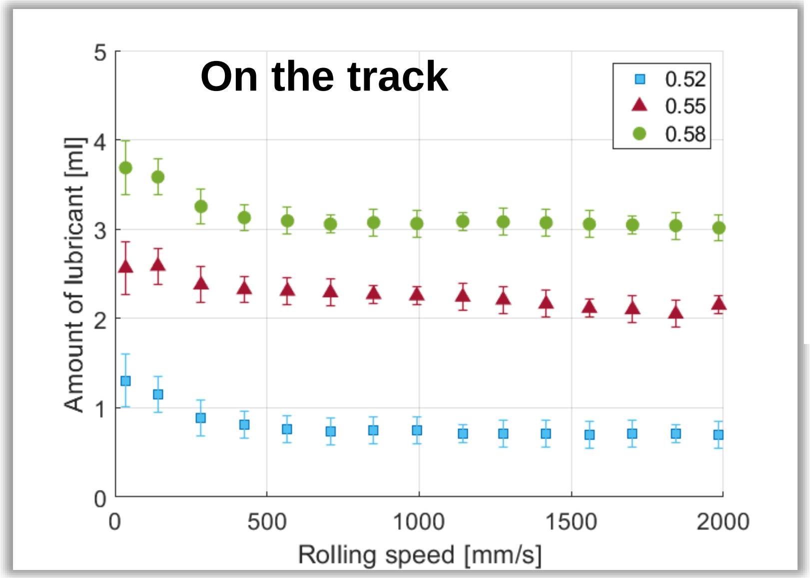
- More lubricant before contact means more film thickness
- Greater capillary force causes more efficient inlet replenishment

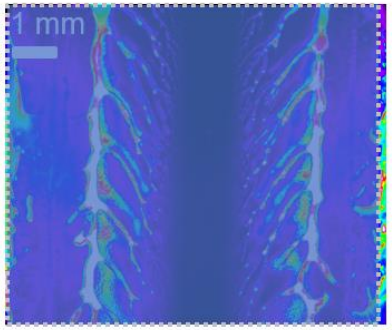
Ball diameter	Conformity (f)	Ellipticity of contact
25.4	**0.52**	8.4
23.8	**0.55**	4.5
22.2	**0.58**	3.3

Observed area









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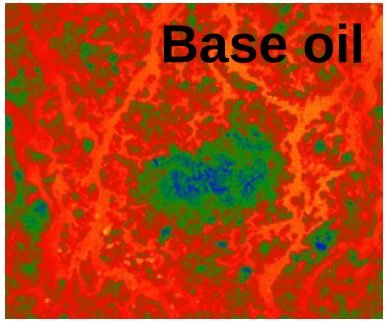
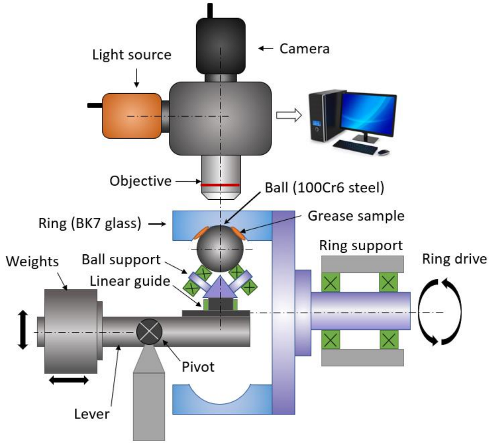
Ball bearing conformity

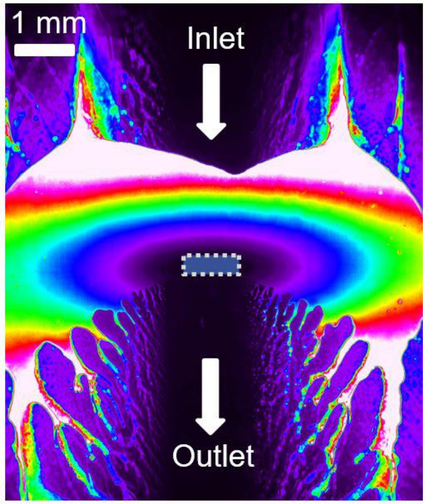


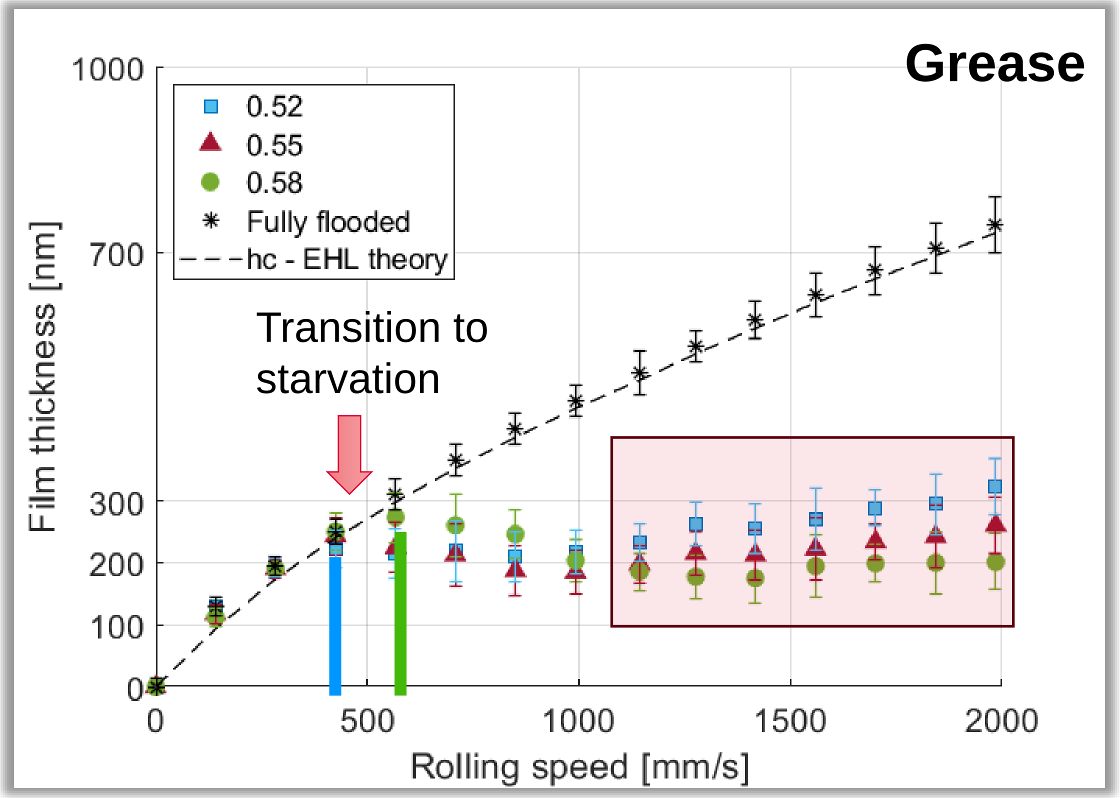


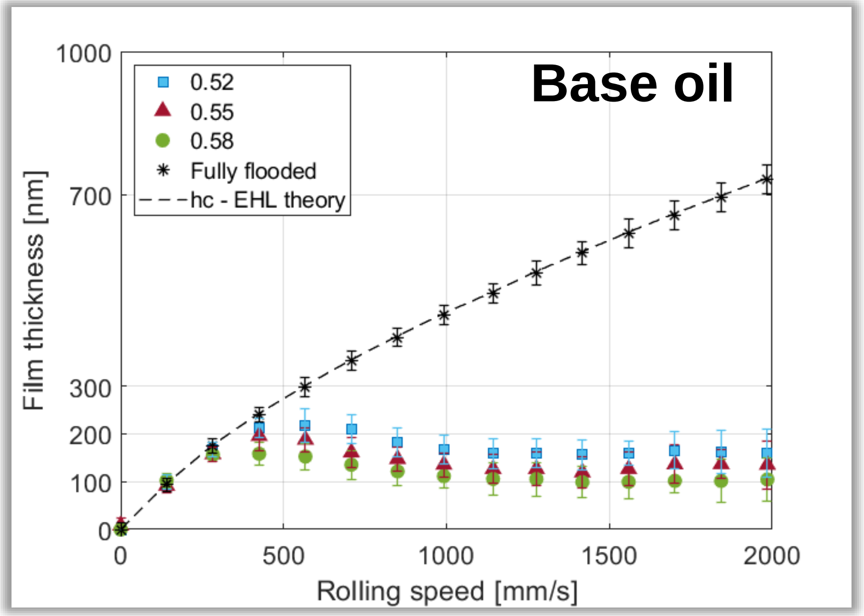
Influence of the amount of lubricant and speed?

