Lecture 2: Surfaces from a manufacturing perspective

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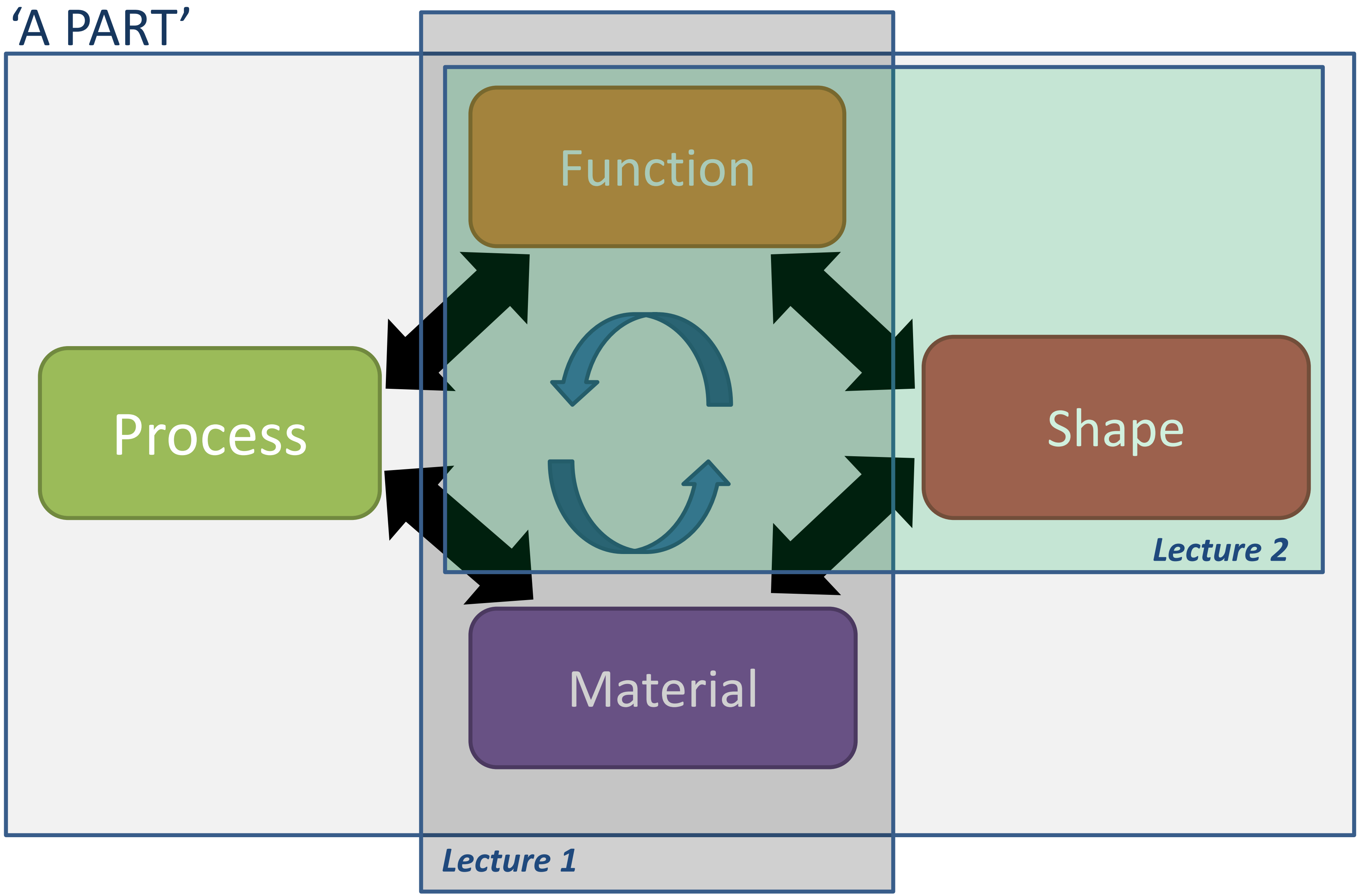
Today's learning objectives

- **Importance** of surfaces in manufacturing
- How do we **define / characterize** a surface?
  - Geometrical parameters, texture
  - Characterizations methods
  - Physical properties



'A PART'
Function
Process
Shape
Material
Lecture 2
Lecture 1

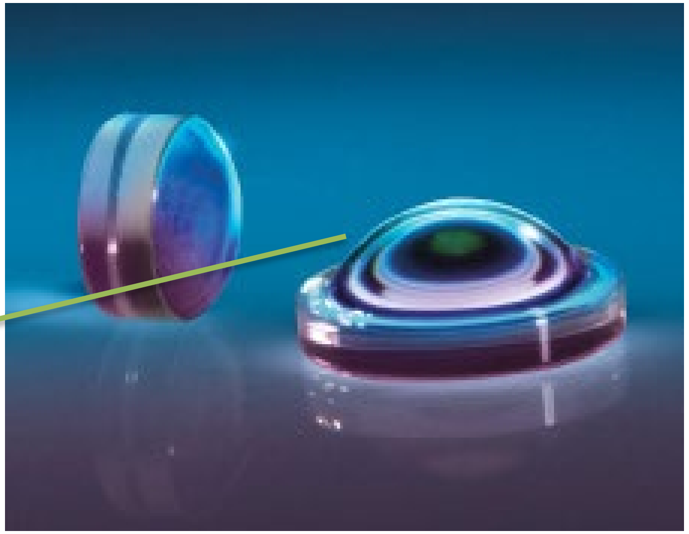
Discussion in class (5 min)

What functions can be associated with a surface?

Surface & functions…

(bizlaunchblog.com)

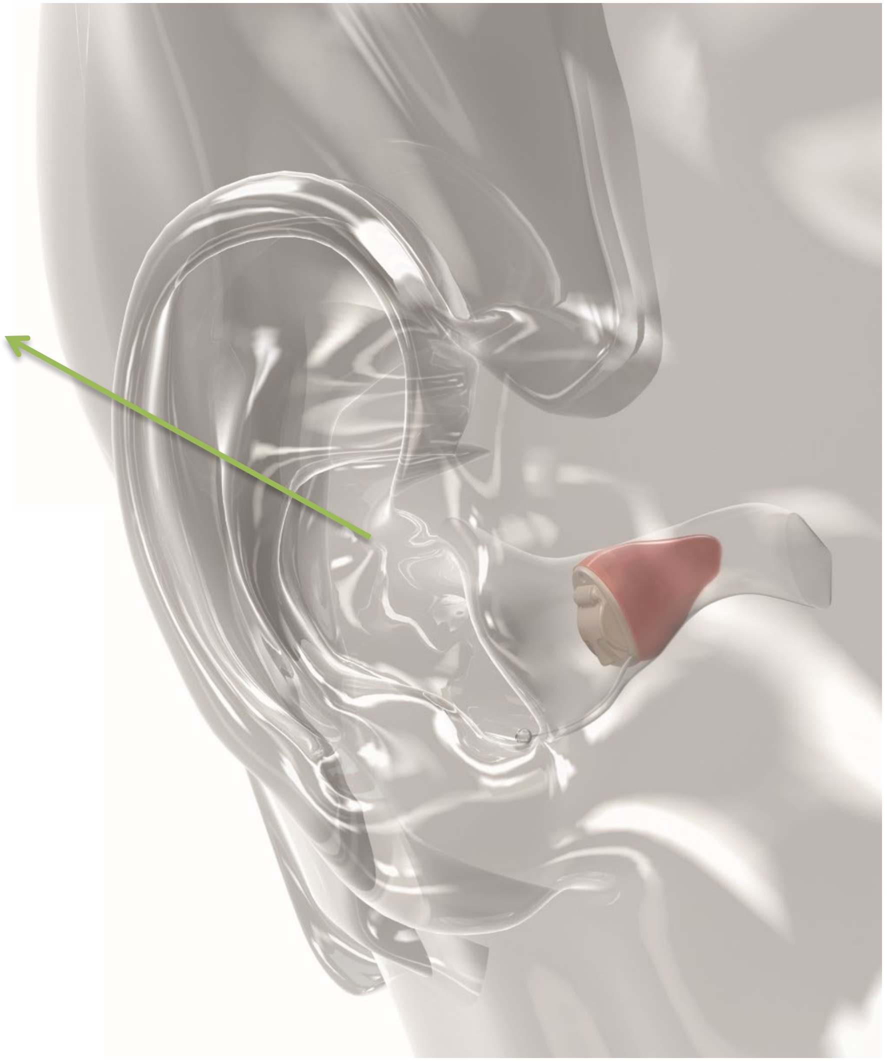
- Transparent
- Scratch resistant
- Others..



- Transparent
- Specific and precise shape
- ‘The shape is the function’

Surfaces & functions…

Soft
Skin-friendly (non allergenic)

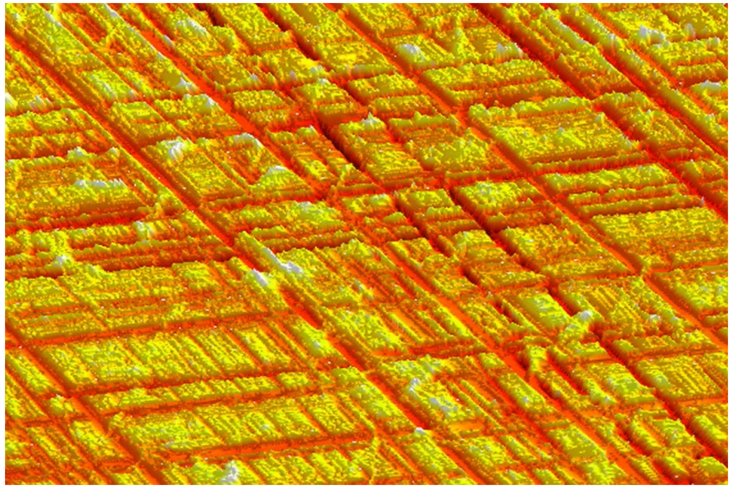


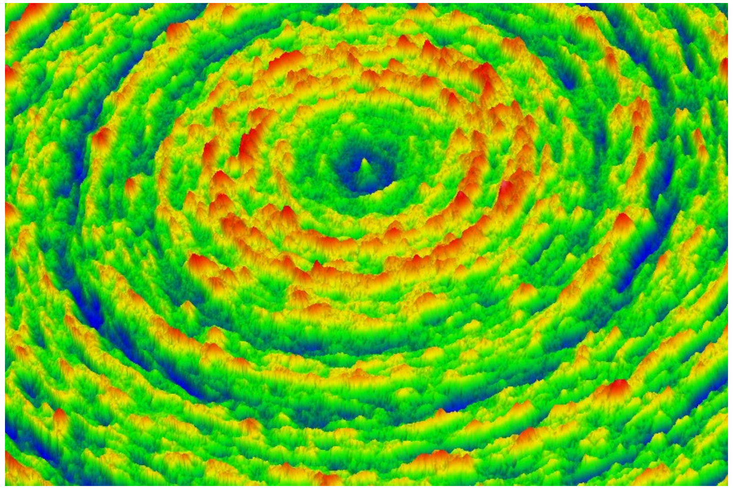
(Phonak, Nano)

Surface and functions…

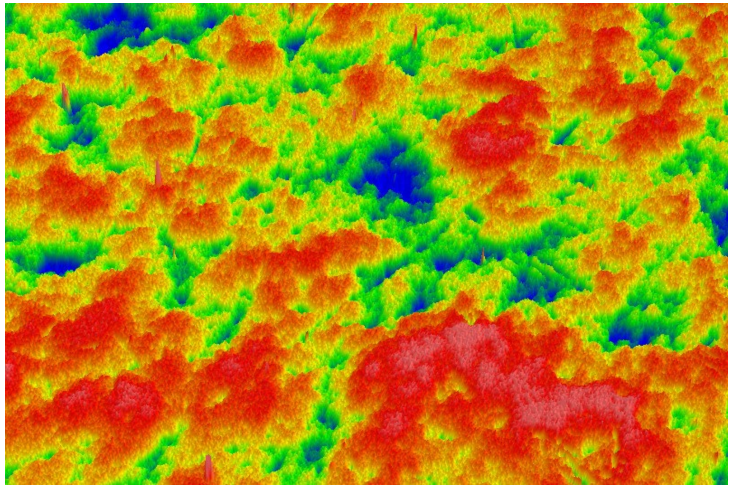
(Girard-Perregaux, Tourbillon bi-axial)

Illustration of surface textures at the microscale



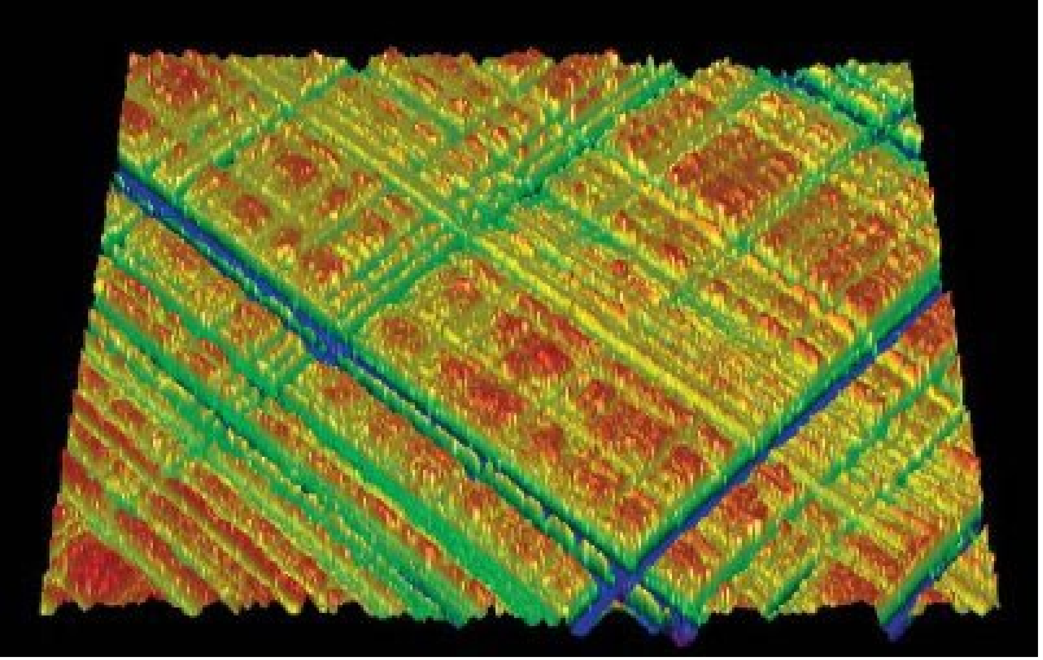


Textured



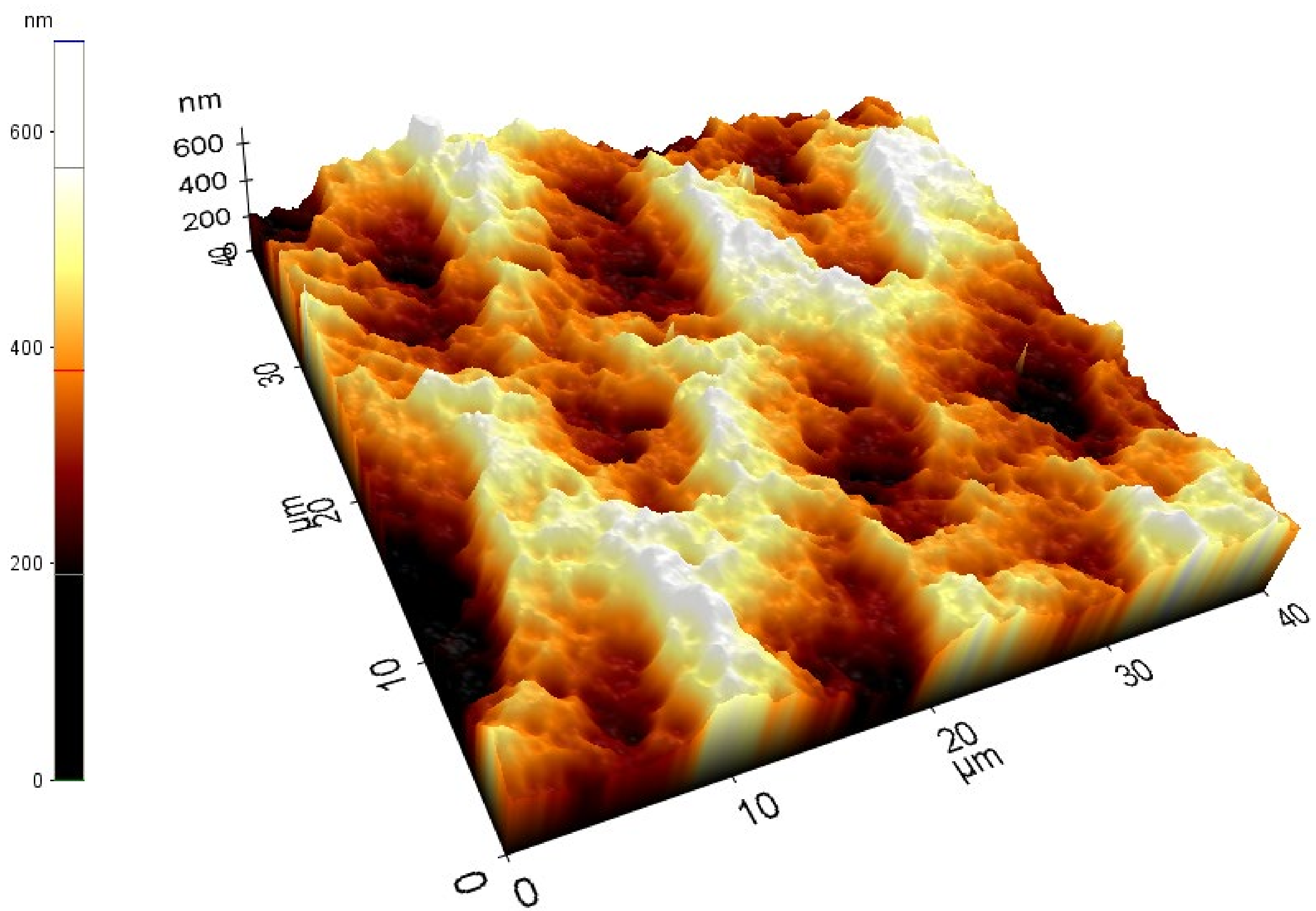
Somewhat random

Examples of different surface finish leading to different textures (cross-hatch, turned, grounded)



(azom.com)

A complex 3D problem!



