EMPA

Materials Science & Technology

Liquid Lubrication

Rowena Crockett, Empa,
Switzerland

CCMX Summer School, Visp 2021

Liquid lubrication

http://images.google.ch

Part 1. Fluid film lubrication

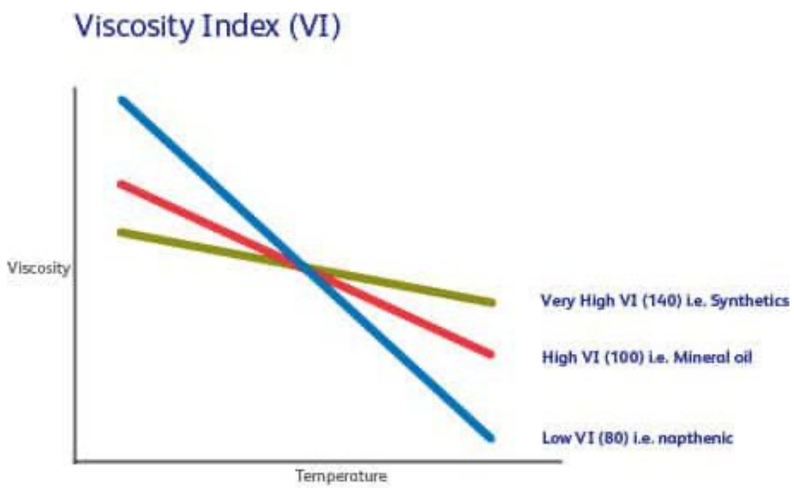
- Base oil
- Stribeck Curve
- The fluid film
- Slip: influence of the surface
- Greases
- Waterbased lubrication

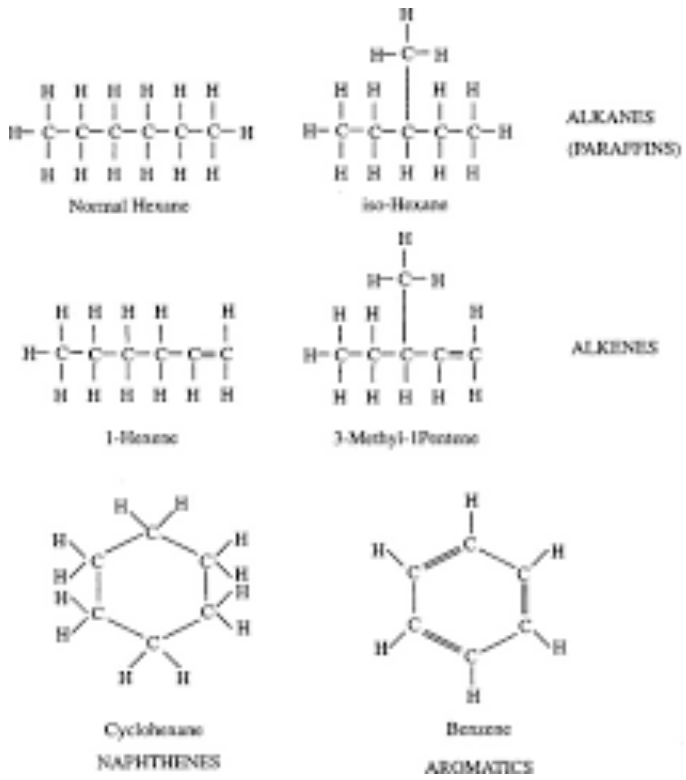
Part 2. Boundary lubrication

- Surface interactions of additives
- 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



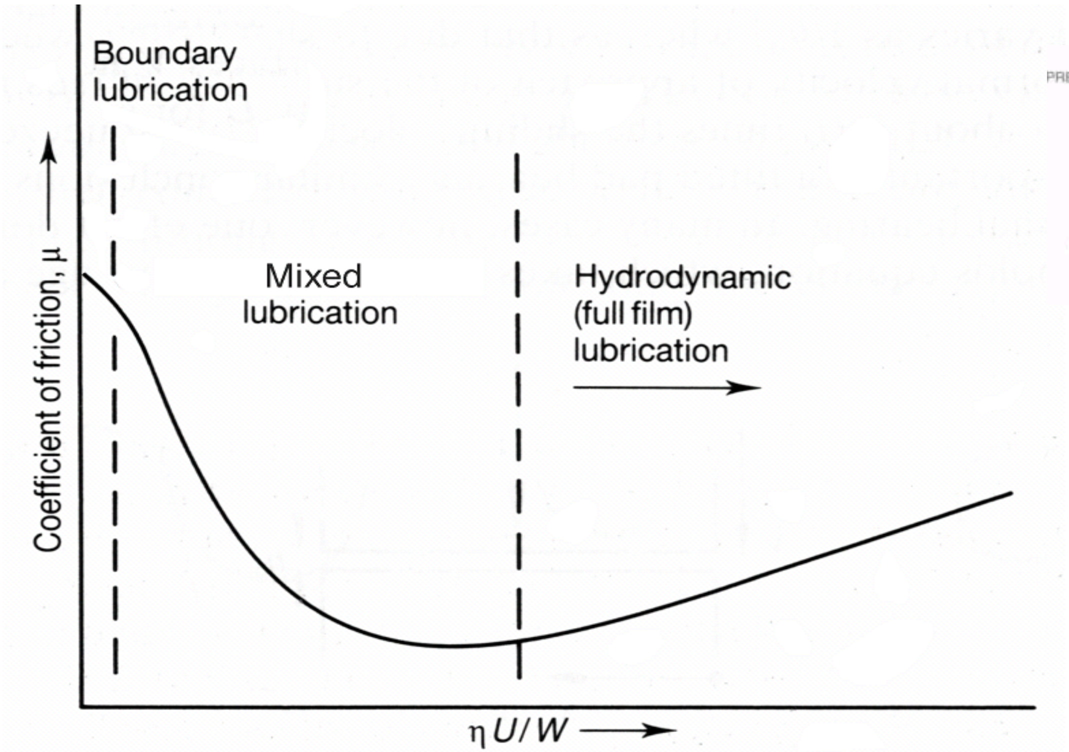


Synthetic Base Oils

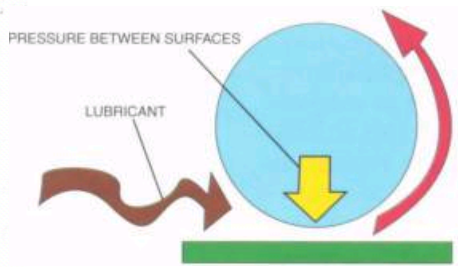
SYNTHETIC FLUID	STRENGTHS	WEAKNESSES	APPLICATIONS
POLYALPHAOLEFINS	High VI, high thermal oxidative stability, low volatility, good flow properties at low temperatures, nontoxic	Limited biodegradability, limited additive solubility, seal shrinkage risk	Engine oil, gear oils, bearing oils, compressor oils, high-temperature grease, lube-for-life applications
DIESTERS AND POLYOLESTERS	Nontoxic, biodegradable, high VI, good low-temperature properties, miscible with mineral oils	Low viscosities only, bad hydrolytic stability, limited seal and paint compatibility	Compressors oils, high-temperature grease, a co-base stock with PAOs, bearing oils, gear oils, oil mist, jet engine oils
PHOSPHATE ESTERS	Fire-resistant, biodegrades quickly, excellent wear resistance, scuffing protection	Low VI, limited seal compatibility, not miscible with mineral oils, moderate hydrolytic stability	Fire-resistant hydraulic fluids used in power plants, factories, marine vessels, mining, aircraft, mobile equipment
POLYALKYLENE GLYCOLS	Excellent lubricity, nontoxic, good thermal and oxidative stability, high VI	Additives marginally miscible, not miscible with mineral oils, limited seal and paint compatibility	Refrigeration compressors, brake fluids (water-soluble), gas compressors (low gas solubility), warm and high-temperature gears, chain lube (clean burn off), metal-working and quenchants, H1 food grade
SILICONES	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	High-temperature fluids, speciality greases, lubricant-contacting chemical, some brake fluids

https://www.bharatpetroleum.in/

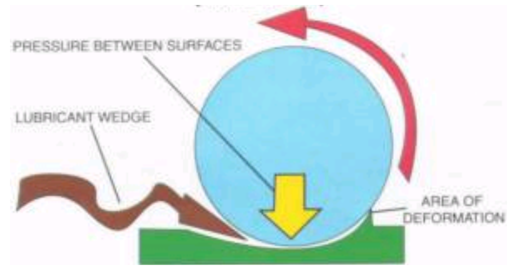
Stribeck Curve: A tool to describe the friction behavior of a liquid lubricant



