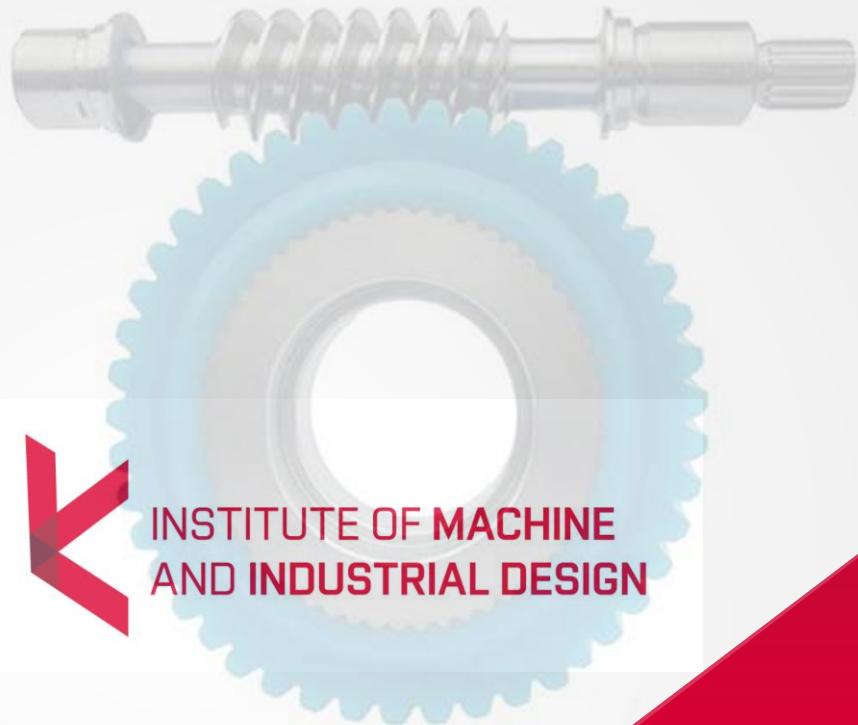


Development of film thickness in elastohydrodynamically lubricated compliant contacts

Ing. Jiří Křupka

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



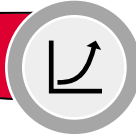
INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN

CONTENT

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

MOTIVATION

Commercial



- Expansion of polymer gears in mechanical engineering

Growth Rate by Region, 2023 – 2028



Source: Mordor Intelligence

Plastic gearbox market, Mordor intelligence (2023)

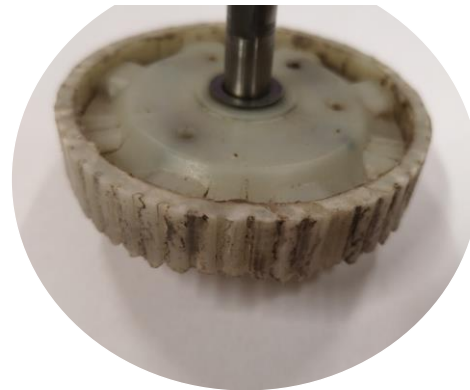


Perspectives

Engineering



- Prevention of the failure modes of polymer gears



Failure of polymer gear, Krupka (2019)

Scientific



- Increase of polymer gears performance under lubricated conditions

EHL

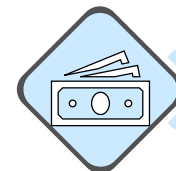


Tribological experiments, Krupka (2019)



Participation in scientific projects

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



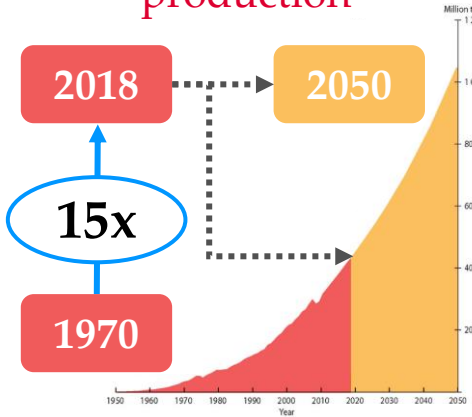
Project funding



INTRODUCTION

Plastics

Growth of plastics production



Plastic products examples



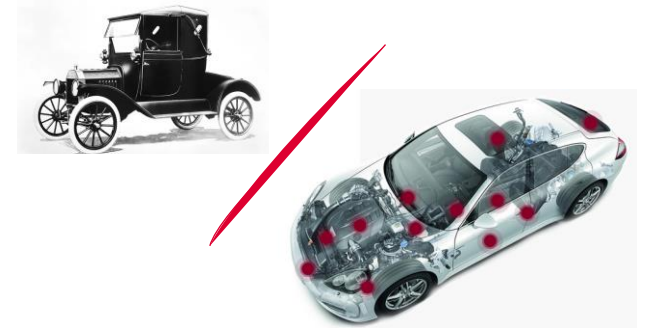
Polymer machine elements



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

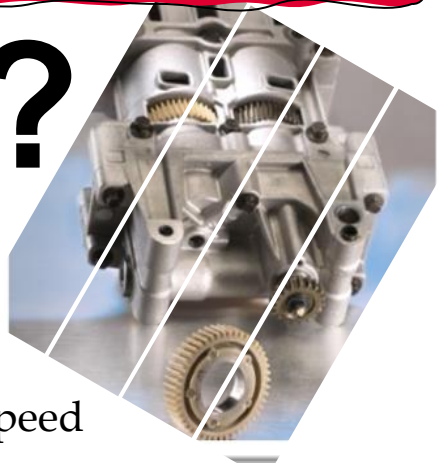
Applications

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



High-performance applications

Transmissions and differentials



High torque

temperature

speed

Lubrication



Dry conditions



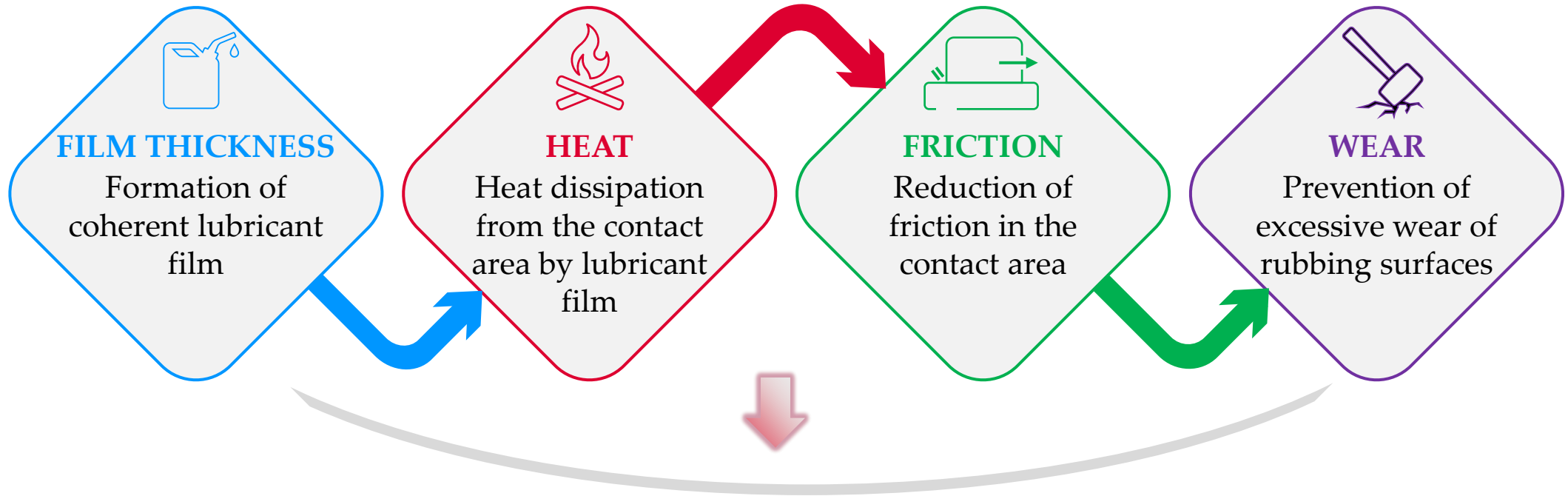
Grease lubrication



Liquid lubrication

Lubricant film thickness

INTRODUCTION



This section is divided into two parts:

- Applied research**: Represented by an icon of a brain and various symbols, indicating theoretical or computational research.
- Practical experiments**: Represented by an image of mechanical gears, indicating hands-on testing.

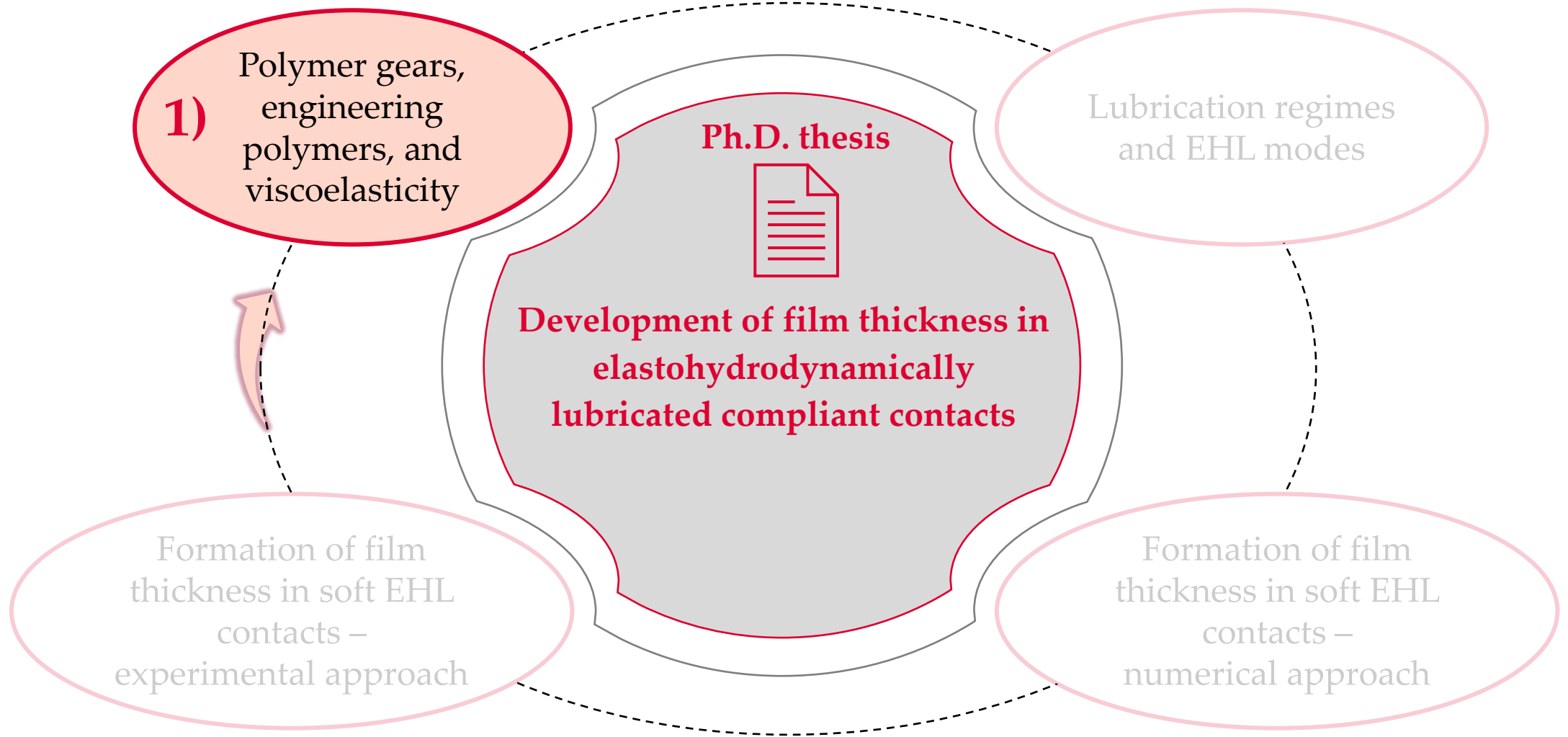
A pink arrow points from the Applied research icon to the Practical experiments image.

