EPFL

Chapter 3
Friction

MSE 485
Tribology
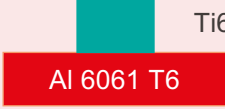
Friction laws

- 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
3. The friction force is independent of sliding speed (Coulomb's law of friction, 1785)

Influence of	Diagram	Parameter	COF
Sliding partner (X)	X / Steel 1032	Al6061 T6	0.38
		Copper	0.28
		Steel 1032	0.23
		Teflon	0.07
Contact configuration	Al 6061 T6 / Ti6Al4V		0.38
	Ti6Al4V / Al 6061 T6		0.29
Environment	Fe / Fe	Vacuum	> 4 (seizure)
		10^{-3} mbar O_2	1.50
		1 mbar O_2	0.40
		Oil film	< 0.10
Roughness	Steel / SS a-C:W coat	R_q 390 nm	0.31
		R_q 220 nm	0.20
		R_q 120 nm	0.09
		R_q 68 nm	0.09

1. Mechanisms

> **1.1 Atomic-level relaxation**

> **1.2 Adhesion at asperities**

> **1.3 Deformation of asperities**

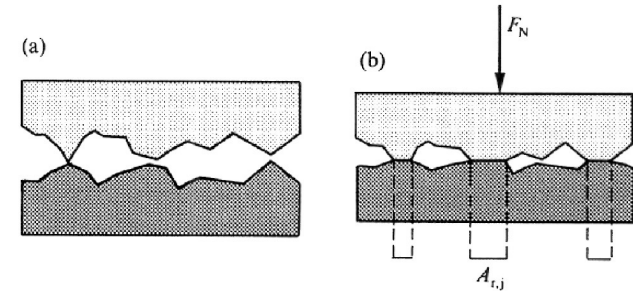2. Energy and temperature of friction

3 Frictional behavior of metals

4 Frictional behavior of ceramics

5 Frictional behavior of polymers

6 Friction of lamellar solids

Landolt Ch. 10.2, Zambelli & Vincent Ch. 2, Hutchings Ch.3

Adhesion at asperities

- Contact between a soft and rough material and a hard and rigid material:

- True contact pressure : $P_r = \dfrac{F_n}{A_r}$

- Under the pressure, asperities deform until the equilibrium pressure, given by the hardness H (indentation), is reached.

$$P_{r,\max} = H = \frac{F_n}{A_{r,\max}} \qquad A_{r,\max} = \frac{F_n}{H}$$

- The friction force F_{adh} is the force necessary to shear the junctions at τ_c = critical shear stress of the material

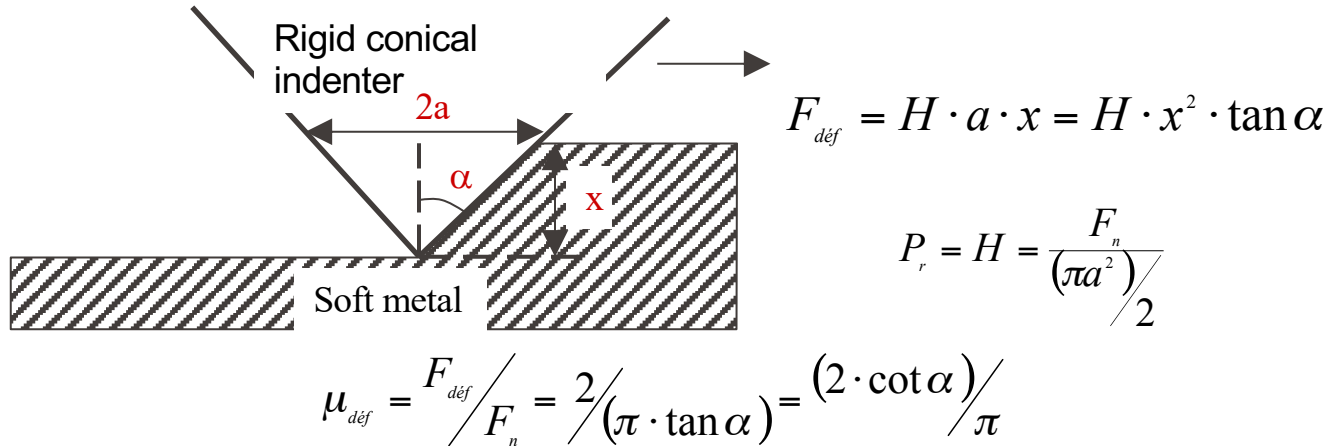$$F_{adh} = A_{r,\max}\,\tau_c \Rightarrow \mu_{adh} = \frac{\tau_c}{H}$$