(Exercise with Gwyddion)

Surfaces: key questions

- **How to translate a functional requirement into a physical surface requirement?**
  - Ex. 'optically transparent' = typ. roughness Ra < 10 nm, why is that?
- **What are essential physical properties of a surface?**
  - Ex. hydrophobic = contact angle with water > 90 deg
- **How to characterize a surface? (Metrology)**
  - Ex. define roughness, waviness, etc.

Properties of surfaces and their characterization

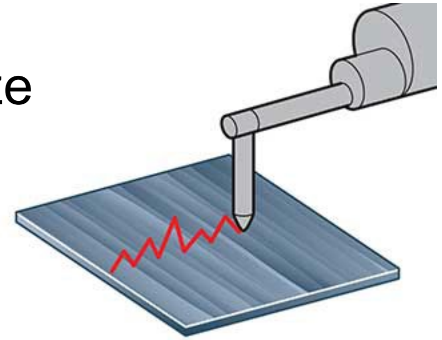
- **Topography characterization**
  - Roughness
  - Waviness
  - Profile
- **Physical properties**
  - Wettability (Hydrophobic, hydrophilic)
  - Mechanical Hardness
  - *Others (chemical, optical, etc.)*

How do we measure surfaces?

Three main methods

- **Optical-based profilometry techniques** – large surface imaging
  - Confocal microscopy / high-depth of field, limited lateral spatial resolution (diffractionlimit)
  - Phase shift interferometry / high resolution along the optical axis (< a few nm), limited lateral spatial resolution (diffraction limit)
  - Digital Holography Microscopy (DHM), etc.

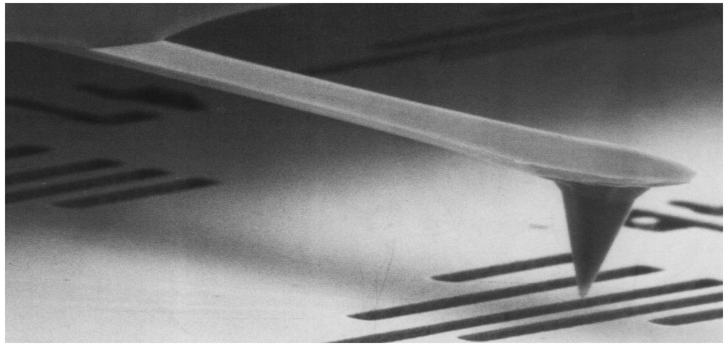
- **Direct contact methods** (stylus)
  - Resolution depends on the actual stylus size
  - Large surface area can be measured
  - Commonly use in industry
  - Contact method

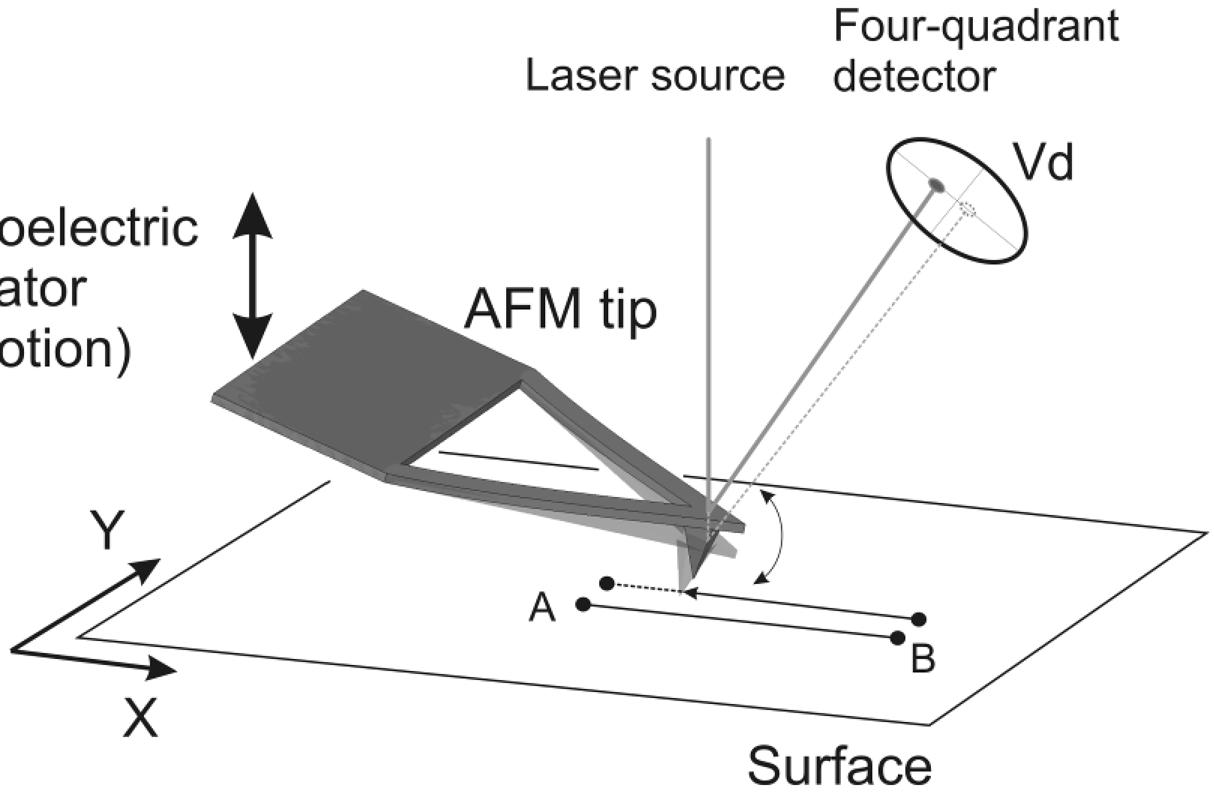


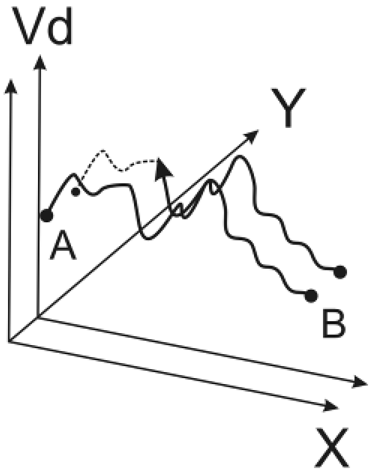
(Illustration Mittutoyo)

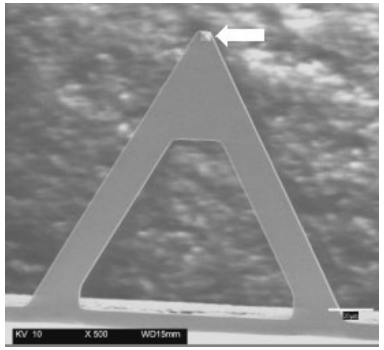
- **Atomic force microscopy** (AFM) – limited surface imaging (typ. 50 x 50 μm^2)
  - Contact and non-contact measurement
  - High resolution (nanoscale down to atomic level in certain conditions)
  - Physical interaction with the specimen

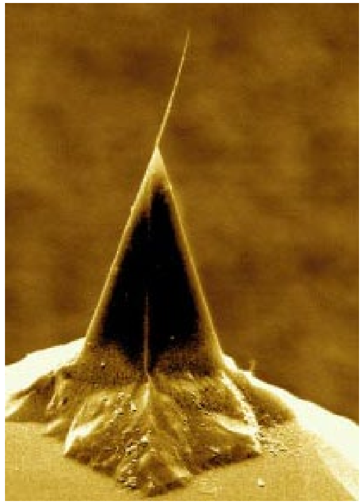
Measuring surface forces at a **nano-scale** level: “Atomic Force Microscope”





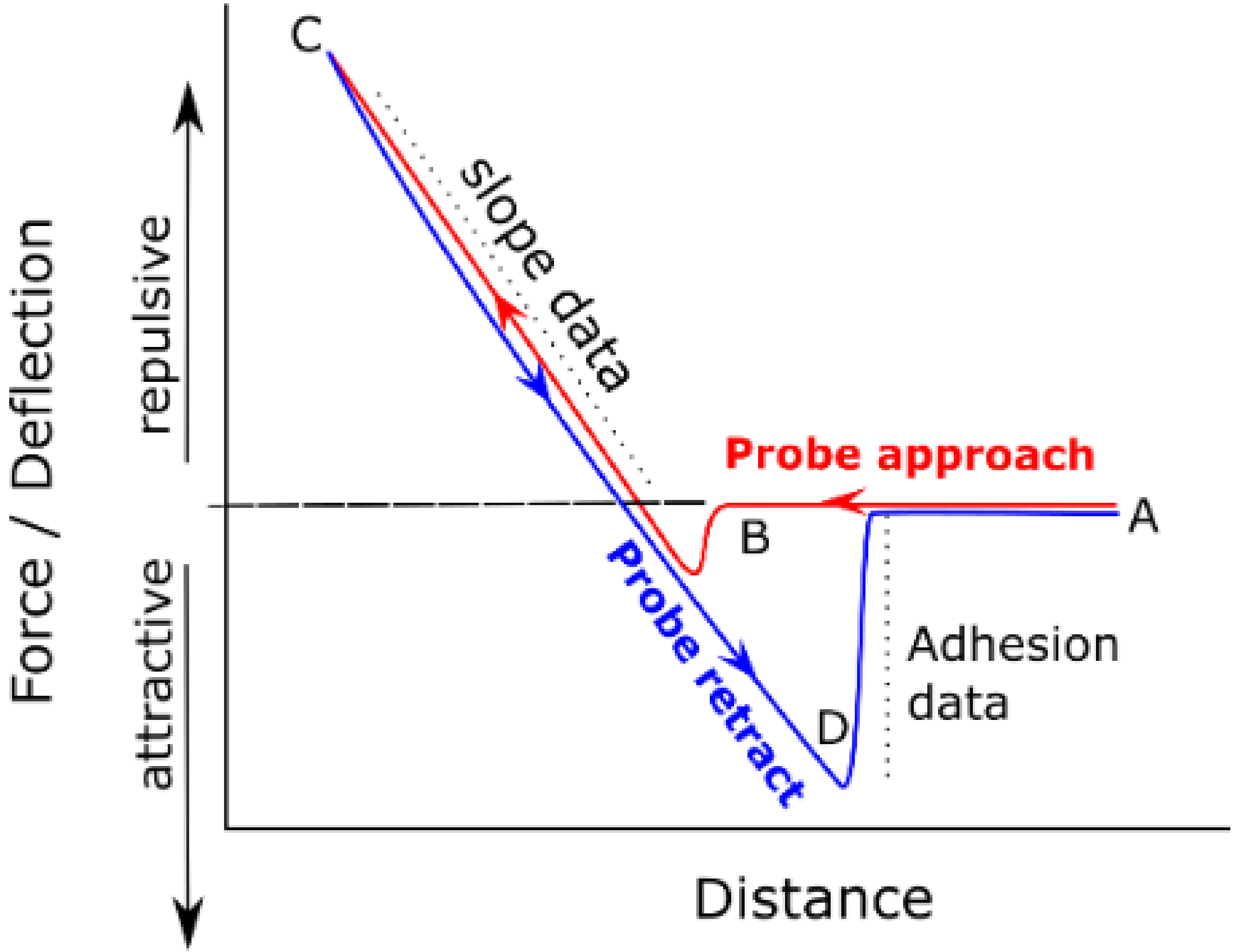






Invented in 1986, Binnig, Gerber, Quate (IBM Zurich Lab)
1986 / (STM) Nobel prize G. Binnig, H. Röhrer (IBM Zurich Lab)

Typical interaction force for an AFM

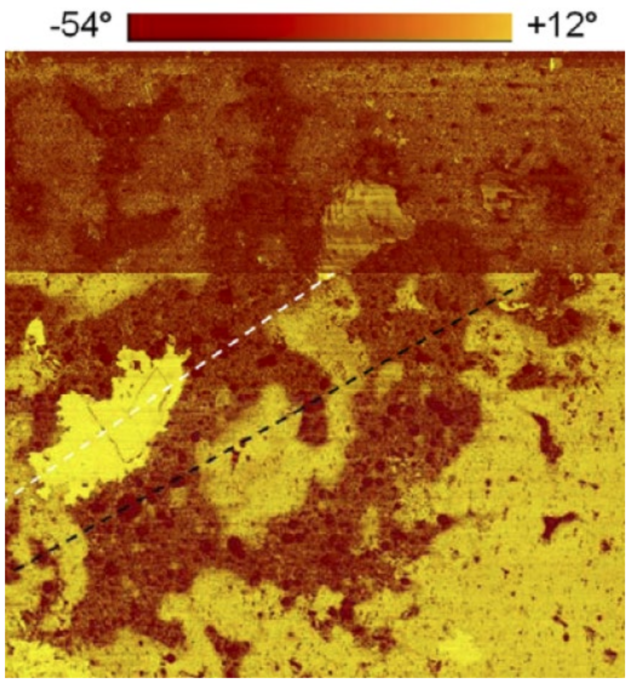


(source: AFMWorks)

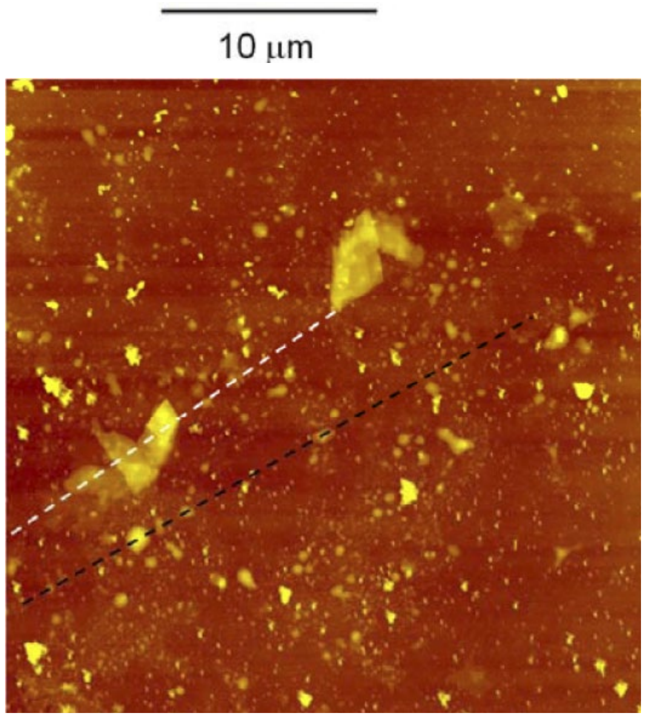
- Force/deflection force provides information about the physics of the surface.
- Specific probes can be used to retrieve rich information, such as thermal transfer, conductivity, etc.
- **An AFM can provide more than just the topography**

Illustration 1: DNA molecules on a silica fiber

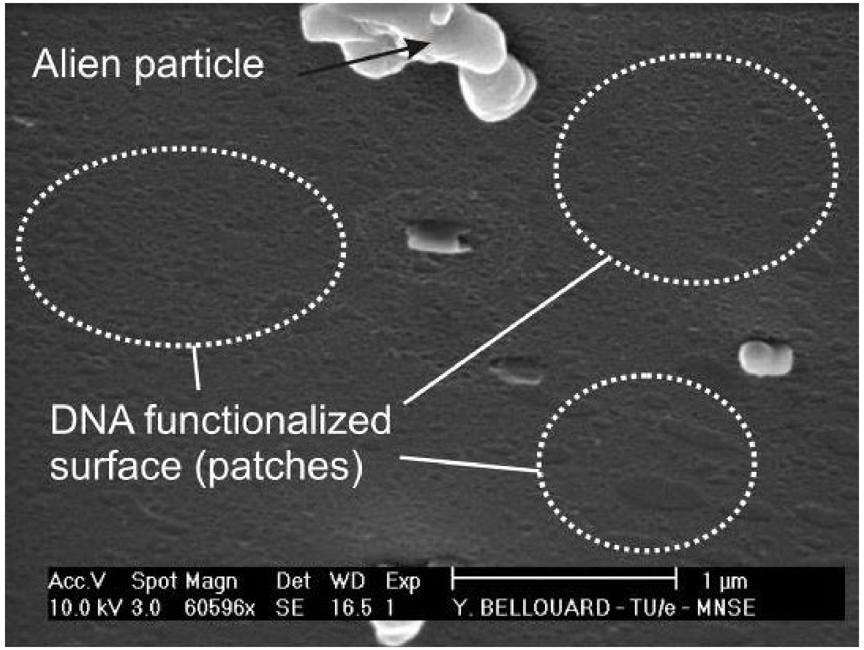
- Atomic Force Microscopy (Phase imaging)



