



# Liquid Lubrication

Rowena Crockett, Empa,  
Switzerland  
CCMX Summer School, Visp 2025

## Part 1. Fluid film lubrication

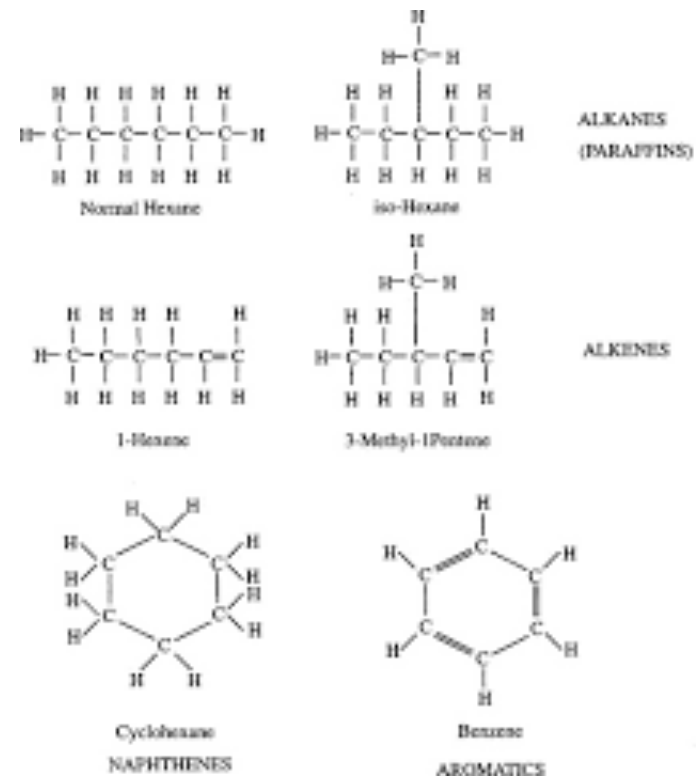
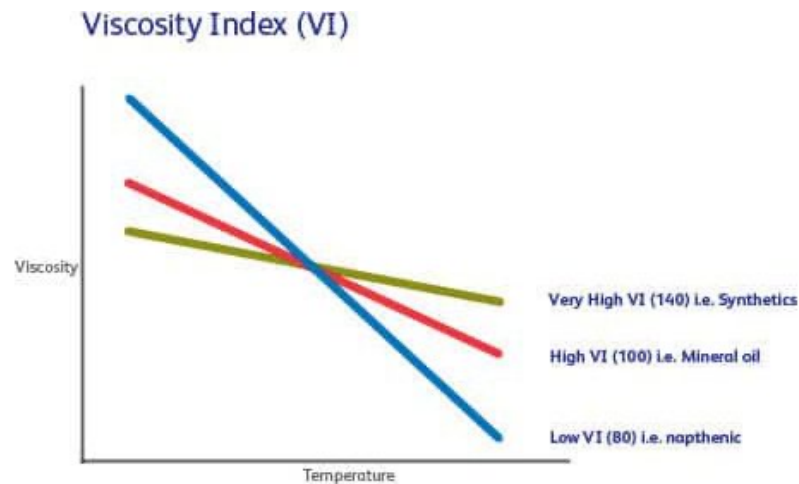
- Base oil
- Stribeck Curve
- The fluid film
- Slip: influence of the surface
- Greases
- Waterbased lubrication

## Part 2. Boundary lubrication

- Wear protection and friction reduction
- Competition for surface coverage
- Stick-slip
- Seals

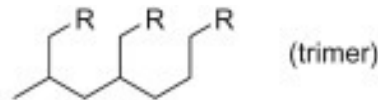
# Mineral base oils

- Paraffinic mineral oil: high viscosity, good viscosity-temperature behaviour (VI = 100)
- Naphthenic mineral oil: Medium viscosity, medium viscosity-temperature behaviour (VI = 0)
- Aromatic mineral oil: Low viscosity, poor viscosity-temperature behaviour

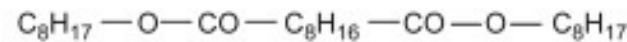


# Synthetic Base Oils

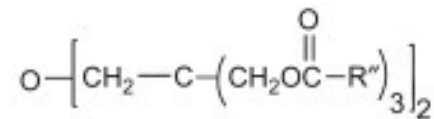
Polyalphaolefine (PAO)



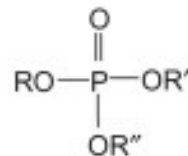
Diester und Polyester



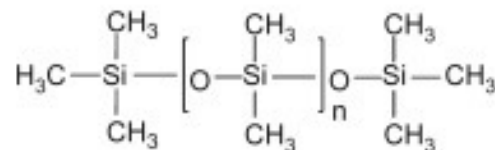
Pentaerythritolester



Phosphate ester



Silicon oil

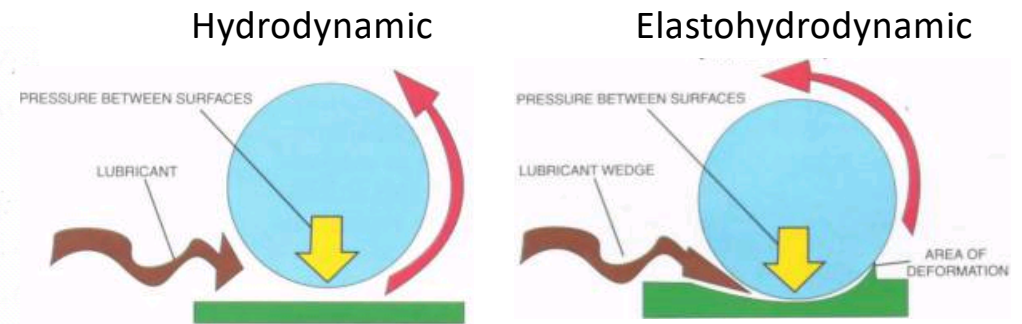
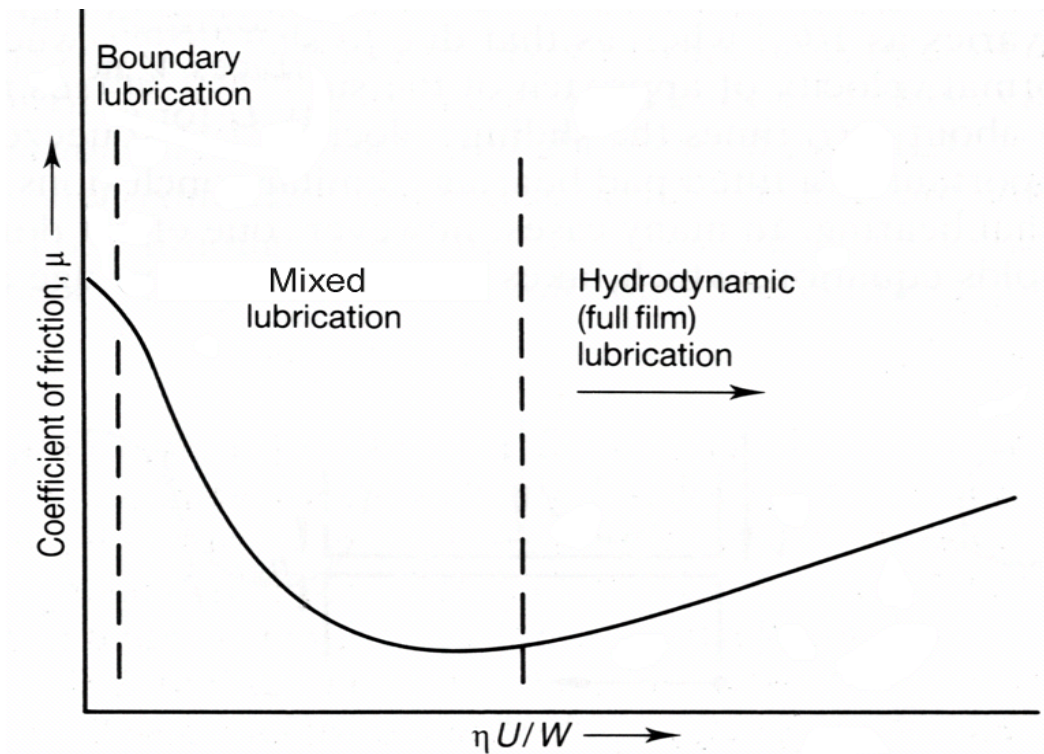


- + High VI, high thermal oxidative stability, low volatility, good flow properties at low temperatures, Nontoxic
- Limited biodegradability, limited additive solubility, poor seal compatibility

- + Fire-resistant, biodegrades quickly, excellent wear resistance, scuffing protection
- Low VI, limited seal compatibility, not miscible with mineral oils, moderate hydrolytic stability

- + Highest VI, high chemical stability, excellent seal compatibility, very poor thermal and oxidative stability.
- Worst mixed and boundary film lubrication properties, not miscible with mineral oils or additives

# Stribeck Curve: A tool to describe the friction behavior of a liquid lubricant

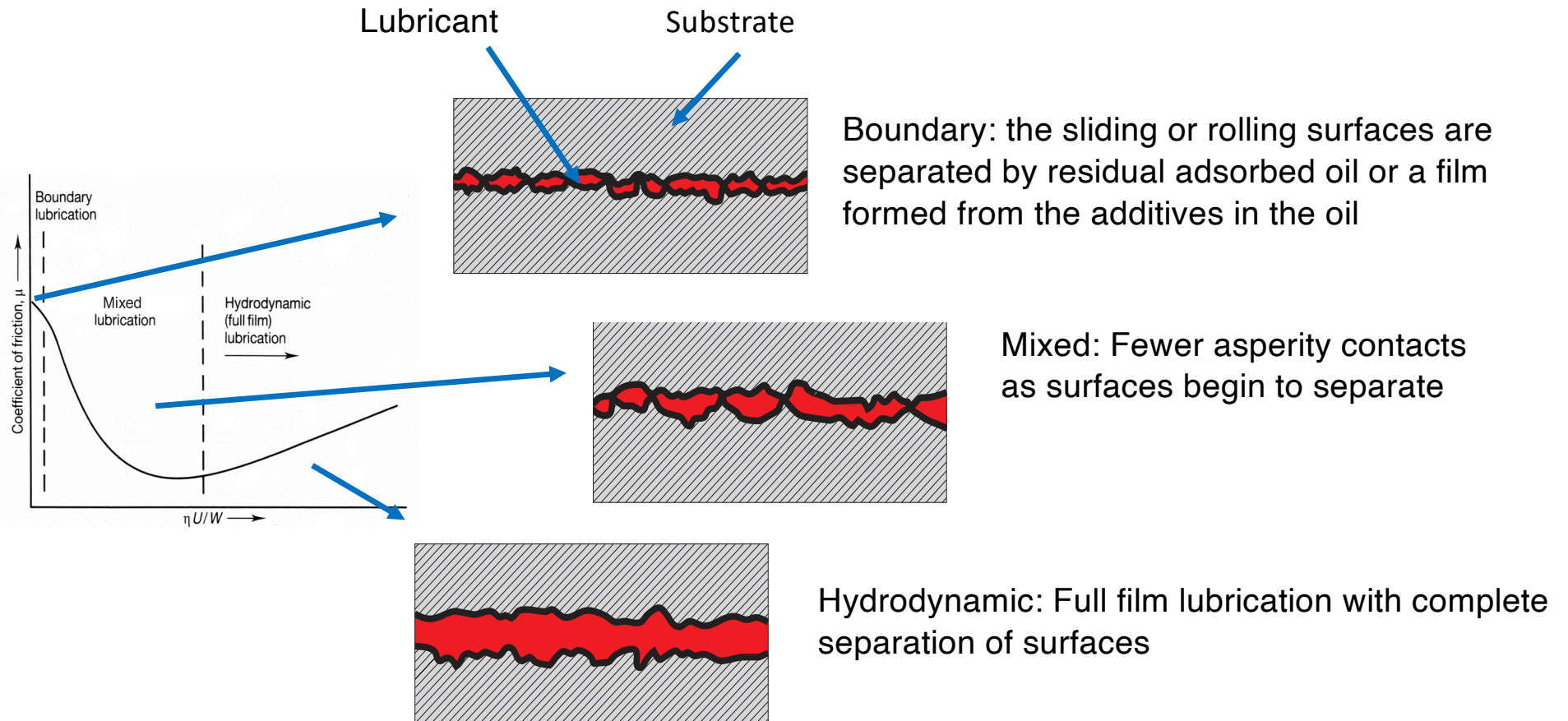


Hersey number

$$\frac{\text{ms}^{-1} * \text{Nsm}^{-2}}{\text{Nm}^{-1}}$$

$(\text{Shaft radius/radial clearance}) * (\text{Dynamic Viscosity} \times \text{Speed}) / \text{load (pressure)}$