This section is enclosed in a red dashed border and contains two parts:

- Basic oriented research**: Represented by an icon of a person at a computer, indicating fundamental research.
- Laboratory experiments**: Represented by an icon of a mechanical component, indicating experimental work.

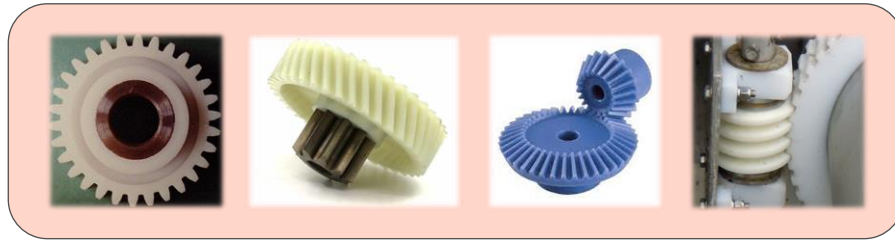
A pink arrow points from the Basic oriented research icon to the Laboratory experiments icon.

STATE OF THE ART



STATE OF THE ART

Polymer gears



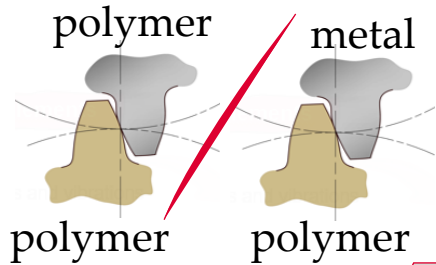
spur

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)

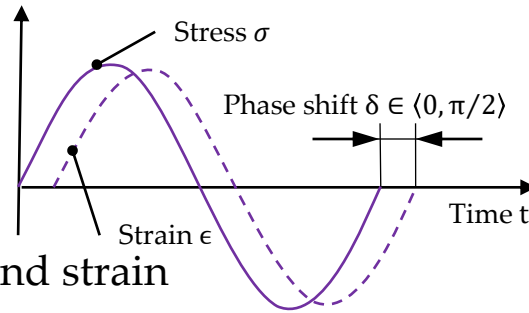
Tribological

Teflon (PFTE)
Molybdenum disulfide (MoS2)

STATE OF THE ART

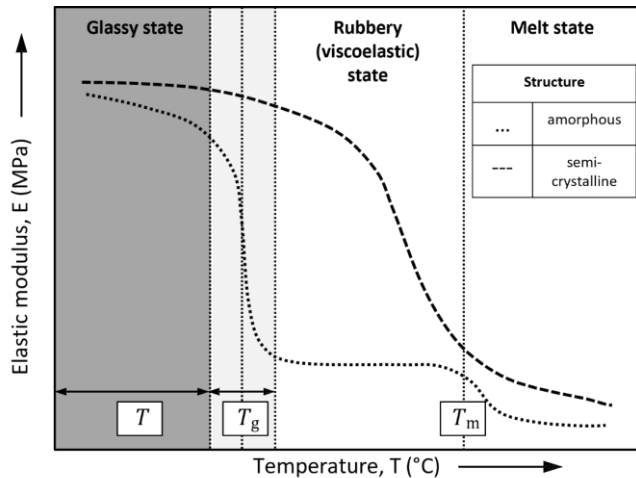
Viscoelasticity of polymers

- Inelastic response of material
- Time dependence between stress and strain
- Significant temperature dependence
- Glass-transition temperature, T_g →



Polymer states

Elastic modulus vs temperature



Glassy $\rightarrow T < T_g$

Rubbery $\rightarrow T \sim T_g$

Melt $\rightarrow T > T_g$

Macromolecular arrangement

Amorphous
(PC, PMMA)

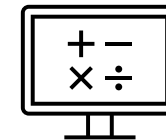
Semi-crystalline
(PA66, PEEK)

Crystalline



Determination of viscoelastic response

Numerical simulation

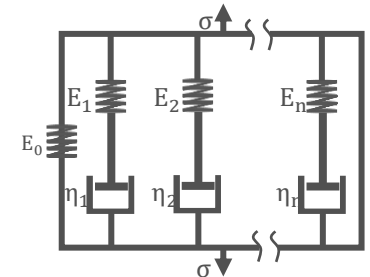


SLS and generalized models

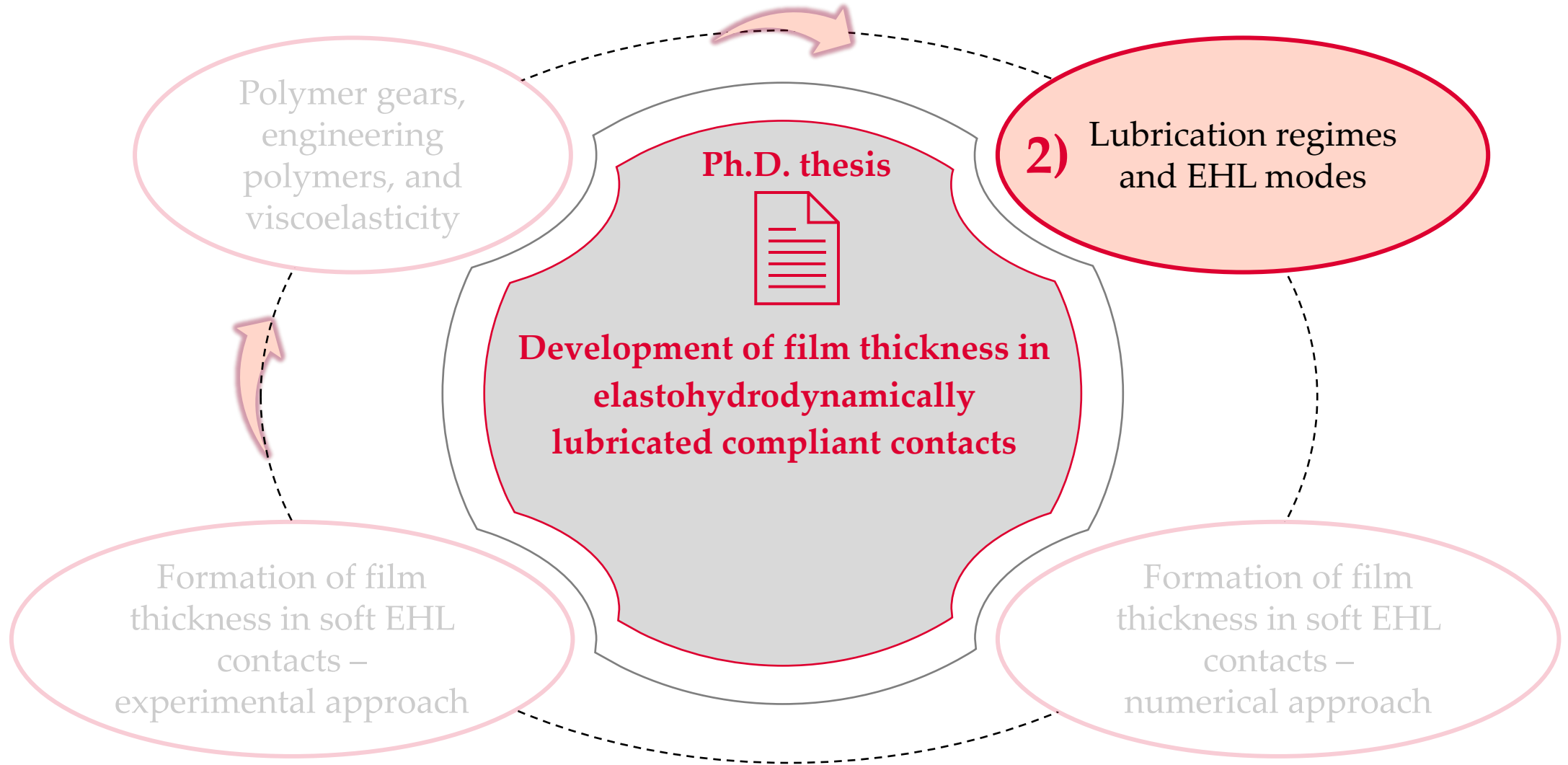
Experiments



Nano-DMA and DMA

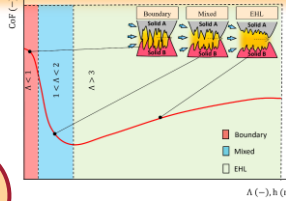


STATE OF THE ART



STATE OF THE ART

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



First findings about (hard) EHL

1950s

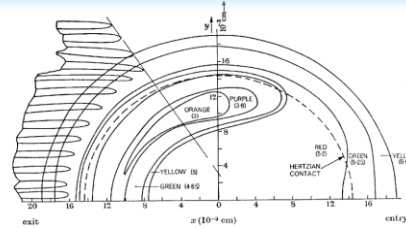
First use of engineering polymers

Intensive research in (hard) EHL

1960s

First use of polymer gears

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



DOWSON, D., 1967

First findings about (soft) EHL

1970s

Growth of polymers in engineering

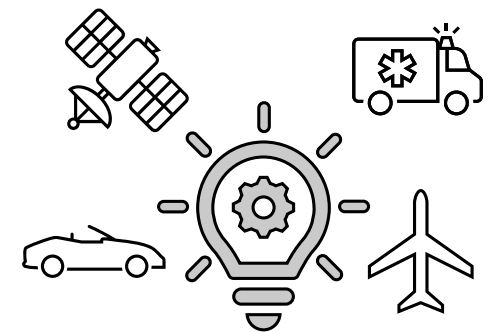
JOHNSON, K. L., 1970



Definition of EHL modes

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

JOHNSON, K. L., 1970



STATE OF THE ART

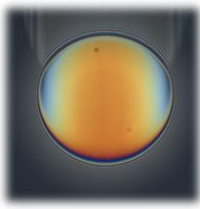
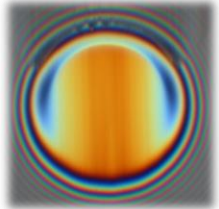
EHL modes

Piezoviscous-elastic (P-E)

Isoviscous-elastic (I-E)