Phase image



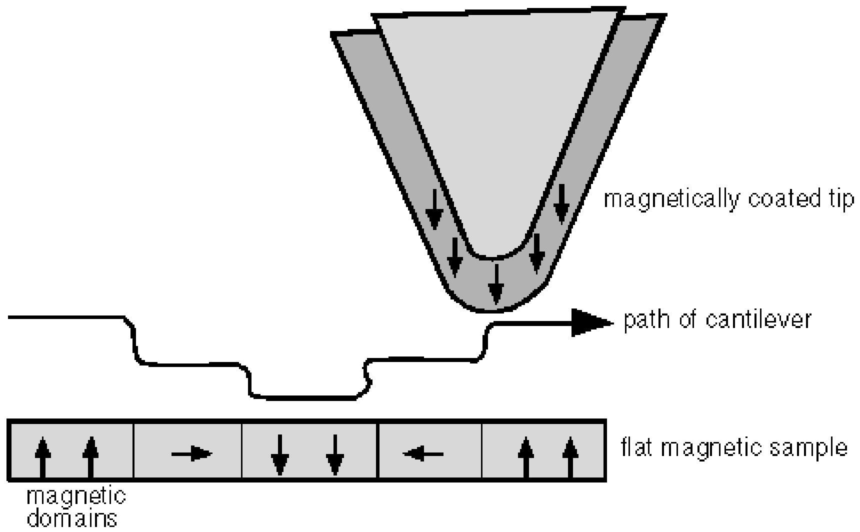
Intermittent contact microscopy



Scanning Electron Microscopy

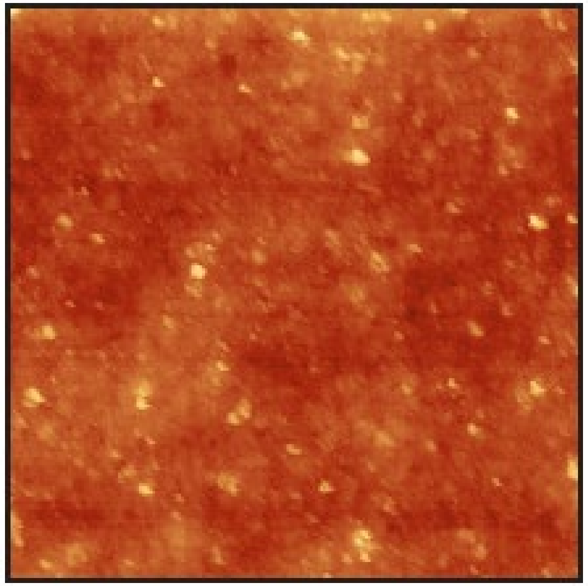
Source: GOLEM project, TU/e (Madani-Grasset, Bellouard)

Illustration 2: Magnetic Force Microscopy



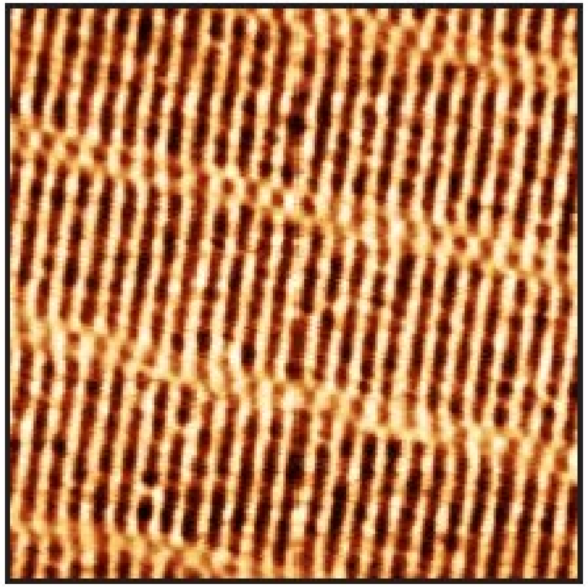
- Ferromagnetic tip: Co, Cr
- Noncontact mode
- van der Waals force: short range force
- Magnetic force: long range force; small force gradient
- Close imaging: topography
- Distant imaging: magnetic properties

Topography surface information



AFM image, Zip Disk 40 x 40 µm

Functional surface information

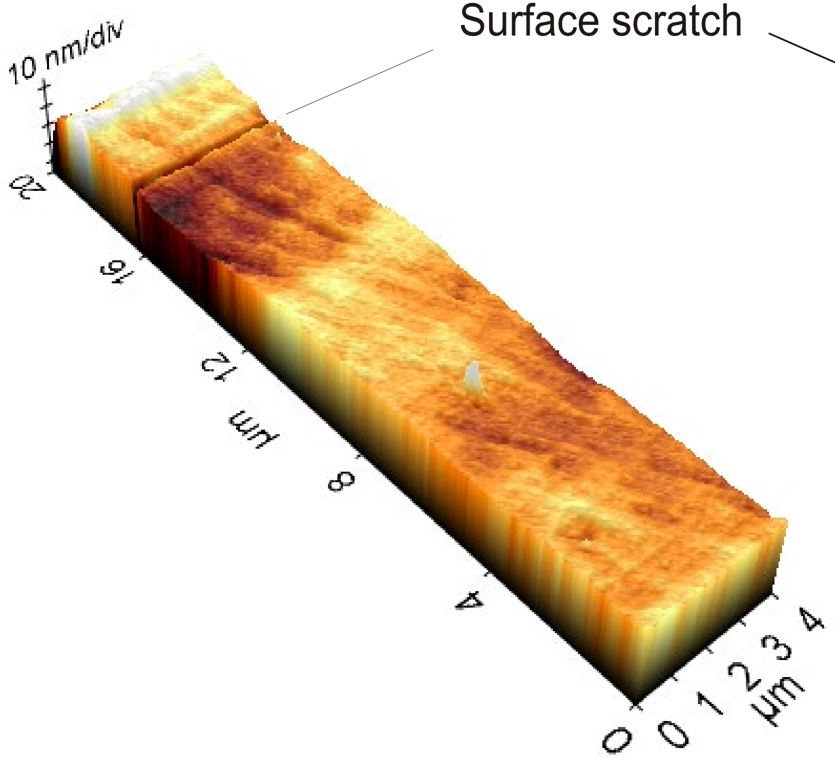


MFM image, Zip Disk 40 x 40 µm

Source : AFM workshops (TM)

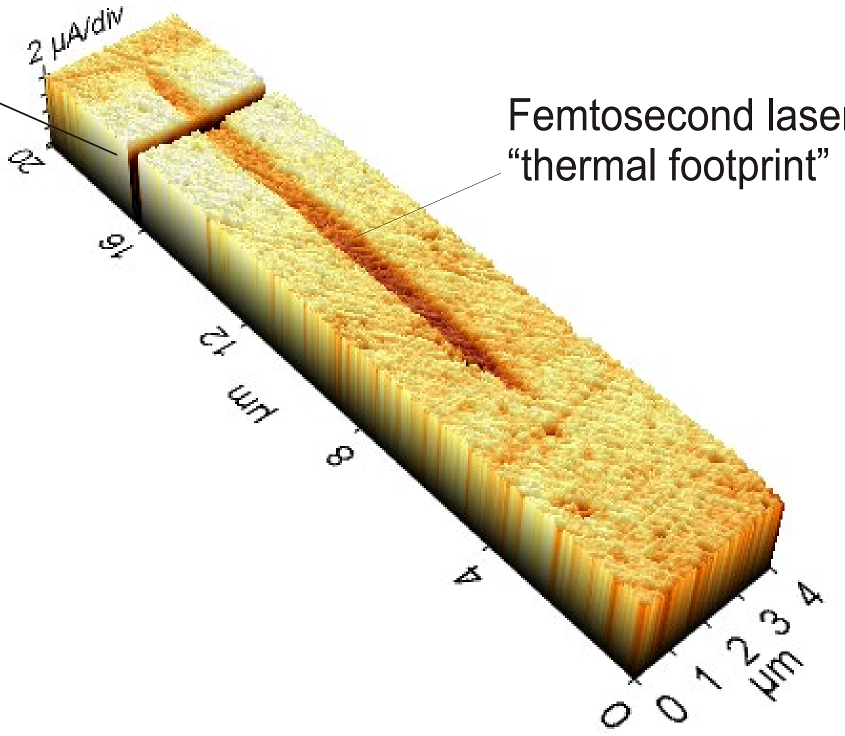
Illustration 3: Waveguide in a glass substrate

Topographic image



Surface scratch

Thermal conductivity map

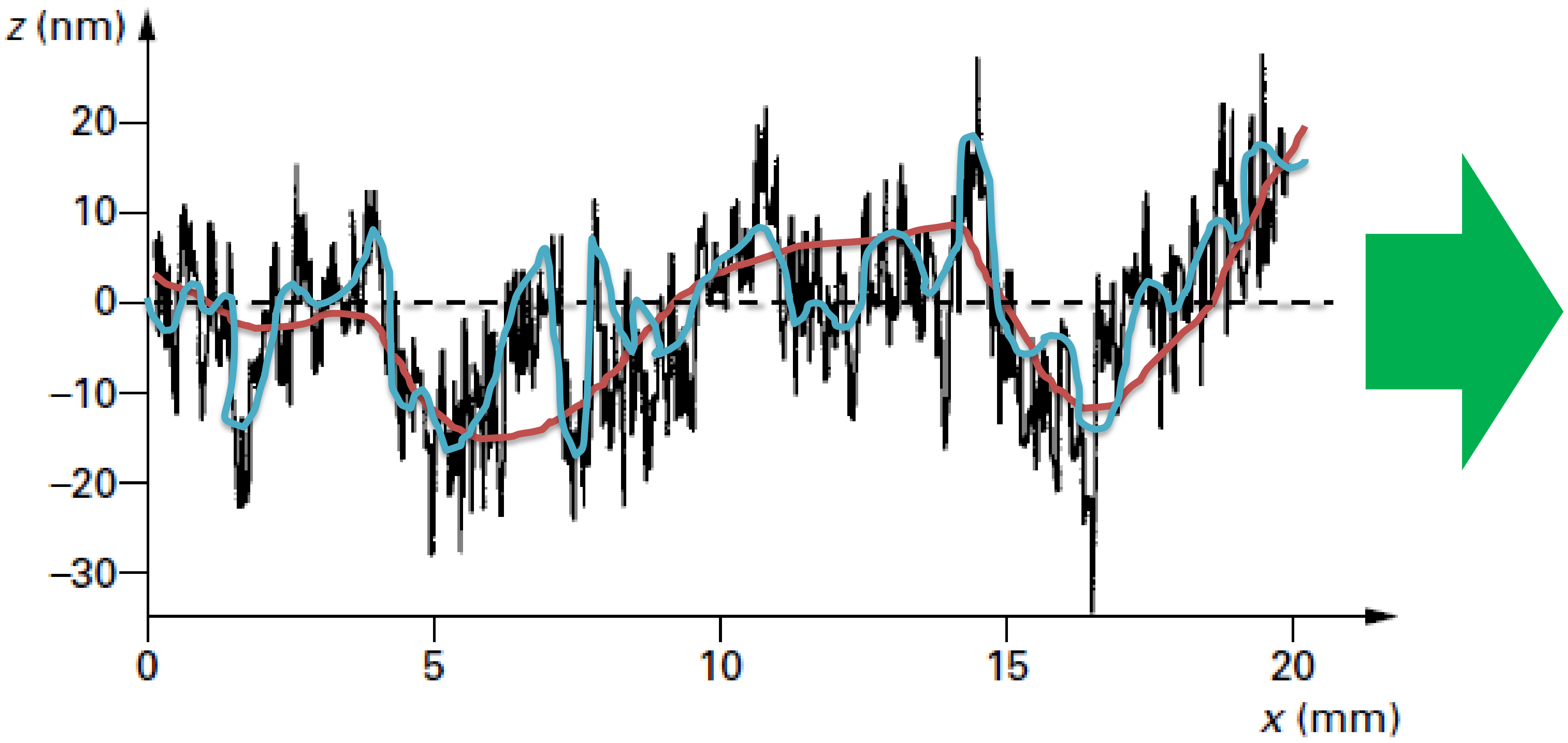


Femtosecond laser
“thermal footprint”

Y. Bellouard et al, Appl. Phys. Lett. 89, 161911 (2006).

‘Geometrical characteristics’ / Topography

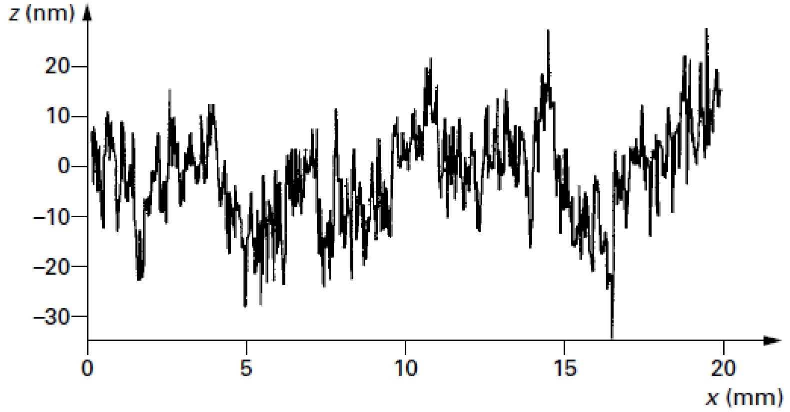
Problem statement



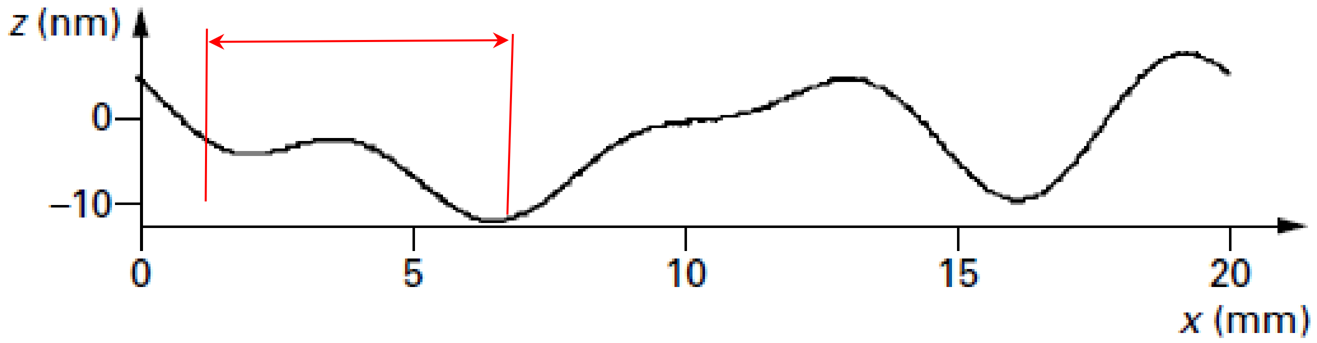
Signal processing methods

(adapted from P. Bouchareine, Techniques de l'ingénieur)

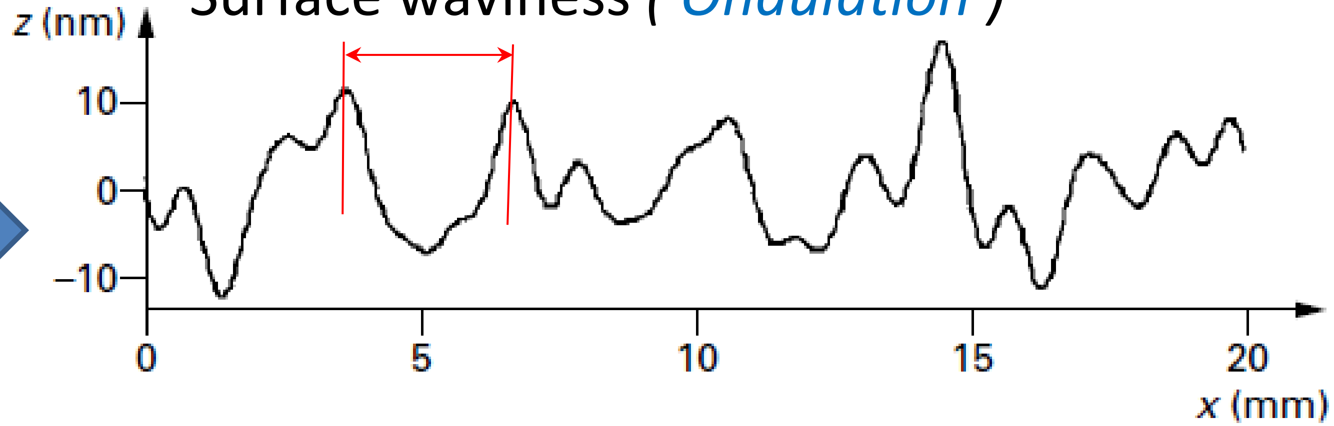
Spectral decomposition



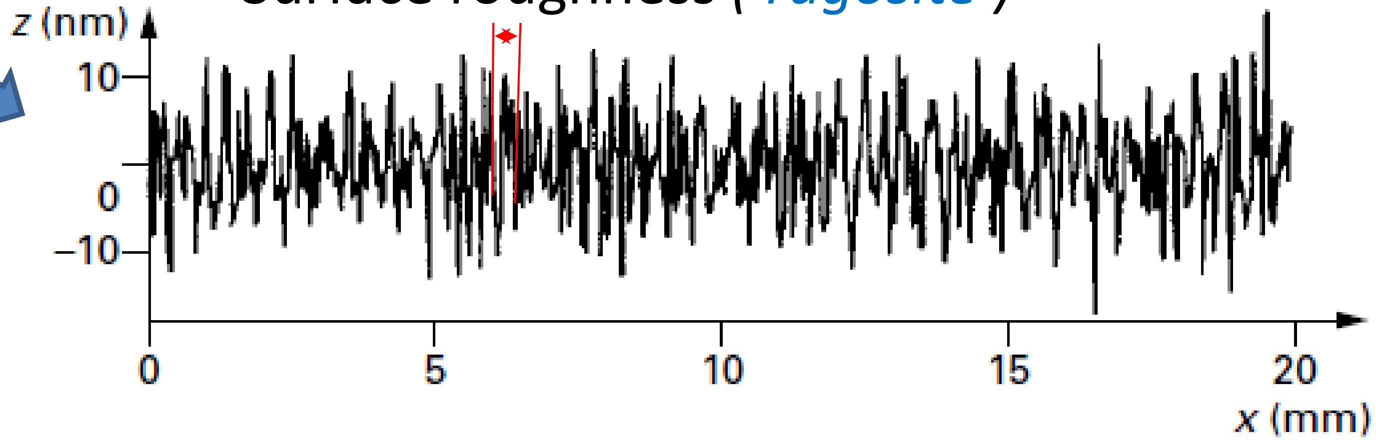
Surface profile deviation (*'Ecart de forme'*)