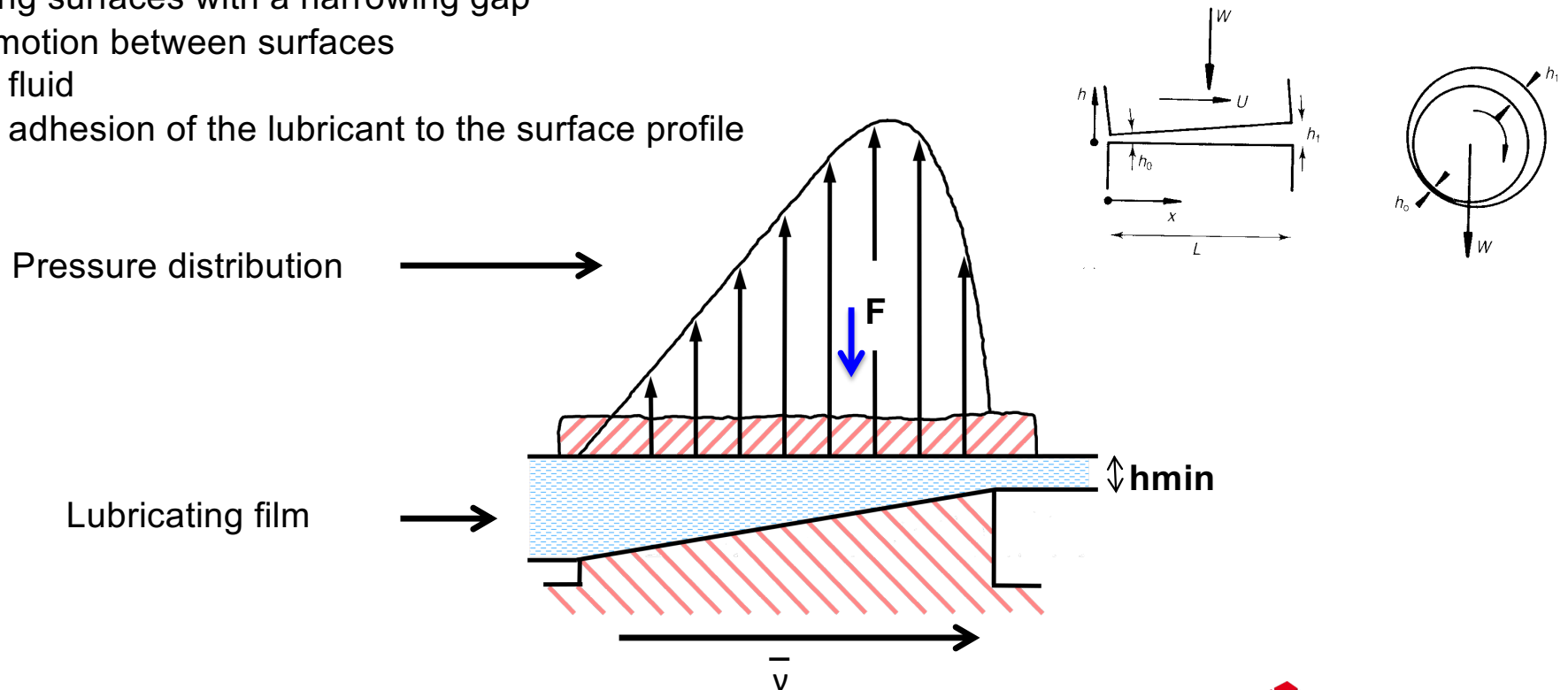
# Friction regimes



# Hydrodynamic Lubrication

## Prerequisites:

- Conforming surfaces with a narrowing gap
- Relative motion between surfaces
- Sufficient fluid
- Sufficient adhesion of the lubricant to the surface profile

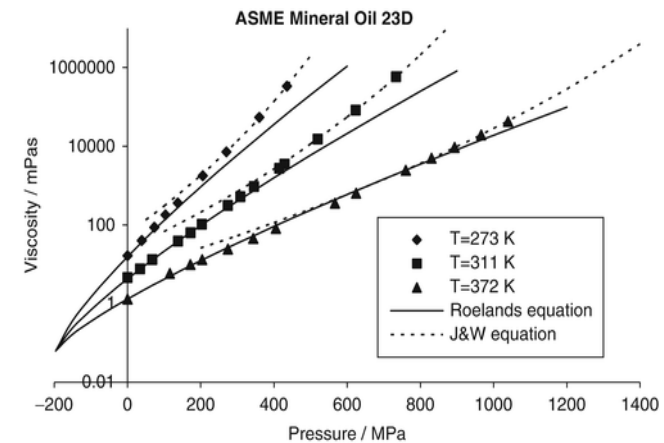


# Hydrodynamic equation

$$h_{\min} = \frac{3.63 \cdot (h \cdot v)^{0.68} \cdot a^{0.49}}{\left(\frac{1}{r_1} + \frac{1}{r_2}\right)^{0.466} \cdot Q^{0.073}} \cdot \frac{E^{-0.117}}{1 - \left(\frac{1}{m}\right)^2} \cdot (1 - e^{-0.68 \cdot k}) \text{ [mm]}$$

$h_{\min}$	[mm]	film thickness in the rolling contact
$a$	[mm <sup>2</sup> /N]	pressure-viscosity coefficient
$h$	[mPa · s]	dynamic Viscosity
$v$	[m/s]	= $(v_1 + v_2) / 2$ = average rolling speed
$r_1$	[mm]	radius of ball
$r_2$	[mm]	radius of inner or outer ring
$Q$	[N]	load
$E$	[N/mm <sup>2</sup> ]	elastic modulus
$1/m$		Poisson's ratio

$k = a/b =$  relationship between axis of the contact area

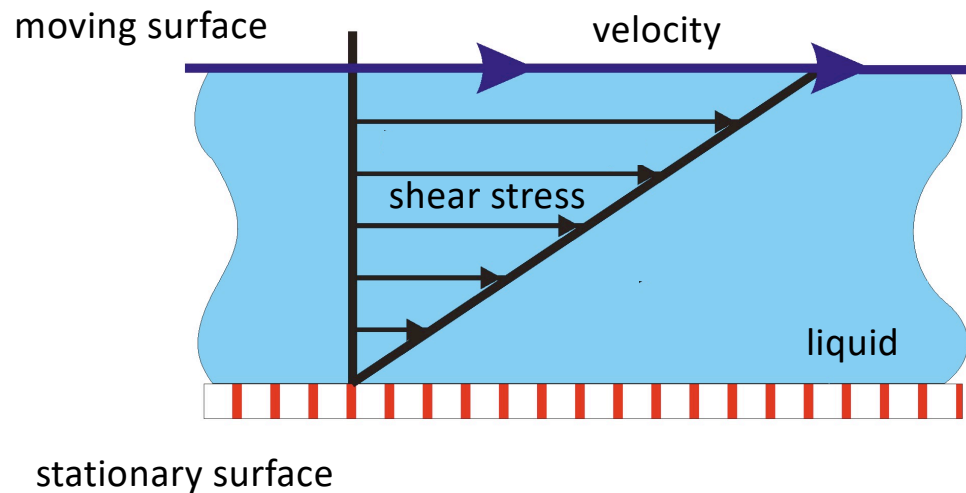


## Factors influencing hydrodynamic lubrication

- $h_{min} > 3 * Ra$
- Load and average speed,
- Contact geometry
- Elastic modulus and Poisson's Ratio of contacting materials
- Dynamic viscosity
- Pressure-viscosity coefficient

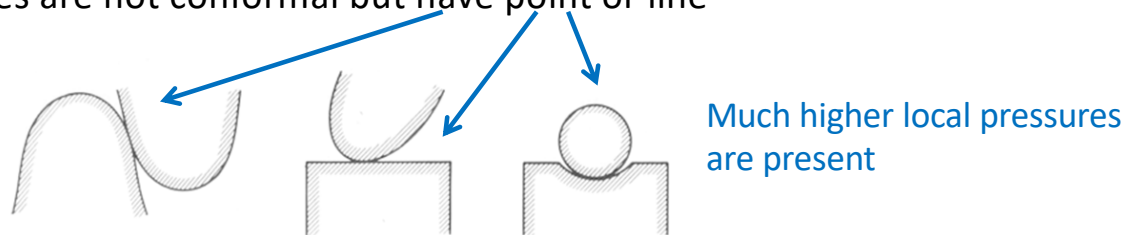
**Viscosity** is a measure of the resistance of a fluid to deform under shear stress

Dynamic viscosity: shear force at a plane inside the liquid per unit velocity gradient, in a direction perpendicular to the plane (Pascal-second or Centipoise)



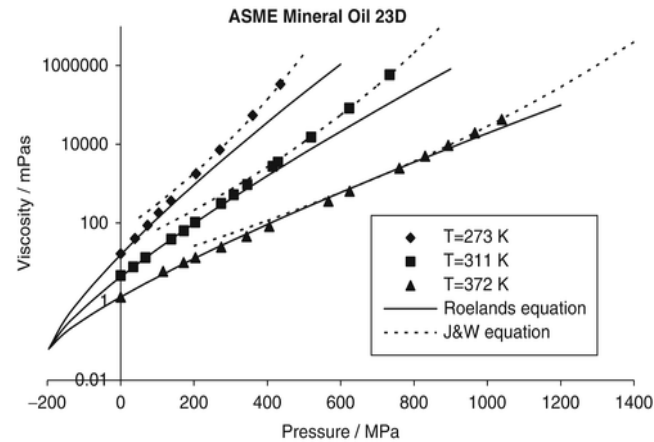
## Elastohydrodynamic lubrication

When the sliding surfaces are not conformal but have point or line contact

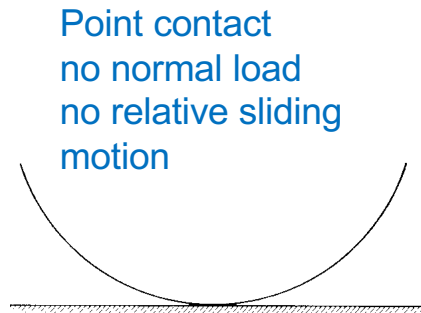


- Important factors: pressure dependence of the viscosity and elastic deformation of the surfaces
- GPa pressures are frequently involved—oil becomes so viscous it is practically solid!

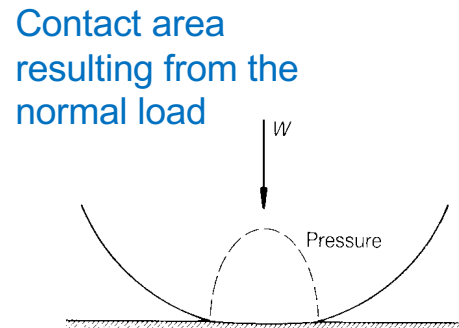
Piezo viscous effect



# Elastohydrodynamic lubrication

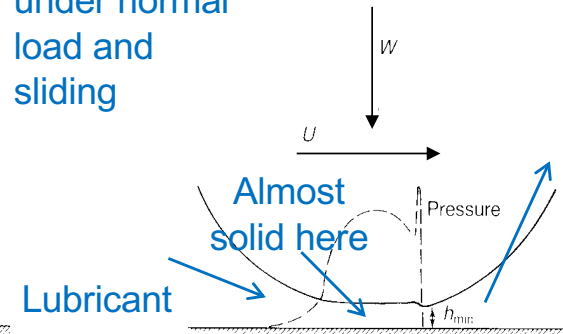


Contact initially occurs at a point



Pressure increases  
↓  
contact area grows

Elastic distortion under normal load and sliding

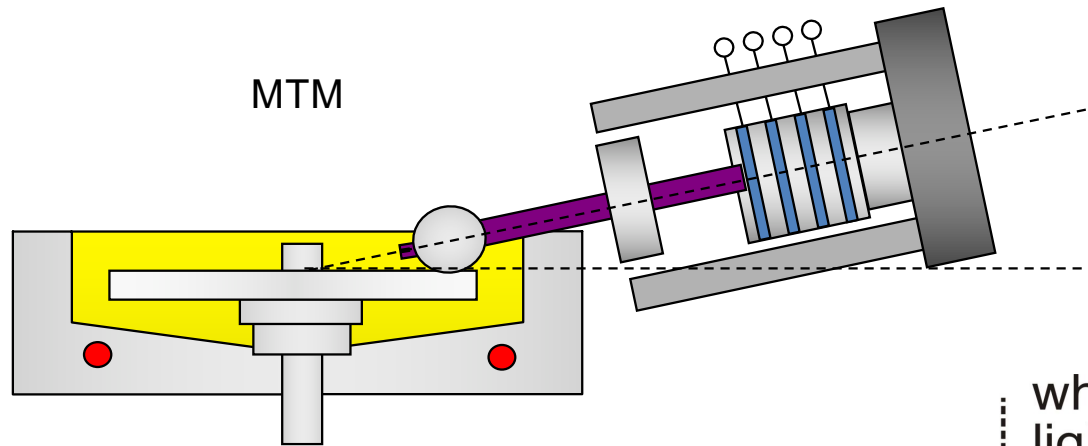


Lubricating film and sphere sliding over the surface

Sudden release of lubricant: elastic modification of one of the solids

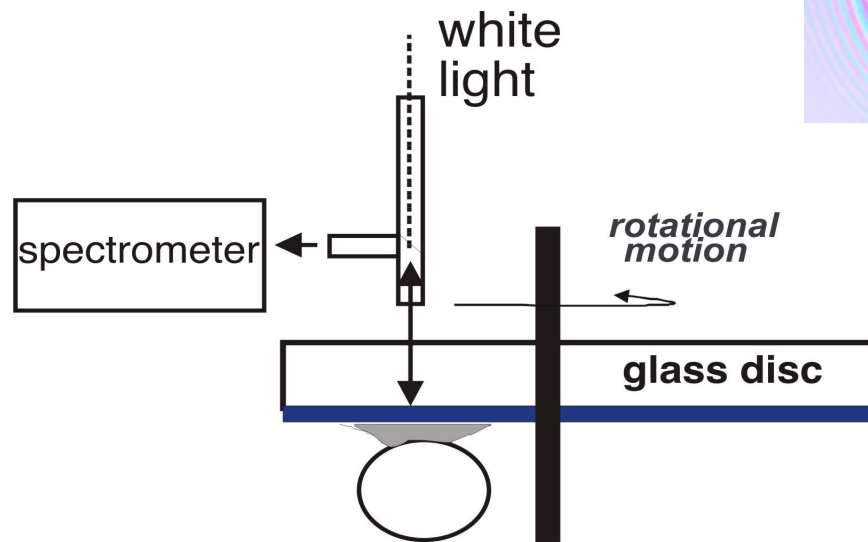
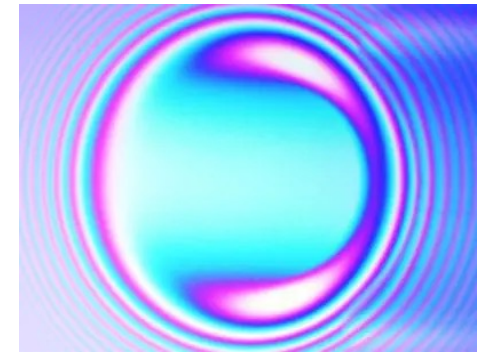
Reynolds equation shows that the gap remains parallel at first with increasing pressure, but then suddenly enlarges on one side

