Lecture 11

Friction, Lubrication and Wear

Definitions

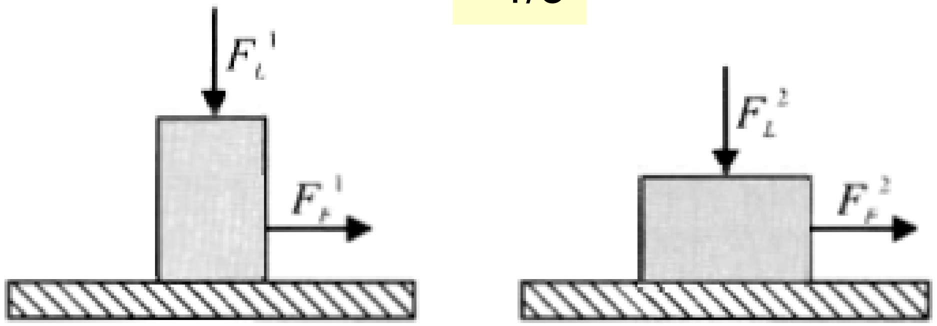
- **Friction** – force between the interacting surfaces that resists or hinders their relative movement
  - Static friction – force to overcome to start movement
  - Dynamic friction – mechanical force between sliding or rolling surfaces
- **Wear** – progressive loss of materials caused by contact and relative movement
- **Lubrication** – aimed on reducing friction and minimizing wear
- **Tribology** – research field dealing with friction, lubrication and wear.

Amontons Law

- in 1699 Guillaume Amontons found that the friction force is proportional to the load and doesn't depend on the contact area

$$F_F = \mu F_L$$

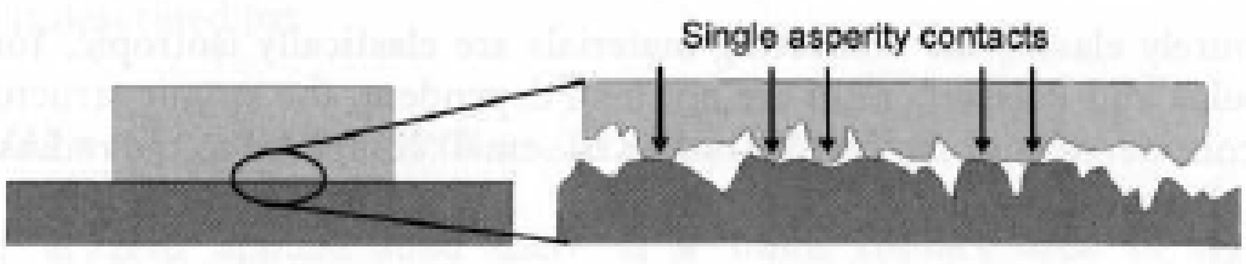
~1/3



- Amontons law is an empirical law, result of several physical phenomena acting at the same time

Amontons Law

- The real contact area is always smaller than the apparent one due to roughness



$$F_F = \tau_c \cdot A_{real}$$

yield stress during shear

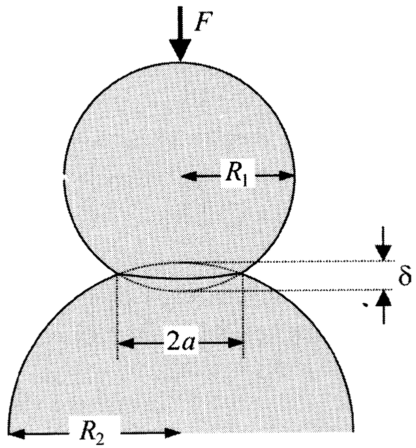
- The real contact area can be measured e.g. using the electrical resistance of the interface or measure hotspots on a transparent solid with IR microscope

Possible origins for Amontons Law

- **Elastic deformation**
  - Hertz law:

$$a^3 = \frac{3R^*}{4E^*} \cdot F_L$$

$$A_{real} \sim F_L^{2/3}$$



  - Assuming Gaussian distribution of sphere sizes one can obtain a linear dependence between the load and the friction
- **Plastic deformation:**
  - As load is applied the plastic deformation will start. It will continue till the pressure reaches some threshold

$$A_{real} \cdot P_m = F_L$$

  - This gives again a linear dependence

Coulomb's law of friction

- Coulomb's law of friction:

The frictional force between the moving surfaces is independent on the relative speed