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

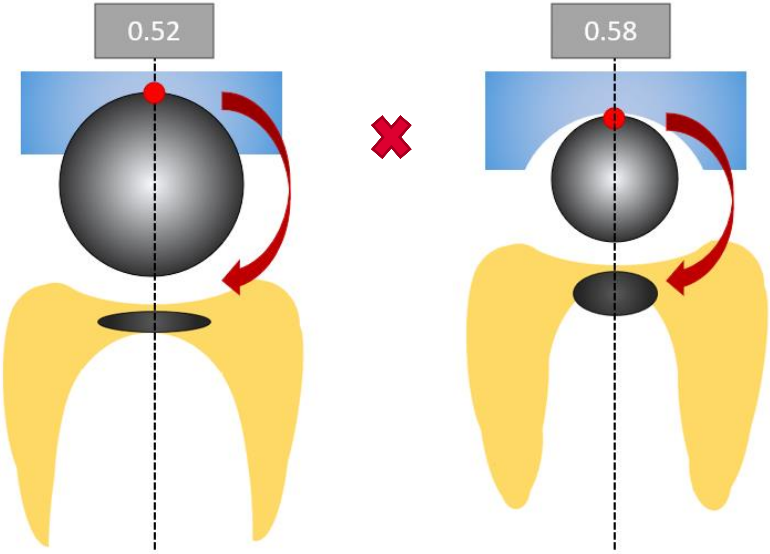
(1.) Hertzian area







Ball bearing conformity

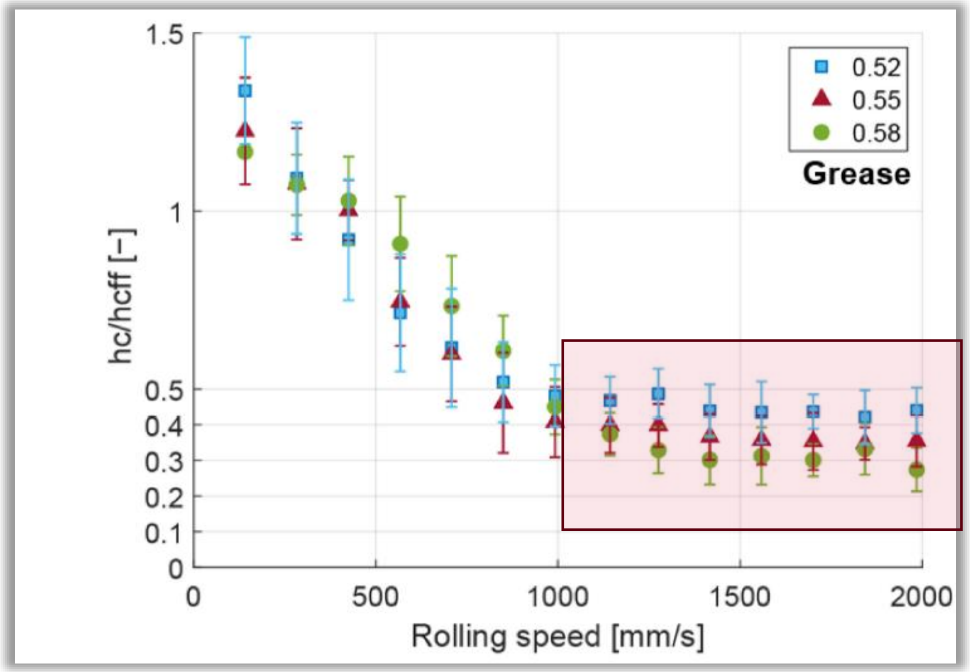


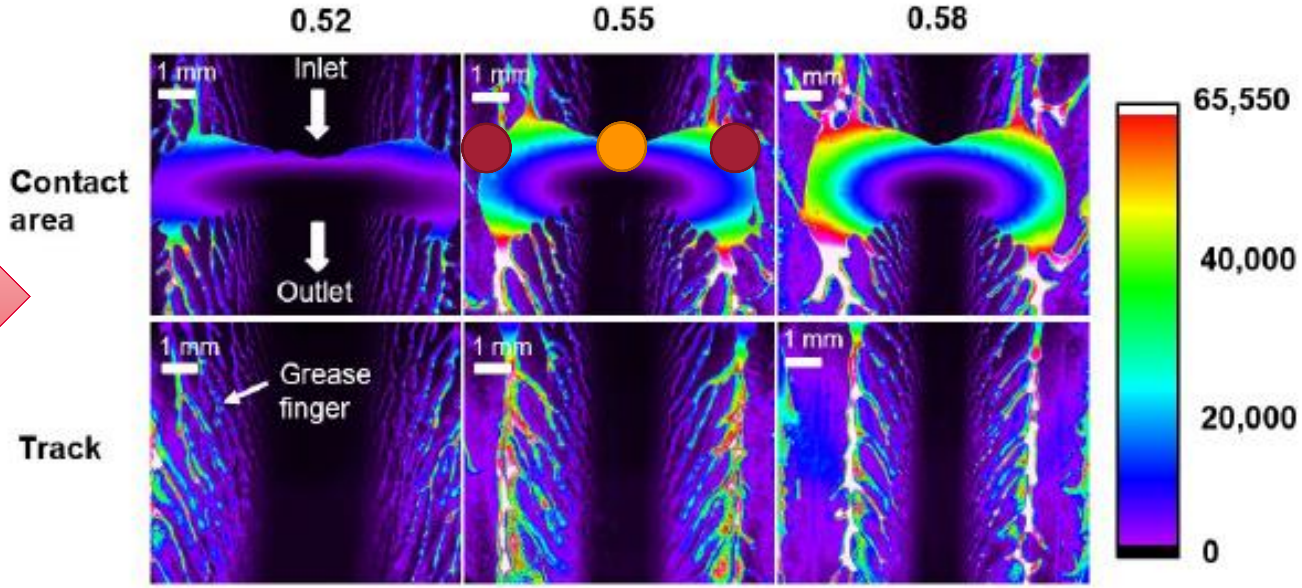
More conformal contacts:

Less lubricant around the contact (RESERVOIRS)

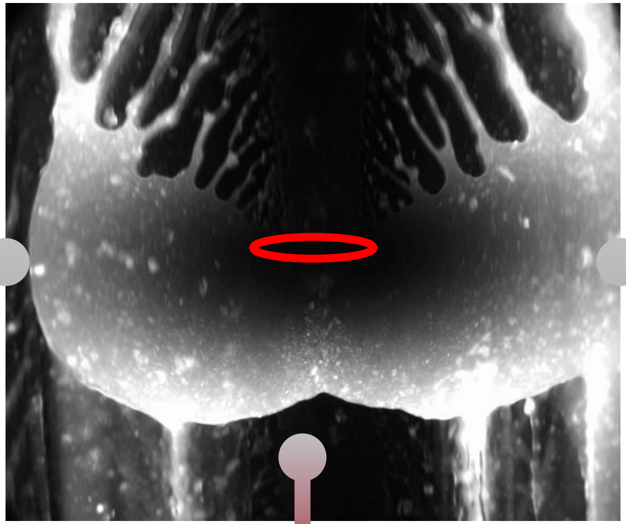
Greater ability to prevent starvation

Narrower gaps create better conditions for meniscus formation

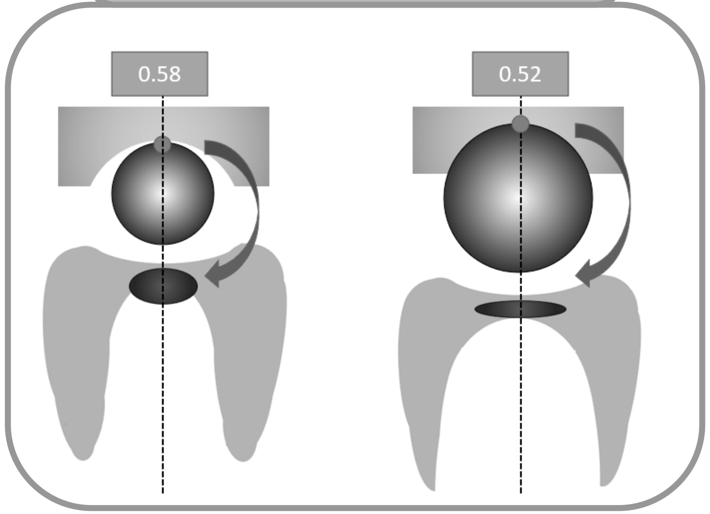




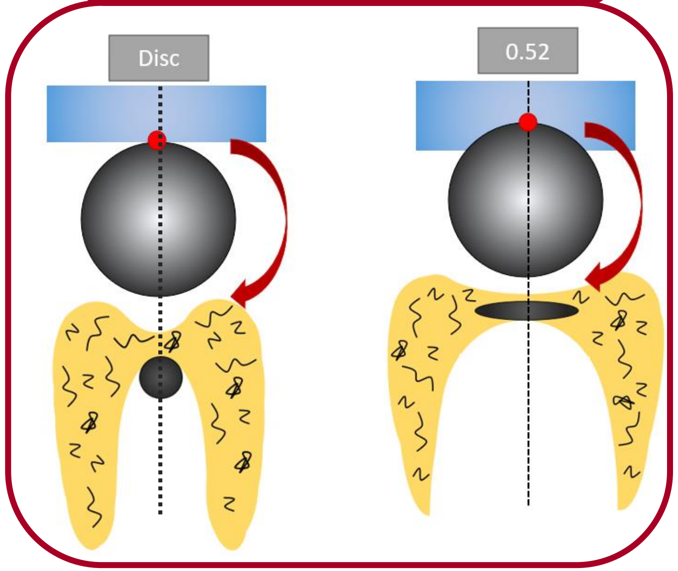
ÚSTAV KONSTRUOVÁNÍ



Conformity and film thickness



Thickener and replenishment



Ball bearing film thickness

Effect of thickener in EHL contact

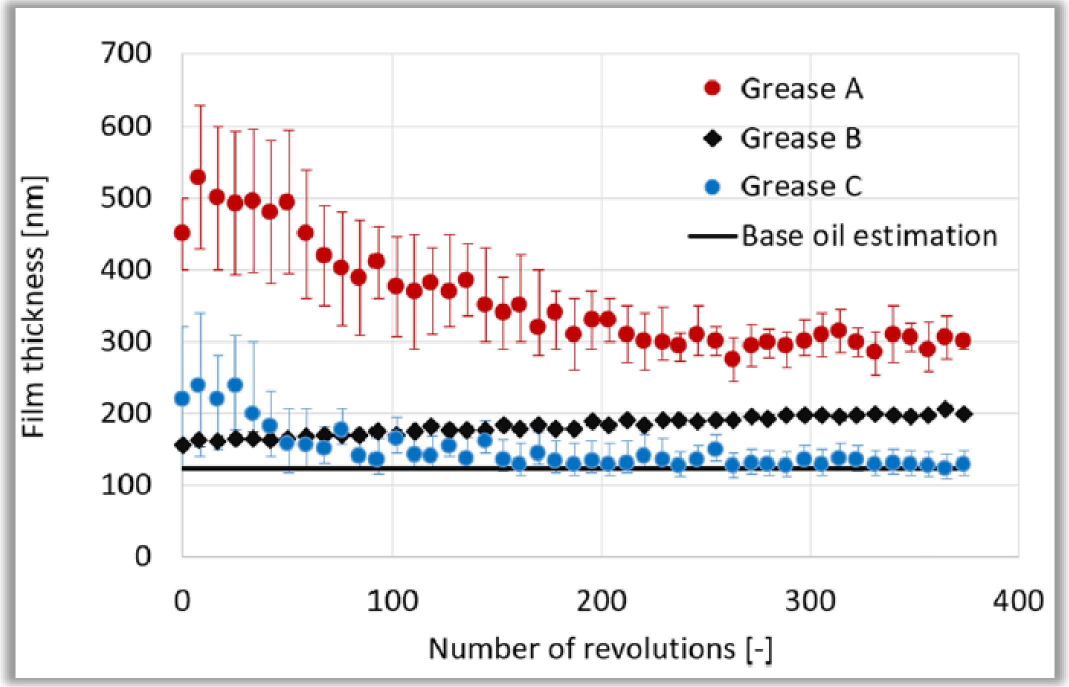
How does the different replenishment affect the behaviour of the thickener in the EHL contact?