# Measurement of fluid film lubrication

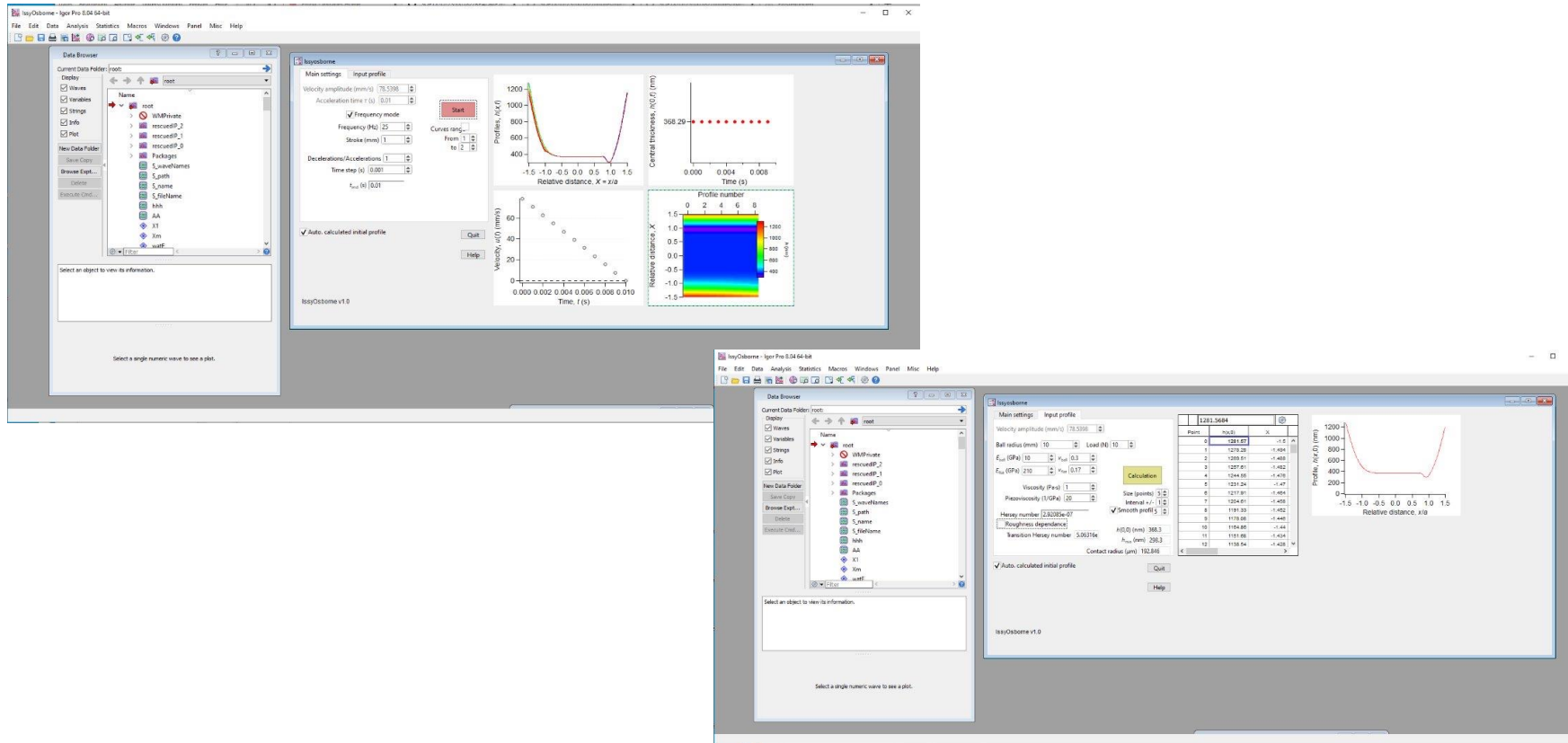


Friction coefficient

Film thickness measurements



# Calculation of fluid film profile



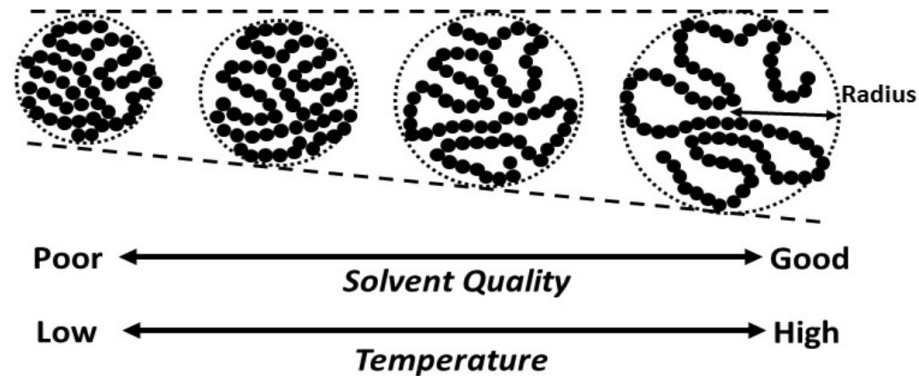
<https://github.com/ElsevierSoftwareX/SOFTX-D-23-00182>

Malik Yahiaoui, Denis Mazuyer, Juliette Cayer-Barrioz

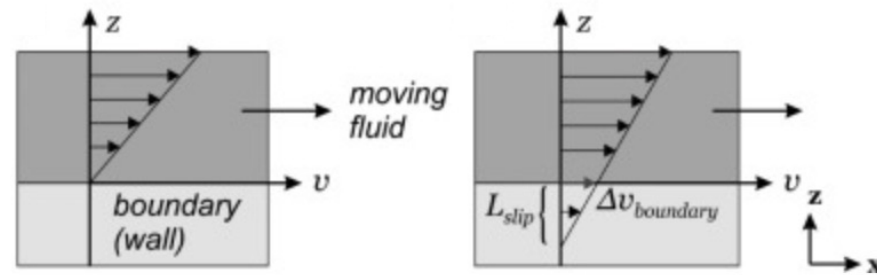
# Hydrodynamic Lubrication: Viscosity improvers

VI improvers are polymers: olefin copolymers (OCP), polyalkylmethacrylates (PMA) and hydrogenated poly (styrene-co-conjugated dienes)

PMA's thicken oils by expansion of the polymer coil with temperature



# Slip



Important factors: liquid-surface interactions, surface roughness, shear rate

No surface interaction  $\longrightarrow$  large slip, no hydrodynamic lubrication  
Strong interaction  $\longrightarrow$  no slip

Bastian E. Rapp, in *Microfluidics: Modelling, Mechanics and Mathematics*, 2017

# Grease

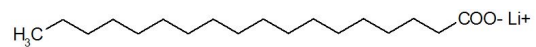
Grease is mostly nasty

Used in extreme conditions or where liquid lubricant would flow away

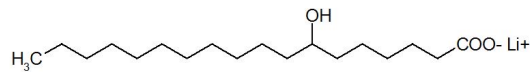
Compositions: Base oil, thickener, additives



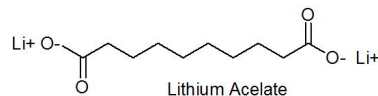
## Examples of thickeners



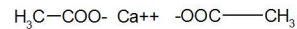
Lithiumstearate



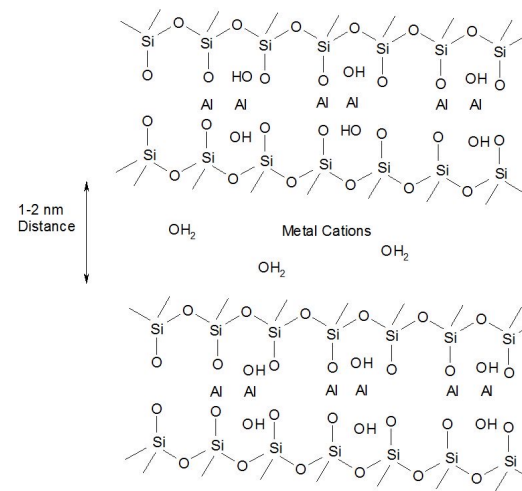
Lithium-12-hydroxystearate



Lithium Acelate



Calciumacetate

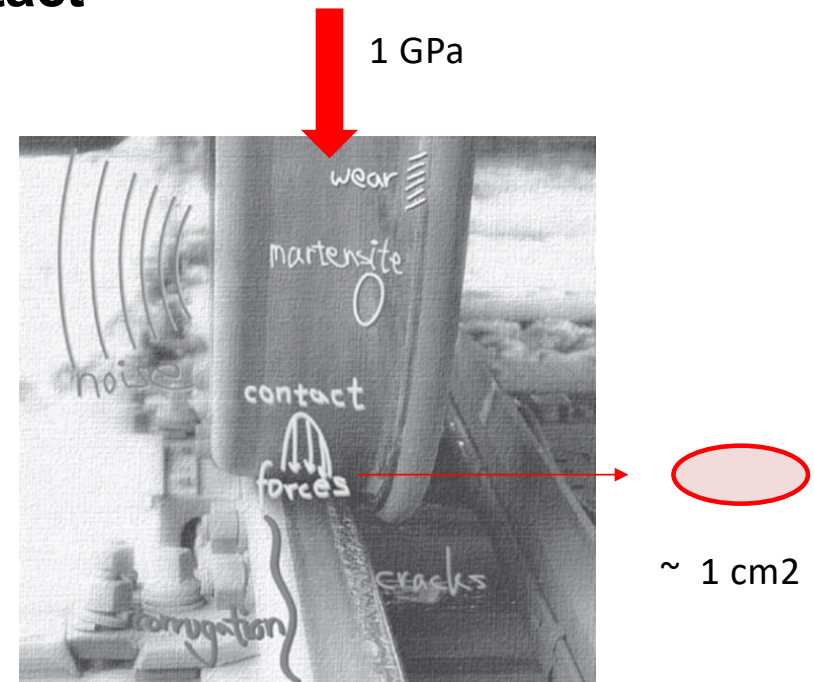
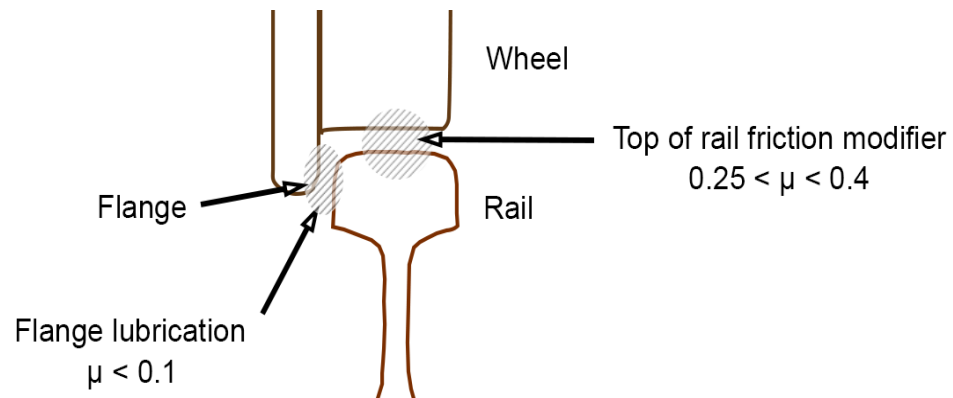


Clays, talc

# Bleeding out



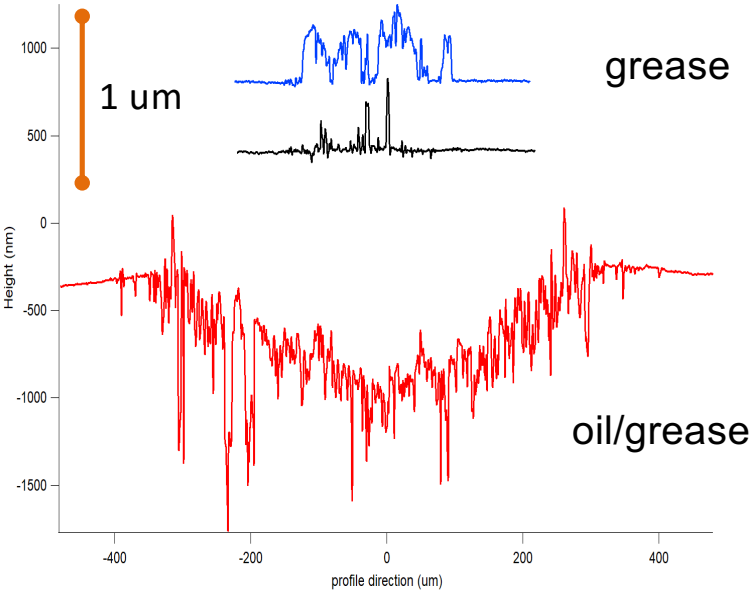
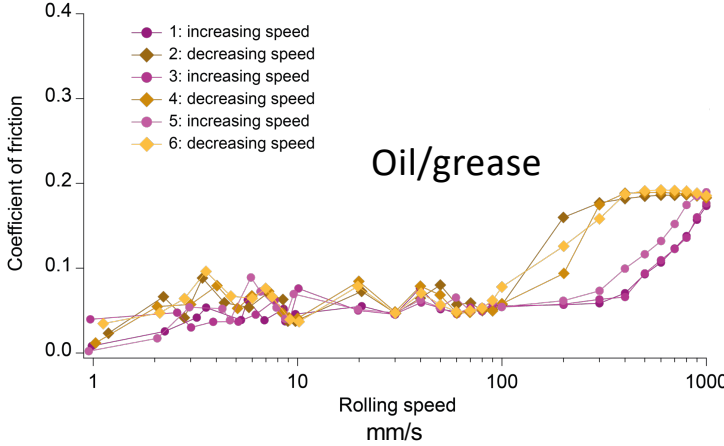
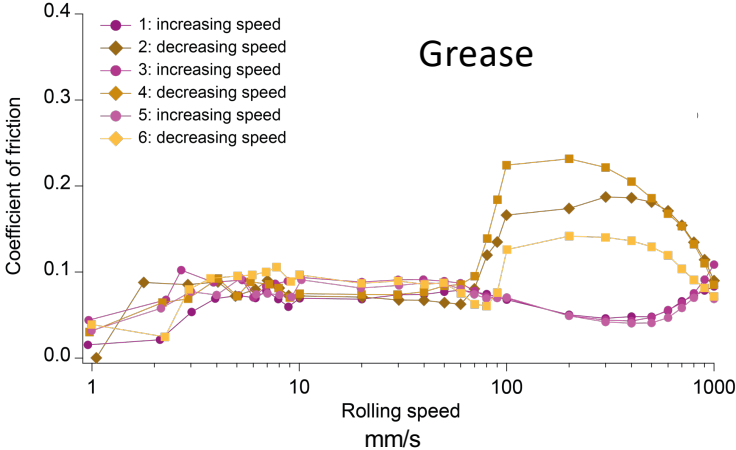
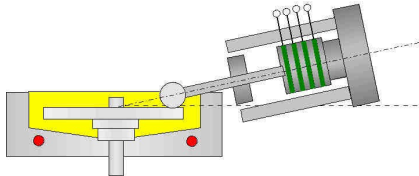
# Friction Management at the Wheel-Rail Contact



From Lewis Roger, and Ulf Olofsson, eds. *Wheel-rail interface handbook*. Elsevier, 2009.

