EPFL

Introduction to Tribology

Anna Igual Munoz

Laboratory of tribology and interfacial chemistry

Science of surfaces in relative motion

Definitions

- 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

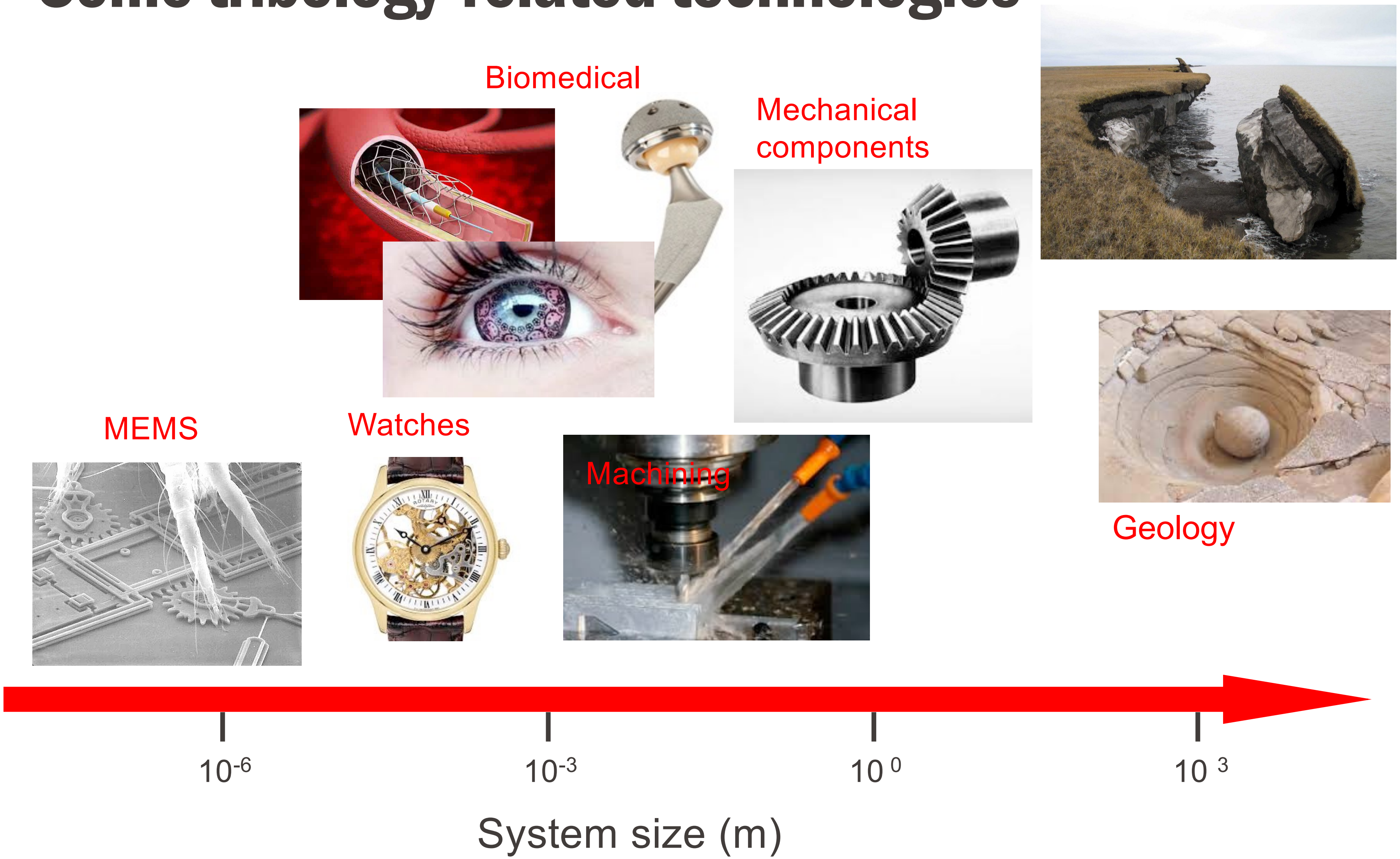
  - Writing

  - Assembly strength (screw, nails, bolts)

  - Landslides

  - Braking

Some tribology-related technologies



Some present challenges and opportunities for tribologists

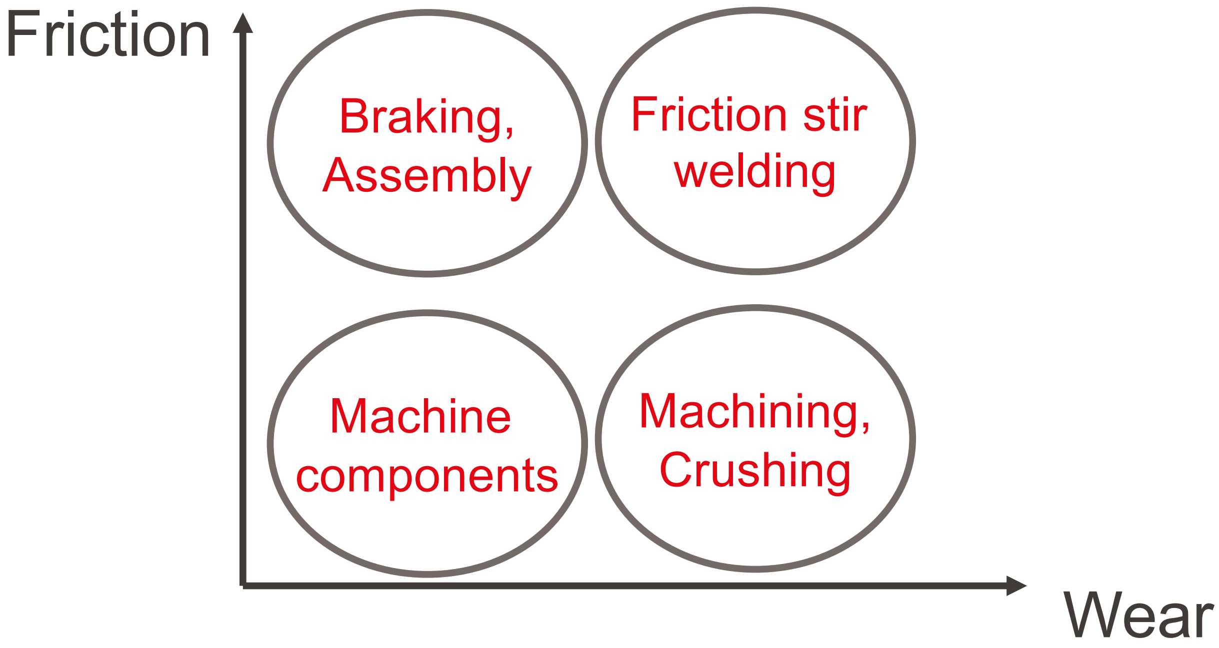
- Hydrogen economy: Storage, generation, transportation, utilization

- 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)

Technological and economic aspects

- Wear and friction are not necessarily negative phenomena to be absolutely avoided!



1. Concept

2. Relevance

3. Tribological contacts
4. Surfaces
5. Contact mechanics
6. Friction
7. Wear
8. Lubrication
9. Tribological system

Impact of economy

Country	Cost /year	Potential savings
UK	24 £billion	2 £billion
Canada	3.7 C$ billion	0.83 C$ billion
Spain	-	13.2 €billion (1.4% of the country's GDP)

Good practice of tribology saves money….among others

Source : H. Czichos, K.H. Habig, Tribologie Handbuch, Vieweg (1992)

Energy impact

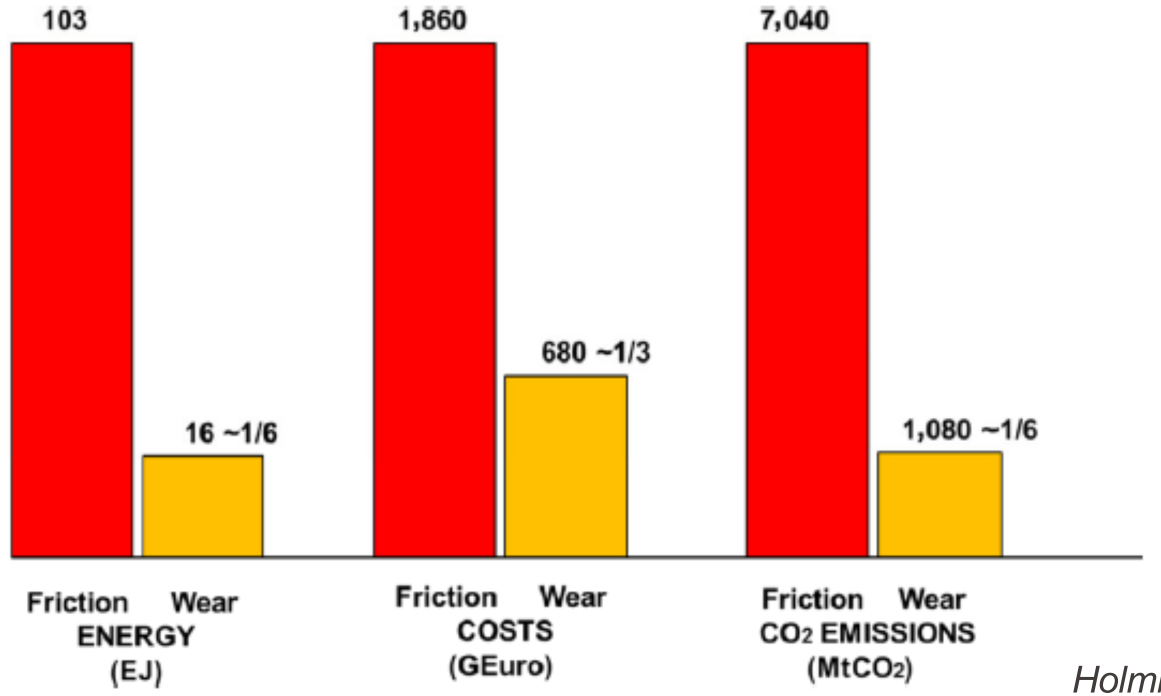
- ~23% (119 EJ) of the world's total energy consumption originates from tribological contacts.
  - 20% (103 EJ) to overcome friction
  - 3% (16 EJ) to remanufacture worn parts and spare equipment due to wear

- Potential reduction 40% in the long term (15 years) by:
  - New surfaces
  - Materials
  - Lubrication technologies for friction reduction and wear protection

Holmberg et al. Friction 5(3): 263–284 (2017)

CO_2 emission by friction accounts for 1/5th of global CO_2 emission (35.000 Mt CO_2)

- Energy consumption, costs and CO_2 emissions due to friction and wear



Holmberg et al. Friction 5(3): 263–284 (2017)