Application to metals

- For metals :

    H ≈ 3 YS τ_c ≈ 0.5 YS

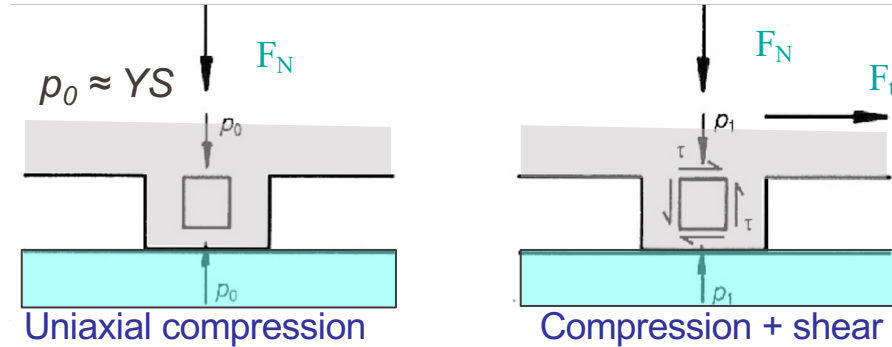Where YS is the yield strength under uniaxial tension.

- Hence : $\mu_{adh} = \tau_c / H = 1/6 \approx 0.17$

- However, in practice μ is generally larger than 0.17 for metal-on-metal non lubricated contacts.

Deformation at asperity contacts

Rigid conical indenter

2a

α

x

Soft metal

$$F_{déf} = H \cdot a \cdot x = H \cdot x^2 \cdot \tan\alpha$$

$$P_r = H = \frac{F_n}{(\pi a^2)/2}$$

$$\mu_{déf} = \frac{F_{déf}}{F_n} = \frac{2}{(\pi \cdot \tan\alpha)} = \frac{(2 \cdot \cot\alpha)}{\pi}$$

- Technical surfaces exhibit values of **α** > 80 → μ_{def} ≤0.12
- Hence theoretically : μ_{def} + μ_{adh}=0.12+0.16 ≤0.28
- However in practice μ > 0.3

Adhesion and plastic deformation of asperities

- By normal (F_n) and tangential (F_t) forces:

$p_0 \approx YS$

Uniaxial compression   Compression + shear

- Tresca: $$p_1^2 + 4\tau^2 = p_0^2$$

$$p_1 = \frac{F_n}{A}$$

$$\tau = \frac{F_t}{A}$$

$$\frac{F_n^2}{A^2} + 4\frac{F_t^2}{A^2} = p_0^2$$

$$F_n = \left(A^2 p_0^2 - 4F_t^2\right)^{0.5}$$

Adhesion and deformation of asperities

- An increase in F_t causes A to increase until $F_t > F_f$, at which point sliding replaces deformation :
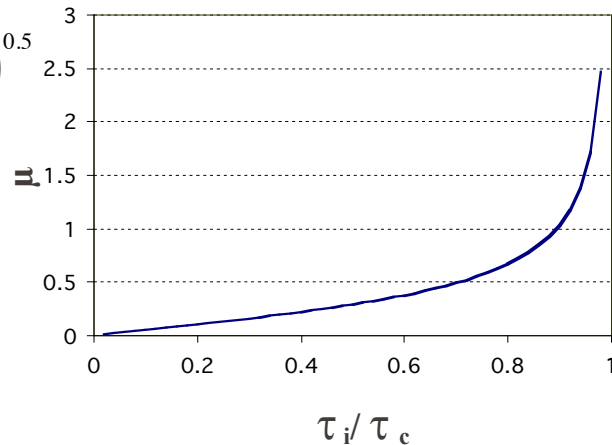
$$F_f = \tau_i A \qquad \tau_i < \tau_c$$