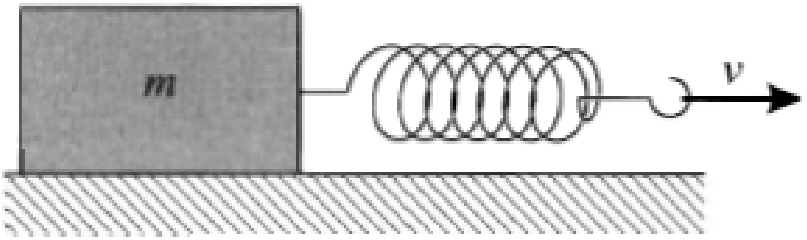
- Coulomb's law of friction is also counterintuitive as the friction is usually dependent on the speed, e.g. Stokes law

Static, kinetic and stick-slip friction

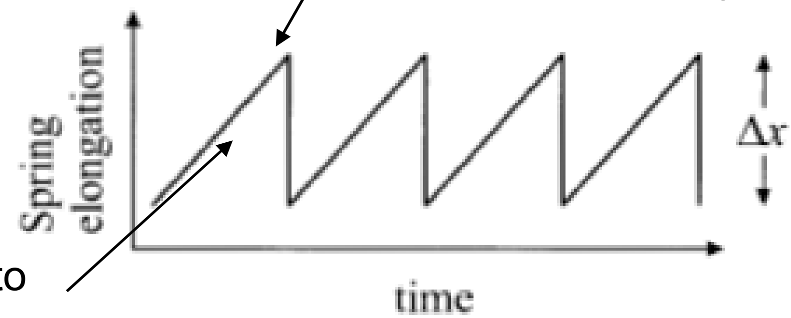
- Static friction:
  - friction force required to start motion,
  - higher than the dynamic friction
- Dynamic (kinetic) friction
  - force needed to sustain sliding
- Stick/slip motion
  - arises when the dragging force is coupled elastically to the sliding body e.g. excitation of a violin string by the bow, squeaking of doors and earthquakes
  - more pronounced at small velocities
  - increases with increasing difference between μ_s and μ_k.
  - more significant with soft springs
- For a block moving at constant velocity we expect:

$$K\Delta x = \mu_k mg$$

- however at the start stick/slip motion can arise due to hysteresis in friction



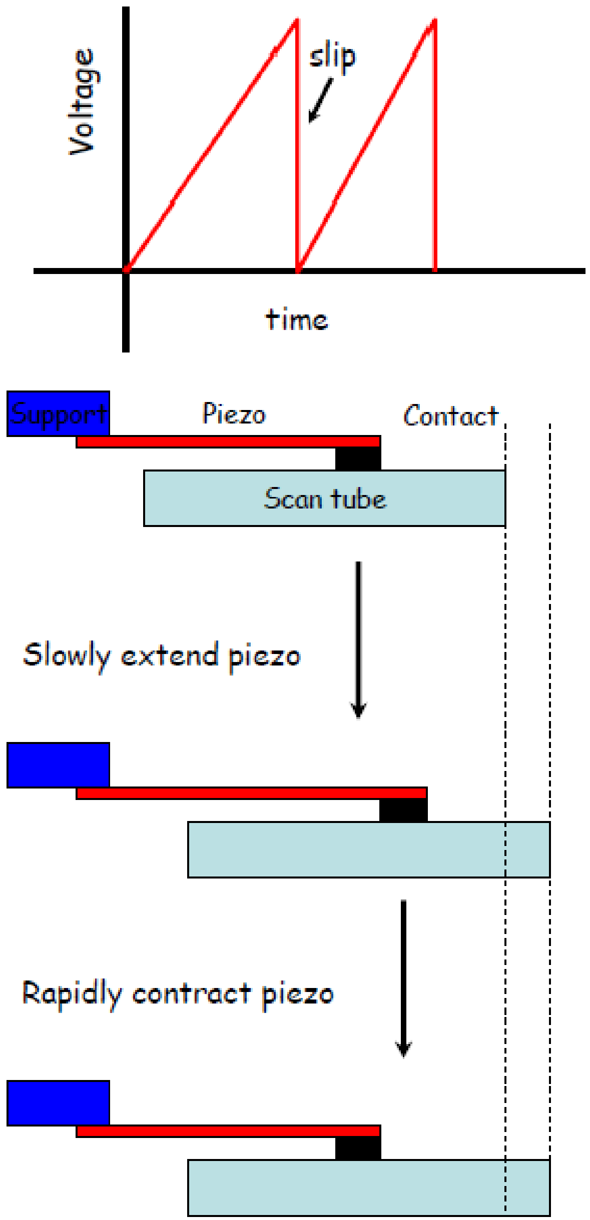
motion starts: $K\Delta x_s = \mu_s mg$

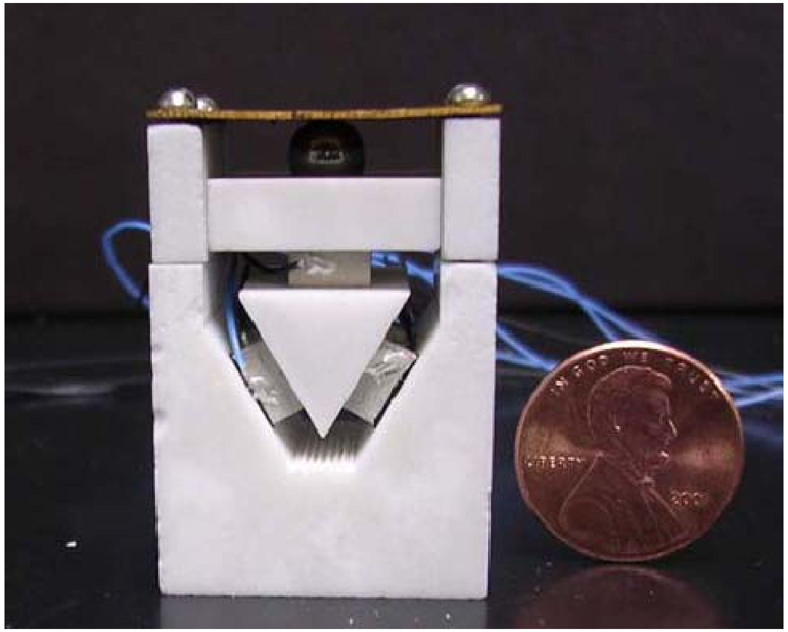


block is accelerated to higher velocity than ***v***:

Stick-slip motion in AFM/STM approach

- Applying a saw-tooth (or parabolic) waveform to a piezo a stick/slip motion can be achieved with fine (<50nm) reproducible steps up or down



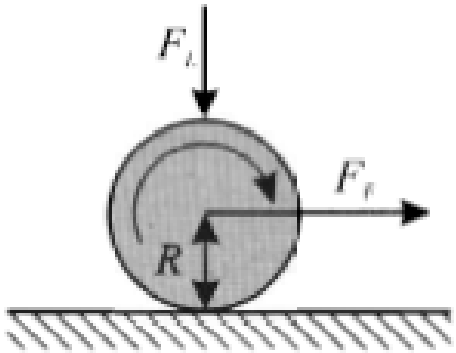


Rolling friction

- Force required to roll an object is usually much less than the one required to slide

$$M = F_F \cdot R = \mu_r F_L$$

torque of the rolling object



Rolling friction

- Rolling of infinitely hard sphere or cylinder should produce no friction.
- In real life there are several **sources of dissipation**:
  - Relative sliding (microslip) due to different elastic moduli of the bodies (seems to be relatively small as dependence on lubrication is usually weak)
  - Adhesion: continuous generation and breaking the contact, e.g. rolling on a sticky tape
  - Plastic deformation: if normal or tangential stress is too high plastic deformation can occur
  - Viscoelastic hysteresis: relaxation processes within the materials
- Rolling friction vs. speed:
  - soft sphere on a hard substrate: linear dependence
  - hard cylinder on viscous surface: initially increases to reach a maximum value and than decreases due to stiffening of material at high speeds

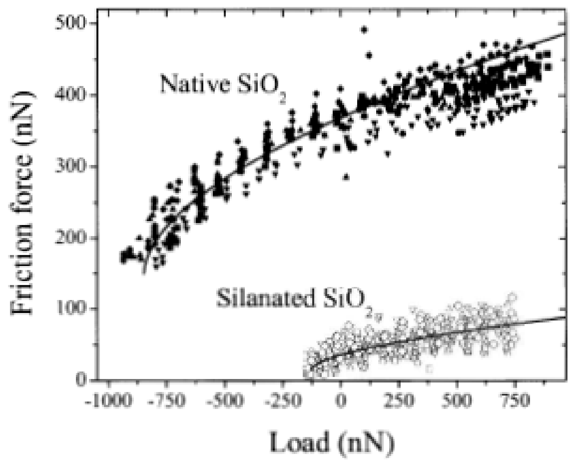
Friction and Adhesion

- Friction will become stronger if an adhesion, e.g. due to van de Waals forces is present

