

Tribology testing of surfaces

Anna Igual Munoz

Tribology and Interfacial Chemistry Lab

- 1. Introduction to tribology**
- 2. What is a surface?**
- 3. How surfaces contact?**
- 4. Main concepts: Friction, wear and lubrication**
- 5. Which experimental techniques allows for testing surfaces?**

- Etymology: from greek “tribos” (to rub) and “logy” (knowledge)
- « Tribology is the science and practice of interacting surfaces in relative motion and of the practices related thereto. »

P. Jost in: Lubrication (Tribology) education and research, A report on the present position and industrial needs, HMSO (1966)

- It hence studies the principles of **friction**, **wear**, and **lubrication**

Examples

- Some phenomena ruled by friction :

- Grasping objects



- Walking



- Writing



- Assembly strength (screw, nails, bolts)



- Landslides

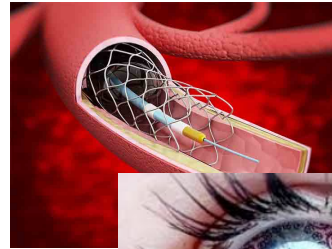


- Braking



Some tribology-related technologies

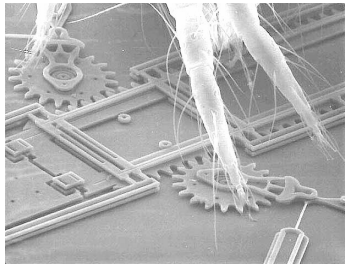
Biomedical



Mechanical components



MEMS



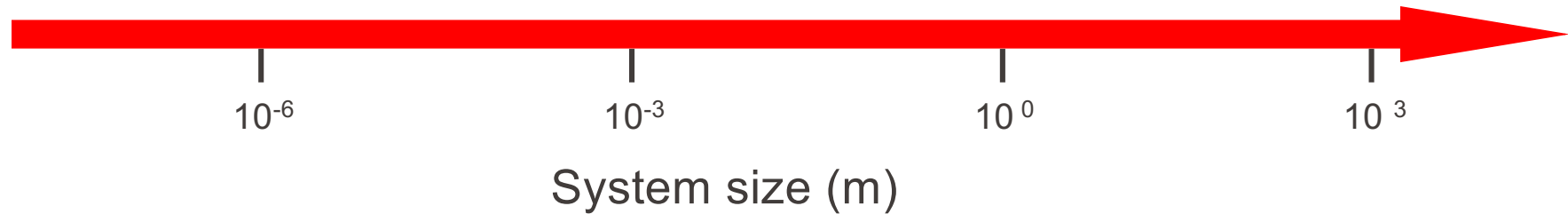
Watches



Machining



Geology

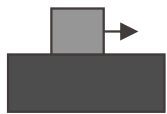


Some present challenges and opportunities for tribologists

- Hydrogen economy: Storage, generation, transportation, utilization
- Transportation (modern electric vehicles): Optimization of gears and dynamic seals (still 57% of the losses are due to friction) *Farfan-Cabrera Tribology International (2019)*
- Energy conversion: wind mills (low speed systems and high loads, marine environment, current generation)



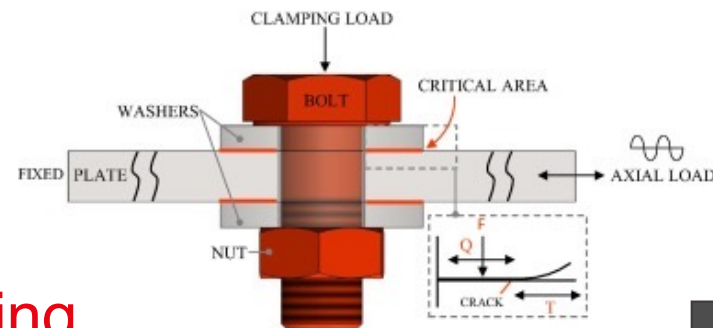
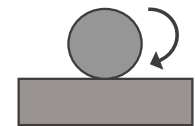
Type of tribological contacts (sliding, rolling, fretting...)



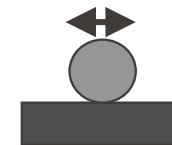
Sliding



Rolling

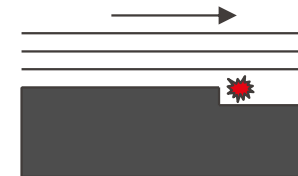
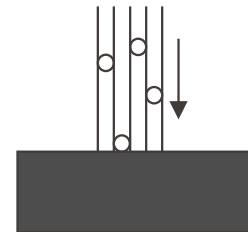
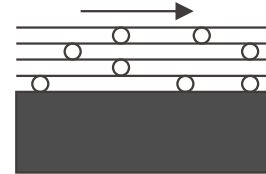


Fretting



Other tribological situations

- Particles carried by a fluid sliding over a body
→ Erosion
- Particules impacting on a body
→ Impact wear
- Gas particles imploding in turbulent fluids
→ Cavitation (*cavitation wear*)



1. Introduction to tribology

2. What is a surface?

3. How surfaces contact?

4. Main concepts: Friction, wear and lubrication

5. Which experimental techniques allows for testing surfaces?

Surfaces: the elements through which solids contact

- 2 dimensional (planar) defect with certain thickness



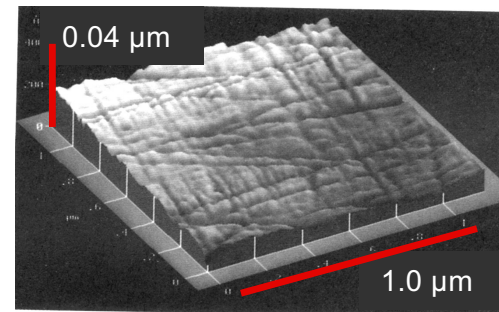
Silicon wafer: atomically flat, uniform chemistry



Steel pipe: rough, partially rusted

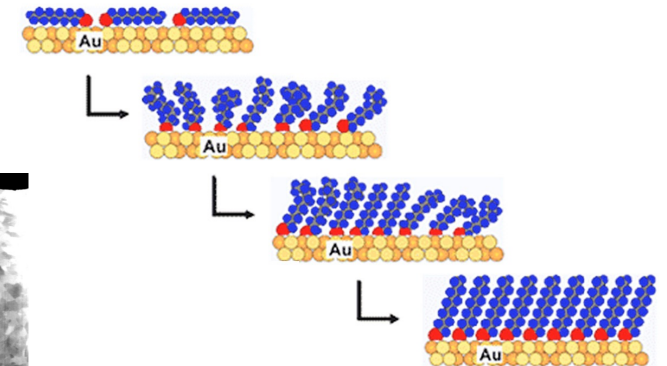
Surfaces: not simple, neither flat

- Topographical features: roughness...
 - Contact area, contact stresses, wetting

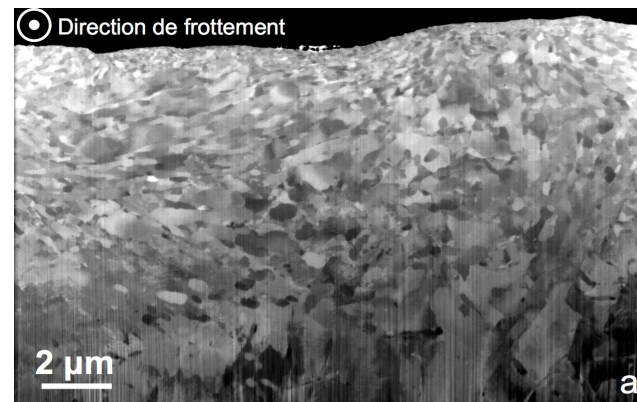


Mirror polished steel surface: AFM image

- Chemical features: adsorbed molecules, oxides...
 - Influences friction



- Microstructural features:
 - Influences wear



Surface topography: characterization of real surfaces

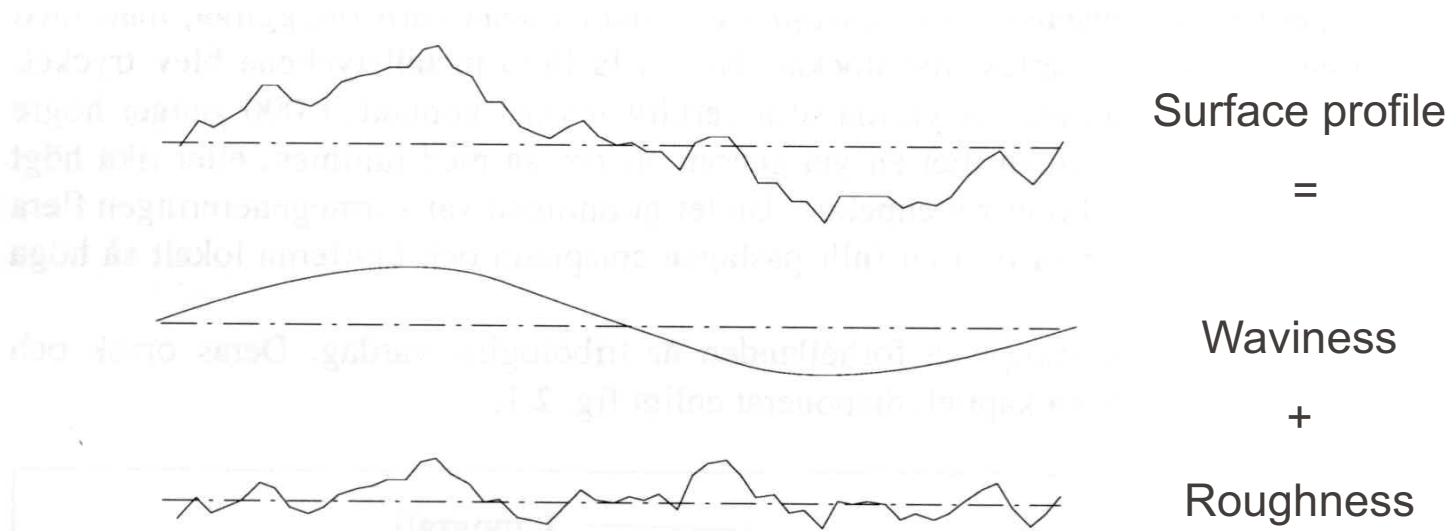


Fig. 2.2 En typisk ytprofil och dess komponenter.

Waviness can be caused by the machining process – a systematic error (vibrations/deflections).

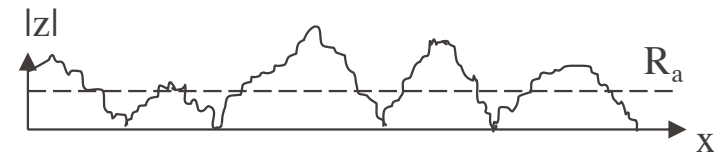
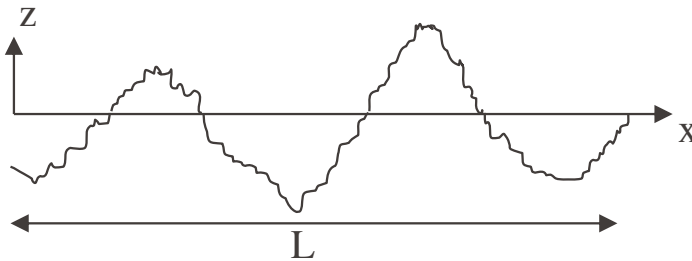
The roughness is a random error produced when material is removed from the surface.

Height parameters

Definition of the most usual parameters : R_a et R_q

- R_a : central line average roughness

$$R_a = \frac{1}{n} \sum_{i=1}^n |z_i|$$



- R_q : root mean square roughness

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n z_i^2}$$

z : height of the profile at position x

n : number of measurement points over the length L

L : measurement length

- The *roughness* of technical pieces is linked to the *machining quality* grade :

Grade	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
R_a μm	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50



turning,
milling,
etching

Coarse
machining



finishing

for $R_a < 0.025 \mu\text{m}$: polishing

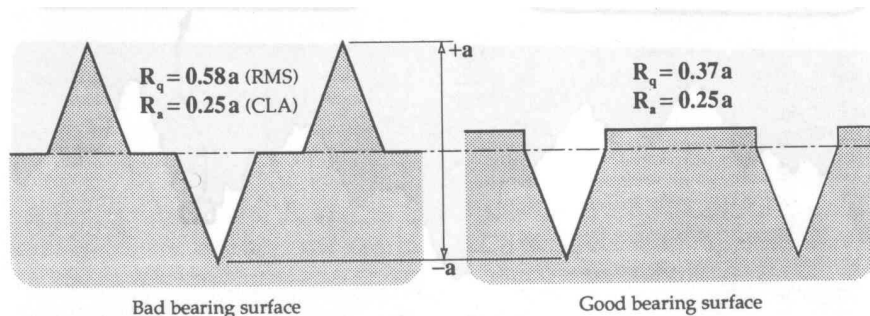


FIGURE 10.6 Effect of averaging on CLA value [9].

