Surfaces and Films CHEM-E5150
Tribology

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Tribology

- Tribology is
  - science and technology of interacting surfaces in relative motion
  - origin in the Greek word *tribos* meaning rubbing
  - friction, lubrication, and wear of engineering surfaces
  - understanding surface interactions in detail and then prescribing improvements in given applications.

Practical objectives of tribology

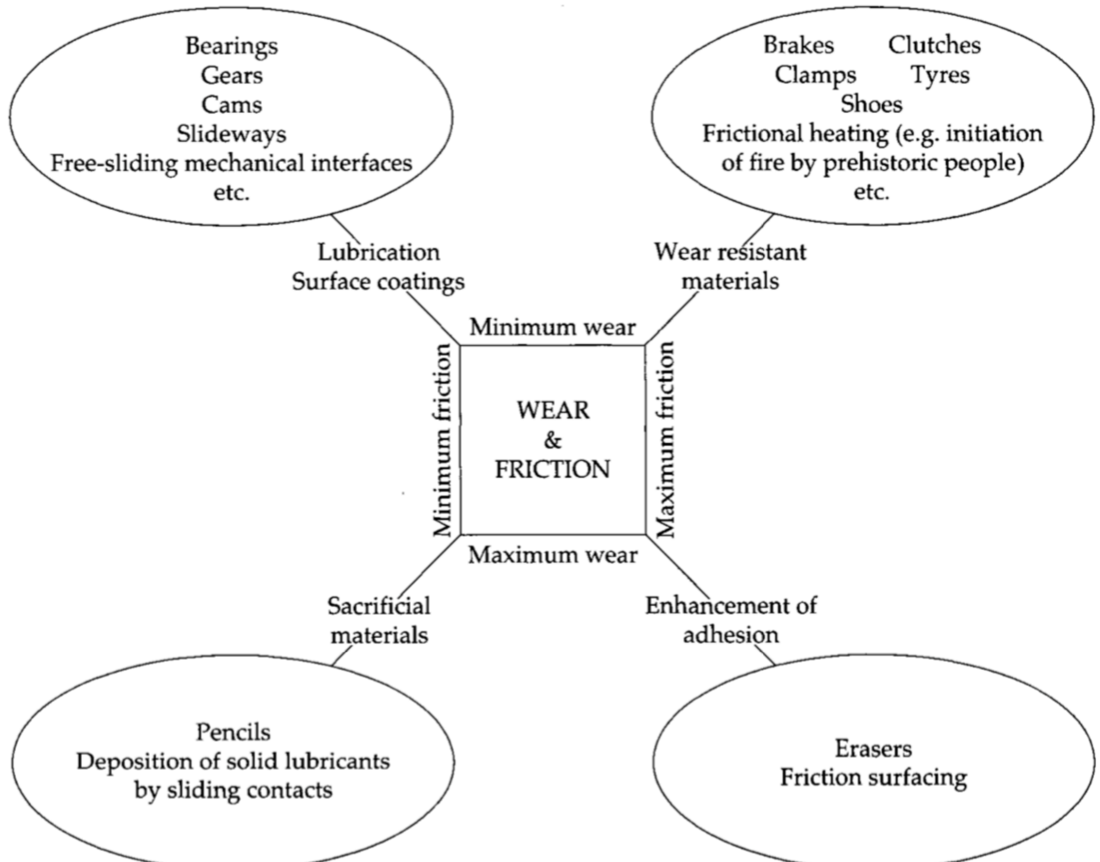
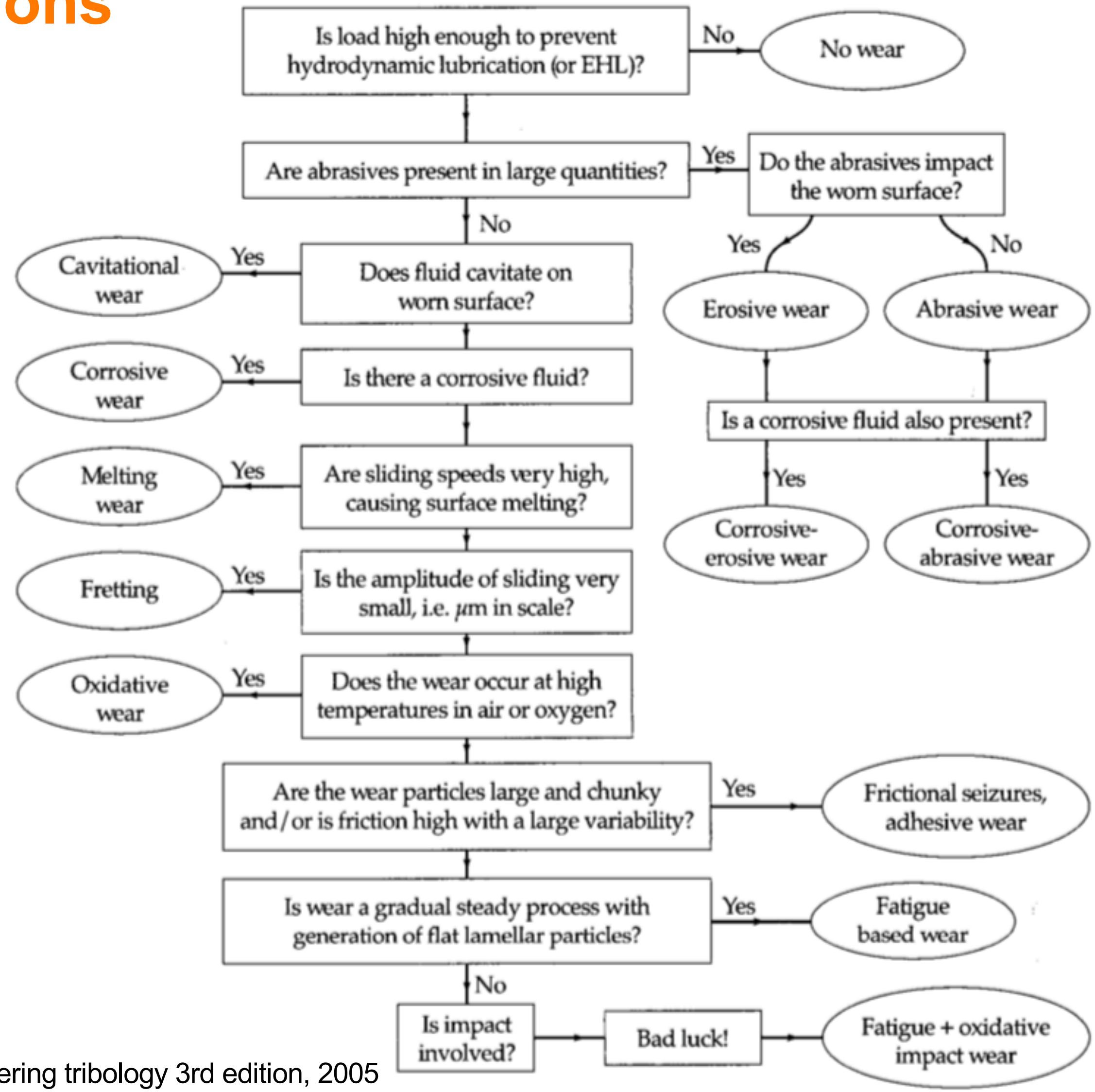


FIGURE 1.1 Practical objectives of tribology.

G.W. Stachowiak, A.W. Bachelor, Engineering tribology 3rd edition, 2005

Operation conditions and type of wear Flowchart



G.W. Stachowiak, A.W. Bachelor, Engineering tribology 3rd edition, 2005

Materials selection quide for wear control

Critical materials property	Wear mechanism							
	Abrasive	Erosive	Cavitation	Corrosive	Fretting	Adhesive	Melting	Fatigue
Hardness	✓	✓	❍	❍	❍	✓	❍	❍
Toughness	❍	✓	✓	❍	❍	❍	❍	✓
Fatigue resistance	✓	✓	✓	❍	✓	❍	❍	✓
Inertness	❍	❍	❍	✓	✓①	❍	❍	❍
High melting point	❍	❍	❍	❍	❍	✓	✓	❍
Heterogeneous microstructure	✓	❍	❍	✖②	❍	✓	❍	❍
Non-metallic character	❍	❍	❍	✓	❍	✓	❍	❍

✓ Important
❍ Marginal
✖ Unfavourable

① Fretting in air for metals
② Homogeneous microstructure inhibits electrochemical corrosion and, with it, most forms of corrosive wear

FIGURE 1.3 General materials selection guide for wear control.

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Dynamic viscosity

$$F \, \alpha \, A \times u/h \qquad (2.1)$$

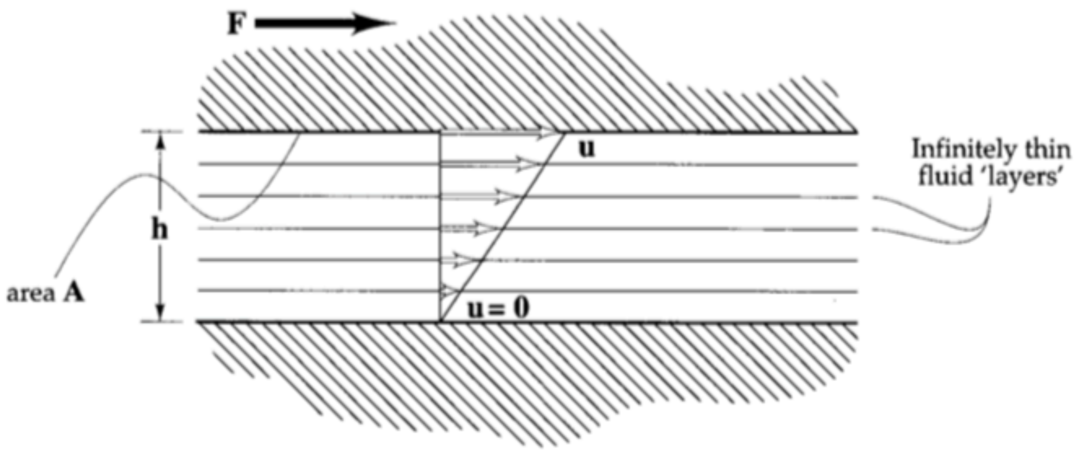


FIGURE 2.1 Schematic representation of the fluid separating two surfaces.