$$F_F = \mu\left(F_L + F_{adh}\right)$$

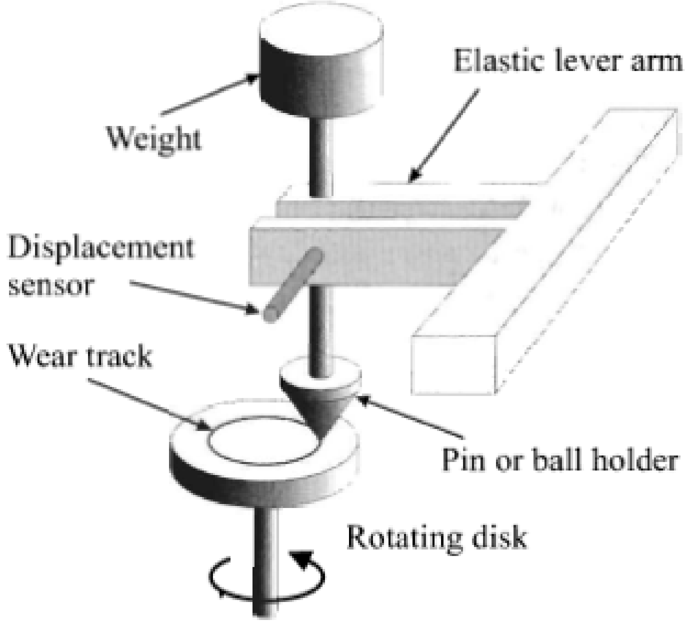
- As weight decreases as r^3, for small objects this contribution is important.
  e.g. for a 5 μm silica sphere gravity force 1.9pN and the adhesion force is measured about of 850 nN

Amontons law is not valid for small contact areas

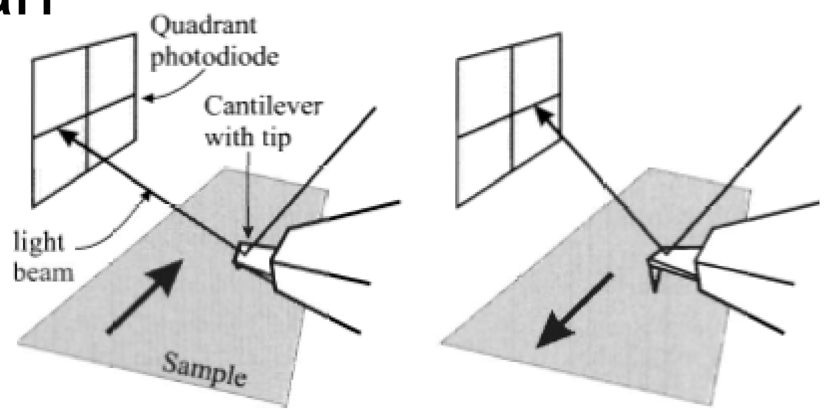


Measuring friction

- Classical devices to measure friction force called **tribometers.** Easiest approach to measure drag force with known load force
- Static force is measured with inclined plane tribometers
- Dynamic friction is measured with pin-on-disk tribometers



- Friction on nanometer scale can be measured with later force (friction) microscopy, LFM
- Damping in QCM is related to slip time of weakly adsorbed layers



Macroscopic friction

- macroscopic friction depends on the nature of the surface:
  - clean metals: μ=3-7
  - oxides: μ=0.6-1
- friction coefficient depends on load, e.g. due to penetration through the surface oxide
- friction coefficient might depend on time in case of plastic deformation:

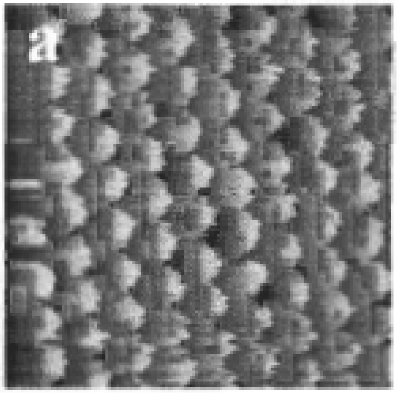
creeping increase in contact area: $\Delta A_{real} \propto \ln(1 + t/\tau)$

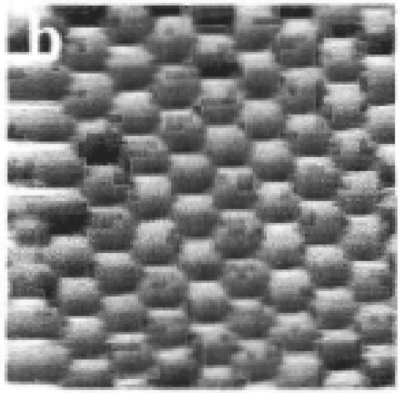
- friction coefficient might depend on local (surface) melting as well as surface phenomena e.g. friction on ice μ=0.03

