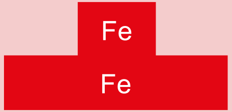
Chapter 3
Friction

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

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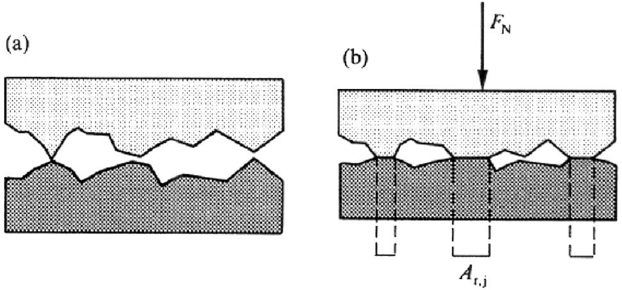
Adhesion at asperities



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

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

- 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

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

Application to metals

- For metals :

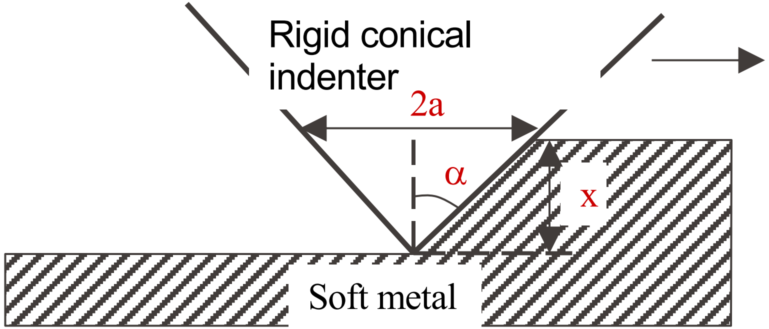
$H \approx 3\ YS$ $\tau_c \approx 0.5\ YS$

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



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

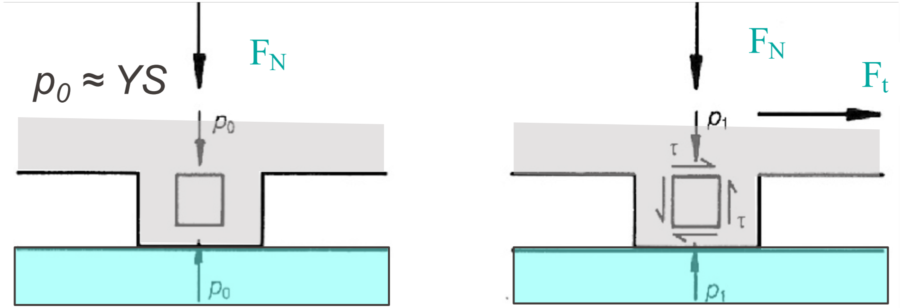
$$P_r = H = \frac{F_n}{\left(\pi a^2\right)/2}$$

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

- Technical surfaces exhibit values of **α** > 80 → $\mu_{\text{def}} \leq 0.12$
- Hence theoretically : $\mu_{\text{def}} + \mu_{\text{adh}} = 0.12 + 0.16 \leq 0.28$
- However in practice $\mu > 0.3$

Adhesion and plastic deformation of asperities

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



Uniaxial compression

Compression + shear

- Tresca:

$$\boxed{p_1^2 + 4\tau^2 = p_0^2}$$

$$p_1 = F_n / A$$

$$\tau = F_t / A$$

$$F_n^2 / A^2 + 4 F_t^2 / A^2 = p_0^2$$

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

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 :