Surface waviness (*'Ondulation'*)



Surface roughness (*'rugosité'*)

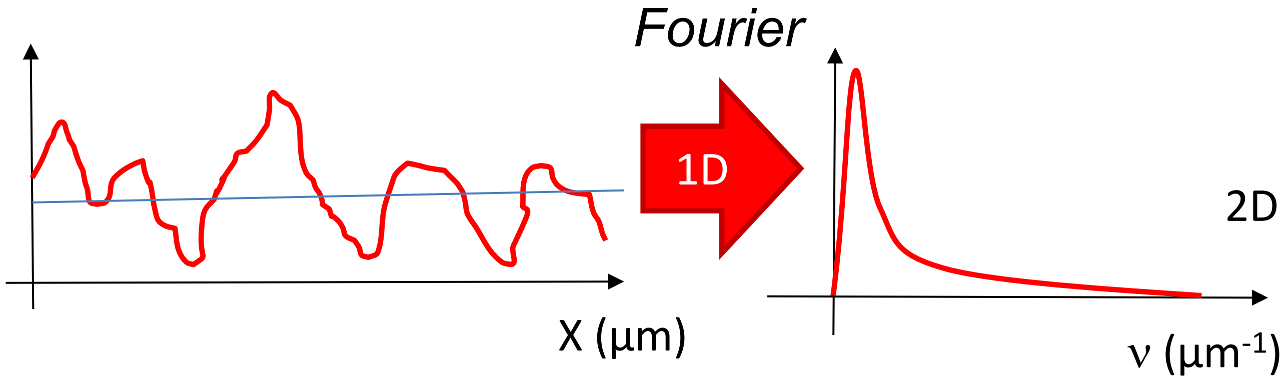


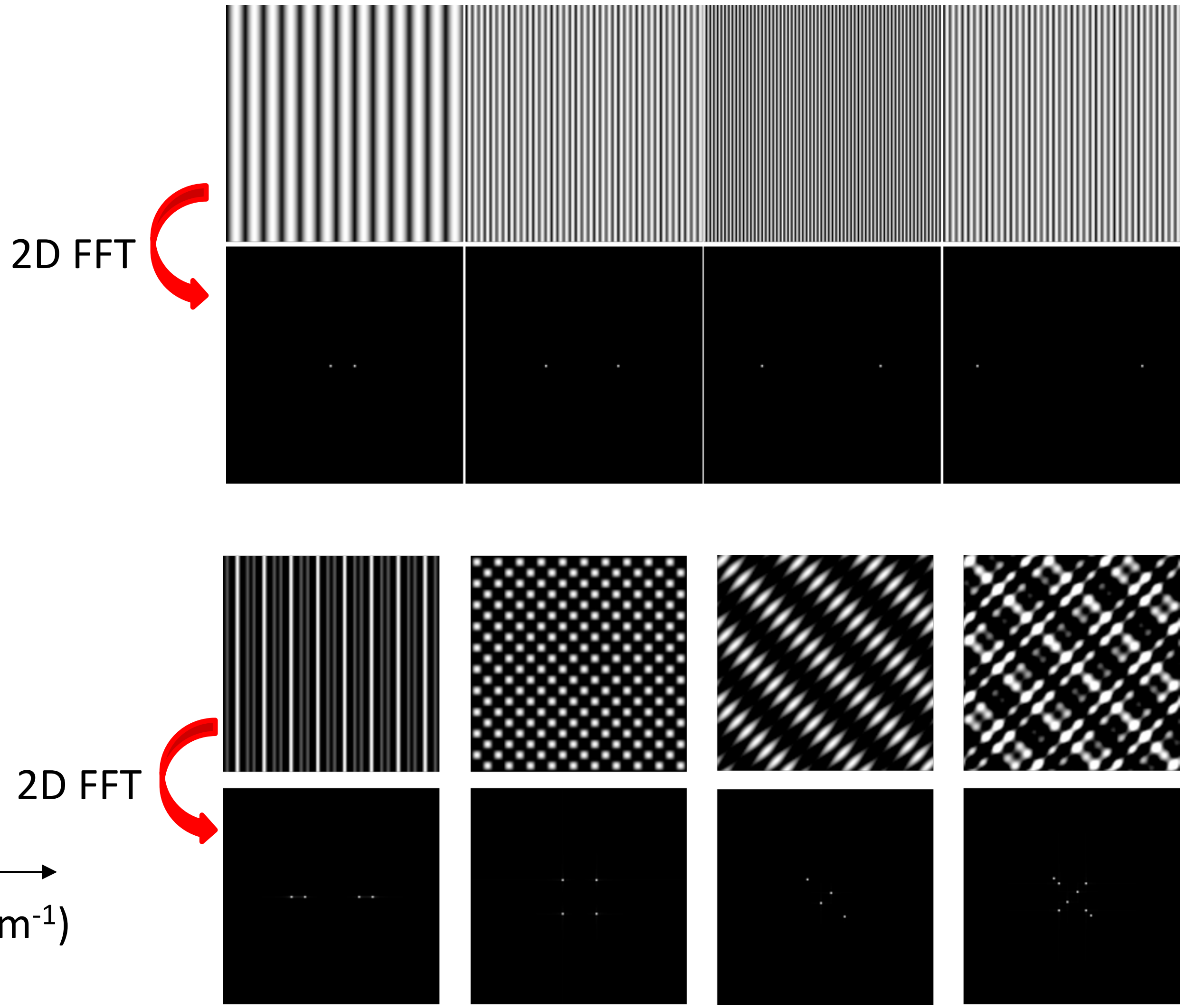
Towards higher spatial wavelength

Fourier analysis in the spatial domain

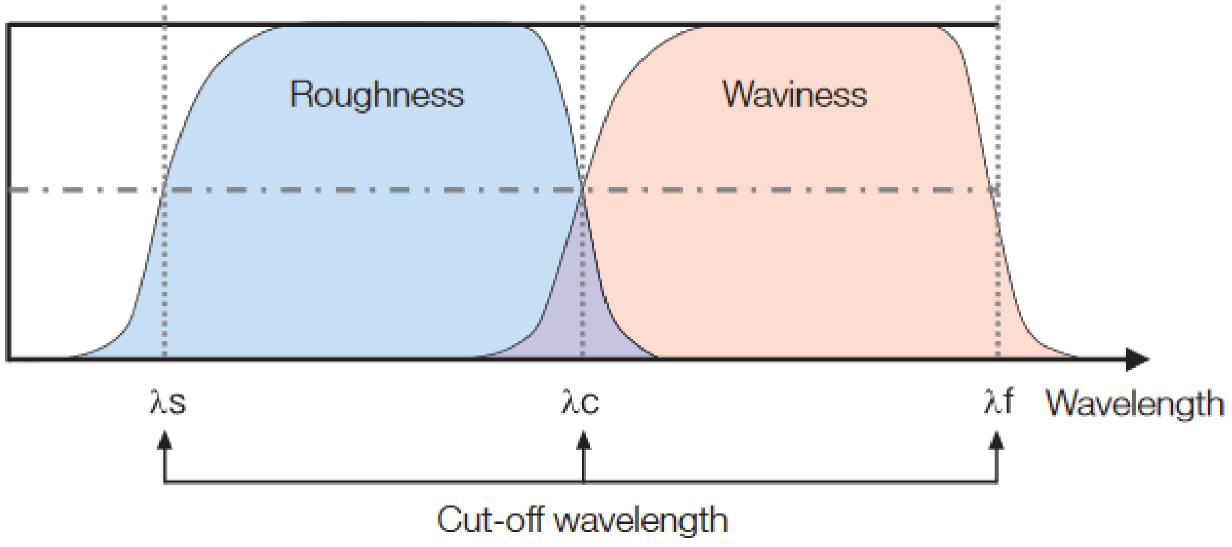
- Concept of spatial frequency
- 2D-Fourier transform

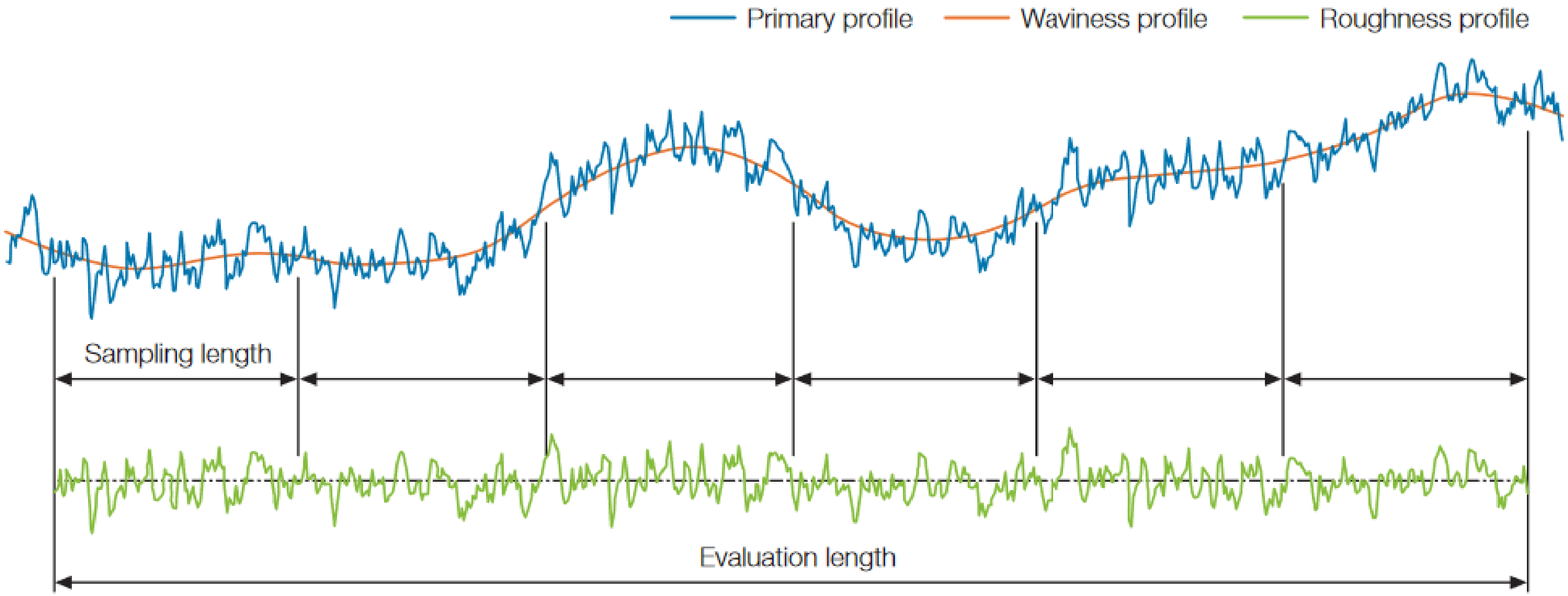
$$S(\nu,\omega)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} s(x,y)\,e^{-2\pi(\nu x+\omega y)}$$





Cut-off frequency





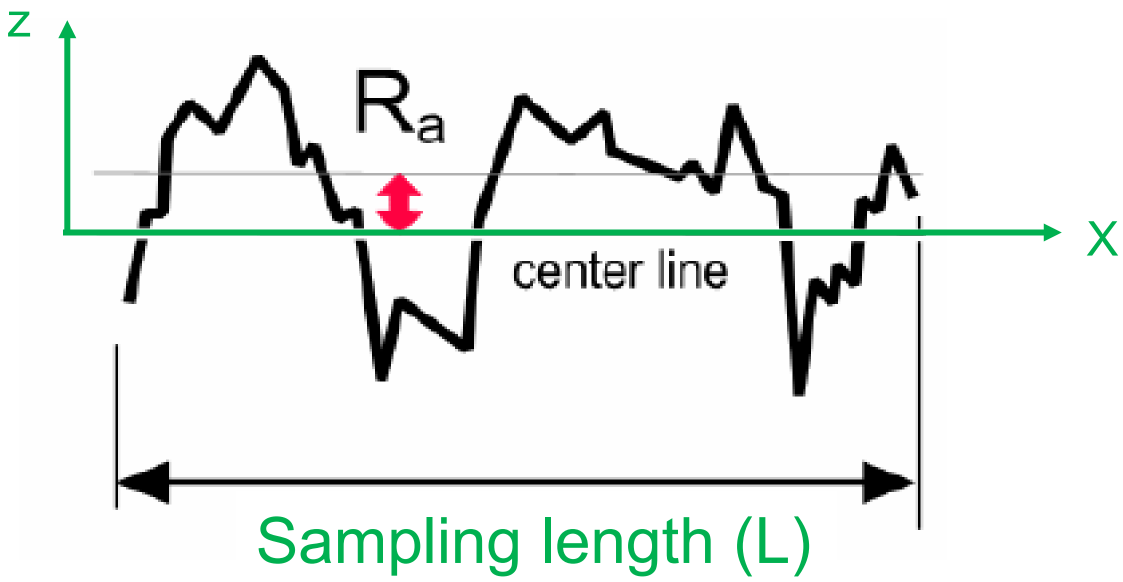
(adapted from Olympus corporation)

Why measuring/defining a surface topology?

- **Surface topography can have a strong impact on the part behavior!**
- Part manufacturing reproducibility / Process control: it tells us about how to the process is evolving / evidence of tool wears, etc.
- Wear state of a surface
- Conformability of a surface with respect to desired functionalities:
  - *Load capacity*
  - *Bearing / lubrication properties*
  - *Optical properties*
  - *Thermal properties, ...*
- It is a signature of a manufacturing process

A common surface metric: the arithmetic average (R_a)

- *A statistical parameters: arithmetic average*
- *Very used in industry!*
- *Often the only one you hear about…*



Sampling length

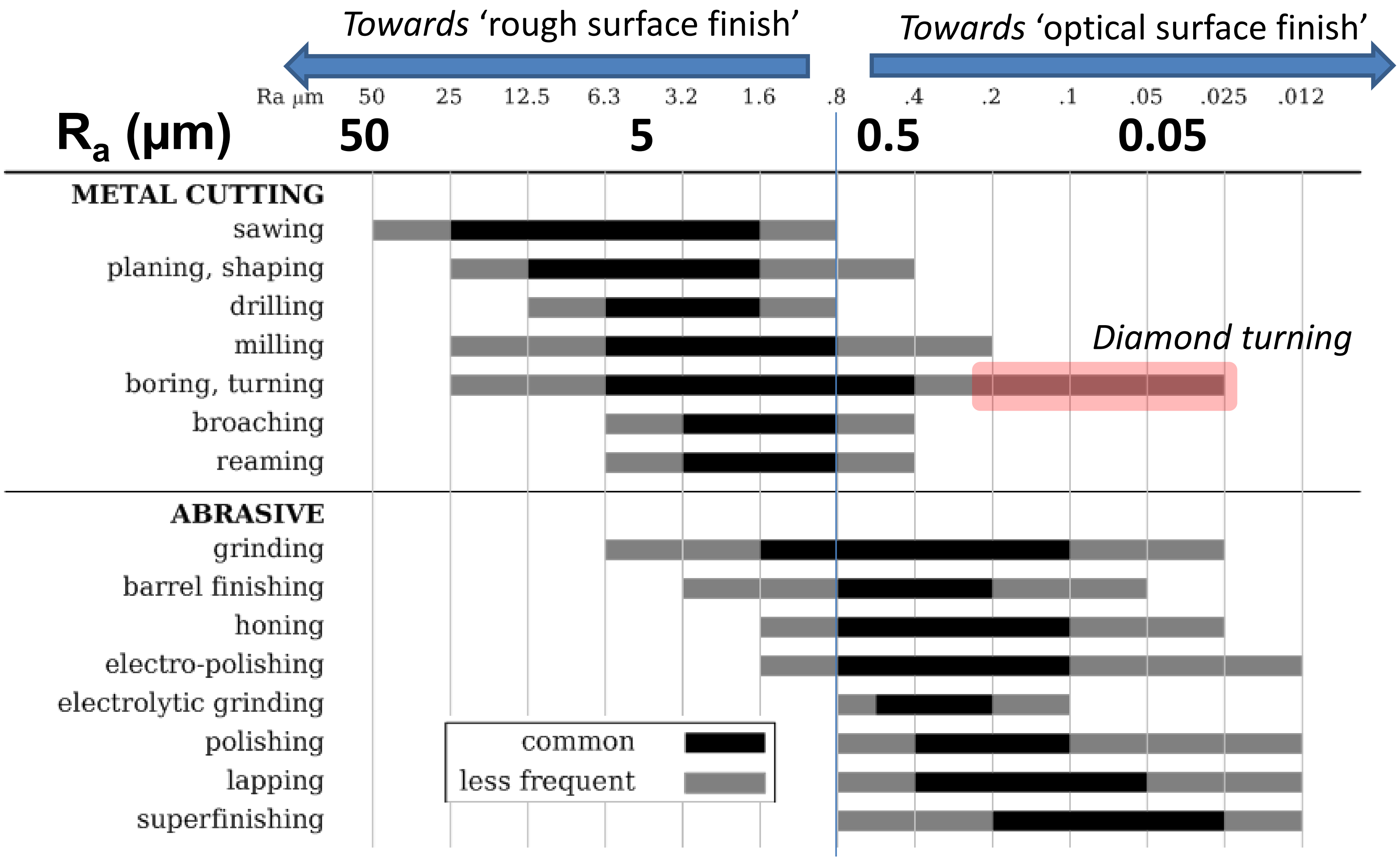
$$R_a = \frac{1}{L}\int_0^L |z(x)|\,dx$$