Environmental impact

- Tyre wear particles:
  - EU: 1.300.000 tons/year
  - Average size 25 µm (4-265 µm)

- Wear of implants:
  - Hip joints: 100.000 particles/step in the body (MoP)

Source : Baensch-Baltruschat et al. Science of the Total Environment (2020)

Savings

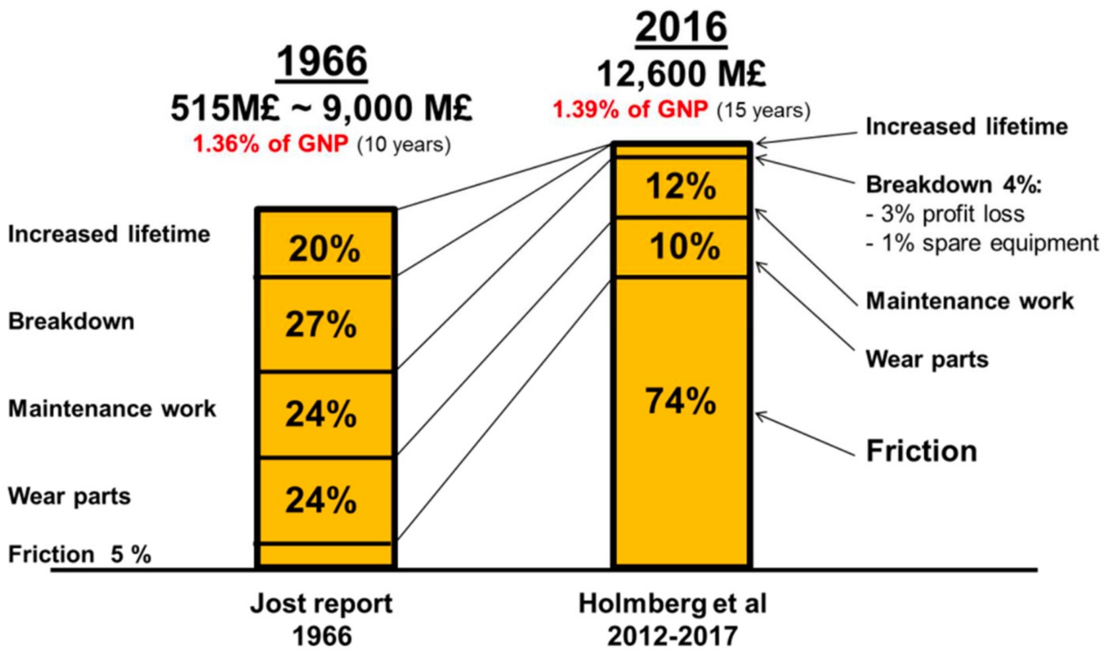
- Possible annual savings in Great Britain (1966) by using modern tribological solutions.

Maintenance	1300 MEuro
Production breakdowns	650 MEuro
Longer life of machines	550 MEuro
Better efficiency of machines	150 MEuro
Energy savings from reducing friction	150 MEuro
Production savings	50 MEuro
Lubricant savings	50 MEuro

Source : H. Czichos, K.H. Habig, Tribologie Handbuch, Vieweg (1992)

Savings

- Possible annual savings in Great Britain (1966 and 2016) by using modern tribological solutions.



Source : K. Holmberg and A. Erdemir Tribology International (2019) 135, 389-396

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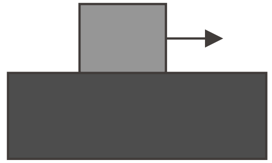
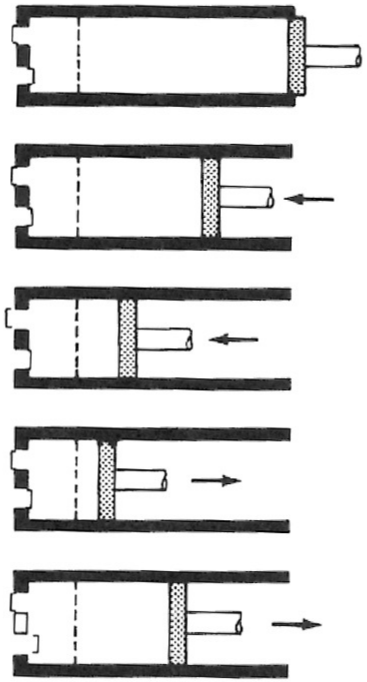
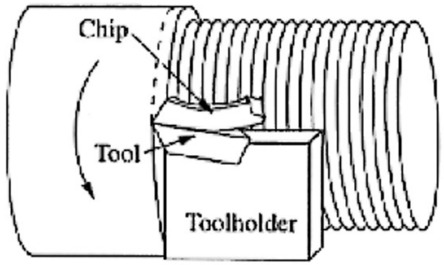
Sliding contacts *(sliding wear)*

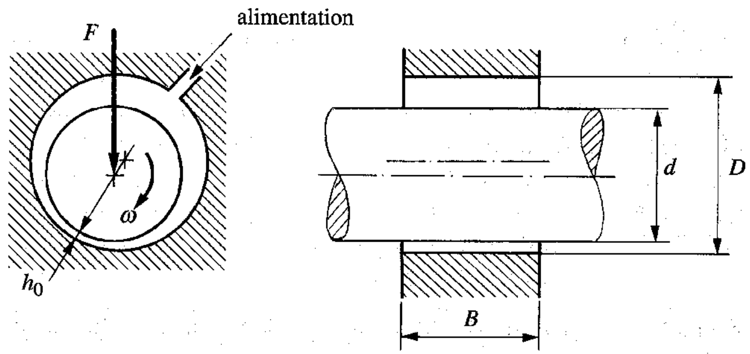




Piston/cylinder

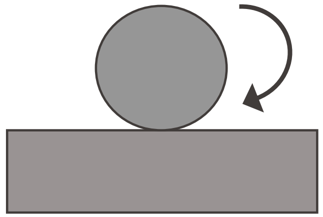


Tool/workpiece during turning

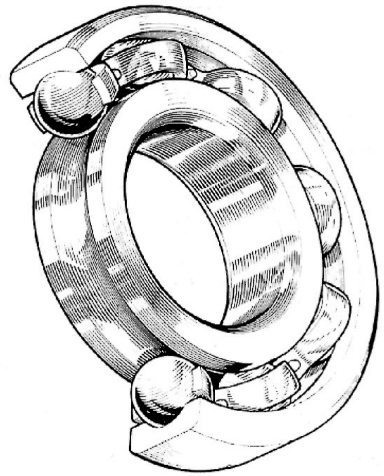


Axle/cushion in a bearing

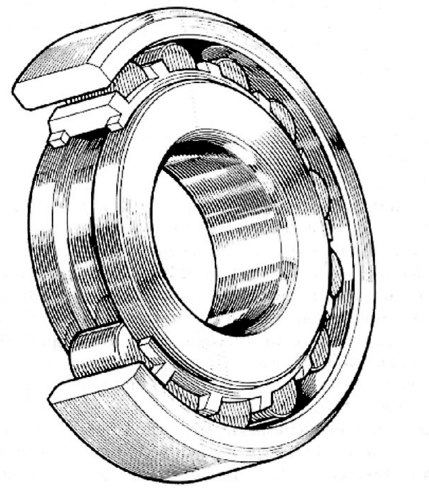
Rolling contacts *(rolling wear)*



- A round body rolling on a counter body

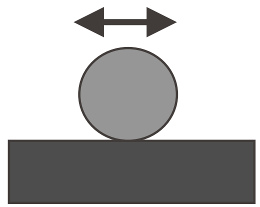


Ball bearing



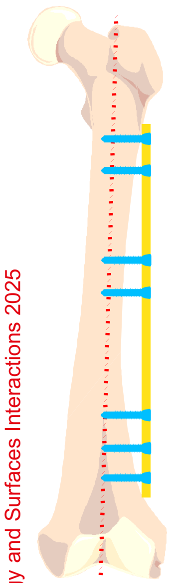
Roller bearing

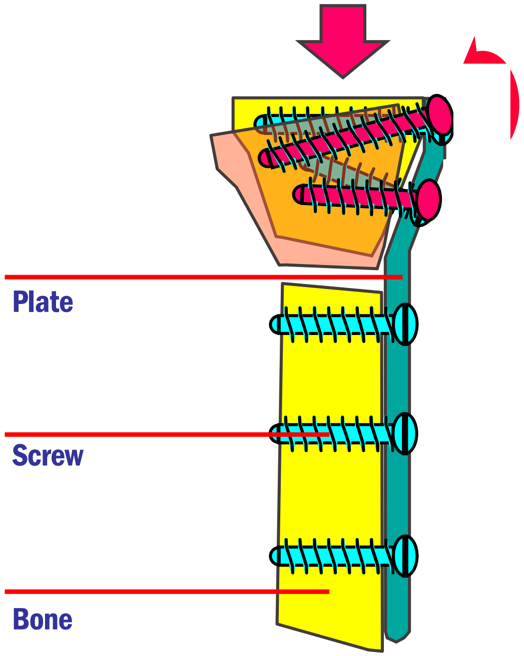
Fretting *(fretting wear)*

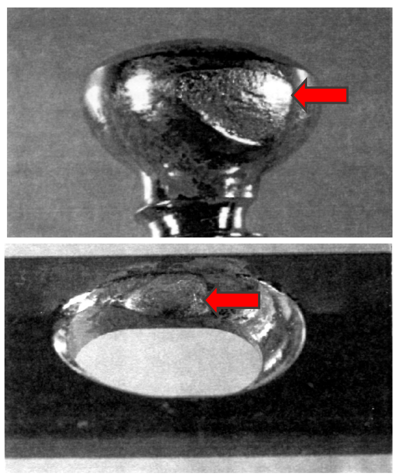


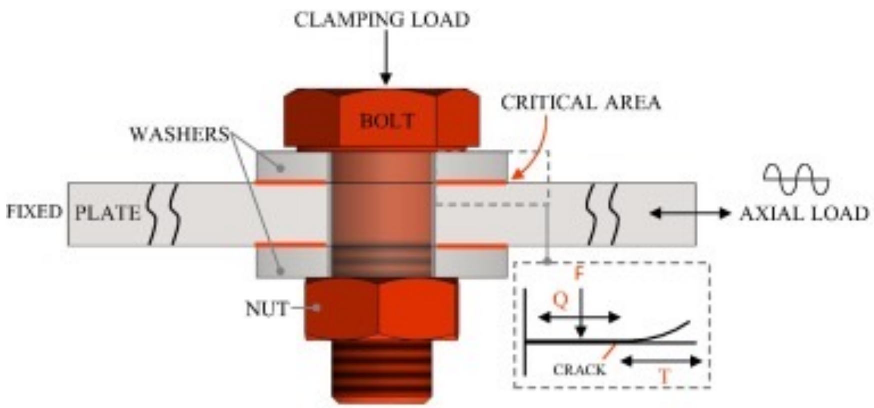
- Low amplitude relative motion (vibration) of two interacting bodies