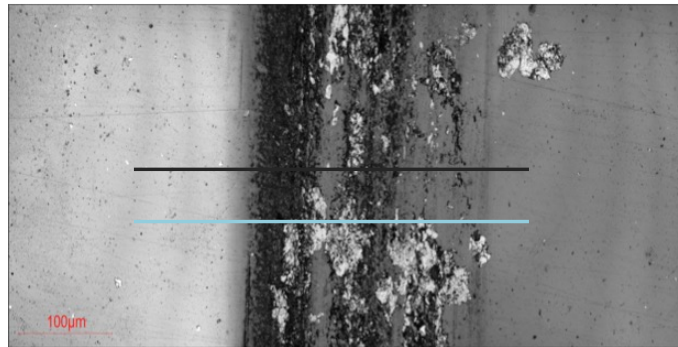
# Bleeding in grease

Mini Traction Machine (MTM)

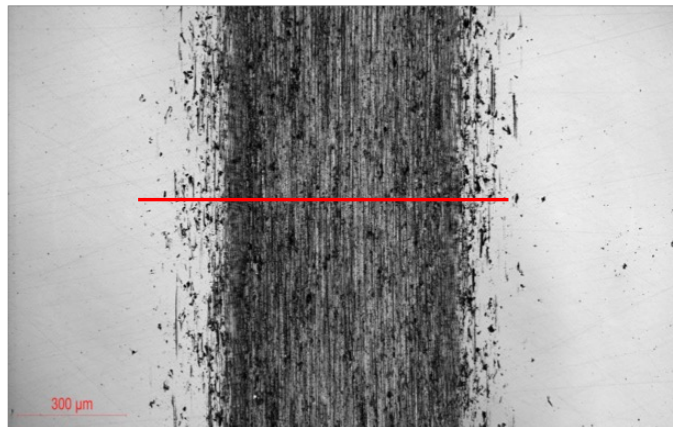


# Wear Behavior

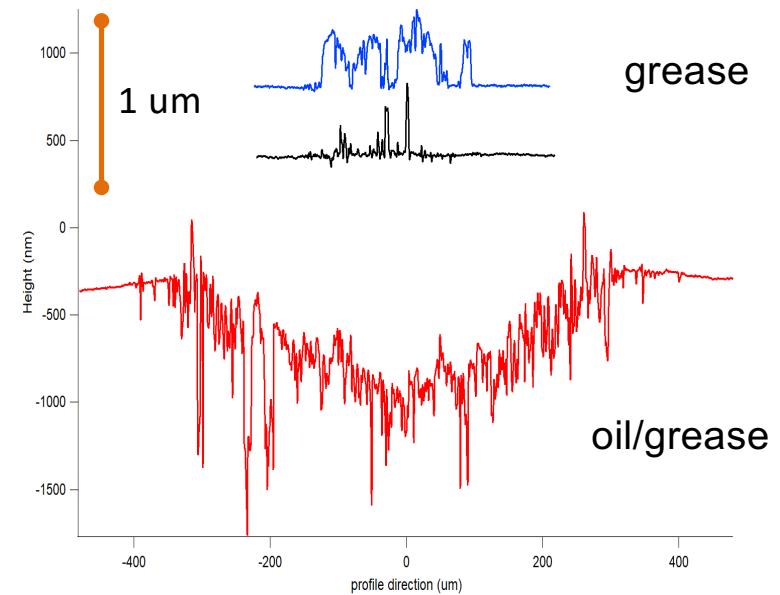
Optical micrographs, end of test



(grease)

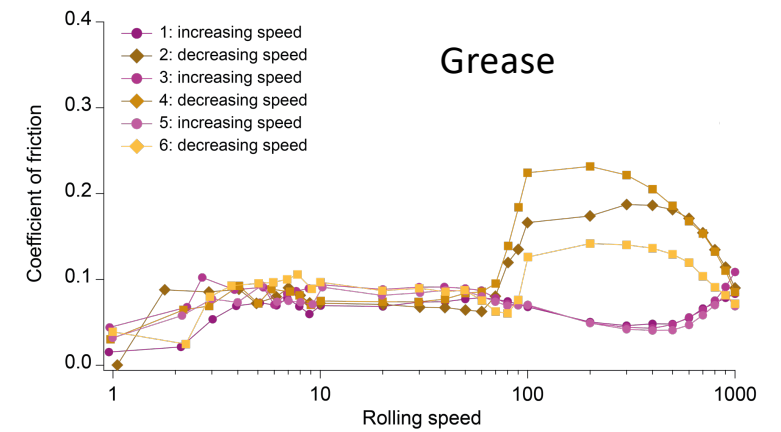
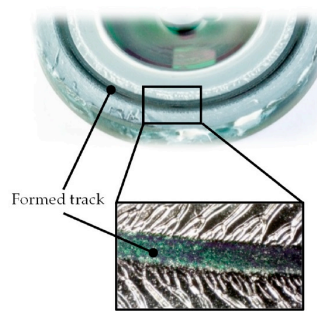


(oil/grease)

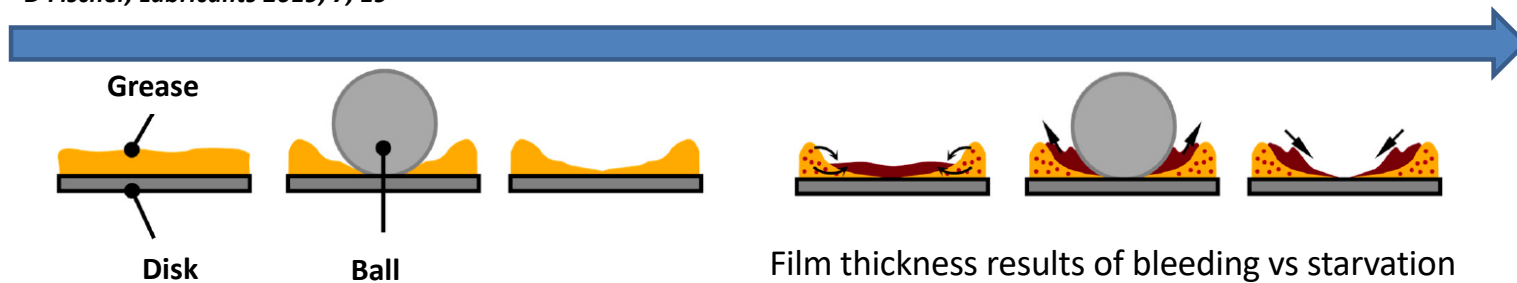


# Grease bleeding

EHL/MX lubrication regime can be established, if a sufficient supply of liquid is available



*D Fischer, Lubricants 2019, 7, 19*



Film thickness results of bleeding vs starvation (+ inertial effects at very high speeds)

# Aqueous-based Lubrication

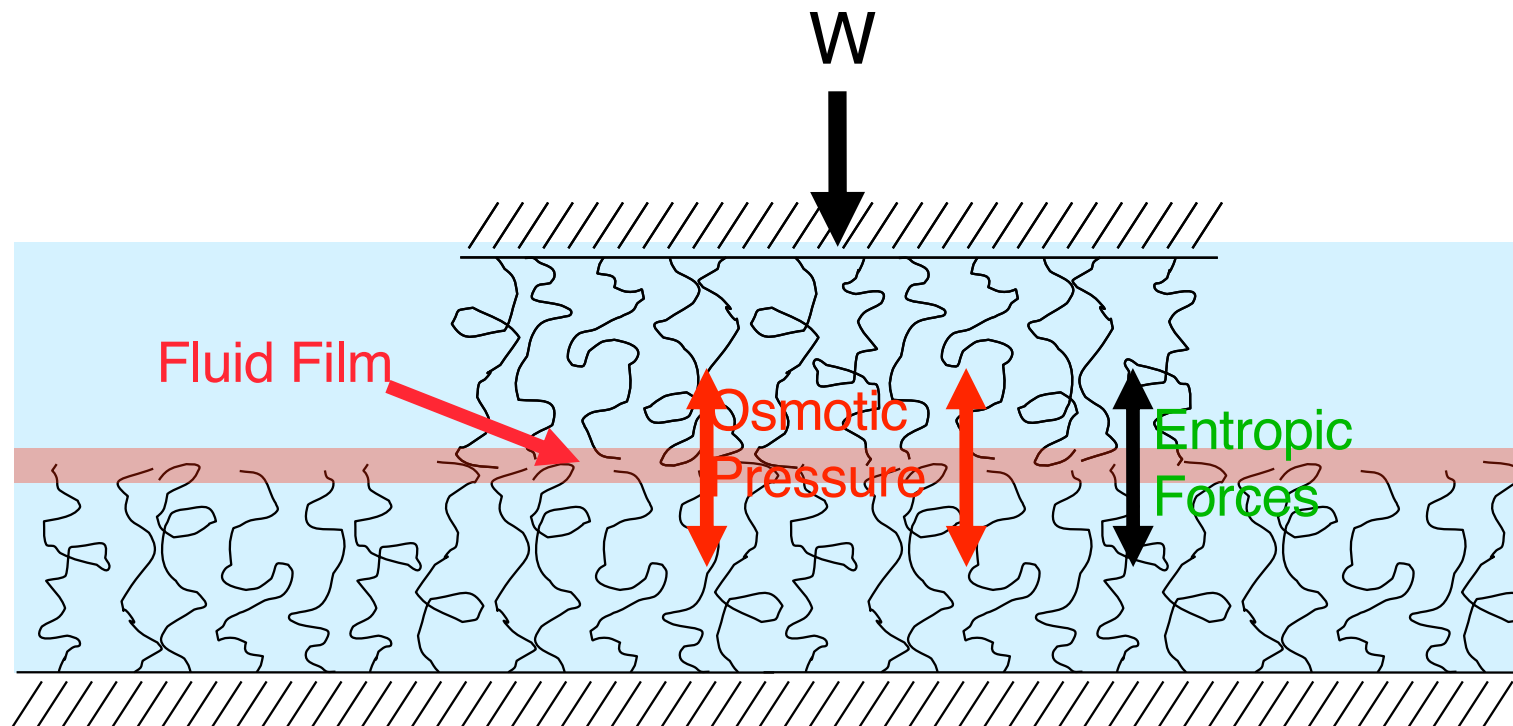
## advantages

- non-flammable
- non-toxic, biocompatible
- cheap, readily available

## disadvantages

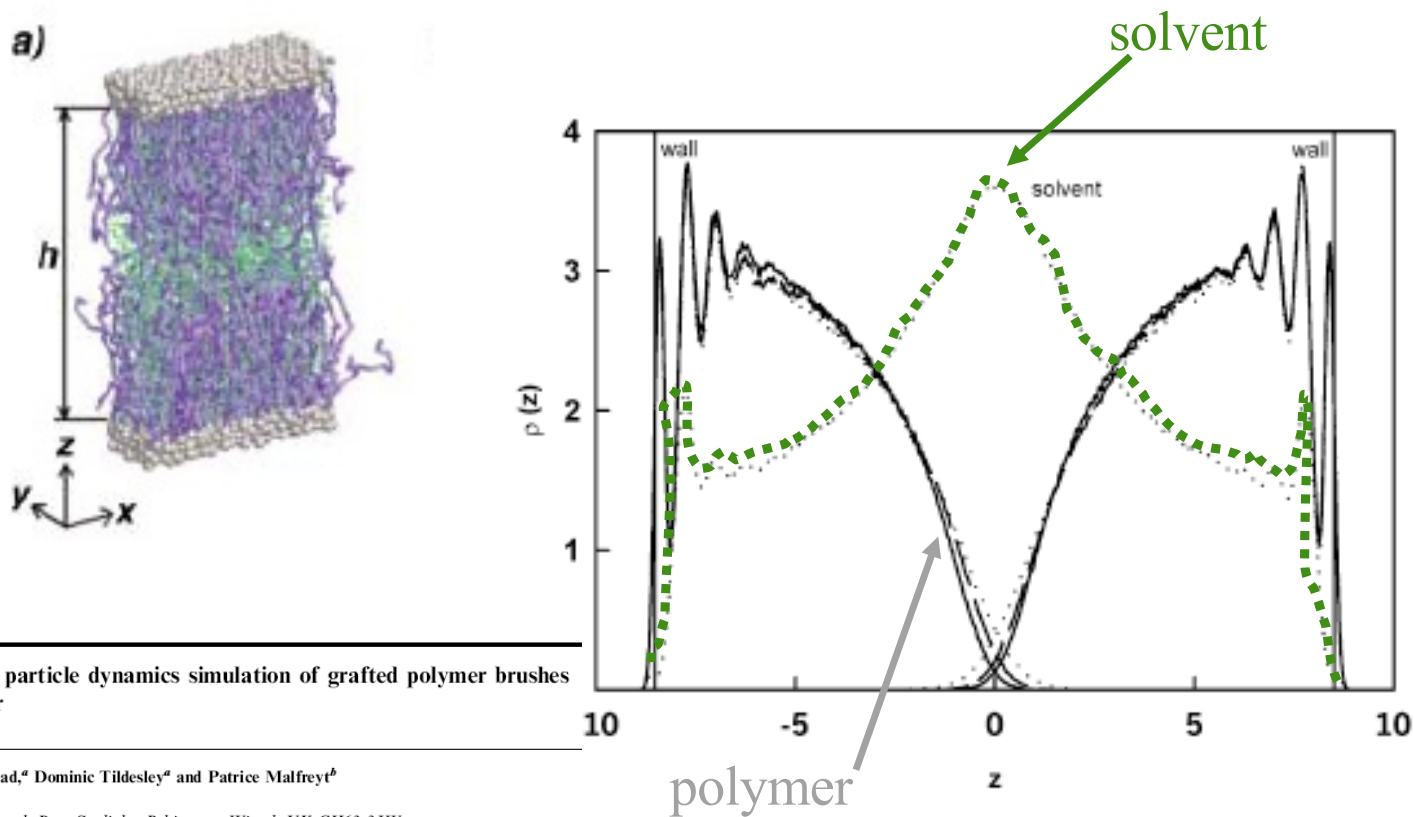
- low viscosity
- viscosity does not increase under pressure (low pressure coefficient of viscosity)