Profile amplitude

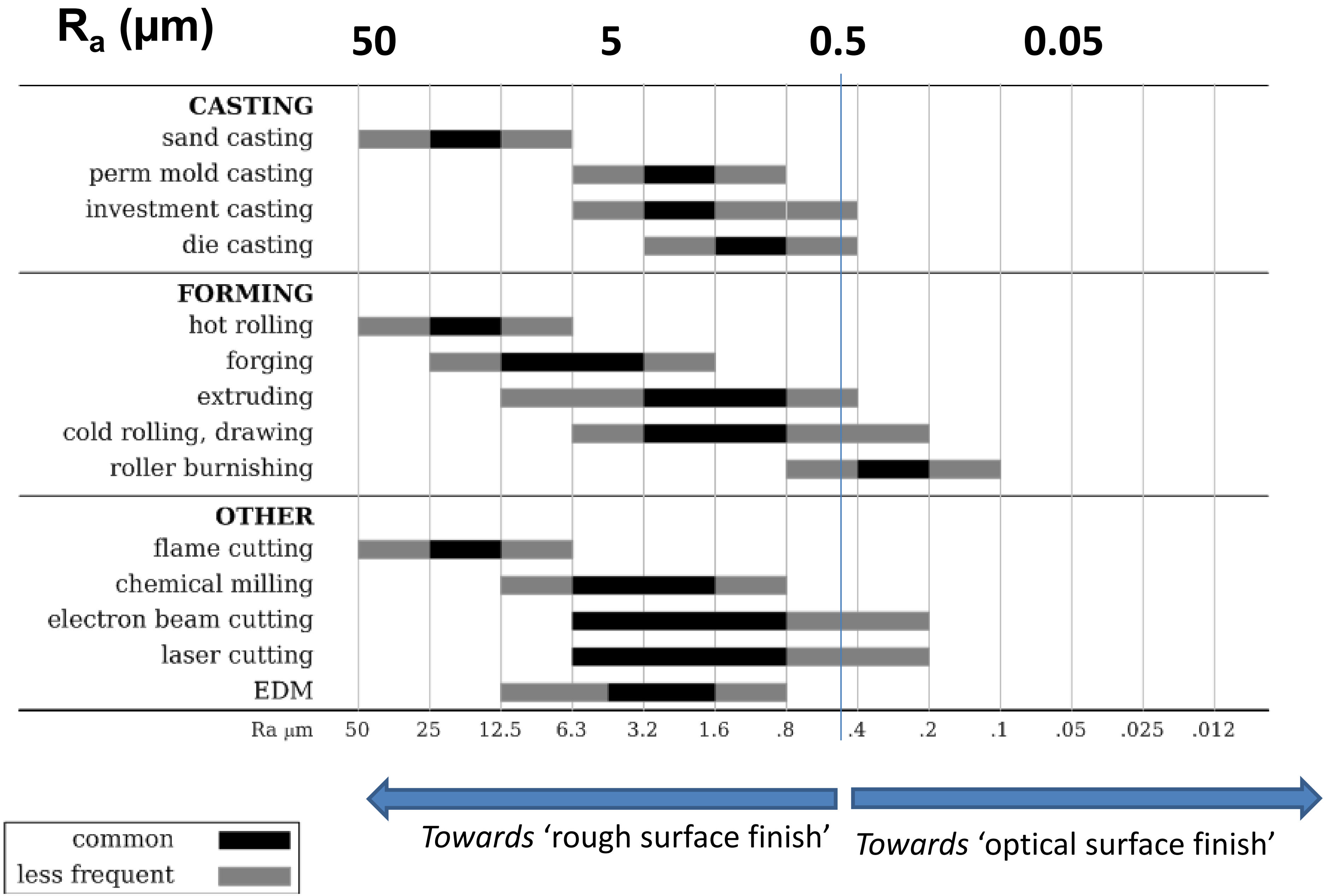
RMS roughness: $R_q = \sqrt{\frac{1}{L}\int_0^L z^2(x)\,dx}$

(illustration adapted from Zygo)

Typical surface finish for various manufacturing processes



(adapted from Emok, 2008)



(Adapted from Emok, 2008)

Same surfaces?

$R_a = 3.05$

$R_a = 3.08$

$R_a = 3.04$

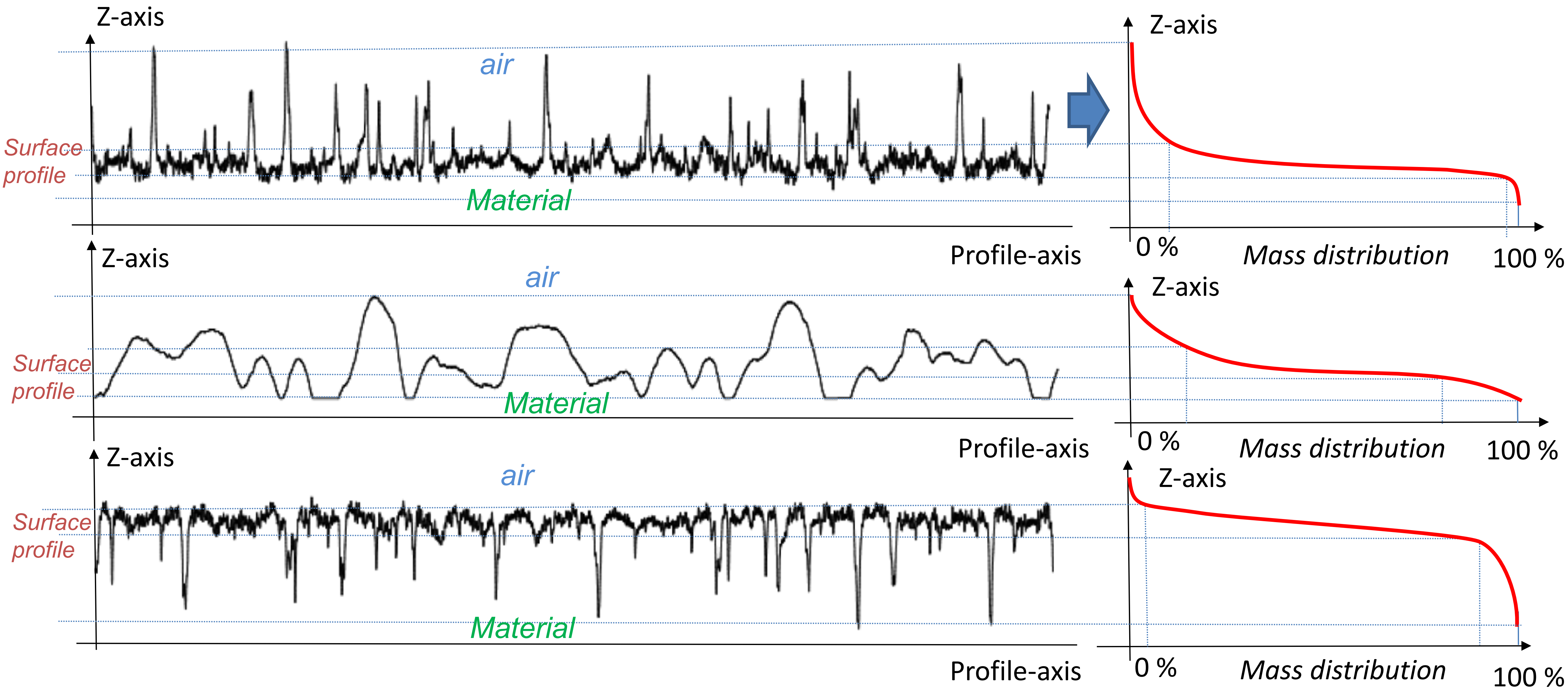
(Adapted from Mittutoyo, 'surface analysis')

Arithmetic averages (Ra or Rq) contains limited information

- Ra (Rq) are **informative** not sufficient to fully describe a surface.
  - It does not say much about the density of peaks
  - It does not tell anything about the shape of the peaks
  - Possible textures
- Manufacturing processes (wether by adding or removing materials) produce a typical surface topology that cannot be only characterized by the Ra.
- Additional surface metrics?

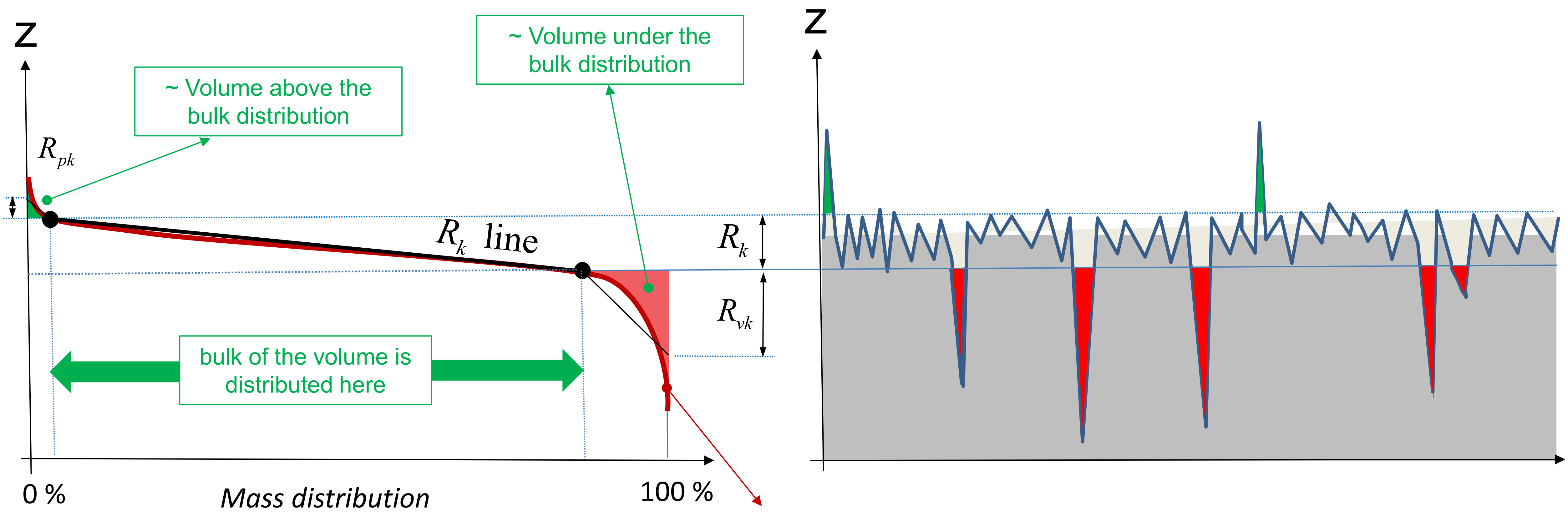
Tribology – Lubrication/Hermetic sealing

Materials ratio curve (‘Abbott-Firestone’ curve): Concept



Interpretation

- Useful for understanding the properties of sealing / bearing surfaces
- Volume above to ensure peak less surface (abrasive mode)
- Volume below are useful for estimating valleys available for lubricant retention, heat dissipation, etc.



The curve tells how is the mass distributed as a function of the depth z

How surface topology parameters correlate with surface functionalities?

Illustration 1: surface roughness and mechanical strength

Influence of roughness on mechanical properties: example

- **Intuitive reasoning:** Lower roughness = more contact points, higher surface strength?

$$\sigma^2 = \frac{1}{L}\int_0^L Z^2 \, dx$$

	σ (µm)	β (µm)	σ/β	N	$N/(\sigma/\beta)^{1/2}$	Ψ	
						A	B
Fine Polishing	0,028	2 400	10^{-5}	9 000	0,073	0,16	0,027
Grinding	0,13	800	$1{,}6 \times 10^{-4}$	6 000	0,061	0,66	0,11
Turning	–	60	0,05	3 400	0,045	11,7	1,9

Contact radius (β)

Contact points (N)

'Plasticity index' (Ψ)
(<1, 'elastic behavior'; >1, 'plastic behavior')

A: Steel / Stainless steel

B: Steel / Nitrured steel (surface treatment)

Examples taken from G. Béranger, H. Mazille, Techniques de l'Ingénieur

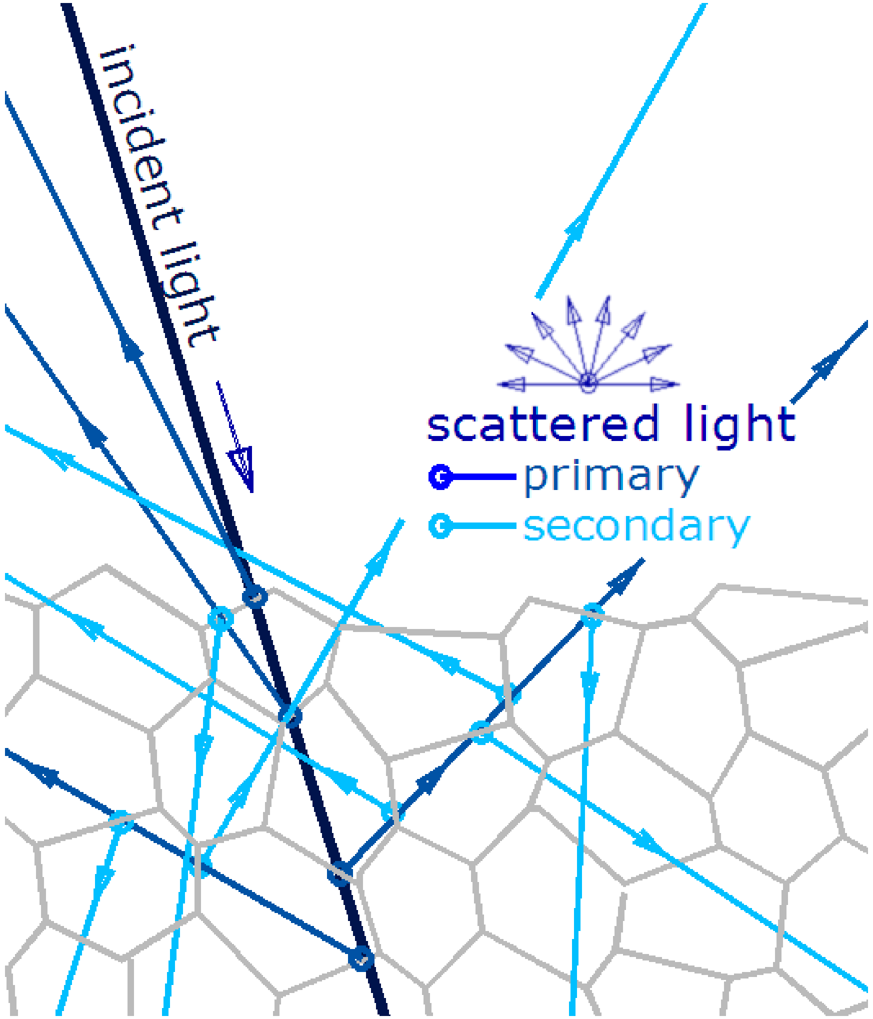
Illustration 2: surface roughness and optical reflectance

A ‘visual’ example: relation between roughness and optical properties

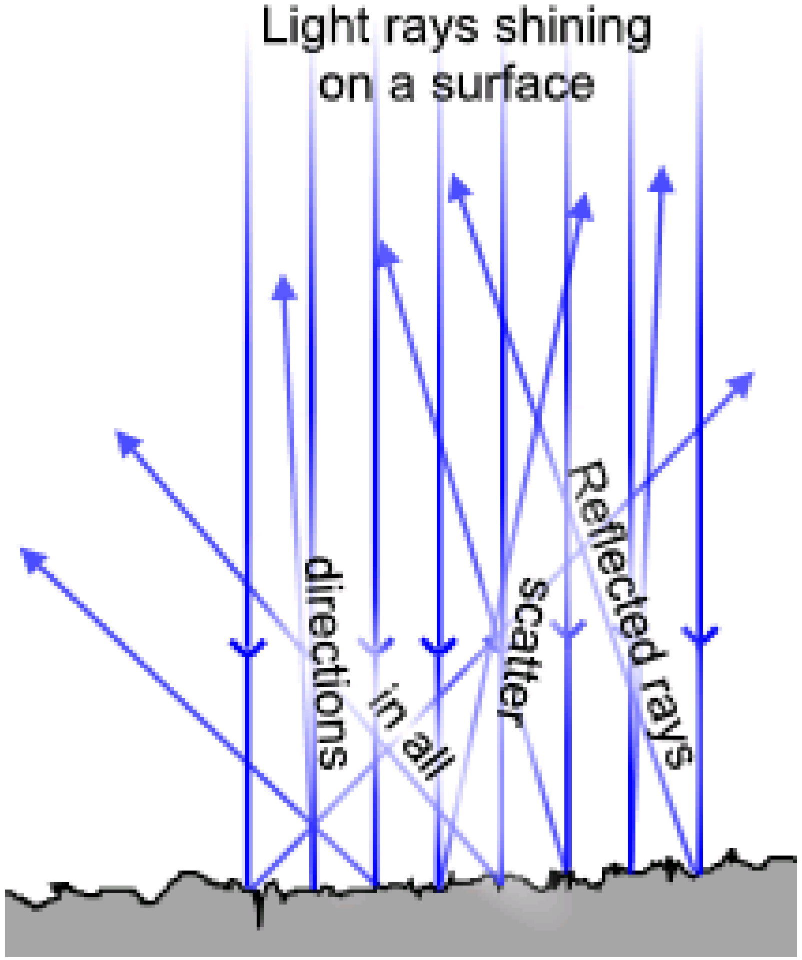
Diffusive surface

Non-Diffusive Surface (**specular** reflection-transmission)