  Wear due to small relative displacements







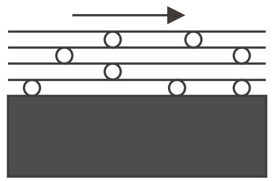


- Screw/plate for orthopaedic fixation : micromovements

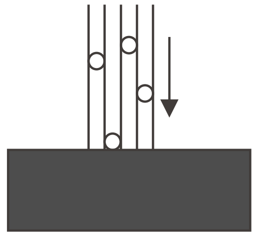
Bolt unions

Other tribological situations

- Particles carried by a fluid sliding over a body
  - → Erosion



- Particles impacting on a body
  - → Impact wear



- Gas particles imploding in turbulent fluids
  - → Cavitation *(cavitational wear)*

Surfaces: the elements through which solids contact

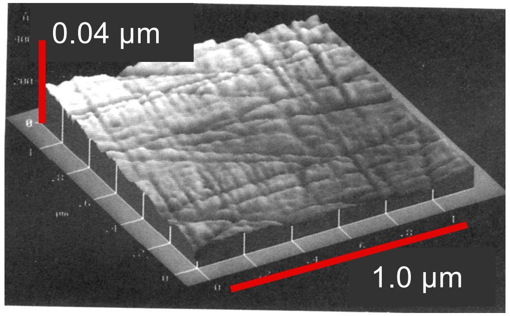
- 2 dimensional (planar) defect with certain thickness

Silicon wafer: atomically flat, uniform chemistry

Steel pipe: rough, partially rusted

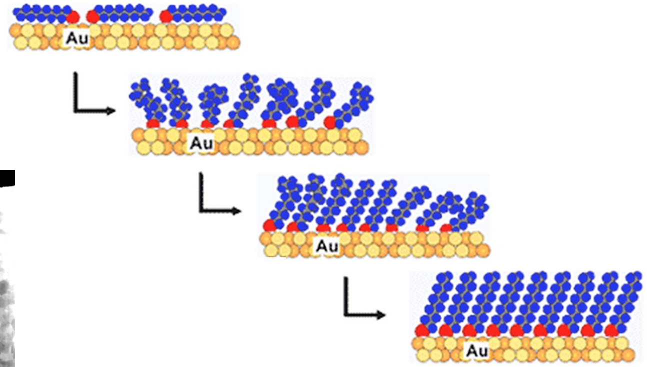
Surfaces: not simple, neither flat

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

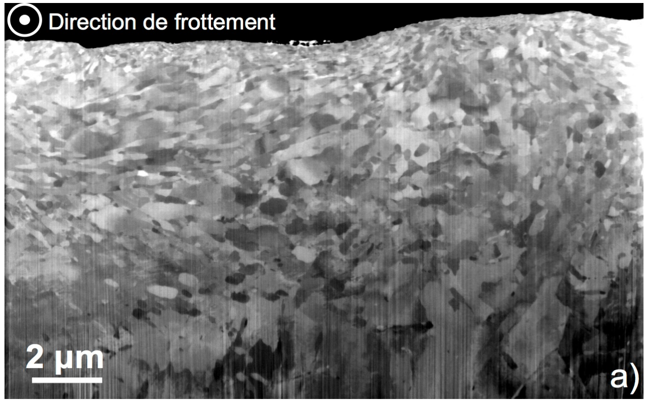


Mirror polished steel surface: AFM image

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



- Microstructural features:
  - Influences wear



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

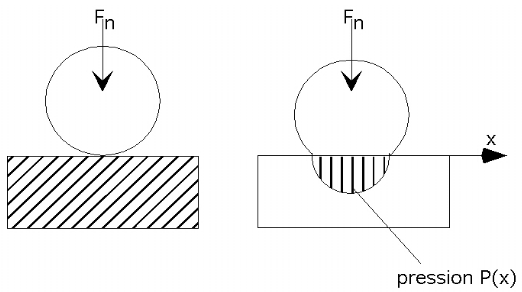
F.P. Bowden

5. Contact mechanics

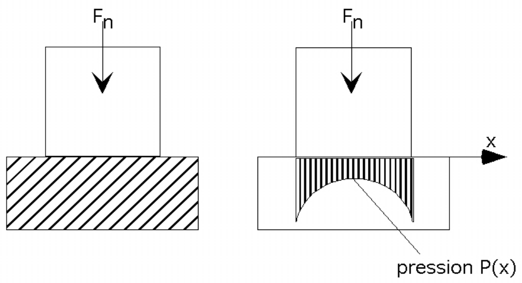
Study of the amplitude and distribution of mechanical stresses in a contact.

- Conformity of the contact

Non-conformal contact :

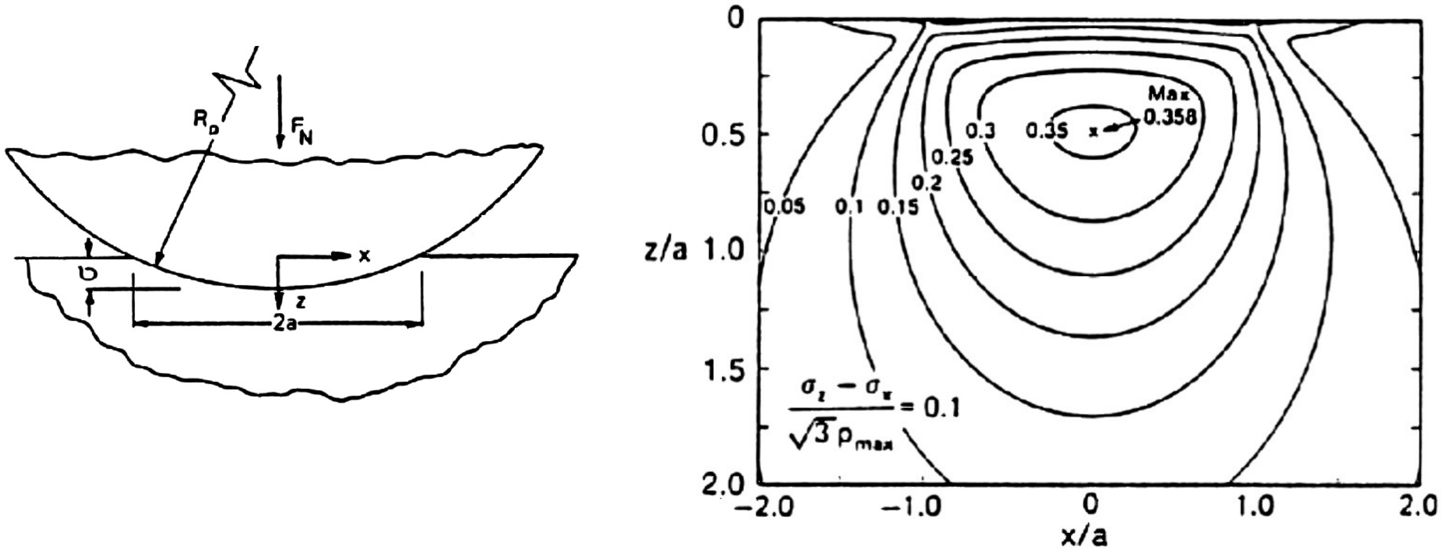


Conformal contact :



Ball-plane contact

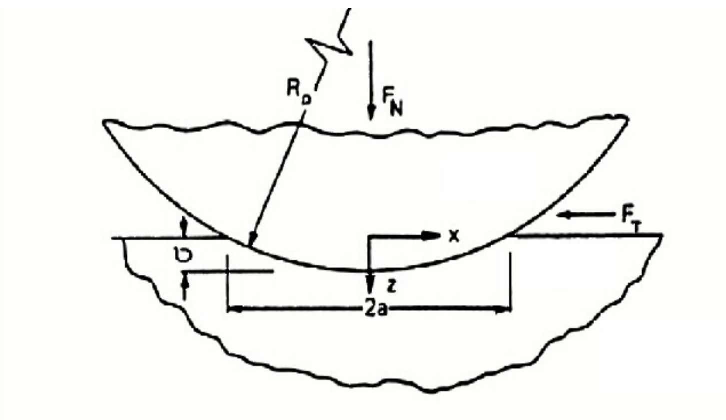
- Distribution of the shear stresses in a ball-plane contact :

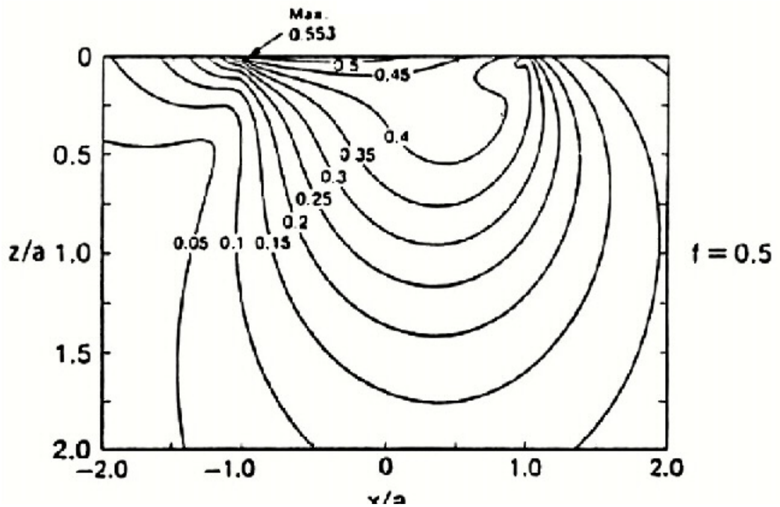


Source : H. Czichos, K.H. Habig, Tribologie Handbuch, Vieweg (1992)

Effect of tangential force

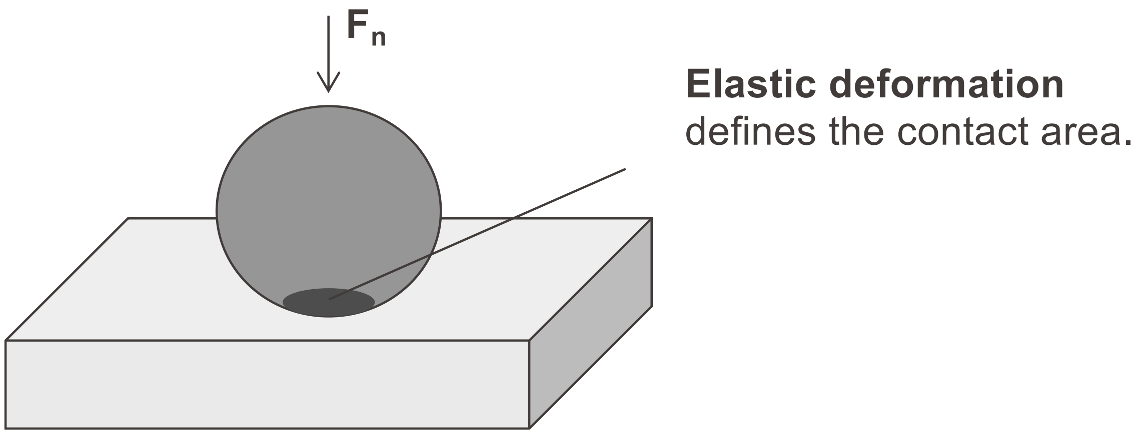
- Ball-plane contact : numerical calculation





Analysis of elastic stress fields

- Hertz mechanics for non-conformal contacts:
  - Calculation of elastic strain and stress in terms of load, geometrical parameters and materials.