Dynamic viscosity

$$F = \eta \times A \times u/h$$

Rearranging gives:

$$\eta = (F/A) \,/\, (u/h)$$

or

$$\eta = \tau \,/\, (u/h)$$

η	is the dynamic viscosity [Pas];
τ	is the shear stress acting on the fluid [Pa];
u/h	is the shear rate, i.e., velocity gradient normal to the shear stress [s^{-1}].

"Poise" $1\ [P] = 100\ [cP] \approx 0.1\ [Pas]$

Kinematic viscosity

$$\upsilon = \eta/\rho$$

where:

- υ is the kinematic viscosity $[m^2/s]$;
- η is the dynamic viscosity [Pas];
- ρ is the fluid density $[kg/m^3]$.

"Stoke" $\mathbf{1\ [S] = 100\ [cS] = 0.0001\ [m^2/s]}$

Viscosity-temperature

Walther	$(\upsilon + \mathbf{a}) = \mathbf{b}\mathbf{d}^{1/T^{c}}$	Forms the basis of the ASTM viscosity-temperature chart

$\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$ are constants;

υ is the kinematic viscosity $[m^2/s]$;

$\mathbf{T}$ is the absolute temperature [K].

Viscosity – temperature of selected oils

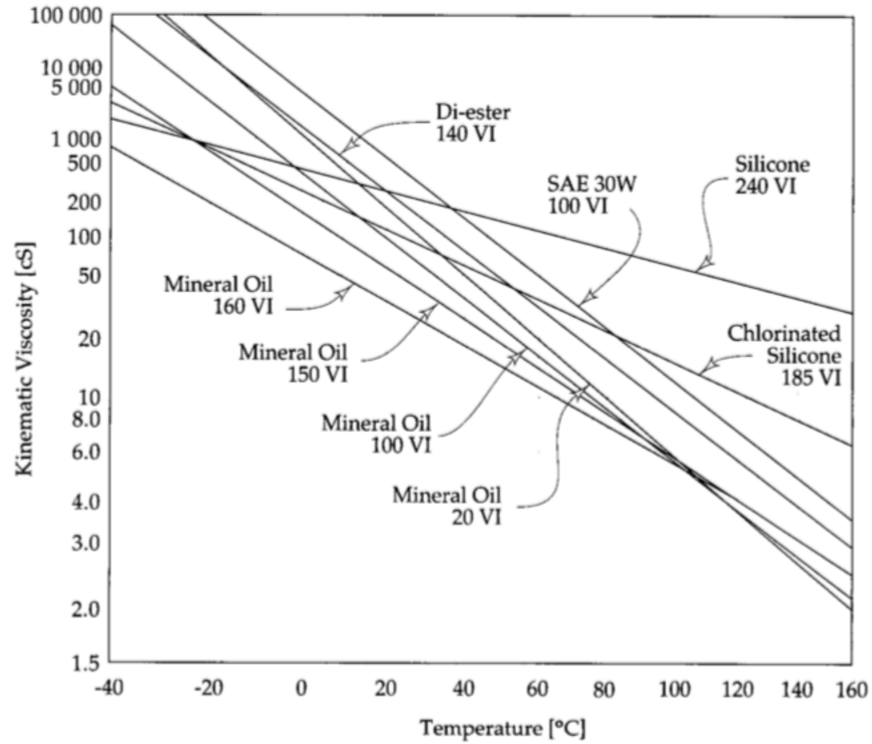
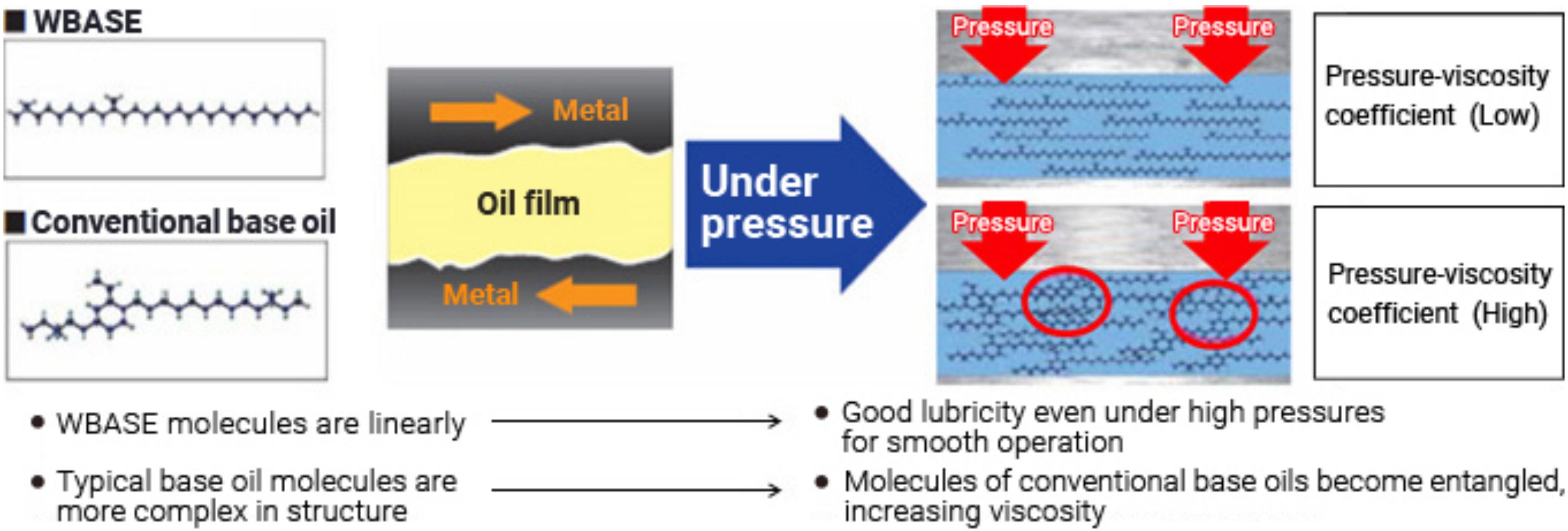


FIGURE 2.2 Viscosity-temperature characteristics of selected oils (adapted from [29 and 22]).

Pressure -Viscosity



https://www.eneos.co.jp/english/company/rd/intro/lubricants/kudokei.html

Viscosity – shear rate Newtonian fluid

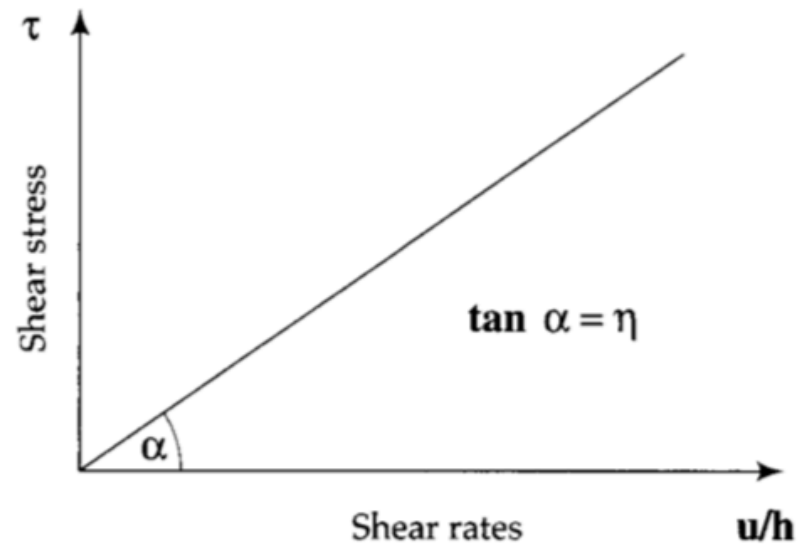


FIGURE 2.5 Shear stress - shear rate characteristic of a Newtonian fluid.

Elasto hydrodynamic lubrication

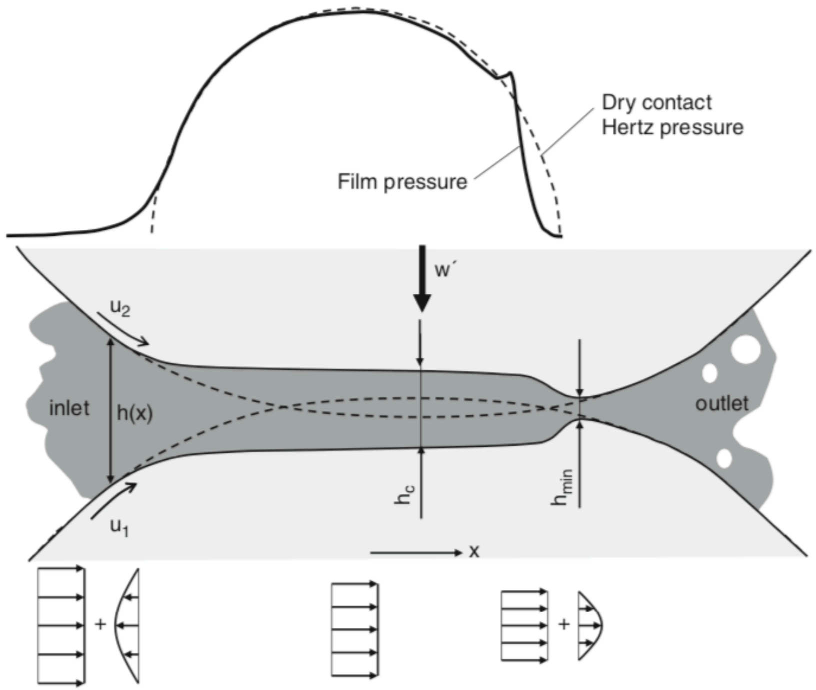
$\eta = \eta_0 \exp(\alpha p)$. (Barus 1893)