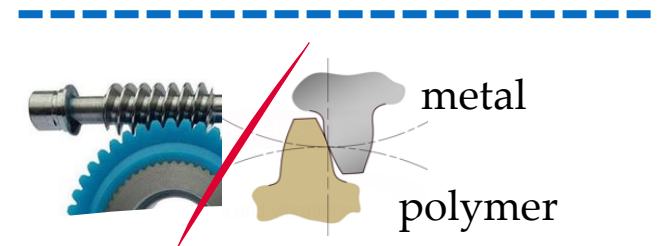
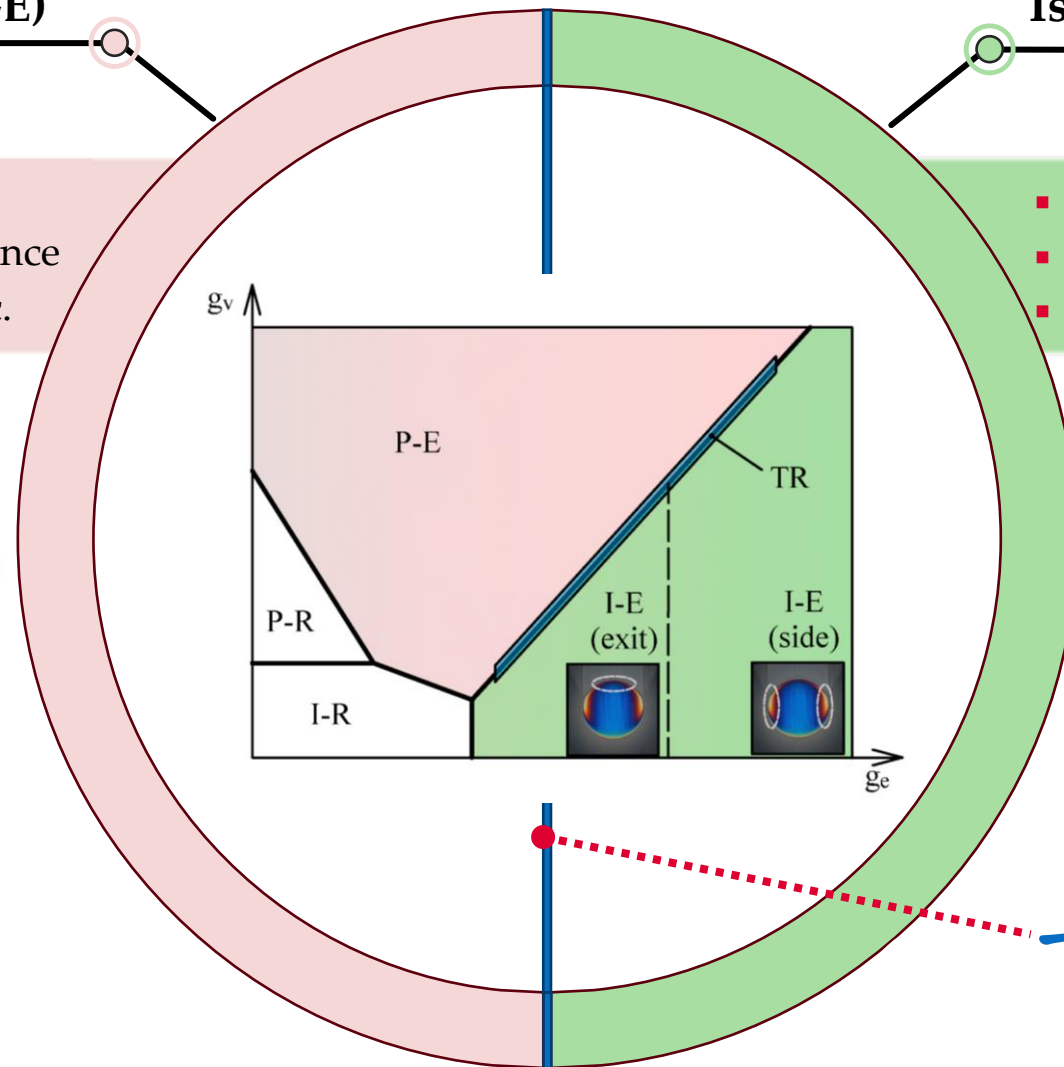
hard EHL

soft EHL



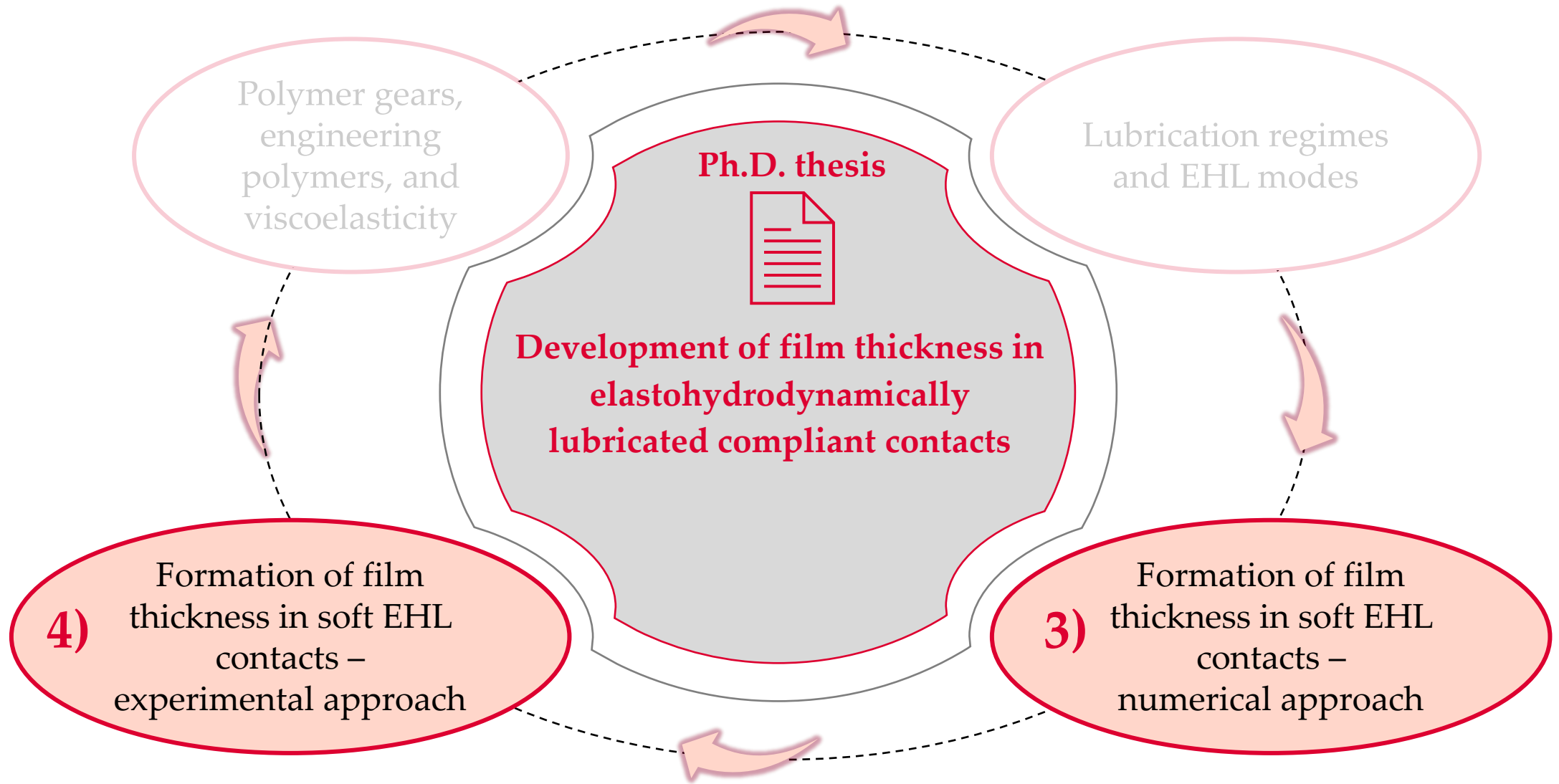
- $p = (0.5 - 4) \text{ GPa}$
- strong p - η dependence
- metals, ceramics etc.

- $p \leq 50 \text{ MPa}$
- 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 disc contacts
- Prediction of magnitude of film thickness
- Definition of parameters \bar{U} and \bar{W}

1980s

Esfahanian et al.

Hooke et al.

- Revisited EHL maps
- Circular and elliptical contacts

1990s

2000s

Myant et al.

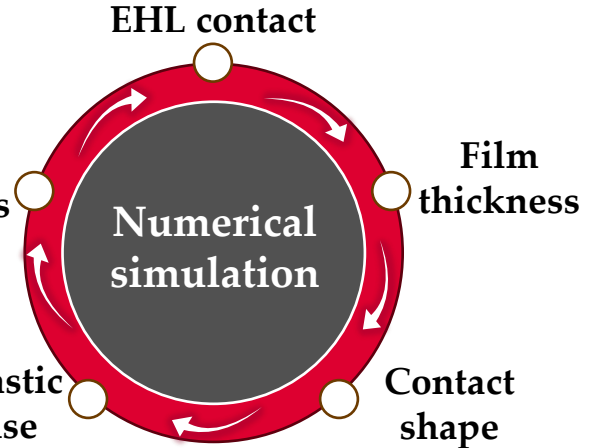
Gasni et al.

Stupkiewicz et al.

Marx et al.

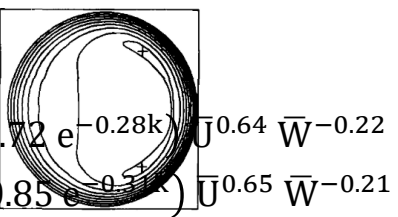
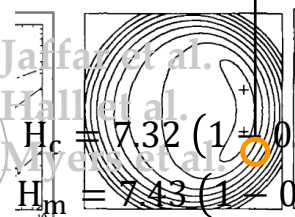
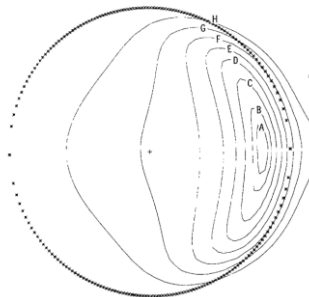
SLS models

Viscoelastic response



2020s

1970s



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

$$H_{im} = 7.43 (1 + 0.85 e^{-0.5k}) U^{0.65} W^{-0.21}$$

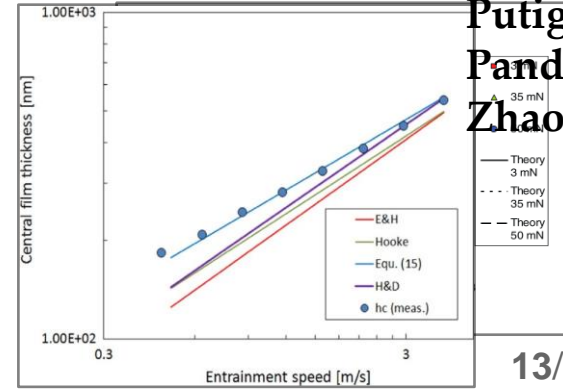
Exit

Side

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

2010s

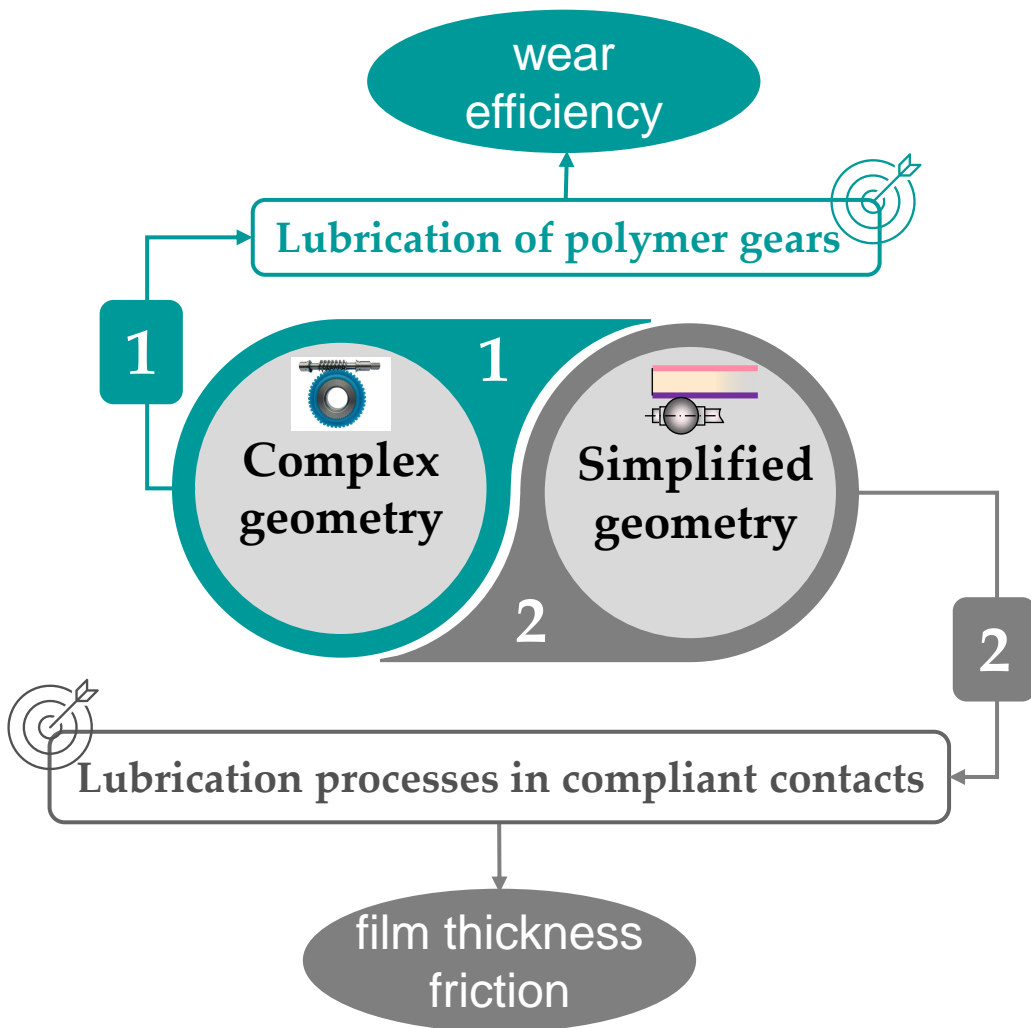
- Circular contact (steel/PEEK/PMMA/BK7 disc)
- Effect of W and SRR
- Chromatic interferometry



