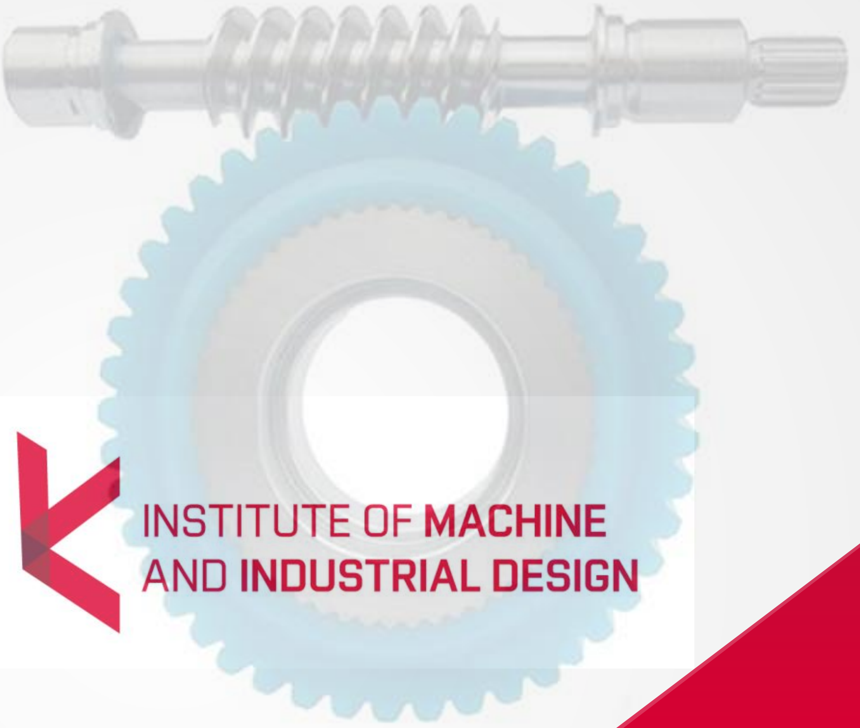
Development of film thickness in elastohydrodynamically lubricated compliant contacts

Ing. Jiří Křupka

Supervisor: **prof. Ing. Ivan Křupka, Ph.D.**



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CONTENT

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

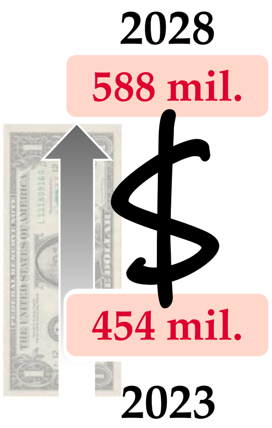
MOTIVATION

Perspectives

Commercial

- Expansion of polymer gears in mechanical engineering

Growth Rate by Region, 2023 – 2028



Plastic gearbox market, Mordor intelligence (2023)

Engineering

- Prevention of the failure modes of polymer gears

Failure of polymer gear, Krupka (2019)

Scientific

- Increase of polymer gears performance under lubricated conditions

Tribological experiments, Krupka (2019)

Participation in scientific projects

Project funding

GAČR
CZECH SCIENCE FOUNDATION

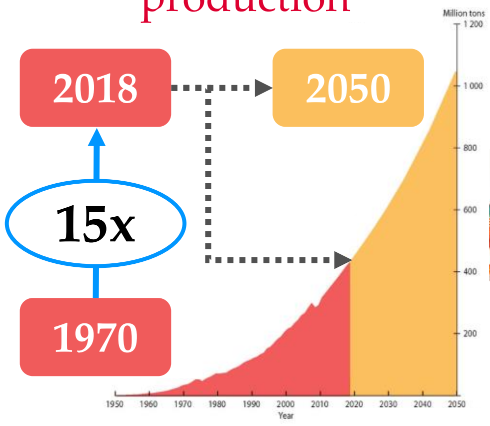
- Thermo-elasto-hydrodynamics of coated polymer gears (Grant No. 18 – 26849J)

INTRODUCTION

Plastics

Grow of plastics production

Plastic products examples

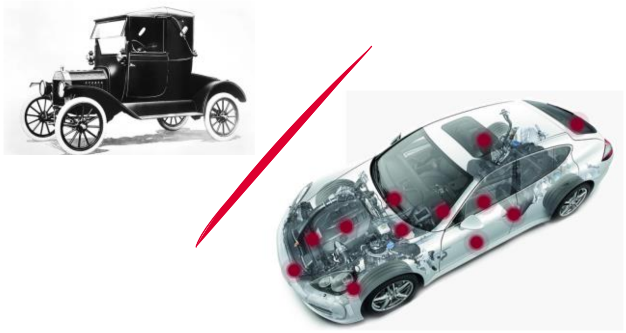


Polymer machine elements

- Low-cost production
- Low mass
- Ability to damp shocks and vibrations
- Silent operation
- Resistance to oils and acids

Applications

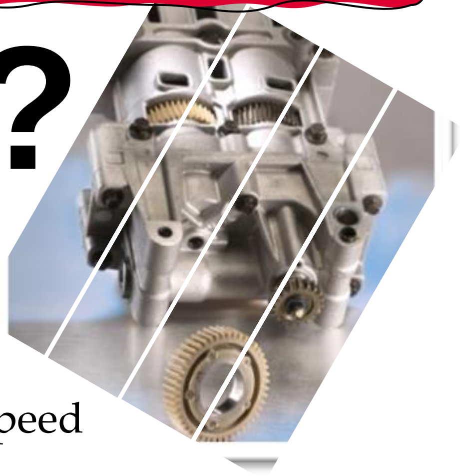
- Automotive industry
- Aerospace industry
- Industrial equipment
- Electrical appliances
- Medical industry



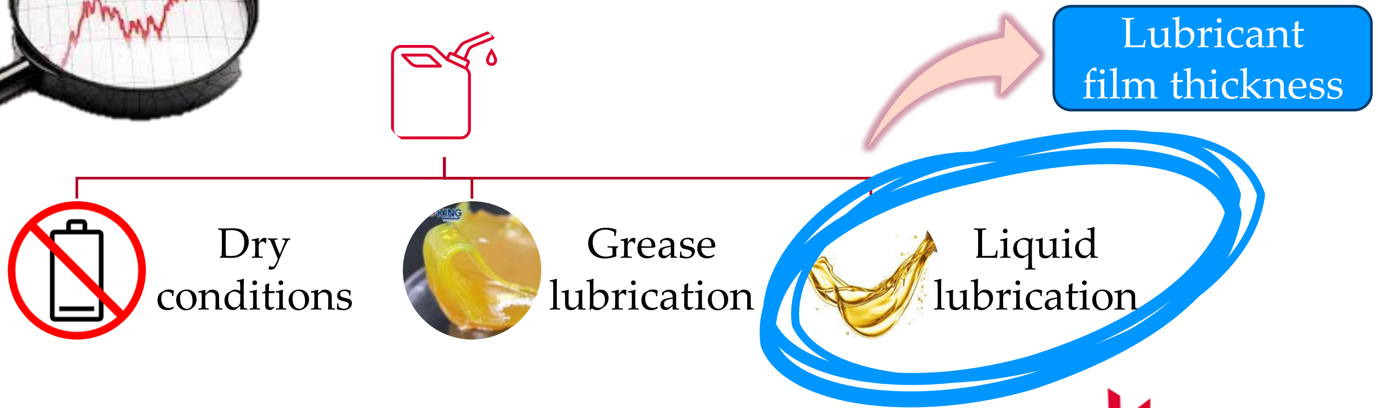
High-performance applications

Transmissions and differentials ?

High torque, temperature, speed



Lubrication



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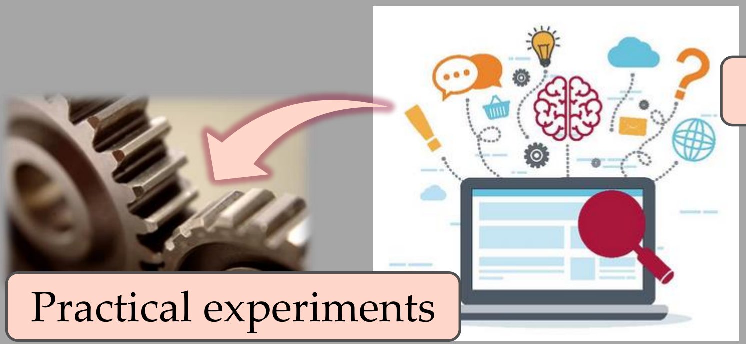
INTRODUCTION

FILM THICKNESS
Formation of coherent lubricant film

HEAT
Heat dissipation from the contact area by lubricant film

FRICTION
Reduction of friction in the contact area

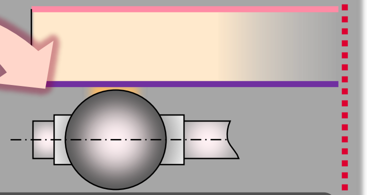
WEAR
Prevention of excessive wear of rubbing surfaces