η viscosity

η_0 viscosity at normal pressure

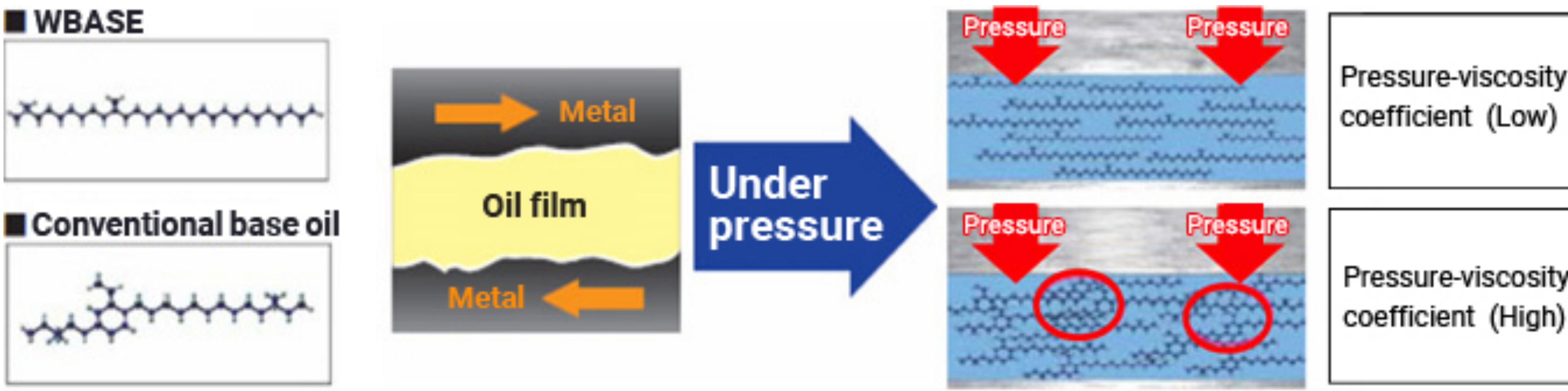
p pressure

α pressure-viscosity coefficient



EHL Film Thickness Behavior, Fig. 1 Typical film thickness profile for an EHL line contact. Flow velocity profiles (Couette + Poiseuille flow) at three different positions are shown in the bottom of the figure

Pressure -Viscosity



- WBASE molecules are linearly → Good lubricity even under high pressures for smooth operation
- Typical base oil molecules are more complex in structure → Molecules of conventional base oils become entangled, increasing viscosity

https://www.eneos.co.jp/english/company/rd/intro/lubricants/kudokei.html

Title

Tribology

Lubricant Films

Solid Suspension Films

- Borate
- Molybdenum Disulfide
- Graphite
- PTFE

Chemical Oil Films

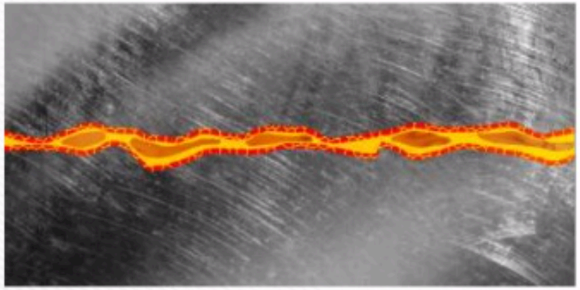
- Oiliness Agents – Fatty Acids
- Zinc Dialkyldithio-phosphate (AW)
- Tricresyl Phosphate (AW)
- Sulfur Phosphorus (EP)

Fluid Films

- Hydrodynamic Lubrication
  Sliding
- Elastohydrodynamic Lubrication
  Rolling - Deformation to carry the load

Boundary

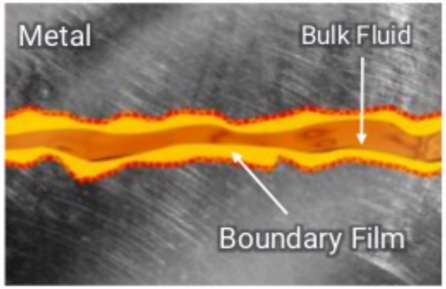
Friction from viscous drag and mechanical contact



If surfaces protected by chemical oil film and/or solid lubricants - minor wear

Thick Film

Friction from viscous drag only



Surfaces protected by viscosity - no wear

Ref: JCF. Godfrey

00269 MLI

Viscosity non-Newtonian fluids

Typically colloids, e.g. cornstarch

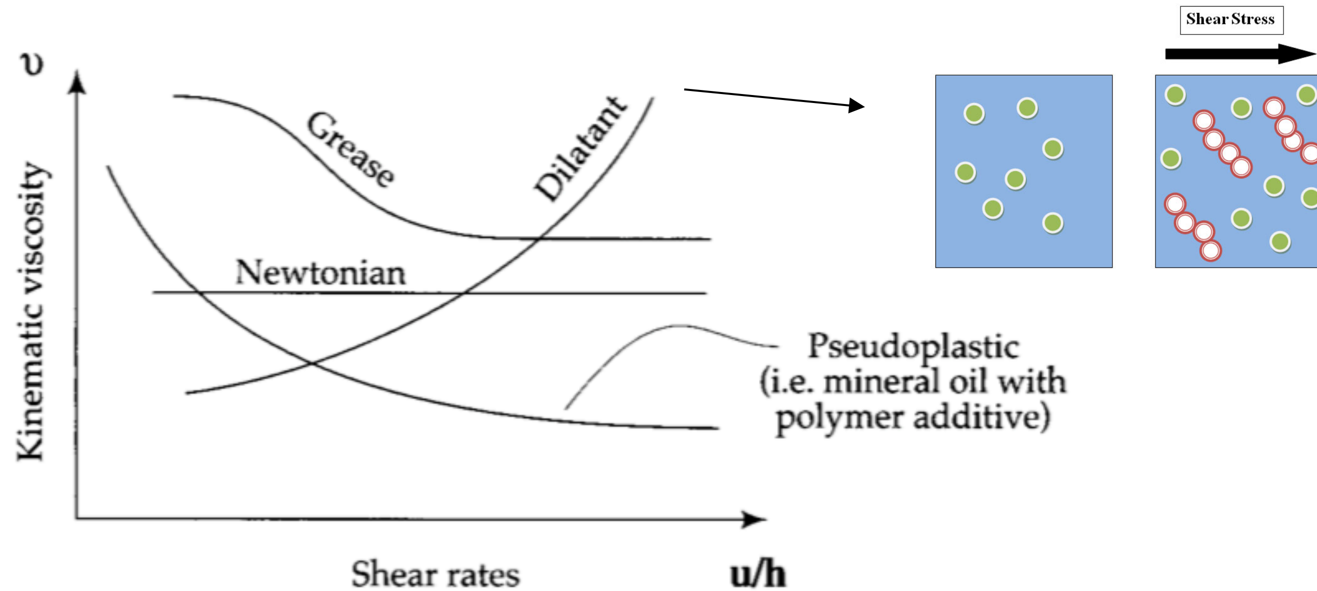
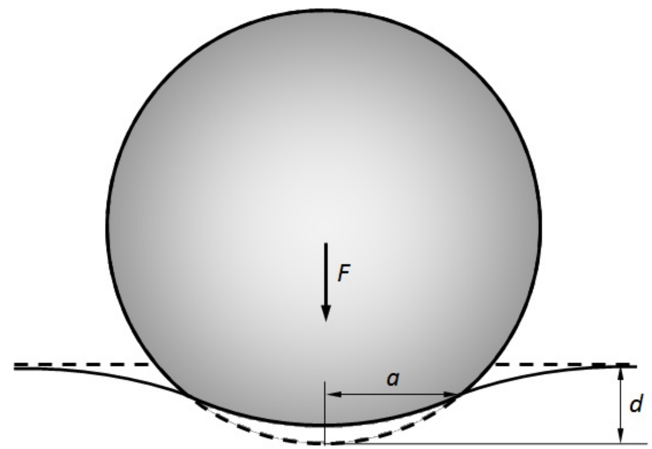


FIGURE 2.6 Viscosity - shear rate characteristics for some non-Newtonian fluids.

Contact mechism

- Herzain contact



Contact mechanism Wiki

Assumptions in Hertzian theory

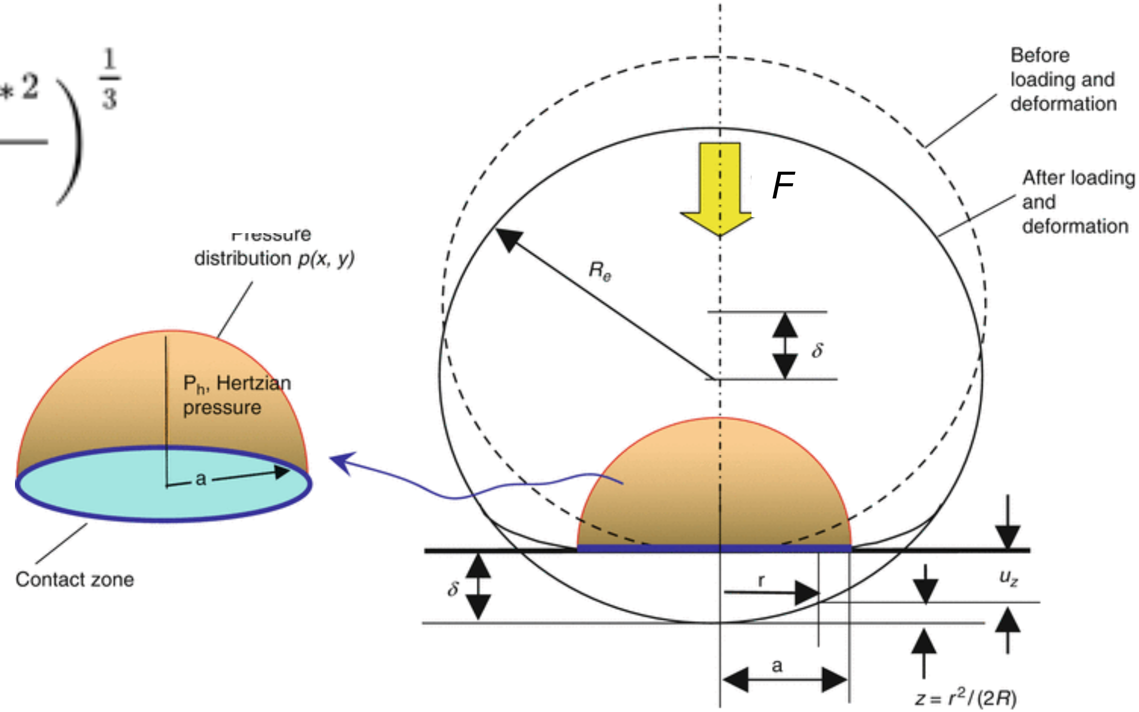
– The following assumptions are made in determining the solutions of **Hertzian** contact problems:
– The strains are small and within the elastic limit.
– The surfaces are continuous and non-conforming (implying that the area of contact is much smaller than the characteristic dimensions of the contacting bodies).
– Each body can be considered an elastic half-space.
– The surfaces are frictionless.