$$F_f = \tau_i A \qquad \tau_i < \tau_c$$

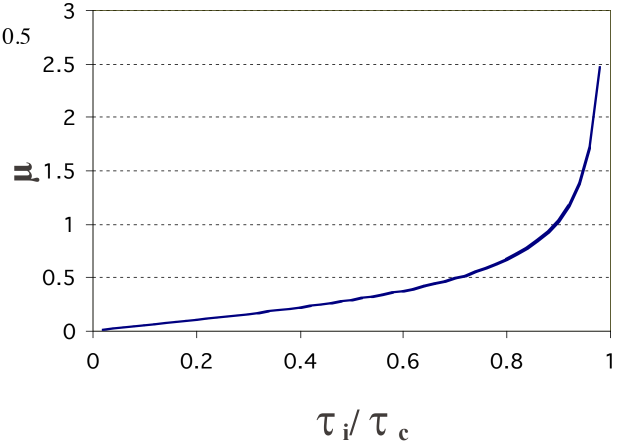
With τ_i : shear stress at the interface

τ_c : critical shear stress of the material

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

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

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



1. Mechanisms

2. Energy and temperature of friction

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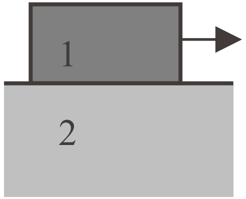
Energy and temperature during friction

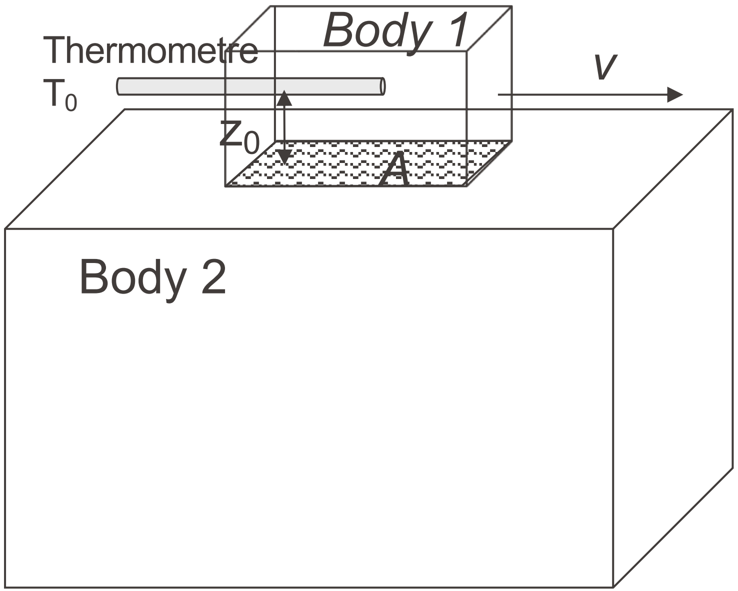


- Dissipated power Wf: $W_f = F_f \mathbf{v}$
- Dissipated power density Q_f: $Q_f = W_f / A$
- The dissipated power generates a thermal flow in each body:

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

A = area of contact [m2]
F_f = frictional force [N]
$\mathbf{v}$ = 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:

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

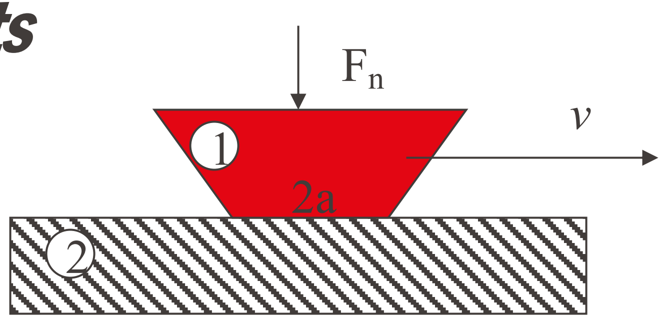
T_s = temperature of the contact [K]