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

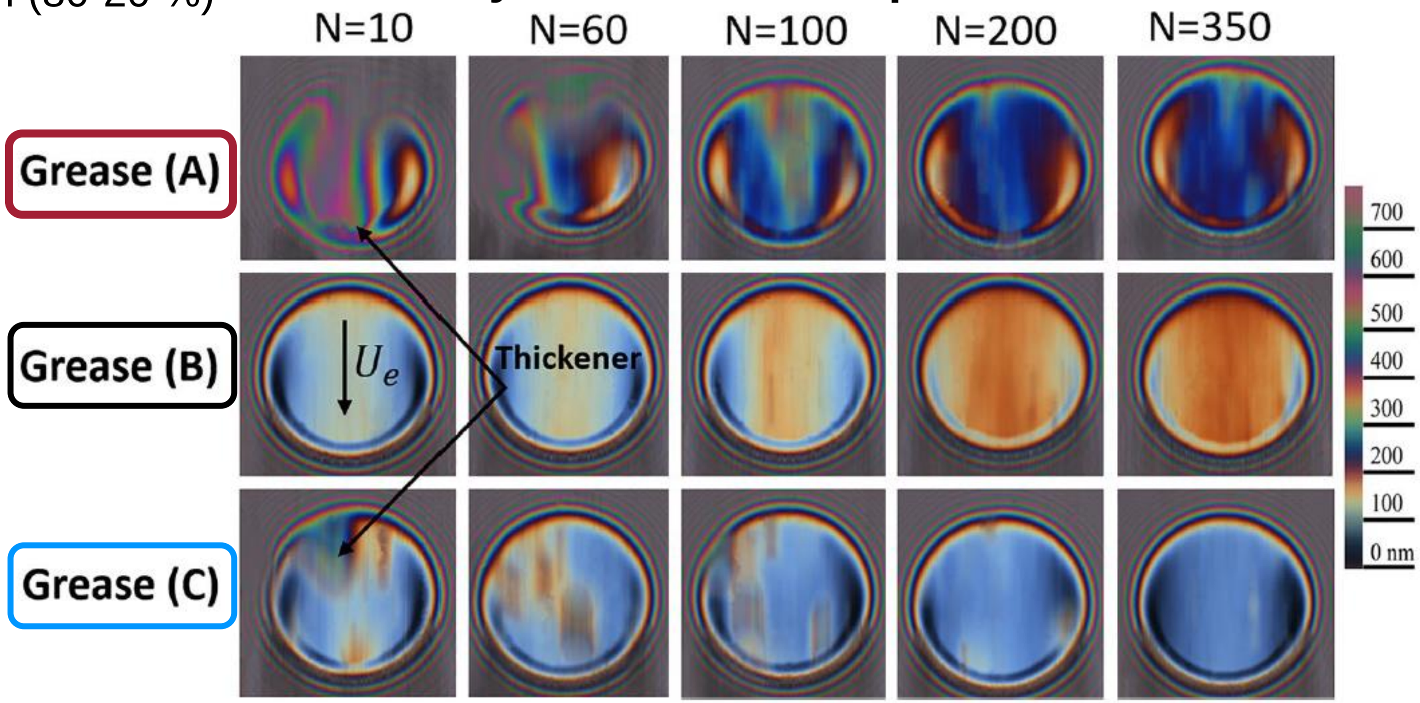
Same base oil

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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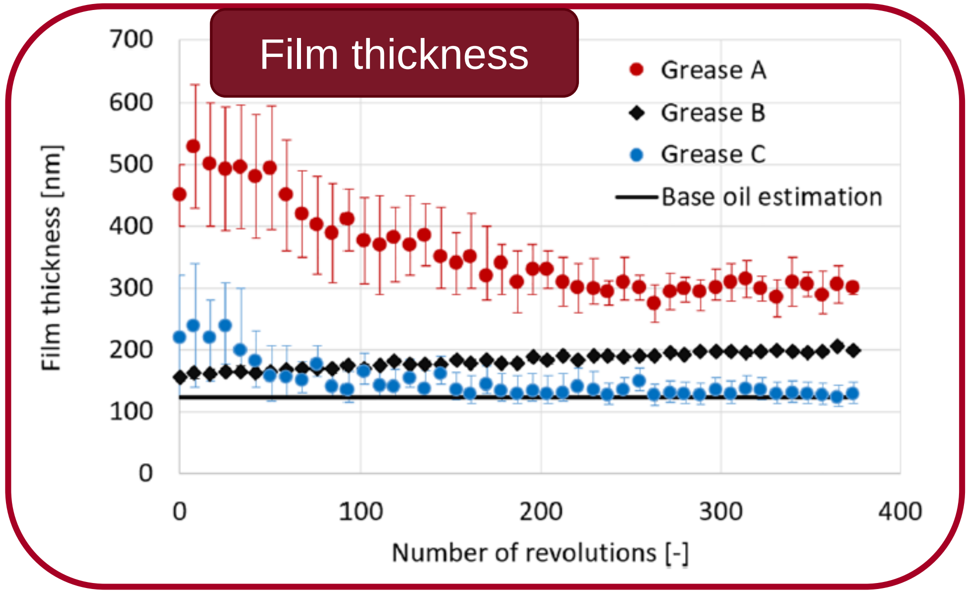
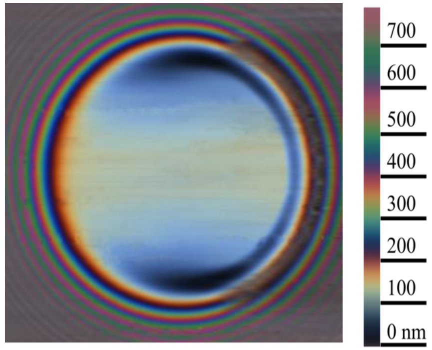
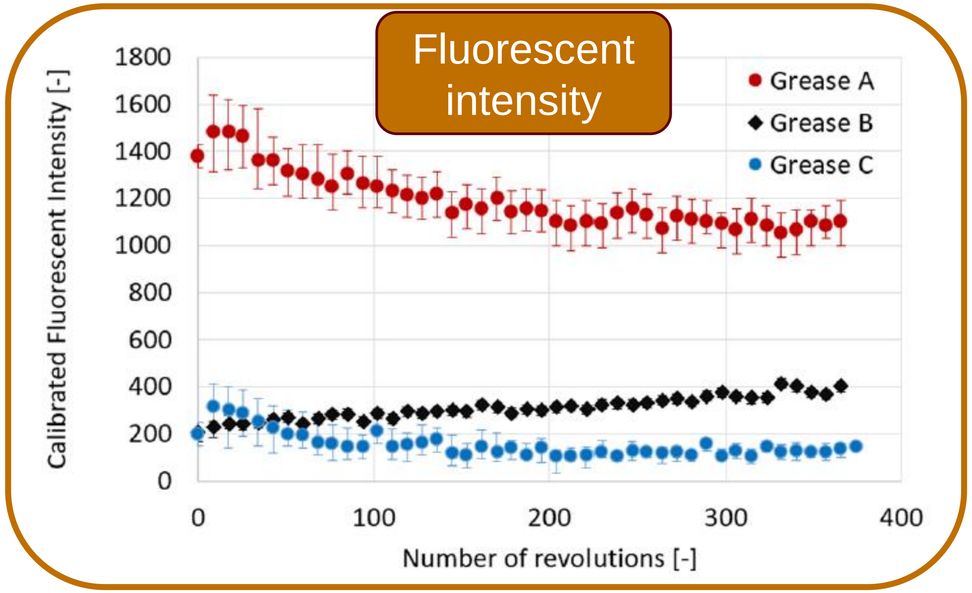
Effect of thickener in EHL contact

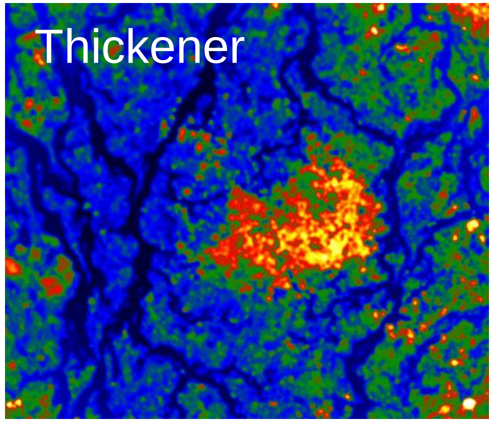
Effect of type and structure of the thickener?

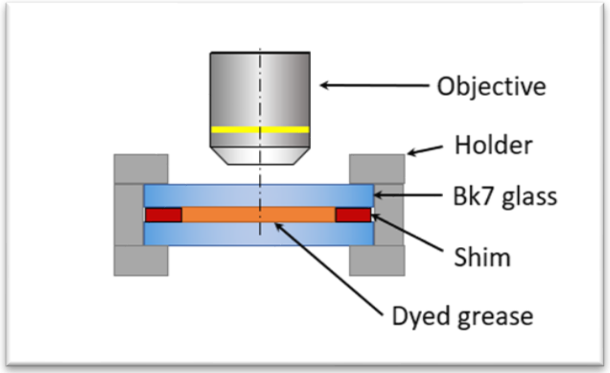
Fully flooded under speed 100 mm/s.