Applied research

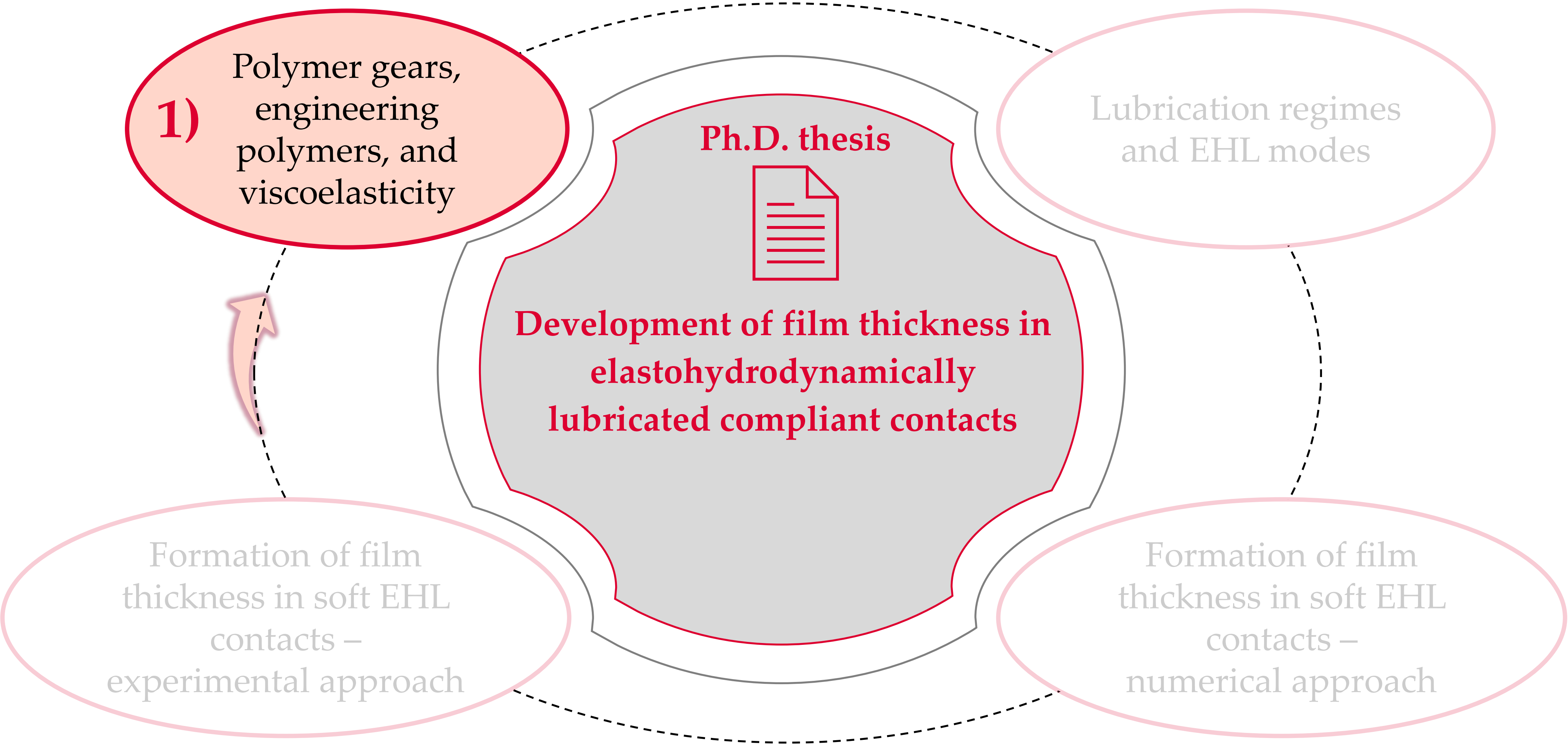
Practical experiments

Basic oriented research



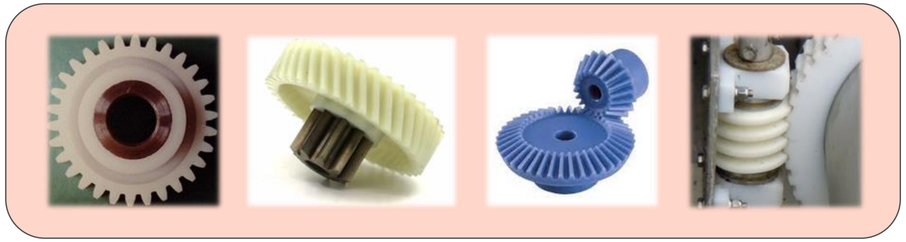
Laboratory experiments

STATE OF THE ART



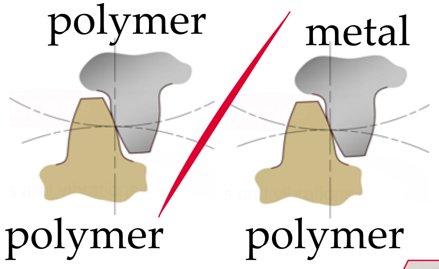
STATE OF THE ART

Polymer gears



spur helical bevel worm

Gearsets



Compliant contact

Failure modes

Engineering polymers

- PA 66, PEEK, POM

Properties / polymer	PA 66	PEEK	POM	PU	PFTE	100Cr6
Maximal service temperature, T_s (°C)	80	250	85	80	250	–
Glass-transition temperature, T_g (°C)	47	143	-40	-60	-100	–
Thermal conductivity, λ (W/m °C)	0.25	0.28	0.27	0.03	0.23	46.6
Thermal expansion, β (10^{-6}·°C)	88	55	93	150	145	12
Elastic modulus, E (GPa)	2.50	3.75	2.80	1.85	0.67	210
Yield strength, R_e (MPa)	90	130	80	90	15	700
Poisson's ratio, ν (-)	0.41	0.40	0.35	0.48	0.46	0.30

Modification of polymer properties

Mechanical

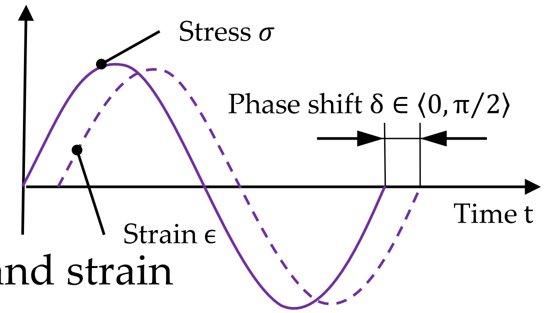
Glass fibers (GF)
Carbon fibers (CF)

Tribological

Teflon (PFTE)
Molybdenum disulfide (MoS2)

STATE OF THE ART

Viscoelasticity of polymers

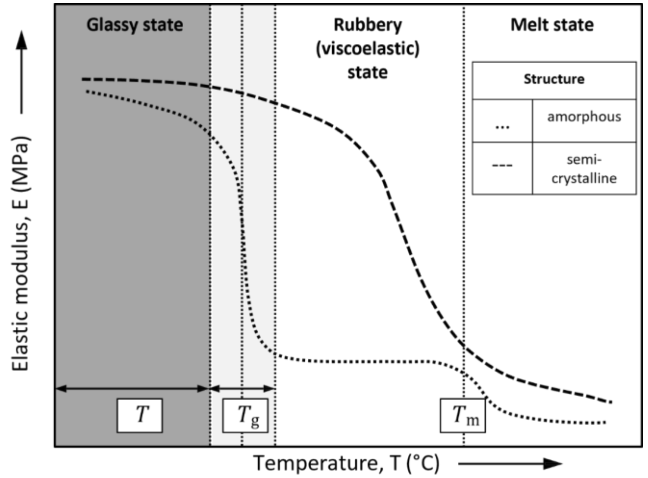


- Inelastic response of material
- Time dependence between stress and strain
- Significant temperature dependence
- Glass-transition temperature, $\mathbf{T_g}$ →

Polymer states

- Glassy → $T < T_g$
- Rubbery → $T \sim T_g$
- Melt → $T > T_g$

Elastic modulus vs temperature



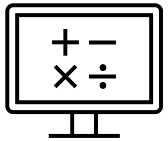
Macromolecular arrangement

- Amorphous (PC, PMMA)
- Semi-crystalline (PA66, PEEK)
- Crystalline

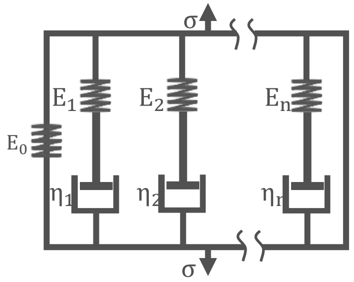
Optical properties | Mechanical properties