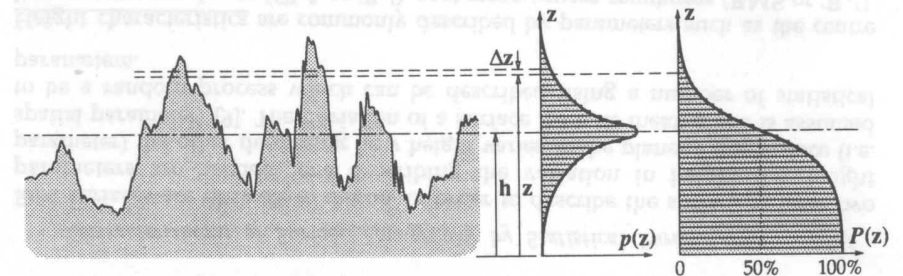
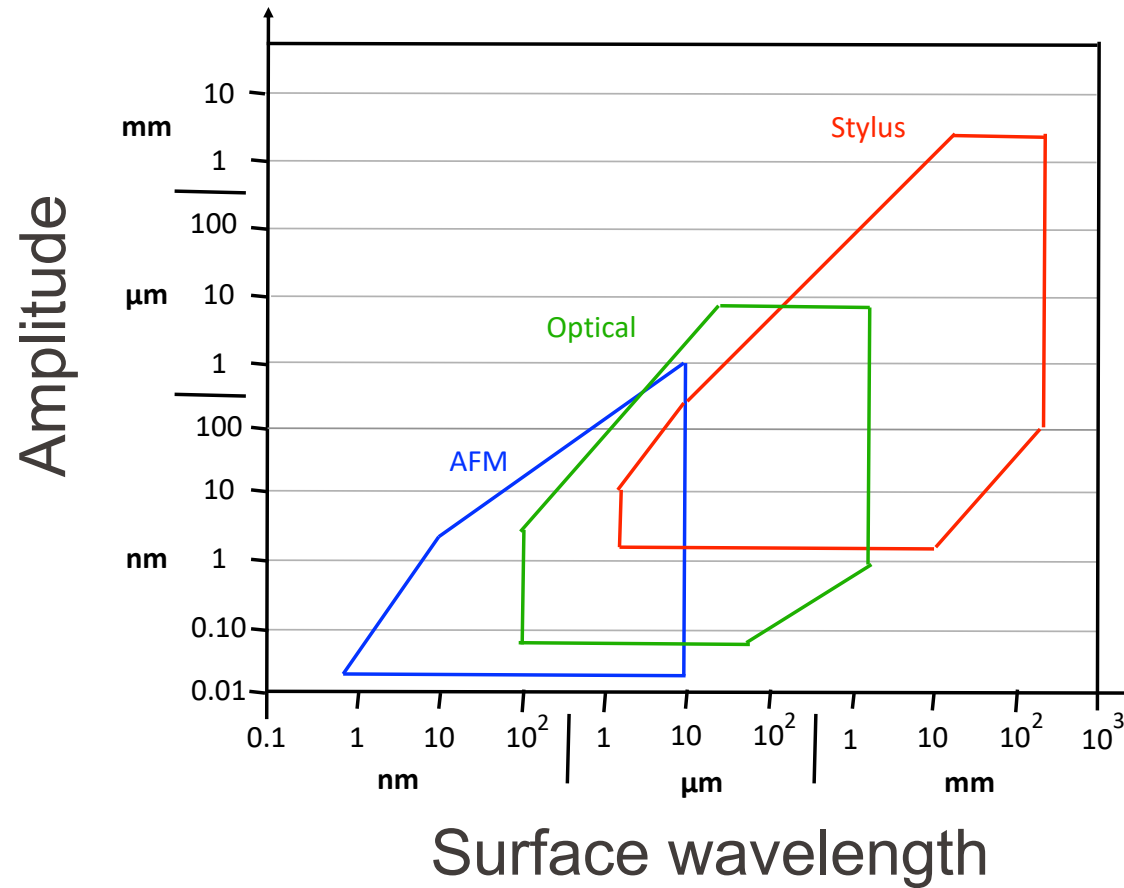


FIGURE 10.4 Determination of a bearing area curve of a rough surface; z is the distance perpendicular to the plane of the surface, Δz is the interval between two heights, h is the mean plane separation, $p(z)$ is the height probability density function, $P(z)$ is the cumulative probability function [9].

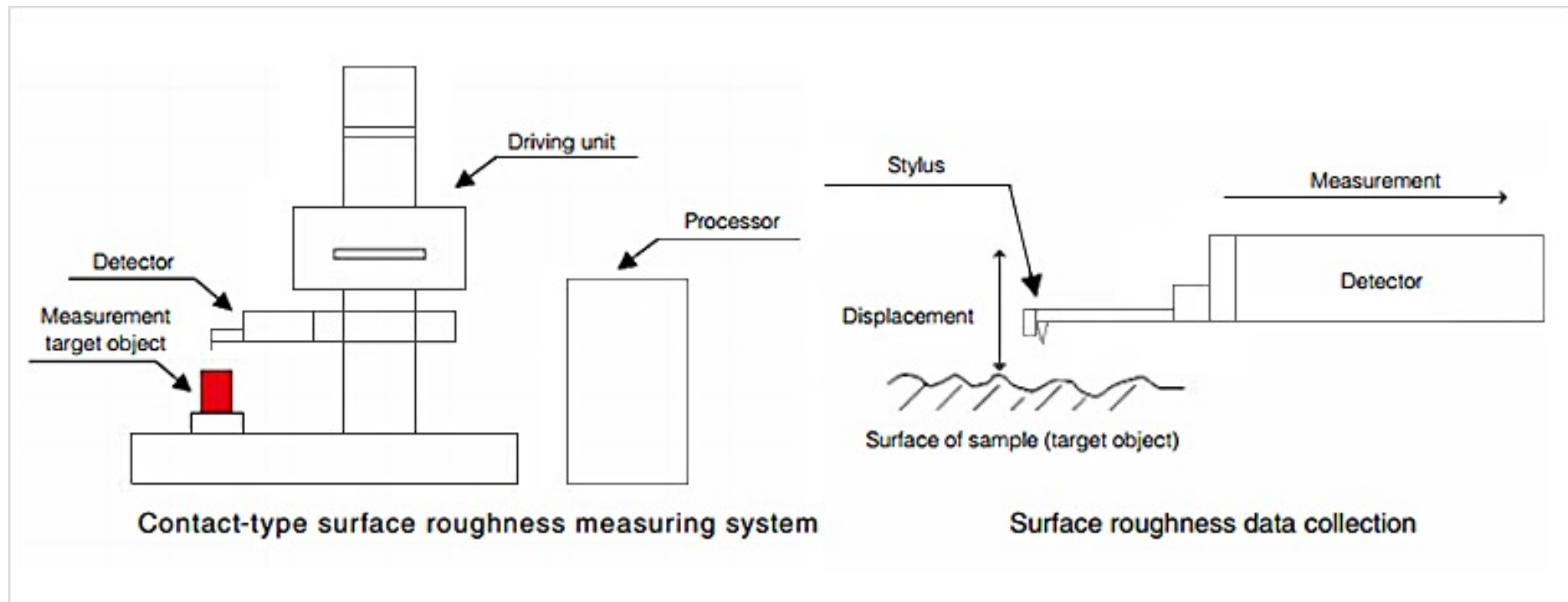
These profiles have the same R_a value, but different rms value. They will have a very different behavior in a sliding contact.

The rms value will be able to differentiate the profiles. The bearing curve (Abbot-Firestone) is useful for evaluating these profiles.

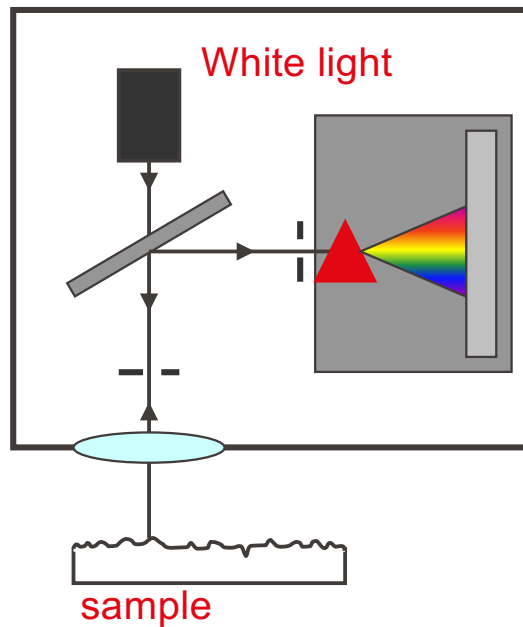
Surface topography: measurement techniques



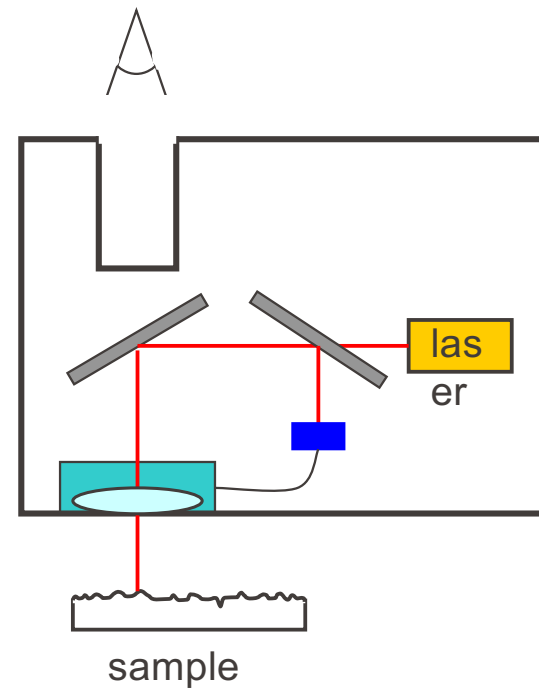
Measurement techniques: stylus profilometer



Chromatic confocal

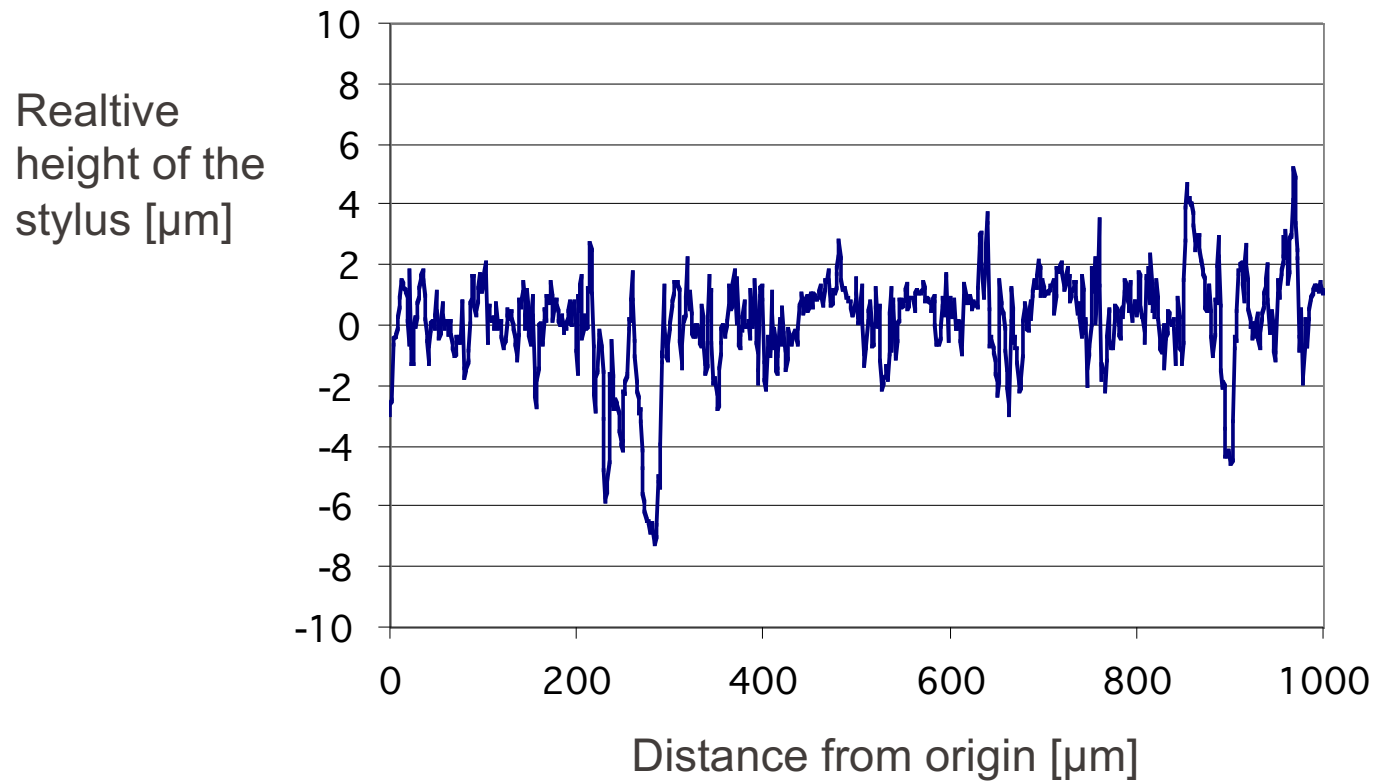


Dynamic focusing



Measurement example

- Two-dimensional topographic measurement:

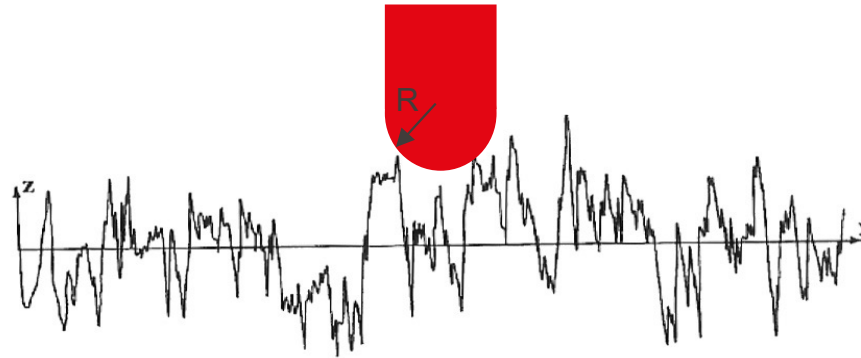


Size of the probe

- Effect of the probe size R on profile measurement :

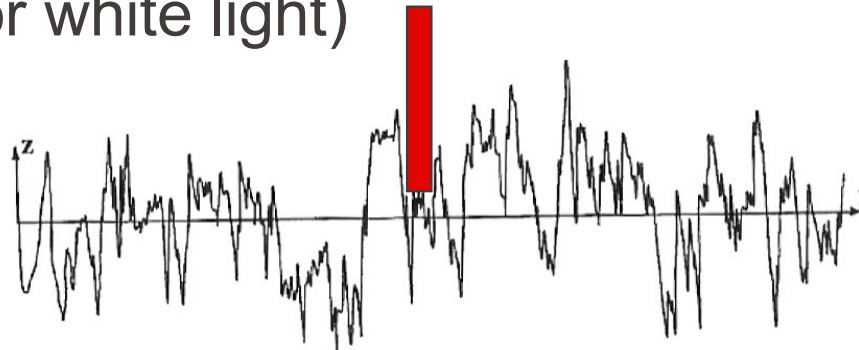
Stylus:

$R = 1-2.5 \mu\text{m}$



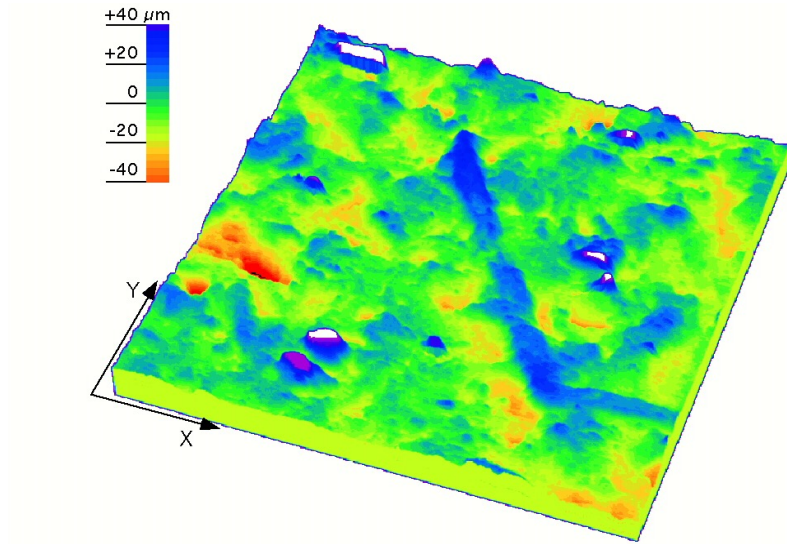
- Optical beam : (laser or white light)

$R = 0.5-1 \mu\text{m}$

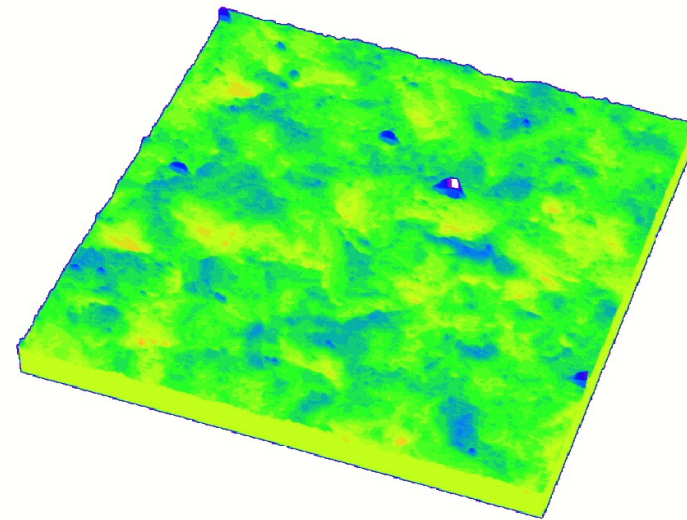


Tri-dimensional profilometry

- Analysed surface : $0.5 \times 0.5 \text{ mm}^2$:



New prosthesis

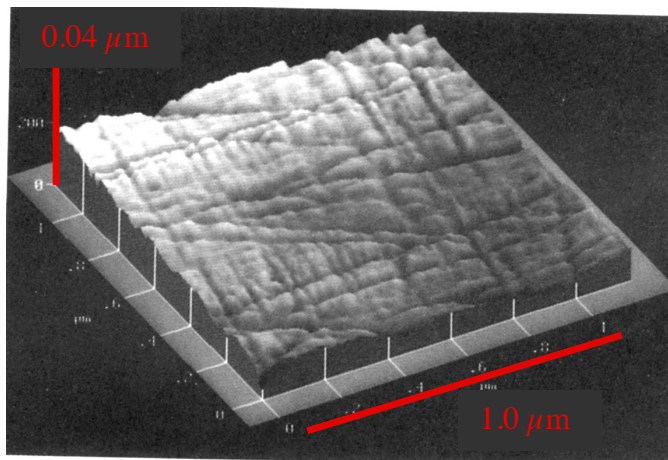


Prosthesis after clinical use

Profilometry vs Atomic force microscopy

- Resolution

Technique	Profilometer	AFM
Direction		
Horizontal	1000 nm	10 nm
Vertical	10 nm	0.1 nm



Mirror polished steel surface: AFM image

“Putting two solids together is rather like turning Switzerland upside down and standing it on Austria – the area of intimate contact will be small”

F.P. Bowden

Key point: OBSERVE

Don't forget to look at the surface!

1. Introduction to tribology

2. What is a surface?

3. How surfaces contact?

Contact mechanics

4. Main concepts: Friction, wear and lubrication

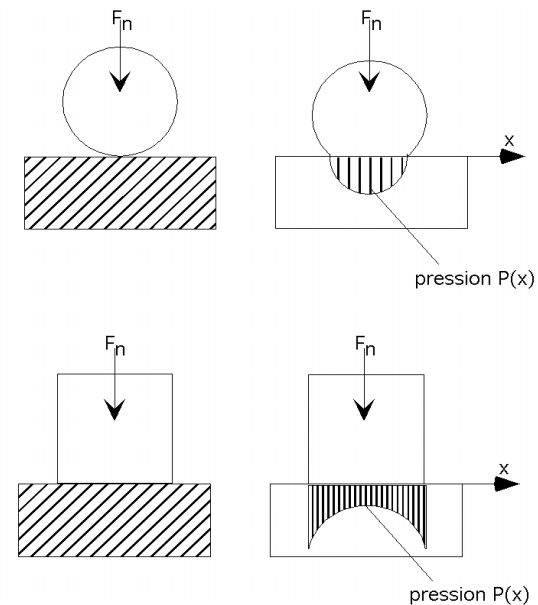
5. Which experimental techniques allows for testing surfaces?

- Study of the amplitude and distribution of mechanical stresses in a contact.

Conformity of the contact :

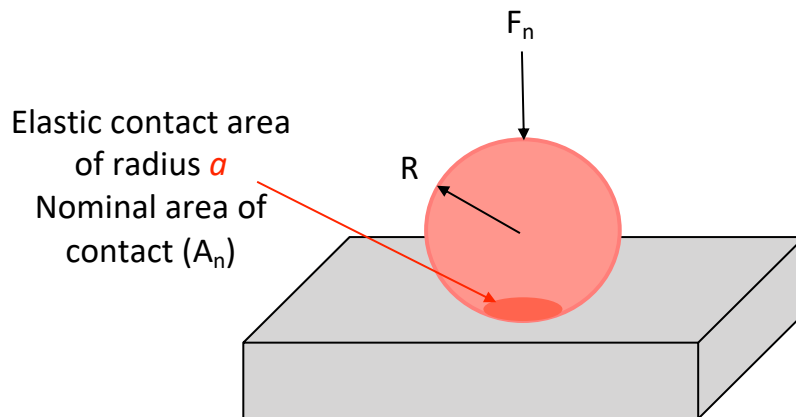
Non-conformal contact :

Conformal contact :



Hertz mechanics for non-conformal contacts:

Calculation of elastic strain and stress in terms of load, geometrical parameters and materials



Ball-plane contact

$$\frac{1}{E'} = 0.5 \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]$$

E = Young's modulus

ν = Poisson's ratio

Radius of contact area (circle) $a = \left(\frac{1.5 F_n R}{E'} \right)^{1/3}$

Maximum contact pressure $p_0 = \frac{3 F_n}{2 \pi a^2}$

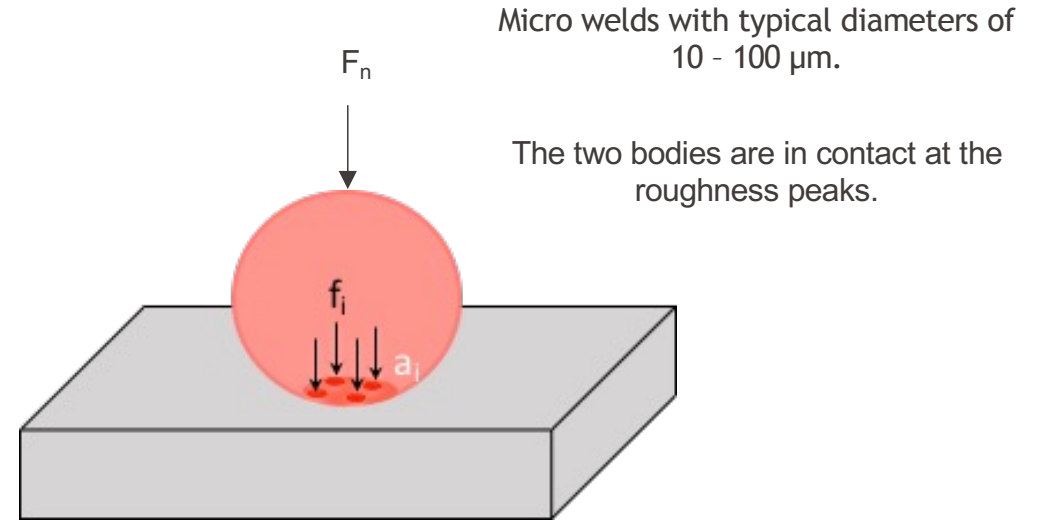
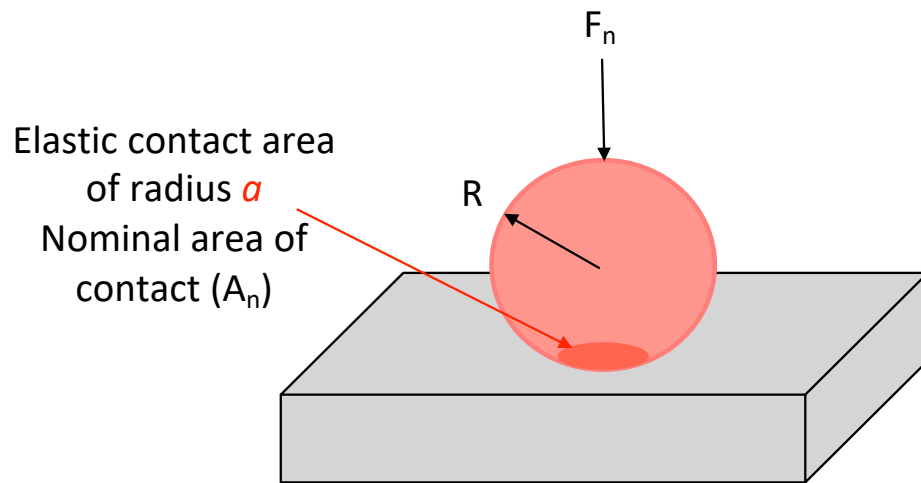
Average contact pressure $p_m = \frac{F_n}{\pi a^2}$

Maximum deflection $w = 1.31 \left(\frac{F_n^2}{E'^2 R} \right)^{1/3}$

Maximum shear stress $\tau_{\max} = \frac{p_0}{3}$

Depth of maximum shear strength $z = 0.638 \cdot a$

Nominal and real contact area



Total load (normal force): $F_N = \sum_{i=1}^n f_i$

Real contact area:

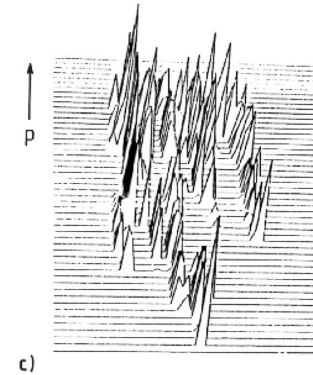
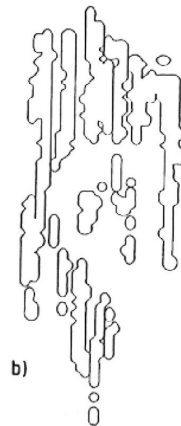
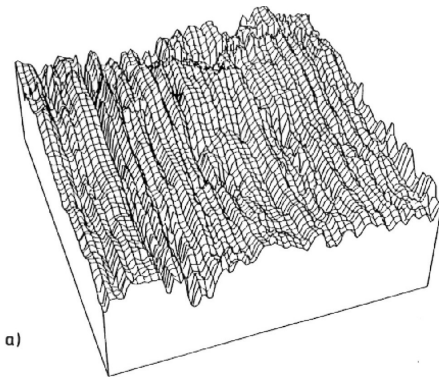
$$A_r = \sum_{i=1}^n a_i$$

$$a_i = \frac{f_i}{H} \Rightarrow A_r = \frac{F_N}{H}$$

First simple assumption:
pure plastic contact

Roughness effect

- Numerical simulation of a model Hertzian contact with a rough steel surface ($F_n = 25$ N, $p_0 = 1$ GPa, elliptical contact area : semi-axes $78\text{ }\mu\text{m}$ and $162\text{ }\mu\text{m}$).
 - a) Representation of the steel surface : area 0.5 mm^2 , maximum relief $4.4\text{ }\mu\text{m}$)
 - b) Contour of the contact area
 - c) Pressure distribution (maximum value **7 GPa**)



West & Sayles, 1988

Onset of plastic deformation

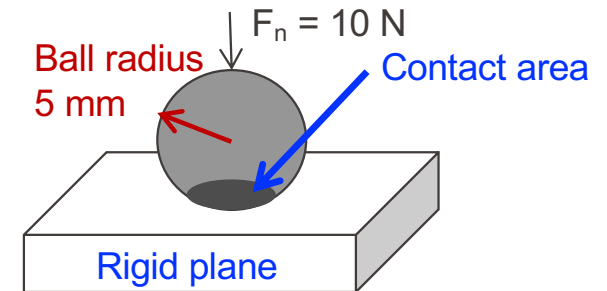
Tresca criterion: plastic deformation occurs when a critical shear stress of $\sigma_Y/2$ (σ_Y : Yield strength in uniaxial traction) is reached

For a ball on plane contact

$$P_0 > 1.61 \sigma_Y$$

$$P_m > 1.07 \sigma_Y$$

Contact mechanics parameters for ball on disk contact



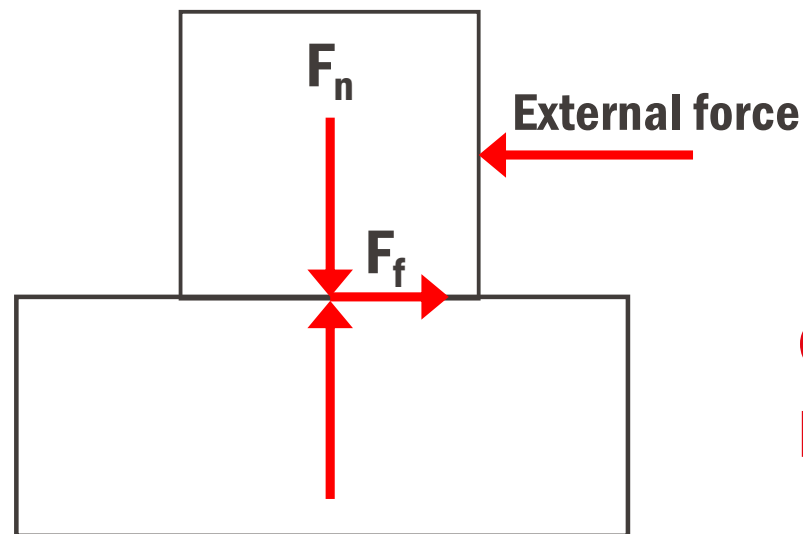
Ball Material	Elastomer	Polymer	Metal	Ceramic	Unit
E Modulus	0.02	1	200	500	GPa
Poisson ratio	0.5	0.5	0.3	0.3	
Radius of contact area	1.121	0.304	0.057	0.043	mm
Average Pressure	3	34	995	1740	MPa
Yield Strength (σ_Y)	10	20	350	350	MPa
Av. Pressure/ σ_Y	0.3	1.7	2.8	5.0	

Softer but more elastic materials can accommodate contact stresses without plastic deformation

1. Introduction to tribology
2. What is a surface?
3. How surfaces contact?
- 4. Main concepts: Friction, wear and lubrication**
5. Which experimental techniques allows for testing surfaces?

What is friction?

- Tangential force (F_f) at the surface between two bodies preventing (static friction) or opposing to (dynamic friction) the relative motion of the two bodies caused by an external force.

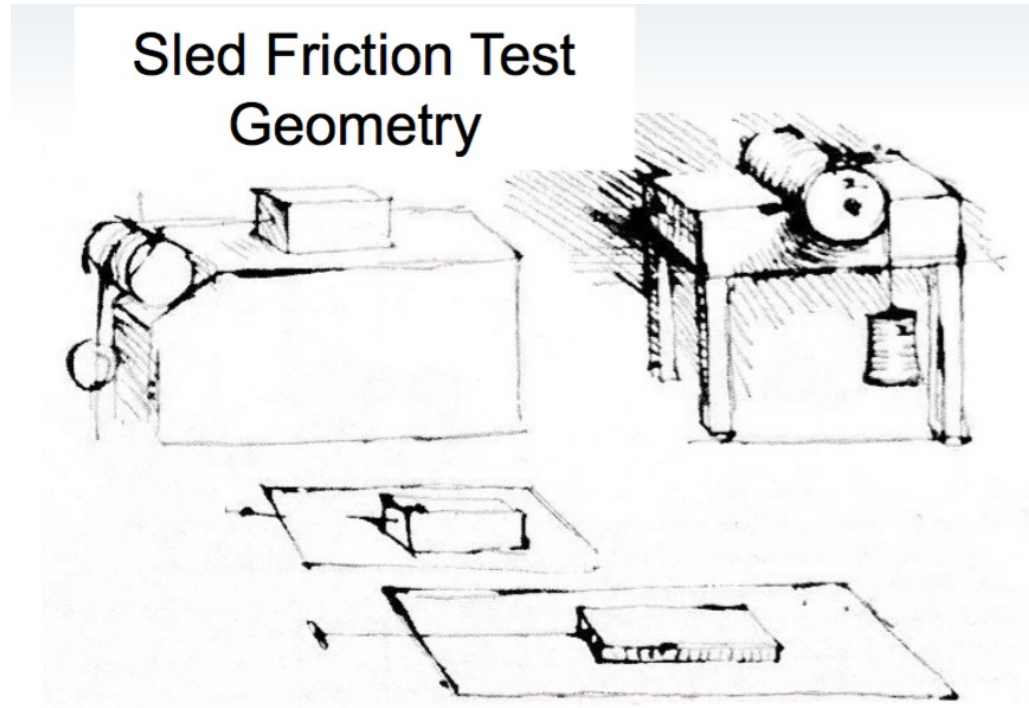


Coefficient of friction:
 $\mu = F_f / F_n$

Motivation to study friction: machine conception



Leonardo Da Vinci

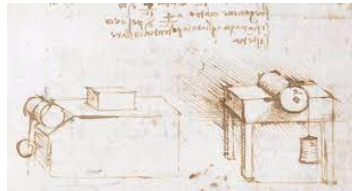


- The friction force is proportional with the applied normal force
- The friction force is independent of the nominal/apparent area of contact

Amontons's laws (1699) – actually already proposed by Da Vinci (1500):

1. The friction force is proportional with the applied normal force: $F_t = \mu F_n$
2. The friction force is independent of the nominal/apparent area of contact
3. The friction force is independent of sliding speed (Coulomb's law of friction, 1785)

DaVinci (1500)



Amontons (1699)

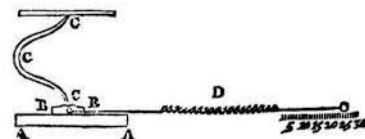
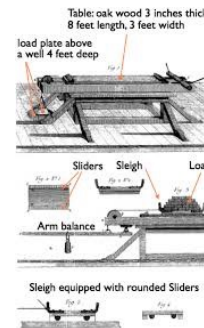


Figure 1.5: Amontons' sketch of his apparatus for friction experiments. The spring D measures the friction force during the sliding process between materials A and B. Spring C adjusts the normal force. (From²)

Coulomb (1785)



Industrial polymers (1920-1940)

Polymers

Metals

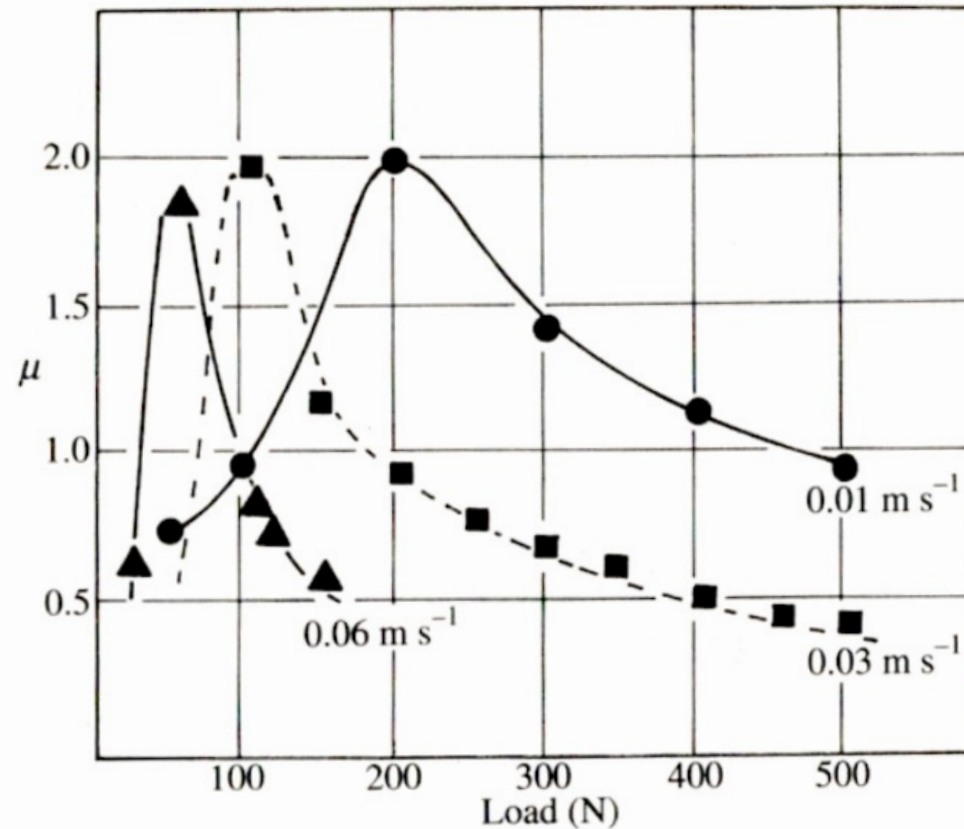
Ceramics

Wood

1500 1600 1700 1800 1900 2000

What about polymers??

CoF versus normal load
for three sliding speeds
for nylon on steel



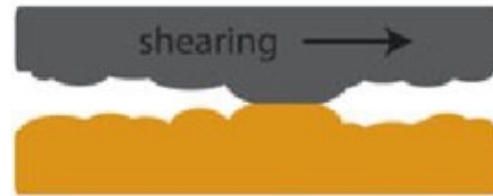
Source: Williams "Engineering Tribology" (1994)

Origin of friction

"Interfacial friction is caused by the ploughing of asperities in the mating surface and adhesion forces between the interacting asperity summits"

F.P Bowden and D. Tabor (1942)

- Adhesion: due to the shear resistance between contacting surfaces.



- Ploughing: due to resistance of surface asperities ploughing the contacting surface.

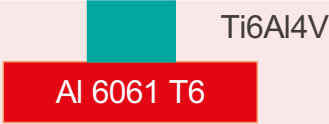


Consequences of friction

- Energy dissipation: heating
- Surface traction: shearing, failure, wear



Friction is a system
parameter – not a material
parameter !

Influence of	Diagram	Parameter	COF
Sliding partner (X)		Al6061 T6	0.38
		Copper	0.28
		Steel 1032	0.23
		Teflon	0.07
Contact configuration			0.38
			0.29
Environment		Vacuum	> 4 (seizure)
		10 ⁻³ mbar O ₂	1.50
		1 mbar O ₂	0.40
		Oil film	< 0.10
Roughness		R _q 390 nm	0.31
		R _q 220 nm	0.20
		R _q 120 nm	0.09
		R _q 68 nm	0.09

Wear: definitions with very different implications

- ***Deterioration*** throughout prolonged use, due to friction
- ***Progressive loss of material*** from the surface of a solid body due to mechanical interactions occurring during contact and relative motion with a solid, liquid or gaseous counter body.
- These two notions are not necessarily related :
 - Durability** of a system functionality
 - Loss** of material

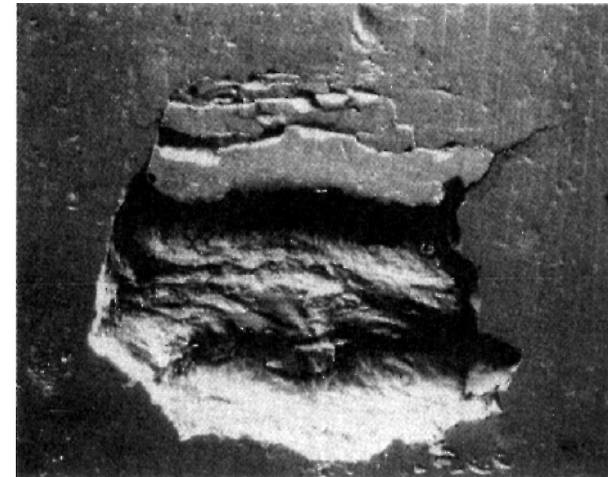
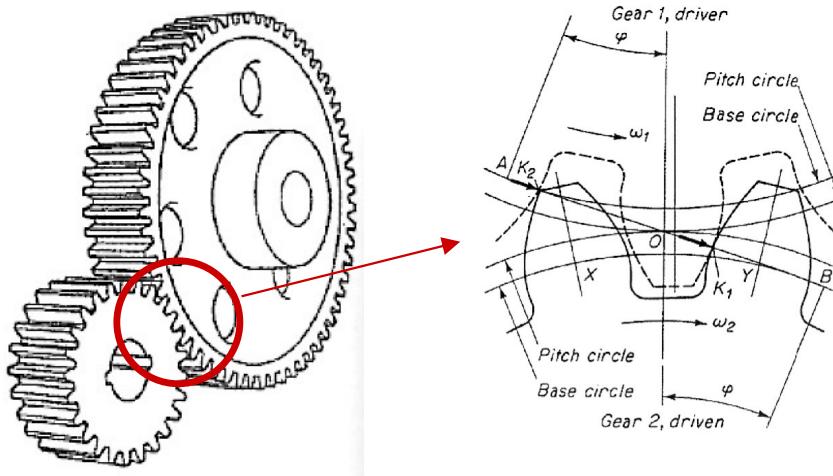
Example of progressive material loss

- Tyres : loss of functionality due to the progressive material removal.