Hydrodynamic



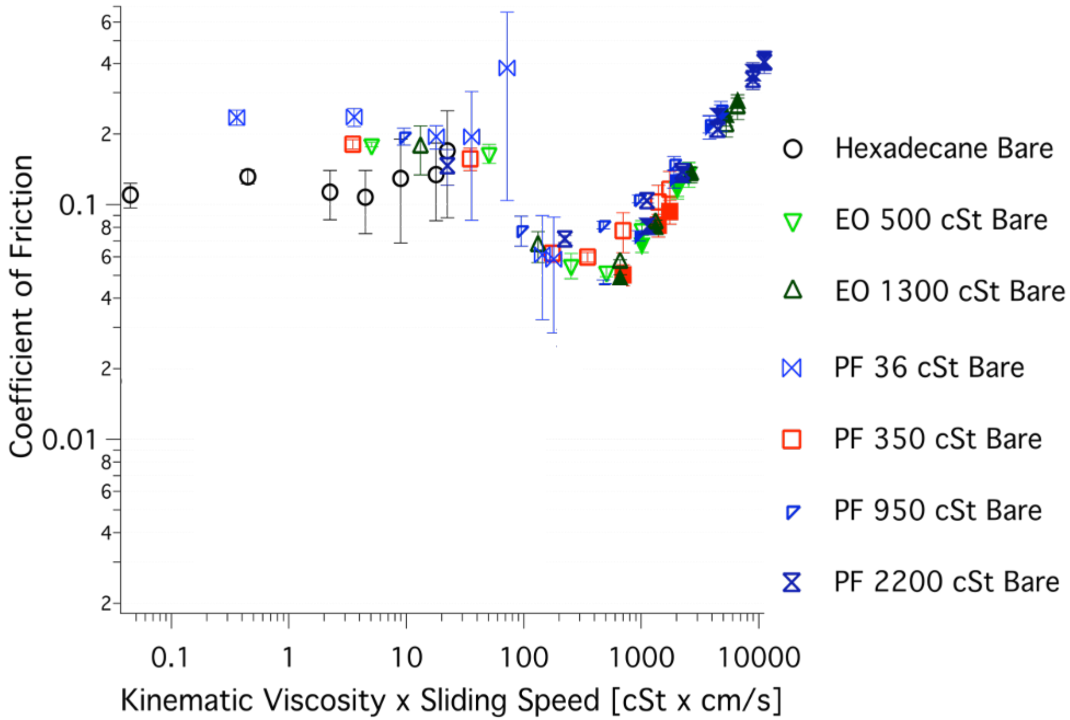
Elastohydrodynamic



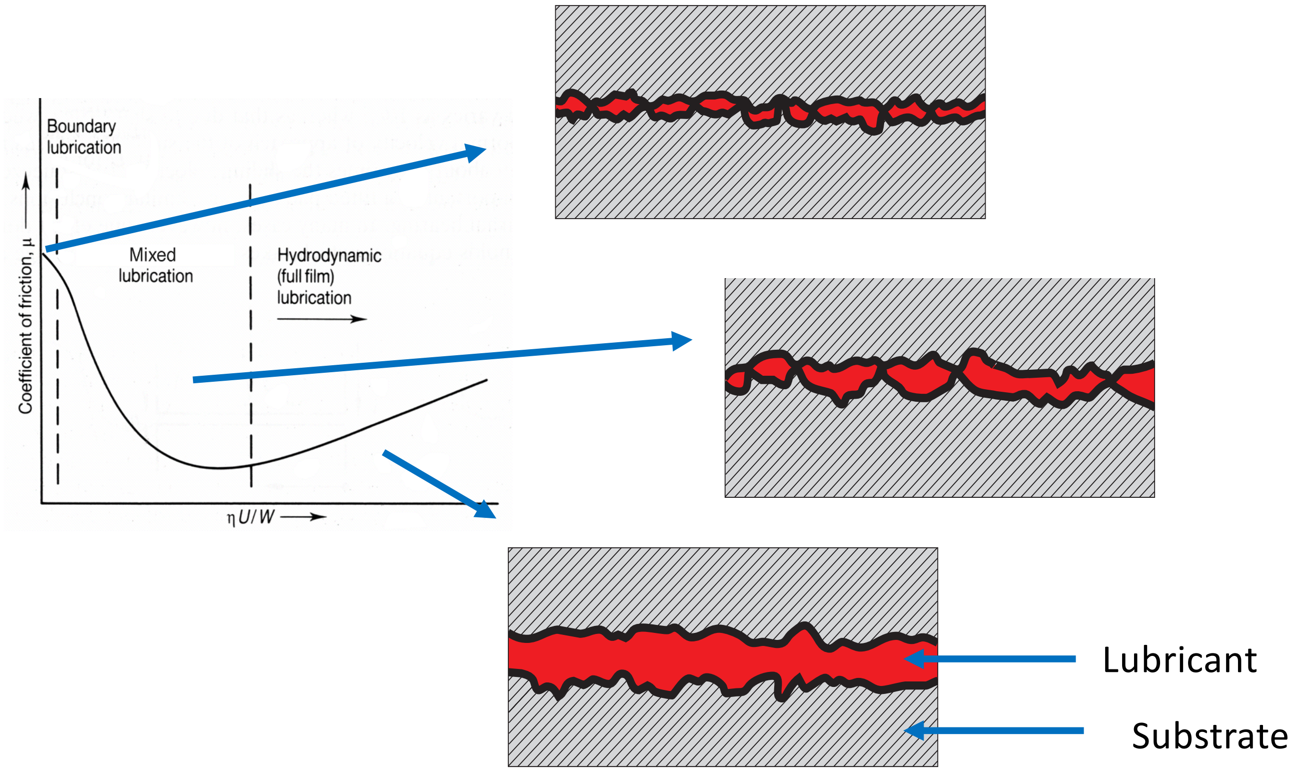
Hersey number $\dfrac{ms^{-1} * Nsm^{-2}}{Nm^{-1}}$

(Shaft radius/radial clearance) *(Dynamic Viscosity x Speed)/load (pressure)

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



Robert M. Bielecki, Maura Crobu, and Nicholas D. Spencer *Tribol Lett* (2013) 49:263–272

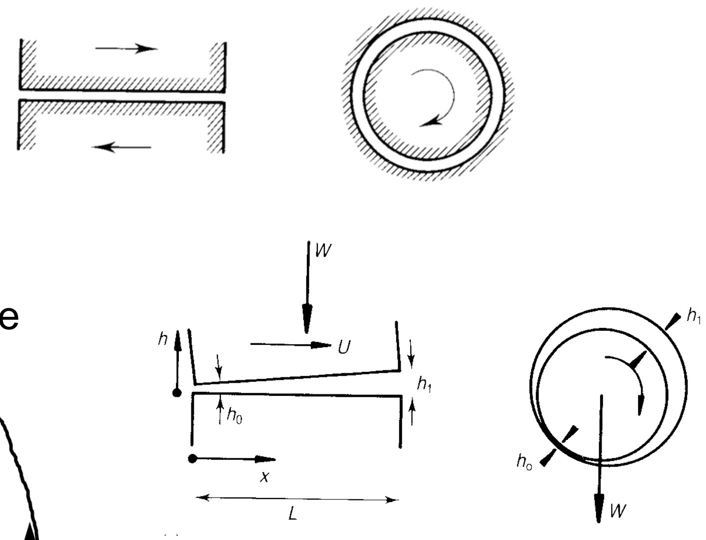


Friction regimes

- Boundary: the sliding or rolling surfaces are seperated by residual adsorbed oil or a film formed from the additives in the oil
- Mixed: Fewer asperity contacts as surfaces begin to seperate
- Hydrodynamic: Full film lubrication with complete seperation of surfaces

Hydrodynamic Lubrication

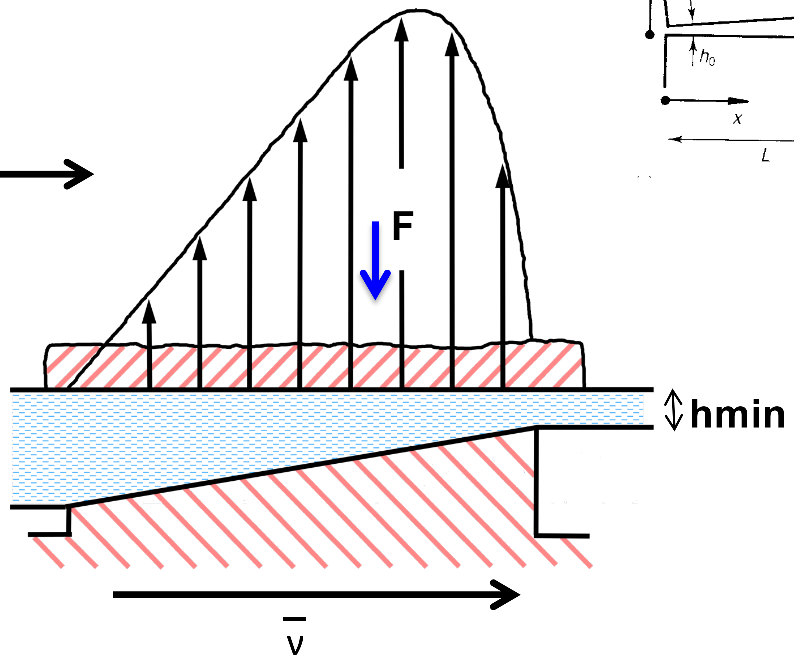
Prerequisites:



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

Pressure distribution

Lubricating film



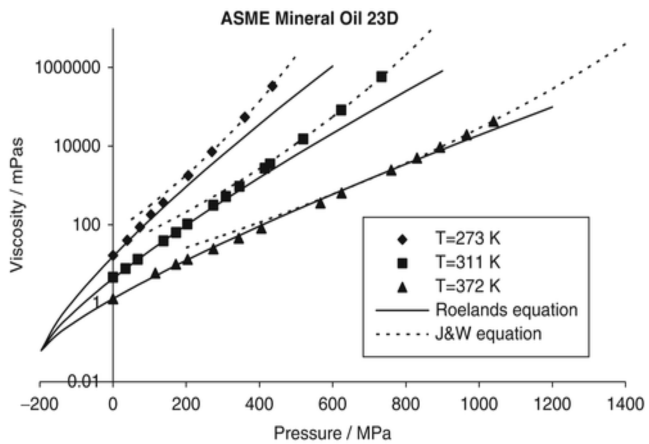
(Denis Mazuyer, Ecole Centrale de Lyon)

Hydrodynamik

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

h_{min}	[mm]	film thickness in the rolling contact
a	[mm²/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/mm²]	elastic modulus
1/m		Poission‘s ratio

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

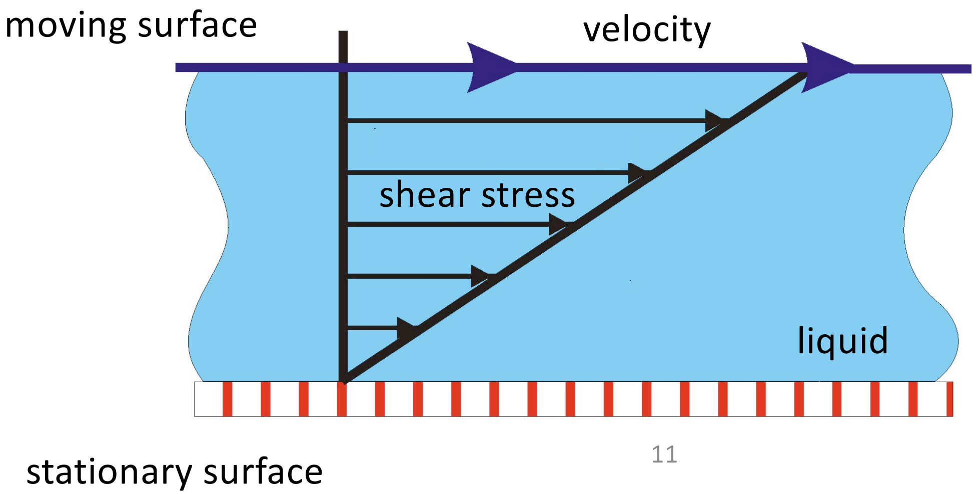


Factors influencing hydrodynamic lubrication

- hmin> 3 * Ra
- Load and average speed,
- Contact geometry
- Elastic modulus and Poission's Ratio of contacting materials
- Dynamic viscosity
- Pressure-viscosity coefficient

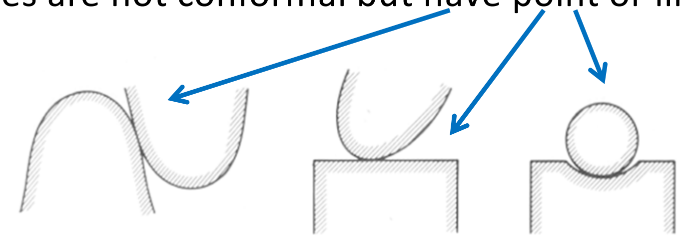
Viscosity is a measure of the resistance of a fluid to deform under shear stress

<u>Dynamic viscosity:</u> 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

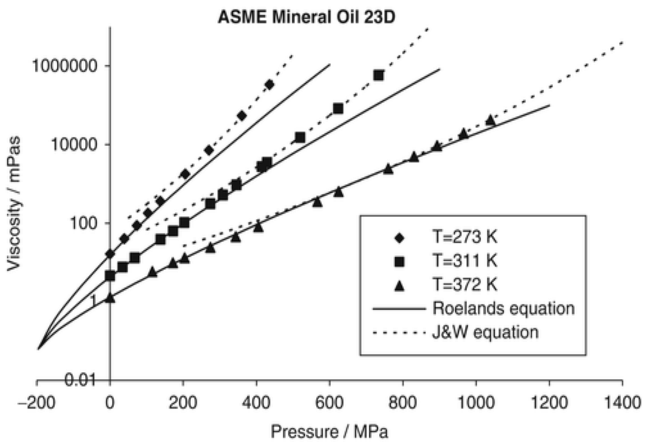
When the sliding surfaces are not conformal but have point or line contact



Much higher local pressures are present

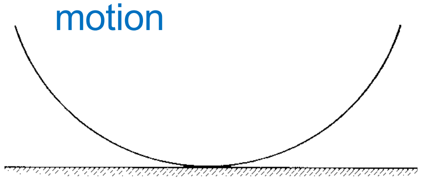
- Important factors: pressure dependence of the lubricant and elastic deformation of the surfaces
- GPa pressures are frequently involved—oil becomes so viscous it is practically solid!