With τ_i : shear stress at the interface

   τ_c : critical shear stress of the material

$$p_0 = 2\tau_c \Rightarrow F_n = 2A\left(\tau_c^2 - \tau_i^2\right)^{0.5}$$

$$\frac{F_f}{F_n} = 0.5 \frac{\tau_i}{\left(\tau_c^2 - \tau_i^2\right)^{0.5}}$$

$$= \frac{1}{2\left[\left(\tau_c/\tau_i\right)^2 - 1\right]^{0.5}}$$

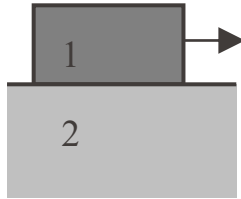1. Mechanisms

2. Energy and temperature of friction

3 Frictional behavior of metals

4 Frictional behavior of ceramics

5 Frictional behavior of polymers

6 Friction of lamellar solids

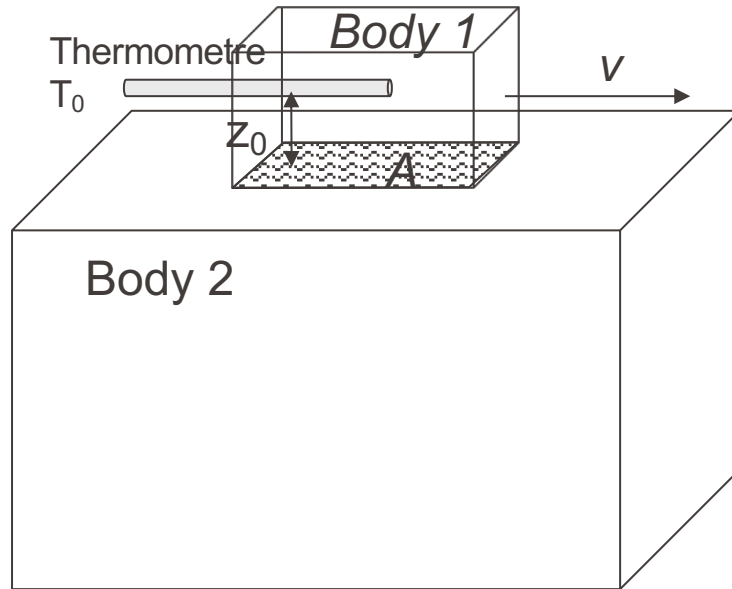*Landolt Ch. 10.2, Zambelli & Vincent Ch. 2, Hutchings Ch.3*

Energy and temperature during friction

- Dissipated power Wf: $W_f = F_f \, \boldsymbol{v}$

- Dissipated power density Q_f: $Q_f = W_f / A$

- The dissipated power generates a thermal flow in each body:

$$Q_1 = \beta \, Q_f \qquad\qquad Q_2 = (1-\beta) \, Qf$$

A = area of contact [m2]
F_f = frictional force [N]
$\boldsymbol{v}$ = sliding velocity [m/s]
β = heat distribution factor (> 0, < 1)

Limiting case 1: homogenous thermal flow over the *nominal contact area*

- A thermometer placed at distance z0 from the contact measures the stationary temperature T_0

- The thermal flow Q_1 can be defined as:

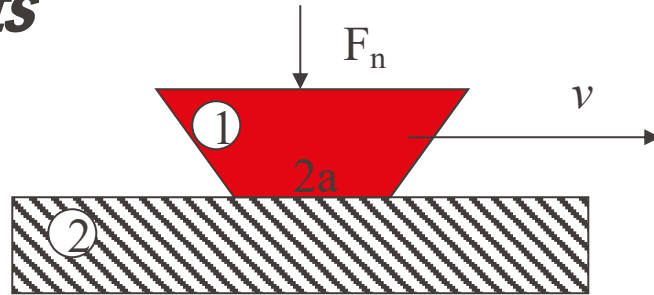$$Q_1 = \beta \cdot Q_f = k_1 \cdot (T_s - T_0)/z_0$$

T_s = temperature of the contact [K]

k_1 : thermal conductivity [$Jm^{-1}s^{-1}K^{-1}$]

- By introducing $Q_f = W / A$ one obtains

$$T_s = T_0 + \beta \cdot F_f \cdot v \cdot z_0 / k_1 \cdot A$$

Limiting case 2: thermal flow restricted to *asperity contacts*

F_n

v

① 1

2a

② 2

Archard-Bock

a = radius of asperity contact area
A_r = asperity contact area
H = hardness
µ = coeff. of friction

Hypotheses :

• Only one asperity contact between bodies 1 and 2 $A_r = \pi a^2 = F_n / H$

• The power dissipated by contact is entirely converted to heat

and only diffuses into body 1.