Microscopic friction

- Atomic stick/slip motion observed on a number of atomically flat materials: graphite , NaF, NaCl, AgBr, MoS_2 etc.
- LFM imaging on a graphite

parallel to scan direction

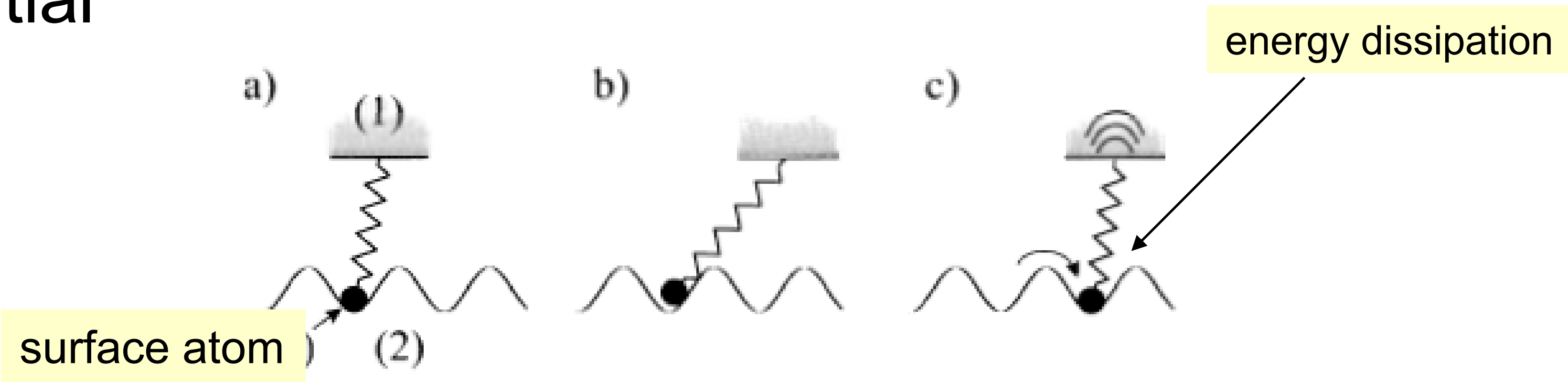




perpendicular to scan direction

Microscopic friction

- **Tomlinson model**: wearless friction due to periodic potential



- explains the Coulomb friction law (independence on the velocity)

$$m_x \ddot{x} = K(x_0 - x) - \frac{\partial V(x,y)}{\partial x} - \gamma_x \dot{x}$$

$$m_y \ddot{y} = K(y_0 - y) - \frac{\partial V(x,y)}{\partial y} - \gamma_y \dot{y}$$

perpendicular to scan direction

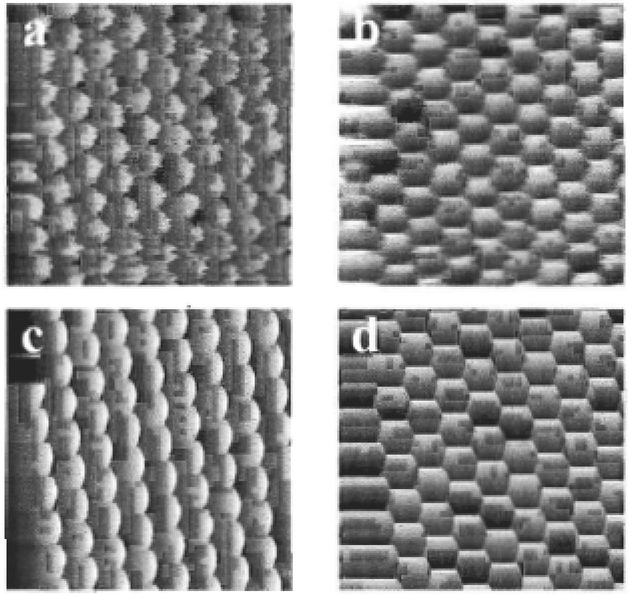
Microscopic friction

- Modeling the atomic stick-slip motion:

$$V(x,y) = -V_0\left[2\cdot\cos\left(\frac{2\pi}{a}\,x\right)\cos\left(\frac{2\pi}{a\sqrt{3}}\,y\right)+\cos\left(\frac{2\pi}{a\sqrt{3}}\,y\right)\right]$$

experiment

model



Microscopic friction

- The loss mechanism can be related to electronic and phononic contribution depending on the material, temperature etc.
- at the nanoscale, the real and apparent area are the same, continuum theories like JKR can be applied to determine the actual contact area
- due to small curvature, AFM tips can penetrate through the lubrication layer