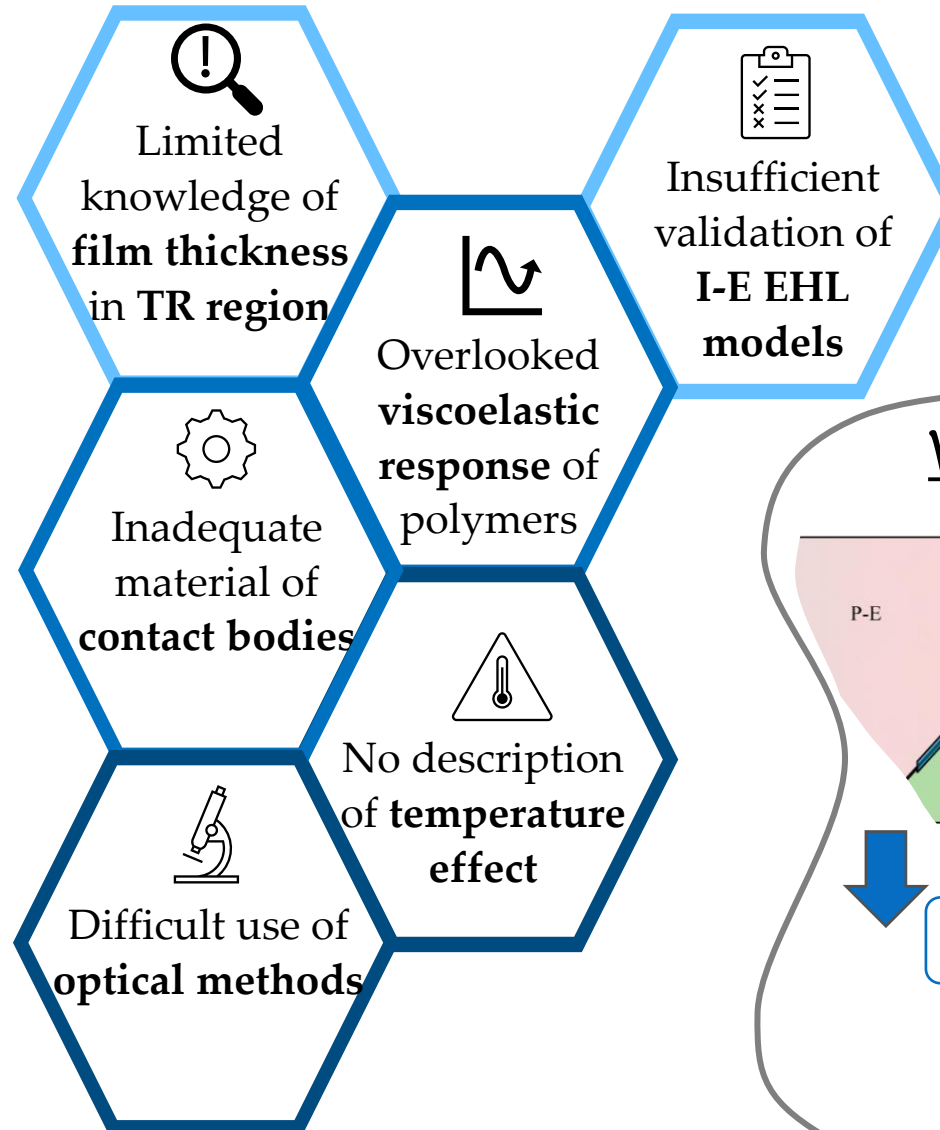
Putignano et al.
Pandey et al.
Zhao et al.