Piezo viscous effect



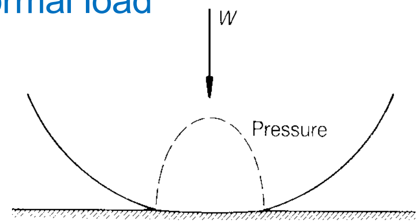
Elastohydrodynamic lubrication

Point contact
no normal load
no relative sliding
motion



Contact initially occurs at a point

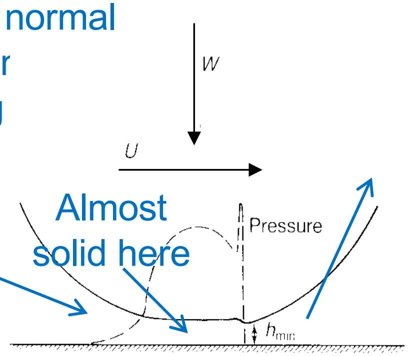
Contact area resulting from the normal load



Pressure increases

contact area grows

Elastic distortion under normal load ar sliding



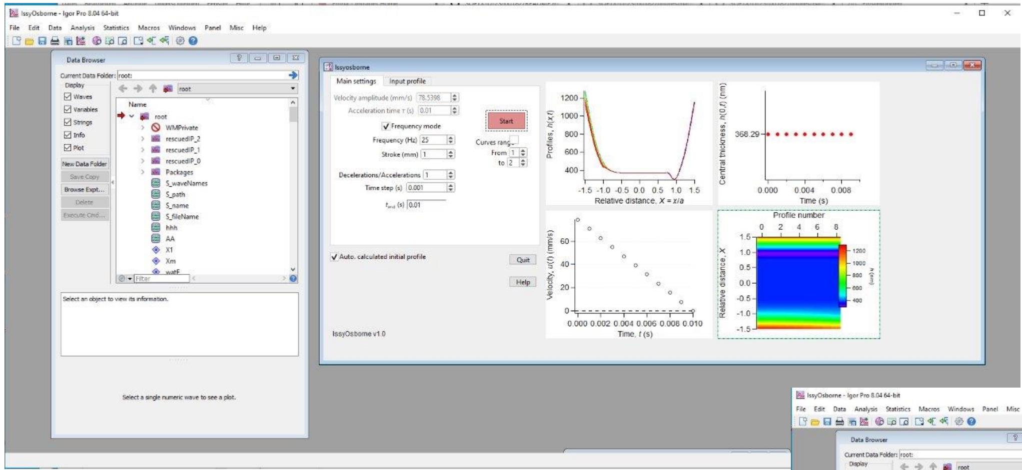
Lubricant

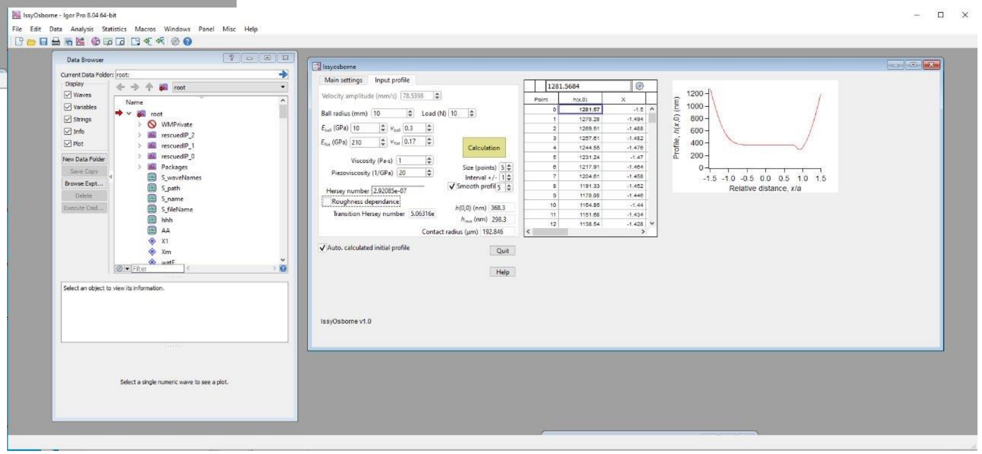
Sudden release of lubricant: elastic modification of one of the solids

Lubricating film and sphere sliding over the surface

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

Calculation of fluid film profile



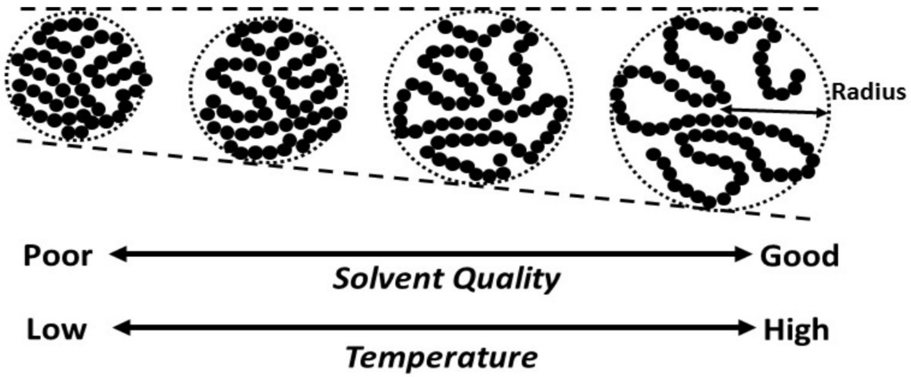


https://github.com/ElsevierSoftwareX/SOFTX-D-23-00182
Malik Yahiaoui, Denis Mazuyer, Juliette Cayer-Barrioz

Hydrodynamic Lubrication: Viscosity improvers

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

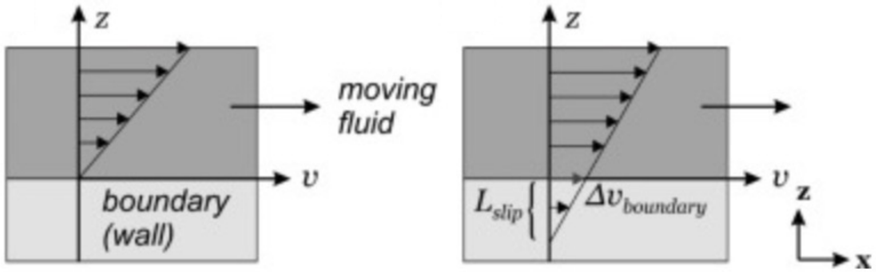
PMAs appear to thicken oils by expansion of the polymer coil with temperature



Olefin copolymers thicken base oils by about the same proportion, regardless of temperature. Therefore the degree of viscosity increase from 100℃ to 40℃ will be less for a polymer-containing low viscosity base oil than a polymer-free higher viscosity base oil of equal 100℃ viscosity.

Michael J. Covitch and Kieran J. Trickett
Advances in Chemical Engineering and Science, 2015, 5, 134-151

Slip



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

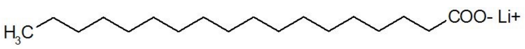
No interaction → large slip, no hydrodynamic lubrication
Strong interaction → no slip

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

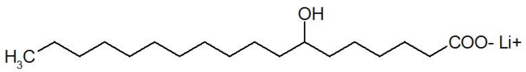
Grease

Grease is mostly nasty
Used in extreme conditions
Compositions: Base oil, thickener, additives

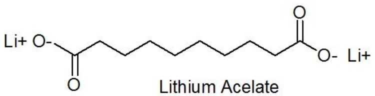
Examples of thickeners



Lithiumstearate



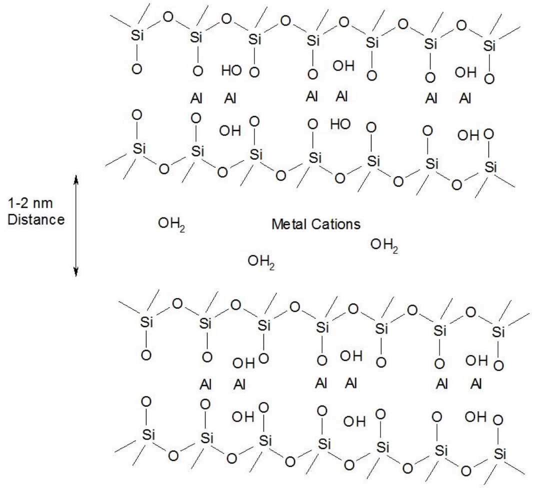
Lithium-12-hydroxystearate



Lithium Acelate

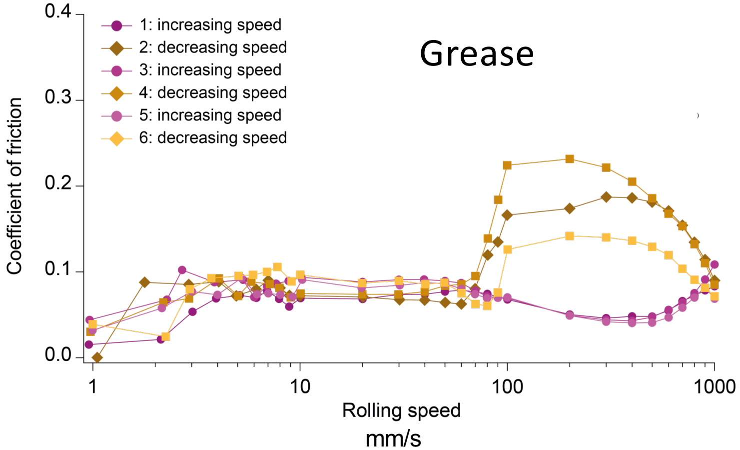
H$_3$C—COO- Ca++ -OOC——CH$_3$

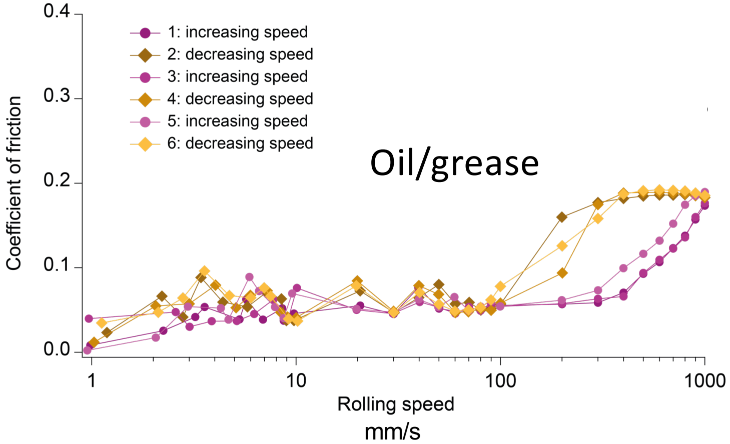
Calciumacetate



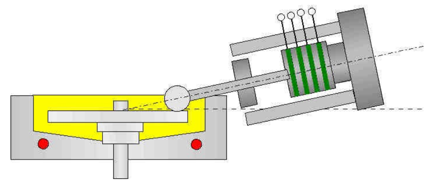
Clays, talc

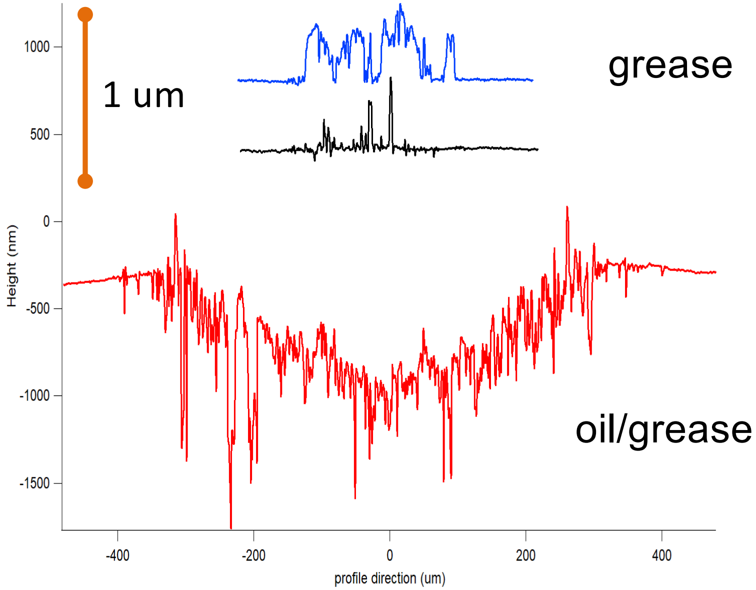
Bleeding in grease





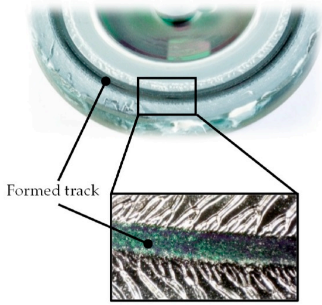
Mini Traction Machine (MTM)