Lubrication

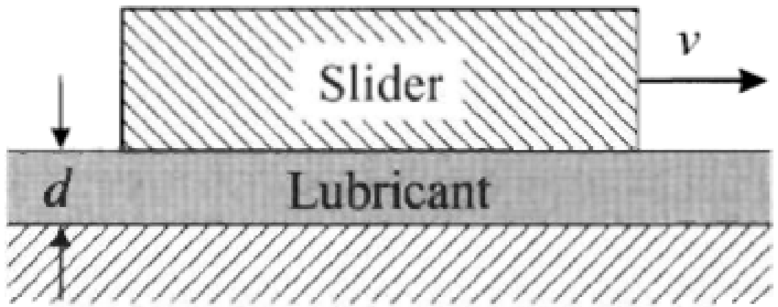
- Lubrication reduces friction and, correspondingly, wear.
- Lubrication regimes (depending on thickness):
  - **hydrodynamic lubrication:**
    lubrication layer is higher than the height of surface asperities
  - **boundary lubrication**:
    lubrication layer is just few molecular layers thick, thinner than roughness
  - **mixed lubrication**

Hydrodynamic lubrication

- In the case of hydrodynamic lubrication, the friction is determined by fluid dynamics

$$F_F = A \cdot \tau_0 = A \cdot \eta \cdot \frac{v}{d}$$

- the assumptions:
  - laminar flow (typically the case, as d is about of 1um)
  - lubricant is a Newtonian liquid



Hydrodynamic lubrication: comments

- Practically, the increase of viscous friction with velocity is slower than predicted by NS, presumably due to local temperature increase

$$\eta = \eta_0 \cdot \exp\left(E/kT\right)$$

also, friction is reduced at higher temperatures

- when pressure on the lubricant layer increases suddenly (like in chain-wheel gears) the lubricant is not expelled from the contact point: elasto-hydrodynamic lubrication
  - viscosity of most lubricants increases with pressure

$$\eta = \eta_0 \cdot \exp\left(\alpha P\right)$$

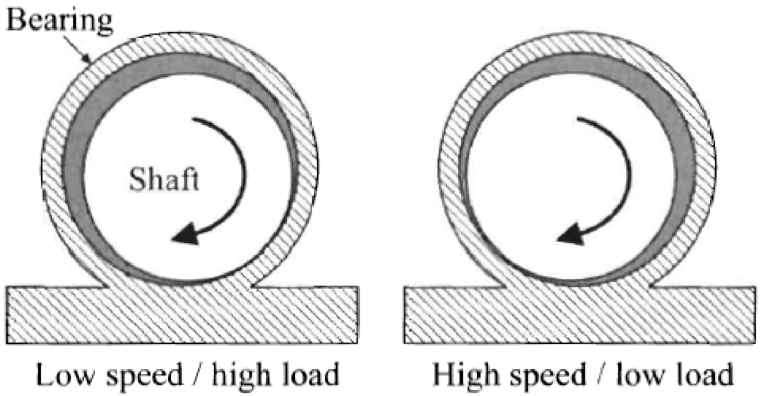
  - solids deform elastically at high pressure, thin oil layer are getting stiff
  - as a result, wear is reduced (except at start/stop) but repeated deformation of solids should be taken into account and could lead to failures