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*



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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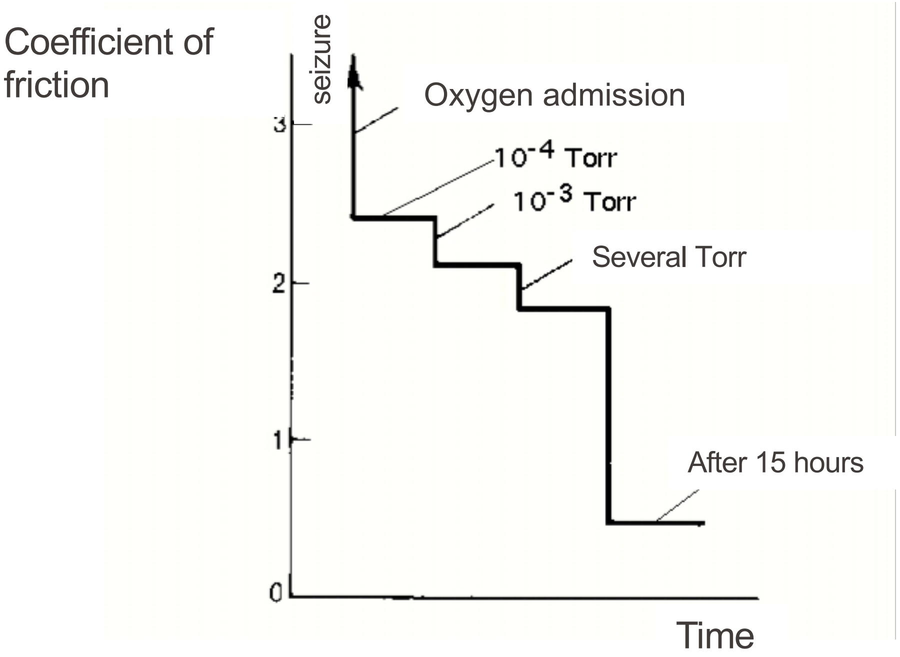
Frictional behavior of metals

- Effect of surface oxidation :

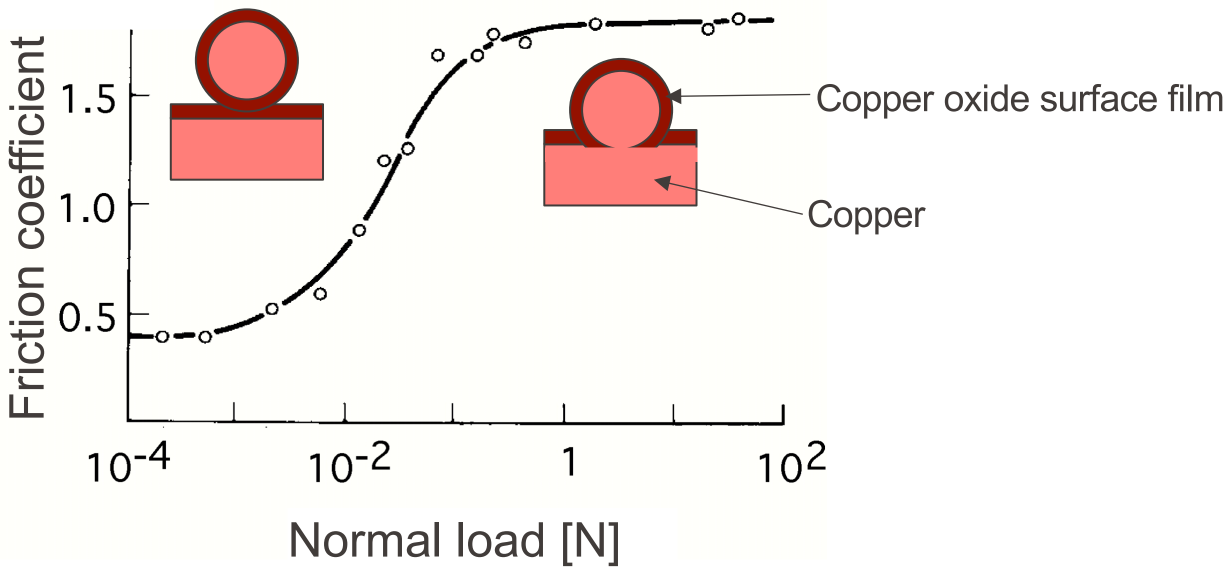
Case of iron-iron friction, initially in vacuum *(Buckley/Hutchings)*



Frictional behavior of metals

- Case of copper-copper friction under different loads.