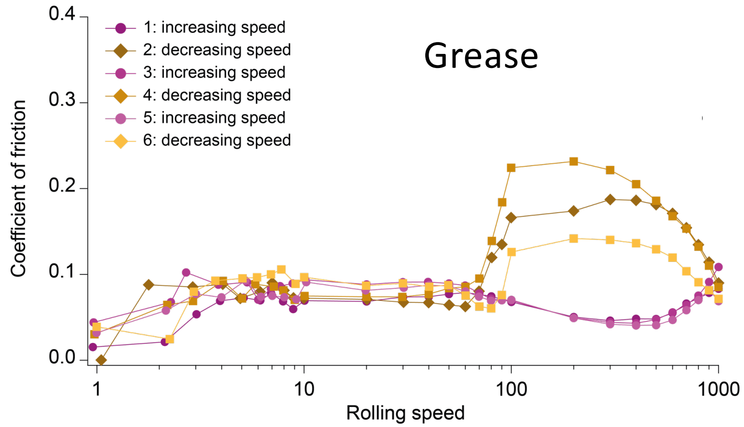




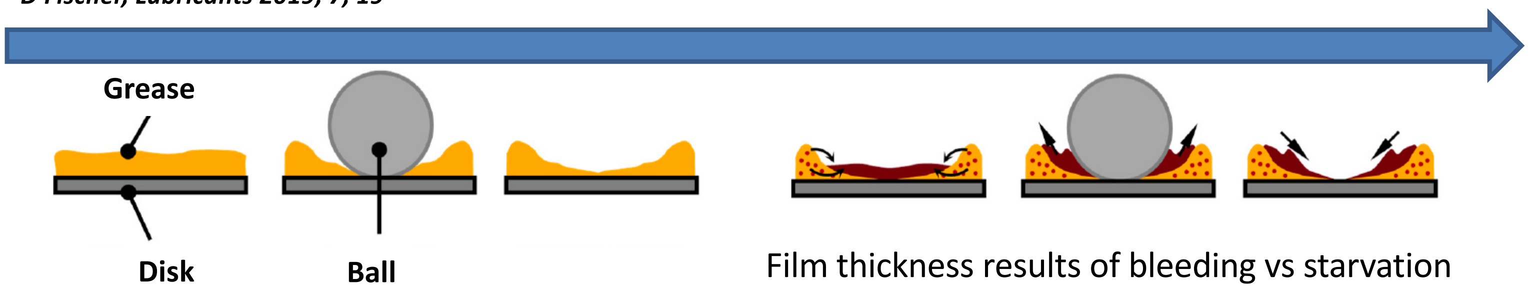
Grease bleeding

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

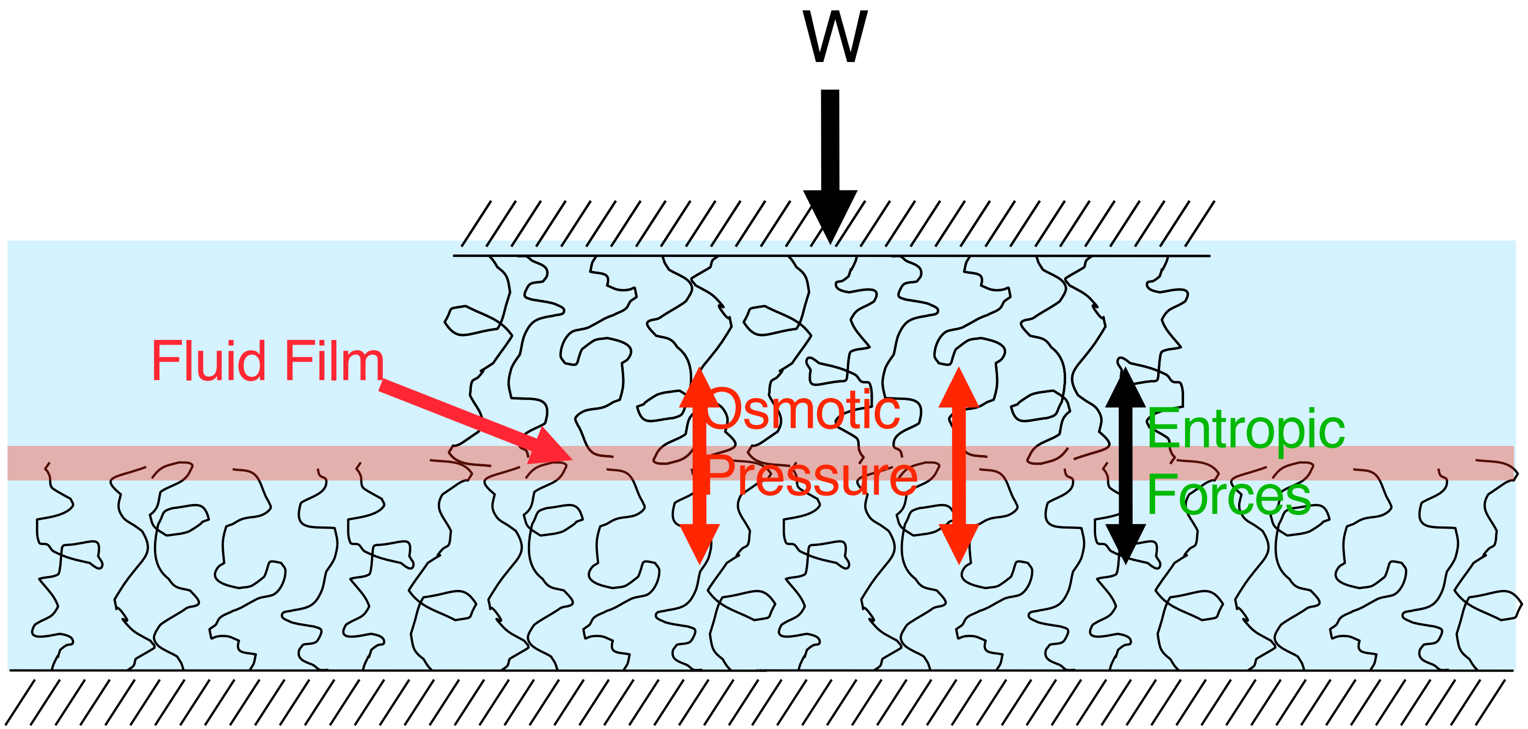
advantages

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

disadvantages

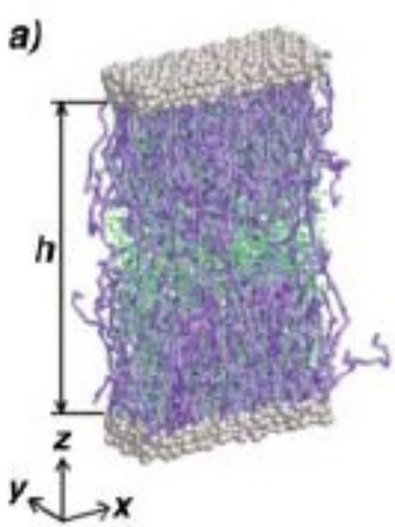
- low viscosity
- viscosity does not increase under pressure (low pressure coefficient of viscosity)

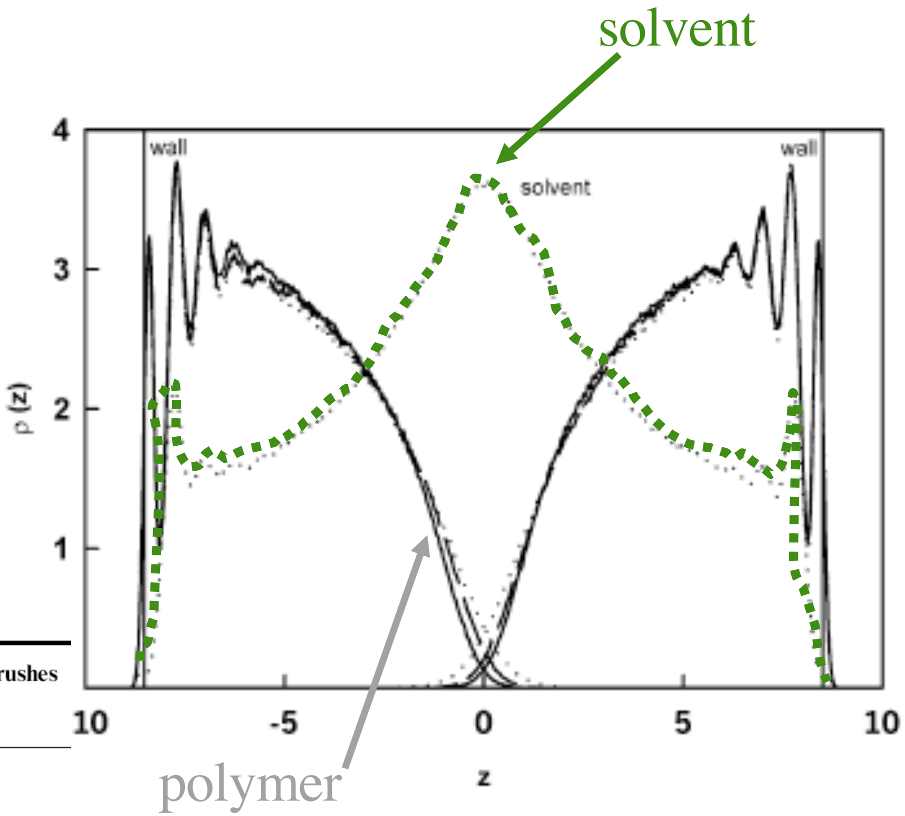
Aqueous based lubrication with polymers



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,[a] Dominic Tildesley[a] and Patrice Malfreyt[b]

[a] *Unilever Research Port Sunlight, Bebington, Wirral, UK CH63 3JW*
[b] *Laboratoire de Thermodynamique des Solutions et des Polymeres, UMR CNRS 6003, 24 avenue de Landais, Universite Blaise-Pascal, 63177, Aubiere Cedex, France*