SUMMARY OF LITERATURE REVIEW

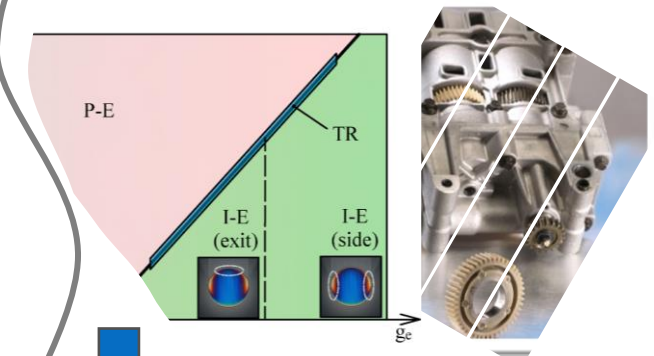
Compliant contacts



Shortcomings



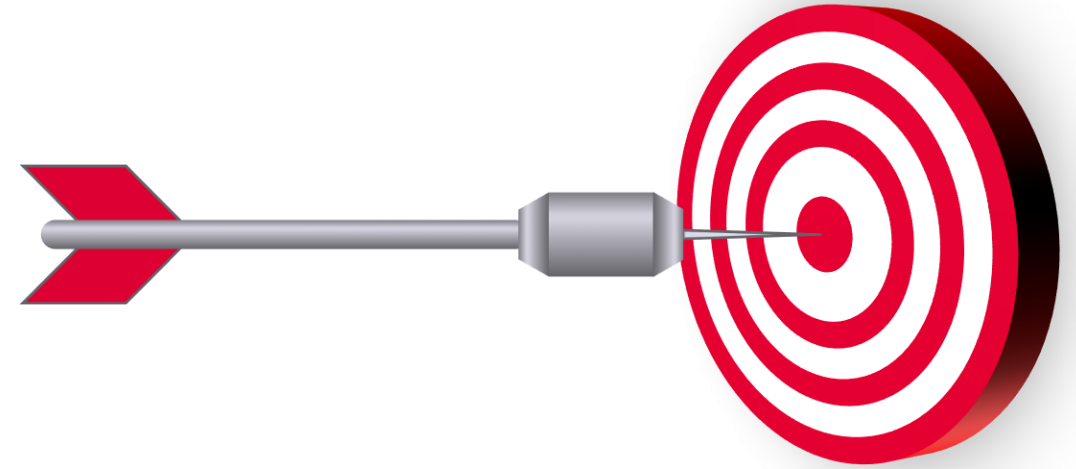
White space



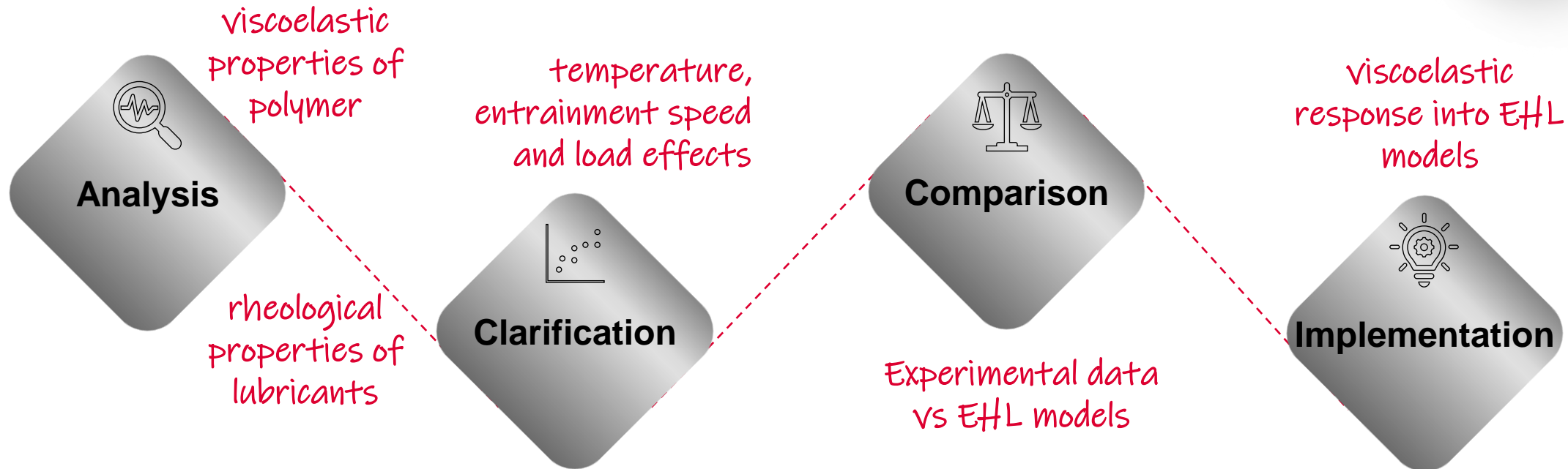
TR region of EHL

AIM OF THESIS

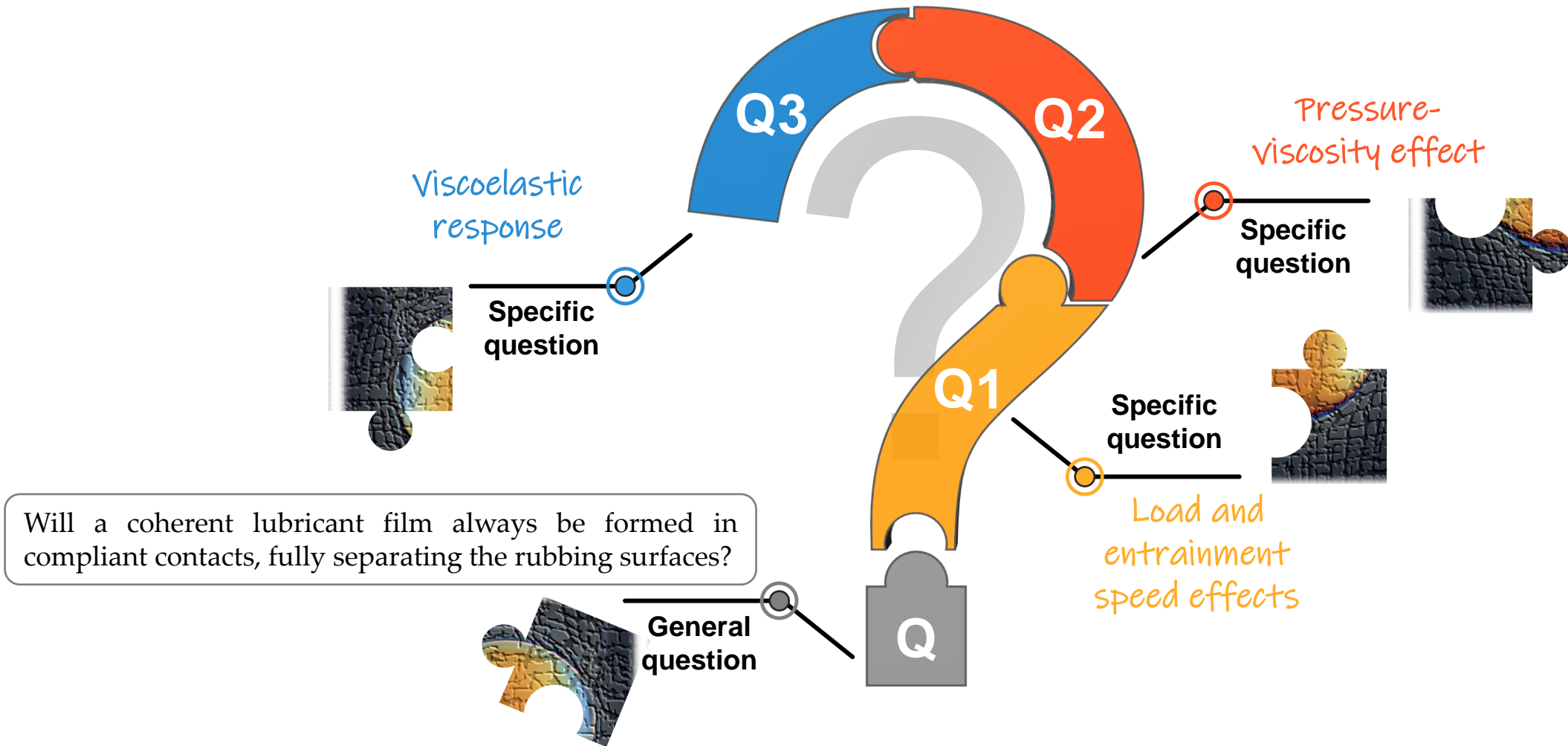
The main aim is to clarify the tribological behavior of the compliant contacts operating in the TR region between the I-E and P-E modes of EHL.



Sub-aims

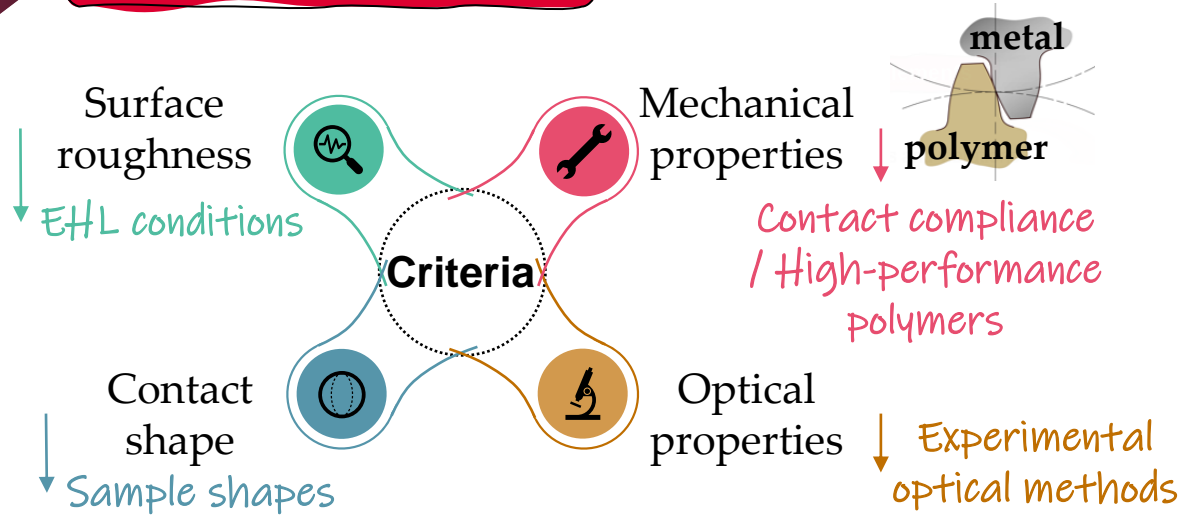


OVERVIEW OF SCIENTIFIC QUESTIONS



MATERIALS AND METHODS

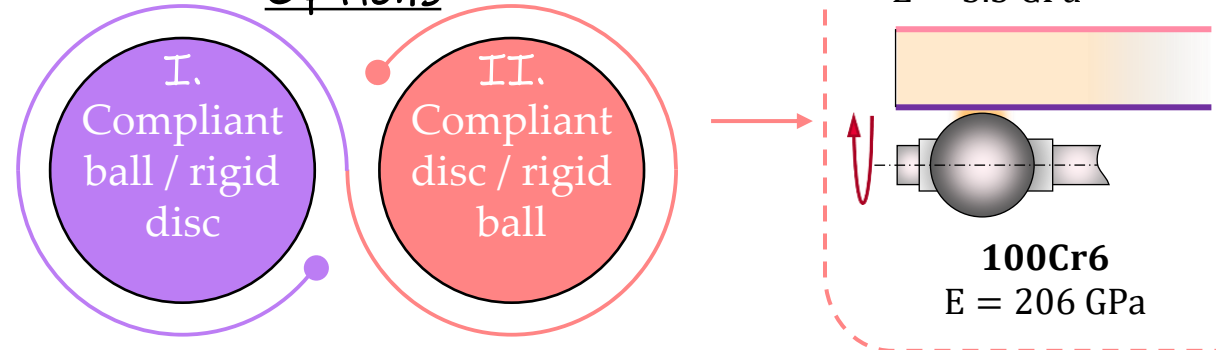
Selection of materials



Simulation of compliant contact

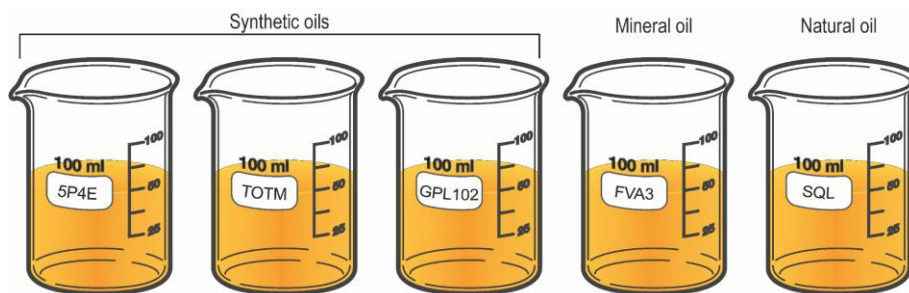
- Amorphous or semi-crystalline polymer
- Circular contact shape

Options



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 ($^{\circ}\text{C}$)	22 – 130
Dynamic viscosity at 40 $^{\circ}\text{C}$, η (Pa s)	0.0157 – 0.37
Pressure-viscosity coefficient at 40 $^{\circ}\text{C}$, 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



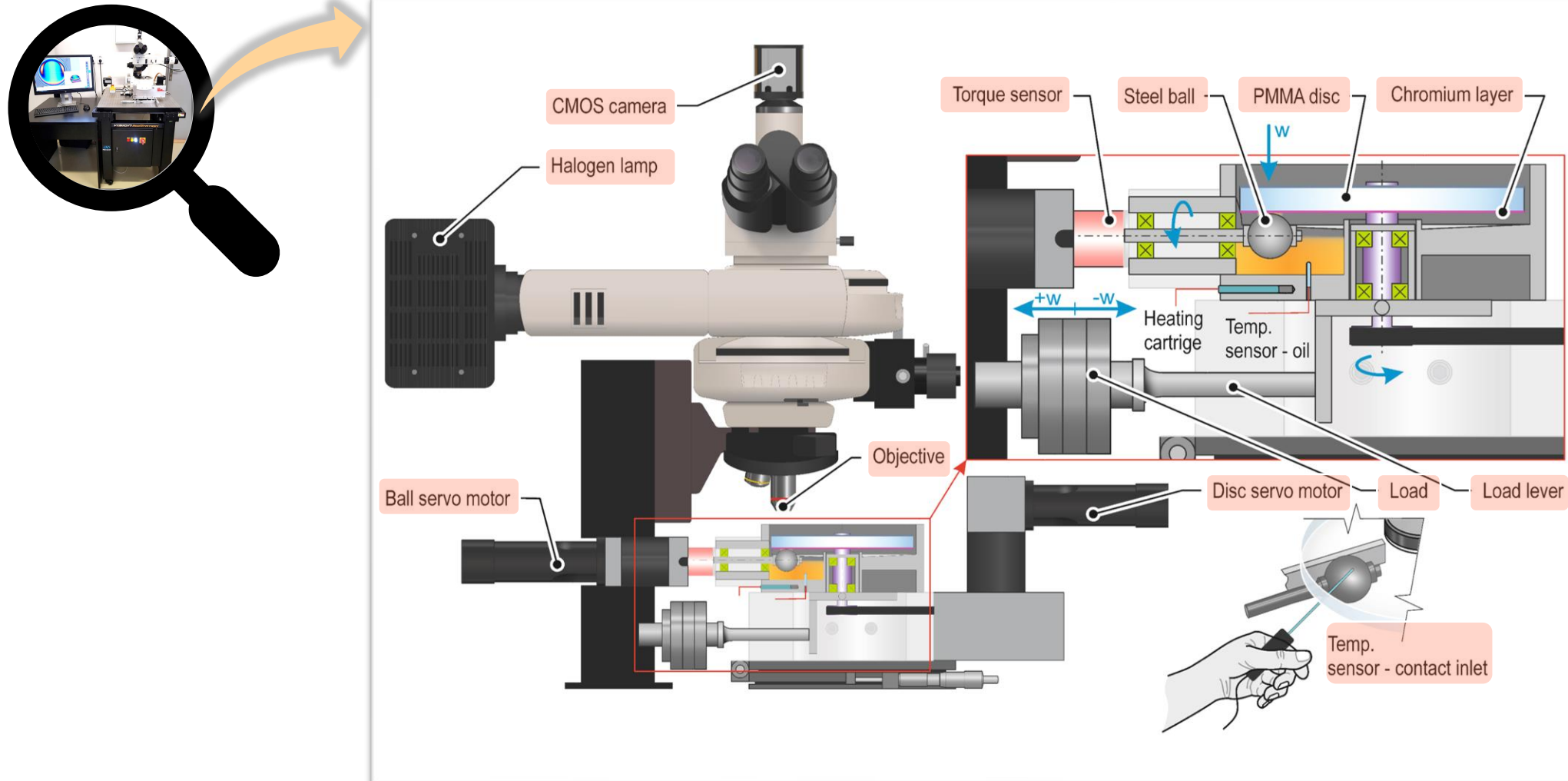
Nano-DMA analysis

Hysitron TI Premier Nanoindenter

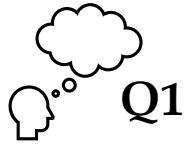


MATERIALS AND METHODS

Rotational optical tribometer



RESULTS AND DISCUSSION



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?