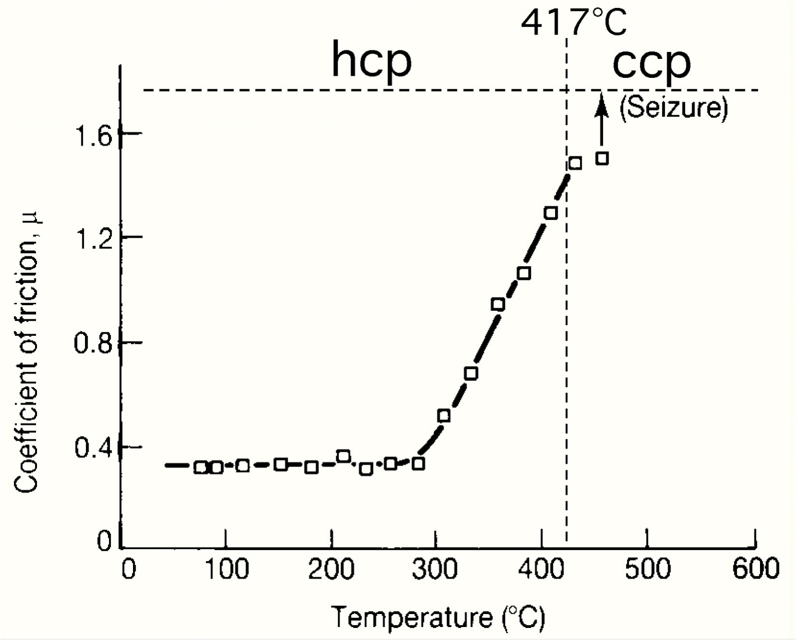
The transition in coefficient of friction can be explained by the surface oxide layer rupturing under high load (according to measures of contact electric resistance).
(Buckley/Hutchings)



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)*



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Frictional behavior of ceramics

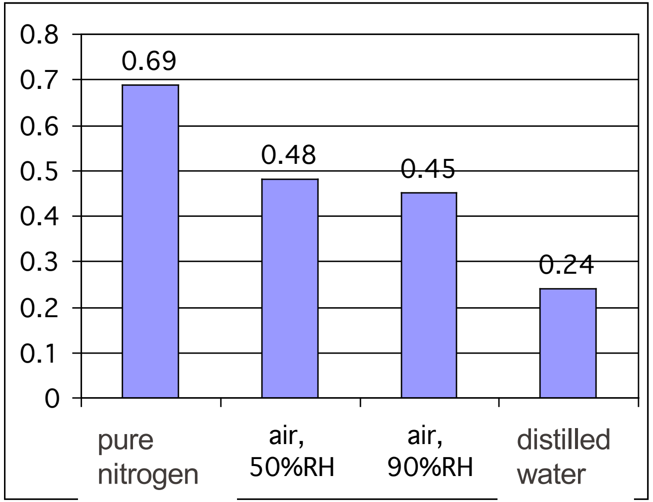
- Chemical inertia due to surface reactions:

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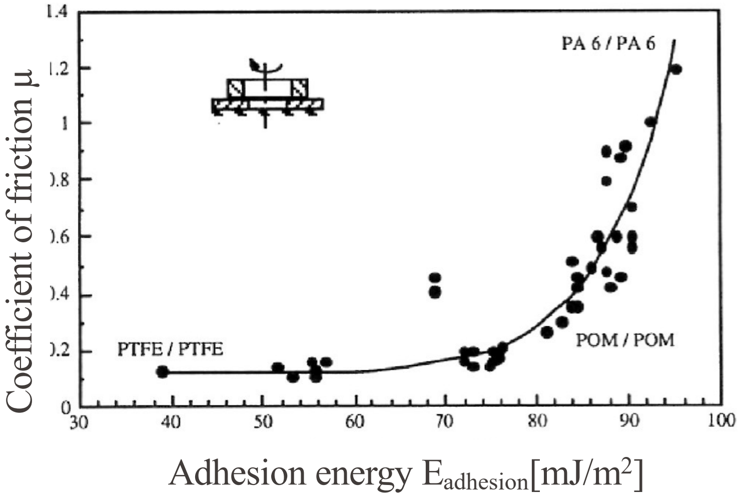
Adhesion: large elastic contact area and high adhesion energies favour adhesion

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



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

Mechanical aspects of contact

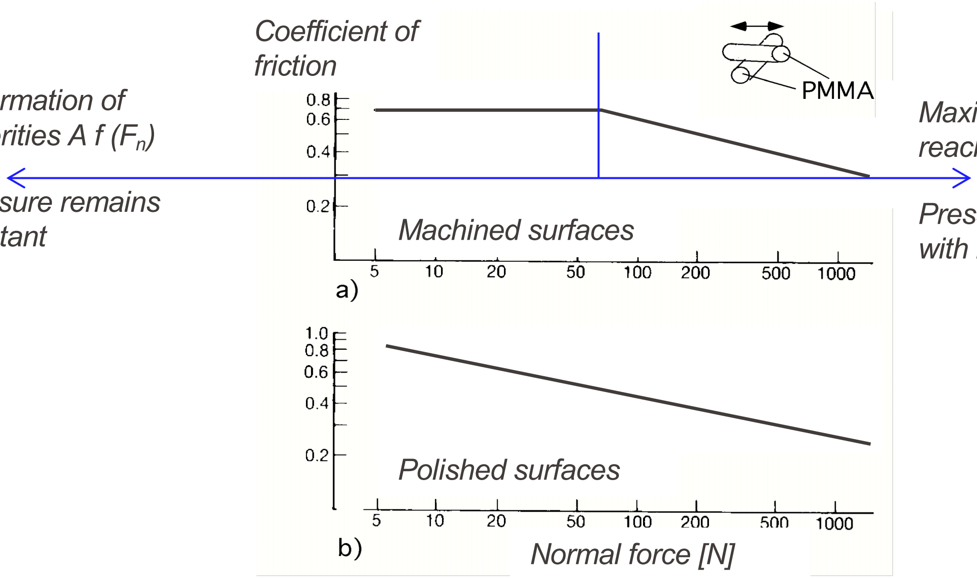
- Case of adhesion : $F_{adhésion} = A \cdot \tau$ *A: geometrical contact area*

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

→ $\mu = F_{adhésion} / F_n = \tau_0 / P + \alpha$ → $\mu\, \mathrm{f}\,(\mathrm{F}_{\mathrm{n}})$

Deformation of asperities A f (F_n)