Determination of viscoelastic response

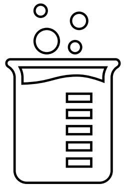
Numerical simulation



SLS and generalized models

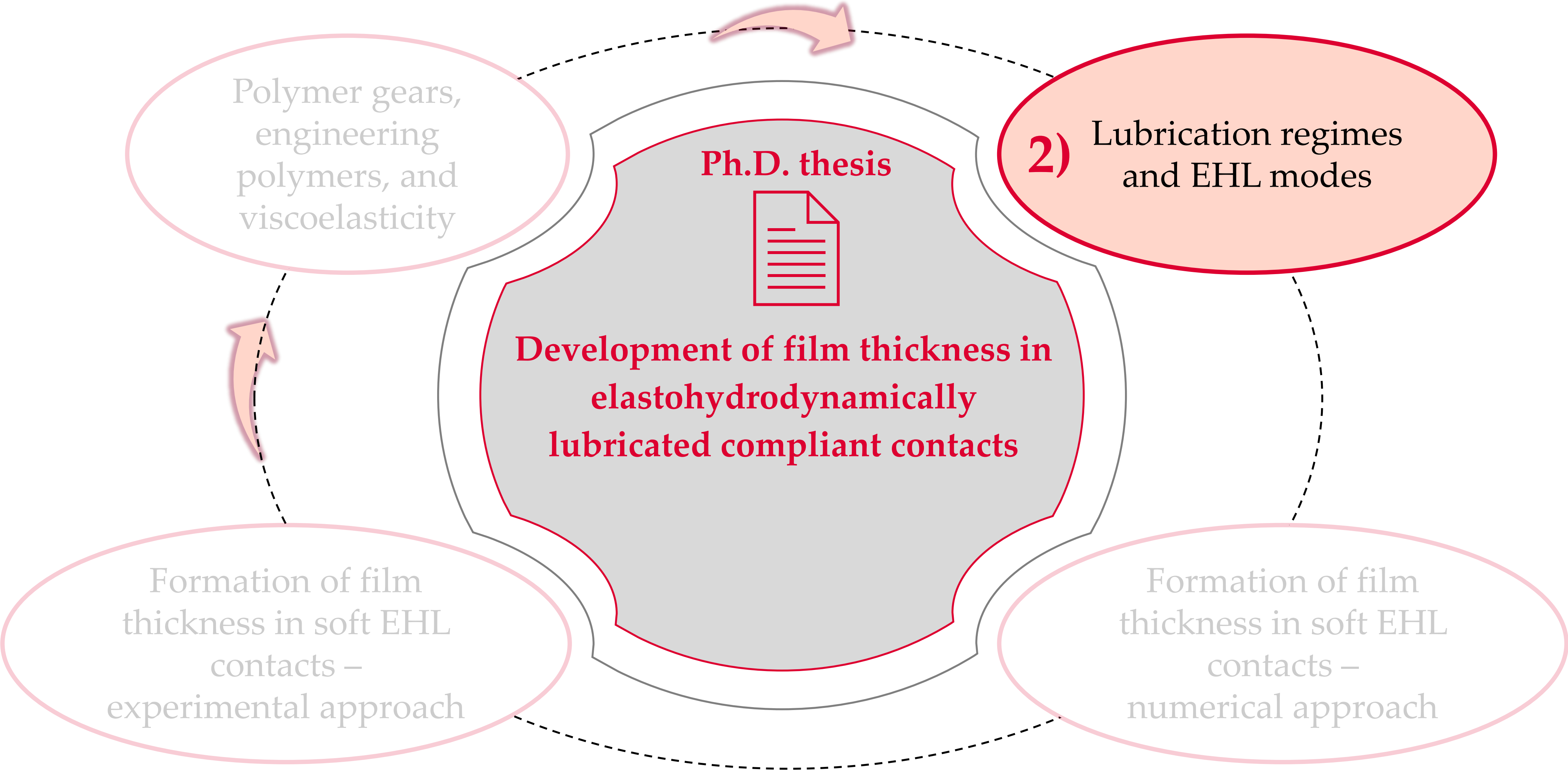


Experiments



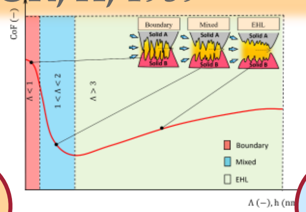
Nano-DMA and DMA

STATE OF THE ART



STATE OF THE ART

GRUBIN, A.N., 1949
BLOK, H, 1959



First findings about (hard) EHL

First use of engineering polymers

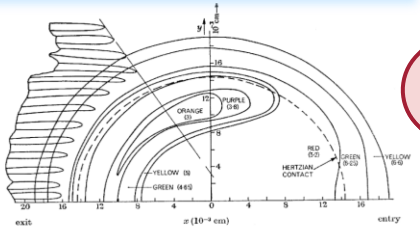
1950s

Intensive research in (hard) EHL

First use of polymer gears

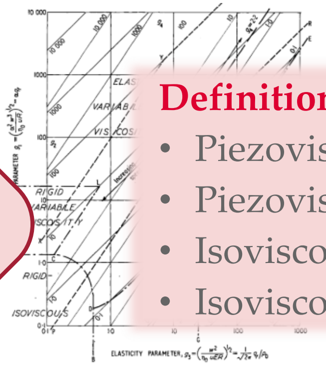
1960s

HOOKE, C. J., 1965
HERREBRUGH, K., 1966
DOWSON, D., 1967
ARCHARD, J. F., 1968



DOWSON, D., 1967

JOHNSON, K. L., 1970



JOHNSON, K. L., 1970

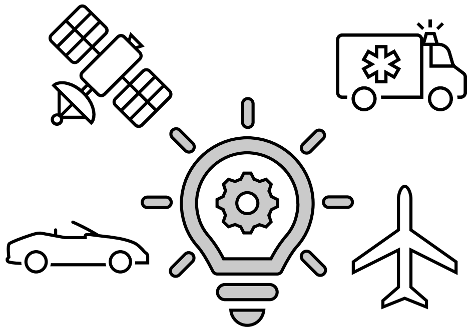
Definition of EHL modes

- Piezoviscous-elastic (P-E)
- Piezoviscous-rigid (P-R)
- Isoviscous-elastic (I-E)
- Isoviscous-rigid (I-R)

First findings about (soft) EHL

Growth of polymers in engineering

1970s

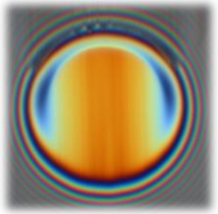


STATE OF THE ART

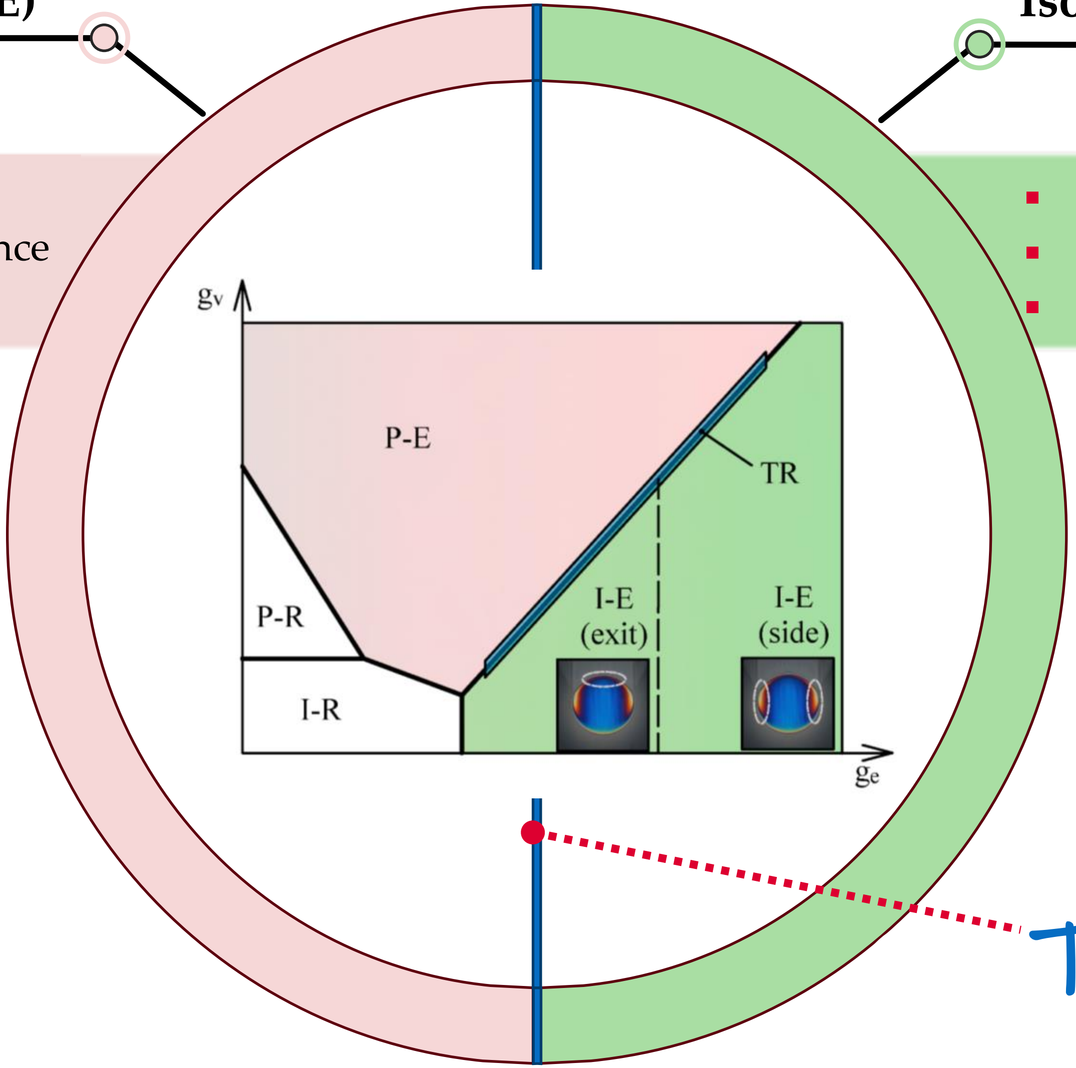
EHL modes

Piezoviscous-elastic (P-E)

hard EHL



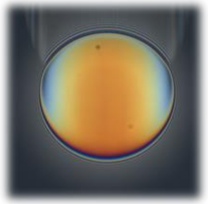
- p = (0.5 – 4) GPa
- strong p-η dependence
- metals, ceramics etc.

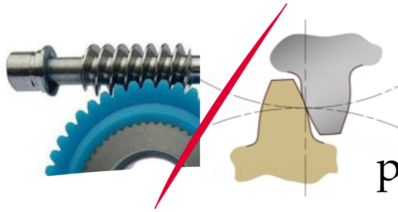


Isoviscous-elastic (I-E)