▪ Derived formula for a ΔT increase in temperature of the asperity
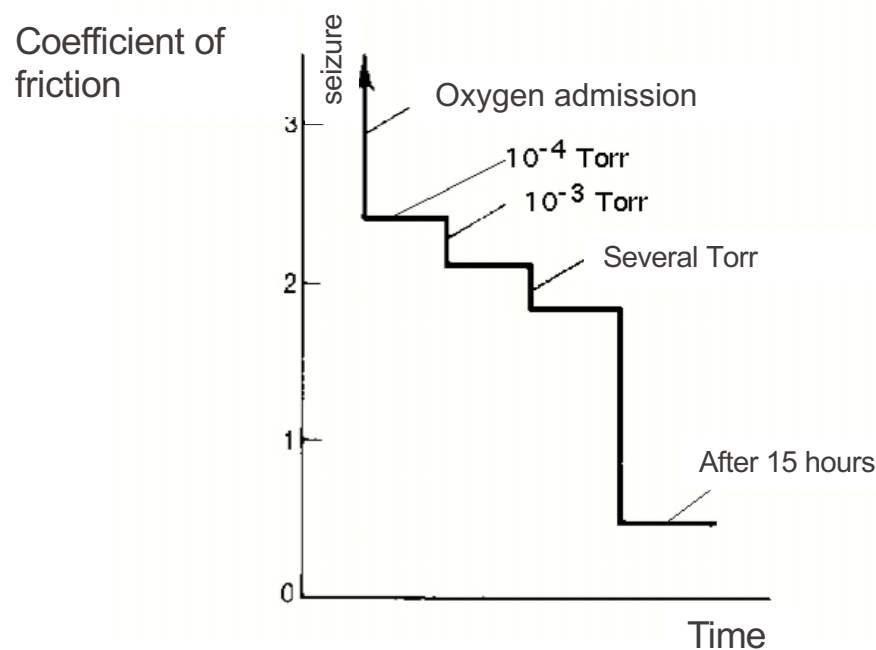 compared to the mean temperature :

$$\Delta T_{max} = \sqrt{\pi} \cdot \mu \cdot v \cdot \sqrt{F_n H} / 4k_1$$

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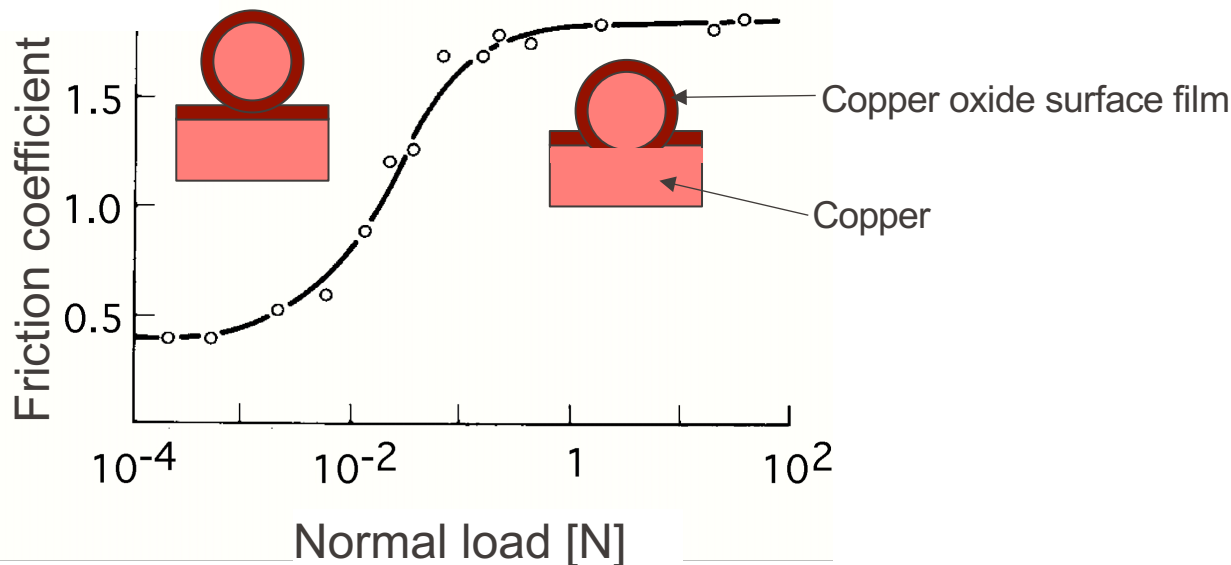*Landolt Ch. 10.2, Zambelli & Vincent Ch. 2, Hutchings Ch.3*