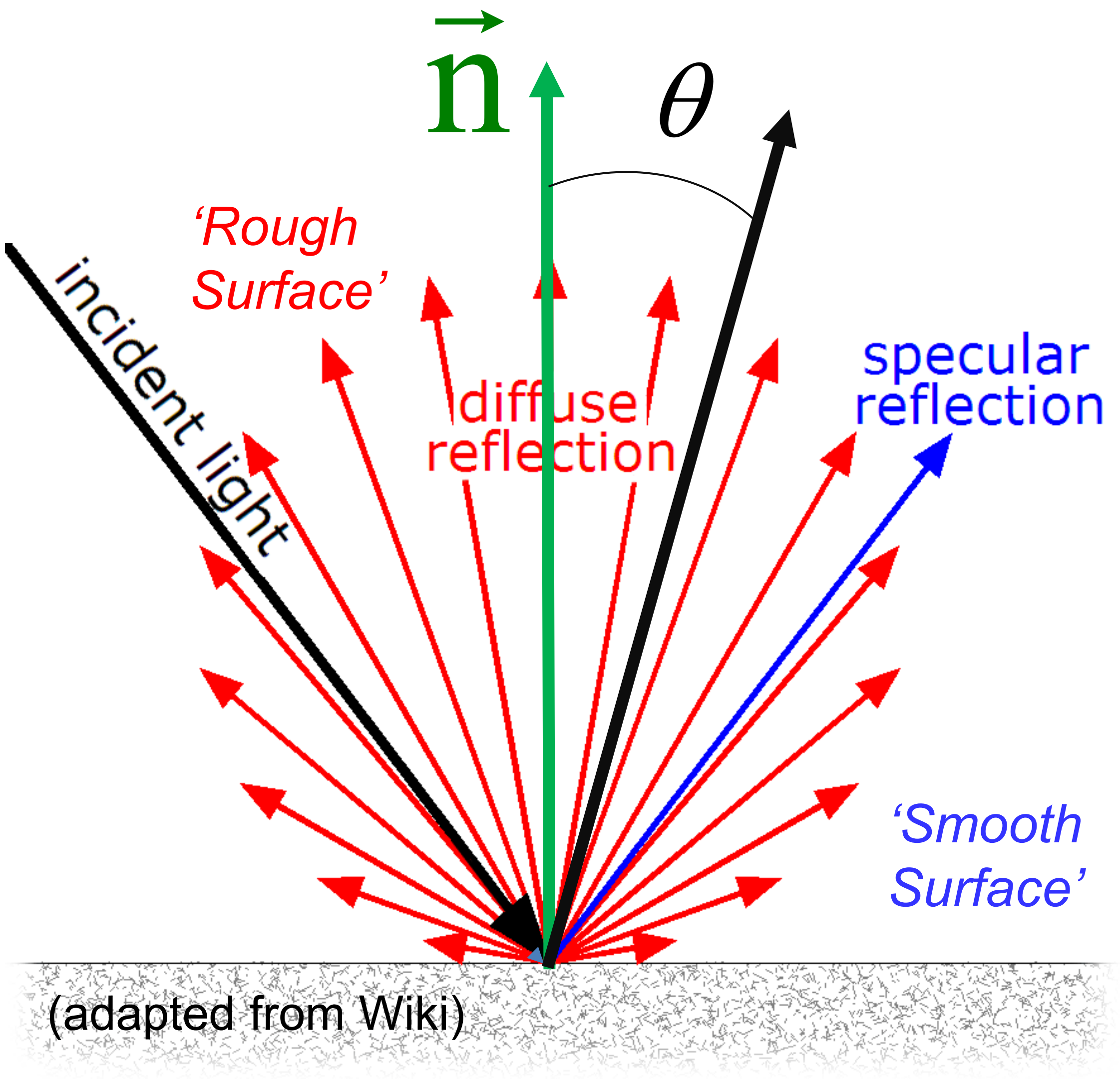
Phenomenological understanding of diffusion effects



(source Wiki)



Diffuse reflection: Lambert model



$$I_d(\theta) \propto I_0 \cos\theta$$

The diffuse reflection at an angle from the normal of the surface is proportional to the cosine of this angle.

Johann Heinrich Lambert (1728–1777)

How ‘smooth’ should a surface be?

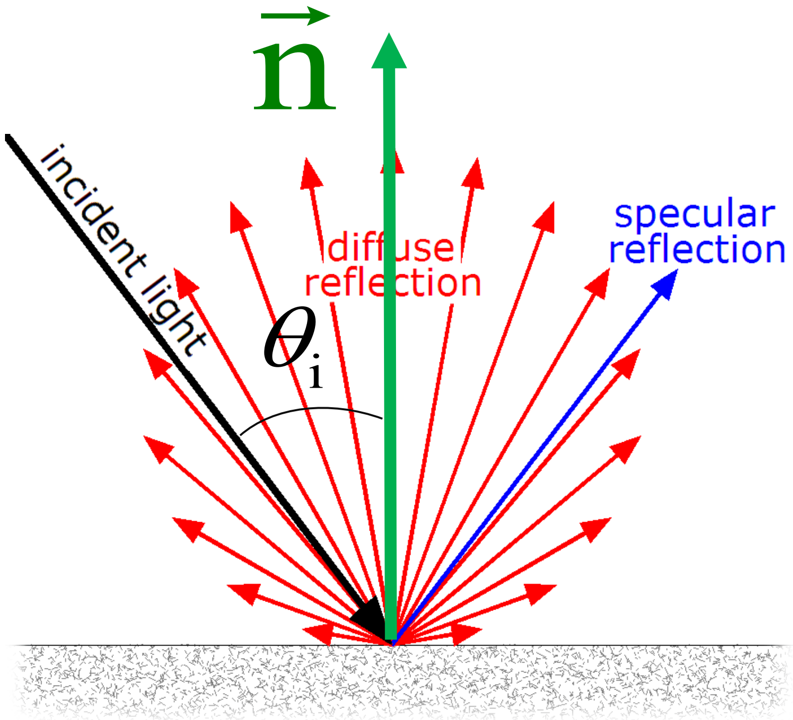
Bennett and Porteus model

$$R_s(R_q) = R_0\left(1 - e^{-\left[4\pi\left(\frac{R_q}{\lambda}\right)\cos\theta_i\right]^2}\right)$$

Total scattered reflection (R_s)

Theoretical reflectance (R_0)

Ratio of the roughness versus wavelength (R_q/λ)

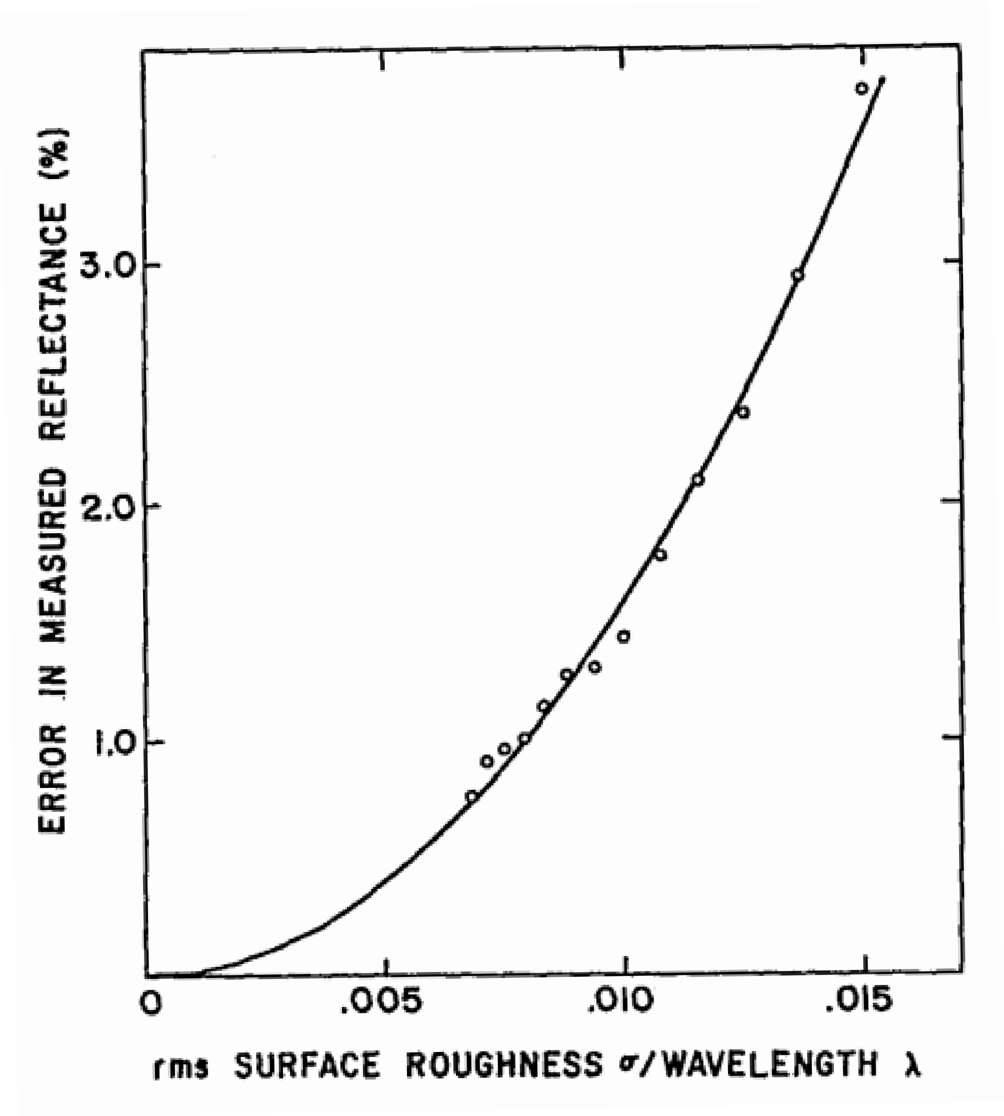


Bennett & Porteus, “Relation Between Surface Roughness and Specular Reflection at Normal Incidence,” JOSA 51, 123 (1961)

Observations

- Optical scattering is proportional to reflectance ⇔ surfaces that reflects light will scatter more light than transmissive surfaces.
- Scattered intensity is related to Rq
- Shorter wavelengths scatters more than longer ones.
- Light scatters more at normal incidence than grazing incidence

Importance

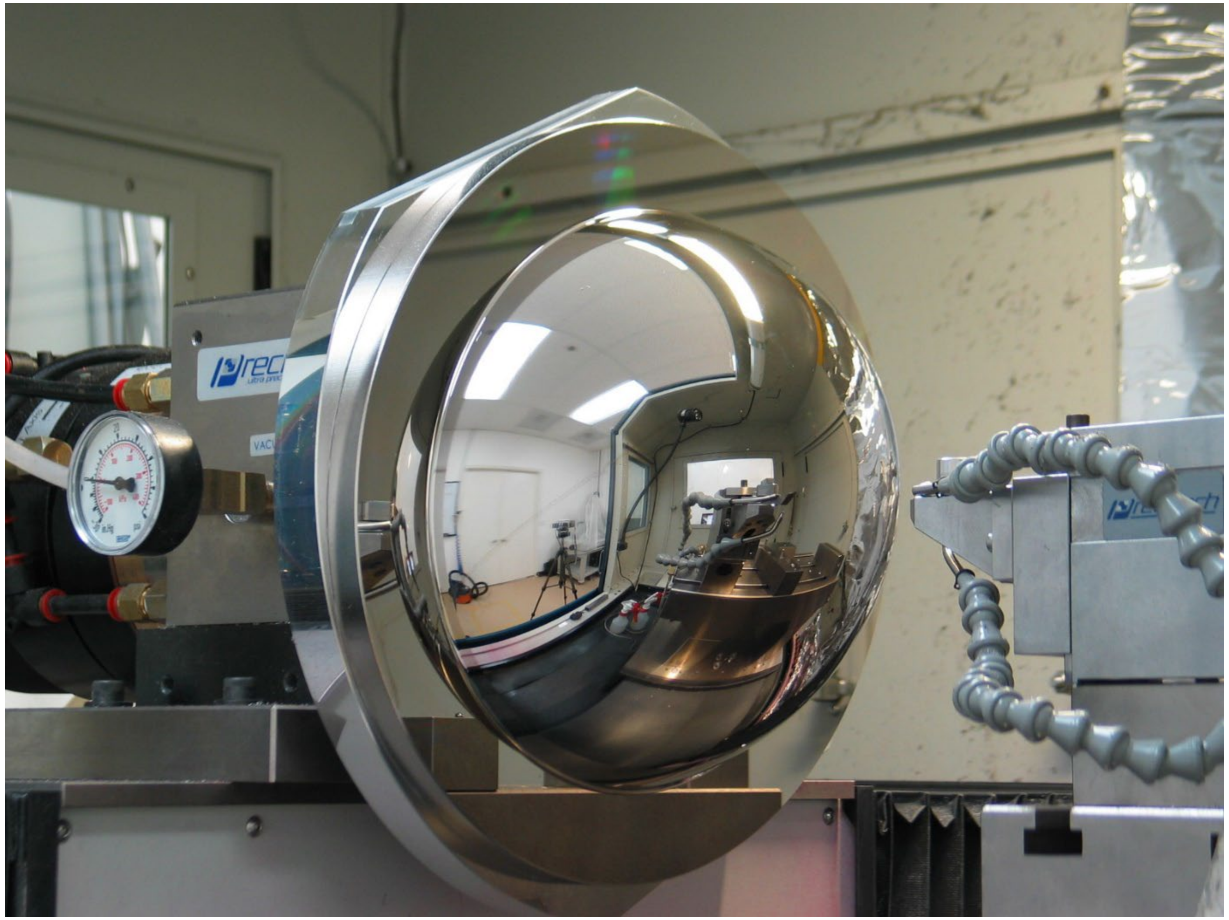


Rq = 25 nm scatters about 10% @ 500 nm !

Single Point Diamond turned surfaces can achieve Rq = 5 nm

Bennett & Porteus, "Relation Between Surface Roughness and Specular Reflection at Normal Incidence," JOSA 51, 123 (1961)

About diamond turning...



Source : NiPro

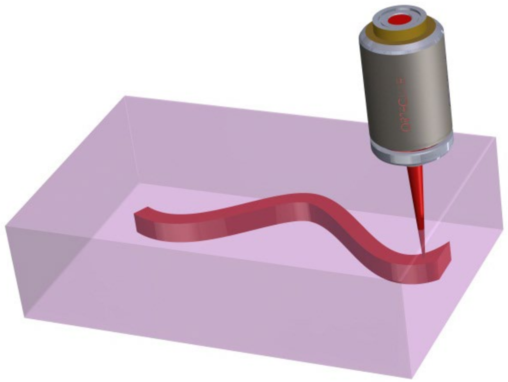
YouTube illustration from Thorlabs:

https://youtu.be/6iRohI_jaYg

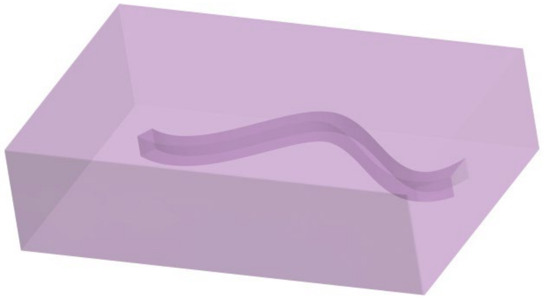
Illustration 3: effect of surface properties on fracture mechanics

3D machining illustration: two-step laser manufacturing

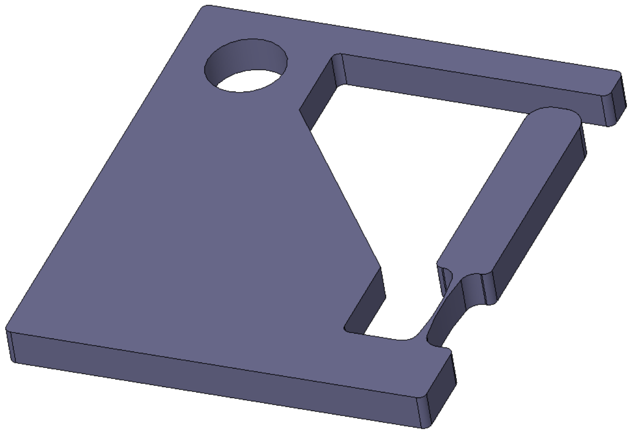
1/ Femtosecond laser exposure **(no ablation)**



2/ Chemical etching **(‘development step’)**



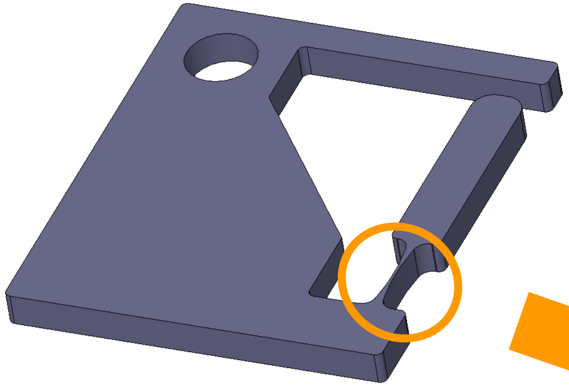
Arbitrarily shaped parts



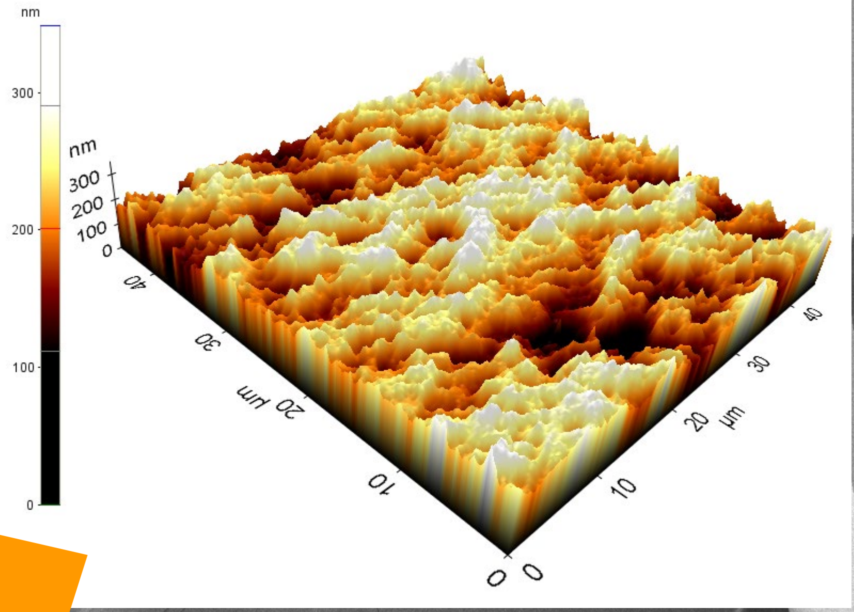
We will discuss it more in the laser-manufacturing lectures!