soft EHL

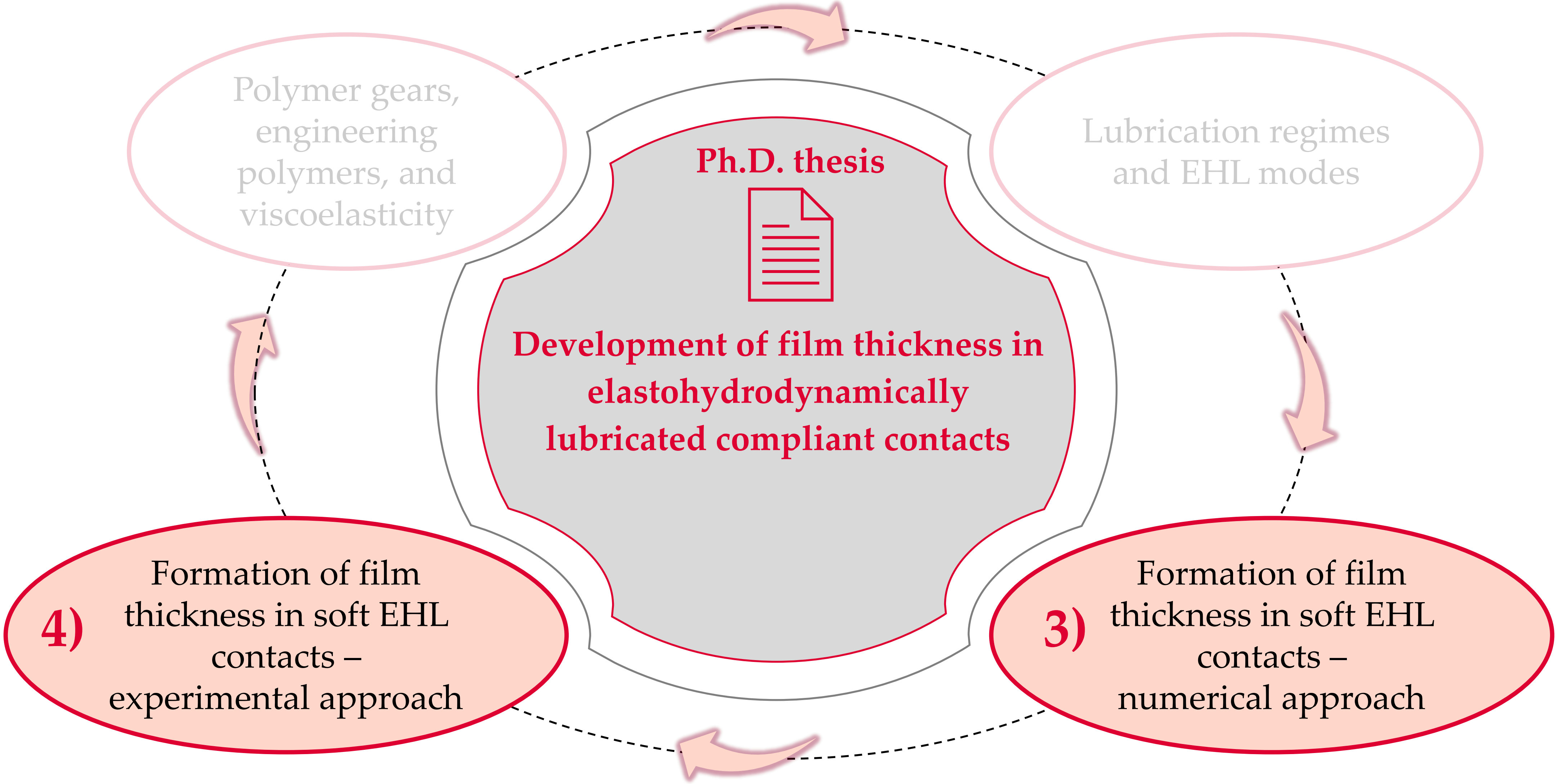
- p ≤ 50 MPa
- weak p-η dependence
- thermoplastics, rubbers etc.





TR region = ?

STATE OF THE ART



STATE OF THE ART- analysis of lubricant film in soft EHL

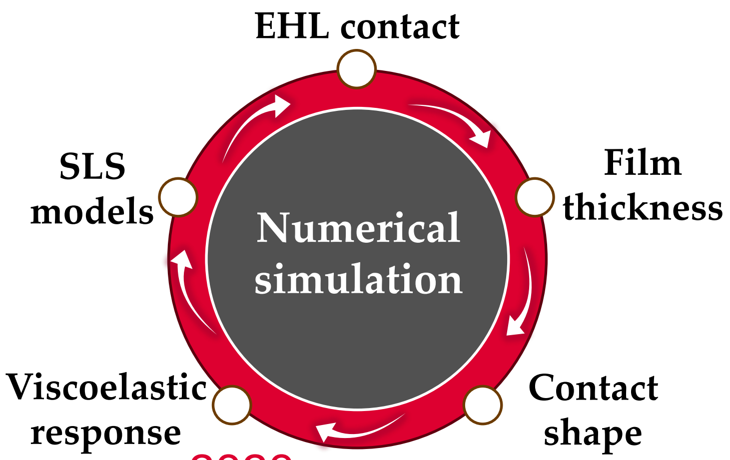
Johnson et al.
Hooke et al.
Hamrock et al.

- Circular, elliptical, and line contacts
- Circular and elliptical contacts
- Formulae of h_c and h_m
- Prediction of film thickness
- $\bar{U}$, $\bar{W}$, and $\bar{G}$ parameters
- Definition of I-Es and I-Er

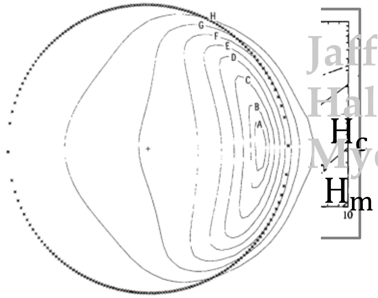
Esfahanian et al.
Hooke et al.

- Revisited EHL maps
- Circular and elliptical contacts

Myant et al.
Gasni et al.
Stupkiewicz et al.
Marx et al.



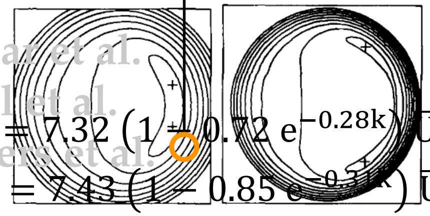
1970s — 1980s — 1990s — 2000s — 2010s — 2020s



Jaffar et al.
Hall et al.
Myers et al.

$$H_c = 7.32\,(1 - 0.72\,e^{-0.28k})\,\bar{U}^{0.64}\,\bar{W}^{-0.22}$$

$$H_m = 7.43\,(1 - 0.85\,e^{-0.31k})\,\bar{U}^{0.65}\,\bar{W}^{-0.21}$$

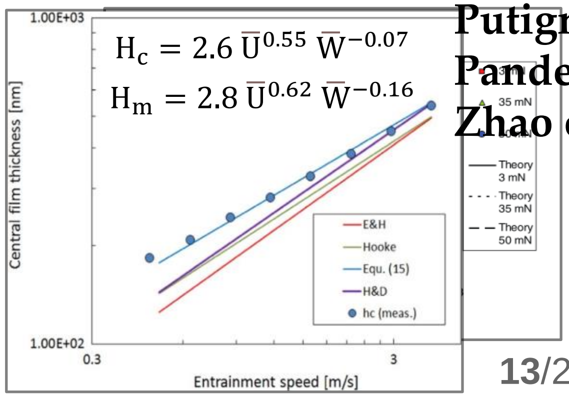


Bohan et al.
Skotheim et al.
Bongaerts et al.

- Circular contact (steel ball / BK7 disc)
- Circular contact (PDMS / PMMA disc)
- Effect of U, W, and SRR
- Effect of U_e, W, and SRR
- Chromatic optical interferometry
- Monochromatic interferometry

$$H_c = 2.6\,\bar{U}^{0.55}\,\bar{W}^{-0.07}$$

$$H_m = 2.8\,\bar{U}^{0.62}\,\bar{W}^{-0.16}$$



Putignano et al.
Pandey et al.
Zhao et al.

SUMMARY OF LITERATURE REVIEW

Compliant contacts

wear
efficiency

Lubrication of polymer gears

1

1 Complex geometry

2 Simplified geometry

2

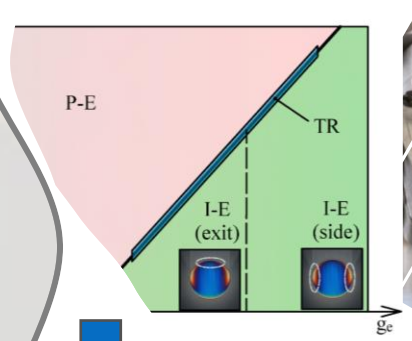
Lubrication processes in compliant contacts

film thickness
friction

Shortcomings

- Limited knowledge of **film thickness in TR region**
- Overlooked **viscoelastic response** of polymers
- Insufficient validation of **I-E EHL models**
- Inadequate material of **contact bodies**
- No description of **temperature effect**
- Difficult use of **optical methods**

White space

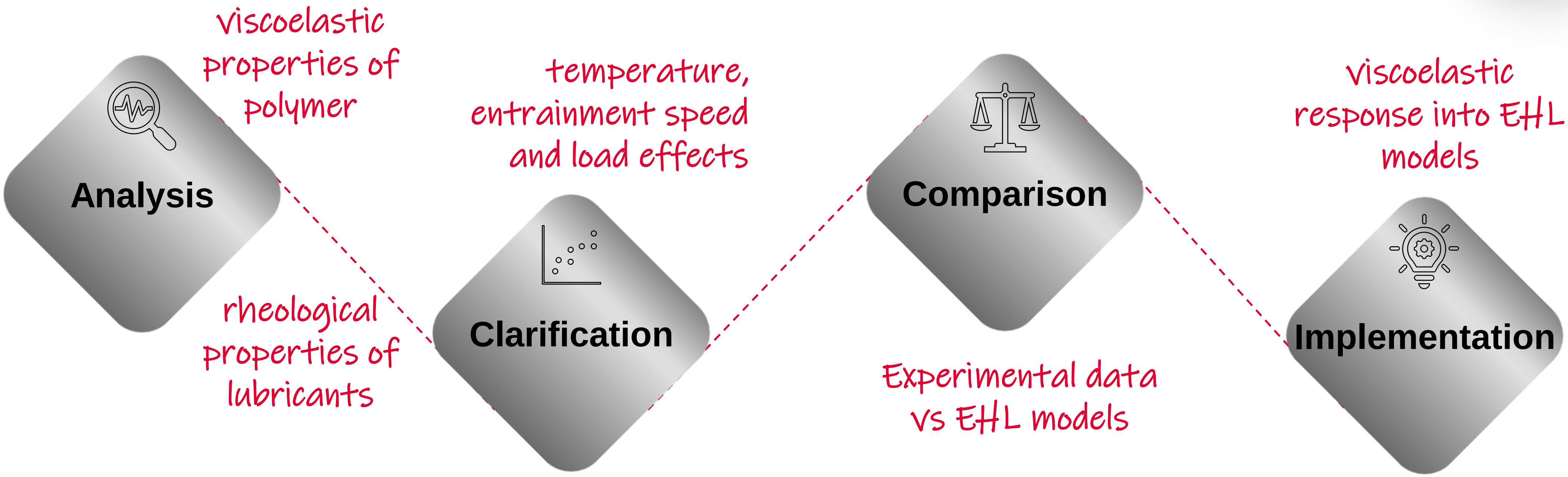


TR region of EHL

AIM OF THESIS

The main aim is to clarify the tribological behavior of the compliant contacts operating in the TR region between the I-E and P-E modes of EHL.