Ball-plane contact

Hertz Contact Mechanics Formalism: example for a ball-plane contact

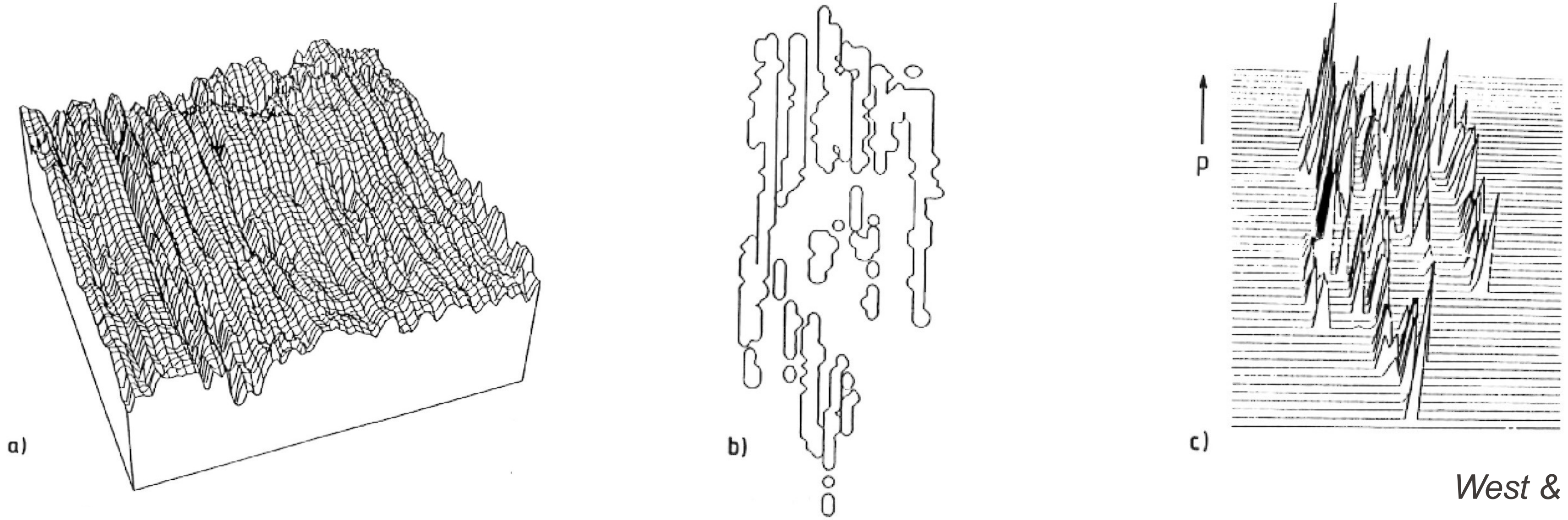
- Radius of contact area (circle) $a = \left(\frac{1.5 F_n R}{E'}\right)^{1/3}$
- Maximum contact pressure $p_0 = \frac{3 F_n}{2 \pi a^2}$
- Average contact pressure $p_m = \frac{F_n}{\pi a^2}$
- Maximum deflection $w = 1.31 \left(\frac{F_n^2}{E'^2 R}\right)^{1/3}$
- Maximum shear stress $\tau_{max} = \frac{p_0}{3}$
- Depth of maximum shear strength $z = 0.638 \cdot a$

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

E = Young's modulus
v = Poisson's ratio

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 µm and 162 µm).
  a) Representation of the steel surface : area 0.5 mm2, maximum relief 4.4 µm)
  b) Contour of the contact area
  c) Pressure distribution (maximum value **7 GPa**)

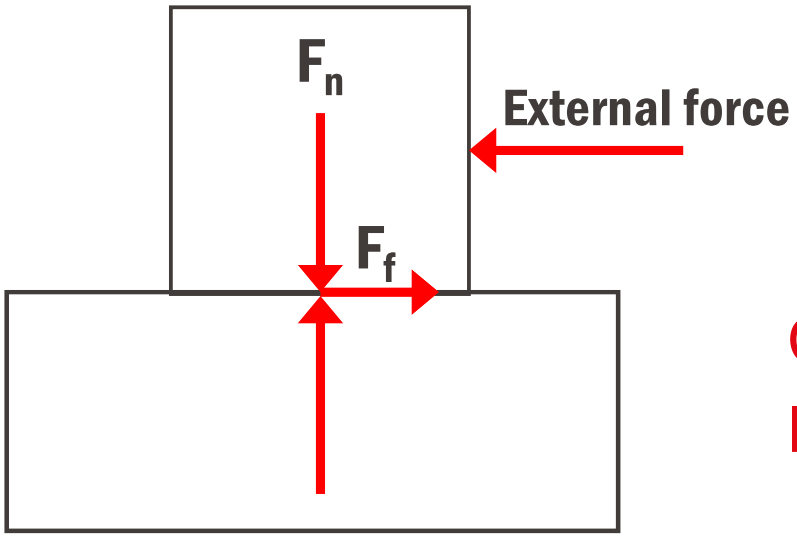


West & Sayles, 1988

6. Friction

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.

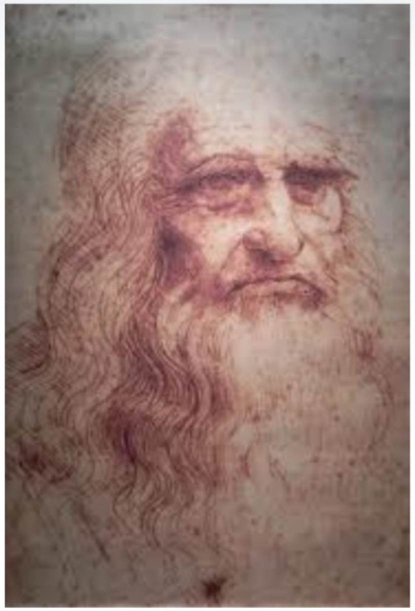


Involved forces

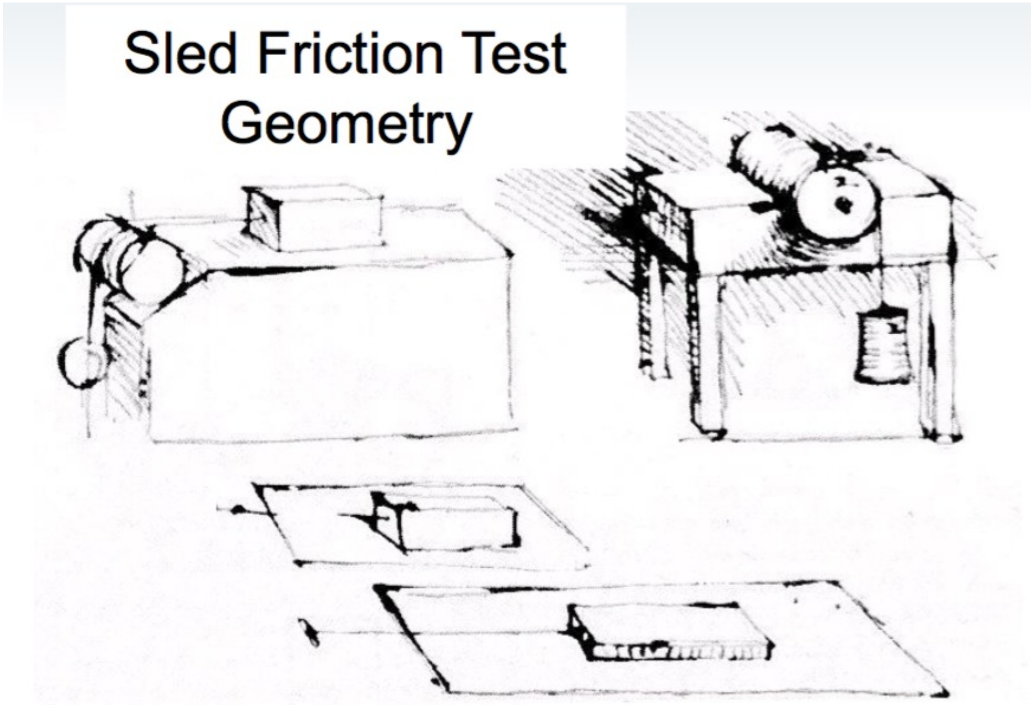
Coefficient of friction:
$\mu = F_f / F_n$

Motivation to study friction: machine conception

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



Leonardo Da Vinci



Friction laws

- Amonton’s laws (1699) – actually already proposed by Da Vinci (1500):

1. The friction force is proportional with the applied normal force: Ft = μ Fn
2. The friction force is independent of the nominal/apparent area of contact

Friction laws

- Amonton’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)

Friction history

DaVinci (1500)

Amontons (1699)

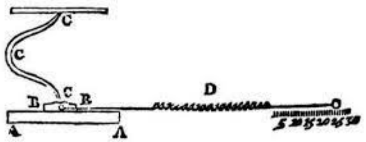
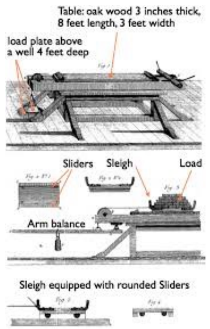


Figure 1.5: Amontons' sketch of his apparatus for friction experiments. The spring D measures the friction force during the sliding process between materials A and B. Spring C adjusts the normal force. (From[1])

Coulomb (1785)



Industrial polymers (1920-1940)