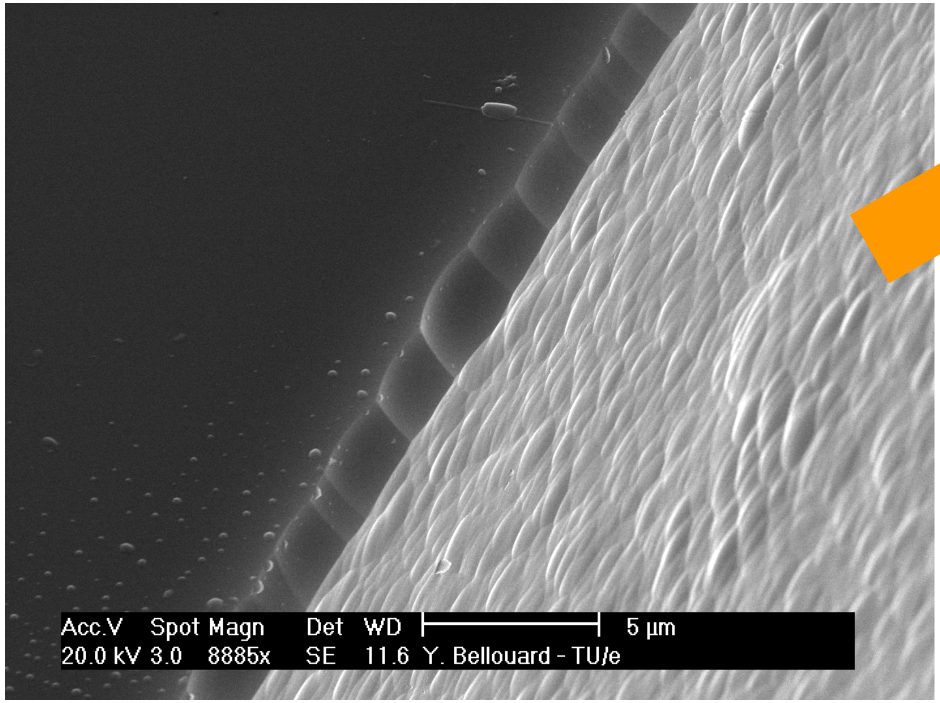
*Y. Bellouard, A. Said, M. Dugan, P. Bado, Optics Express, **12**, 2120-2129 (2004).*

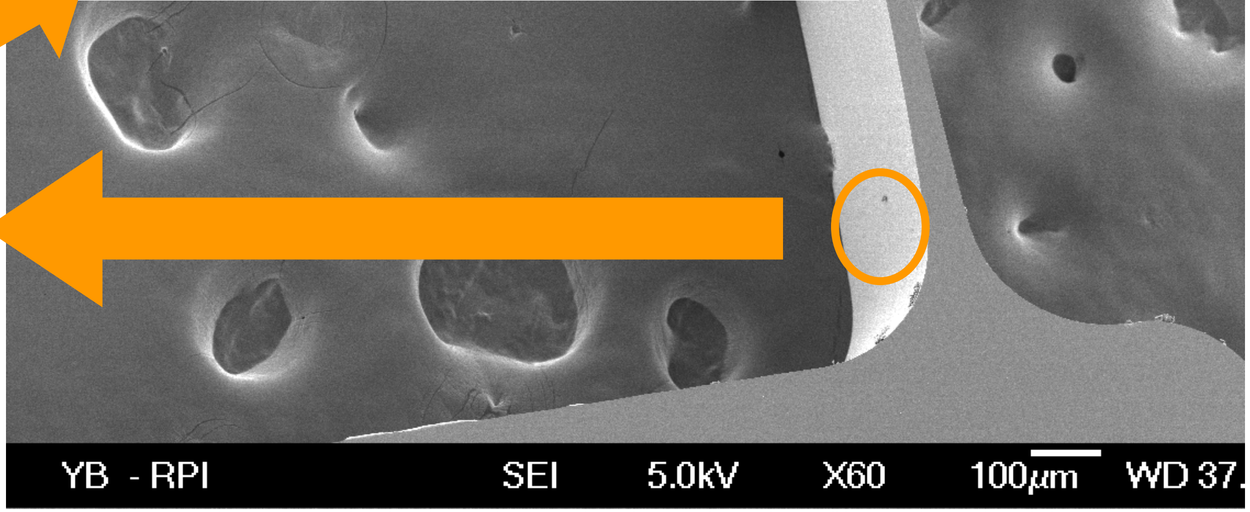
Micro-manufacturing illustration



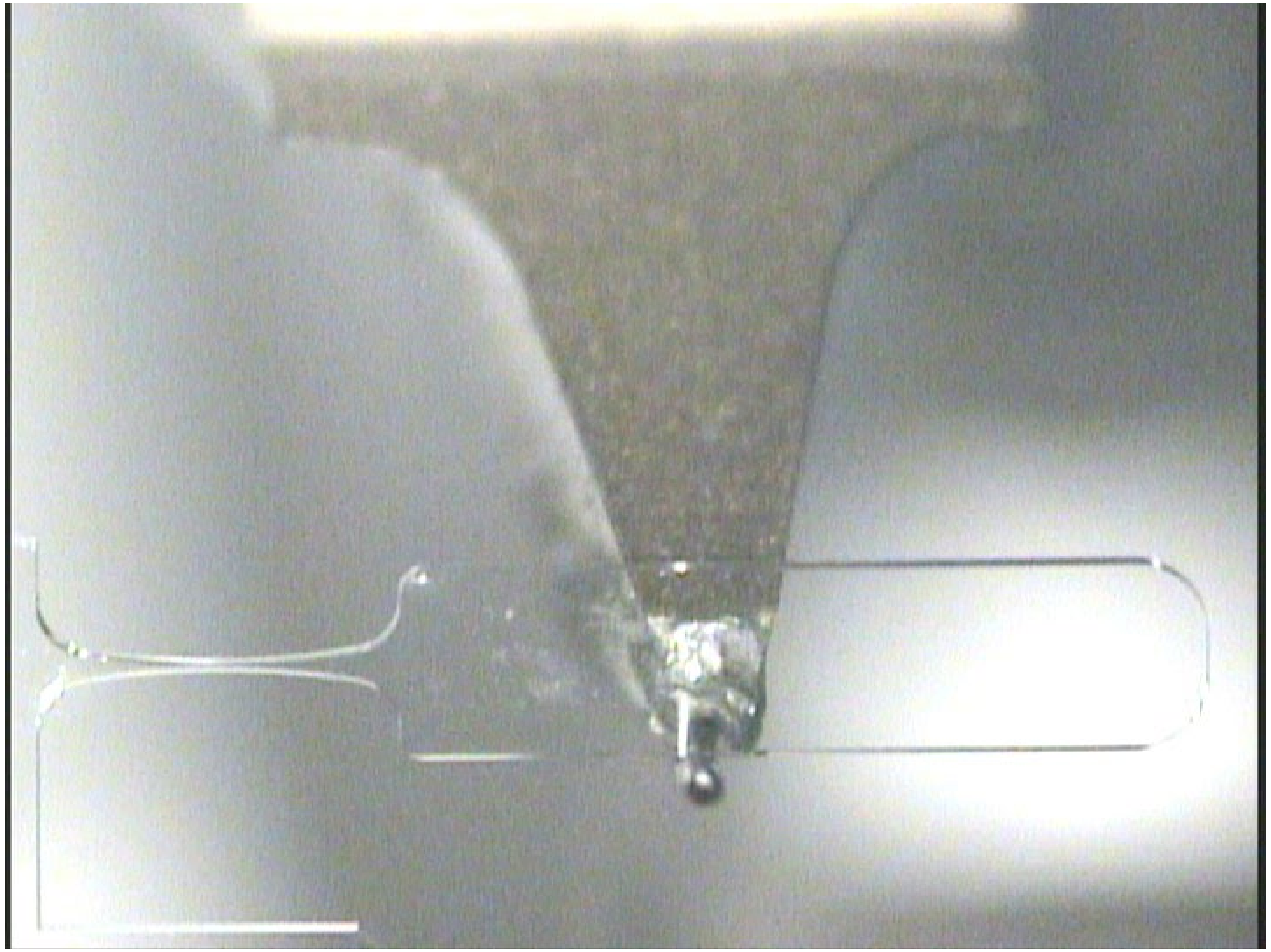
Roughness Rq (RMS) ≈ 200 - 300 nm



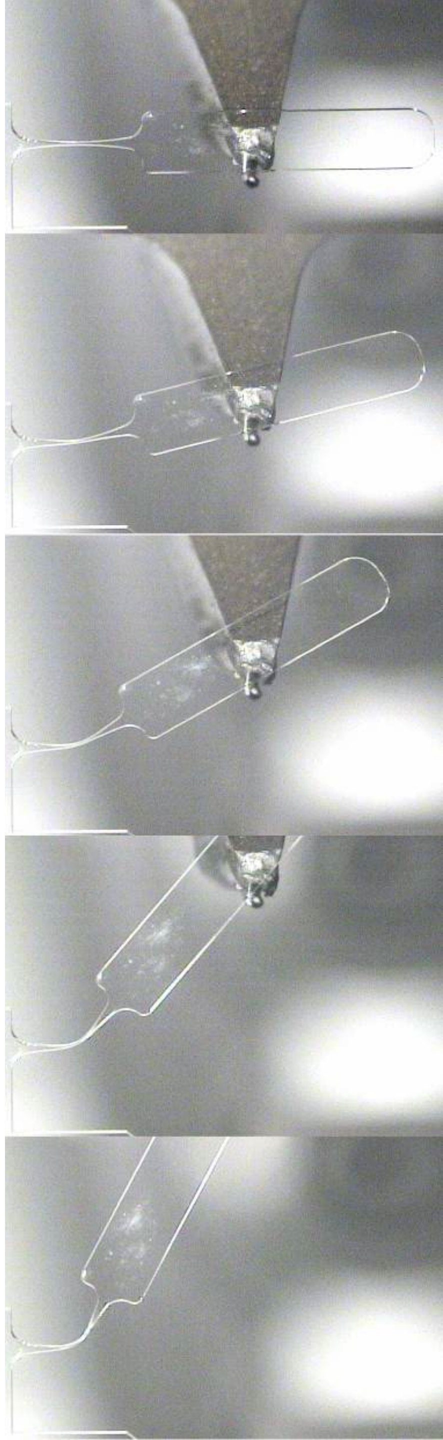




Glass flexure strength depends on etching time...

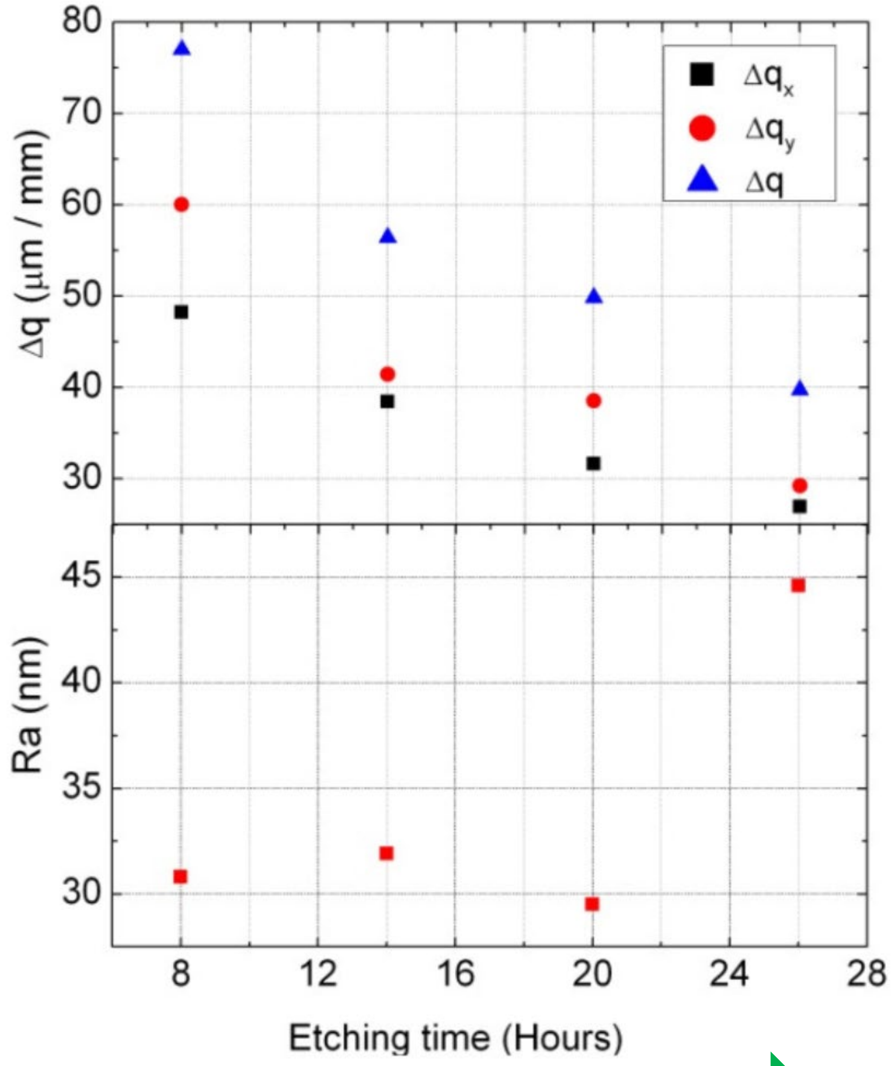


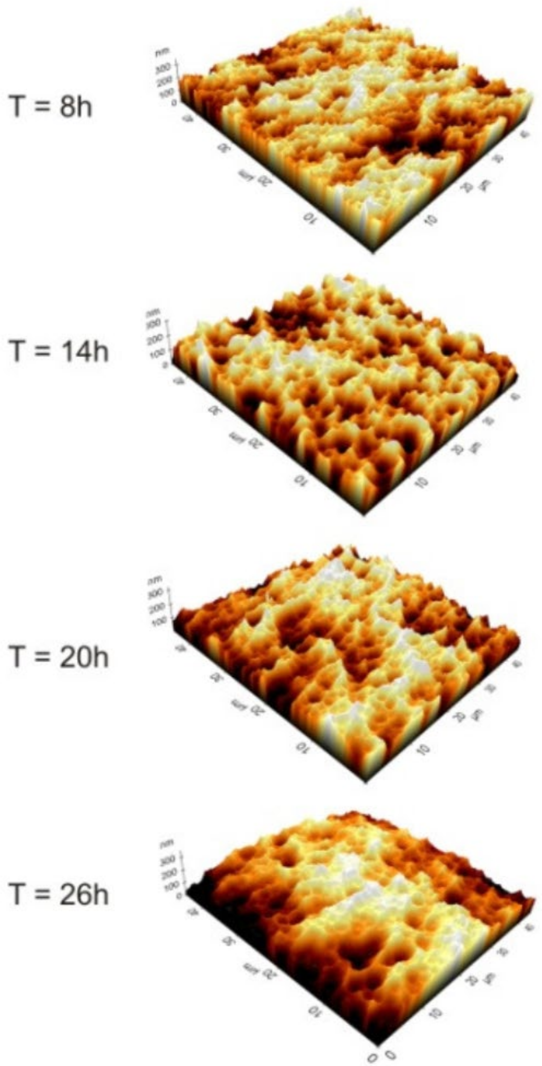
Stress locally well above 2 GPa!



Observation: The more we etch, the higher the strength. Why is it such?

Interpretation using surface parameters, hybrid parameters





RMS hybrid parameter

$$\Delta_q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{dy}{dx}\right)^2 dx}$$

Sampling length

Derivative of the profile ~Density of peaks

The arithmetic average roughness (Ra) **is not changing**, but the density of peak **decreases** (Δ_q)

Less peaks **>** Lower stress concentration **>** lower probability for glass failure

Example of a surface functional properties characterization: the hardness of a surface

Physical properties: hardness

- How do we quantify it?

Various metrics: **Vickers** (VH), Brinell, Rockwell, Knoop.

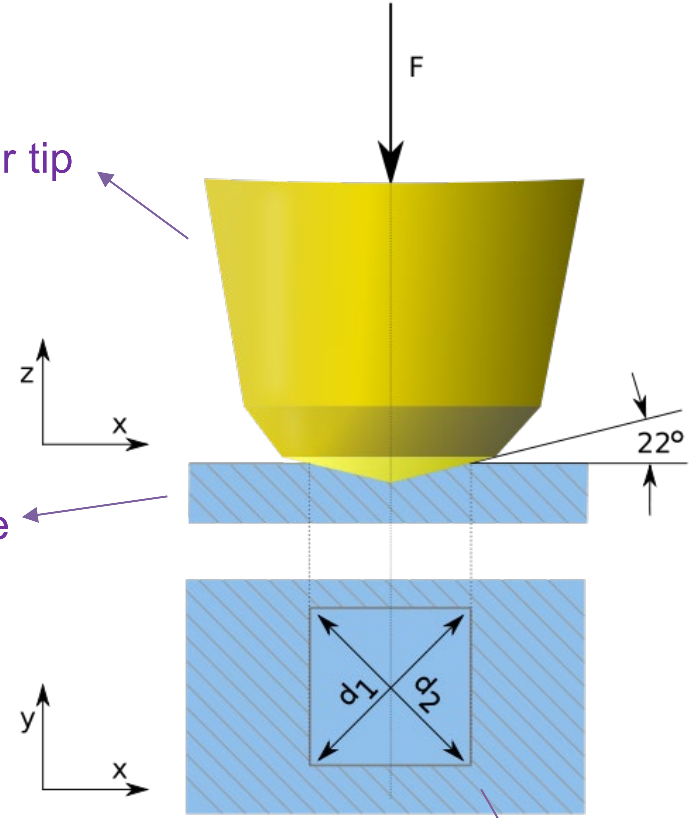
Most used!