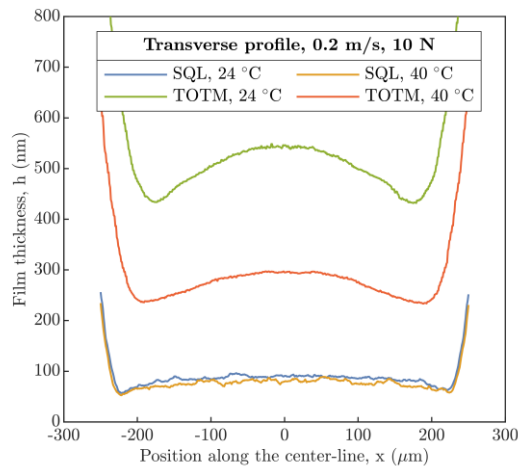
Load effect – below T_g

H1.a

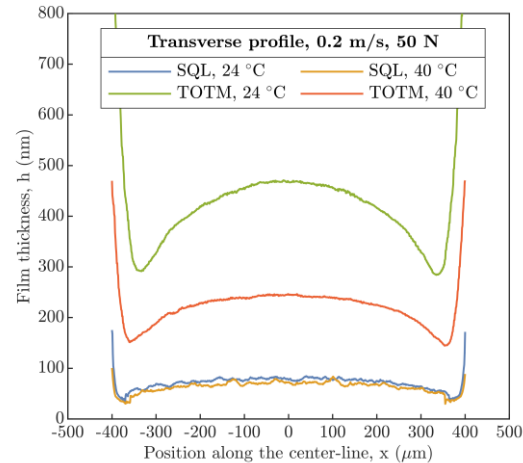
“The effect of load will be significantly dependent on the operating temperature below T_g , where the load-dependent behavior of the film thickness will be manifested.”



Film shape – transverse profiles

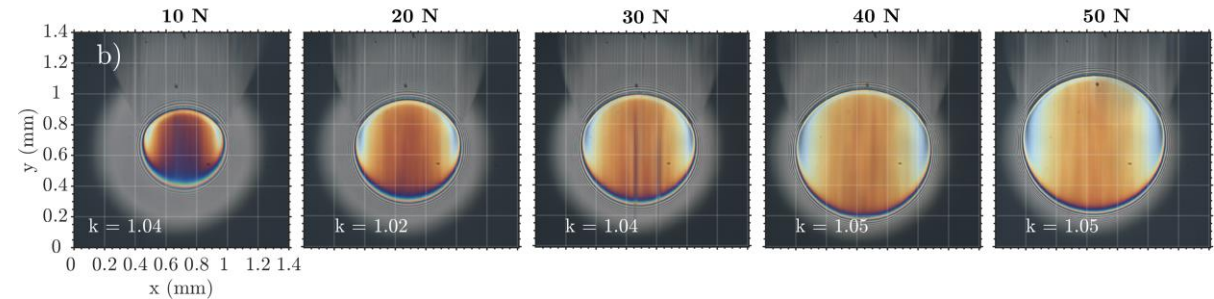


10 N



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.

RESULTS AND DISCUSSION



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?

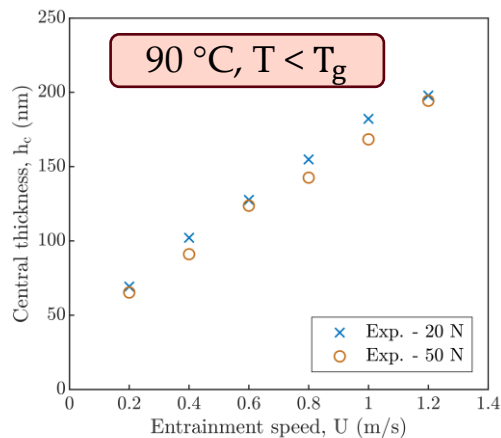
Load effect – above T_g (PMMA $T_g \sim 105^\circ\text{C}$)

H1.b

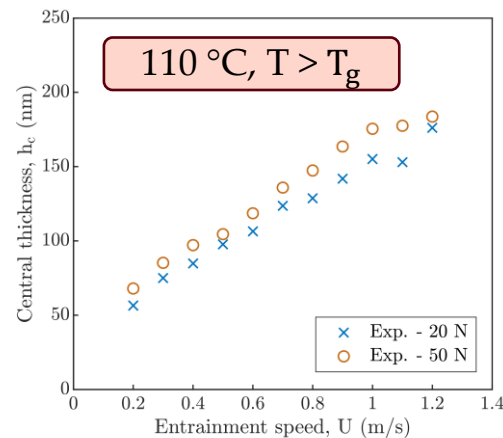
“Near and above T_g , the load-dependent behavior of the fluid-film thickness will be negligible although a significant increase in the contact area and asymmetric deformation of the contact shape will be exhibited.”



Central film thickness

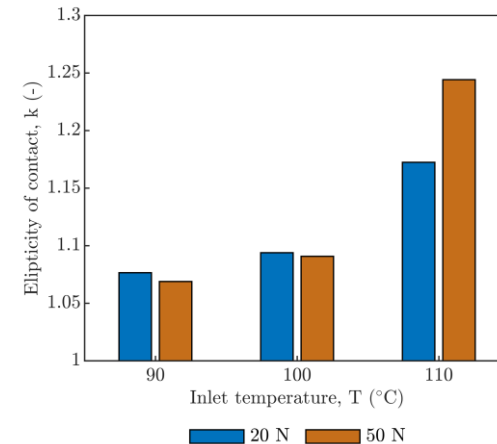


(a)

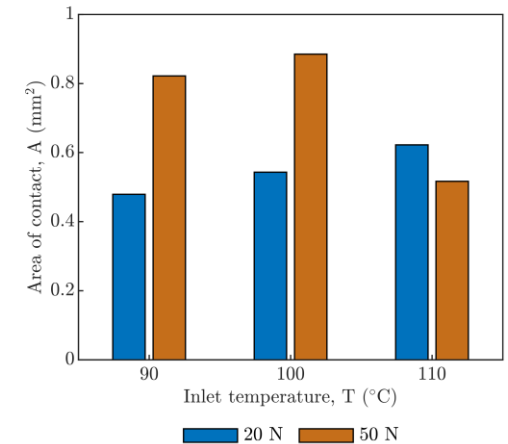


(b)

Ellipticity



Contact area



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

RESULTS AND DISCUSSION



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?

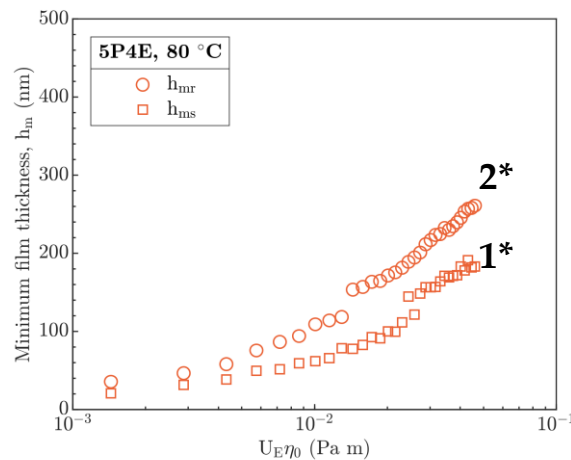
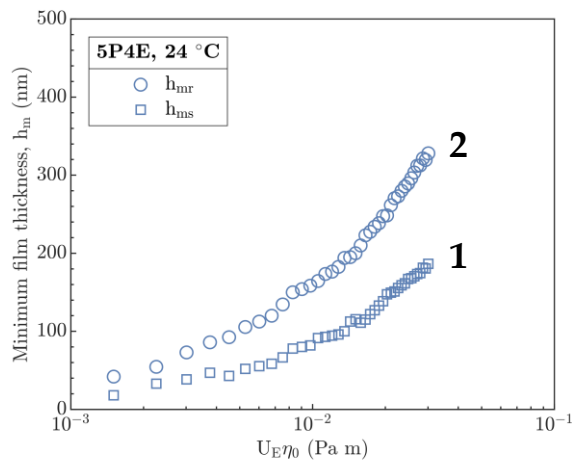
Entrainment speed effect

H1.c

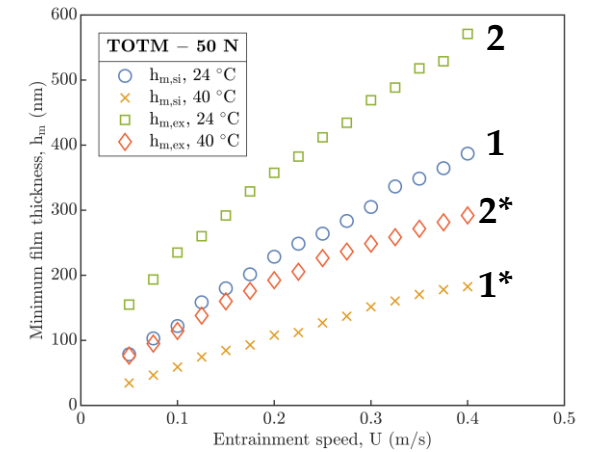
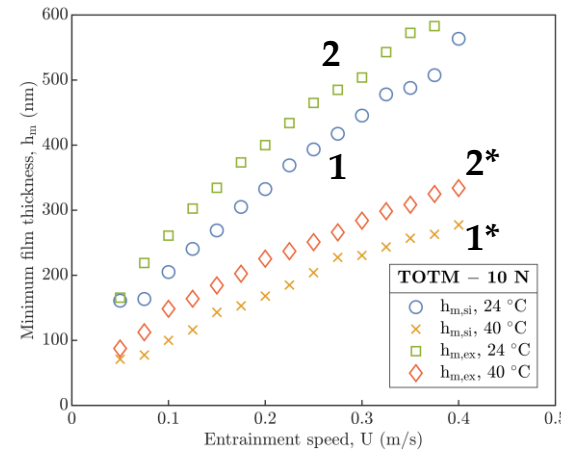
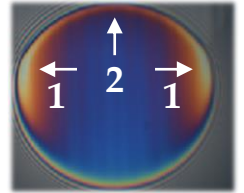
“The increase of the entrainment speed will cause a transition of minimum film thickness from the side lobes to the exit of the contact. However, the shape of the compliant contact will be only slightly affected.”



Minimum film thickness – 5P4E

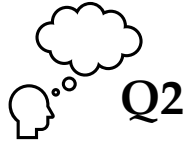


Minimum film thickness – TOTM



- 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 $U_e \rightarrow$ minimum at the side lobes.

RESULTS AND DISCUSSION



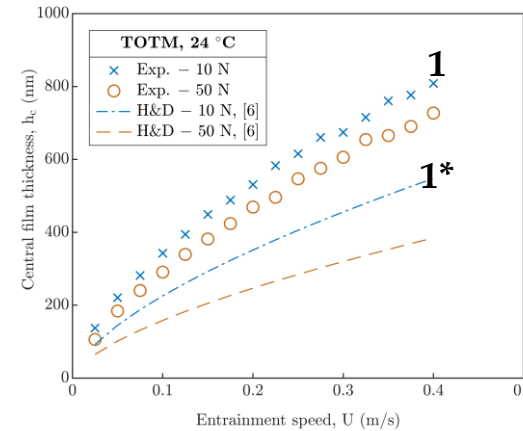
How the rheological response of the lubricant contributes to the formation of the fluid-film thickness in the TR region of the EHL, considering a different effect in the I-E and P-E modes of the EHL?

Pressure-viscosity effect

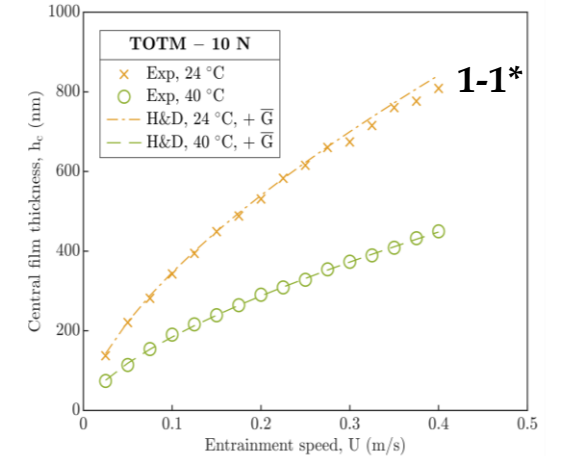


"In accordance with the EHL theory, the pressure-viscosity response of the lubricant to the formation of the fluid film thickness is usually neglected in the I-E mode of EHL. However, this effect will be more significant in the TR region than in the I-E mode."

hc – H&D I-E



hc – H&D I-E + \bar{G}



TOTM

Rheological exp.