Polymers

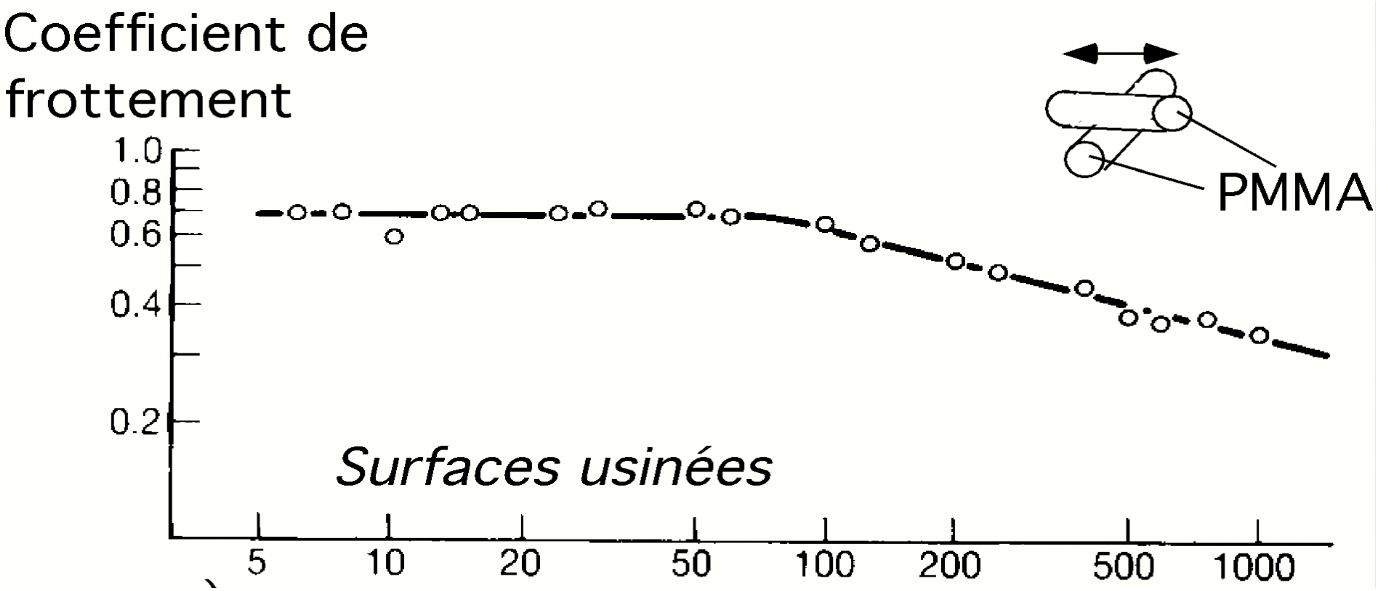
Metals

Ceramics

Wood

1500 1600 1700 1800 1900 2000

What about polymers??

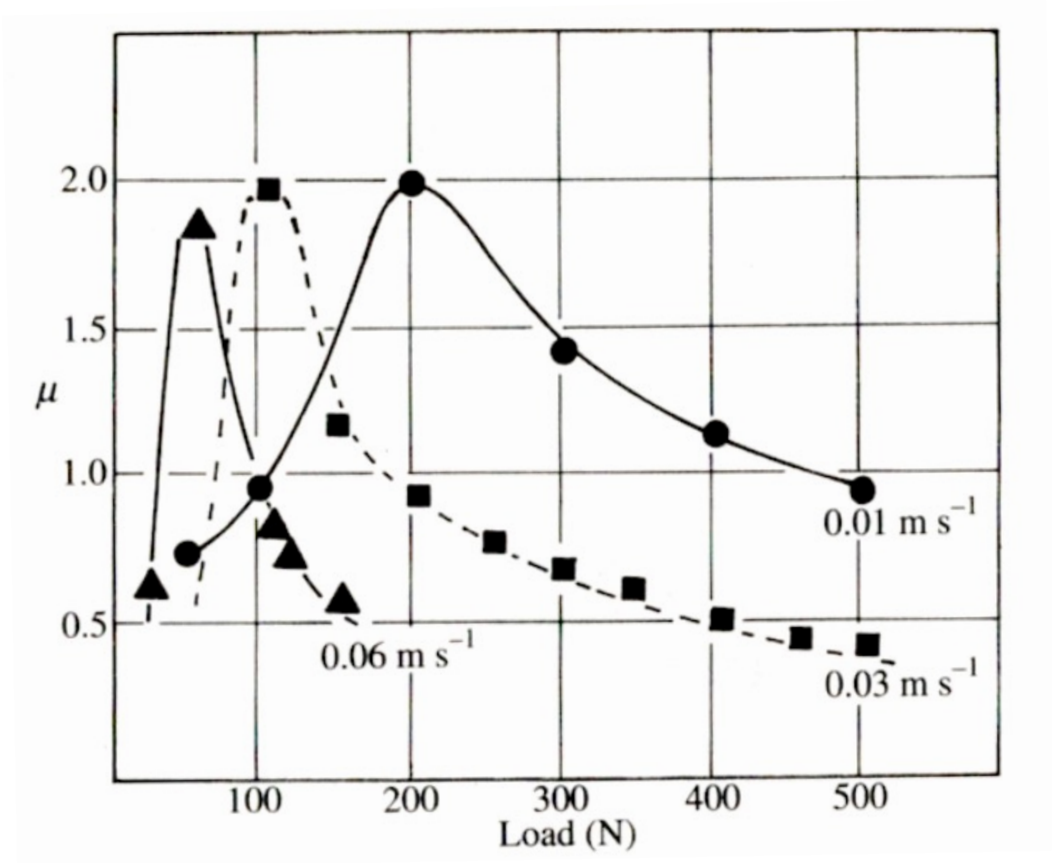


Normal force

Source: Hutchings & Shipway "Tribology" (2017)

What about polymers??

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



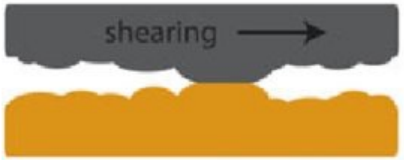
Source: Williams "Engineering Tribology" (1994)

Origin of friction

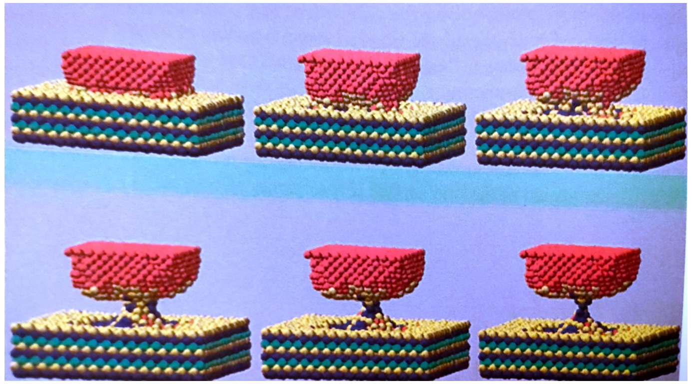
"Interfacial friction is caused by the ploughing of asperities in the mating surface and adhesion forces between the interacting asperity summits"

F.P Bowden and D. Tabor (1942)

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

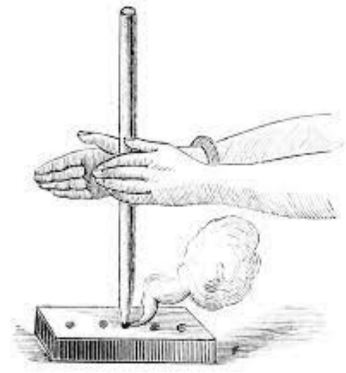


- **Ploughing**: due to resistance of surface asperities ploughing the contacting surface.



Source: Hutchings & Shipway "Tribology" (2017)

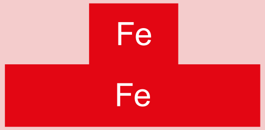
Consequences of friction



- 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

7. Wear

Definitions with very different implications

- ***Deterioration*** throughout prolongated 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

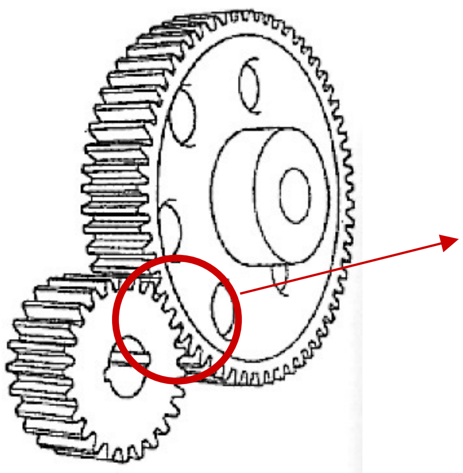
  Loss of material

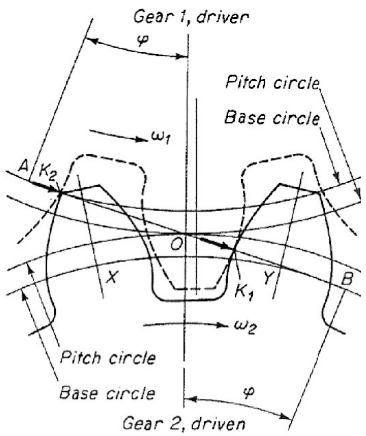
Example of progressive material loss

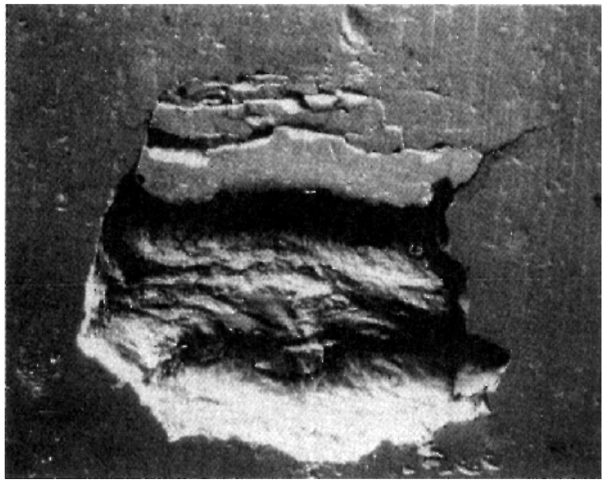
- Tyres : loss of functionality due to the progressive material removal.

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.