Example of sudden loss of function by wear

- Gears : loss of functionality due to the sudden removal of a single tiny particle after long operational periods without any significative loss of material.



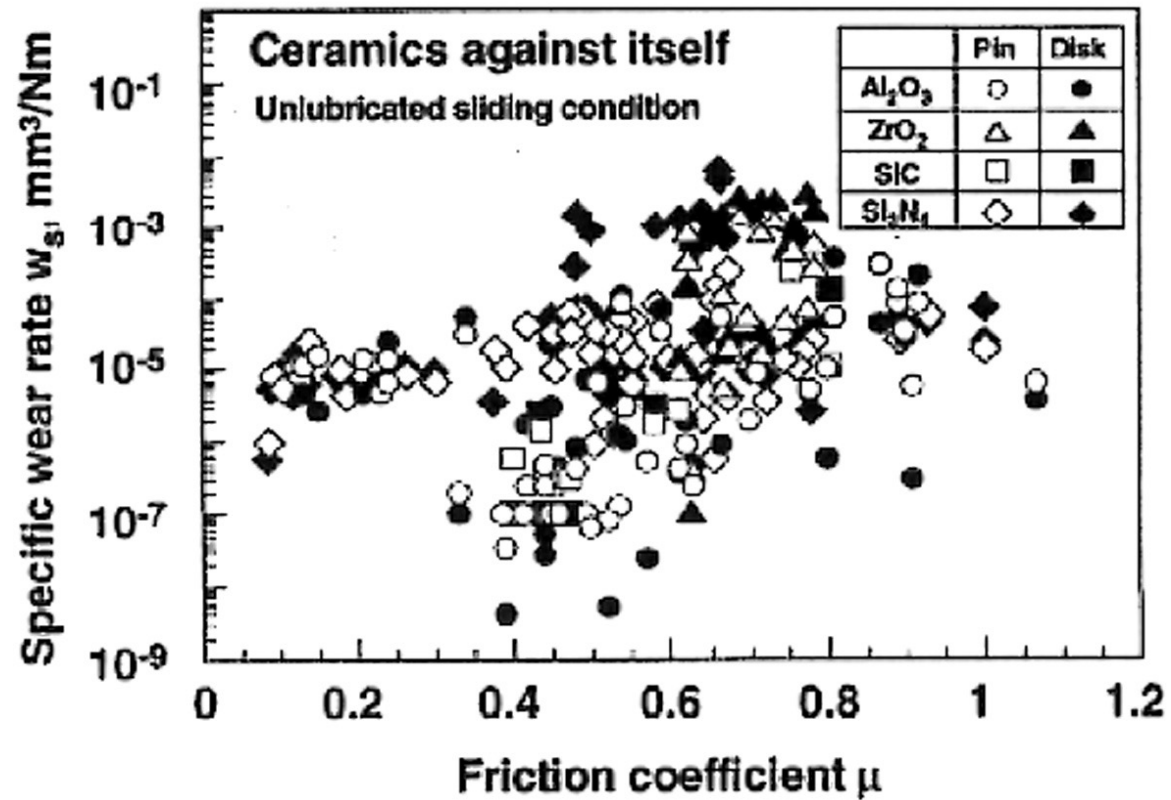
Fatigue failure of a bearing steel component.

H. Czichos, Tribology, Springer 1978

Wear rate and friction

(Kato 2001)

- No obvious correlation between these two parameters.



First wear study: gold coins and material loss

Experiments and Observations on the various Alloys, on the specific Gravity, and on the comparative Wear of Gold. Being the Substance of a Report made to the Right Honourable the Lords of the Committee of Privy Council, appointed to take into Consideration the State of the Coins of this Kingdom, and the present Establishment and Constitution of His Majesty's Mint. By Charles Hatchett, Esq. F.R.S. Read January 13, 1803. [Phil. Trans. 1803, p. 43.]

- Experimental conditions (Charles Hatchett 1803):
 - Material: Type of gold (ductile or hard)
 - Topography: coins with flat, smooth, and broad surfaces and coins with protuberant parts
 - Mechanical variables: sliding speed, pressure, type of contact and contact geometry
- Quantification of wear: coin weight loss

Wear formalism

Outcome of two centuries of scientific effort to quantify wear:

- Numerous equations available for wear.

Meng and Ludema (Wear 181-183(2) (1995) 443-457) identified:

182 equations for wear published between 1955 and 1995.

625 involved variables, either as **numerator** or **denominator**

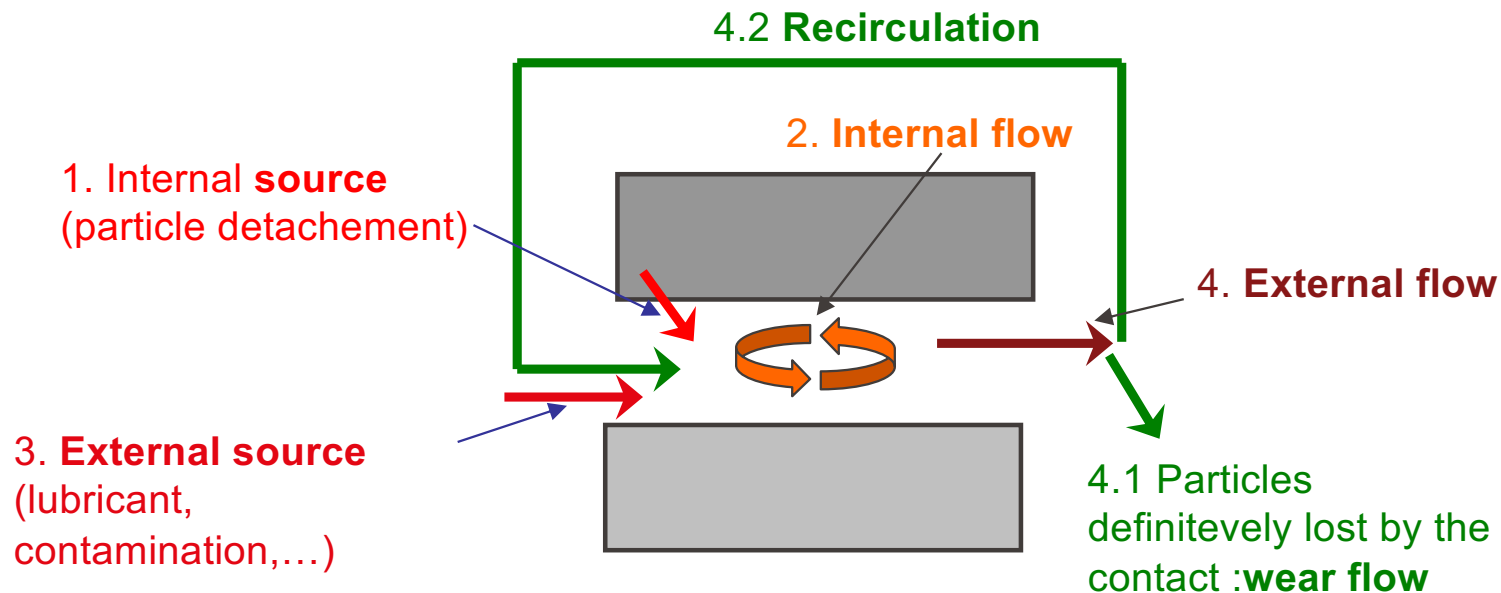
- No single predictive model/equation of wear exists per today.
- Wear involves chemical and physical interactions with the mechanical components – difficult to model.

No universal formalism !

Existing laws apply to very specific cases only !

More than a mass loss: Third body concept and material flow

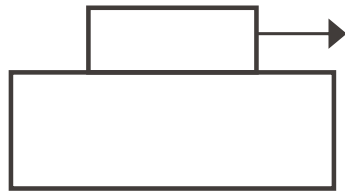
- Wear can be described as a flow of particles:



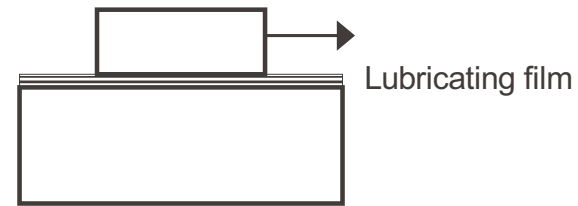
Wear is a system response
Wear resistance is not a
material property

What is lubrication?

- Reduction in friction and/or wear by interposing a separating film of lubricant between two interacting bodies in relative motion.



Non lubricated contact



Lubricated contact

- Lubricants : liquid, gas, solid, semi-solid, powder

The first recorded lubrication – 2400 B.C.

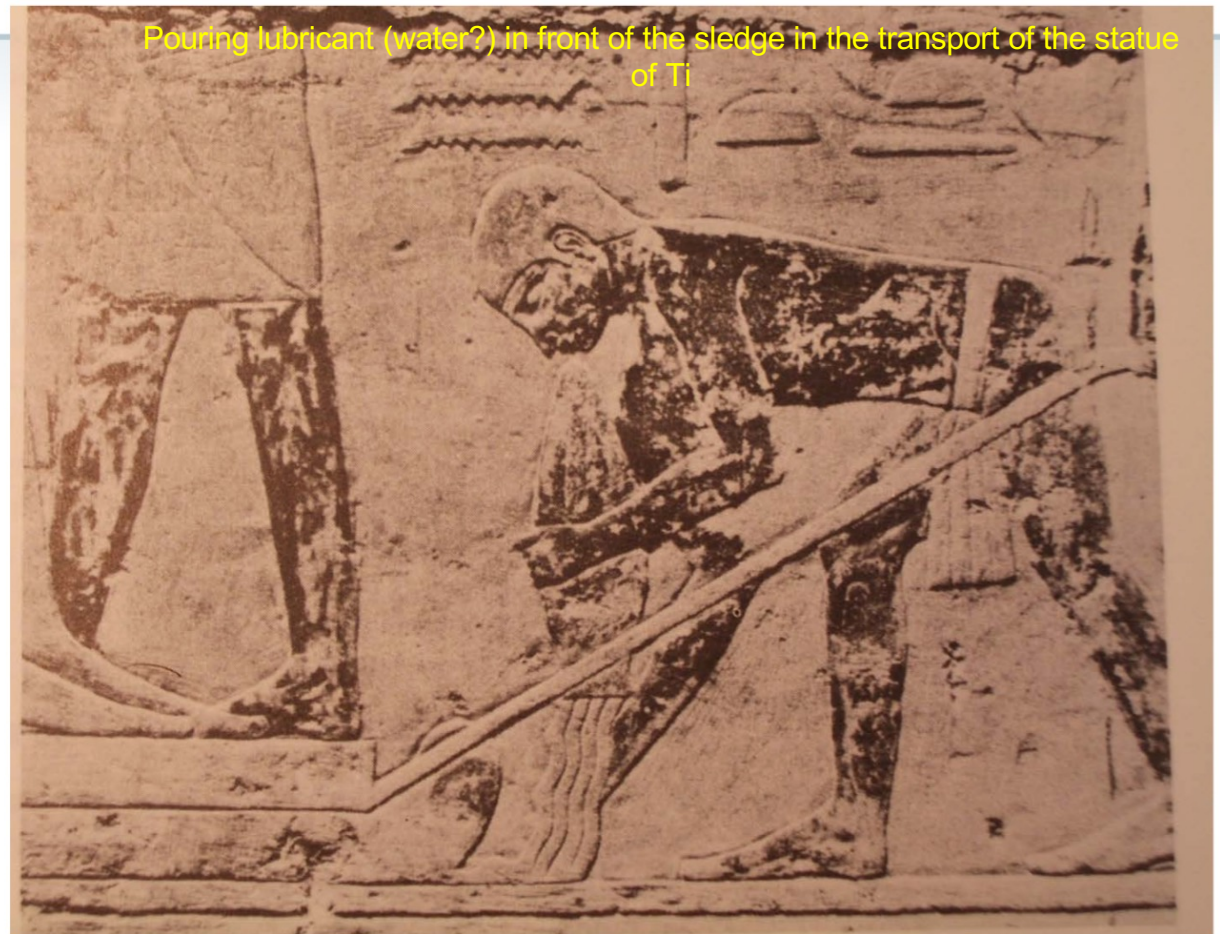
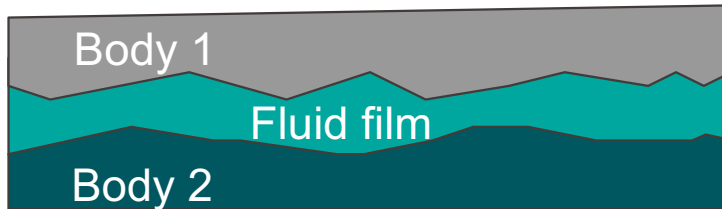


Figure taken from "History of Tribology" by Duncan Dowson

Formalism for hydrodynamic lubrication: Reynolds equation (1886)

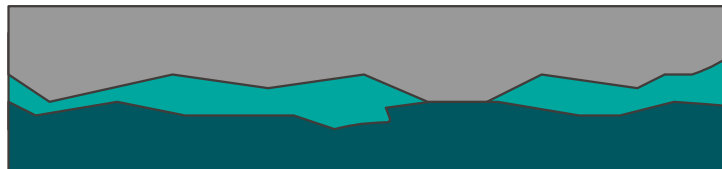
- Based on Navier-Stokes equation for fluid mechanics, it allows to calculate the thickness of the lubricant film formed in the contact.
- Assumptions
 - The fluid is Newtonian
 - The flow is laminar
 - The fluid adheres to the walls
 - The fluid film is incompressible, and of negligible inertia and weight

Regimes of fluid lubrication



Hydrodynamic regime

The film is thick enough to entirely separate the two surfaces.