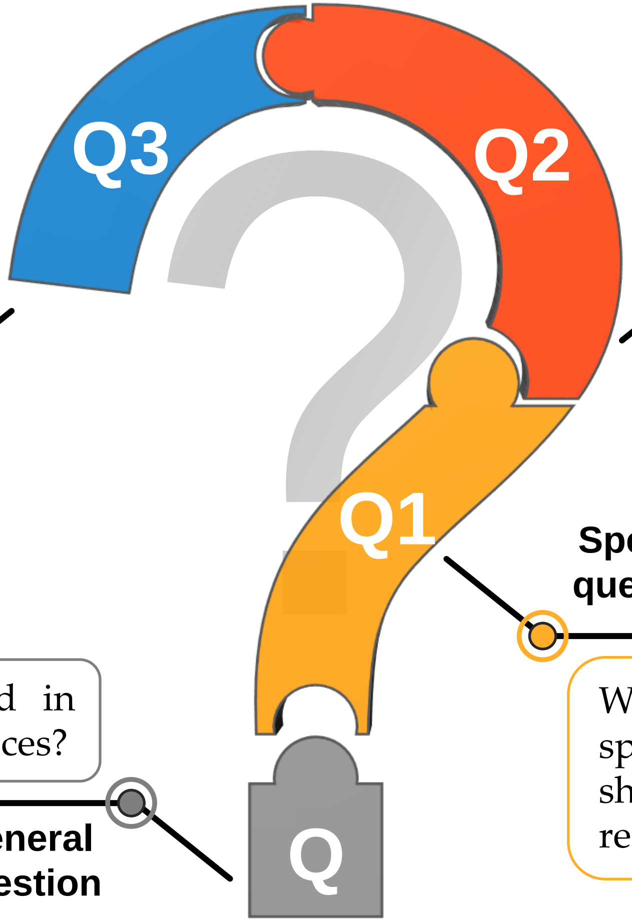
Sub-aims



OVERVIEW OF SCIENTIFIC QUESTIONS

What is the contribution of the constitutive viscoelastic response of the material in the compliant contacts to the formation of fluid film thickness and contact shape changes in the TR region of EHL?

Specific question



How the rheological response of the lubricant contributes to the formation of the fluid-film thickness in the TR region of the EHL, considering a different effect in the I-E and P-E modes of the EHL?

Specific question

Specific question

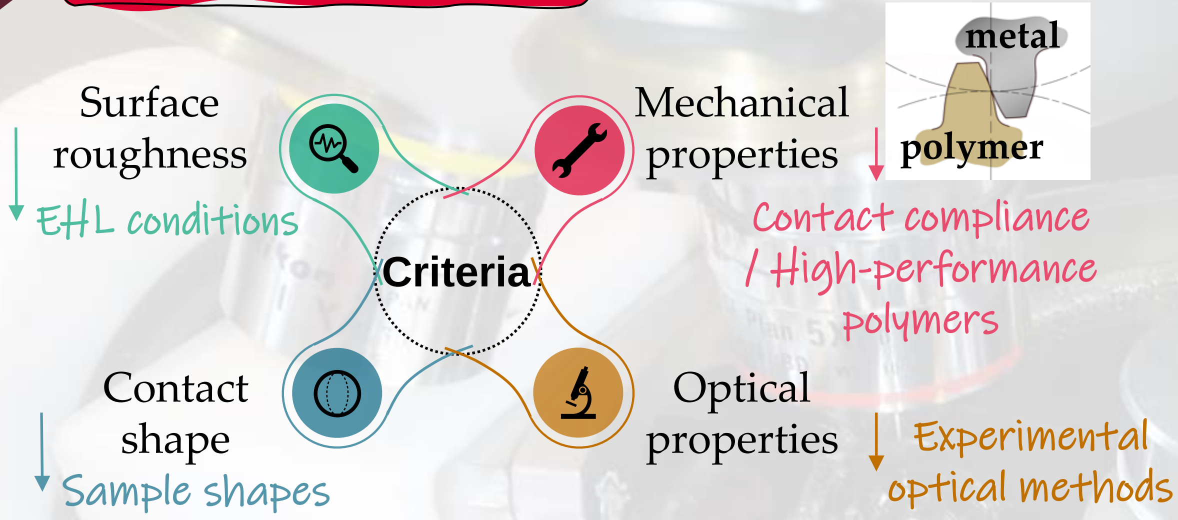
What is the effect of the load and entrainment speed on the fluid-film thickness and the contact shape in the compliant contact operated in the TR region of EHL?

Will a coherent lubricant film always be formed in compliant contacts, fully separating the rubbing surfaces?

General question

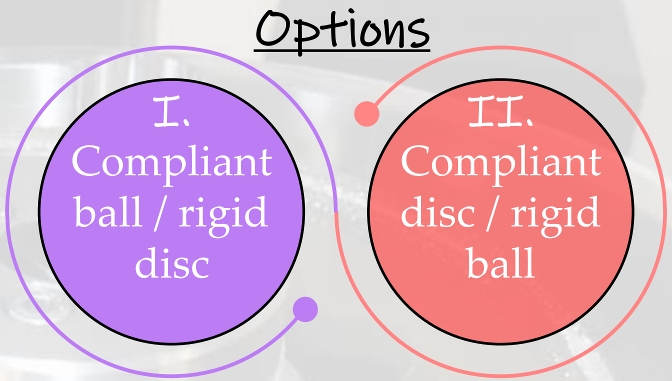
MATERIALS AND METHODS

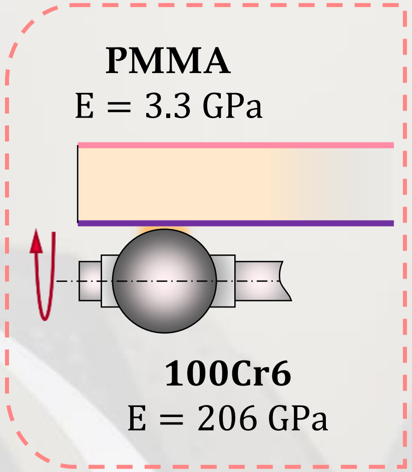
Selection of materials



Simulation of compliant contact

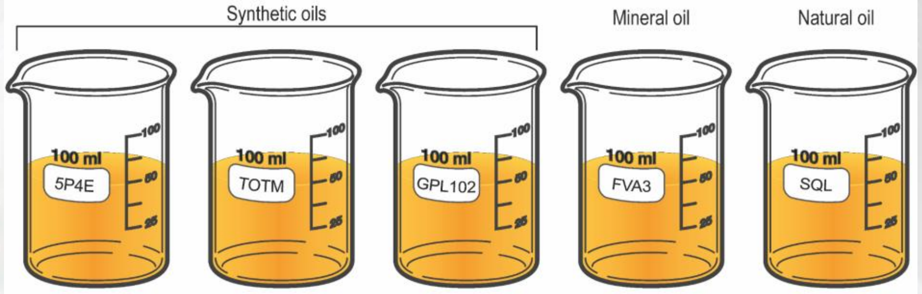
- Amorphous or semi-crystalline polymer
- Circular contact shape





Selection of lubricants

- Reference mineral, synthetic and natural lubricants (5P4E, TOTM)
- Wide viscosity interval



Overview of experimental conditions

Property	Interval / Value
Entrainment speed, U_E (m/s)	10^{-4} – 10^{1}
Normal load, W (N)	5 – 100
Temperature, T (°C)	22 – 130
Dynamic viscosity at 40 °C, η (Pa s)	0.0157 – 0.37
Pressure-viscosity coefficient at 40 °C, α (GPa^{-1})	18.1 – 37.0
Sliding-rolling ratio, SRR	-1 – 1
Ellipticity, k	1

MATERIALS AND METHODS

Experimental equipment

Surface texture analysis

Bruker 3D optical profilometer

Rheological analysis of lubricants

HAAKE RotoVisco1 viscometer

Rheological analysis of lubricants

HPV viscometer (BUT, Czech Republic)

Lubricant film analysis

Rotational optical tribometer (BUT, Czech Republic)