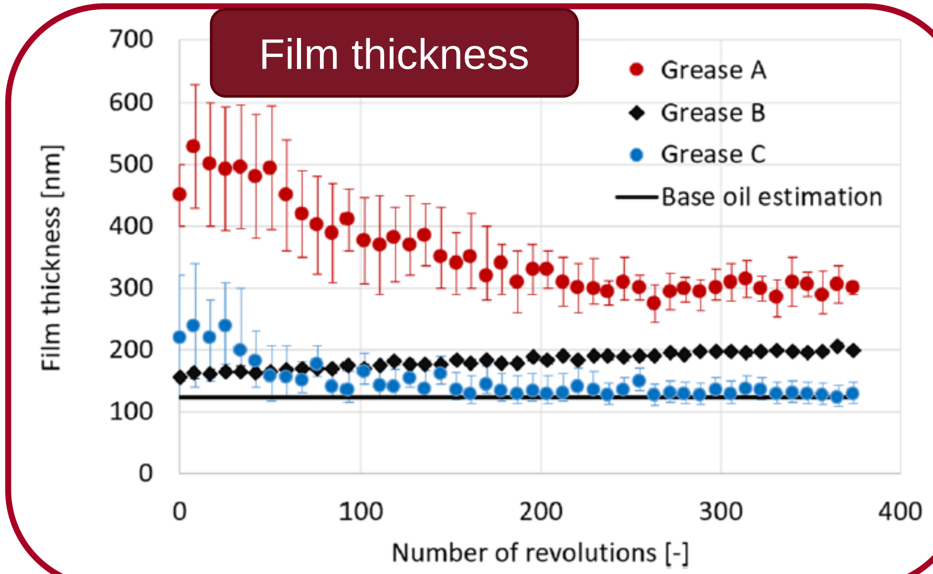


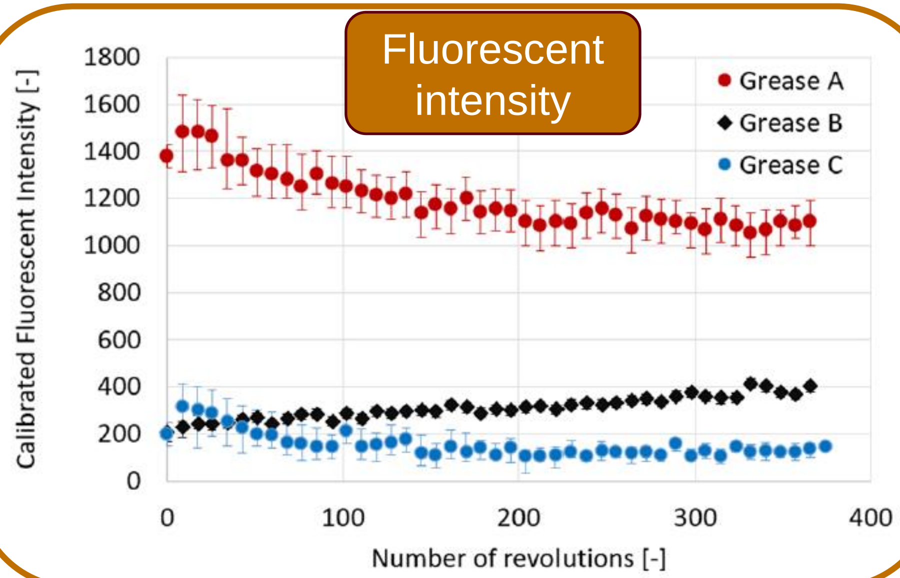


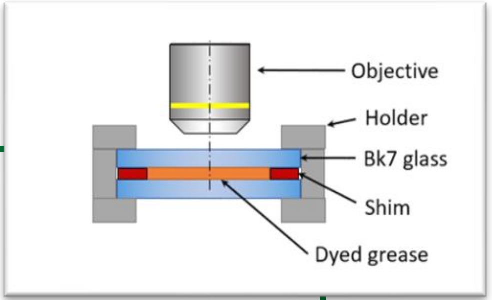
ÚSTAV KONSTRUOVÁNÍ

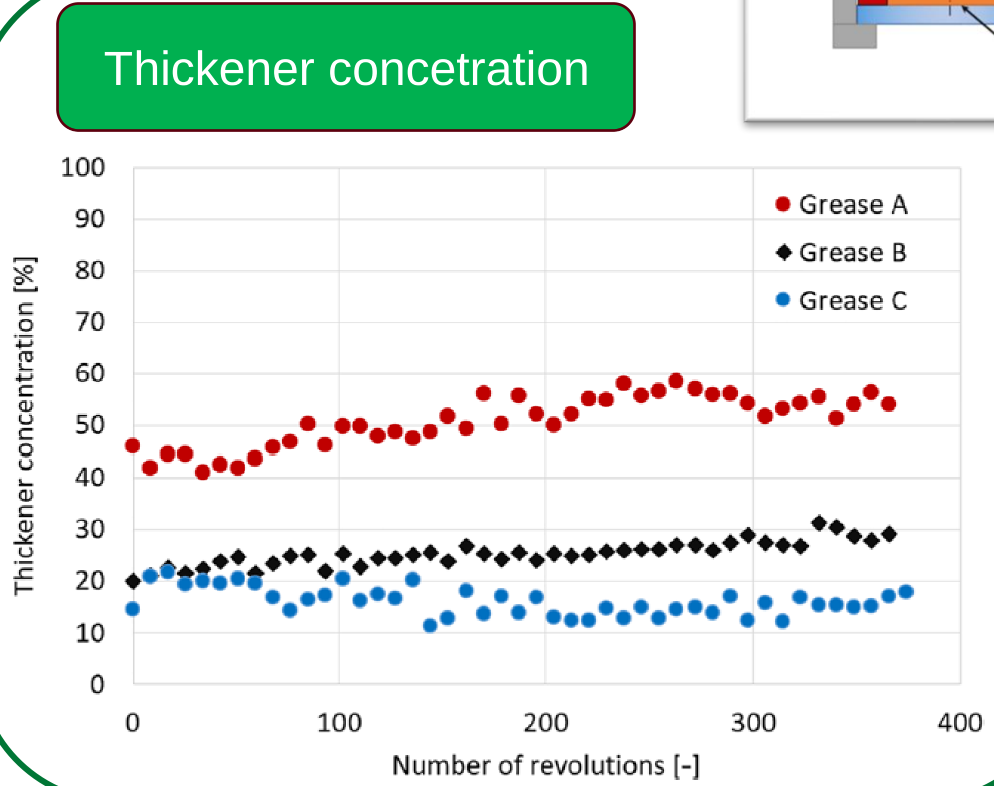
Effect of thickener in EHL contact

Effect of type and structure of the thickener?







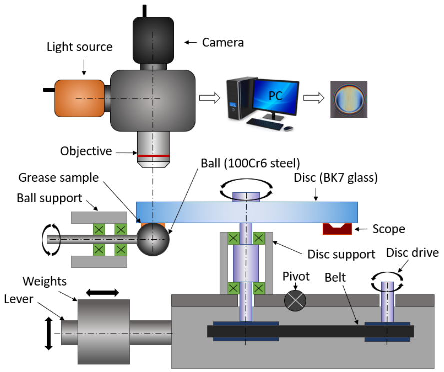


- **Lithium grease** has the original thickener representation after time
- **Alicyclic di-urea grease (A-B)** has a concentration increase over time