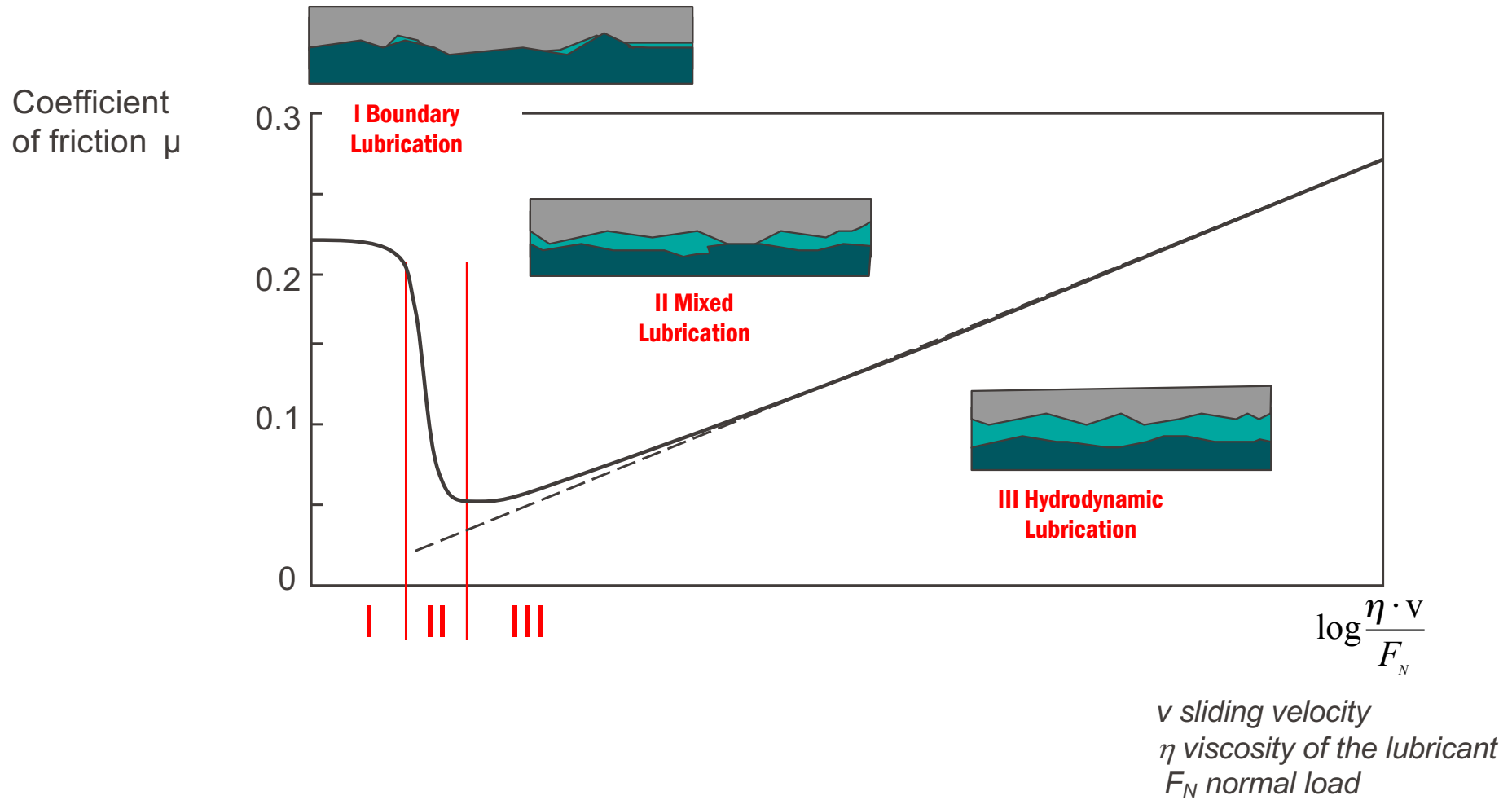
Mixed regime



Boundary regime

The film is not thick enough to separate the two surfaces. The friction is determined by the contacts between asperities.

Fluid lubrication regimes: Stribeck curve



Boundary lubrication

- Intimate contact between bodies
- Controlled by the formation of nanometer-thick films either through adsorption or through chemical reaction on the contacting materials.
- Physico-chemical properties of the oil, of its additives, and of the materials are crucial.

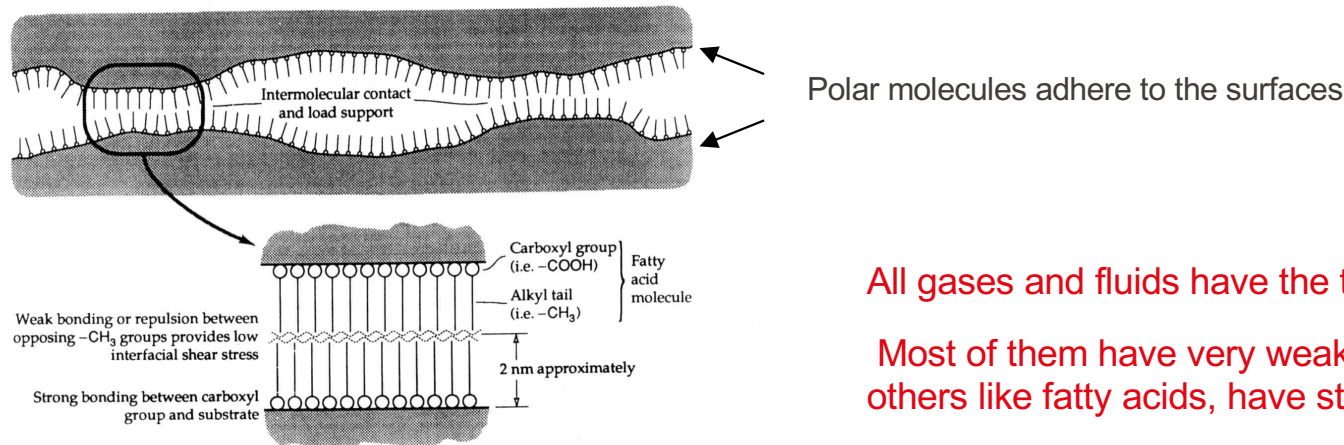


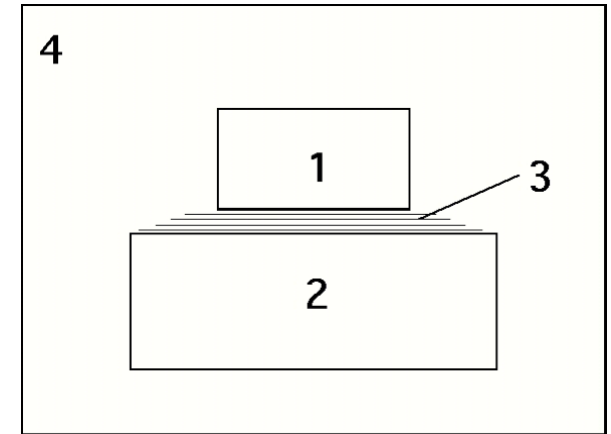
FIGURE 8.4 Low friction mono-molecular layer of adsorbed organic polar molecules on metallic surfaces.

All gases and fluids have the tendency to adhere to surfaces.

Most of them have very weak bonds to the surface, while others like fatty acids, have strong bonds to metal surfaces.

A tribology system is characterized by

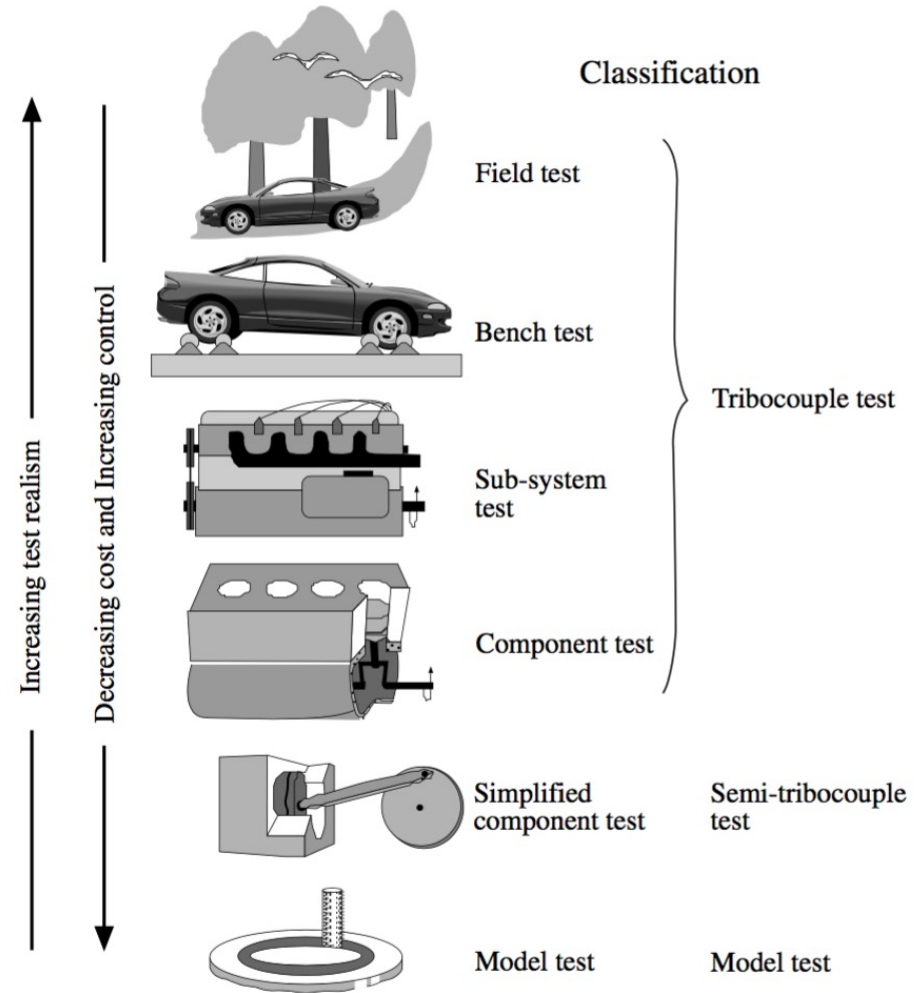
- **Loading:**
 - Type of motion, normal force, speed, temperature...
- **System structure :**
 - Elements : body and counter body 1 et 2, lubricant 3, environment 4
 - Properties: geometry, materials, surfaces
- **Interactions** between the elements generate friction and wear and therefore may modify the structure of the system. For example:
 - Wear can change the geometry of elements, or
 - Heating due to friction can reduce the strength of a material in contact.