DMA analysis

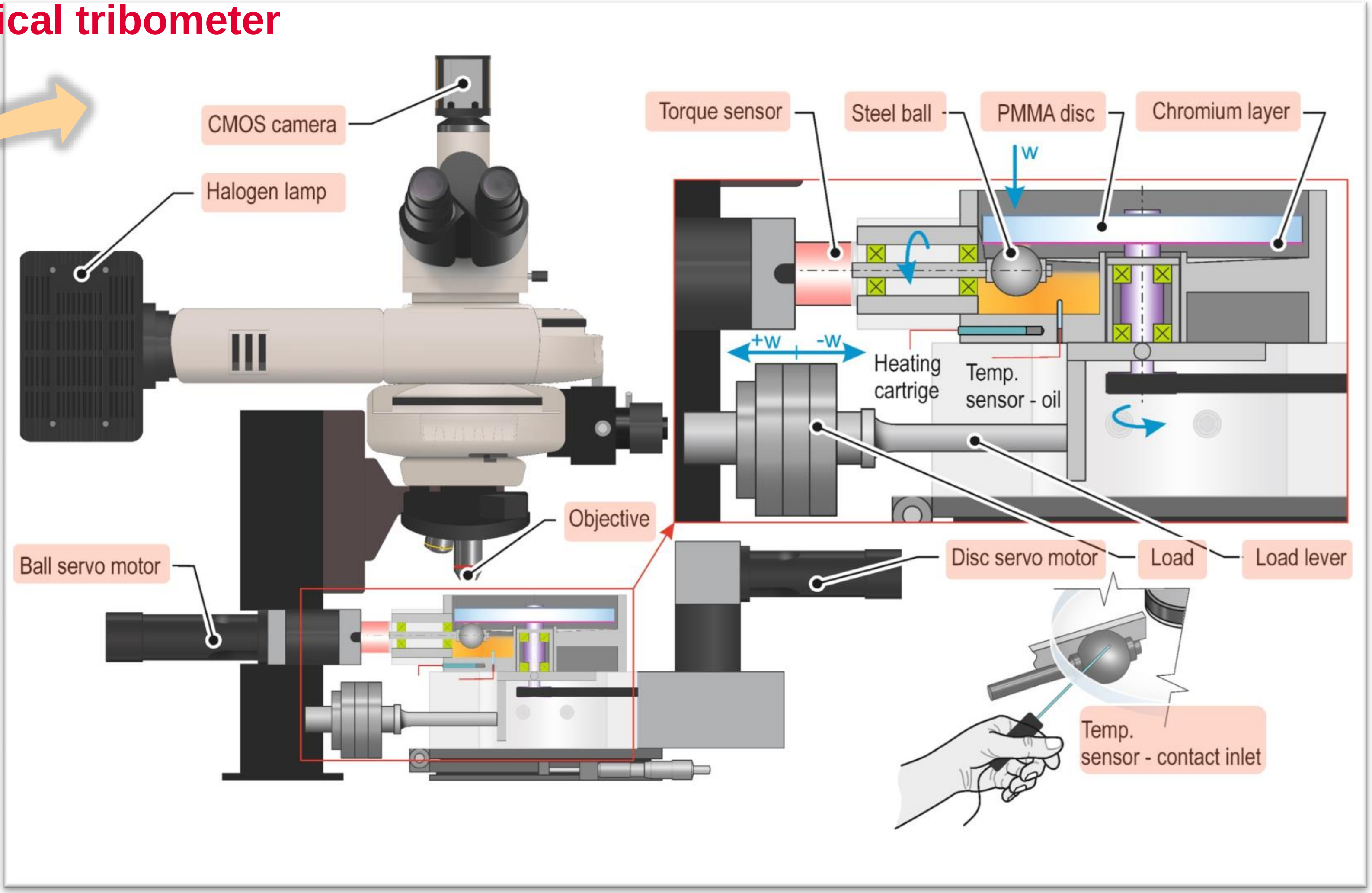
DMA1 dynamic mechanical analyzer

Nano-DMA analysis

Hysitron TI Premier Nanoindenter

MATERIALS AND METHODS

Rotational optical tribometer



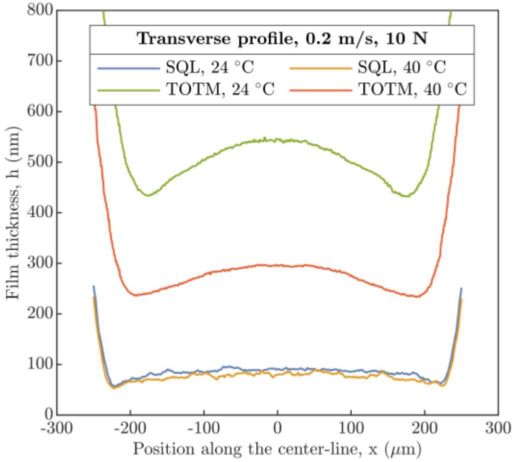
RESULTS AND DISCUSSION

Q1 What is the effect of the load and entrainment speed on the fluid-film thickness and the contact shape in the compliant contact operated in the TR region of EHL?

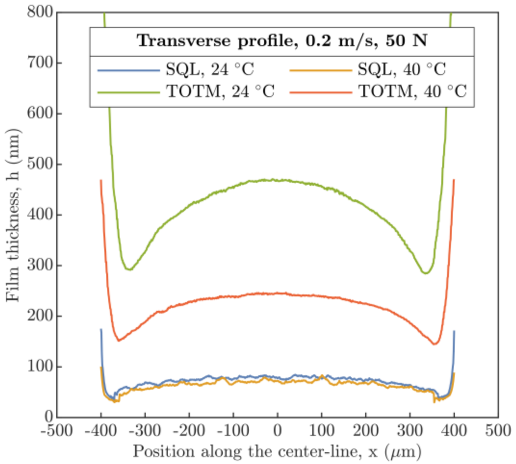
Load effect – below Tg

H1.a *"The effect of load will be significantly dependent on the operating temperature below T_g, where the load-dependent behavior of the film thickness will be manifested."*

Film shape – transverse profiles

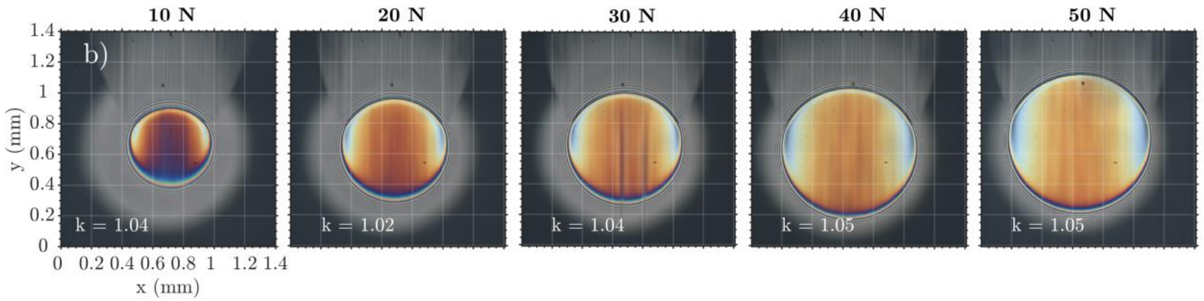


10 N



50 N

Ellipticity and contact area



- Load transmitted directly through the fluid → no interaction between surface asperities,
- Significant reduction in lubricant film as a function of load,
- Δ between central and minimum lubricant film gradually increases with magnitude of load,
- Only slight increase in ellipticity with magnitude of load.

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RESULTS AND DISCUSSION

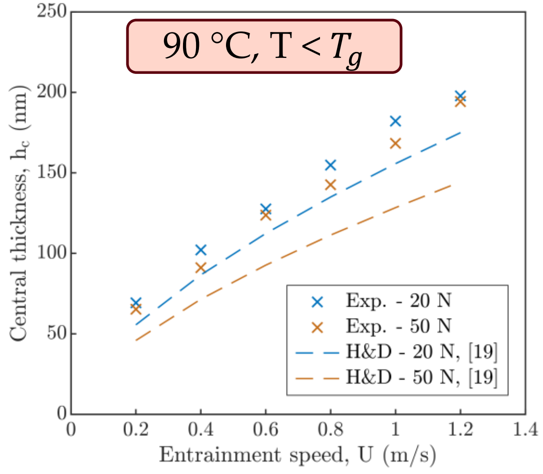
Q1 What is the effect of the load and entrainment speed on the fluid-film thickness and the contact shape in the compliant contact operated in the TR region of EHL?

Load effect – above Tg (PMMA Tg ~ 105 °C)

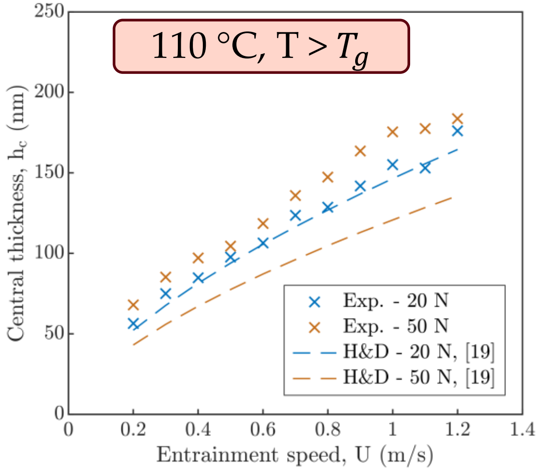
H1.b *“Near and above T_g, the load-dependent behavior of the fluid-film thickness will be negligible although a significant increase in the contact area and asymmetric deformation of the contact shape will be exhibited.”*

✗

Central film thickness

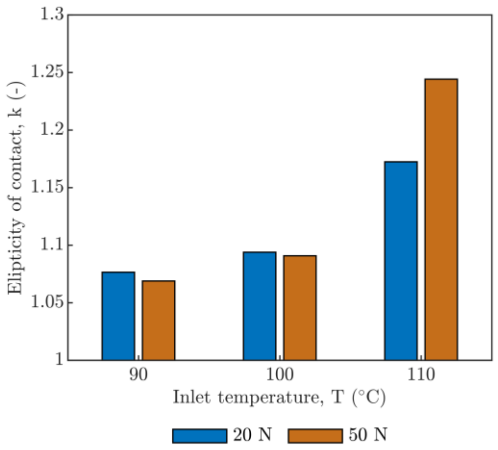


(a)

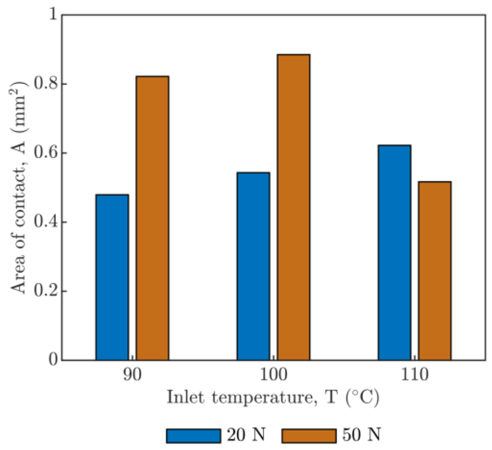


(b)

Ellipticity



Contact area



- Above T_g, the lubricant film surprisingly increase as a function of load,
- Above T_g, significant increase in ellipticity with load → change of contact shape from circular to elliptical,
- Below T_g, contact area gradually increase with load up to T_g. Above T_g, opposite effect discovered.