Pressure remains constant

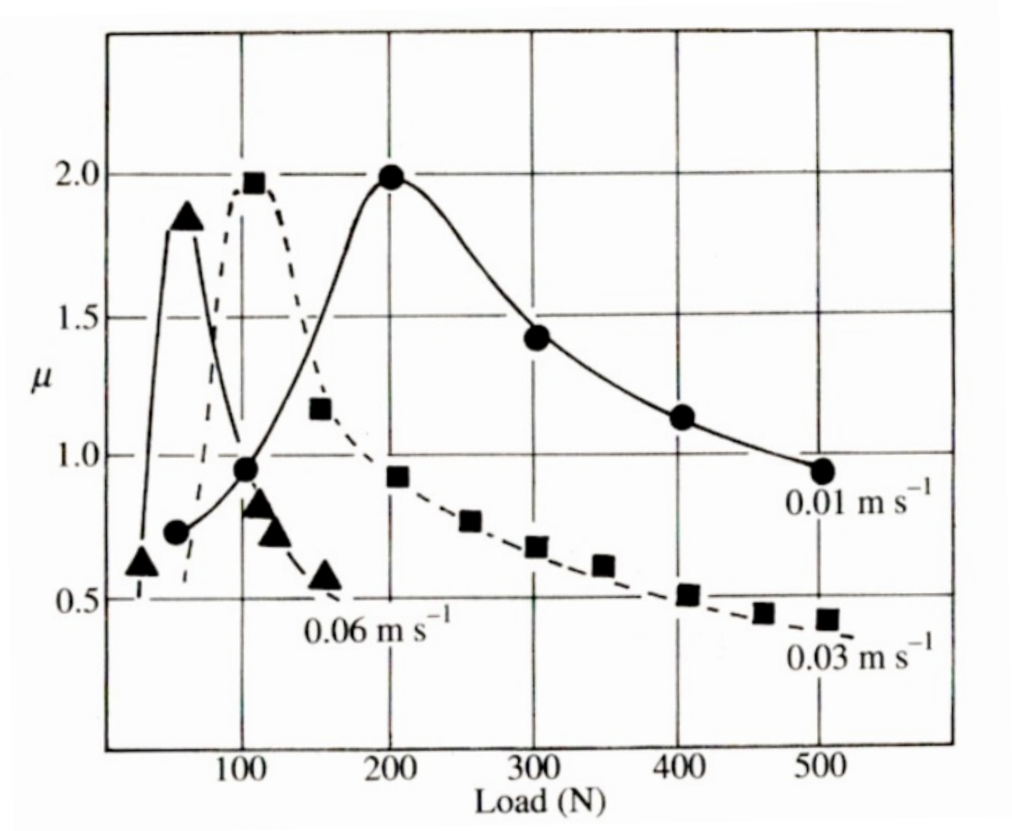


Maximum contact area reached

Pressure increases with load

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)

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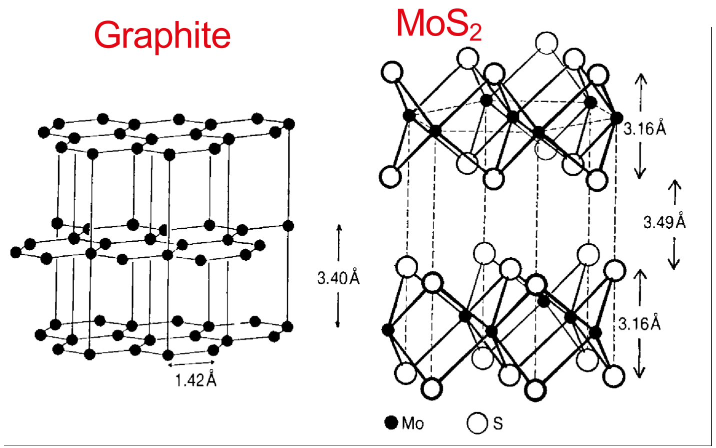
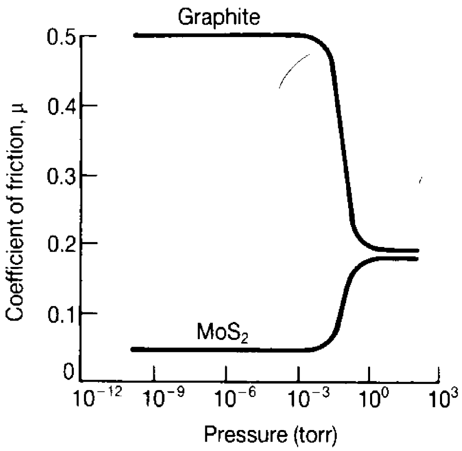
Lamellar solids: Bragg’s hypothesis



- 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.