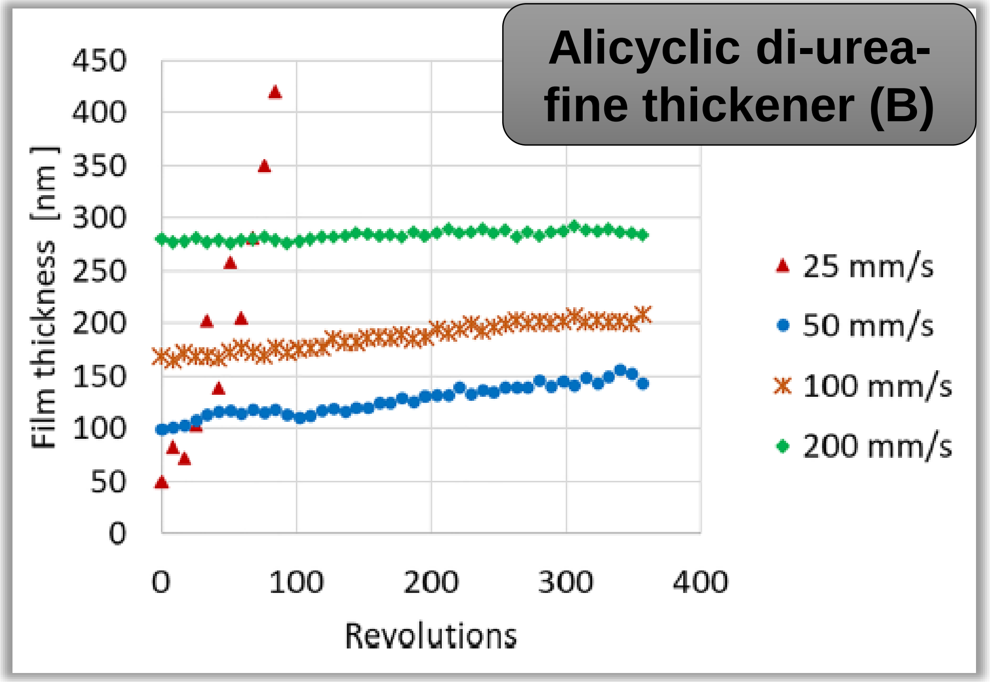
ÚSTAV KONSTRUOVÁNÍ

Effect of thickener in EHL contact

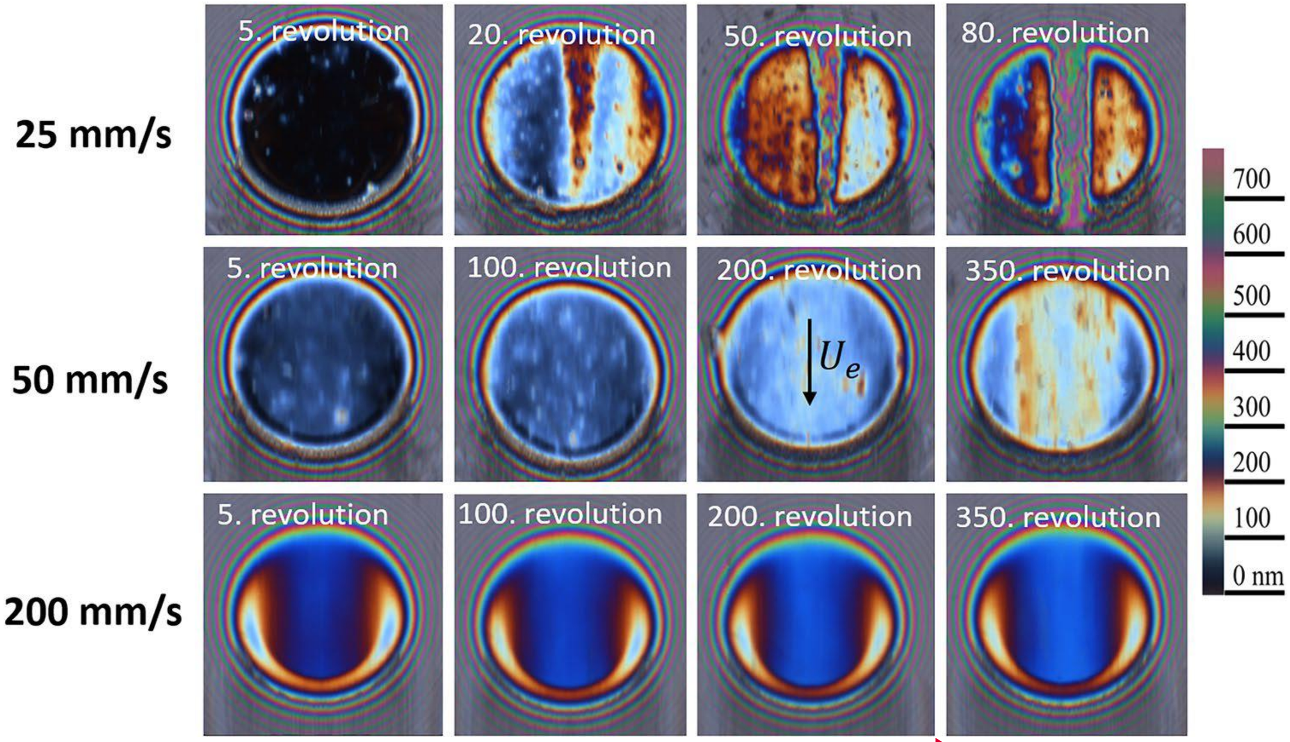
And effect of speed?



- 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



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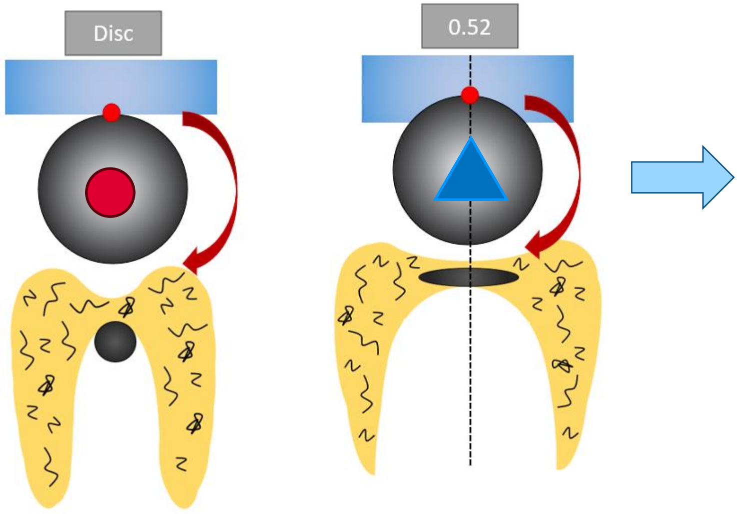
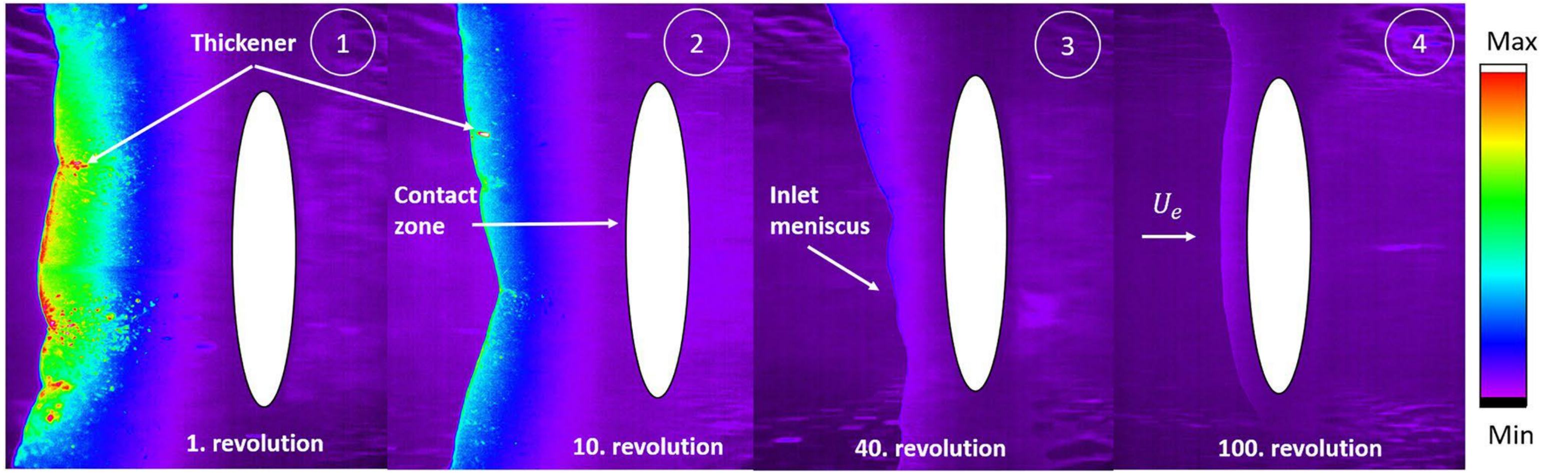
Effect of thickener in EHL contact

Alicyclic di-urea-fine thickener (B)