## Aqueous based lubrication with polymers



X. Yan, S.S. Perry, N.D. Spencer, S. Pasche, S.M. De Paul, M. Textor, M.S. Lim, *Langmuir* 2004, 20, 423-428

# Density Distribution of Polymer and Solvent



Dissipative particle dynamics simulation of grafted polymer brushes under shear

Danial Irfachsyad,<sup>a</sup> Dominic Tildesley<sup>a</sup> and Patrice Malfreyt<sup>b</sup>

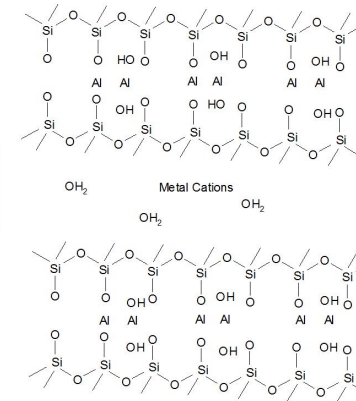
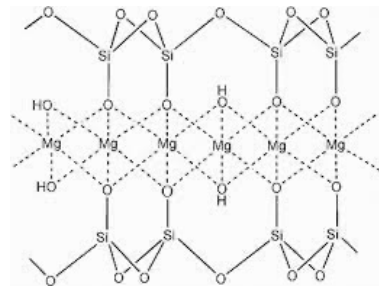
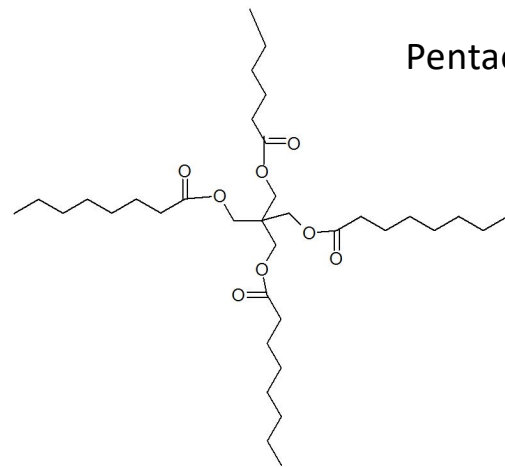
<sup>a</sup> Unilever Research Port Sunlight, Bebington, Wirral, UK CH63 3JW

<sup>b</sup> Laboratoire de Thermodynamique des Solutions et des Polymères, UMR CNRS 6003, 24 avenue de Landais, Université Blaise-Pascal, 63177, Aubiere Cedex, France

Received 22nd November 2001, Accepted 22nd April 2002

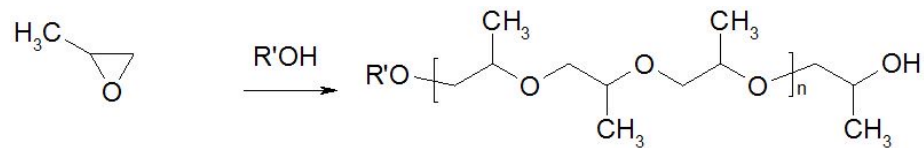
First published as an Advance Article on the web 27th May 2002

# Thickeners for water-based hydraulic fluids



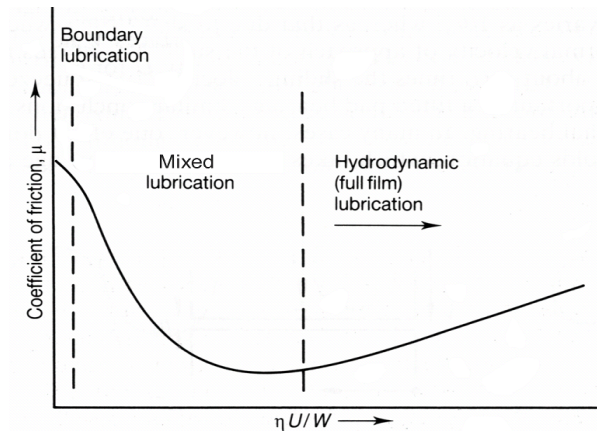
Clays or talc

## Polypropylene Glycols



# Summary

- Ideally, machinery will operate in the hydrodynamic or elastohydrodynamic regimes
- Choice of base oil based on cost, operating conditions, safety
- Additives used to improve fluid film formation of base oil

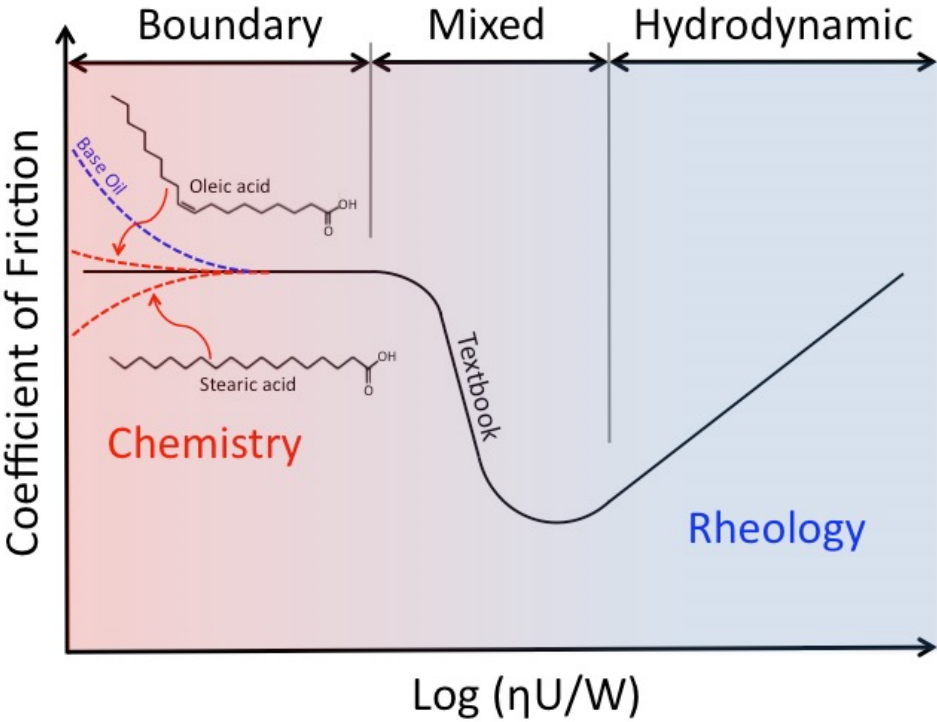


# Liquid Lubrication

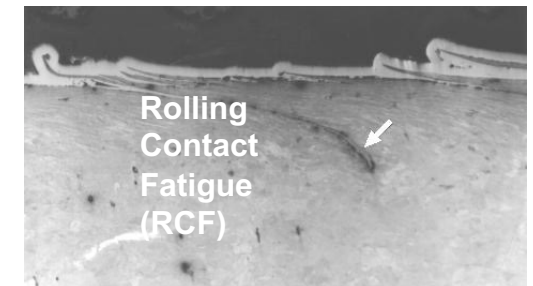
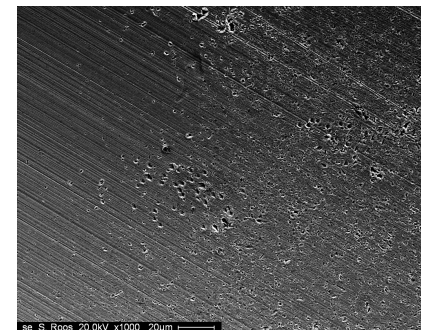
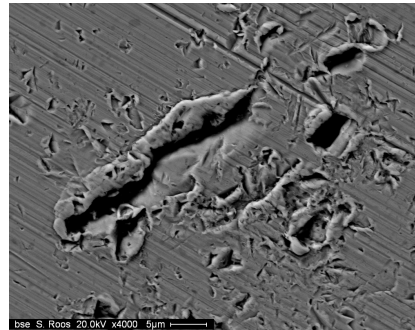
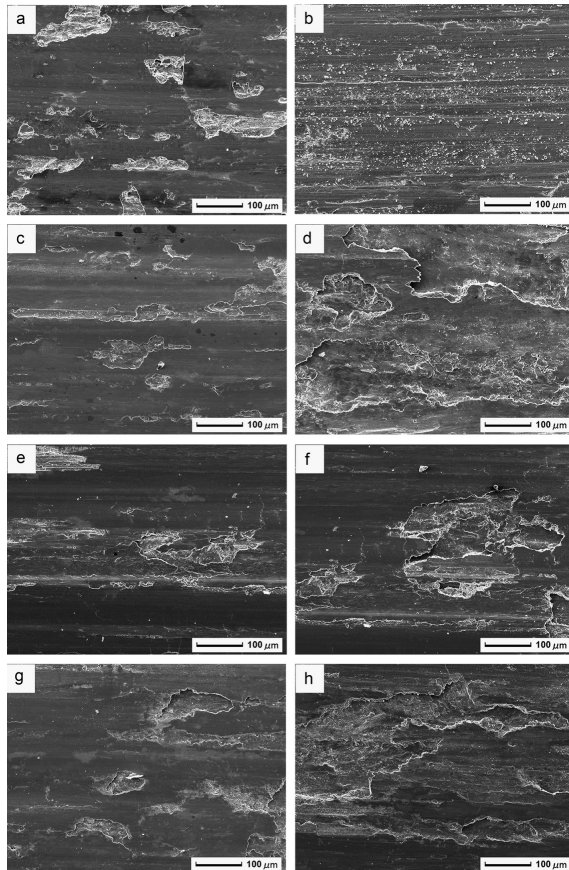
## Part 2. Boundary Lubrication

- Surface interactions of additives
- Competition for surface coverage
- Mechanisms of wear protection and friction control
- Stick-slip
- Seals

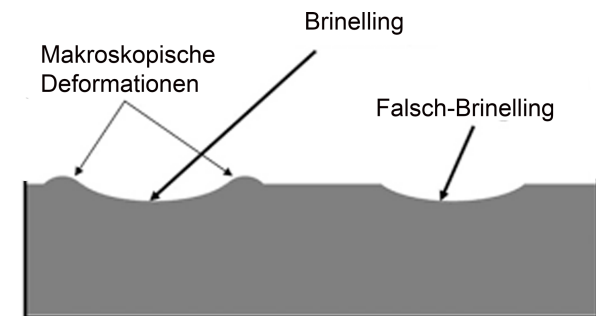
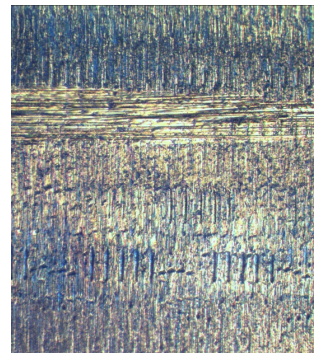
# Stribeck Curve



# Surface protection

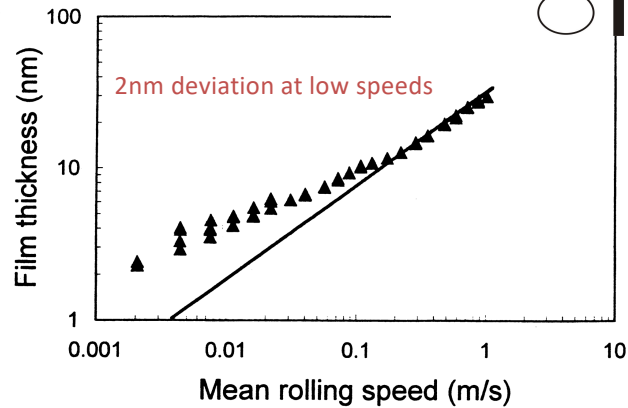
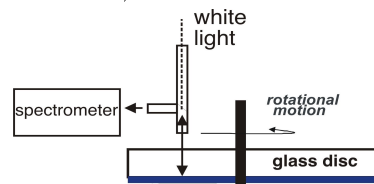
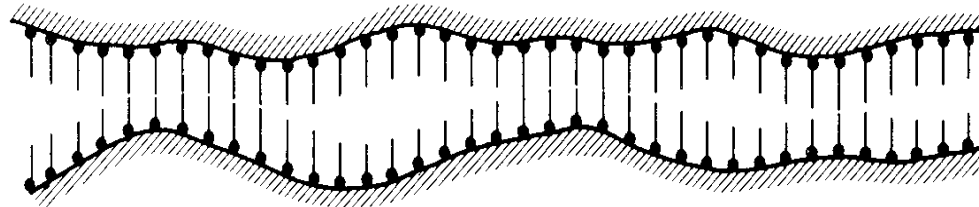
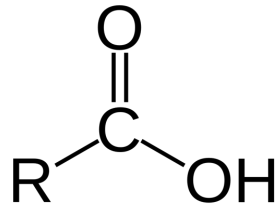


Plastic deformation at surface



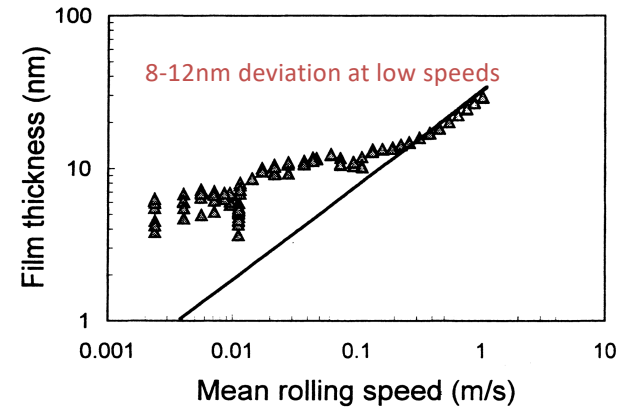
False Brinelling/Brinelling on the raceway