RESULTS AND DISCUSSION

Q1

What is the effect of the load and entrainment speed on the fluid-film thickness and the contact shape in the compliant contact operated in the TR region of EHL?

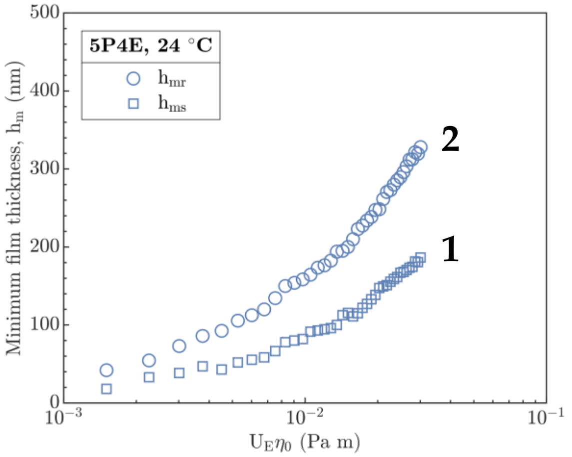
Entrainment speed effect

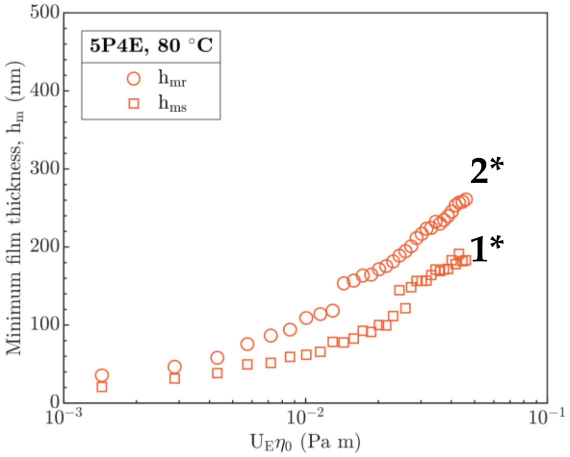
H1.c

"The increase of the entrainment speed will cause a transition of minimum film thickness from the side lobes to the exit of the contact. However, the shape of the compliant contact will be only slightly affected."

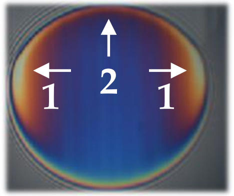
✗

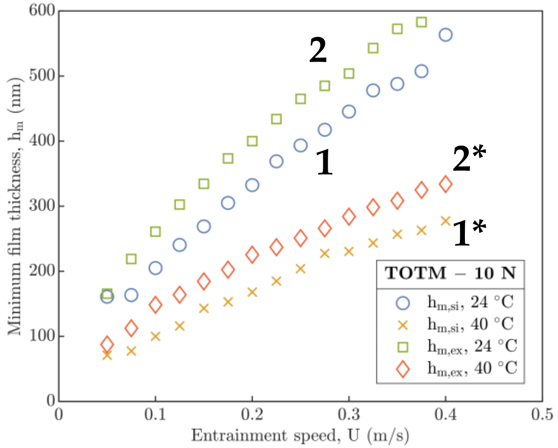
Minimum film thickness – 5P4E

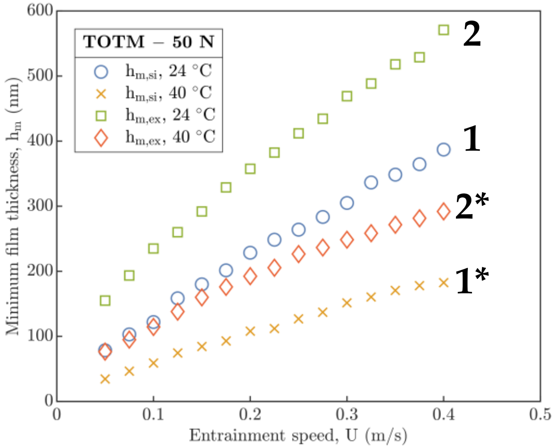




Minimum film thickness – TOTM







- Δ between the film thickness at the side lobes and at the exit from the contact gradually increased with U_e,
- No transition of minimum film thickness as a function of U_e → minimum at the side lobes.

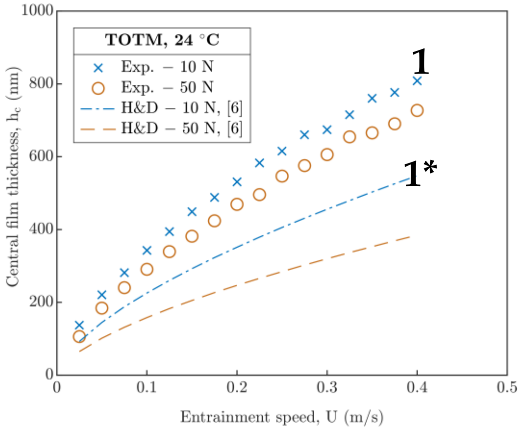
RESULTS AND DISCUSSION

Q2 How the rheological response of the lubricant contributes to the formation of the fluid-film thickness in the TR region of the EHL, considering a different effect in the I-E and P-E modes of the EHL?

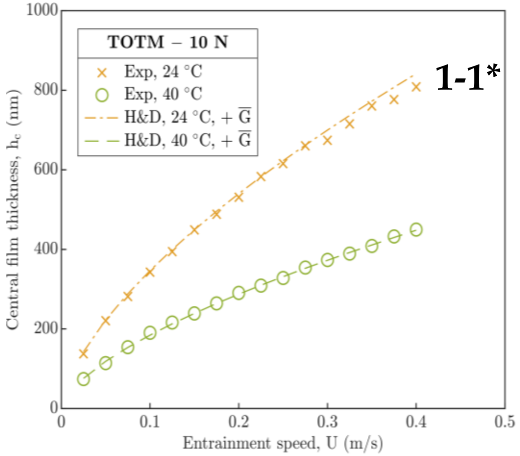
Pressure-viscosity effect

H2.a *"In accordance with the EHL theory, the pressure-viscosity response of the lubricant to the formation of the fluid film thickness is usually neglected in the I-E mode of EHL. However, this effect will be more significant in the TR region than in the I-E mode."*

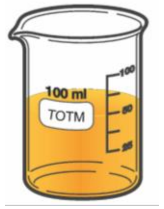
hc – H&D I-E



hc – H&D I-E + $\bar{G}$



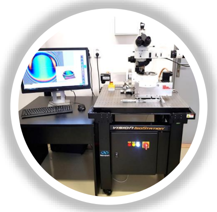
TOTM → **Rheological exp.** → $\eta - p$ → **PV coef. α**



(measured by Ing. Polnicky)

$\bar{G} = E'\alpha$

Film thickness exp. → **Data regression** → **H&D I-E + $\bar{G}$**



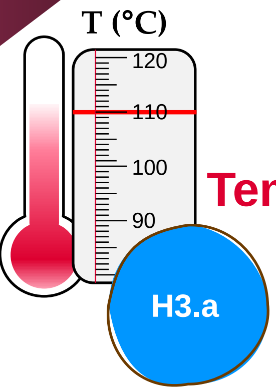
h_c

P-E → x = 0.53
I-E → x = 0
TR → x = ?

$$H_c = 7.32\,\left(1 - 0.72\,e^{-0.28k}\right)\,\bar{U}^{0.64}\,\bar{W}^{-0.22}\,\bar{G}^{0.085}$$

RESULTS AND DISCUSSION

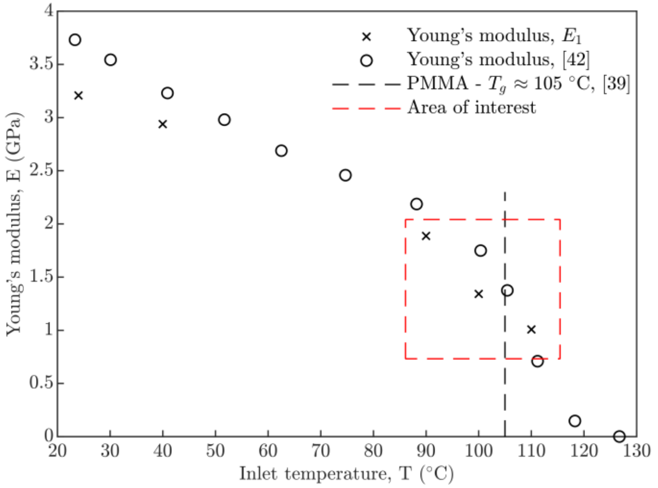
Q3 What is the contribution of the constitutive viscoelastic response of the material in the compliant contacts to the formation of fluid film thickness and contact shape changes in the TR region of EHL?



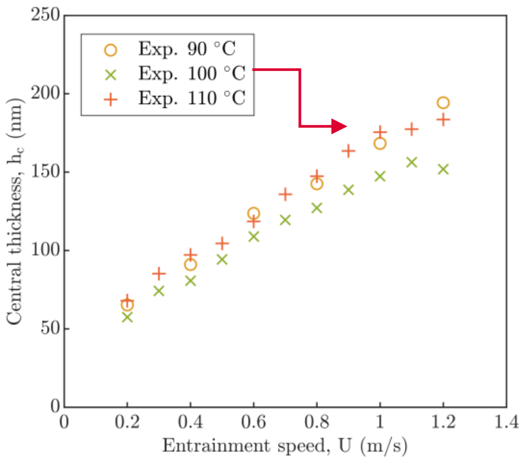
Temperature effect

"The increase in temperature will cause a significant decrease in material stiffness, and, consequently, in terms of the EHL theory, a shift from the TR region to the I-E mode of EHL, which will take effect by increasing the fluid-film thickness in the compliant contact."