Herzian pressure (sphere on flat)

MAXIMUM PRESSURE:

$$p_0 = \frac{3F}{2\pi a^2} = \frac{1}{\pi}\left(\frac{6FE^{*2}}{R^2}\right)^{\frac{1}{3}}$$

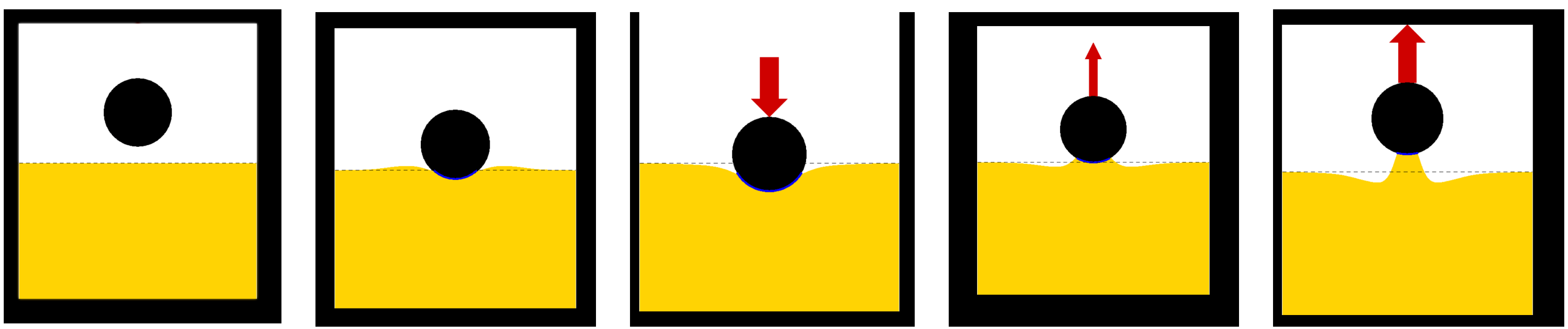
$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$



https://media.springernature.com

Johnson-Kendall-Roberts (JKR) model of elastic contact

incorporate the effect of adhesion in Hertzian contact



Levels of tribological testing

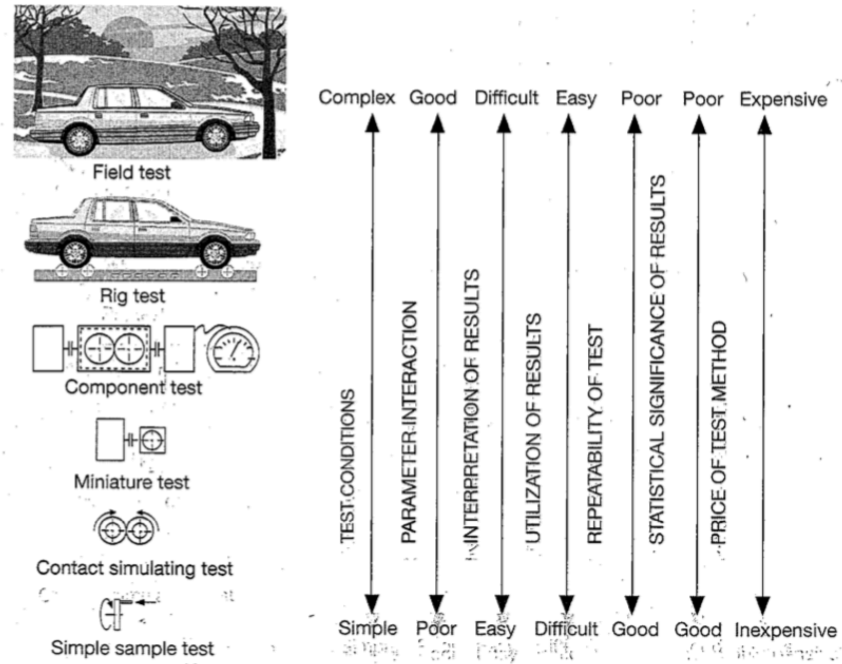


Fig. 5.23. Levels of simulation in tribological testing.

Tribology International Volume 31 Numbers 1–3 1998

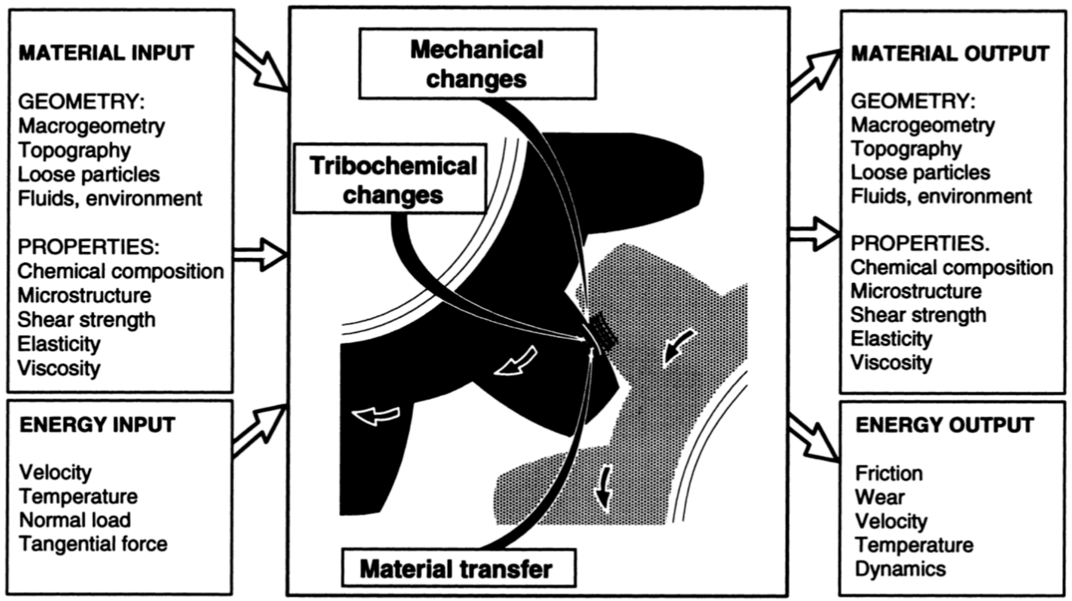


Fig. 1 The tribological process in a contact between two surfaces includes mechanical and tribochemical changes as well as material transfer

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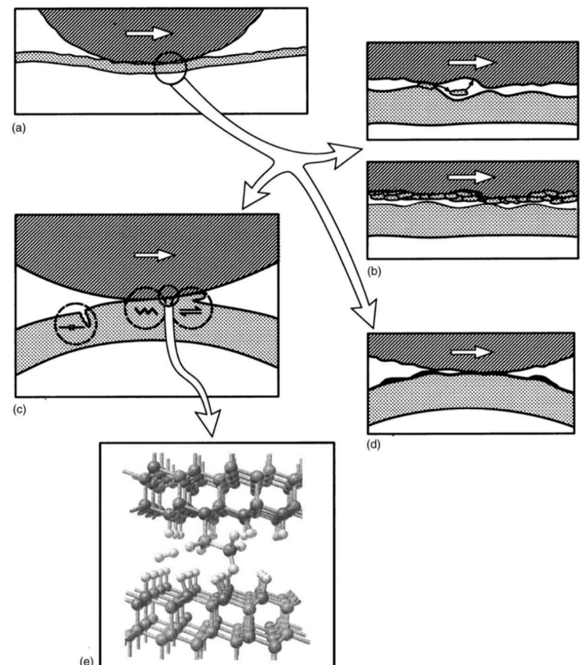

Fig. 2 Tribological contact mechan
tribochemical and (e) nanomechani

Tribology International Volume 31 Numbers 1–3 1998

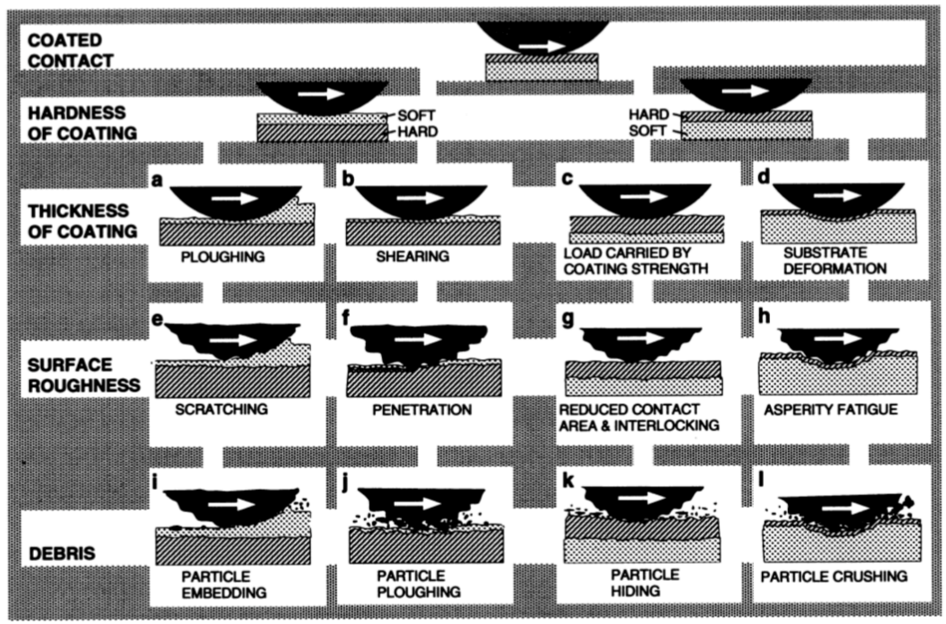

Fig. 3 Macromechanical contact conditions for different mechanisms that influence friction when a hard spherical slider moves on a coated flat surface