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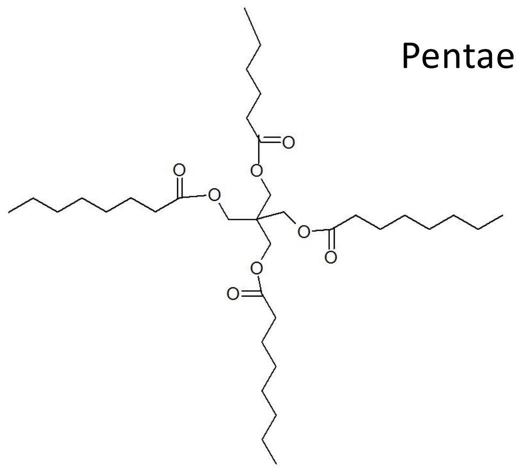
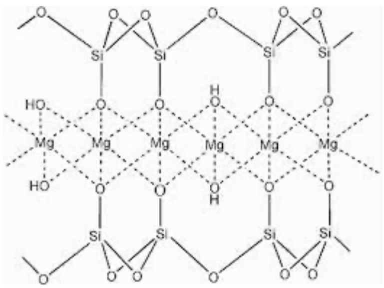
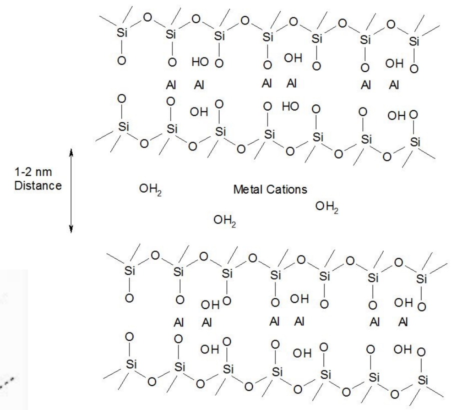
Thickeners for water-based hydrolic fluids

Pentaerythrolesters

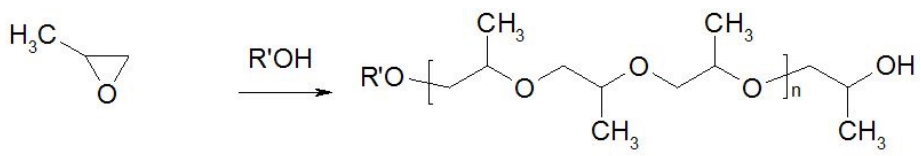






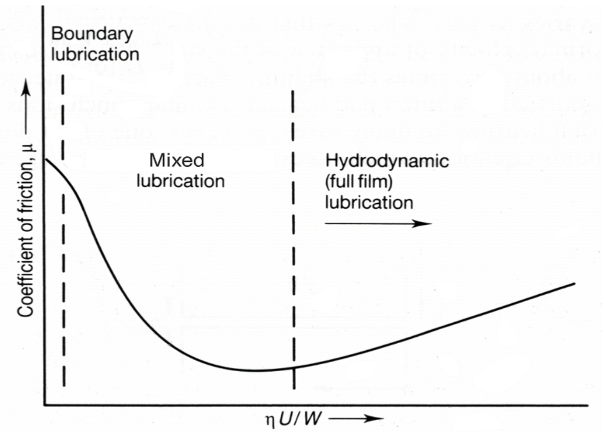
Clays or talc

Polypropylene Glycols



Summary

- Ideally, machinary 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

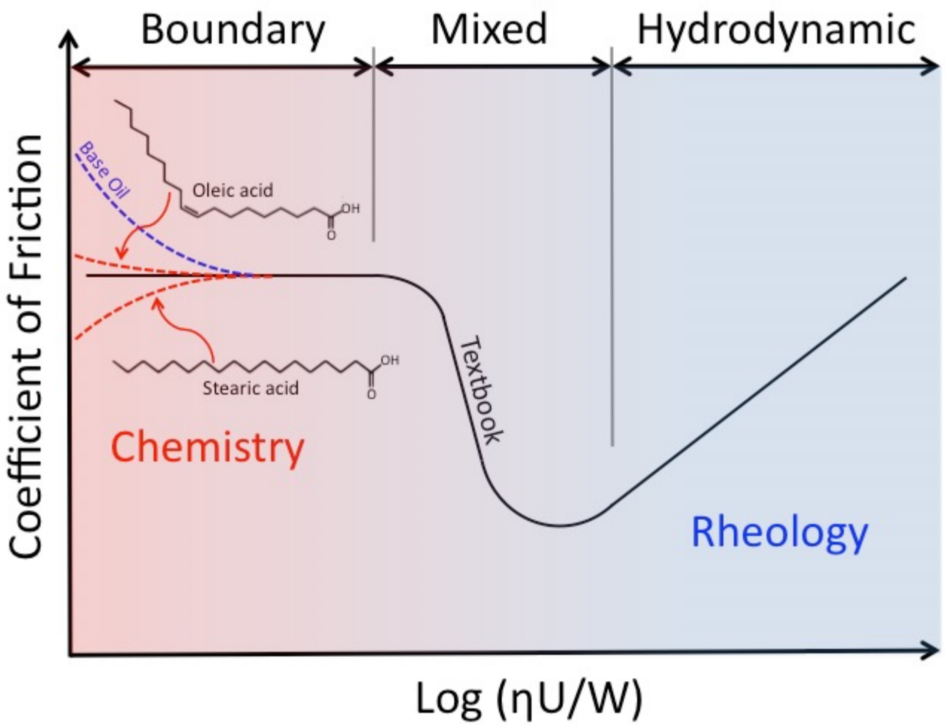


Liquid Lubrication

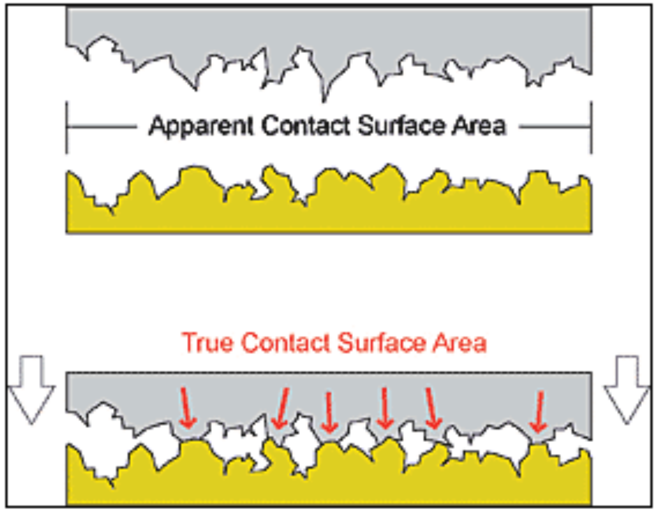
Part 2. Boundary Lubrication

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

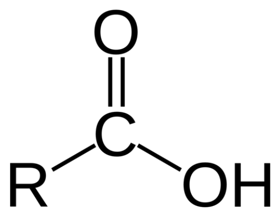
Stribeck Curve

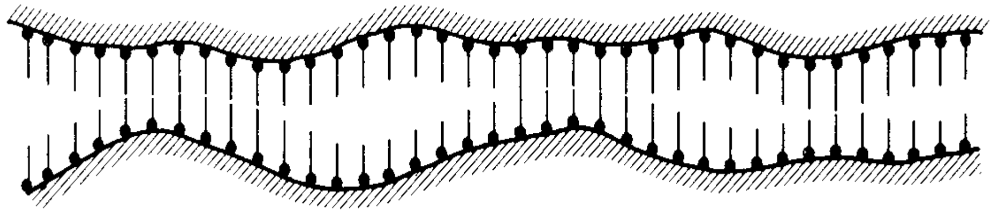


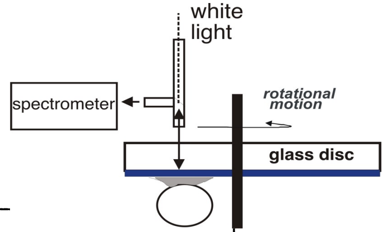
Contact area:
Friction modifiers and antiwear additives only required to function in the true contact area



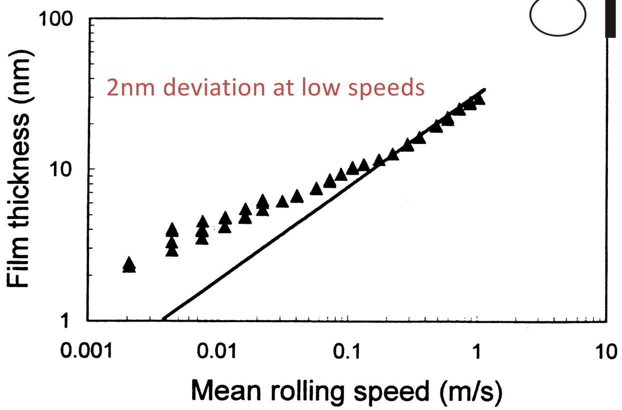
Friction modifiers

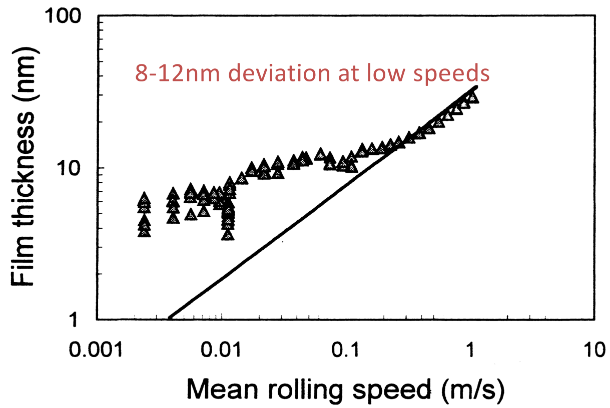






EHL film thickness measurements





octadecanoic acid (1% in hexadecane dry)

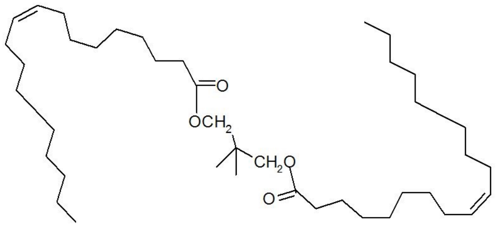
octadecanoic acid (1% in hexadecane, wet)

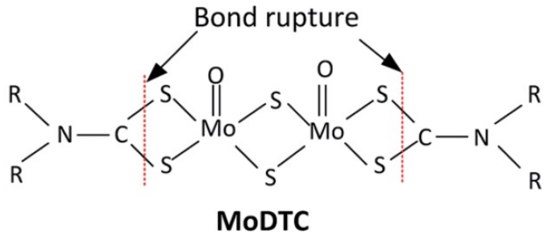
Formation of iron carboxylate salts in the prescence of water