# Friction modifiers



octadecanoic acid (1% in hexadecane dry)

## EHL film thickness measurements



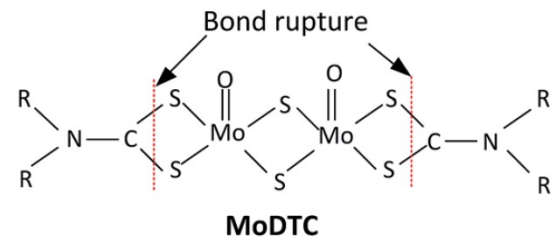
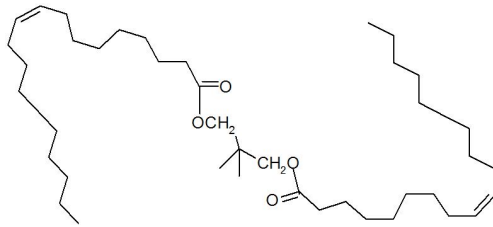
octadecanoic acid (1% in hexadecane, wet)

Formation of iron carboxylate salts in the presence of water

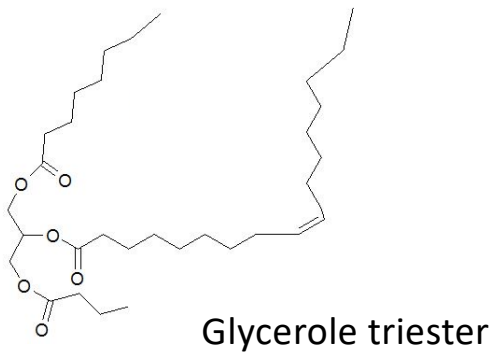
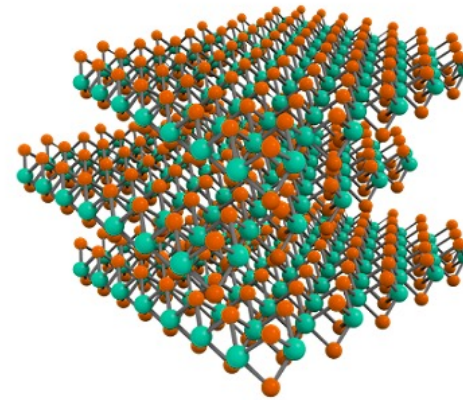
Hugh Spikes, Tribology International, 2001, 34, 789

## Other friction modifiers

Neopentylglycol dioleate



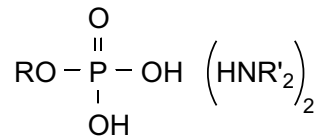
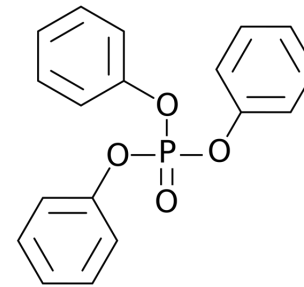
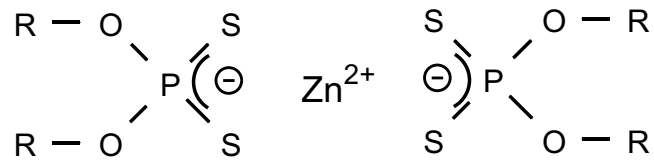
Molybdenum Dithiocarbamate



Glycerole triester

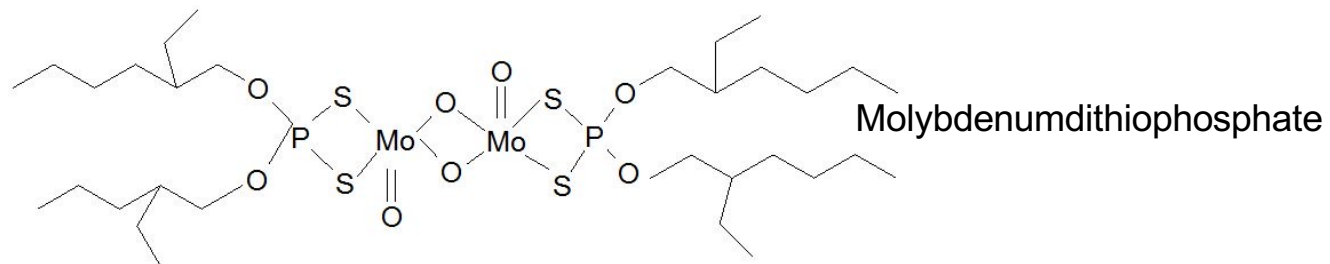
# Anti-wear additives

Zinc dialkyl dithiophosphate



Amine phosphate

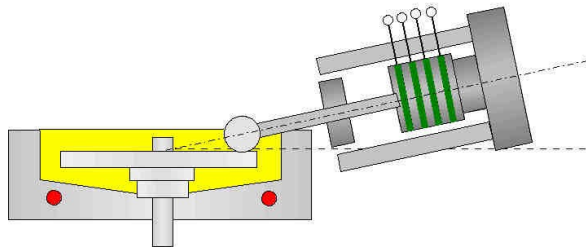
Triphenylphosphate



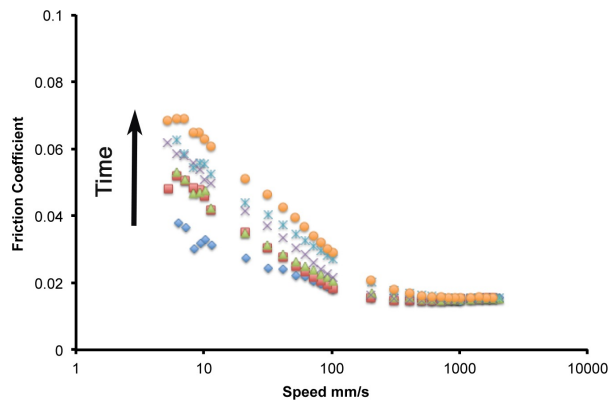
Molybdenum dithiophosphate

# Friction behavior of ZnDTP

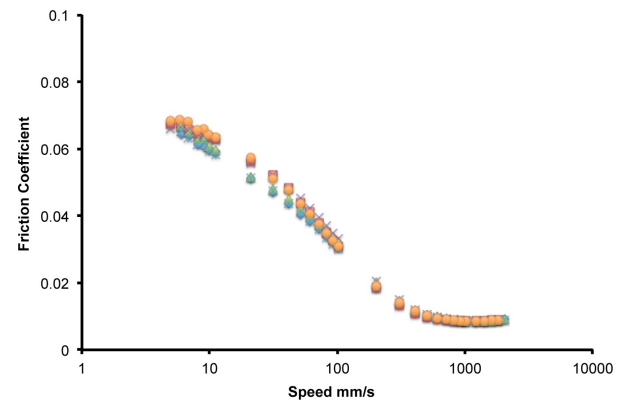
Mini Traction Machine (MTM)



Load: 40 N  
Speed: 5 to 1000 mm/s  
Slide-roll-ratio: 50%  
Temperature 80 °C  
Low viscosity base oil

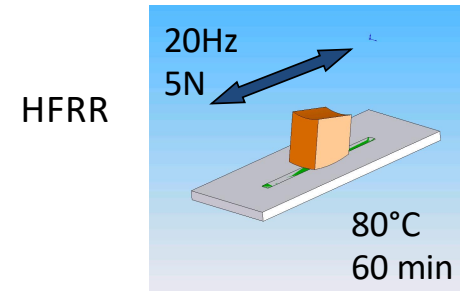


First measurements

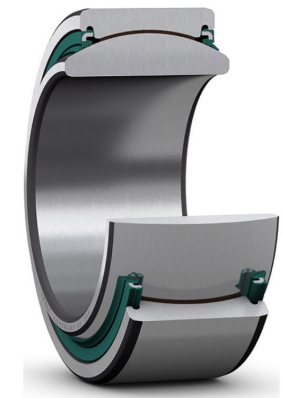


Last measurements

# Topography of tribofilm on steel: Comparison of ZnDTP and amine phosphate (AP)

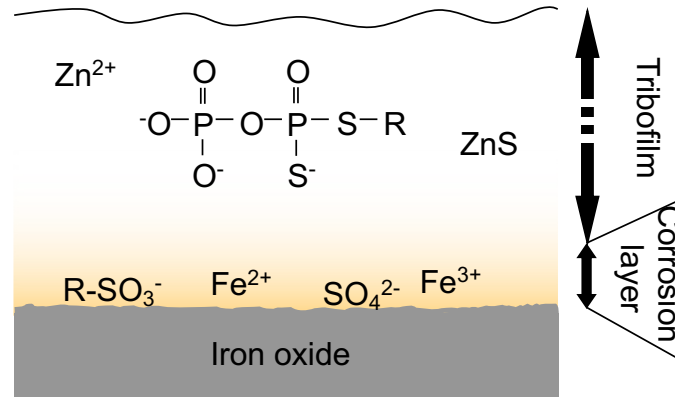
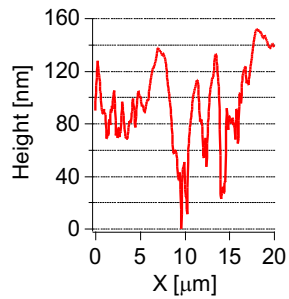
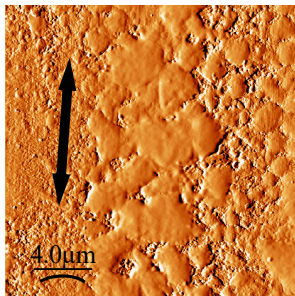


Segment of joint bearing

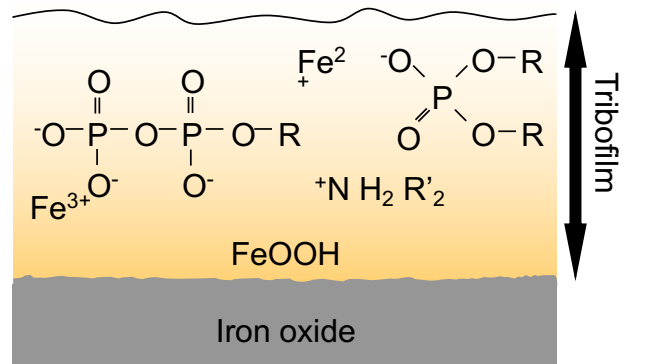
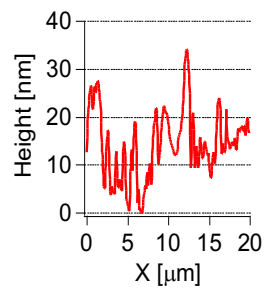
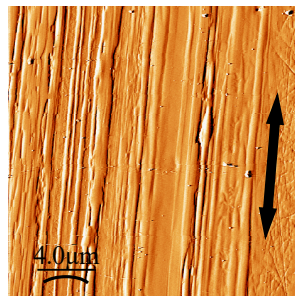


Diameter 50.8 mm

ZnDTP



AP

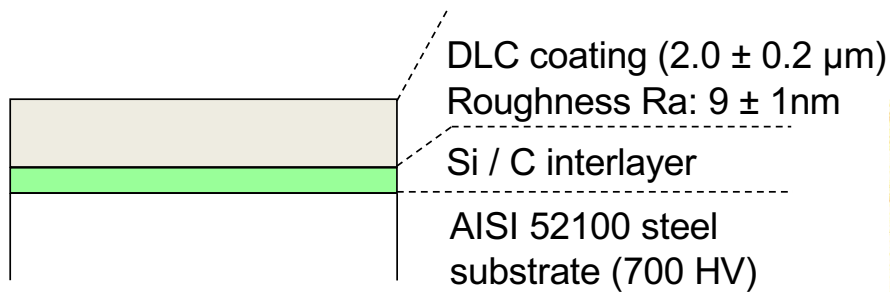


# DLC coatings

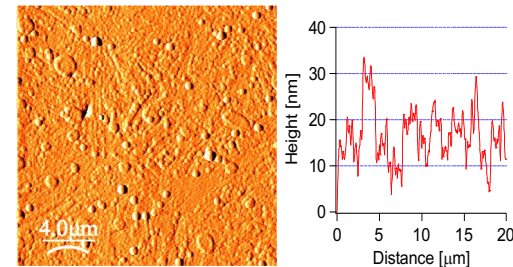
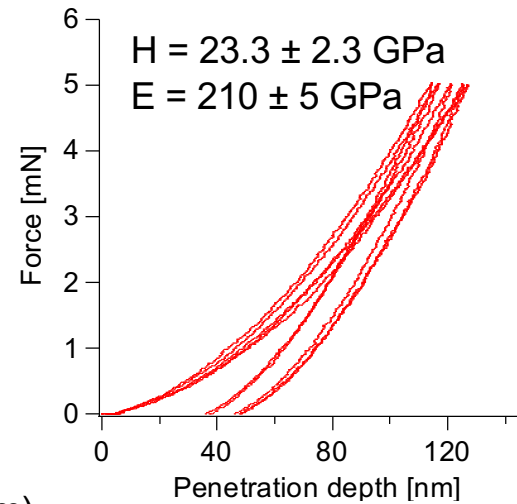
**Hydrogenated amorphous carbon coatings** (a-C:H) deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD)

Gases:  $C_2H_2$ , Ar.

The AISI 52100 steel is also used for the steel/steel tribological tests.