$\eta - p$

PV coef. α

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

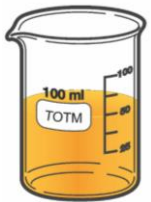
Film thickness exp.

Data regression

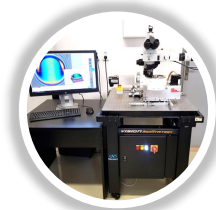
H&D I-E + \bar{G}

- P-E $\rightarrow x = 0.53$
- I-E $\rightarrow x = 0$
- TR $\rightarrow x = 0.084$

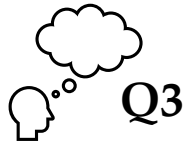
h_c



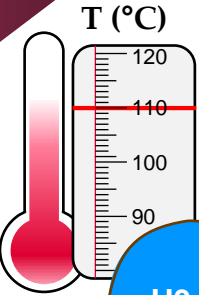
(measured by Ing. Polnicky)



RESULTS AND DISCUSSION



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?



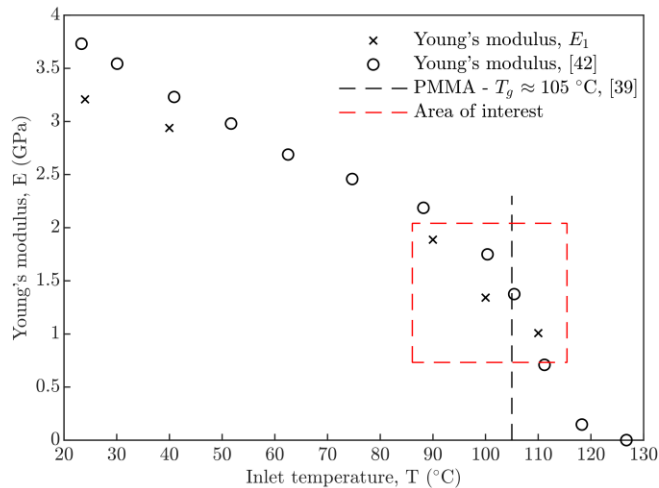
Temperature effect

H3.a

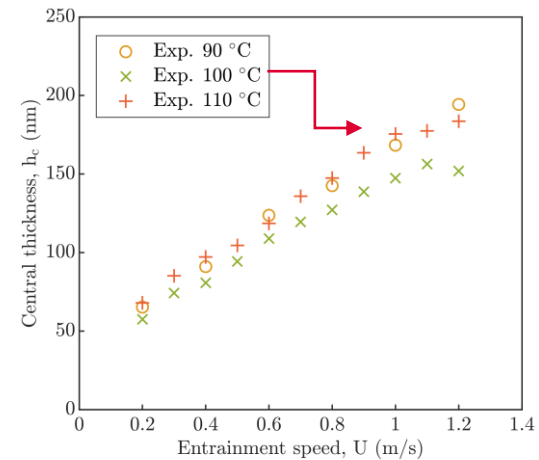
"The increase in temperature will cause a significant decrease in material stiffness, and, consequently, in terms of the EHL theory, a shift from the TR region to the I-E mode of EHL, which will take effect by increasing the fluid-film thickness in the compliant contact."



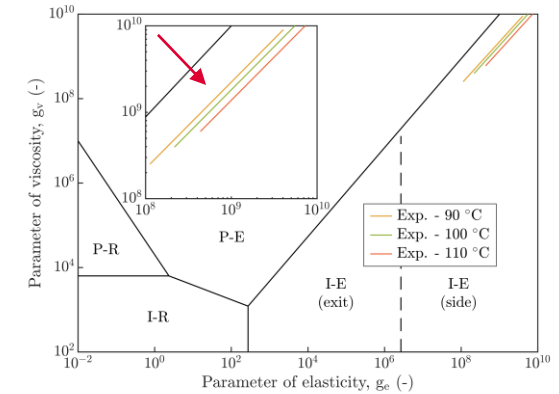
Elastic modulus of PMMA vs temperature



Central film thickness



Validation of EHL mode

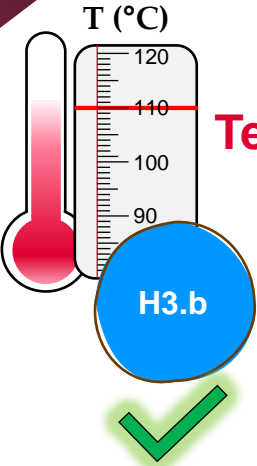


- Above T_g , increase of central thickness with temperature was discovered despite lubricant viscosity decrease \rightarrow contact softening,
- Shift of contact operation region from TR to I-E mode of EHL as a function of temperature.

RESULTS AND DISCUSSION



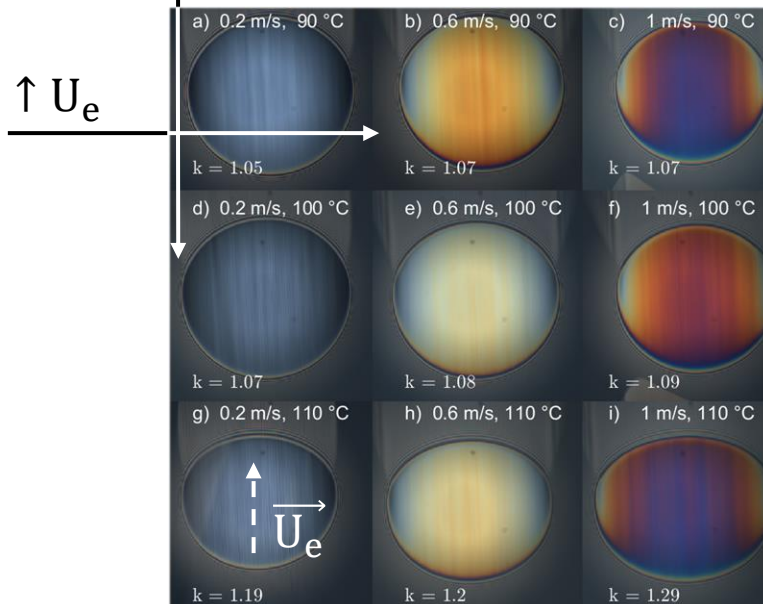
What is the contribution of the constitutive viscoelastic response of the material in the compliant contacts to the formation of fluid film thickness and contact shape changes in the TR region of EHL?



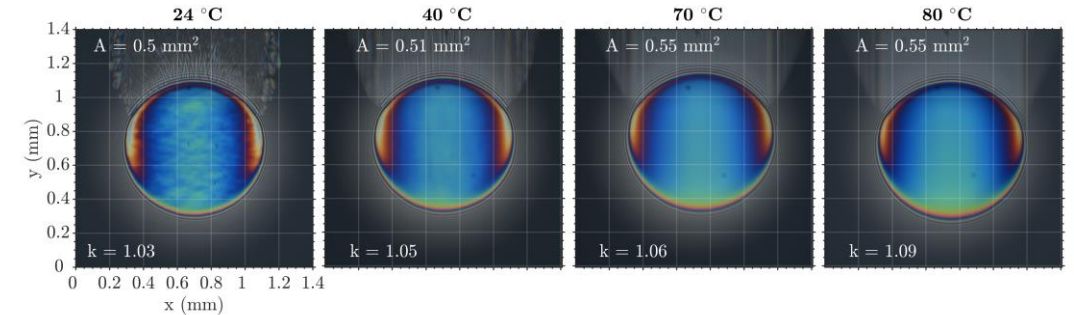
Temperature effect

“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 T_g 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 perpendicular direction to U_e ,
- Running contact is always dimensionally smaller relative to static contact,
- Below T_g , ellipticity of contact is almost unchanged relative to the T and U_e ,
- Above T_g → fully flooded conditions without film thickness defects,

RESULTS AND DISCUSSION

Viscoelasticity effect



"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 $\tan \delta$ parameters
- Time-temperature superposition
- Generalized Maxwell model
- Relaxation modulus E_r

Analysis of film thickness

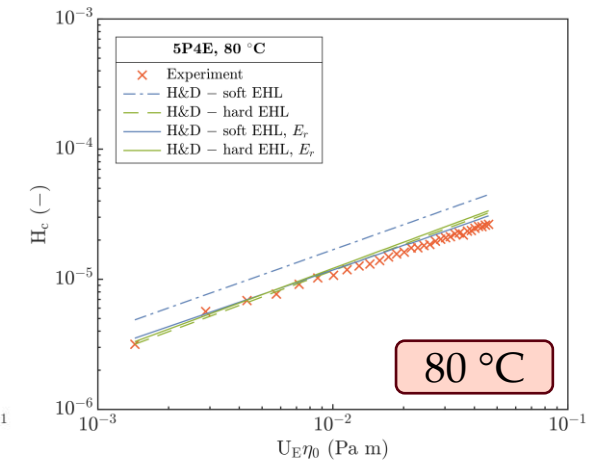
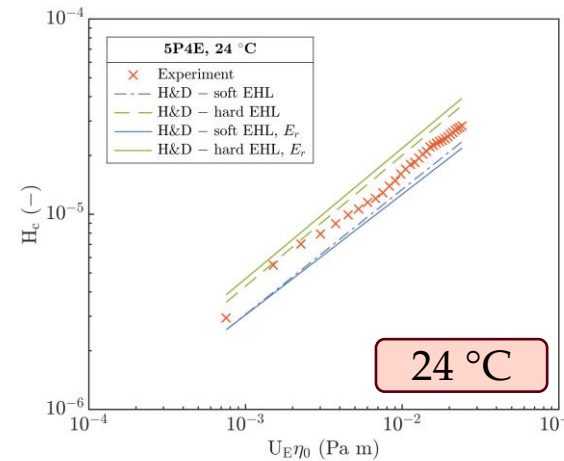
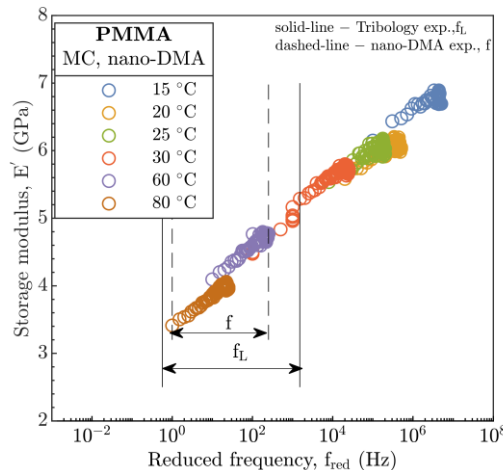
H&D – I-E and P-E models (substitution E_r)

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

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

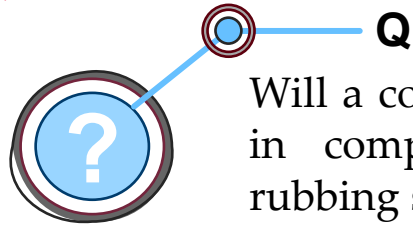
Experimental data vs H&D models

Time-temperature superposition



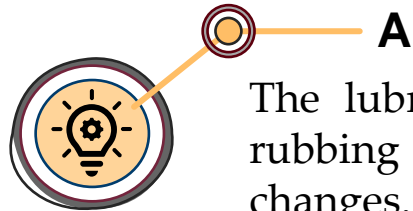
CONCLUSION

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 %**)



2022

- 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

2023

THANK YOU FOR YOUR ATTENTION



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Replies to Prof. Glovnea's comments and questions

" The research questions are complemented by a number of hypotheses; In my view these are too many. It also looks like some of these hypotheses end with a phrase which is rather a conclusion not a hypothesis (e.g., H1c, H2 and H3a). "

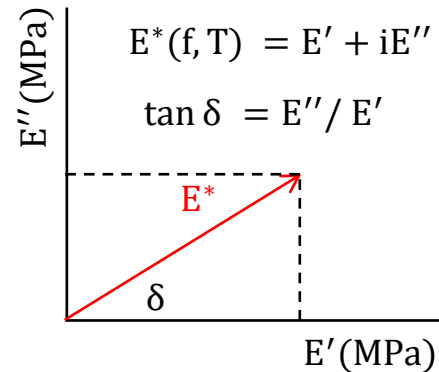
- I agree with this comment, because today I clearly see that some of my steps during my research may have been arranged and formulated differently. I am fully aware of it, and this also motivates me to do it better in my future research work.