Hugh Spikes, Tribology International, 2001, 34, 789

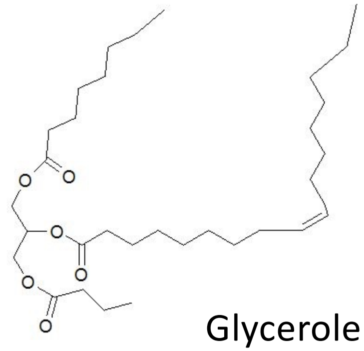
Other friction modifiers

Neopentylgylcoledioleate

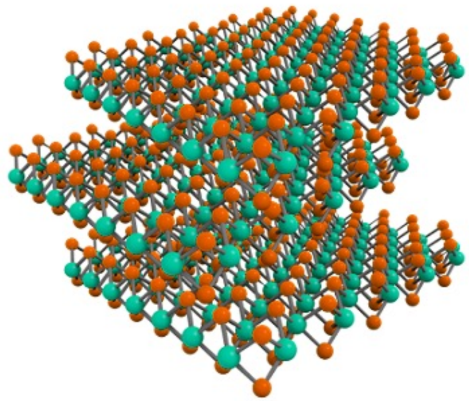




Molybdenum Dithiocarbamate

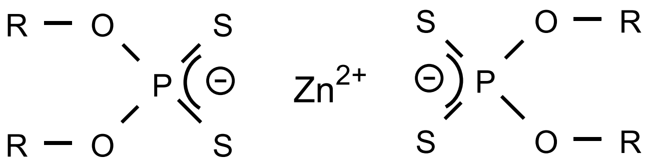


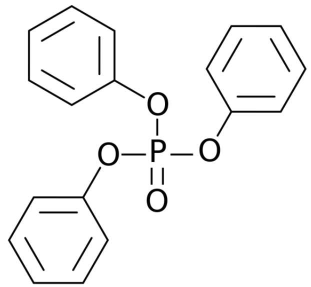
Glycerole triester

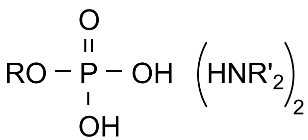


Anti-wear additives

Zinc dialkyl dithiophosphate

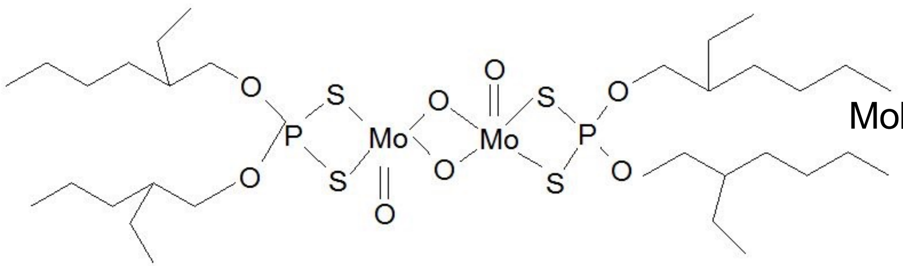






Amine phosphate

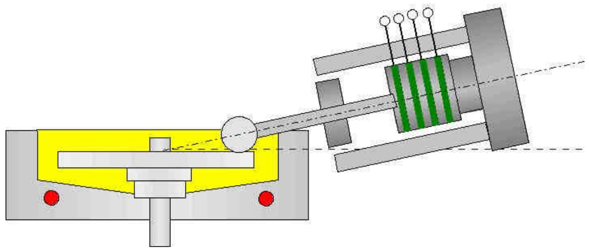
Triphenylphosphate



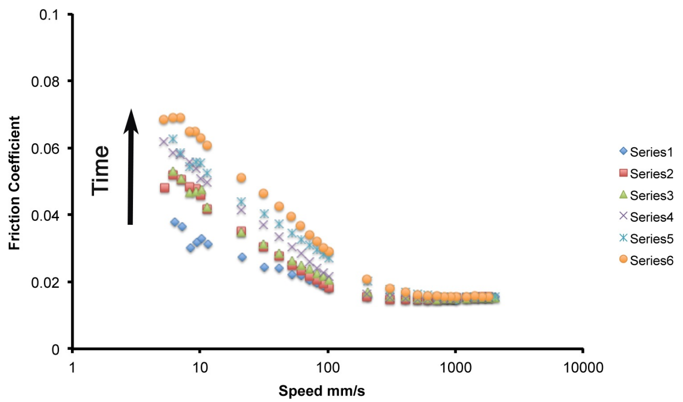
Molybdenumdithiophosphate

Friction behavior of ZnDTP

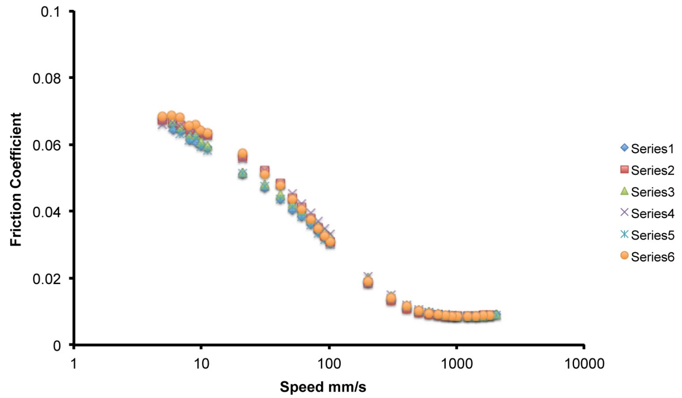
Mini Traction Machine (MTM)



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



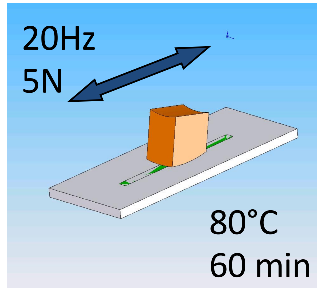
First measurements



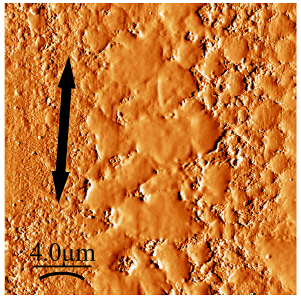
Last measurements

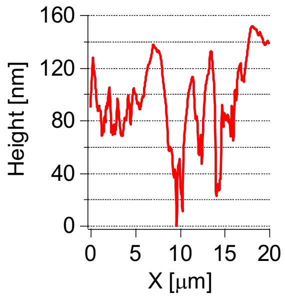
Topography of tribofilm on steel: Comparison of ZnDTP and amine phosphate (AP)

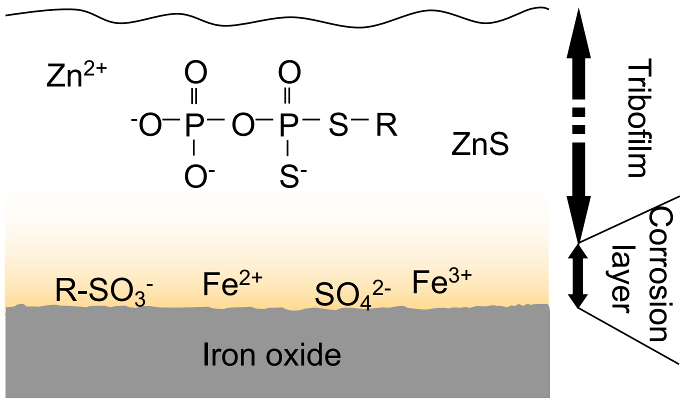
HFRR



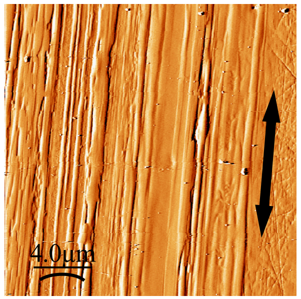
ZnDTP

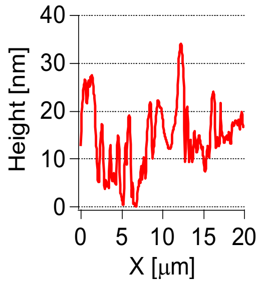


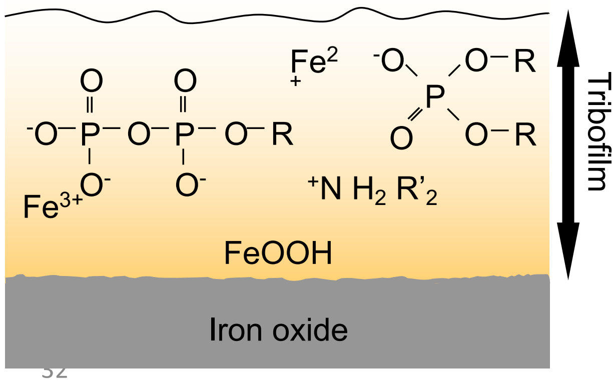




AP





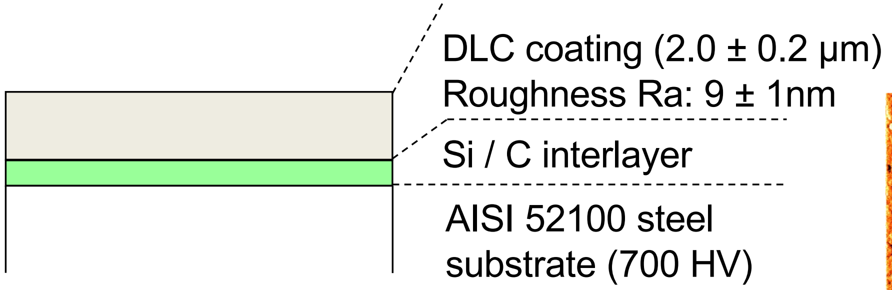


DLC coatings

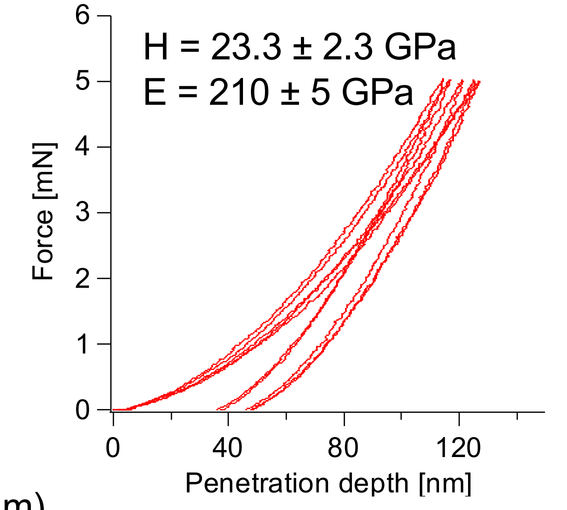
Hydrogenated amorphous carbon coatings (a-C:H) deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD)

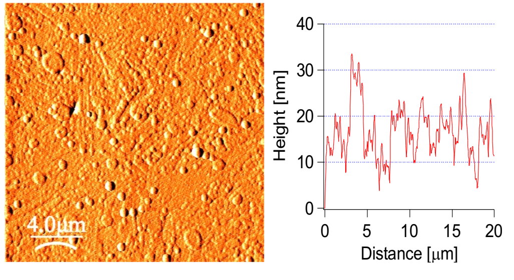
Gases: C_2H_2 , Ar.

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



Hardness of the DLC coating measured by nanoindentation

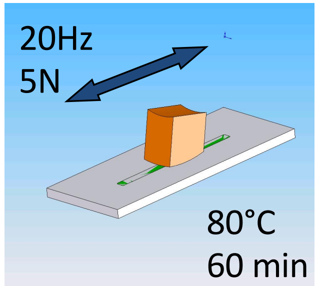




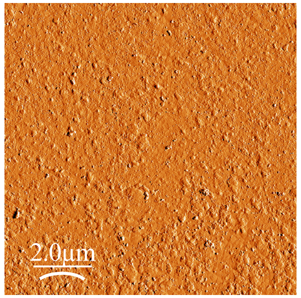
AFM observation of a DLC coating as-deposited surface