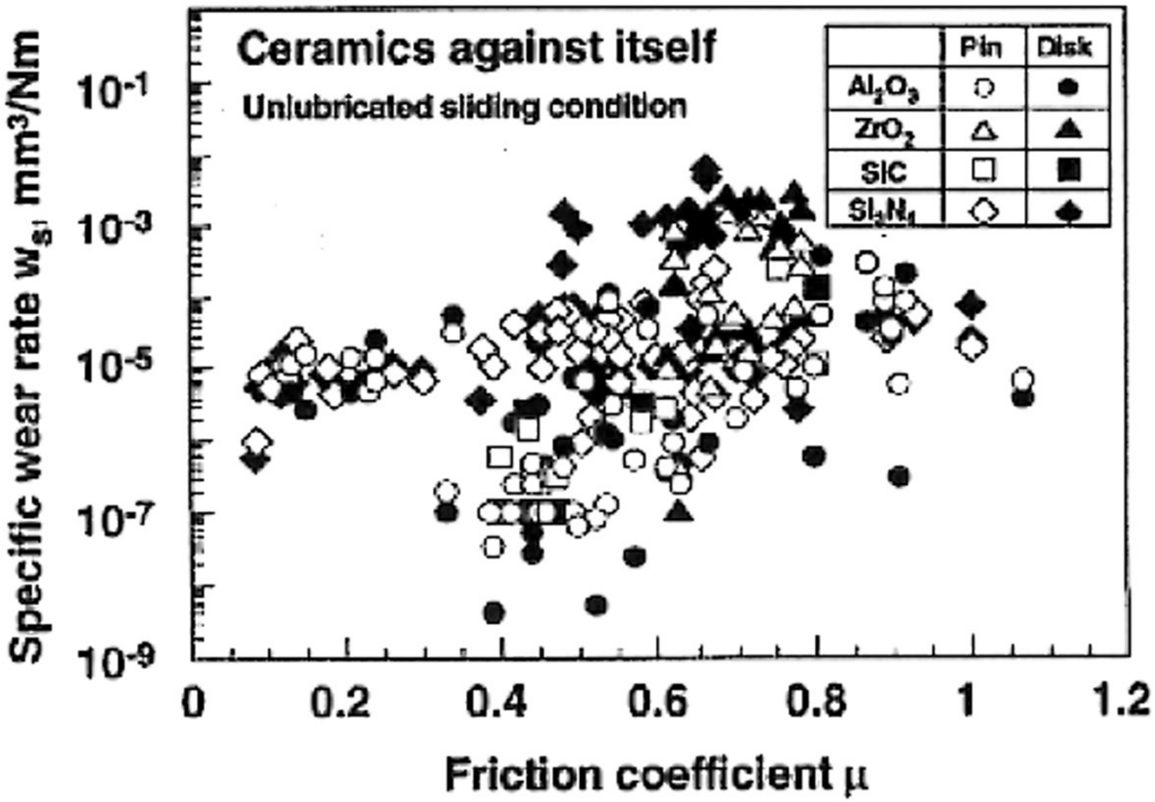
Fatigue failure of a bearing steel component.

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 !

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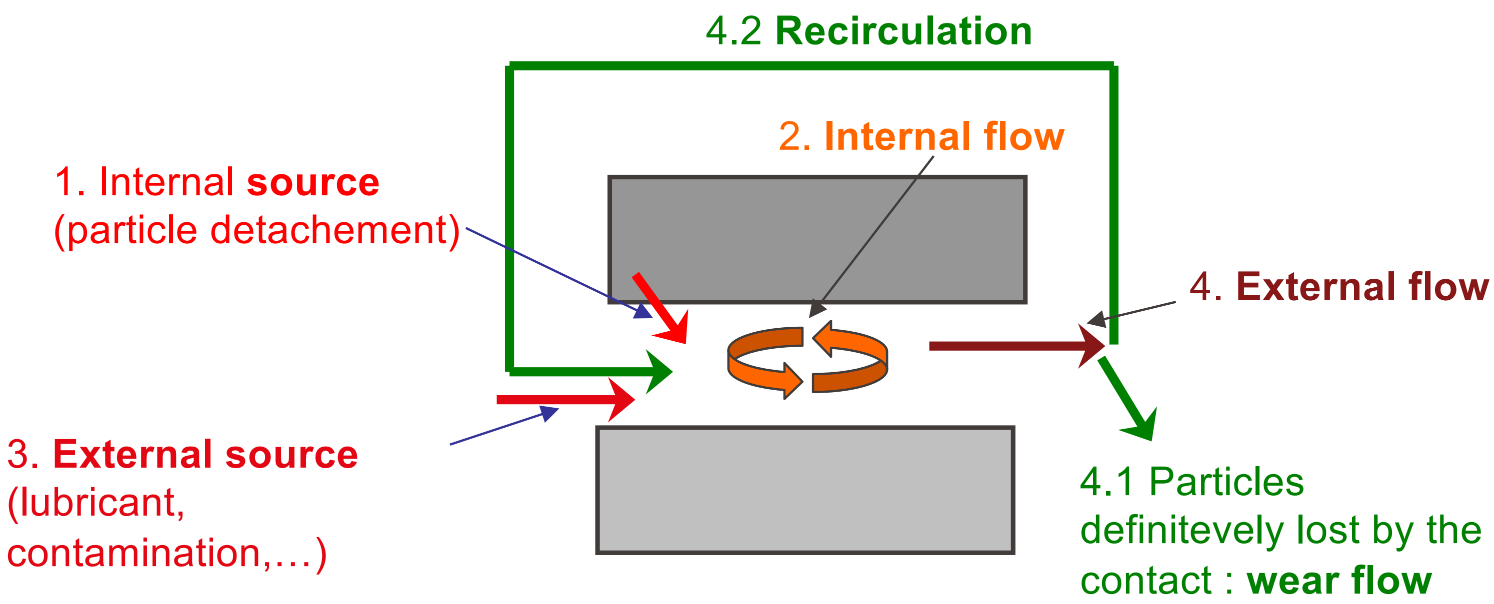
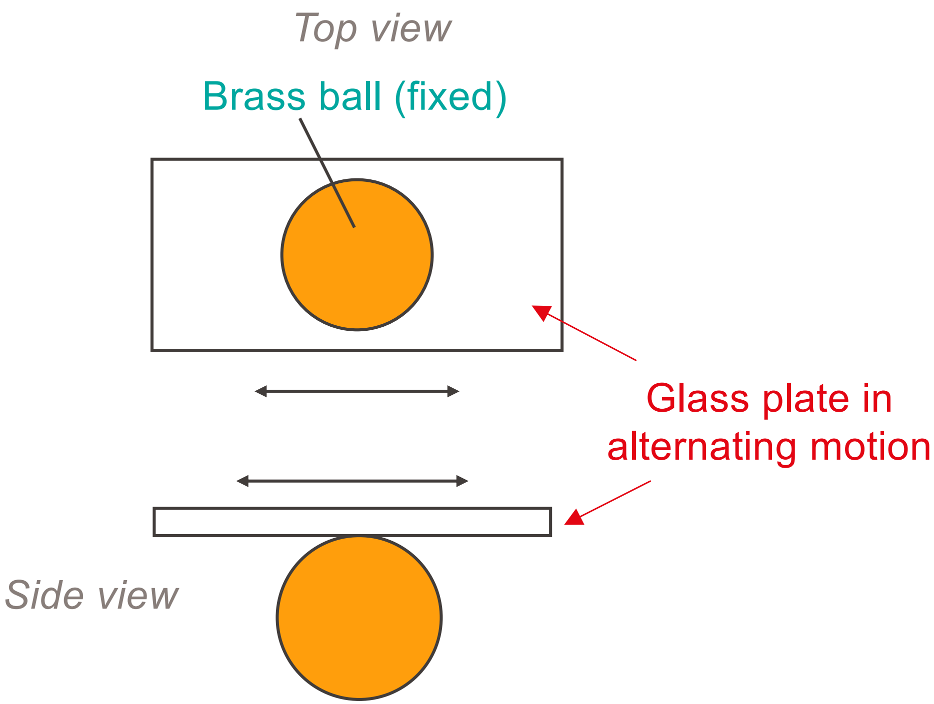
More than a mass loss: Third body concept and material flow

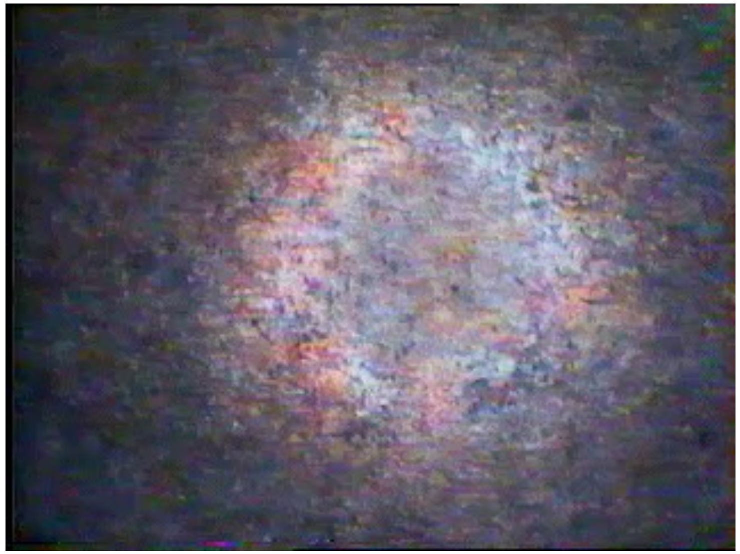
- Wear can be described as a flow of particles:



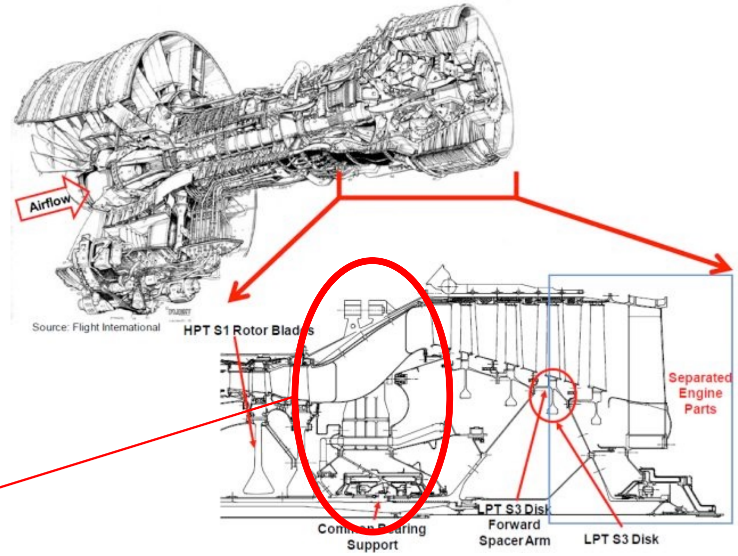
Experimental evidence

- Microscopic observation of the formation of a third body on a glass/brass contact.





Wear of bearings in 4 engine planes



Wear of bearings mounted in external engines more severe than in internal ones.

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

8. Lubrication

What is lubrication?