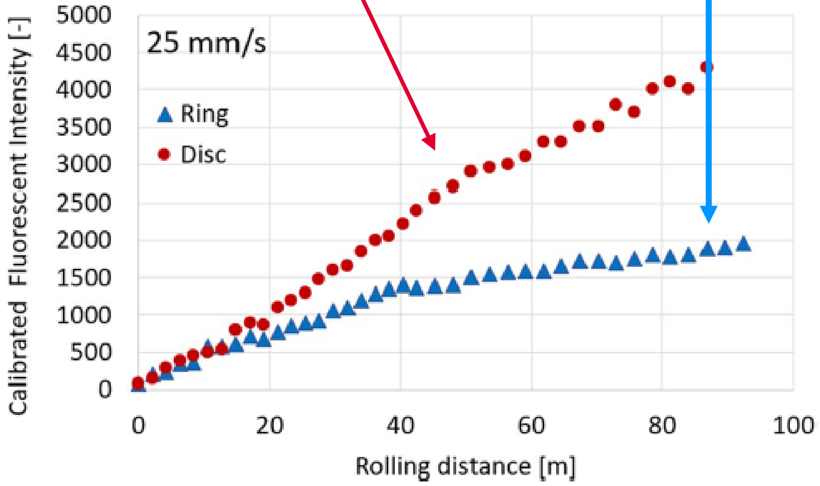


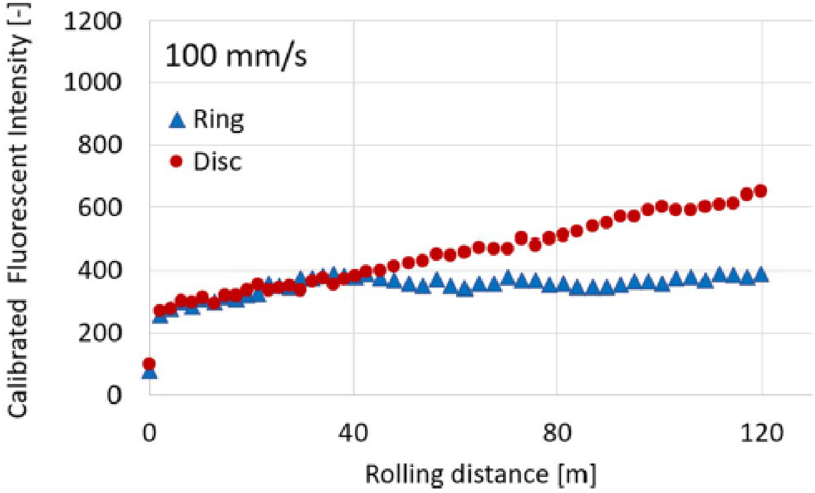
Artificial replenishment

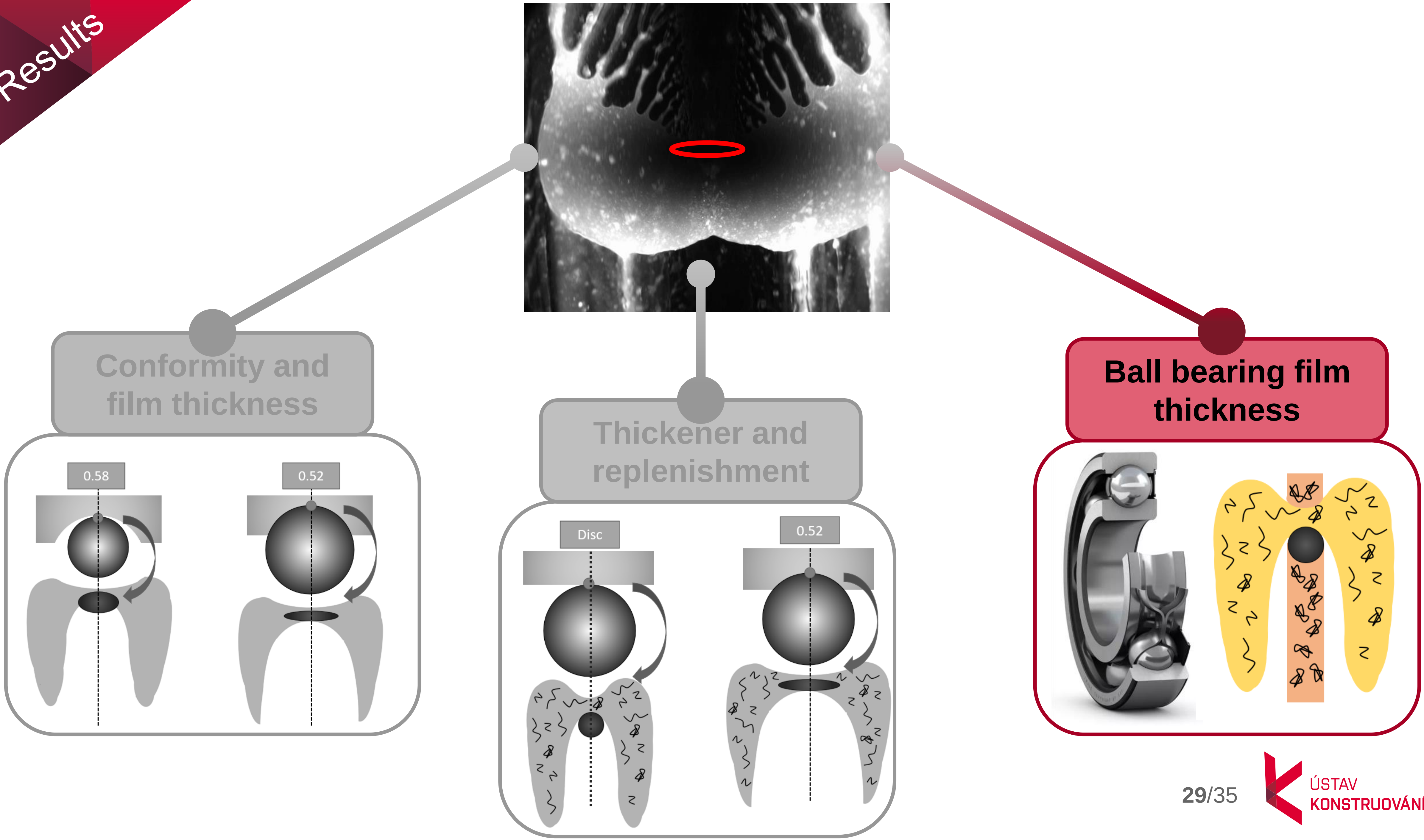
Natural replenishment

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

Natural replenishment=> less amount lubricant around






Conformity and film thickness
0.58
0.52
Thickener and replenishment
Disc
0.52
Ball bearing film thickness