Replies to Prof. Glovnea's comments and questions

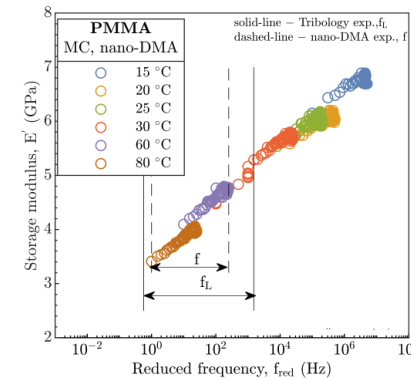
" Hypothesis H3c states: "An increase in the loading frequency of the solid material, referred to as the entrainment speed in the EHL..". This is new to me and I cannot see how loading frequency can be defined and entrainment speed; it is needs clarifications. "

Viscoelastic response

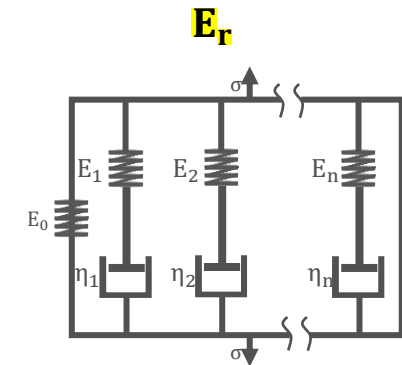
- f – loading frequency
- T – temperature
- E' – storage modulus → elastic part
- E'' – loss modulus → viscous part
- $\tan \delta$ – damping factor



Time-temperature superposition

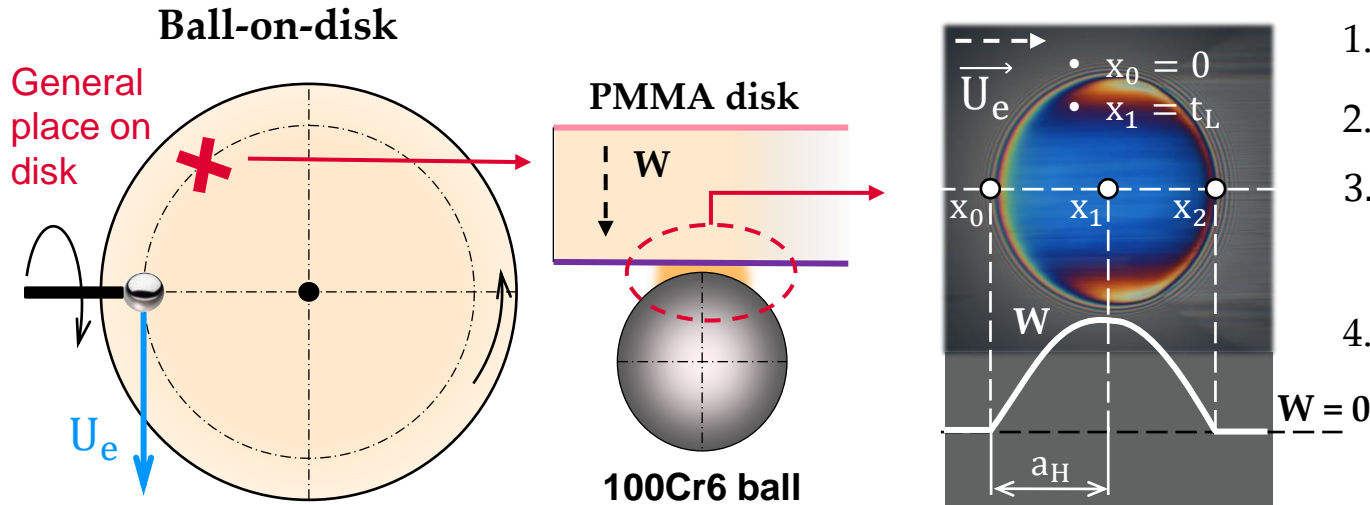


Maxwell model – relaxation modulus



Replies to Prof. Glovnea's comments and questions

" Hypothesis H3c states: "An increase in the loading frequency of the solid material, referred to as the entrainment speed in the EHL..". This is new to me and I cannot see how loading frequency can be defined and entrainment speed; it is needs clarifications. "

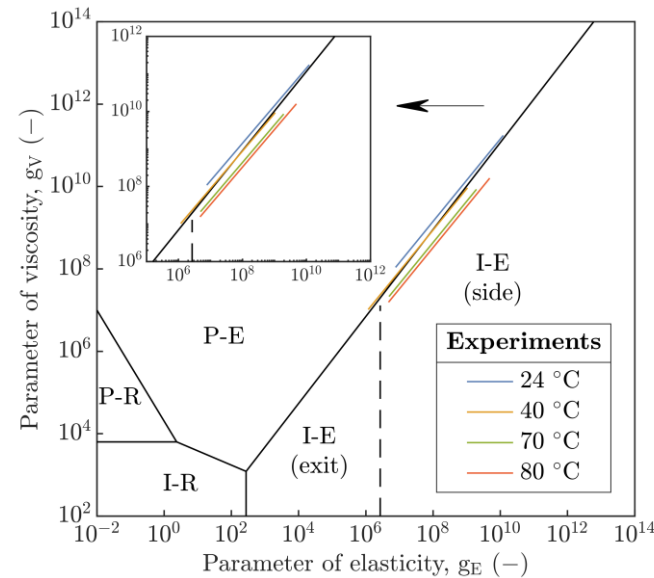
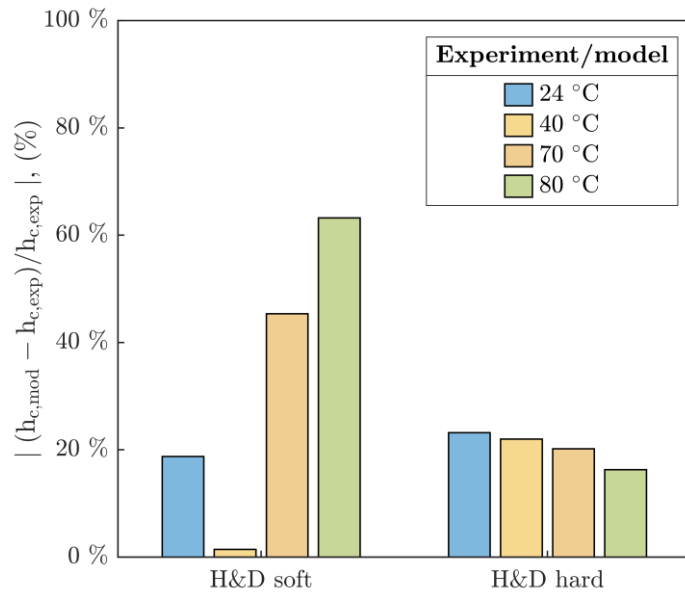


1. Loading frequency $f_L = \frac{U_e}{a_H}$, $\rightarrow t_L = \frac{1}{f_L}$
2. Relaxation modulus $E_r(t_L, T)$ of PMMA – Maxwell model
3. Substitution of E_r to formula of reduced modulus E_R – EHL
 - $2/E_R = (1 - \nu_1^2)/E_1 + (1 - \nu_2^2)/E_r$
4. Calculation of film thickness – I-E H&D formula $\rightarrow \bar{U}, \bar{W}$
 - $H_c = 7.32 (1 - 0.72 e^{-0.28k}) \bar{U}^{0.64} \bar{W}^{-0.22}$

Replies to Prof. Fillot's comments and questions

" In some configurations, film thickness results are in good agreement with hard-EHL usual prediction formulae. This is surprising since polymer surfaces are considered above glass transition temperature where the viscoelastic behaviour should be dominant. "

- The agreement of the measured data to the hard model corresponds to the assumed operation of the contact close to the transition between I-E and P-E modes of EHL according to the EHL map where the mixed behavior corresponding to both EHL modes can be expected. Due to a significant difference to the soft model, there was an effort to include the viscoelastic response of the polymer.



Replies to Prof. Fillot's comments and questions

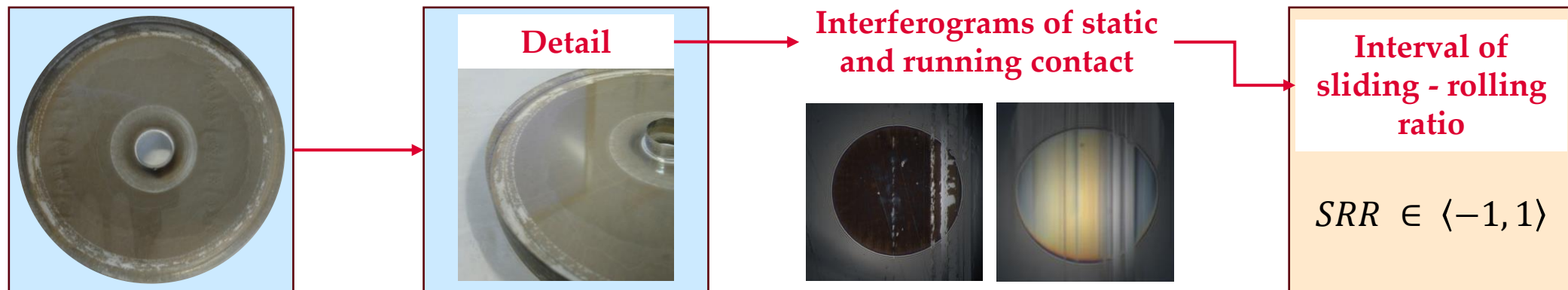
" It is mentioned that the slide-to-roll ratio (SRR) has almost no effect on film thickness, except at pure sliding, where the film thickness expectedly decreases. But the thermal effects that may be the cause of this result could be investigated deeper. For example, do we expect a difference between PMMA disc at rest or steel ball at rest (i.e. SRR = +2 or -2) ? Heat transfers in the solid at rest would be probably very different between these two situations "

- The first is the focus of my doctoral thesis, which dealt with the lubrication of compliant contacts with reference to practical applications, especially to polymer gears. Under these conditions, pure sliding conditions generally do not occur despite the partial sliding-rolling (SRR = $\pm 50\%$) during the gear mesh along the pressure line with the exception of the pitch point, where SRR = 0.

Replies to Prof. Fillot's comments and questions

" It is mentioned that the slide-to-roll ratio (SRR) has almost no effect on film thickness, except at pure sliding, where the film thickness expectedly decreases. But the thermal effects that may be the cause of this result could be investigated deeper. For example, do we expect a difference between PMMA disc at rest or steel ball at rest (i.e. SRR = +2 or -2) ? Heat transfers in the solid at rest would be probably very different between these two situations "

Degradation of Cr layer deposited on PMMA disc by SRR



- The second and more significant reason was due to the experimental limitations related to the contact between the PMMA disc and steel ball under SRR conditions. In terms of optical interferometry, a semi-reflective Cr layer was applied to the bottom side of the PMMA disc to enhance light interference.
- With increase in SRR, this layer was significantly damaged and gradually wiped off the disc surface. As a result, measuring and evaluating the film thickness became almost impossible.