Frictional behavior of metals

- Effect of surface oxidation :

Case of iron-iron friction, initially in vacuum *(Buckley/Hutchings)*

Coefficient of friction

seizure

Oxygen admission

10^{-4} Torr

10^{-3} Torr

Several Torr

After 15 hours
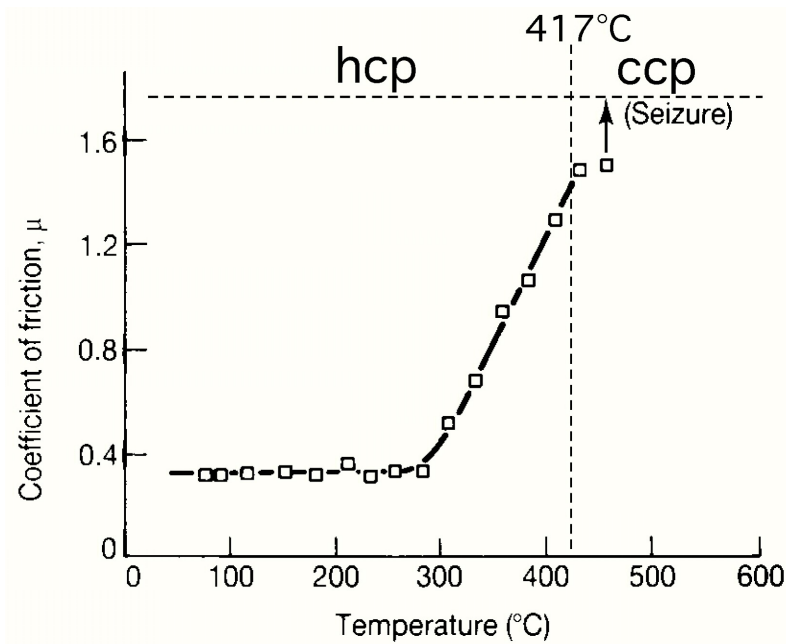
Time

Frictional behavior of metals

- Case of copper-copper friction under different loads.

The transition in coefficient of friction can be explained by the surface oxide layer rupturing under high load (according to measures of contact electric resistance). *(Buckley/Hutchings)*

Frictional behavior of metals

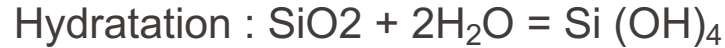- Case of cobalt-cobalt friction, at different temperatures.

The transition in coefficient of friction can be explained by the phase transition taking place at 417°C. The cubic phase is more ductile than the hexagonal phase *(Buckley/Hutchings)*

Landolt Ch. 10.2, Zambelli & Vincent Ch. 2, Hutchings Ch.3

Frictional behavior of ceramics

- Chemical inertia due to surface reactions:

  Oxidation : $Si_3N_4 + 6H_2O = 3SiO_2 + 4NH_3$

  Hydratation : $SiO2 + 2H_2O = Si(OH)_4$

- Friction highly depends on the surface chemistry and hence on the environment.

Coefficient of friction of sintered silicon nitride sliding on itself in different atmospheres.
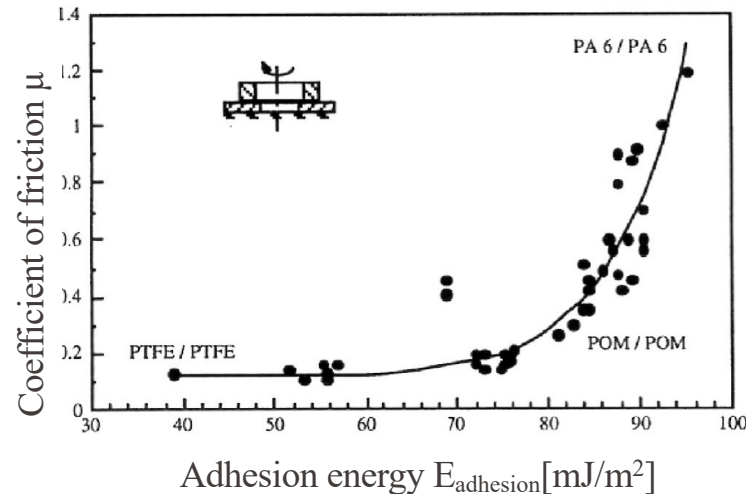*(Hutchings 1992)*