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

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

Technology started very early… 2400 BC

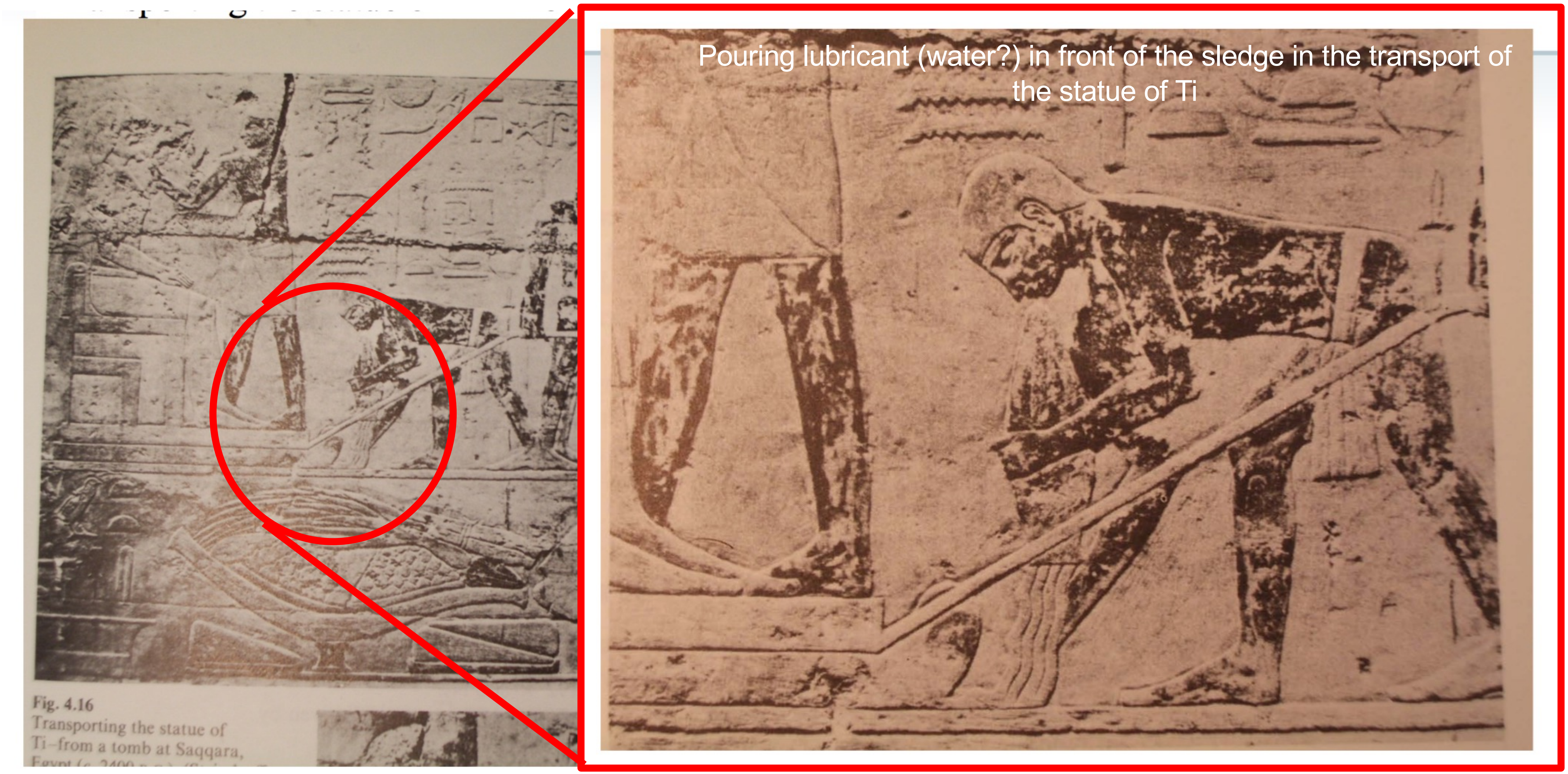


Figure taken from "History of Tribology" by Duncan Dowson (1993)

A. Igual Munoz

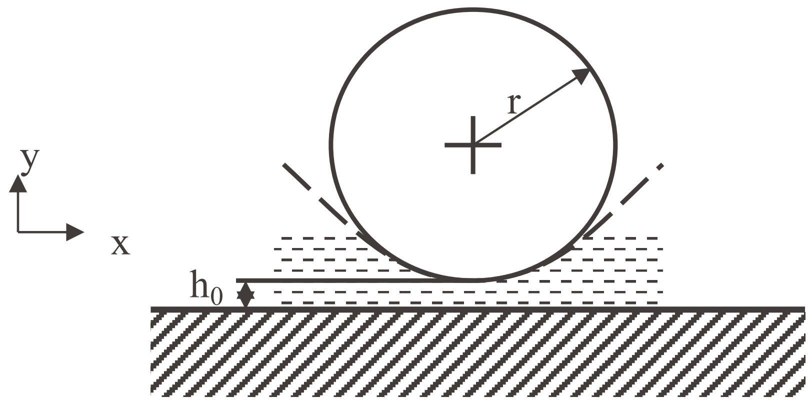
Formalism for hydrodynamic lubrication: Reynolds equation (1886)

- 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

Formalism for the cylinder/plate contact

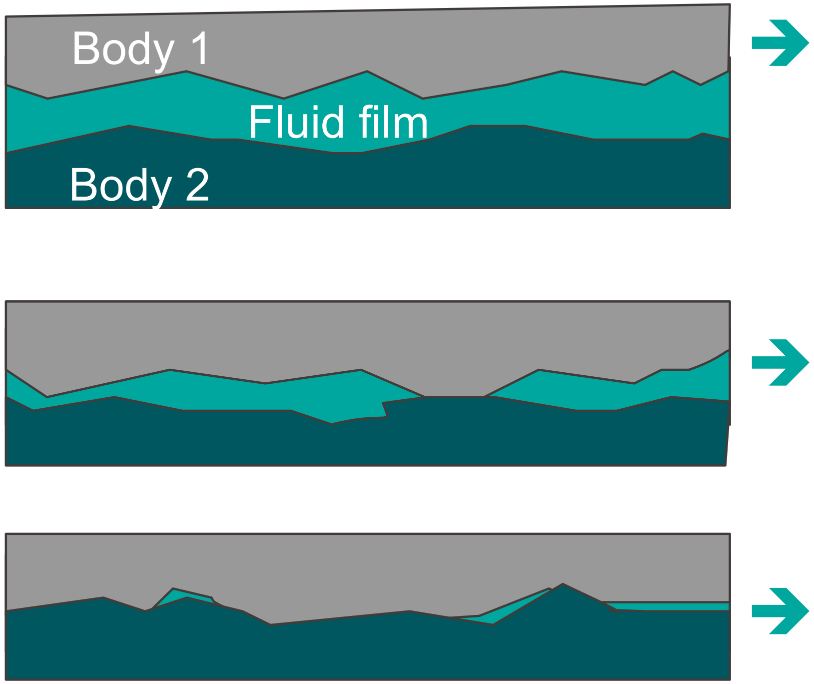


- Thickness of the film h_0 : $$h_0 = 2.45 \cdot r \cdot L \cdot \eta \cdot v / F_N$$

L= length of the cylinder
η = fluid viscosity
v= linear speed of the cylinder relatively to the plate
F_N= normal load

Source: Czichos, Tribology, Elsevier (1978)

Regimes of fluid lubrication

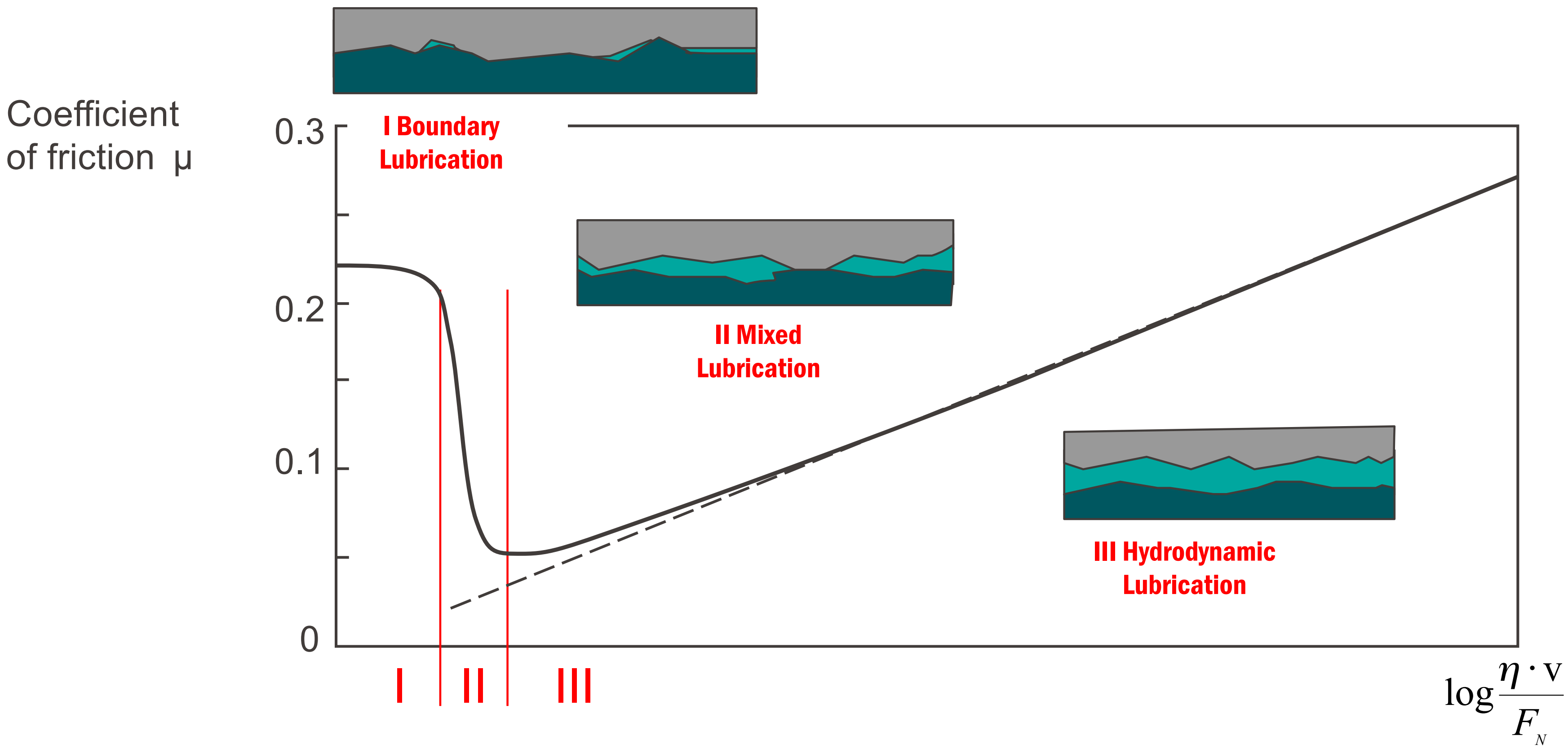


Hydrodynamic regime
The film is thick enough to entirely separate the two surfaces.