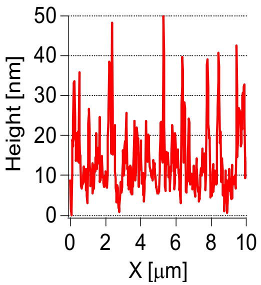
ZnDTP and AP on DLC

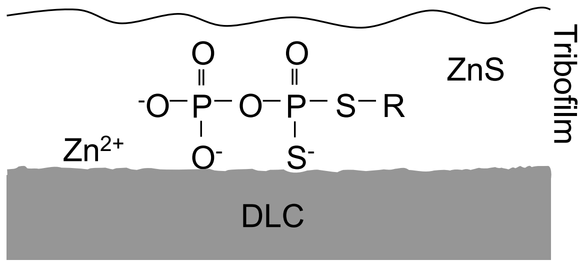
HFRR



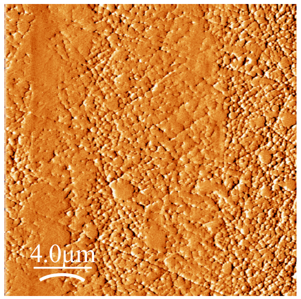
ZnDTP tribofilm on DLC

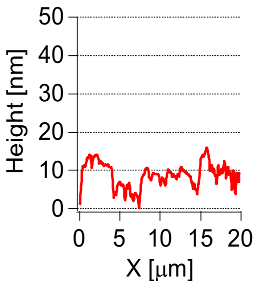


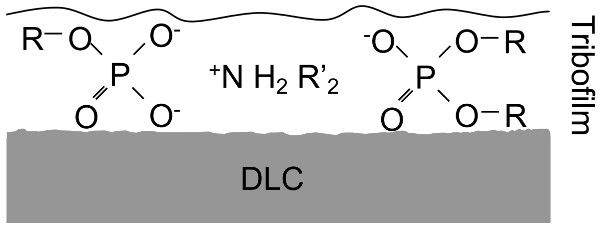




AP tribofilm on DLC



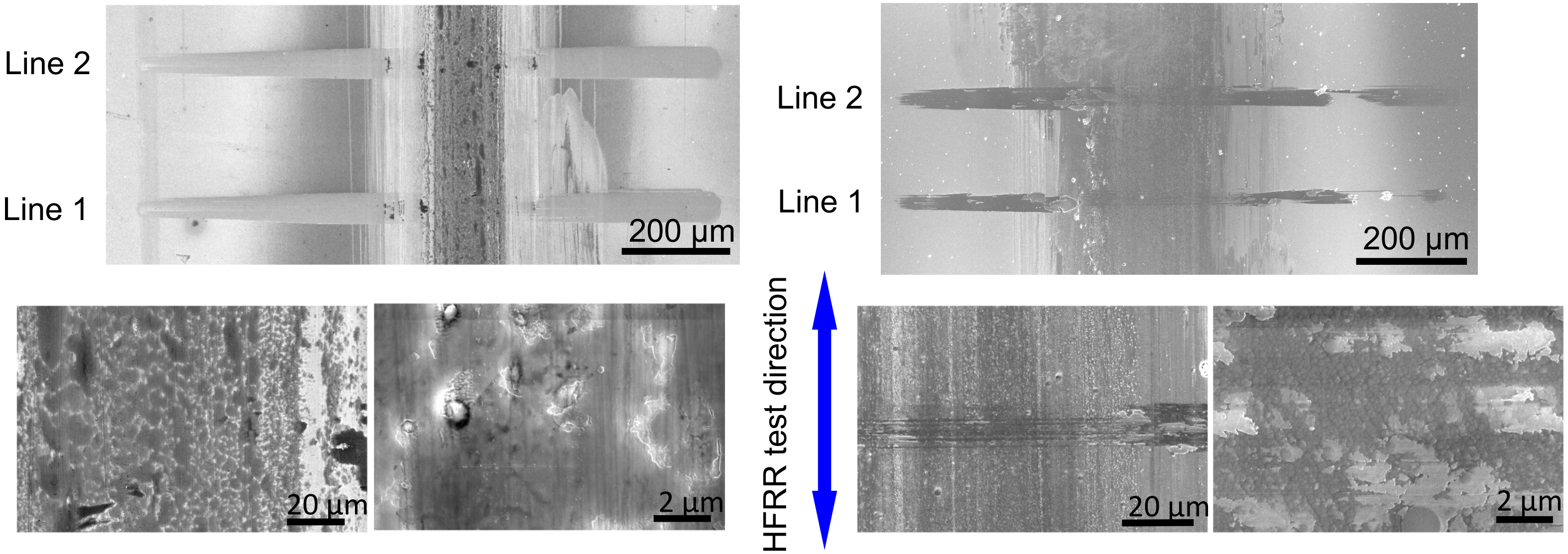




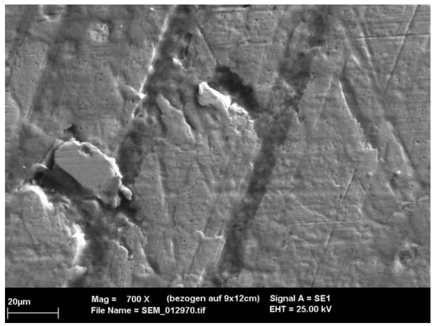
ZnDTP provided some wear protection but AP accelerated wear

Comparison of ZnDTP on steel and DLC surfaces

ZnDTP



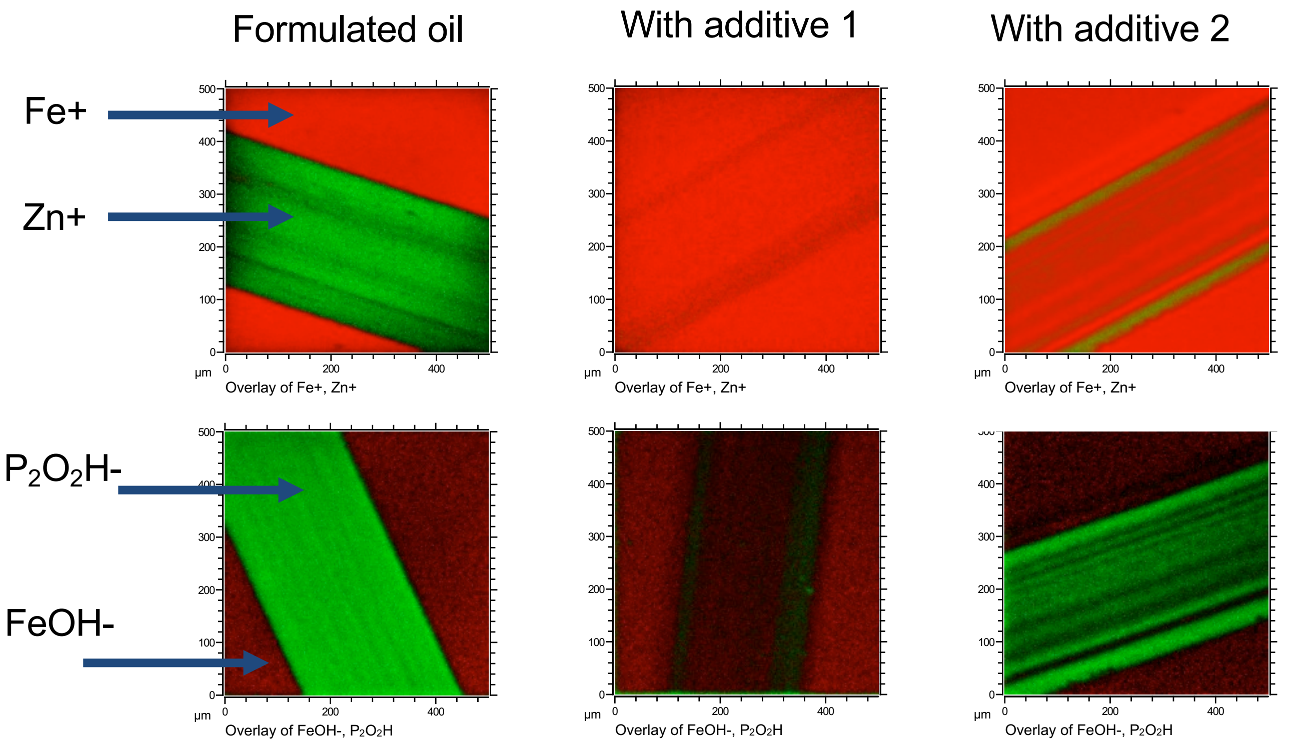
Corrosion layer results in good adhesion and eventually to damage to oil lubricated surfaces



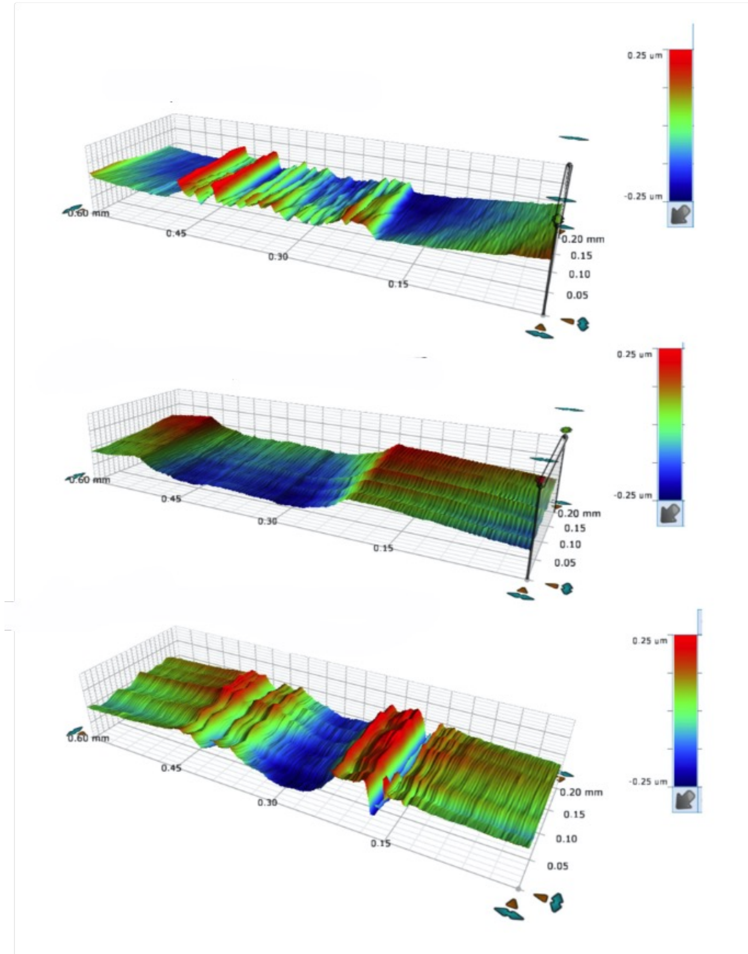
Competition for the surface

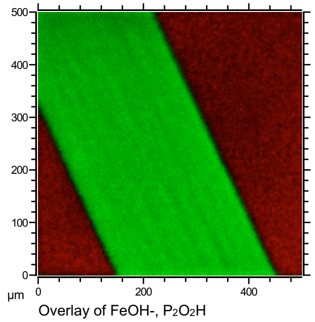
- For Viscosity
  - *Viscosity-index improvers*
  - *Pour-point depressants*
- For Lubricity
  - *Friction modifiers*
  - *Extreme-pressure and antiwear additives*
- Controlling Chemical Breakdown
  - *Detergents to prevent sludge*
  - *Corrosion inhibitors*
  - *Antioxidants*
- For Contaminant Control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