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Adhesion: large elastic contact area and high adhesion energies favour adhesion

- ERHARD's empirical relation : $\mu = 0.12 + 4.8 \cdot 10^{-6} \exp(0.13 E_{adhésion})$
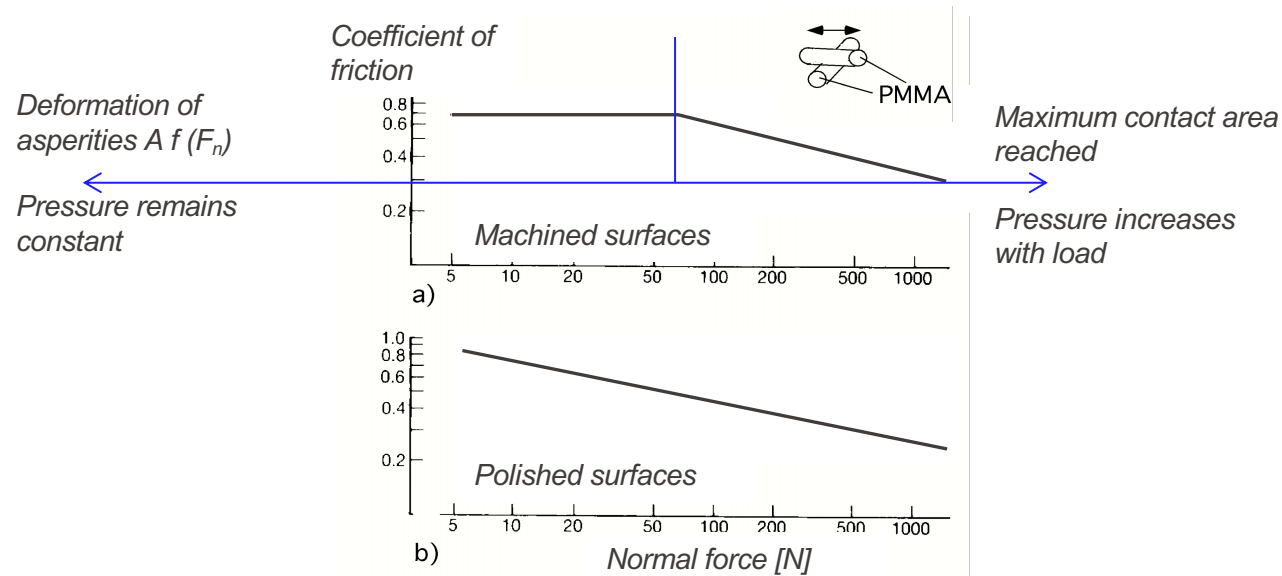

Erhard, 1980. Contact pressure 0.09 MPa, sliding speed 120 mm/s, sliding distances > 10 km, room temperature.
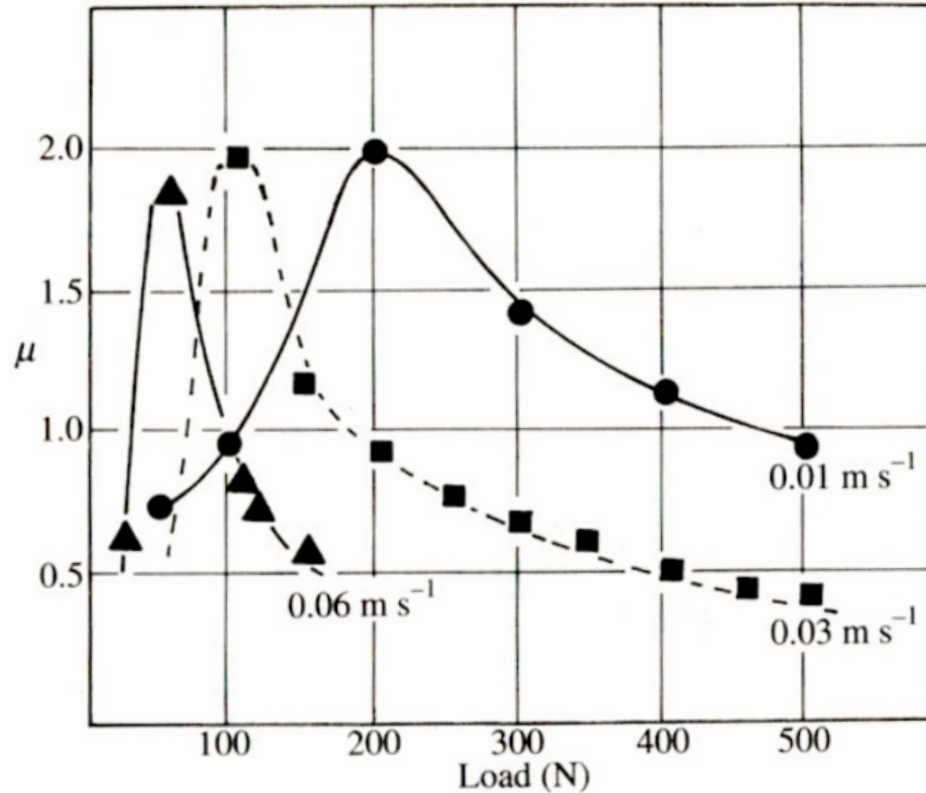
Mechanical aspects of contact