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



v sliding velocity
η viscosity of the lubricant
F_N normal load

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.

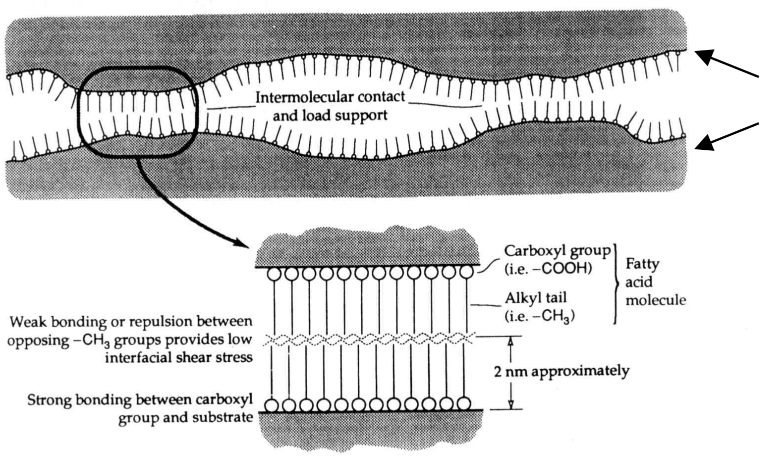


FIGURE 8.4 Low friction mono-molecular layer of adsorbed organic polar molecules on metallic surfaces.

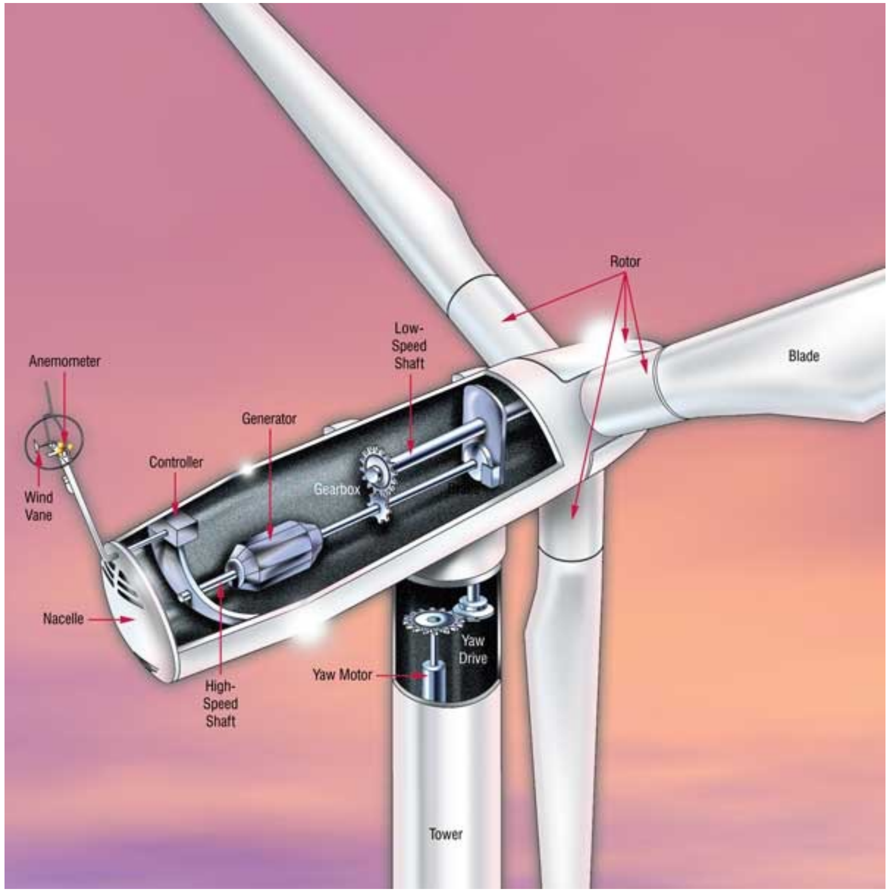
Polar molecules adhere to the surfaces

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.

Back to low speed systems and high loads…

Source: Luo et al. Friction 8(4): 643–665 (2020)



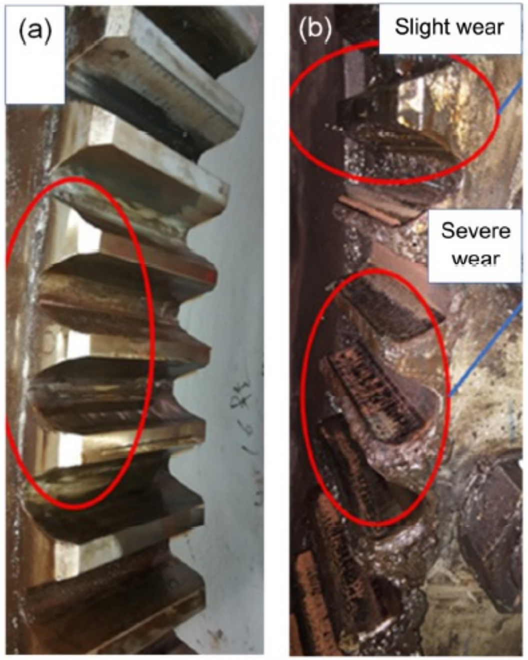
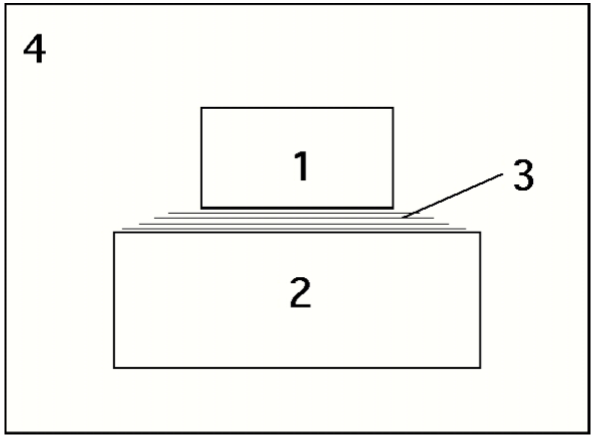


Fig. 17 Wear of gears in a wind turbine.

9. Tribological system

A tribology system is characterized by

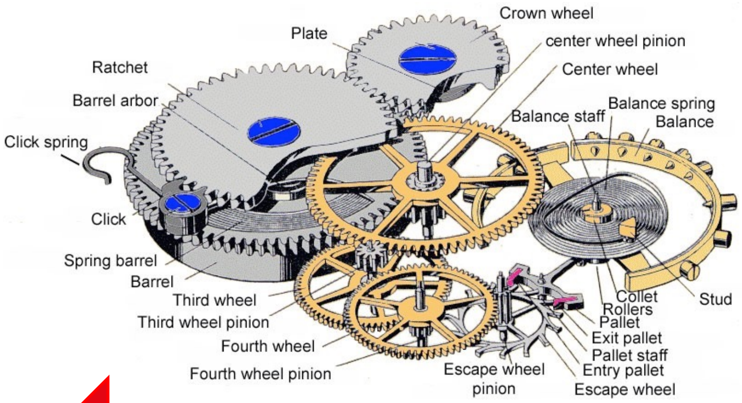
- **Loading**:
  - Type of motion, normal force, speed, temperature…
- **System structure** :
  - Elements : body and counter body 1 et 2, lubricant 3, environment 4
  - Properties: geometry, materials, surfaces

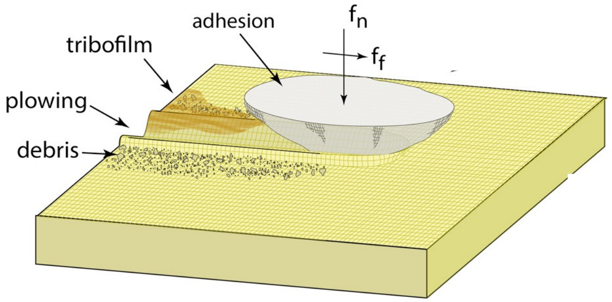


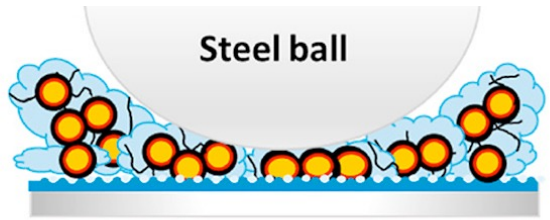
- **Interactions** between the elements generate friction and wear and therefore may modify the structure of the system. For example:
  - Wear can change the geometry of elements, or
  - Heating due to friction can reduce the strength of a material in contact.

H. Czichos,Tribology, 1971

Tribology: multiscale-multiphysics science







mm | μm | nm

SYSTEM

Mechanics
Geometry,
Loads, vibrations
Motion
Heat, mass transport
Lubrication

MACROSCOPIC CONTACT

Material science
Elastic deformation
Roughness
Asperity deformation
Structural transformation
Cracking

MICROSCOPIC CONTACT

Surface chemistry and physics
Surface reactions
Third bodies
Electrostatic repulsion

La tribologie apporte la richesse de sa complexité

Y. Berthier

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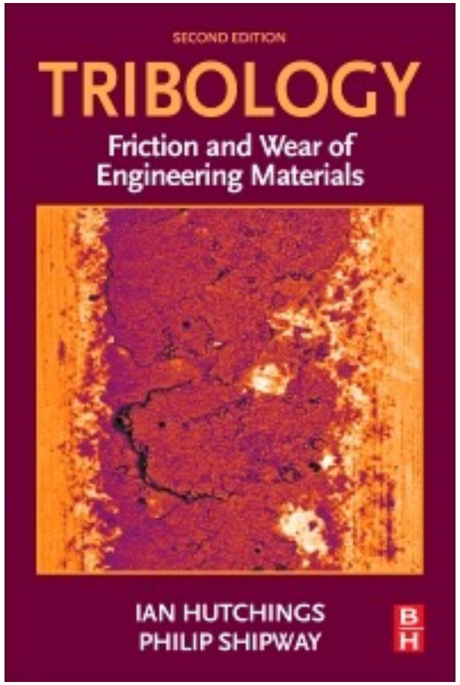

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Questions???