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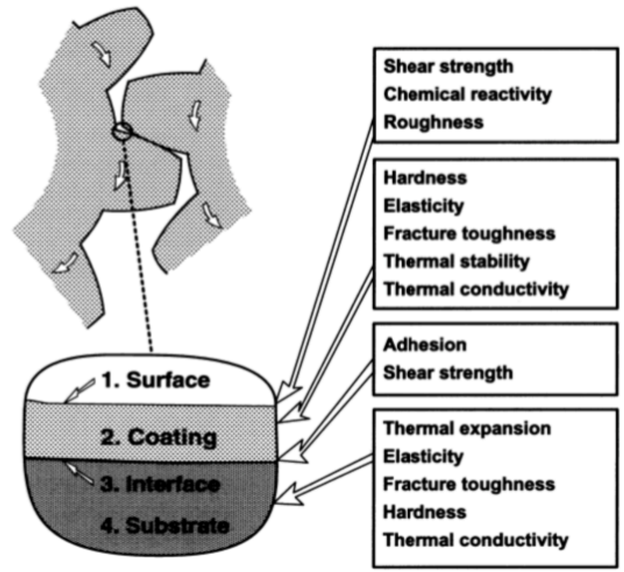

Fig. 4 Tribologically important properties in different zones of the coate

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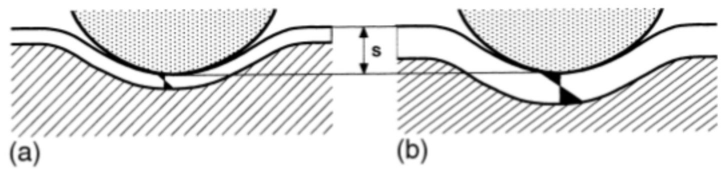

Fig. 5 (a) Thin hard coatings on a soft substrate generate lower stresses in the coating and at the coating/substrate interface compared with (b) thick hard coatings with the same deflection

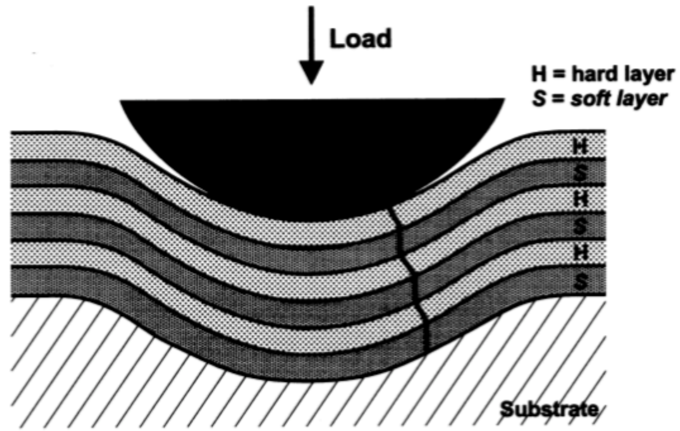

Fig. 6 A multilayer coating with alternate hard and soft layers can allow deflection to occur under load without yielding of the hard layers. They effectively slide over each other, with shear occurring in the soft layer. The pattern of shear is illustrated by the line through the film, which was initially straight in the unloaded condition

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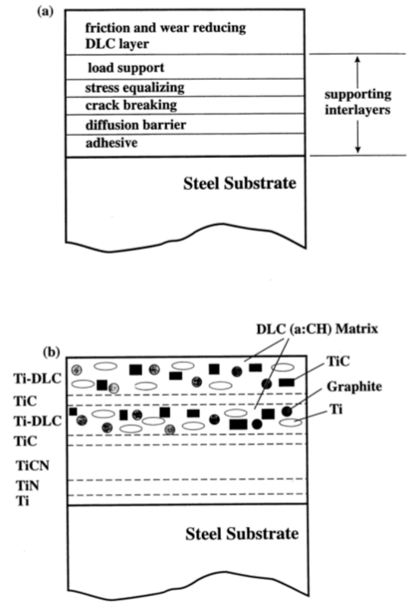

Fig. 7 (a) A functionally graded multilayer coating design to utilise specific layers for distinct properties. (b) A particular multilayer coating tested by Voevodin et al.[25]

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Scrac

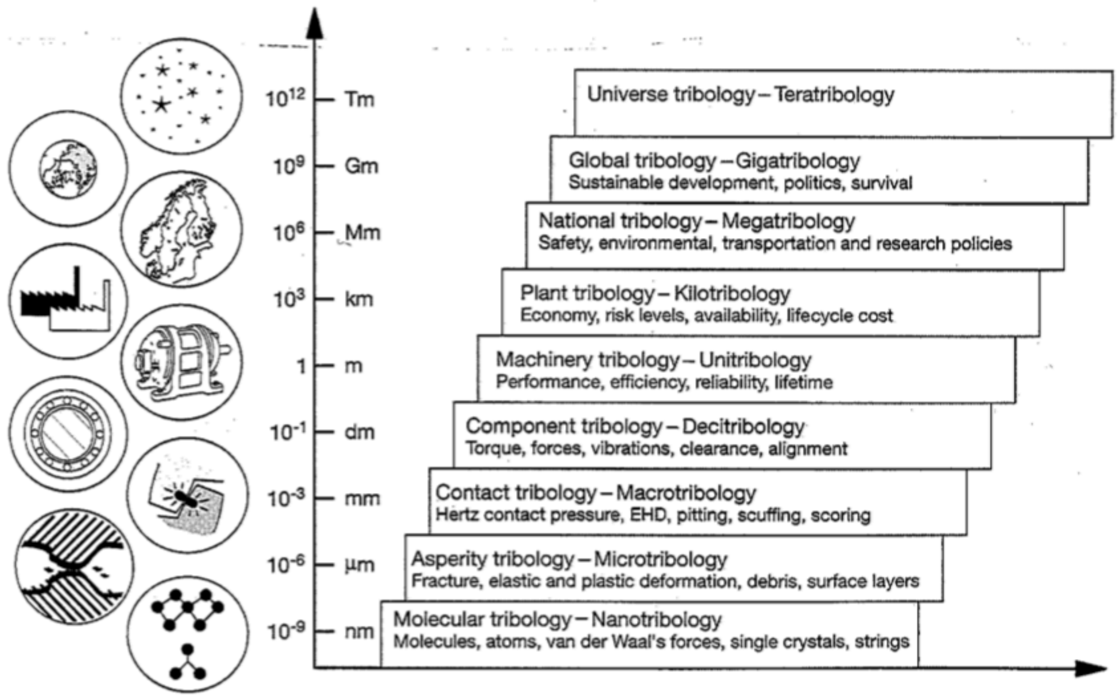

Fig. 3.71. Scales of tribology from nanotribology to teratribology (Holmberg, 2001).

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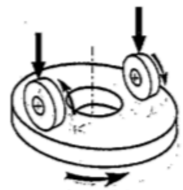
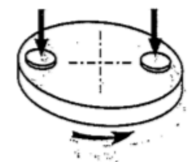
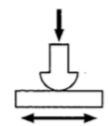
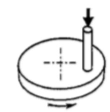
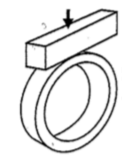
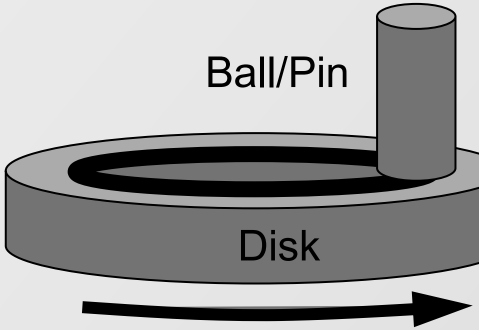
	Dry abrasion (Taber)	Wet slurry abrasion
Test configuration		
Test purpose	Determination of the abrasive wear rate and the Taber wear index of material surfaces.	Determination of the abrasive wear rate and the abrasion resistance of materials and treatments.
Specimens	Flat face of the disk abraded by two rubber bonded abrasive wheels (CS-10).	Two specimen pads loaded against a rotating circular plate.
Test conditions	Load 9.81 N. Wheels cleaned with abrasive paper every 1000 revolutions. Test is run without lubricant.	Load 112 N. Runs in bath of abrasive slurry.
Measurements	Weight loss. Taber wear index = weight loss/1000 revs (mg).	Volume loss.
Wear types/ comments	Low stress abrasion.	High stress grinding abrasion. Low stress abrasion.

Table 5.4. Wear and friction test methods for tribological evaluation of coated surfaces. Typical parameters are given but many variations of these are in use.

	Pin-on-flat (ASTM)	Pin-on-disk (VAMAS)	Block-on-ring (ASTM)
Test configuration			
Test purpose	Determination of wear rate and coefficient of friction at low loads and speeds and with small specimens.	Determination of sliding wear rate and coefficient of friction.	Determination of adhesive wear rate of materials.
Specimens	A pin or a ball rubbing against a plate.	A pin or a ball rubbing on a rotating plate.	A steel ring is rotated against a stationary block.
Test conditions (typical)	Reciprocating sliding frequency 5 Hz. Stroke length 10 mm. Load 25 N. Temperature 18–23°C. Humidity 40–60% RH. Specimen can be dry or fully immersed in lubricant.	Sliding speed 0.1 m/s. Load 10 N. Sliding distance 1 km. Temperature 23°C. Humidity 50% RH.	Ring speed (max) 7000 rev/min. Load (max) 6000 N. Duration 5400–24,000 cycles. Specimen can be dry or immersed in oil or other fluid.
Measurements	Weight loss of disk. Height loss of pin. Wear track profilometry. Ball wear area measurement. Friction force.	Height loss of pin. Wear track profilometry. Ball wear area measurement. Friction force.	Test block weight loss. Scar width. Ring weight loss. Friction force. Lubricant film load-carrying capacity.
Wear types/comments	Mild adhesive wear suitable for tribological coating evaluation.	Mild and severe adhesive wear. Suitable for tribological coating evaluation.	Mild and severe adhesive wear. Lubricated wear.