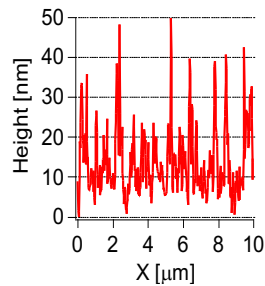
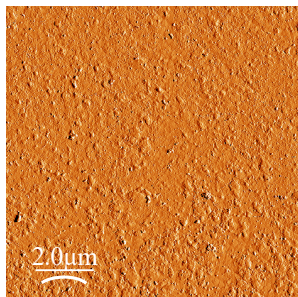
## Hardness of the DLC coating measured by nanoindentation



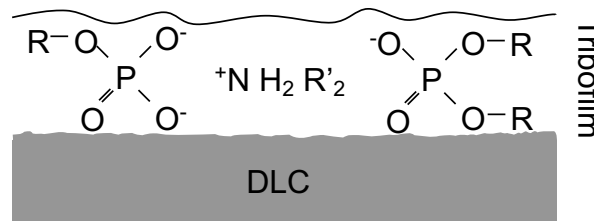
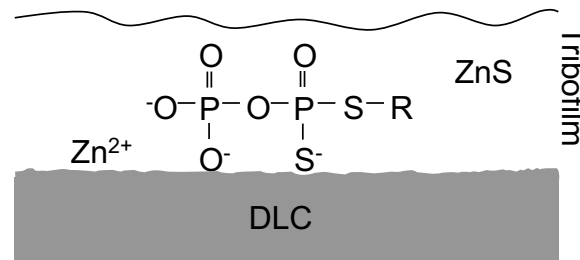
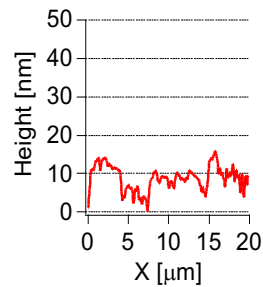
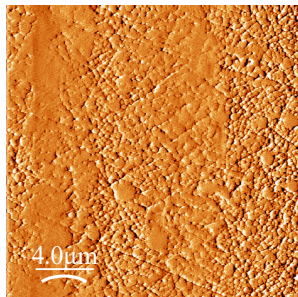
AFM observation of a DLC coating as-deposited surface

## ZnDTP and AP on DLC

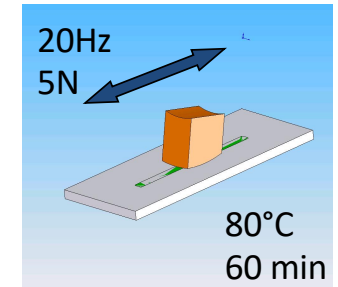
ZnDTP tribofilm on DLC



AP tribofilm on DLC



HFRR



Segment of joint bearing

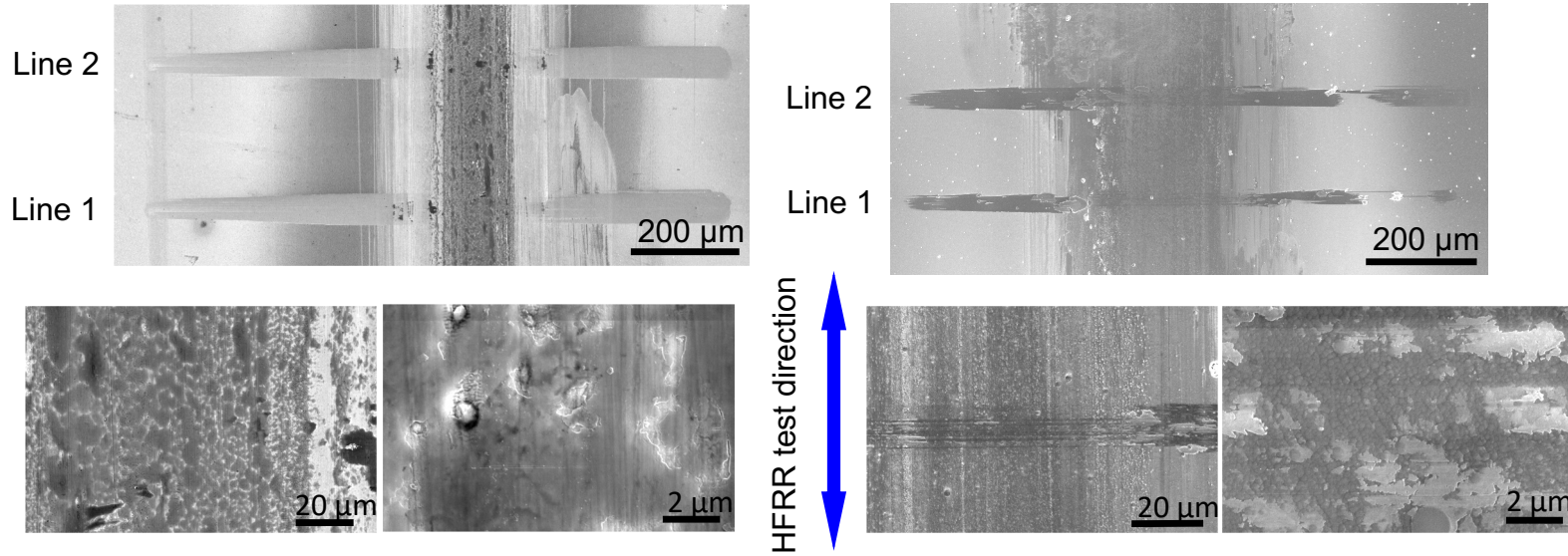


ZnDTP provided some wear protection but AP accelerated wear

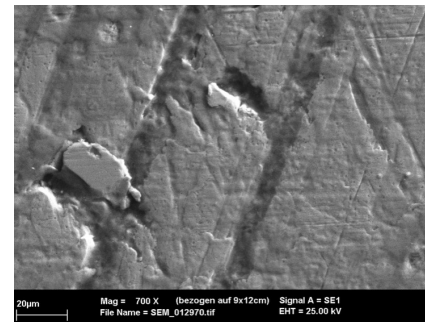
Diameter 50.8 mm

# Comparison of ZnDTP on steel and DLC surfaces

ZnDTP



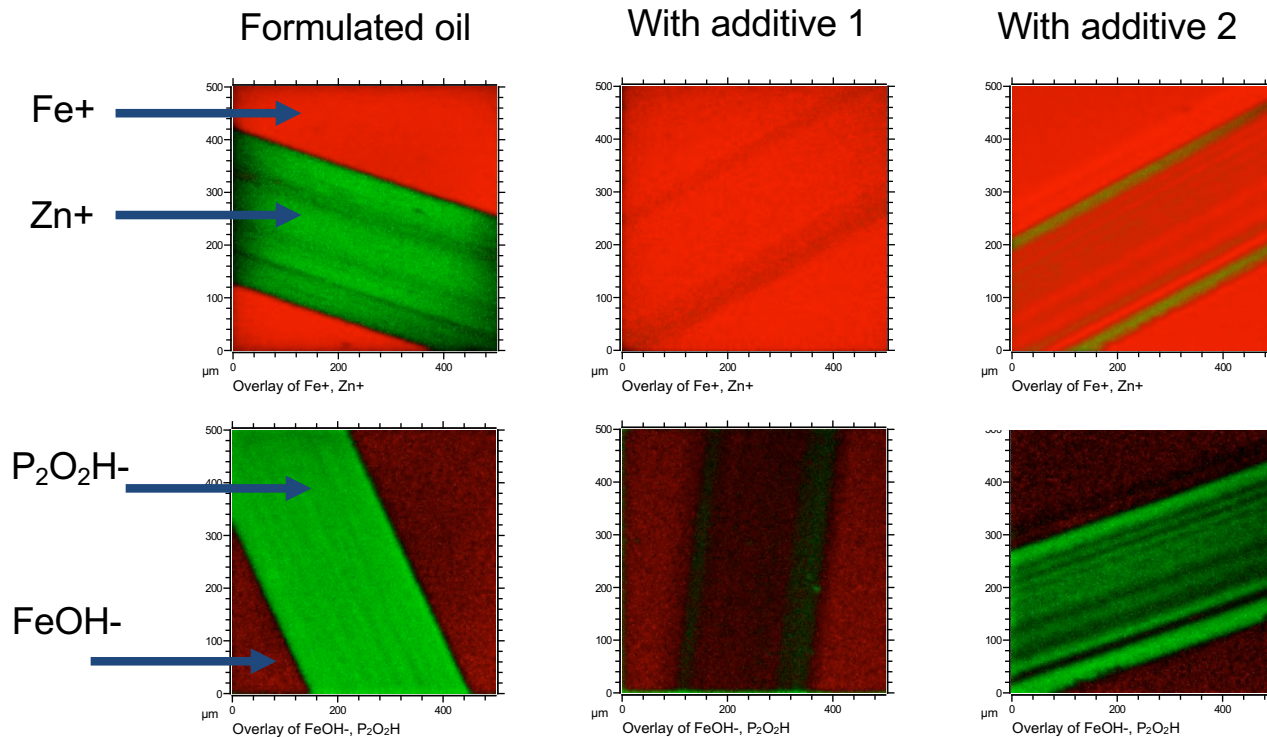
Corrosion layer results in good  
adhesion and eventually to damage  
to oil lubricated surfaces



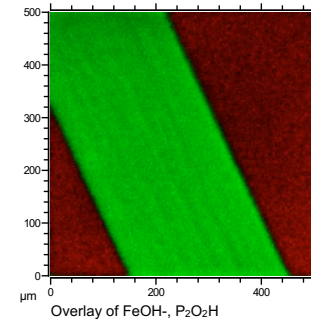
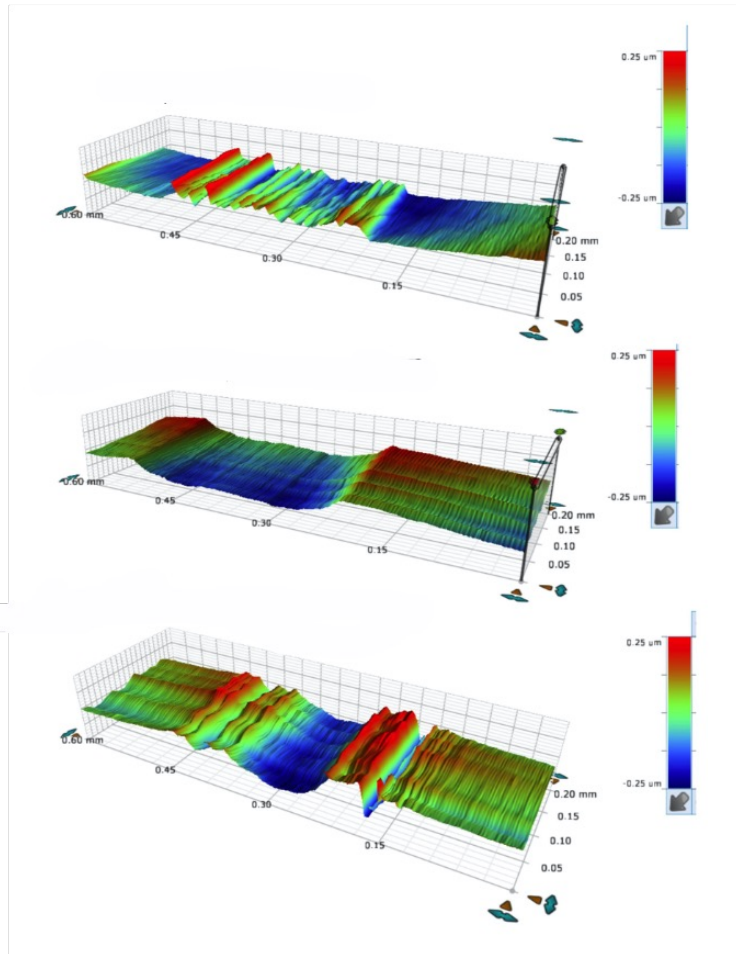
# Competition for the surface

- For Viscosity
  - *Viscosity-index improvers*
  - *Pour-point depressants*
- For Lubricity
  - *Friction modifiers*
  - *Extreme-pressure and antiwear additives*
- Controlling Chemical Breakdown
  - *Detergents to prevent sludge*
  - *Corrosion inhibitors*
  - *Antioxidants*
- For Contaminant Control
  - *Dispersants (to suspend soot)*
  - *Antifoam agents*
  - *Antimisting agents*

Competition for the surface: will an antiwear additive still work when a new friction modifier is added?  
Analysis of surface with Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS)