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

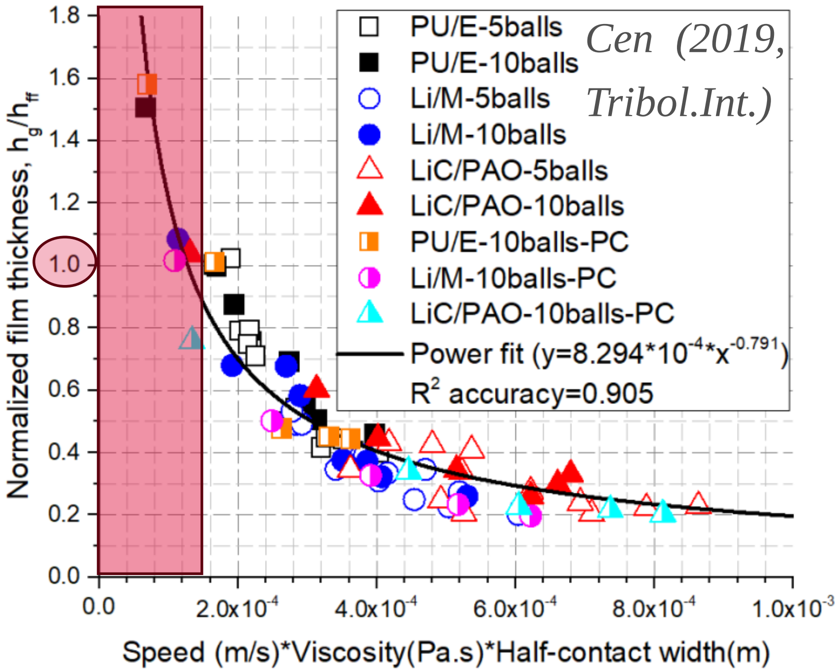
Samples

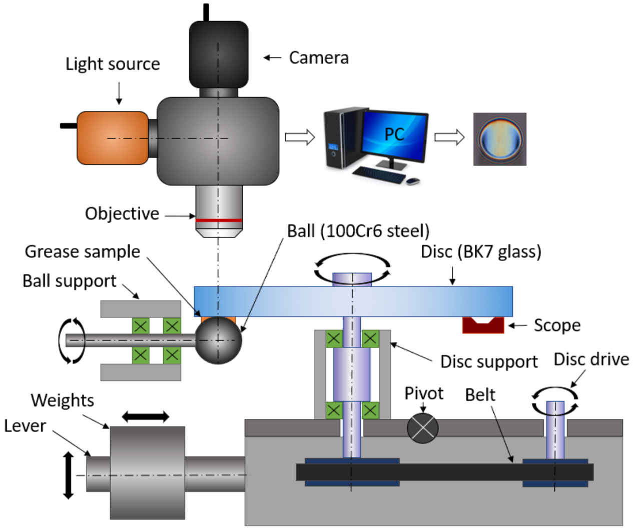
Alicyclic di-urea-normal thickener

Lithium complex

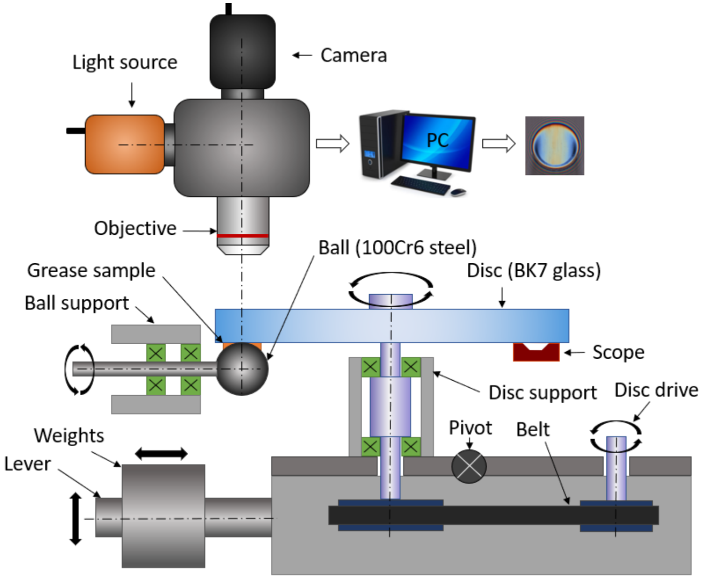
Aliphatic di-urea-fine thickener

Same base oil

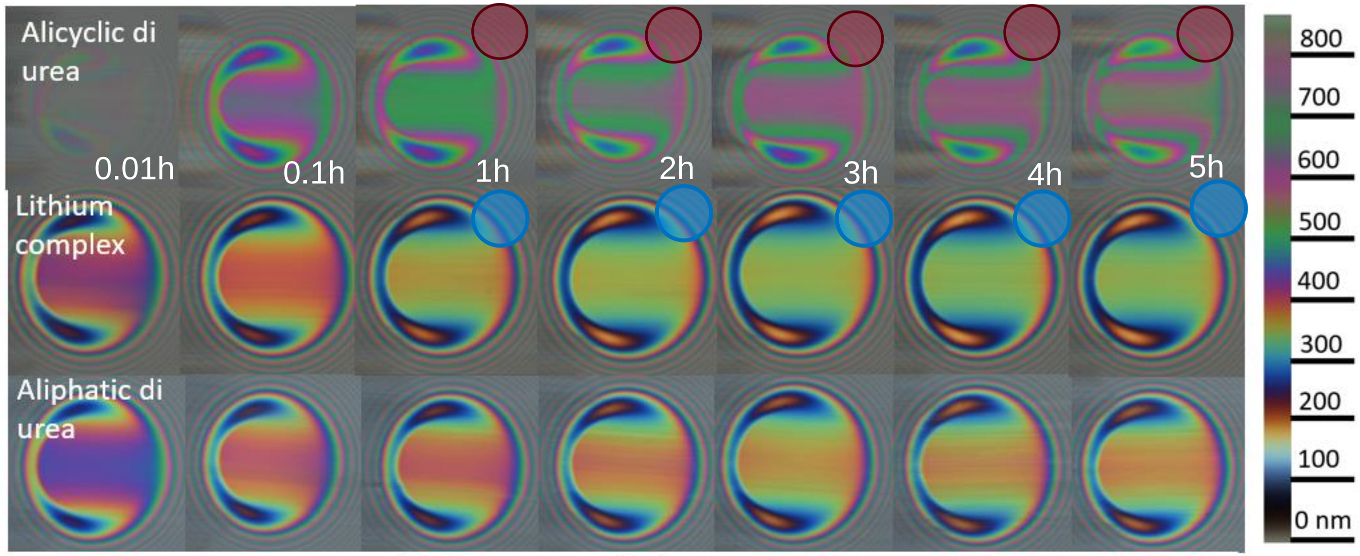




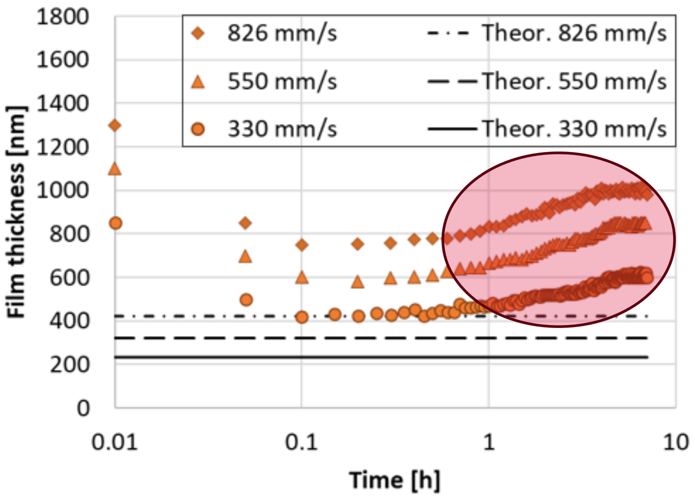
Ball bearing film thickness



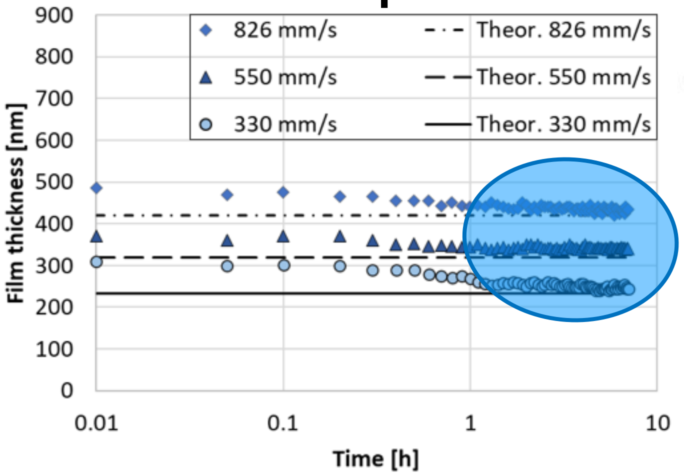
Constant speed 550 mm/s under fully flooded conditions

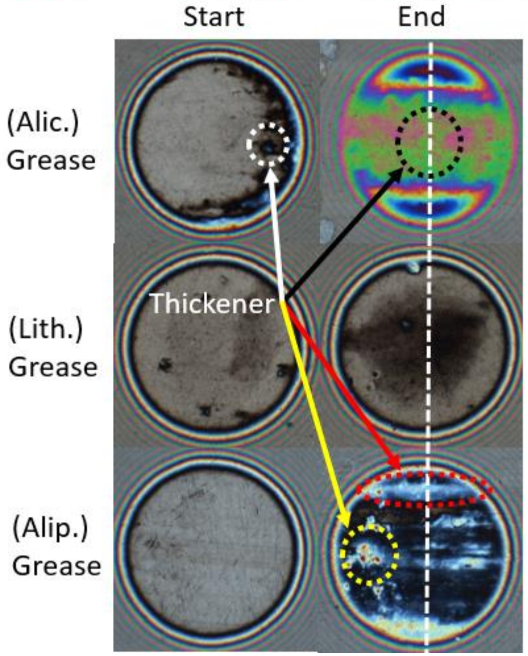


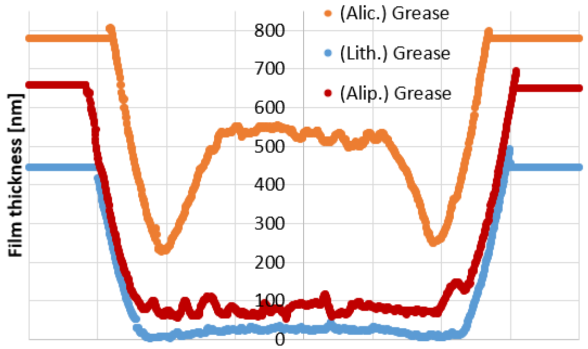
Alicyclic di-urea



Lithium complex







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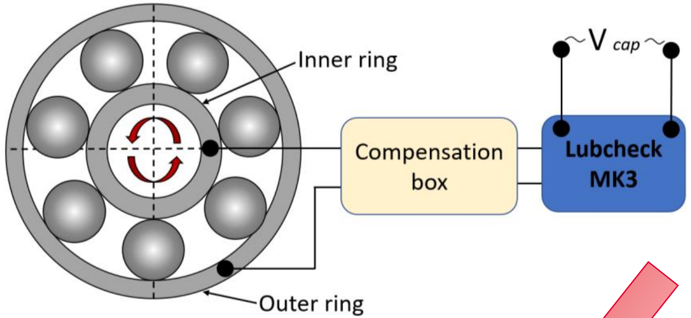
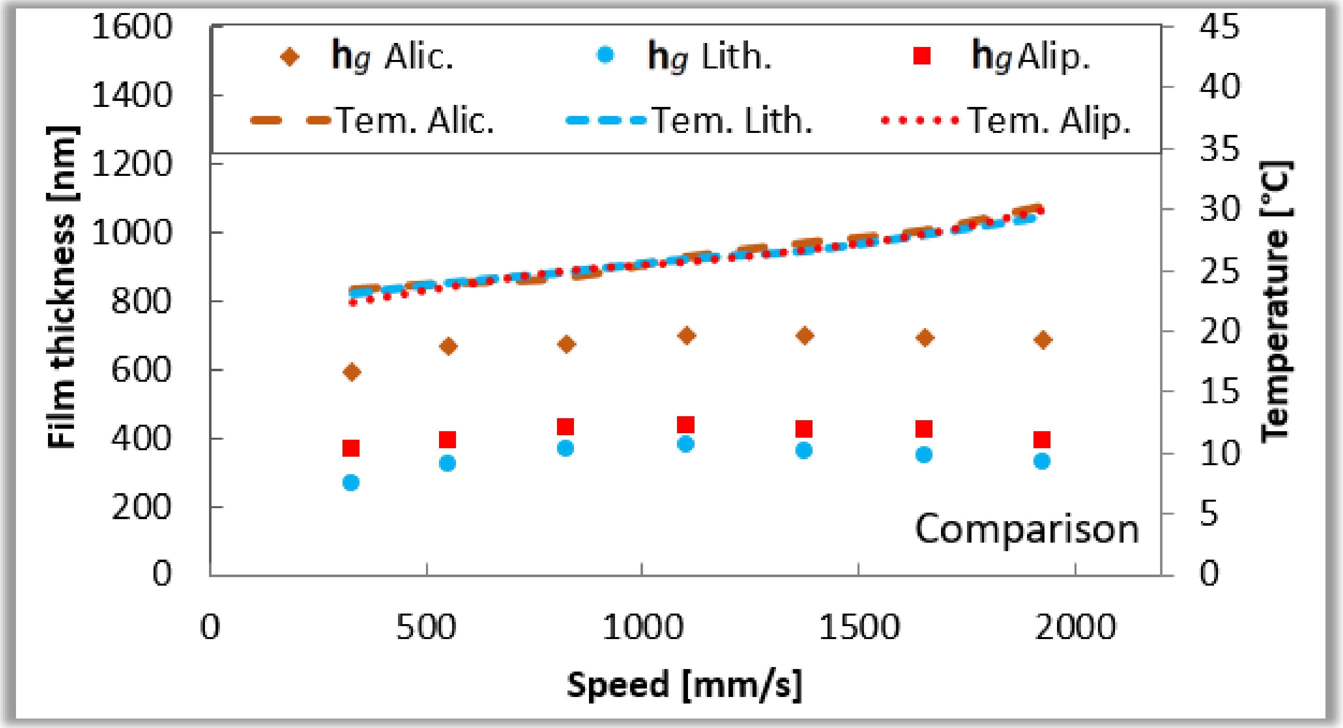
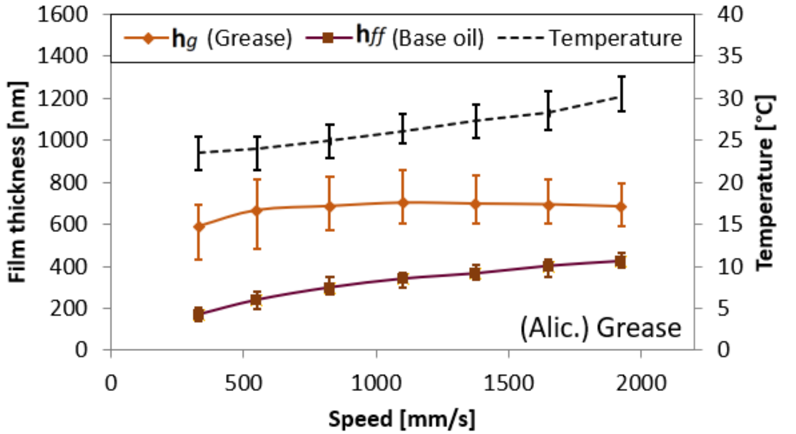
Ball bearing film thickness

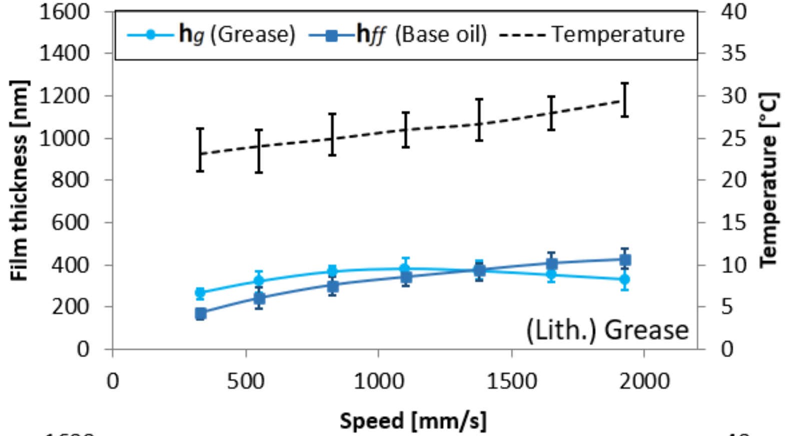


- The difference between film thickness.
- Minimum difference in bearing operating temperature.