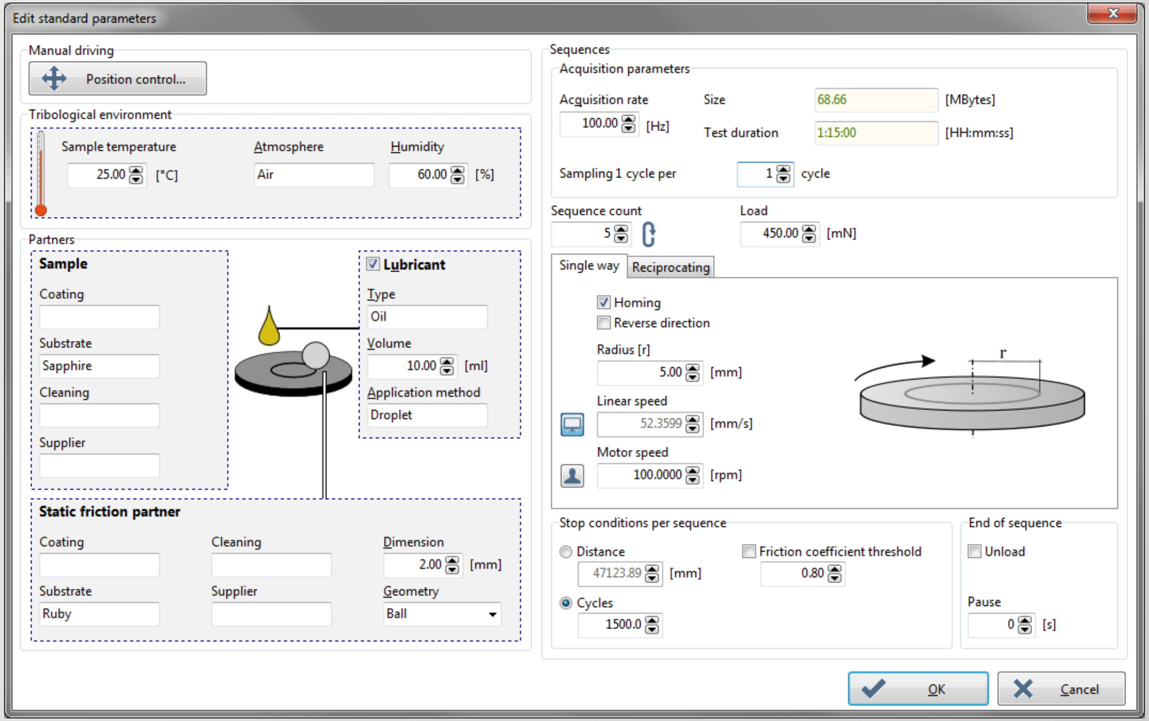
Tribology Testing - Overview



- “Simple” system and highly reproducible measurement
- Simulate real frictional conditions
  - Contact pressure
  - Movement mode
  - Sliding speed
  - Static partner (size, geometry, mechanical properties, etc)
  - Lubrication
  - Environmental condition (temperature, vacuum, humidity, etc)

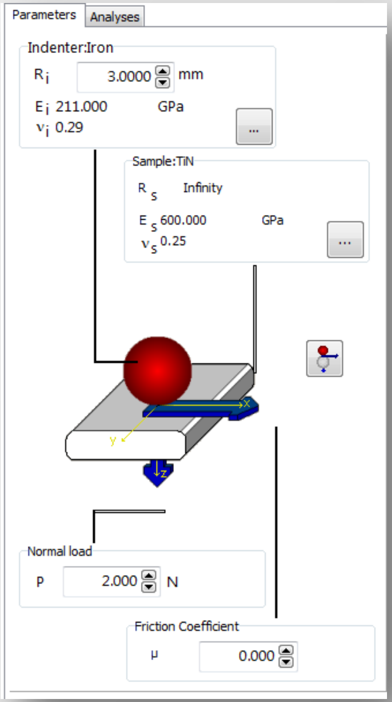
Tribology Testing - Overview

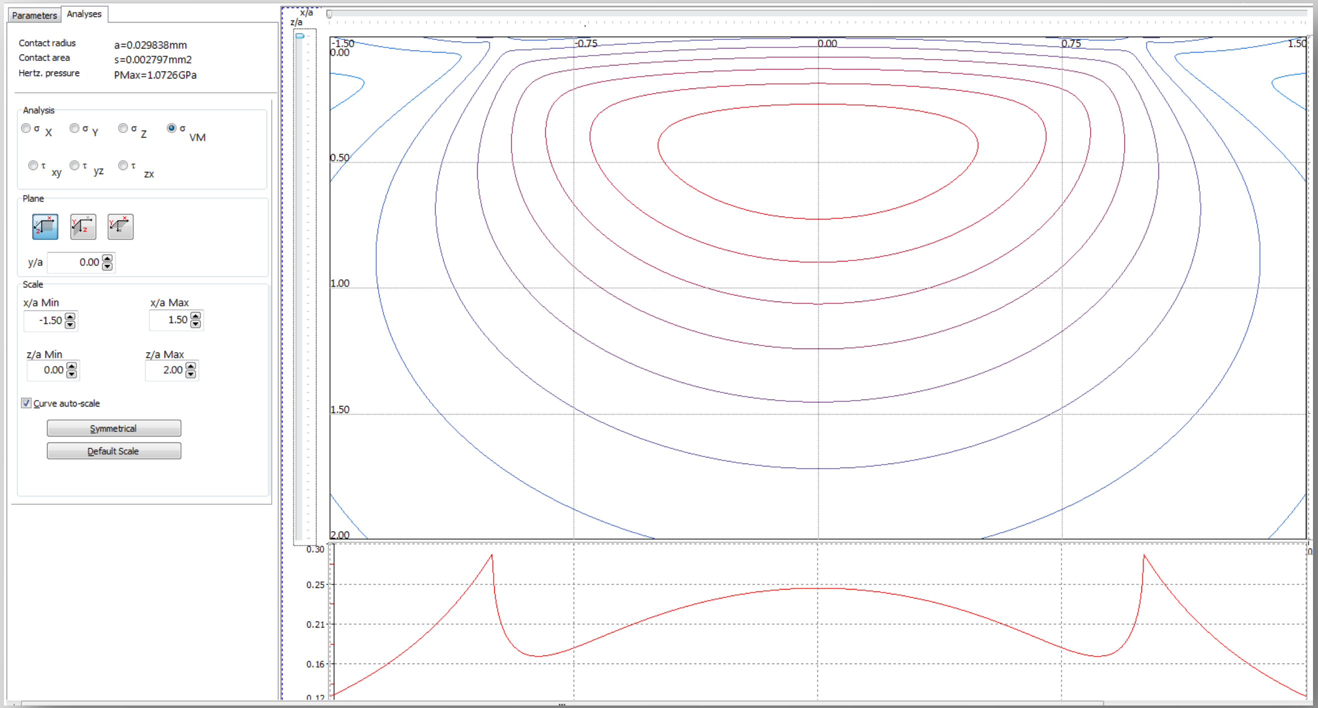
Anton Paar



Tribology Testing - Contact Mechanics Modeling

Modeling software included inside every Anton Paar Tribometer package





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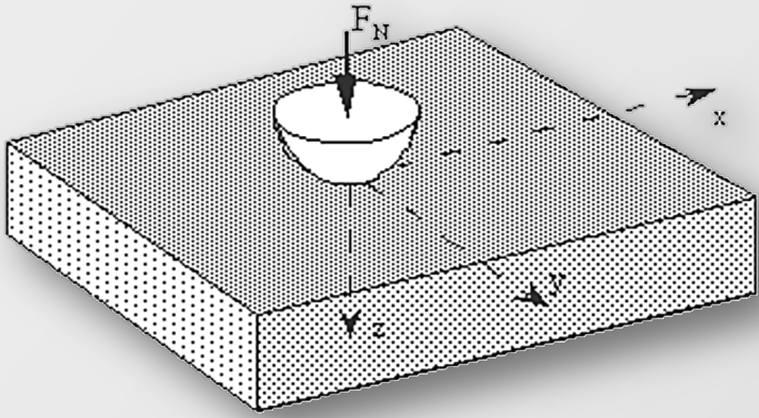
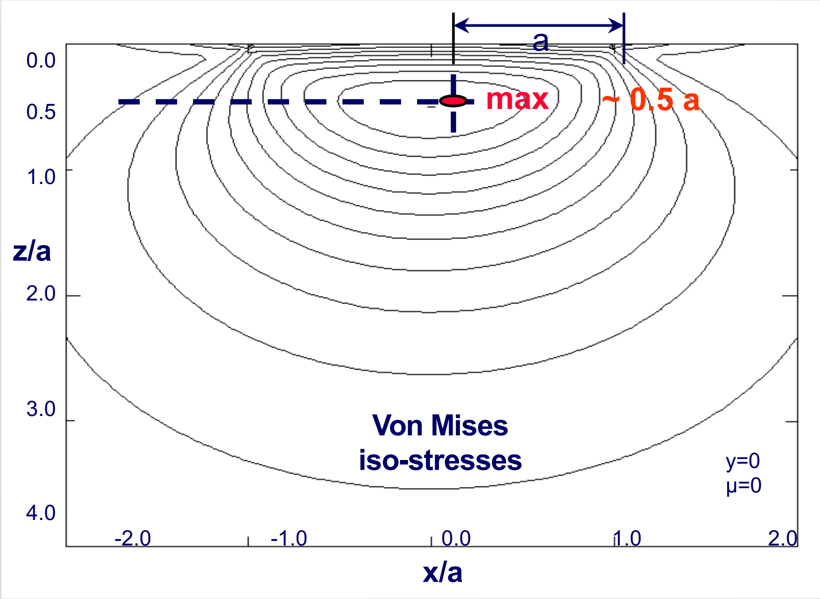
Hertz contact model (ball on flat)