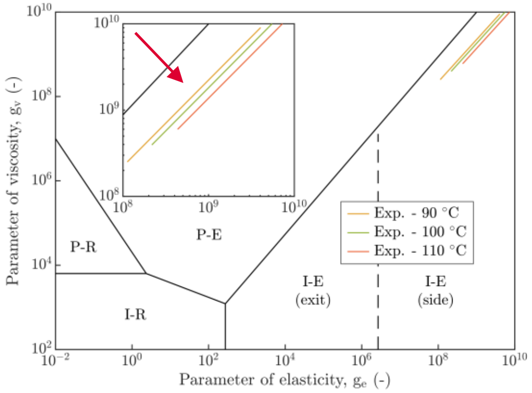
Elastic modulus of PMMA vs temperature



Central film thickness



Validation of EHL mode

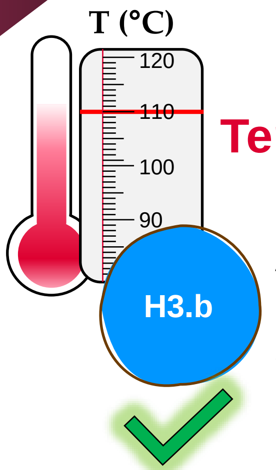


- Above T_g, increase of central thickness with temperature was discovered despite lubricant viscosity decrease → contact softening,
- Shift of contact operation region from TR to I-E mode of EHL as a function of temperature.

RESULTS AND DISCUSSION

Q3

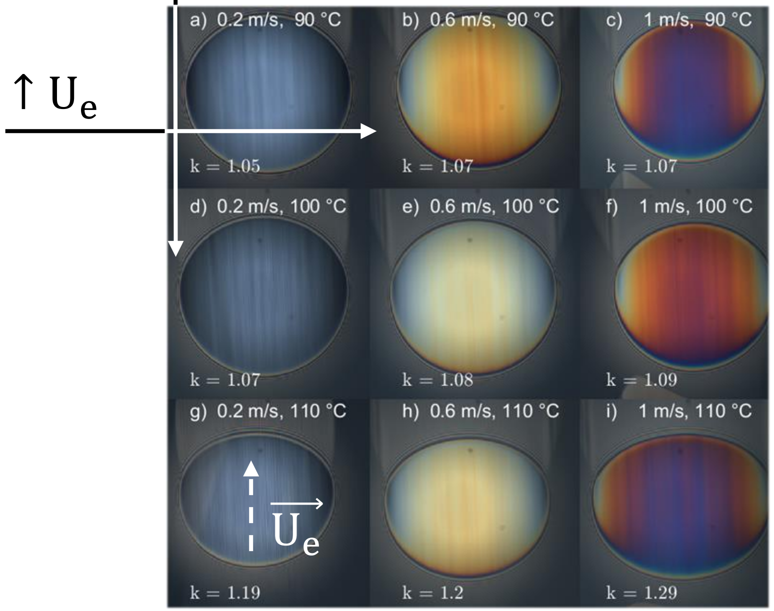
What is the contribution of the constitutive viscoelastic response of the material in the compliant contacts to the formation of fluid film thickness and contact shape changes in the TR region of EHL?



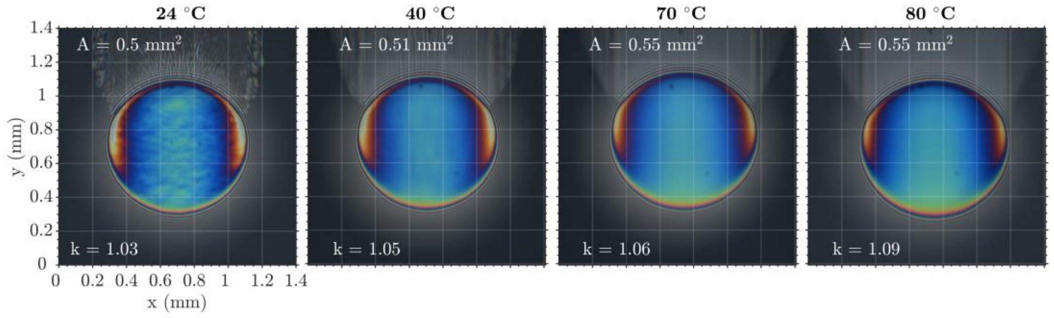
Temperature effect

"The temperature effect will be more critical for the conformational viscoelastic changes in the internal polymer structure influencing the contact shape rather than for possible defects by forming an unstable lubricant film and even above the Tg of solid material."

↑ T | **Contact shape – near and above T_g**



Contact shape – below T_g



- Anisotropic deformation of the contact with T prevalent in direction perpendicular to Ue,
- Running contact always dimensionally smaller relative to static contact,
- Below Tg, ellipticity of contact almost unchanged relative to the T and Ue,
- Above Tg → fully flooded conditions without film thickness defects,

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RESULTS AND DISCUSSION

Viscoelasticity effect

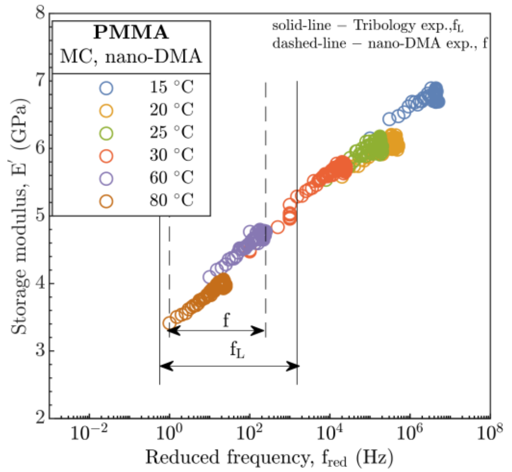
H3.c

"An increase in the loading frequency of the solid material, referred to as the entrainment speed in the EHL, will make the compliant contact much stiffer, resulting in a decrease in the fluid-film thickness, although this effect will weaken with increasing temperature."

Analysis of viscoelastic properties

- Nano-DMA experiments
- E*, E‘, E‘‘ and tan δ parameters
- Time-temperature superposition
- Generalized Maxwell model
- Relaxation modulus Er

Time-temperature superposition



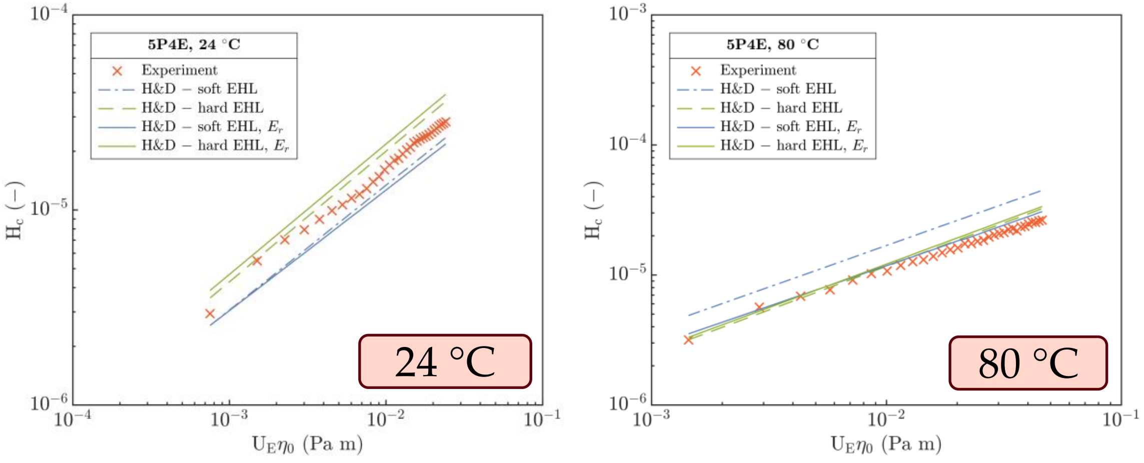
Analysis of film thickness

H&D – I-E and P-E models (substitution Er)

$$H_c = 7.32\left(1 - 0.72\ e^{-0.28k}\right)\overline{U}^{0.64}\ \overline{W}^{-0.22}$$

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

Experimental data vs H&D models



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CONCLUSION

General question Q

Q

Will a coherent lubricant film always be formed in compliant contacts, fully separating the rubbing surfaces?

A

The lubricant film always fully separated the rubbing surfaces despite the contact shape changes.

Impacted research papers 3 x

Main contributions of the thesis

- Identification of **fluid-film thickness** and **contact shape** changes in compliant contacts operating in the **TR region** of EHL.
- Implementation of the experimentally obtained **viscoelastic response** of the solid material and the **rheological response** of the lubricant into the **EHL models**.
- Experimental investigation of the film thickness in compliant EHL contacts operated near the **glass-transition temperature** by the **optical interferometry method.**

CONCLUSION

Journal papers with IF

A

- **KRUPKA**, **Jiri**, DOCKAL, Krystof, KRUPKA, Ivan and HARTL, Martin. Elastohydrodynamic Lubrication of Compliant Circular Contacts near Glass-Transition Temperature. Lubricants [online]. 13 July 2022. Vol. 10, no. 7, p. 155. DOI: 10.3390/lubricants10070155 **(PAPER A, IF = 3.5, Q2, Author's contribution 75 %)**

lubricants

2022

B

- **KRUPKA, Jiri**, DOCKAL, Krystof, KRUPKA, Ivan and HARTL, Martin. Polymer Lubrication: Pressure–Viscosity–Temperature Dependence of Film Thickness for Highly Loaded Compliant Contacts in Elastohydrodynamic Lubrication Regime. Journal of Tribology [online]. 1 February 2023. Vol. 145, no. 2. DOI: 10.1115/1.4055558 **(PAPER B, IF = 2.5, Q3, Author's contribution 75 %)**

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C

- **KRUPKA, Jiri**, DOCKAL, Krystof, SEDLACEK, Tomas, REBENDA, David, KRUPKA, Ivan and HARTL, Martin. Viscoelastic Response of Elastohydrodynamically Lubricated Compliant Contacts below Glass-Transition Temperature. Polymers [online]. 30 May 2023. Vol. 15, no. 11, p. 2528. DOI: 10.3390/polym15112528 **(PAPER C, IF = 5.0, Q1, Author's contribution 62 %)**

polymers

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THANK YOU FOR YOUR ATTENTION

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