- Case of adhesion : $F_{adhésion} = A \cdot \tau$ *A: geometrical contact area*

                                      τ : shear resistance

- For polymers τ depends on the hydrostatic pressure P: $\rightarrow$ $\tau = \tau_0 + \alpha \cdot P$
- For a polymer film between two rigid plates P = F_n/A

$\rightarrow$ $\mu = F_{adhésion} / F_n = \tau_0 / P + \alpha$ $\longrightarrow$ $\mu \, f \, (F_n)$

Deformation of asperities A f (F_n)

Pressure remains constant

Coefficient of friction

Machined surfaces

a)

Polished surfaces

b)

Maximum contact area reached

Pressure increases with load

Normal force [N]
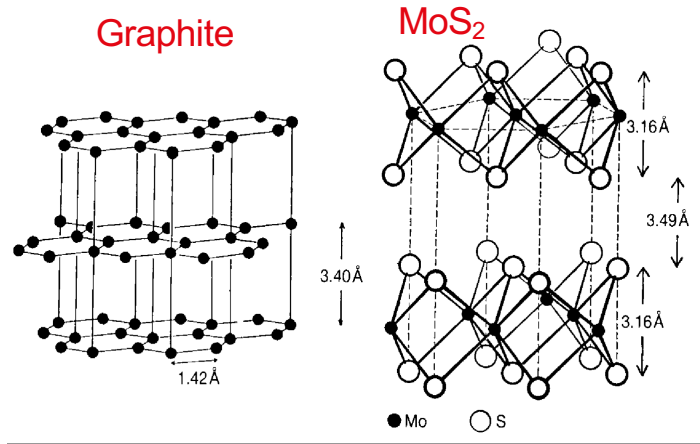
PMMA

Because of viscoelasticity friction may vary with sliding speed

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

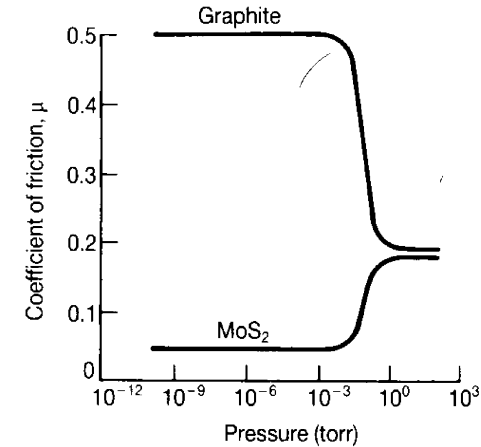*Source: Williams "Engineering Tribology" (1994)*

Landolt Ch. 10.2, Zambelli & Vincent Ch. 2, Hutchings Ch.3

Lamellar solids: Bragg's hypothesis

Graphite   MoS$_2$

- Anisotropy of the properties due to the lamellar structure : strong lamellar bond but weak interlamellar bond. Bragg's hypothesis : low friction because of low inter-lamellae shear resistance. However some lamellar solids exhibit high friction (mica, Ca(OH)2), contrary to others (tungsten disulfide, cadmium chloride, …) which are used as solid lubricants.

- Evolution of the friction coefficient for different air pressures. (Buckley)

- The lubricating properties of graphite and MoS$_2$ therefore depend on their environment.