Contact Radius $$a = \left(\frac{3FR}{4E^*}\right)^{1/3}$$

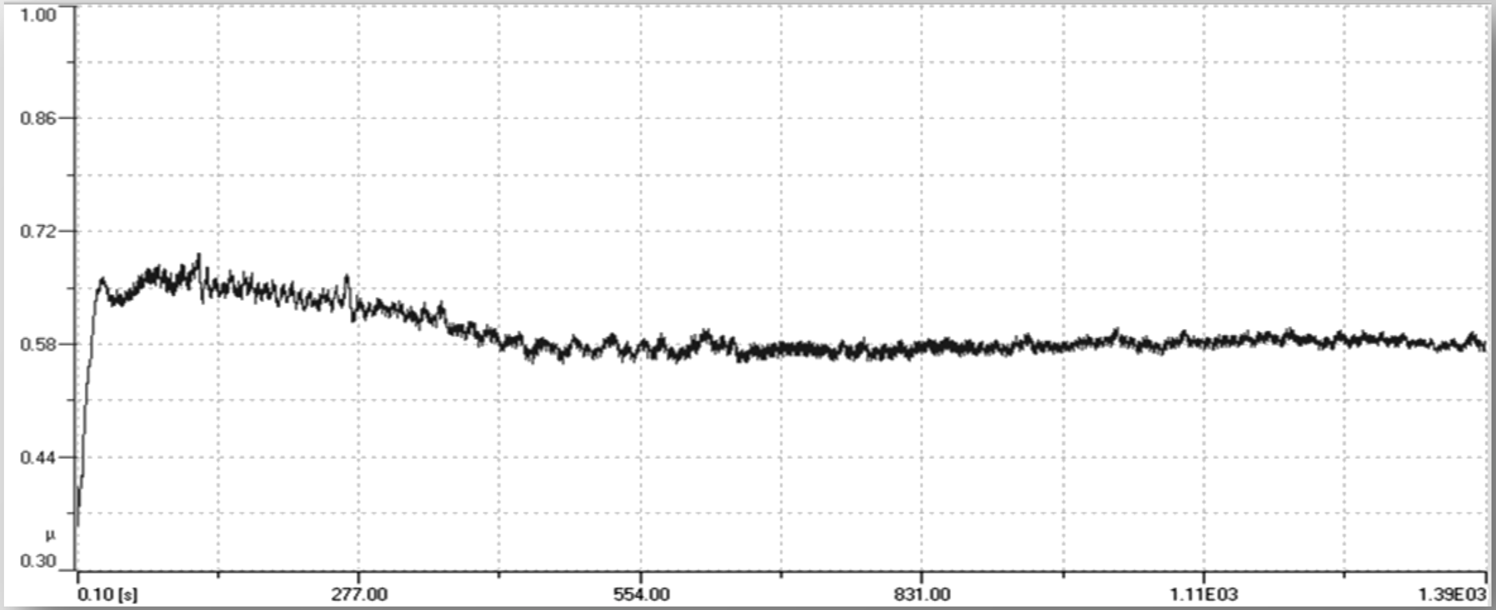
Mean Contact Pressure $$P_m = \left(\frac{4E^*}{3\pi}\right)\frac{a}{R}$$

For coated materials, max Von Mises stress is important

F: normal load, R: ball radius, E*: reduced modulus

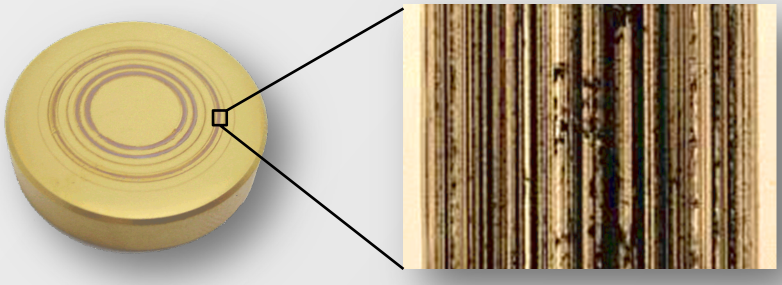
Tribology Testing - Coefficient of Friction

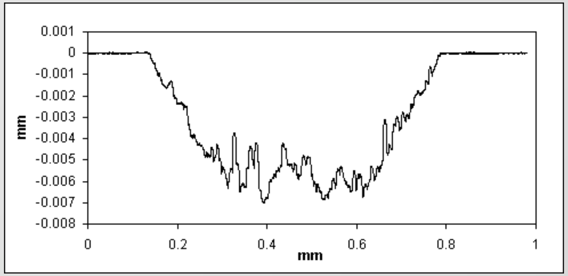
100Cr6 Steel ball against TiN coated steel



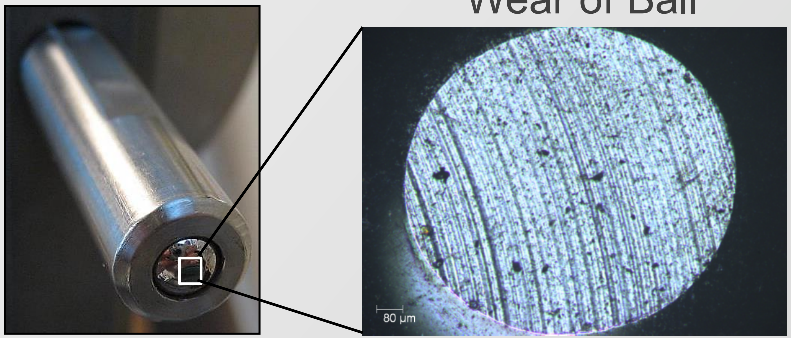
Tribology Testing - Wear

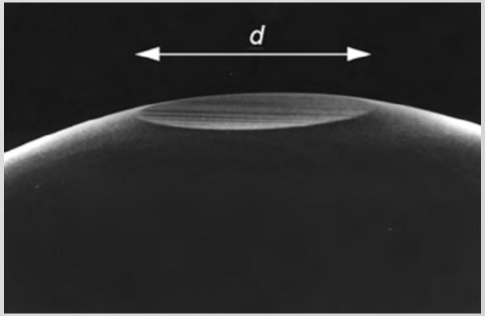
Wear of Sample



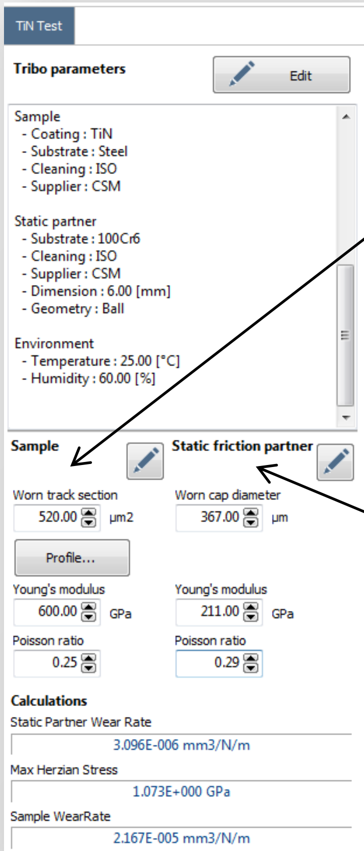


Wear of Ball





Tribology Testing - Wear



Sample wear volume = Cross section area * wear track circumference

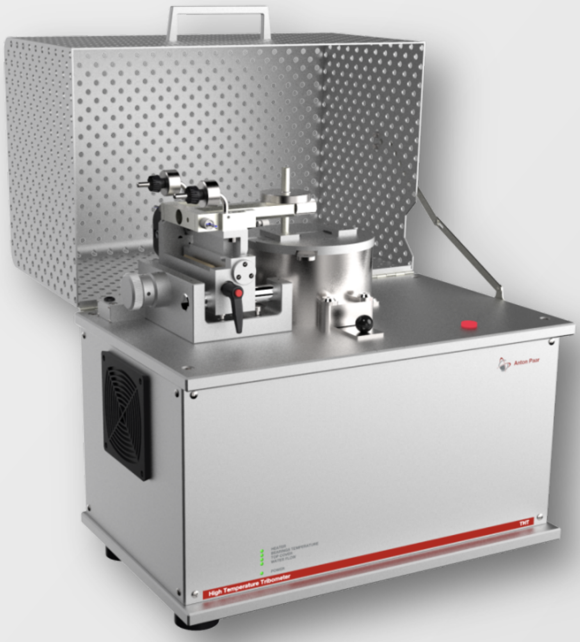
Ball wear volume = Volume of the worn cap

Wear Rate $$K = \frac{V}{Fl}$$

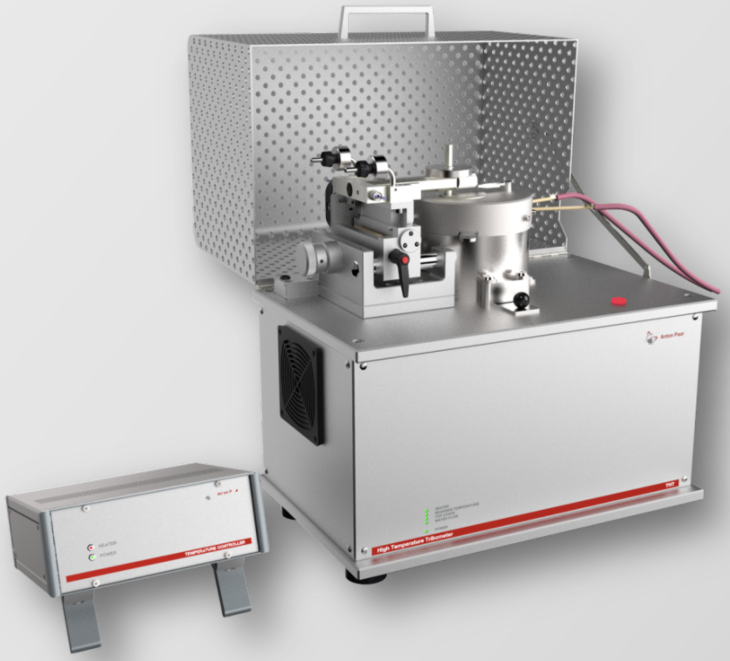
V: wear volume, *F*: normal load, *l*: sliding distance