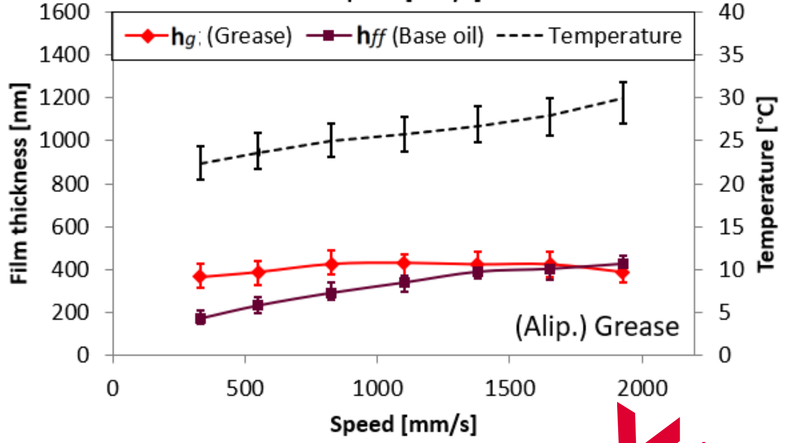




Alicyclic di urea



Lithium complex



Aliphatic di urea

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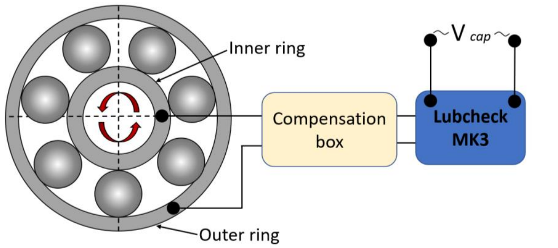
Ball bearing film thickness

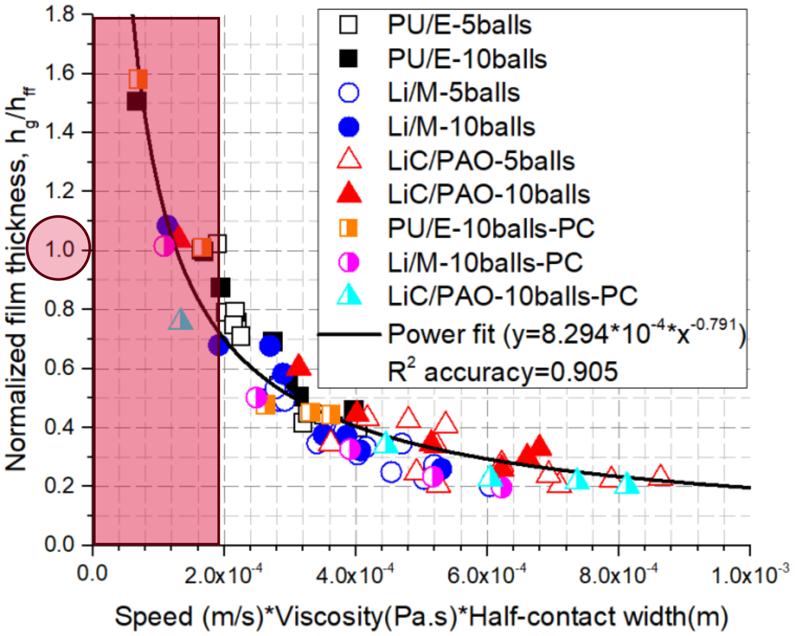


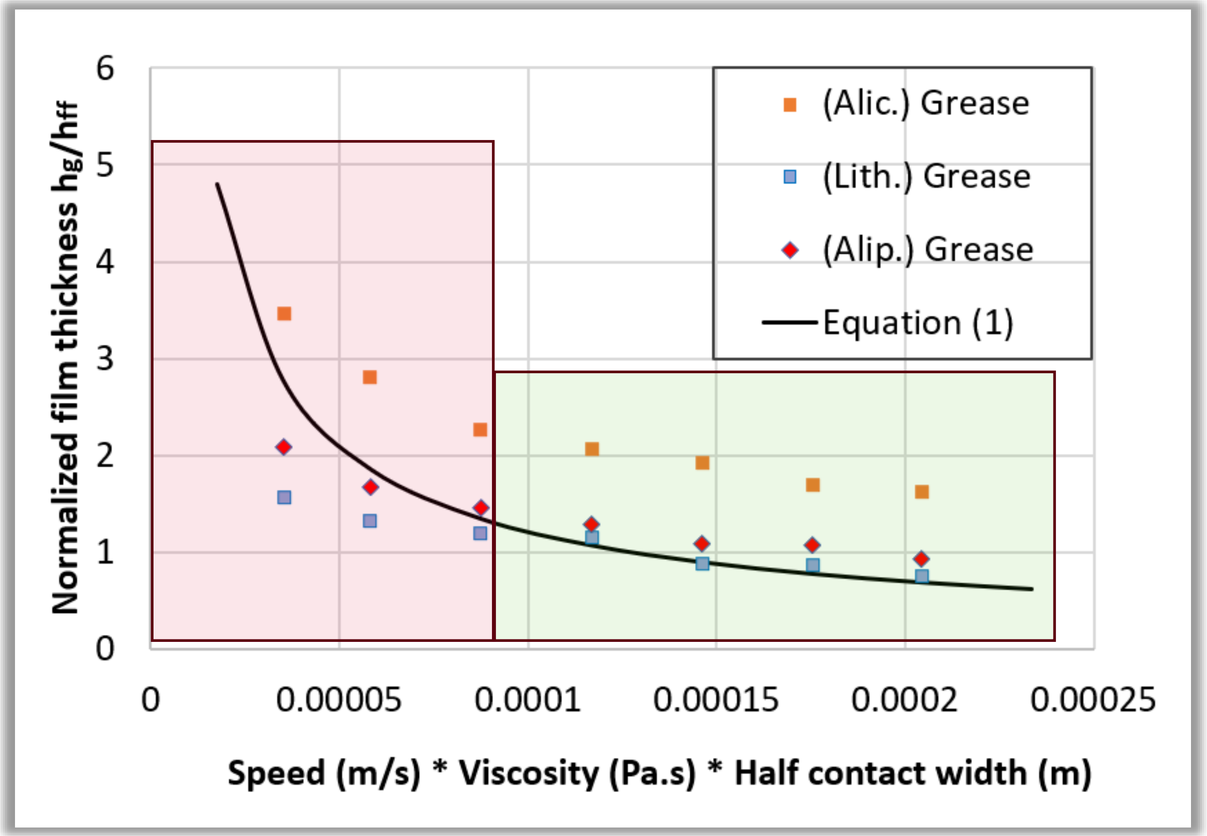
Deviation in the area of very low speeds

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

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

Conformity and film thickness

- 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.

Thickener and replenishment

- 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.

Ball bearing film thickness

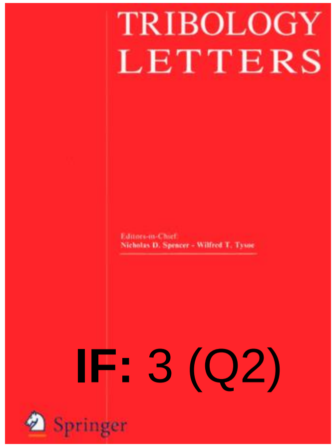
Thesis layout

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

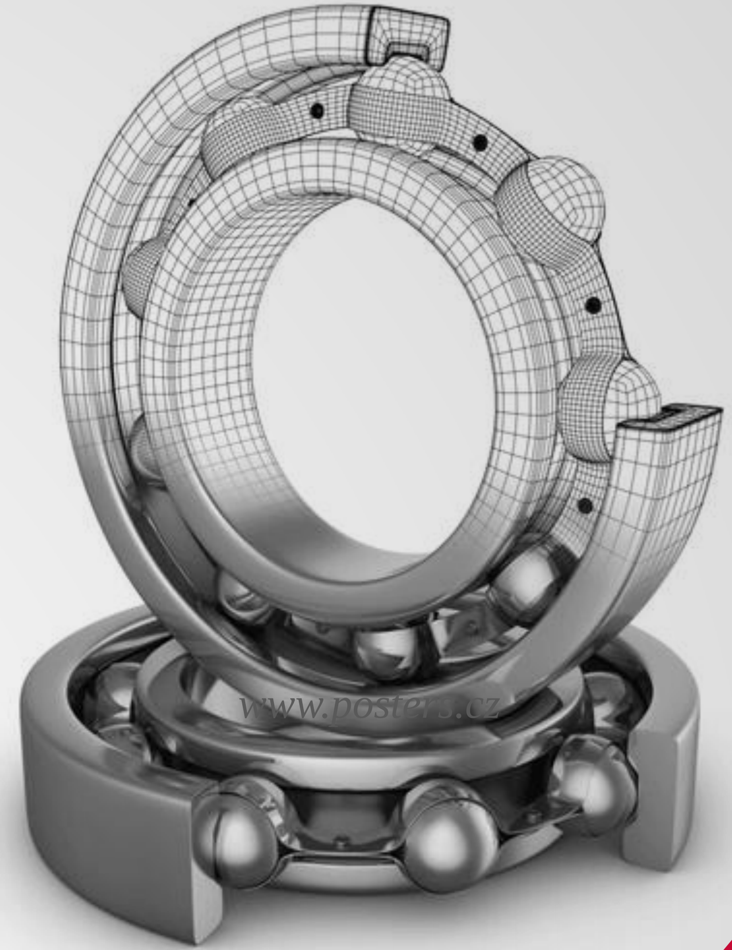
Kostál, D.; **Okál, M.;** Křupka, I.; Hartl, M. From single contact devices to rolling bearing simulator. World Tribology Conference, 2022, Lyon, France.

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.

THANK YOU FOR YOUR ATTENTION



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