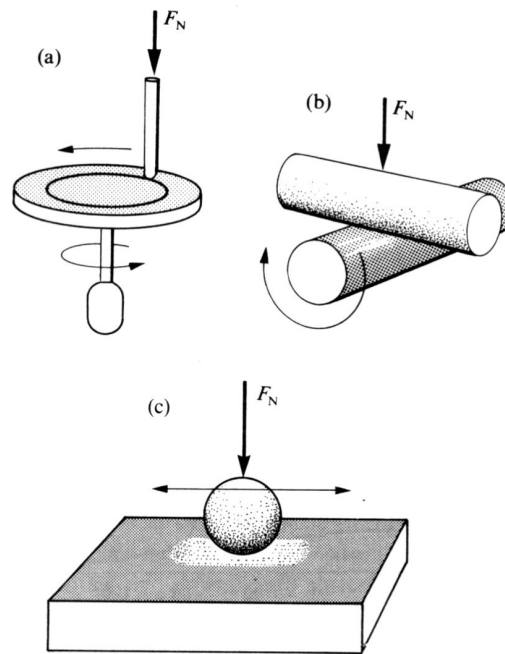
1. Introduction to tribology
2. What is a surface?
3. How surfaces contact?
4. Main concepts: Friction, wear and lubrication
- 5. Which experimental techniques allows for testing surfaces?**

Classification of tribotest depending on the degree of realism

N. Axen et al. "Friction and wear measurement techniques" of *Modern Tribology Handbook*, CRC Press 2001



Main laboratory devices used to study wear (tribometers) :



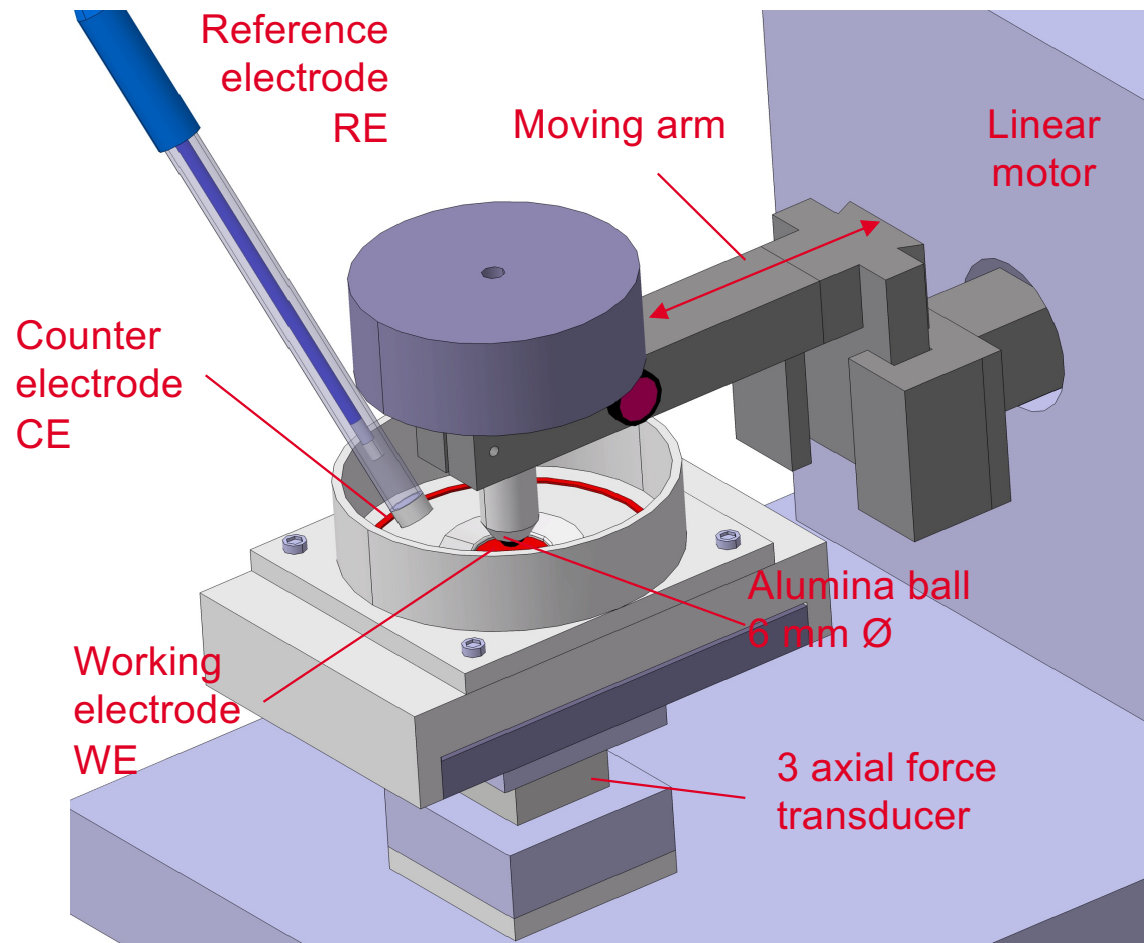
Wear is assessed by volumetric or gravimetric analysis of the material loss after experiment interruption.

Fig. 10.11 -Devices used for the experimental study of wear : pin on disc test (a), Crossed-cylinder test (b), Alternating motion test (c)

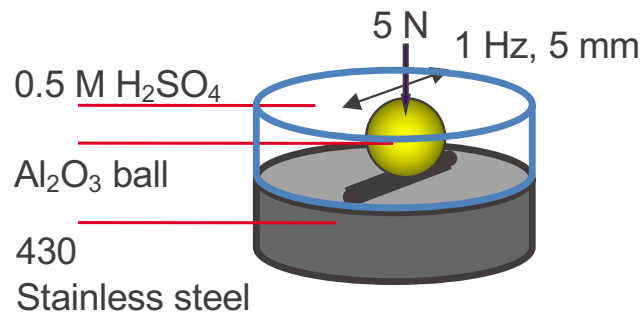
Pin on disc tribometer at TIC



Tribo-electrochemical test rig

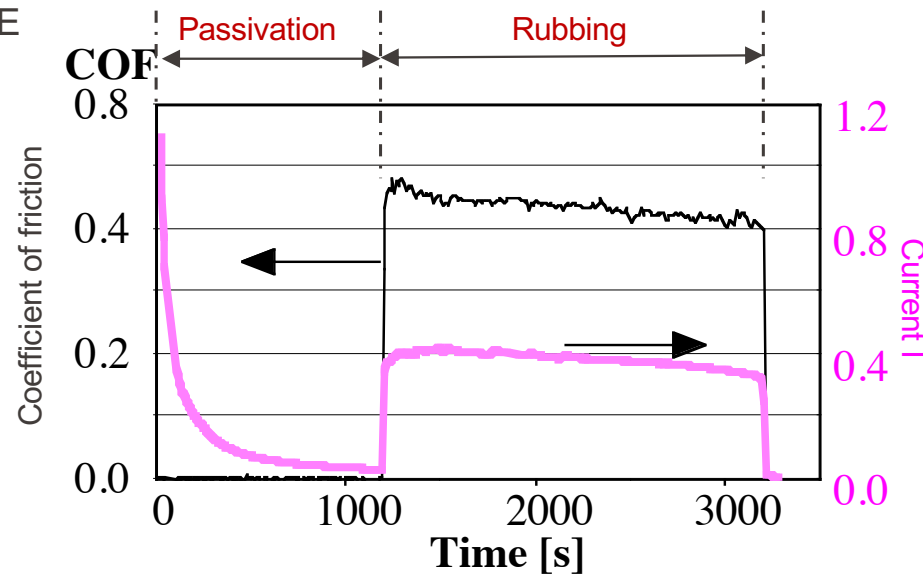


Wear accelerated corrosion



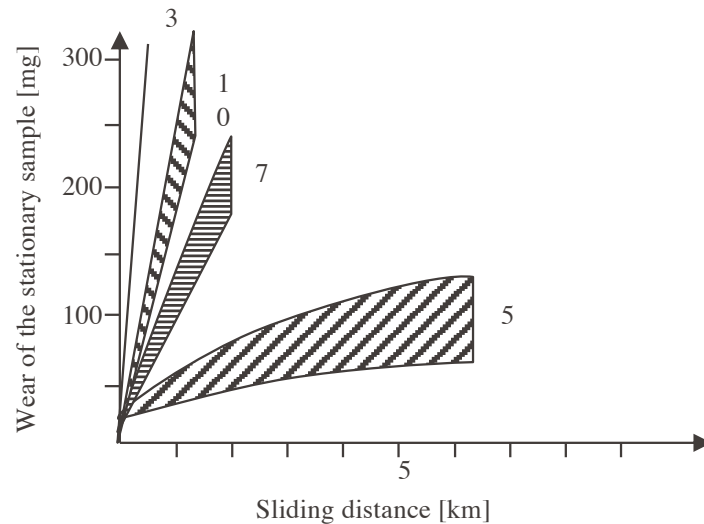
Rubbing duration: 2000 s
Imposed potential: 0.25 V MSE

Current density (corrosion rate):
before rubbing $\approx 1 \mu\text{A}/\text{cm}^2$
during rubbing $\approx 10^5 \mu\text{A}/\text{cm}^2$



Enhancement of corrosion can be recorded using tribo-electrochemical experiments

■ **1964:** 1st inter-laboratory wear test



- 21 laboratories measured wear, as a function of sliding distance, of same materials couples using various tribometers under identical load and speed.

■ **1986:** 2nd inter-laboratory wear test

■ Thanks to a strict control of :

- Surface roughness
- Surface contamination (cleaning)
- Geometry and size
- Wear measurement procedures
- Relative humidity (12-78%)
- Type of motion
- Load, speed, vibrations

■ Replicability could be improved :

- Steel on steel wear :
 $70 \pm 20 \mu\text{m/km}$ (steel)
- Ceramic on steel wear :
 $81 \pm 29 \mu\text{m/km}$ (steel)

Quantification of wear

- Experience shows that the wear volume V_{wear} is often :

$$V_{\text{wear}} \propto (\text{sliding distance } L)$$

$$V_{\text{wear}} \propto (\text{normal load } F_n)$$

$$V_{\text{wear}} \propto (1 / \text{hardness } H)$$

- Different ways to define the wear rate T_{wear} exist :

$$T_{\text{wear}} = V_{\text{wear}} / L \quad (\text{volume loss per unit of sliding distance } [\text{mm}^3/\text{m}])$$

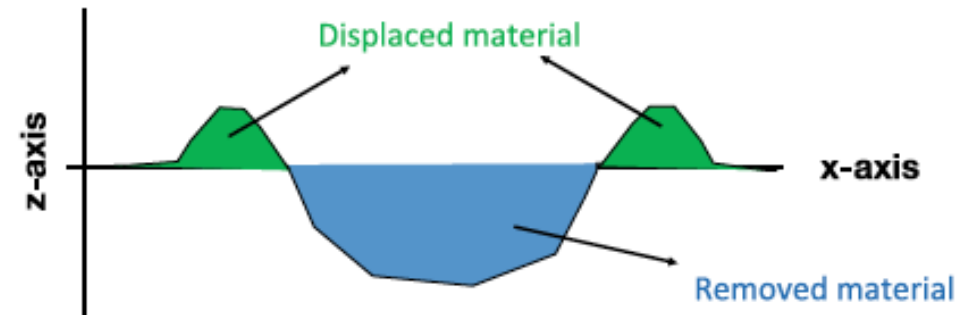
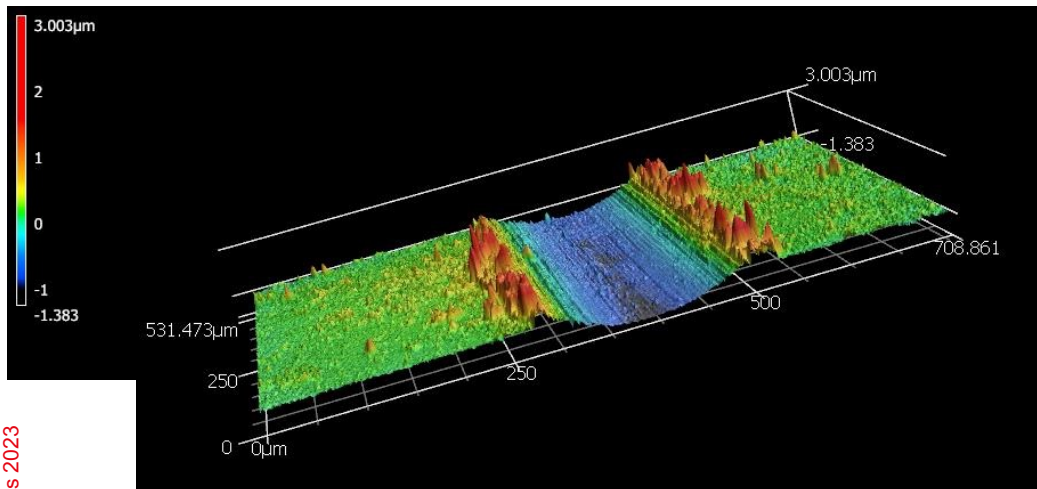
$$T_{\text{wear}} = V_{\text{wear}} / (L F_n) \quad (\text{wear coefficient } [\text{mm}^3/\text{m N}])$$

$$T_{\text{wear}} = V_{\text{wear}} H / (L F_n) \quad (\text{dimensionless wear coefficient})$$

- NOTE : These expressions do not necessarily take into account chemical (oxidation, corrosion, ...), metallurgical (hardening, ...) or physical (T, particles, ...) transformations that may occur during a tribological test.