High Temperature Tribometer (THT)

Anton Paar



THT up to 800˚C



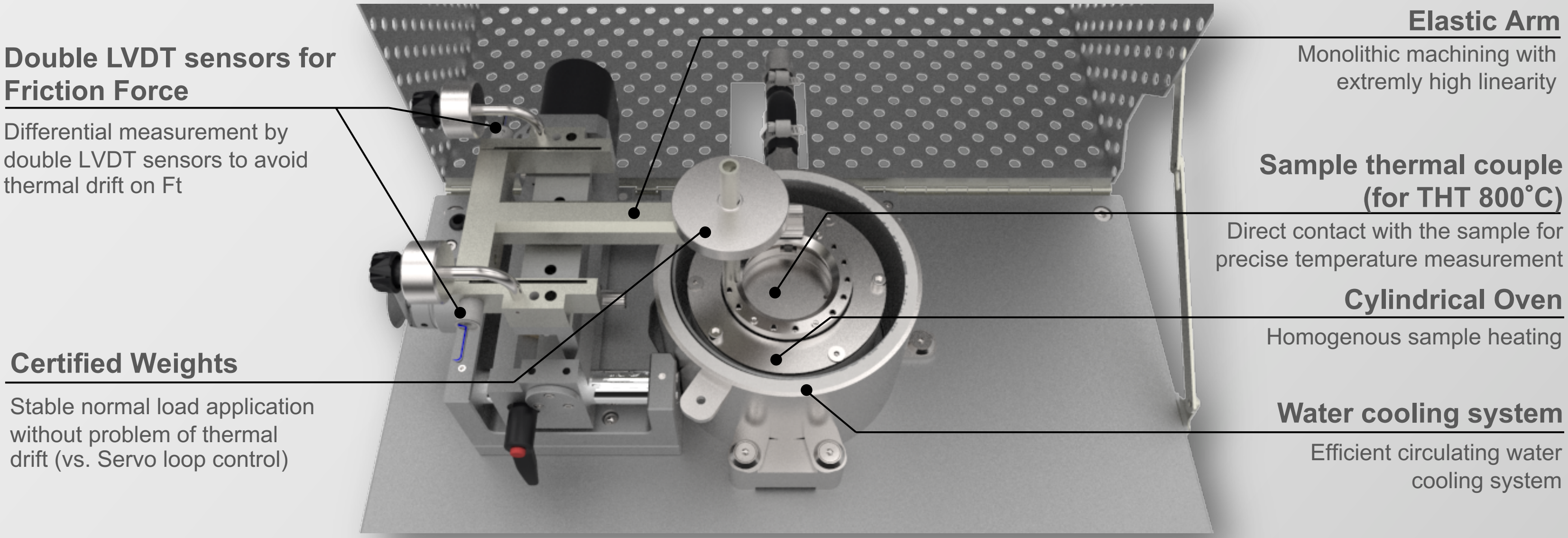
THT up to 1000˚C

Water chiller included

for all THT

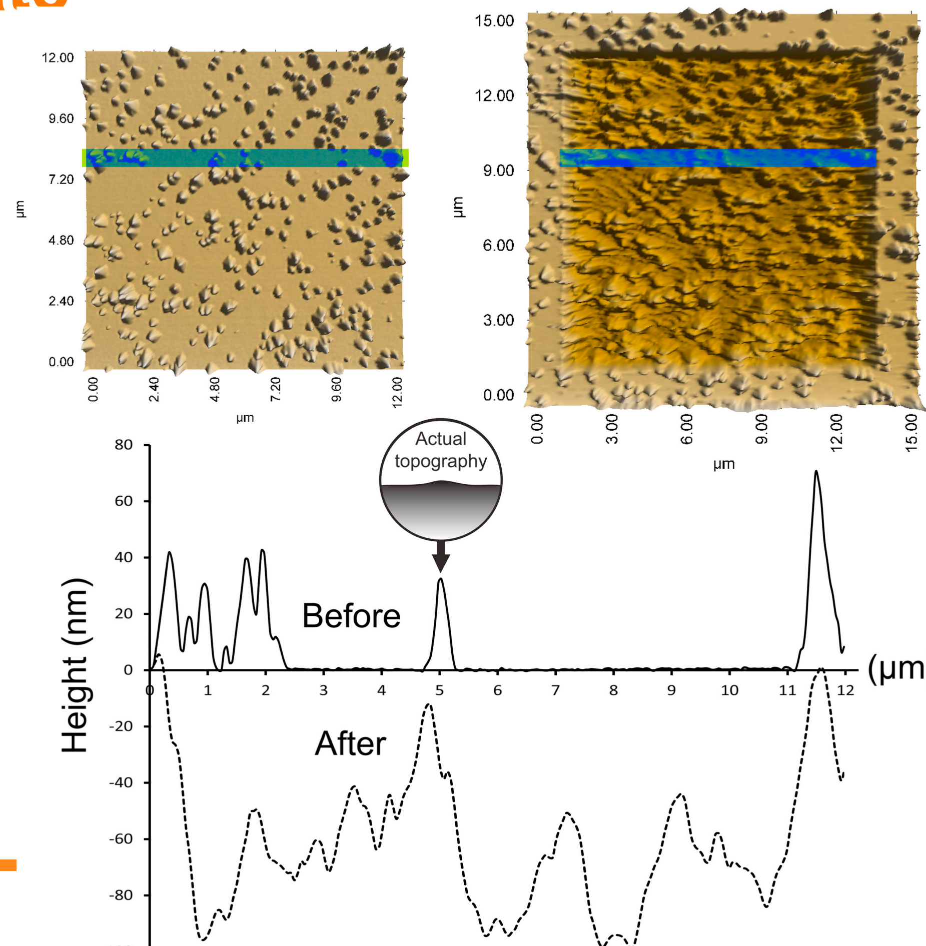
High Temperature Tribometer (THT)

- Double LVDT sensors to cancel thermal drift error
- Cylinderical Oven for homogenous sample heating
- Water cooling system for efficient temperature control and safe utilization



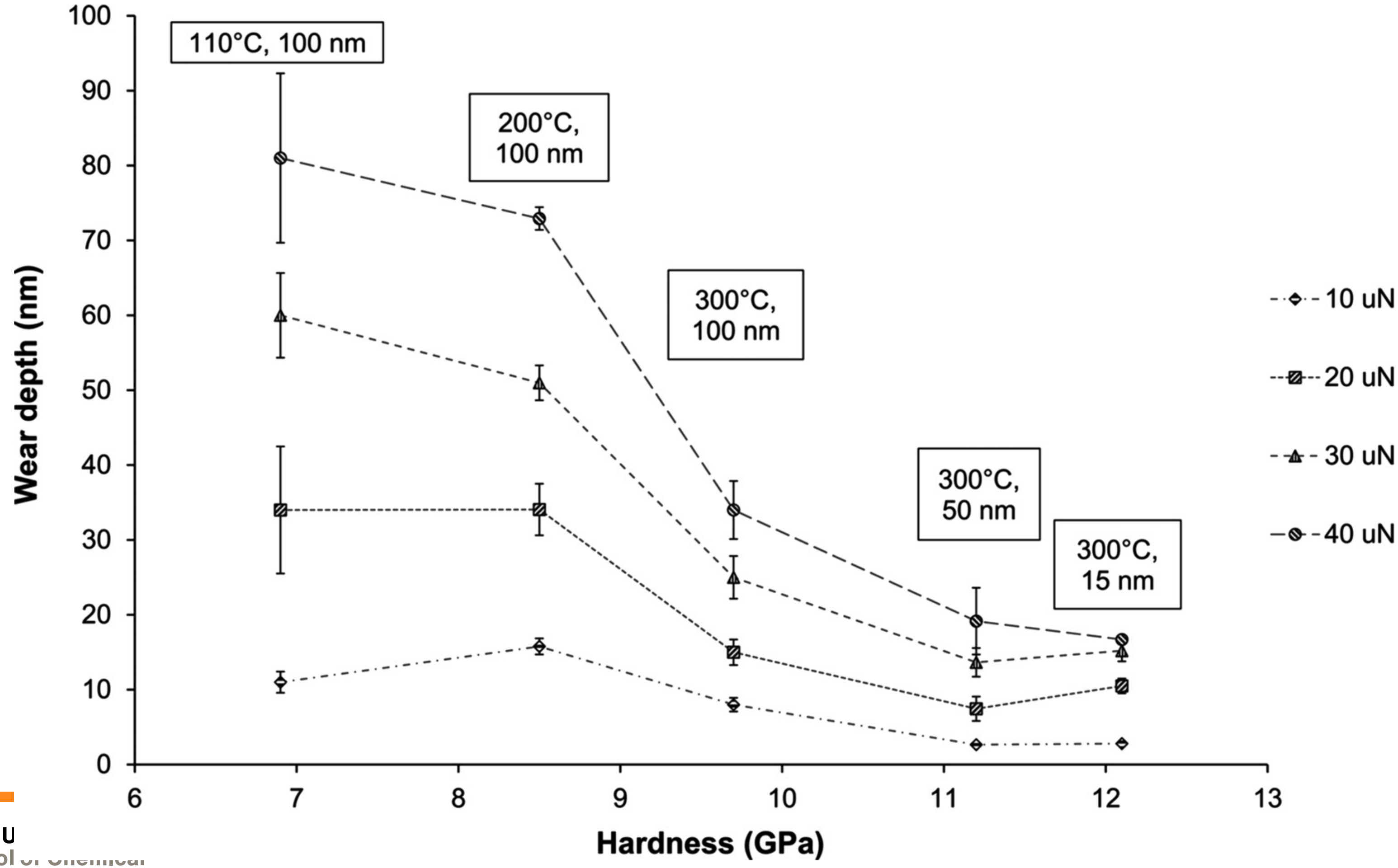
Nano tribology

Diamond tip (Berkovich) wear of ALD TiO2 on a silicon substrate



Jussi Lyytinen et al., Volumes 342–343, 15 November 2015, Pages 270-278

Effect of ALD processing temperature to abrasive nano wear



Jussi Lyytinen et al., Volumes 342–343, 15 November 2015, Pages 270-278