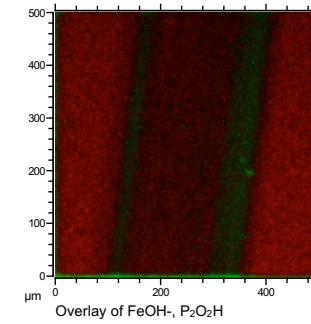


# Wear

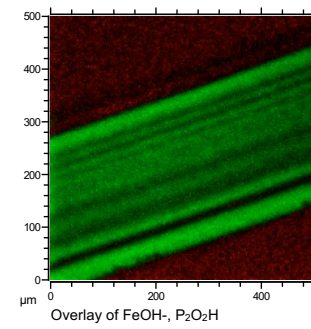


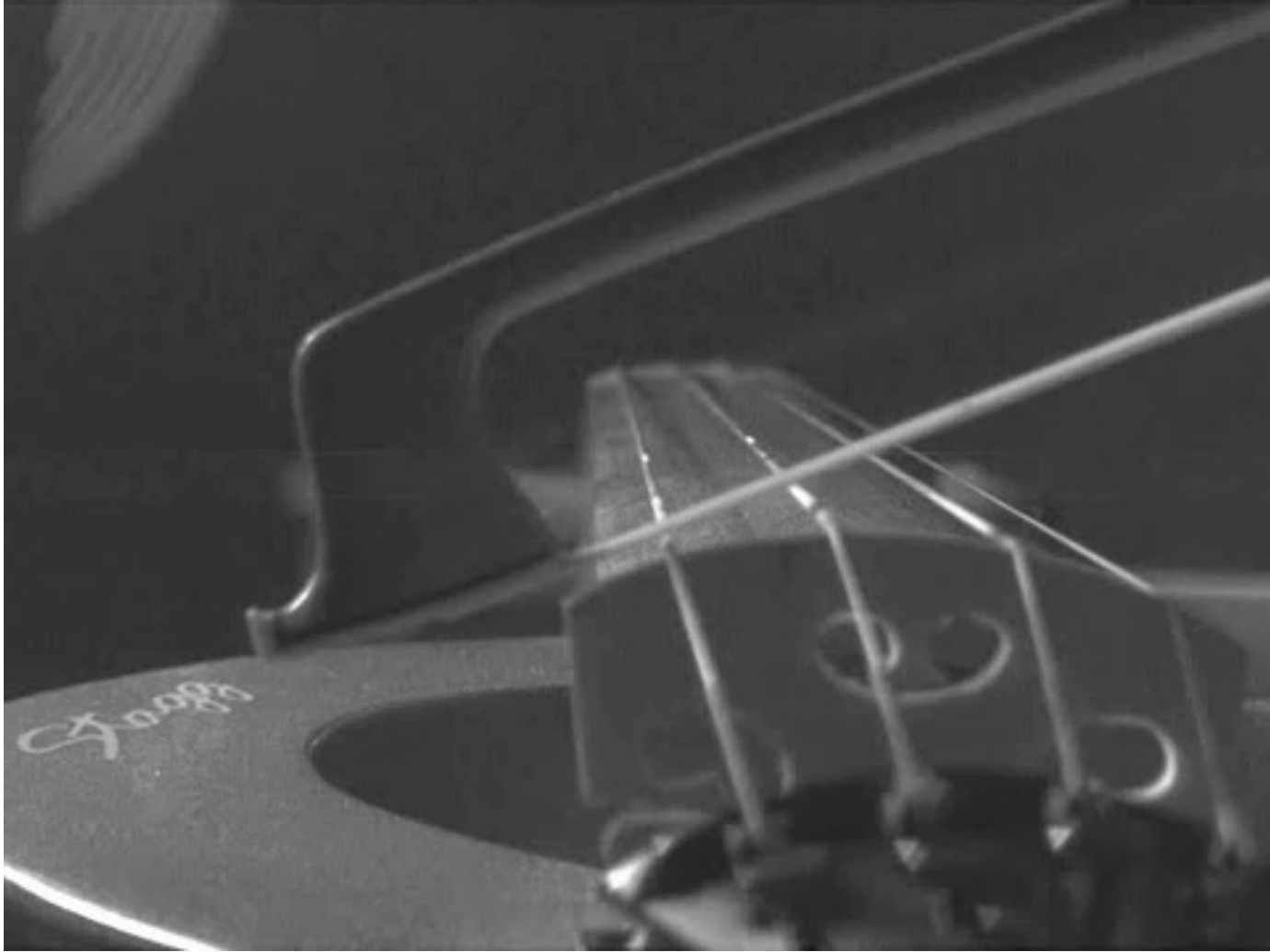
Oil

With additive 1

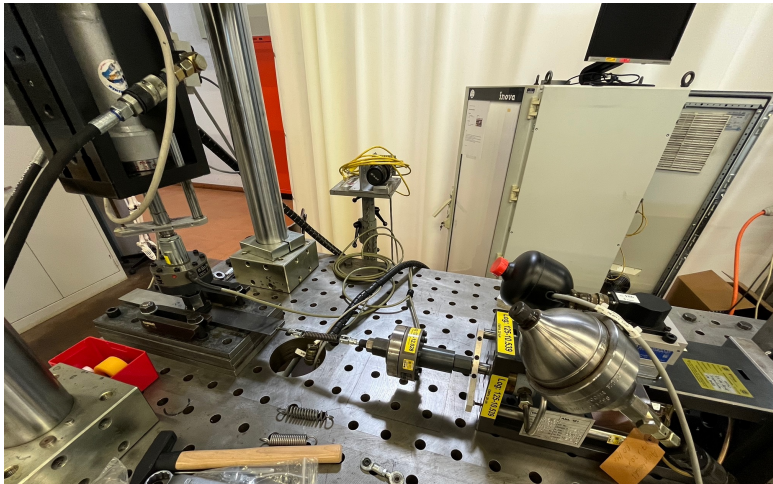


With additive 2

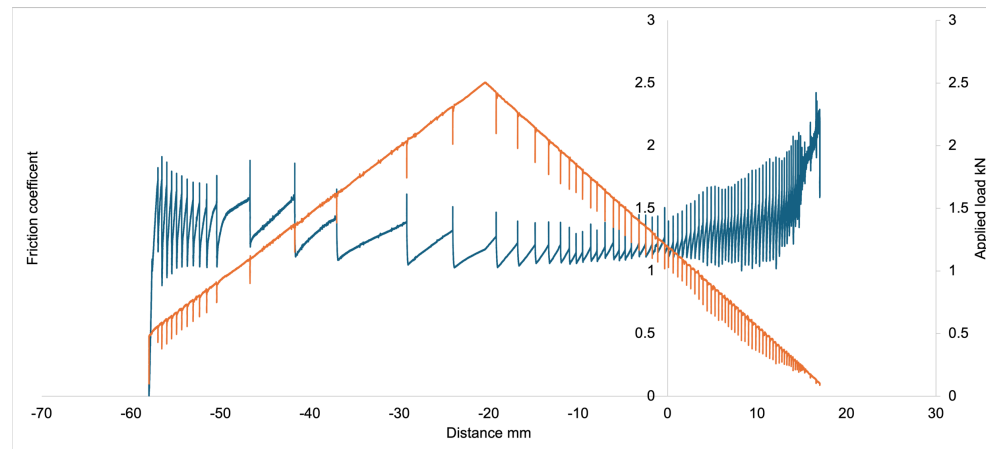




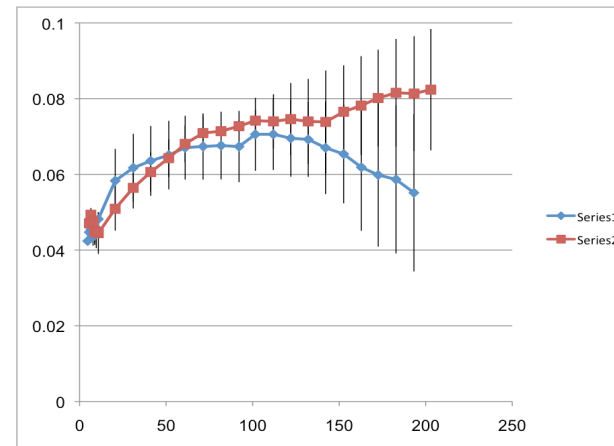
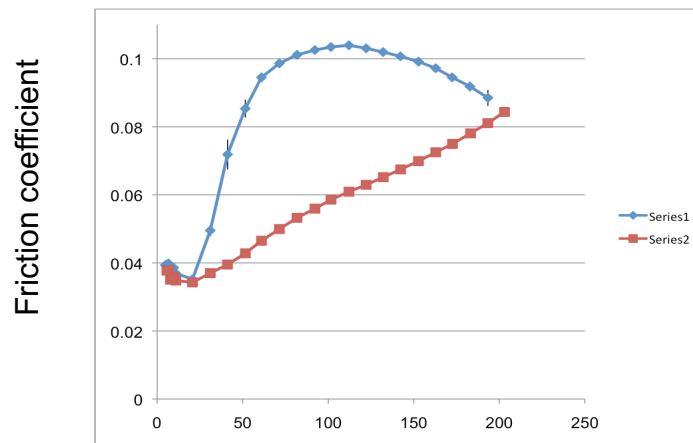
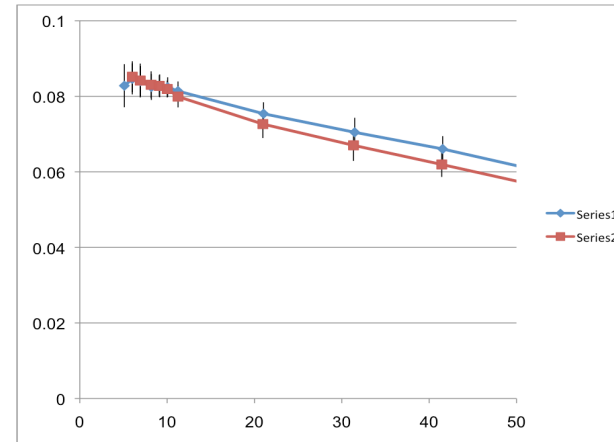
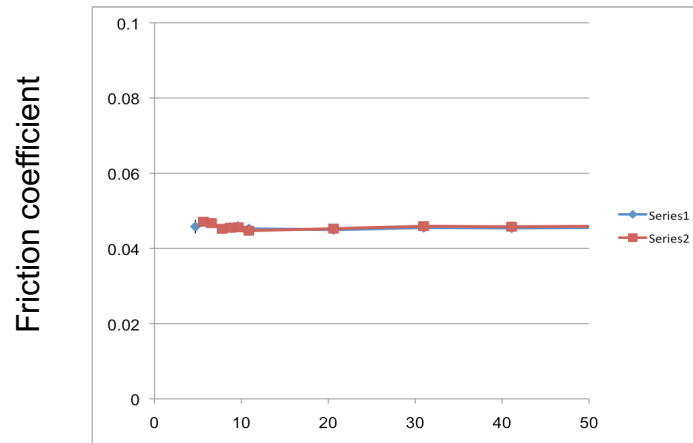
# Measurement of stick-slip



Speed 0.3 mm/s



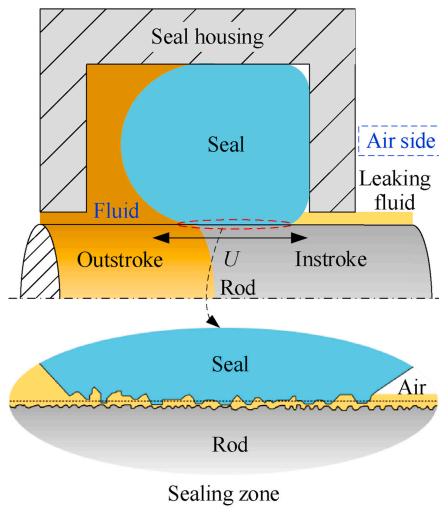
# Friction instabilities – Kinetic stick-slip



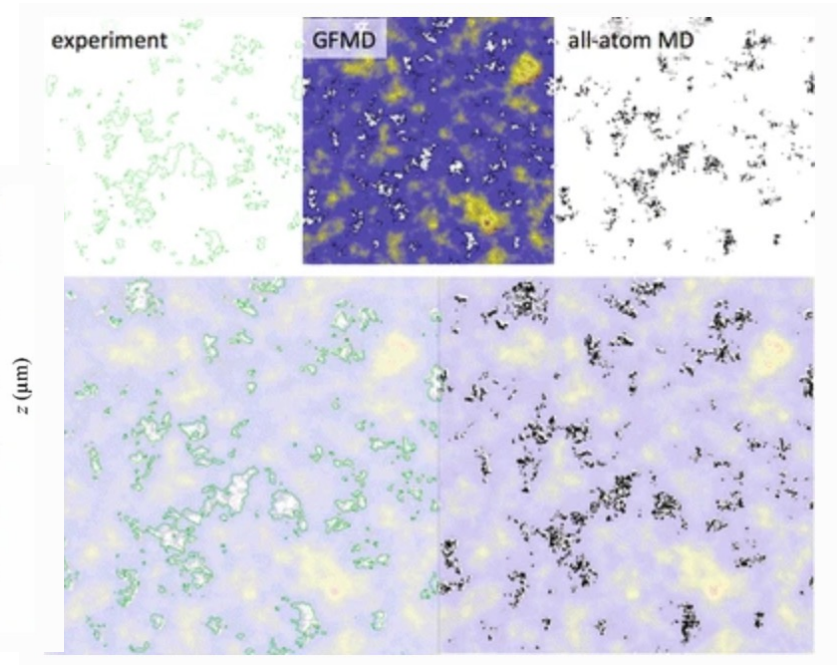
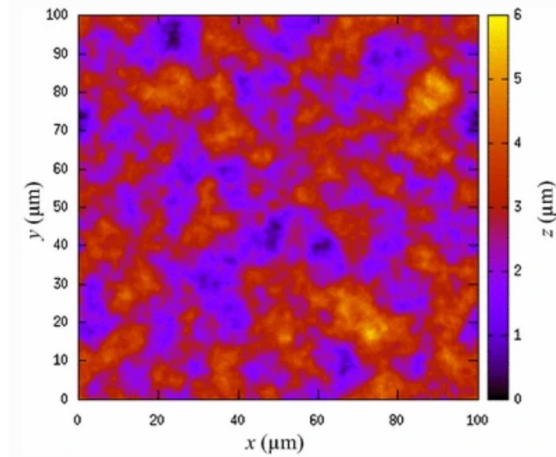
Speed  
mm/s

Speed  
mm/s

# Seals



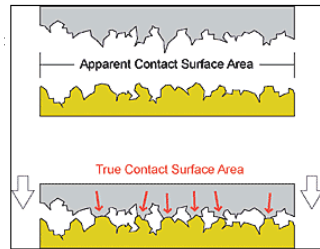
Theoretical countersurface



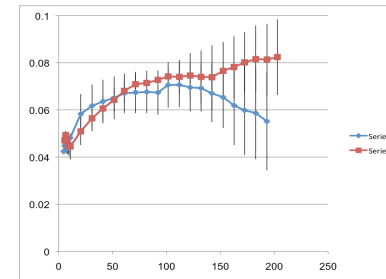
B. Wang, X. Meng, X. Peng, Y. Chen, *Tribology International*, 2021, 156, 106791

M. H. Müser et al (35 authors), *Tribology Letters*, 2017, 65, 118

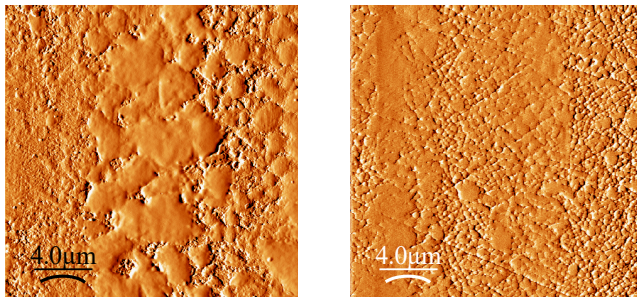
# Summary



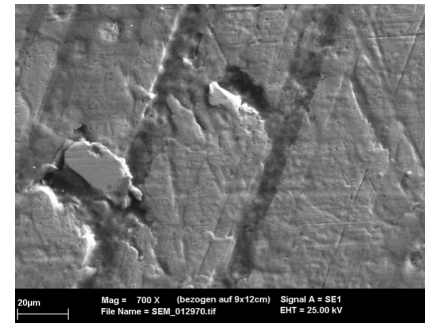
Reduction of friction and prevention of wear



Stabilisation of friction



Additives mainly designed for use with steel



Good adhesion has negative consequences