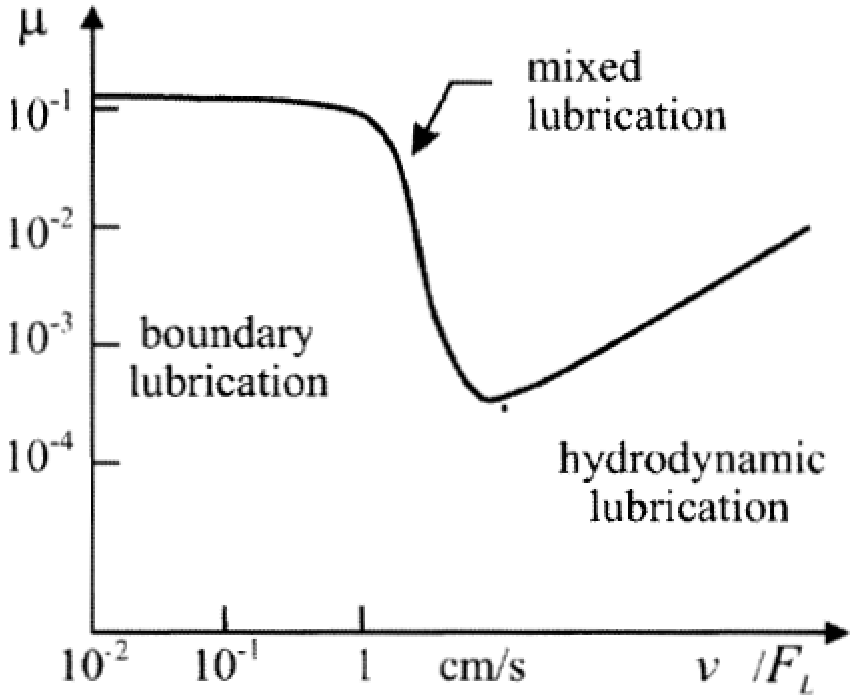
Boundary lubrication

- occurs at low sliding velocities and high loads when the lubricant is squeezed from the gap
- leads to higher friction (x100) than in the hydrodynamic regime
- the friction mainly depends on the nature of lubricant than on its viscosity
- important effect is reduction of adhesion, small Hamaker constant helps to reduce vdWaals forces between the surfaces.

Mixed lubrication

- Depending on the speed and load the same mechanism might be in the boundary, hydrodynamic or mixed regime:





Stribeck diagram

Thin film lubrication

- thin film lubrication – lubrication with films of molecular thickness.
- Non-DLVO effects related to (re-)ordering of molecular layers are important
- no-slip condition might be violated

Lubricants

- Major types of lubricants:
  - oil (petroleum or synthesis)
  - grease (oil + dispersion of a thickening agent)
  - solid lubricant (graphite, MoS_2)
- Characterized by
  - viscosity (viscosity index: kinematic viscosities at 40ºC and 100ºC compared to standard paraffin oil with weak T-dependence (100) and naphthenic oil with strong T-dependence (0)
  - volatility
  - ageing behavior (contamination, oxidation, thermal decomposition)

Wear

- Progressive loss of material from a body caused by contact and relative movement of a containing solid or liquid or gas
- Archard's law of adhesive wear

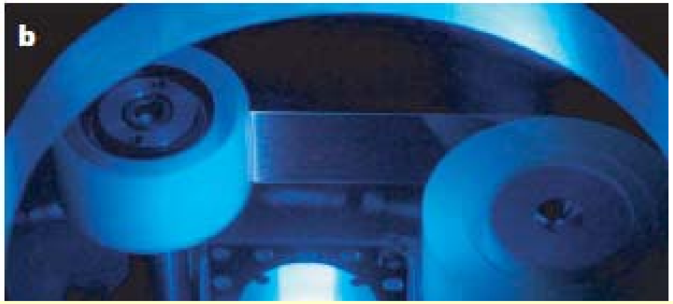
$$\Psi = k_w \cdot \frac{F_L v}{H}$$

material loss (Ψ), hardness (H)

- Types of wear:
  - **abrasion**: wear in contact with harder material or hard particles
  - **erosion**: wear due to impingement by a stream containing solid particles (e.g. sand blasting)
  - **cold welding** effect due to adhesive contact
  - **surface fatique** due to periodic load in the contact zone
  - **fretting wear**: in case of small oscillatory movement of the surfaces, the wear particles stay in the the contact area
  - cavitation caused wear, due to bubble formation
  - wear due to **tribochemical reactions** (caused by elevated temperatures, low energy electrons emission, removal of protective oxide layer, increase reactivity due to roughening, dangling bond, caused by plastic deformation).

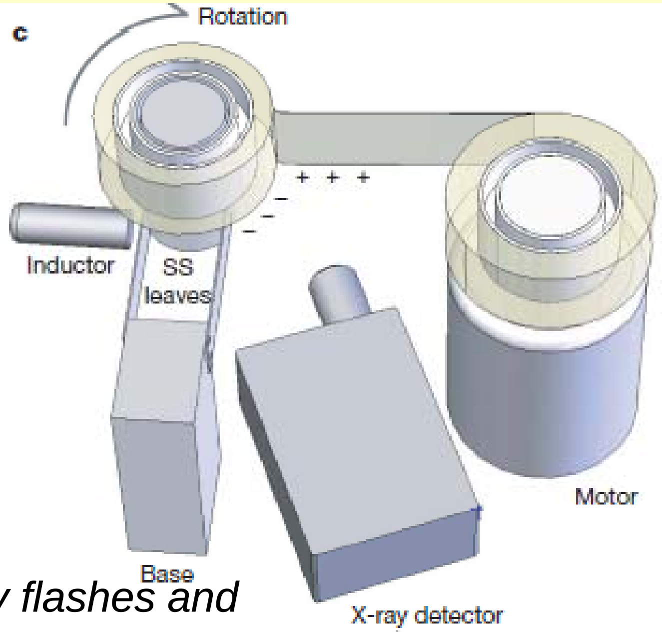
Triboluminescence of a Scotch tape

- Breaking adhesion between two surfaces can produce significant energy in form of UV-VIS radiation and even X-rays (first discovered in 1939 and 1953, elaborated experiment in 2008)