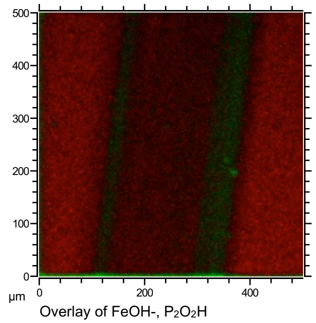


Track wear

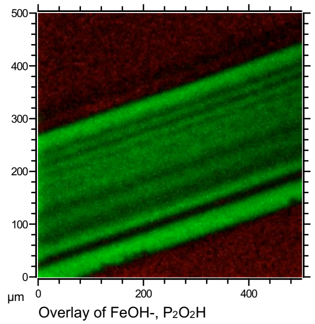




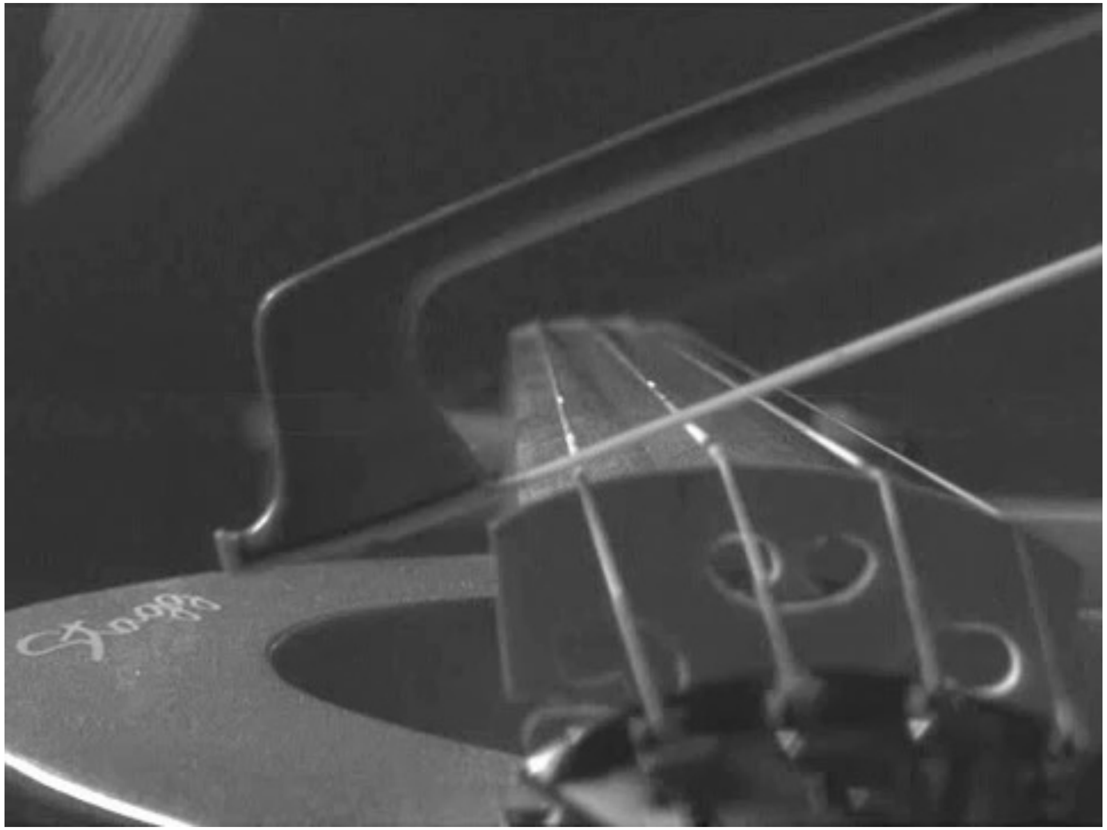
Oil



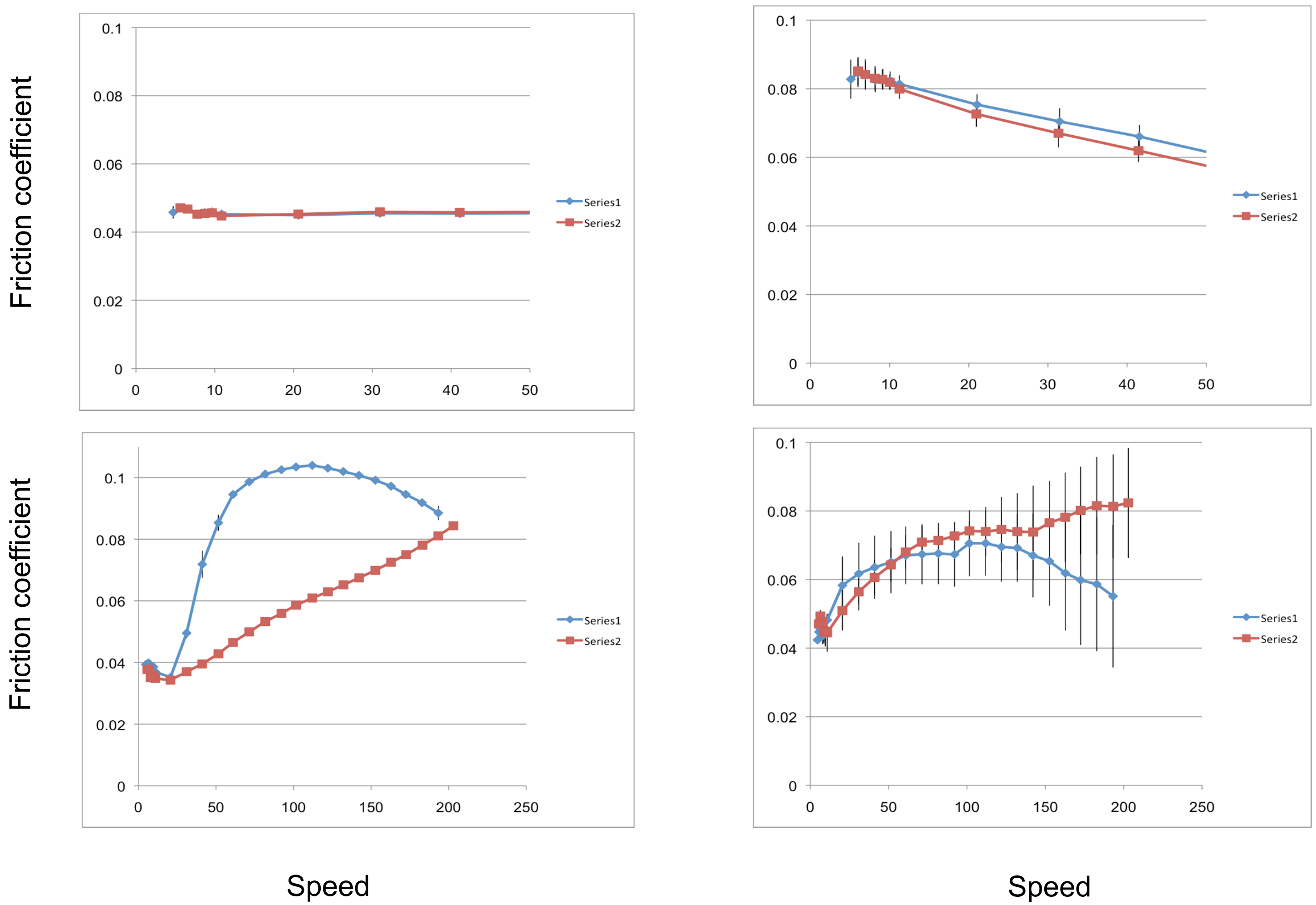
With additive 1



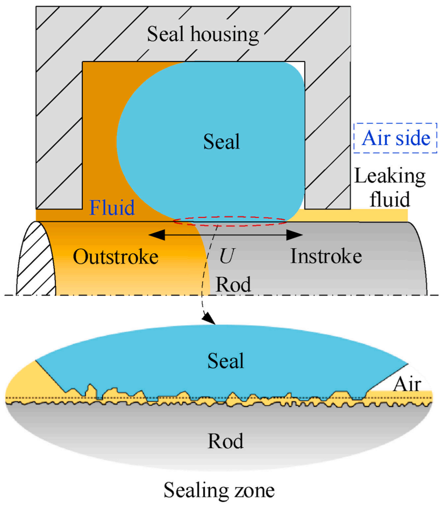
With additive 2



Friction instabilities – Kinetic stick-slip

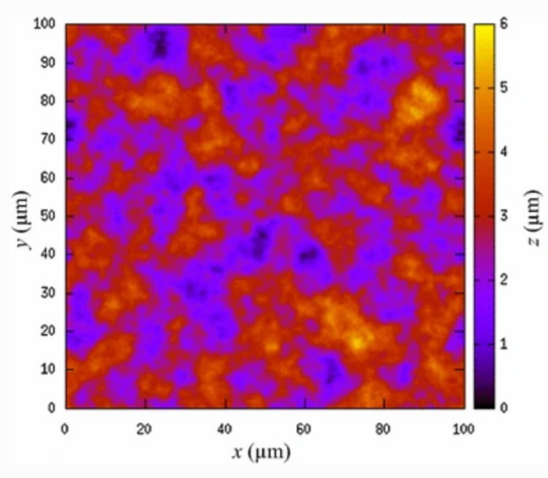


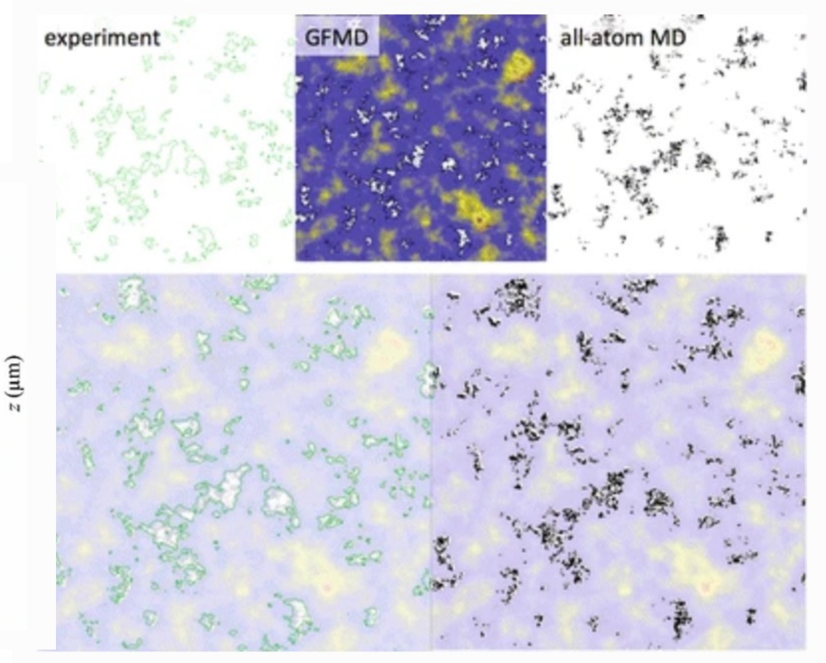
Seals



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

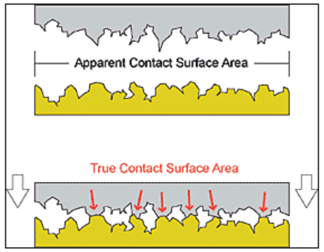
Theoretical countersurface



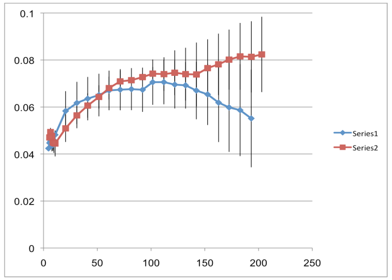


M. H. Müser et al (35 authors), *Tribology Letters*, 2017, 65, 118

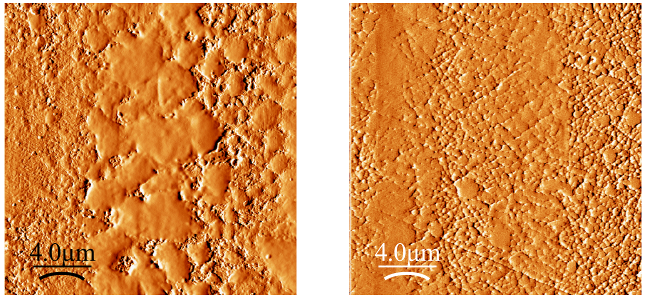
Summary



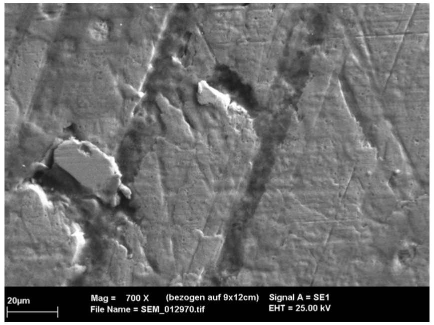
Reduction of friction and prevention of wear



Stabilisation of friction



Additives mainly designed for use with steel



Good adhesion has negative consequences