Wear track volume

- Geometry of the wear track
- Wear track volume (V_{wear})

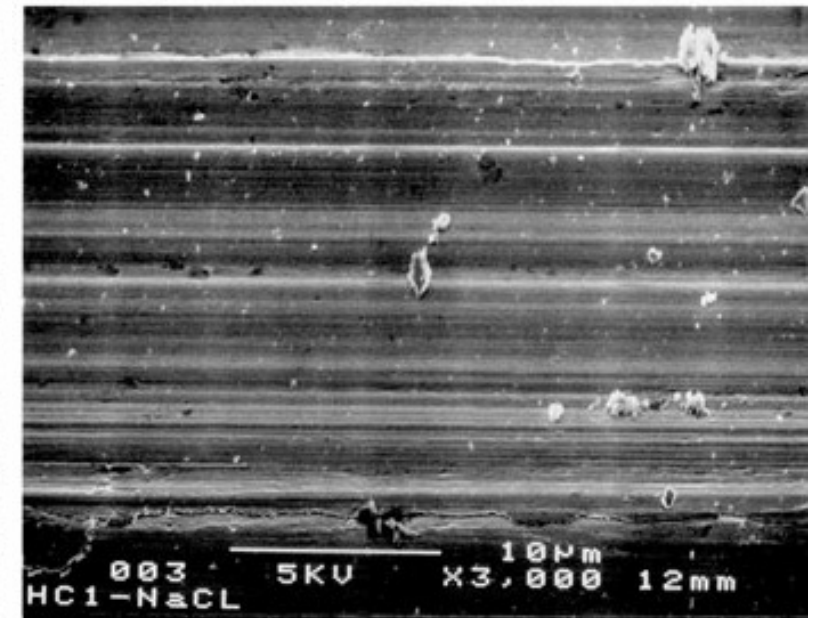
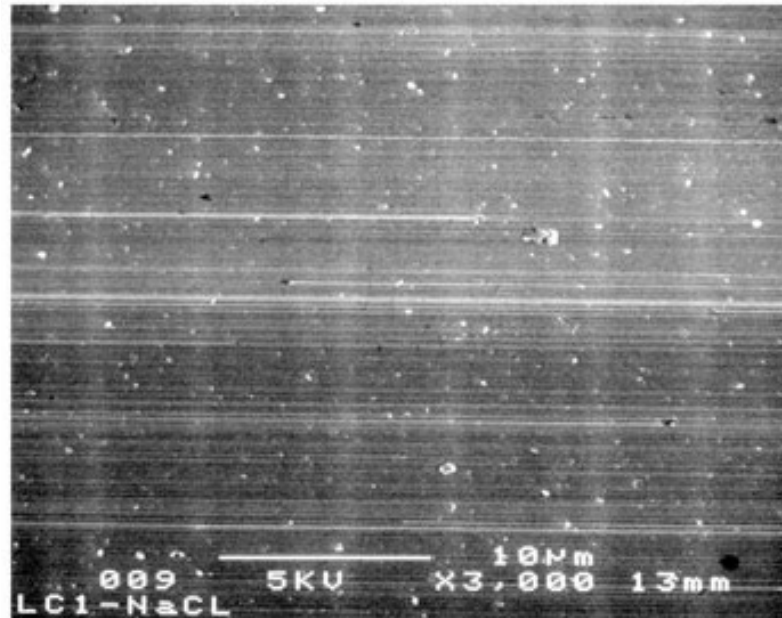


Laser scanning profilometer or confocal microscopy

Morphology of worn surfaces

- Optical microscopy
- Scanning electron microscopy
- AFM

CoCrMo alloys in 0.14M NaCl at applied passive potential sliding against alumina



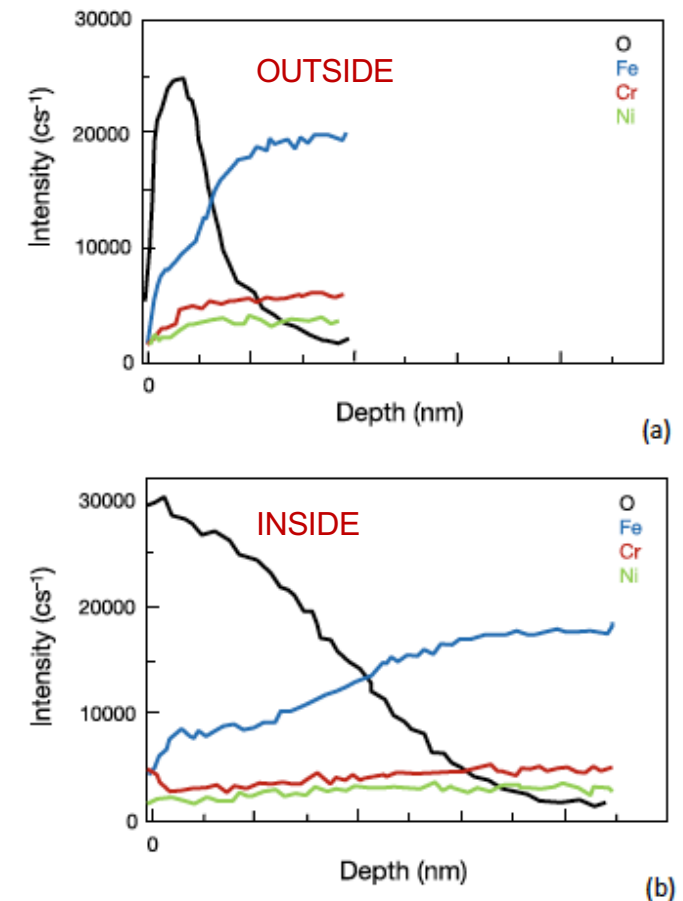
Igual et al. J Mater Sci: Mater Med (2011) 22:437–450

Surface chemistry modification

- AES Auger electron spectroscopy
- XPS X-ray photoelectron spectroscopy
- SIMS Secondary ion mass spectroscopy

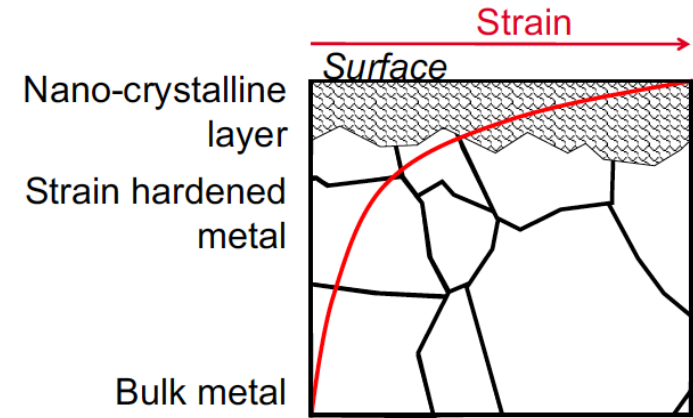
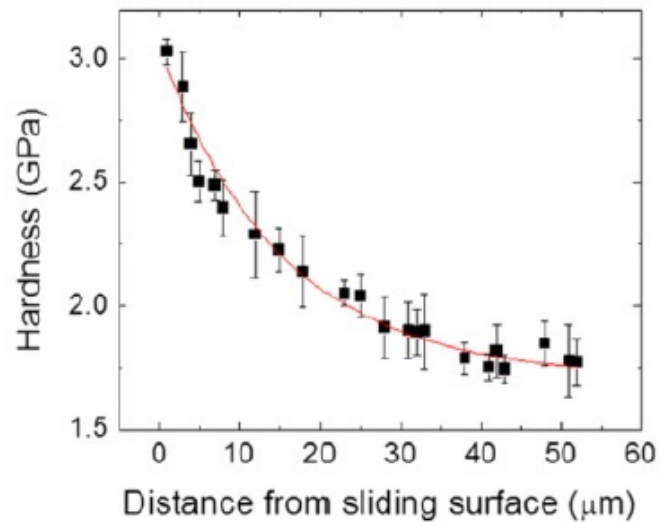
Thicker oxide film inside the wear track indicating the presence of a third body through which wear occurs

AES profiles outside and inside the wear track of an AISI 304L after a tribocorrosion test carried out in water at pH 6.9 (300 °C and 154 bars)



Subsurface characterization

- Metallographic cross sections
- Micro-nano hardness
- XRD
- TEM
- FIB

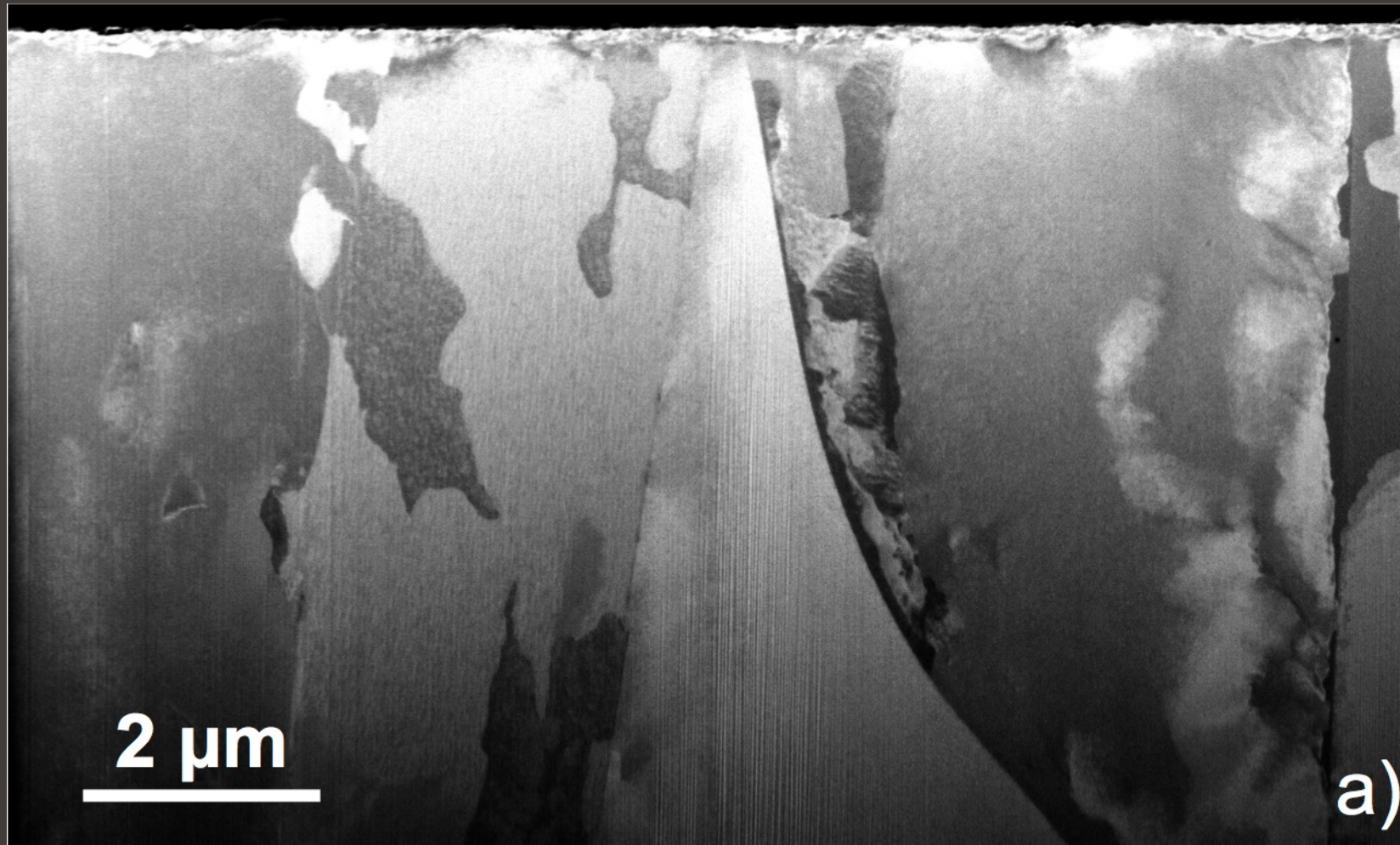


Tribological Transformed Surface (TTS)

Evolution of hardness below the wear track formed on a Ag-28.1 Cu alloy by rubbing against martensitic steel.

W. Cai, P. Bellon, Wear 303 (1) (2013)

FIB cross section of polished, unworn 304L steel



TTS (Tribological Transformed Surface) generated during tribocorrosion of passive 304L SS (FIB cross section)



Key point: OBSERVE

Don't forget to look at the surface!

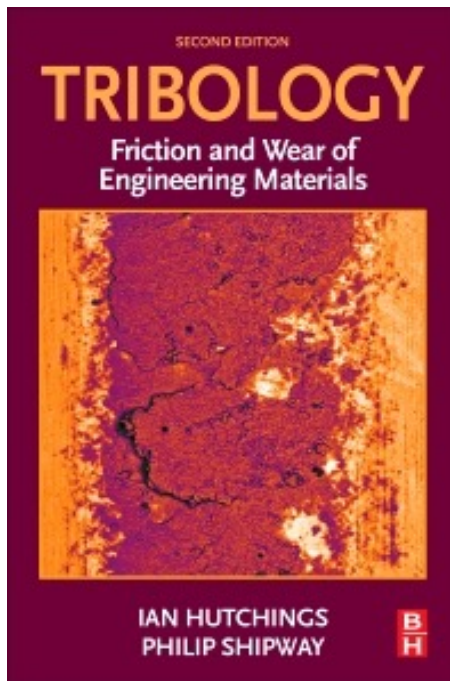
Take-home messages

- Engineering surfaces are complex and have a physical and chemical properties which play an important role in tribology.
- Friction and wear are not material properties but they are system properties highly affected by surface features
- Wear is a complex phenomenon that leads to modification of surfaces and depends on the interplay of chemical and mechanical interactions.

Tribology Friction and Wear of Engineering Materials (2nd Edition)

Authors: Ian Hutchings Philip Shipway

ISBN: 9780081009512



Other reference books on Tribology

- **Engineering Tribology**
J.A. Williams
Oxford University Press (1994) ISBN 0-19-856503-8 G.W.
- **Engineering Tribology**
Stachowiak et A.W. Batchelor
Elsevier (1993) ISBN 0-444-89235-4
- **Physical Analysis for Tribology**
T.F.J Quinn
Cambridge University Press (1991) ISBN 0-521-32602-8
- **Contact Mechanics**
K. L. Johnson
Cambridge University press, (1985) ISBN 0-521-34796-3