apparatus illuminated by scintillations

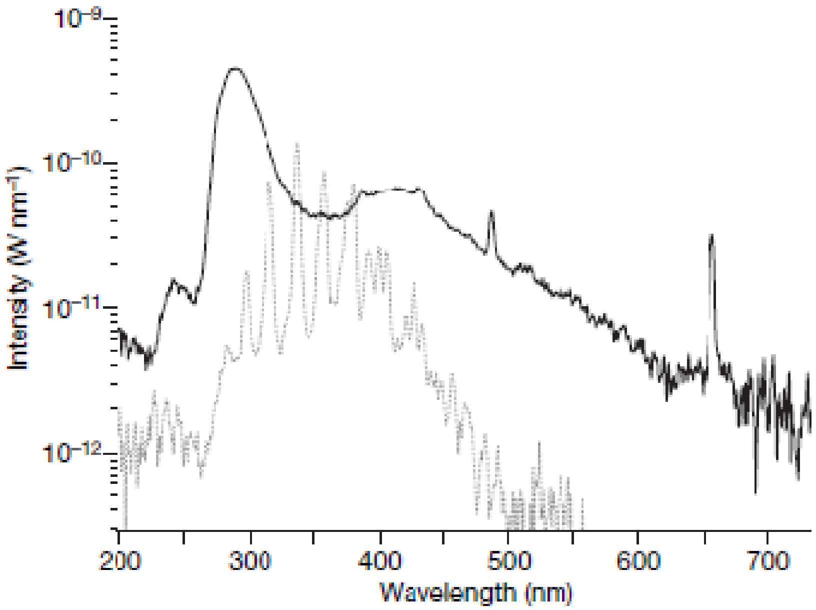
- Suggested mechanism:
  - charge separation during peel-off the tape when positive charges left on acrylic adhesive and negative on the polyethylene roll
  - this eventually leads to a discharge
  - and Bremsstralung X-ray radiation



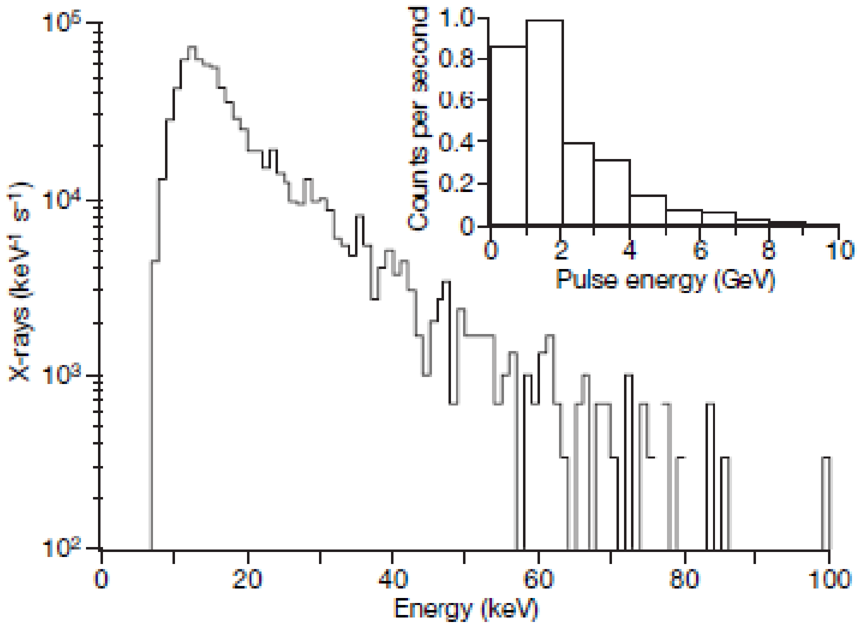
Carlos G. Camara et al, "Correlation between nanosecond X-ray flashes and stick–slip friction in peeling tape", Nature 455, 1089 (2008)

Triboluminescence of a Scotch tape

- Sufficient discharge currents power (0.2mW, estimated field $10^6 – 10^7$ V/cm, density 10^{11}-$7x10^{12}$ electron/cm^2, depending on the model)
- Can act as a simple source of X-rays sufficient for imaging applications



light spectra, in vacuum and in air, 1atm (gray)



X-ray spectra in vacuum

Carlos G. Camara et al, "Correlation between nanosecond X-ray flashes and stick–slip friction in peeling tape", Nature 455, 1089 (2008)

Problems

- End of chapter: 11.2, 11.3