Vickers hardness

Applied force

$$HV = C\left(\frac{F}{d^2}\right) \quad with \quad C = 0.0189 \quad and \quad d = \frac{d_1 + d_2}{2}$$

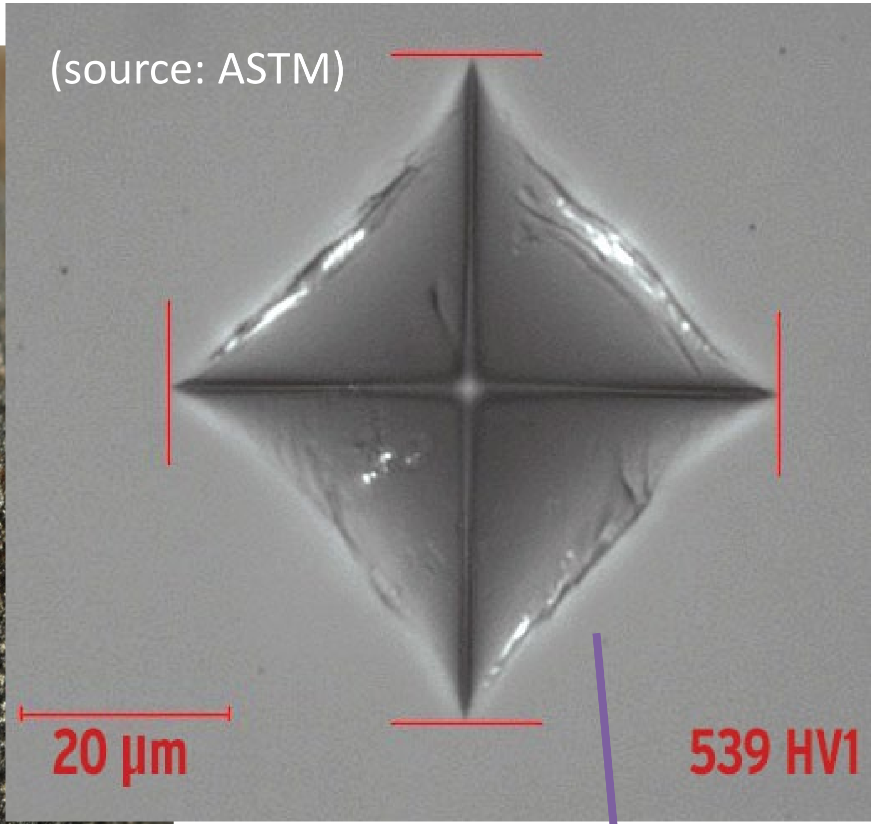
Geometry of the indenter



(source Wiki)

Footprint of the surface

In SI unit: **MPa**, but also expressed in HV (kgf/mm²) … (just divide by 9.807)

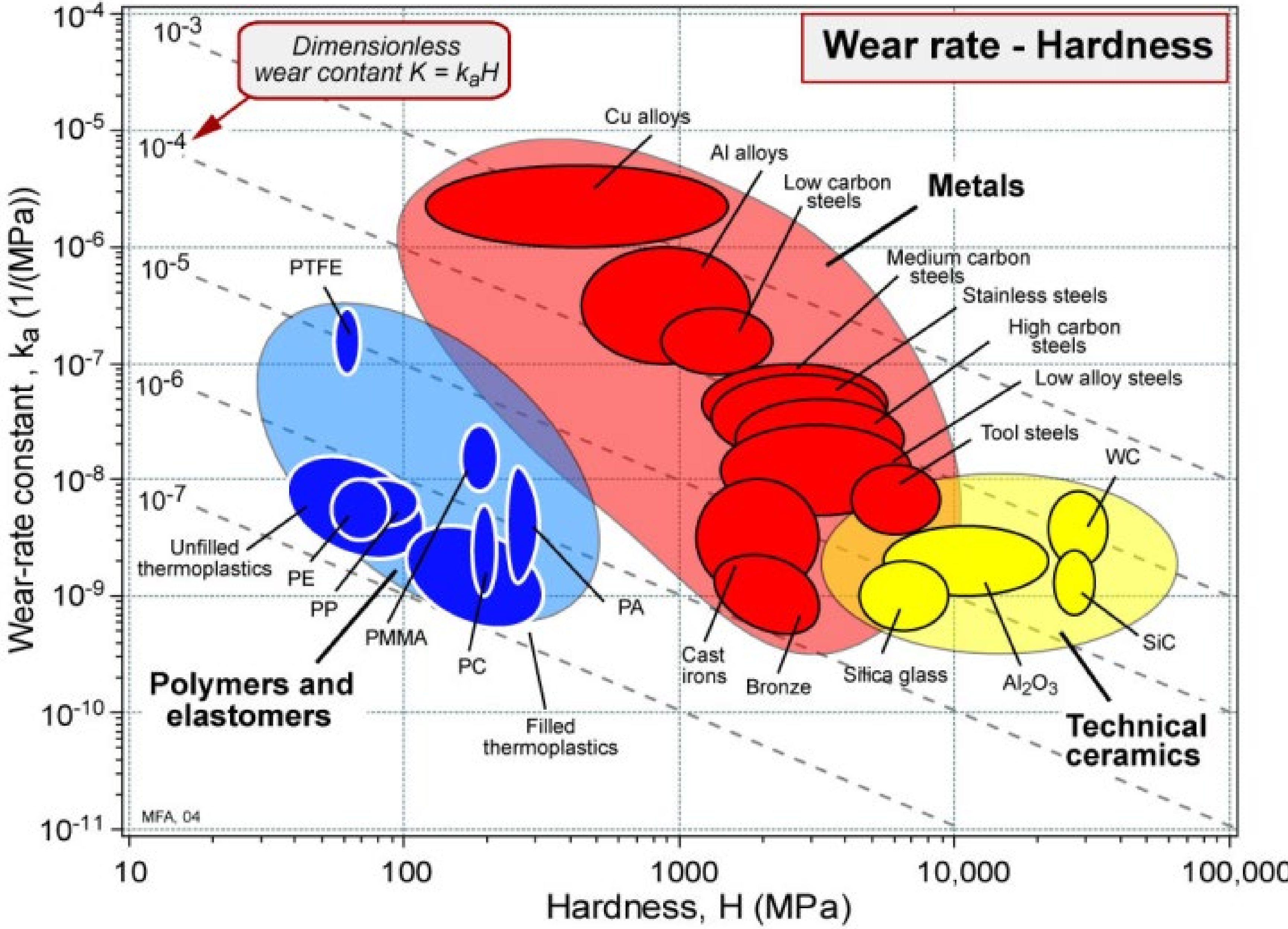


Indenter footprint on the surface

Source R. Tanaka - http://www.flickr.com/photos/fluor_doublet/6864844960/

Hardness versus wear rate plot

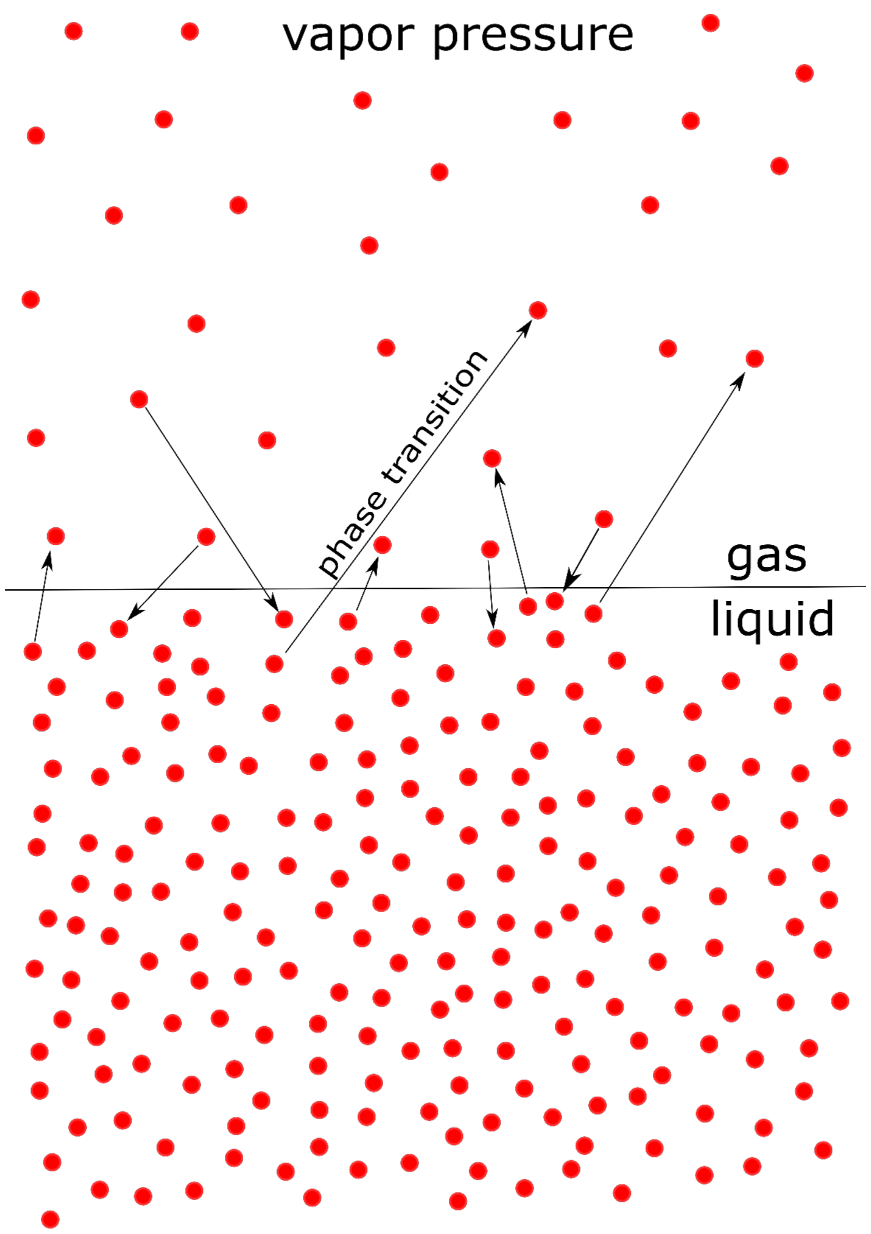
Perhaps counter-intuitive: the higher the hardness does not necessarily mean the most wear-resistant!



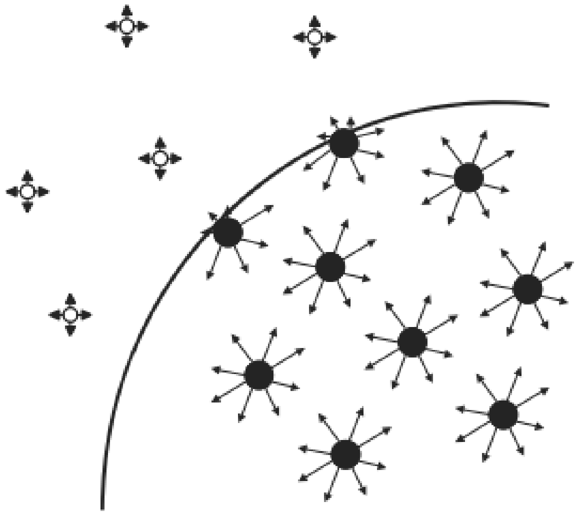
(source Ahsby)

Example of a surface functional properties characterization: wetting properties of a surface

Surface Tension



- Molecules of a liquid attract each others
  - Hydrogen bonding forces for polar molecules
  - Van der Waals forces for other molecules



Imbalance of this attractive force at an interface leads to ***surface tension***

Important definition: Surface Tension

Surface tension has units of **N/m (J/m²)**. If *S* is the total surface are of an interface and *γ* is the surface tension, then the total **energy stored** in the interface is

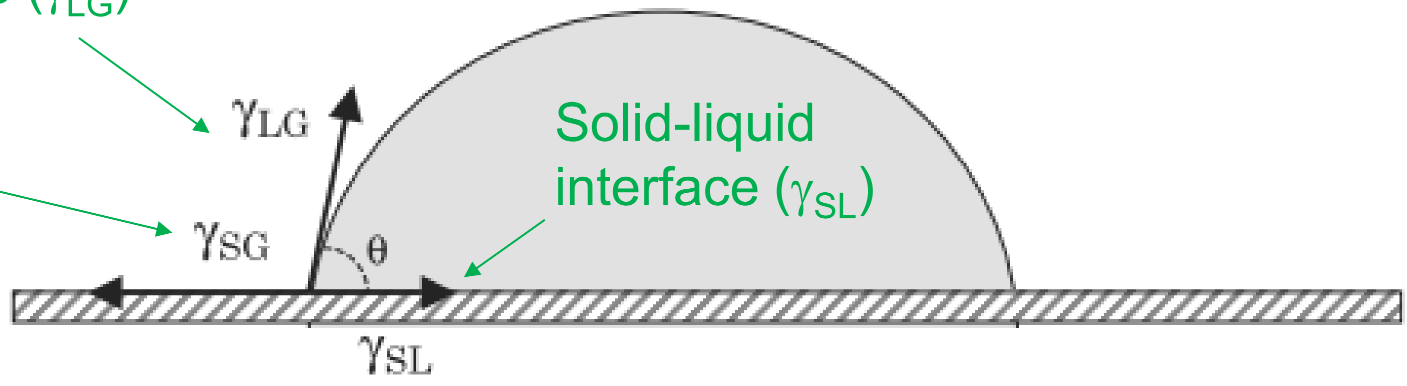
Surface tension N/m (J/m²)

$$E = \gamma S$$

Energy (J)

Surface (m²)

Wettability: Young's law



The **contact angle** at the intersection of three interfaces is entirely determined by balancing the **surface tensions** of each interface. ('Equilibrium of forces')

$$\gamma_{\text{Liq-Gas}} \cos\theta = \gamma_{\text{Sol-Gas}} - \gamma_{\text{Sol-Liq}}$$

*If θ > 90, the surface is said to be '**hydrophobic**'*
*If θ < 90, the surface is said to be '**hydrophilic**'*

Contact angle generally depends on the wetting history!

- Hysteresis in wetting
- Surface are not perfect and has defects
- The liquid has a certain mass / contacts may deform, etc.
- Concept of **advancing** and **receding** angles

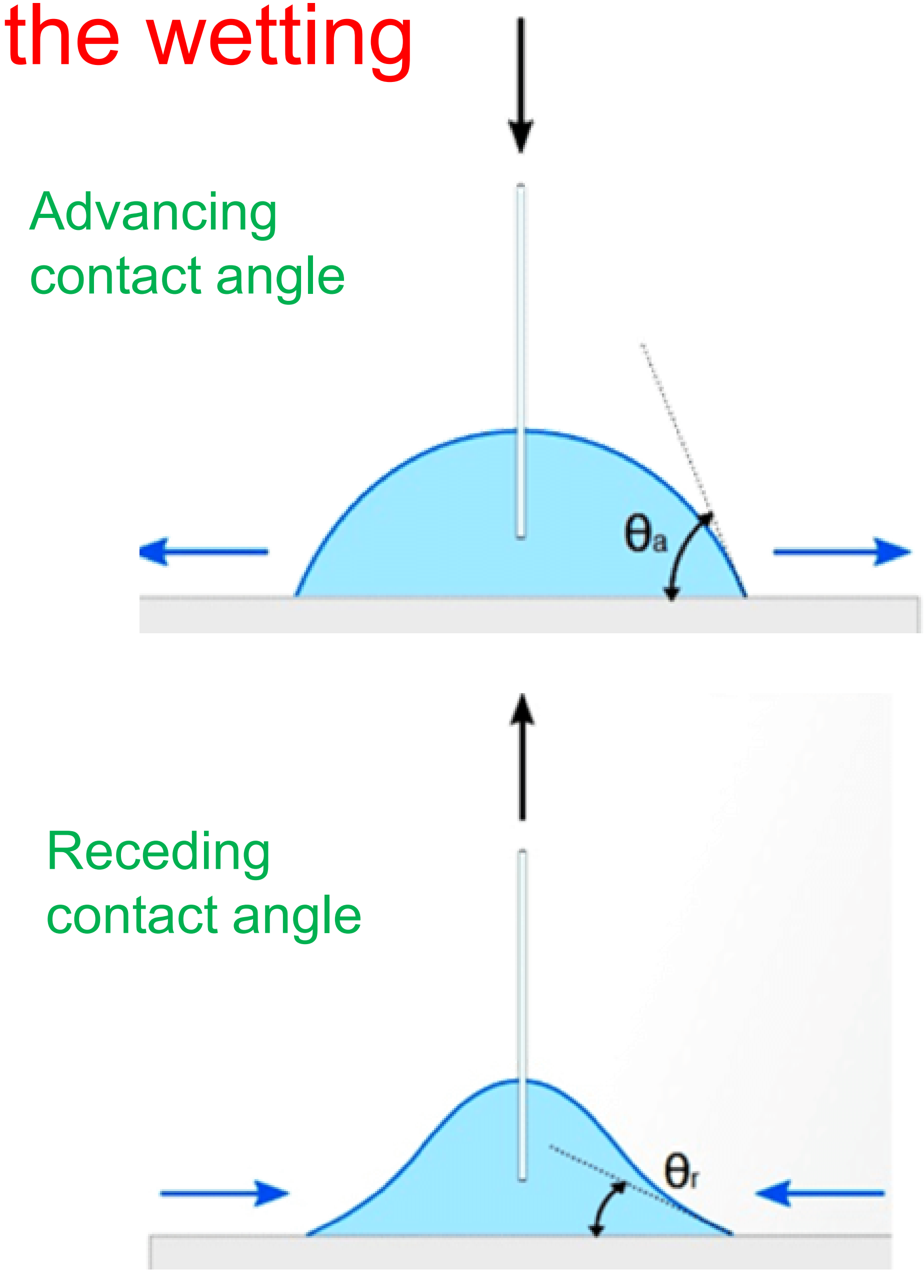
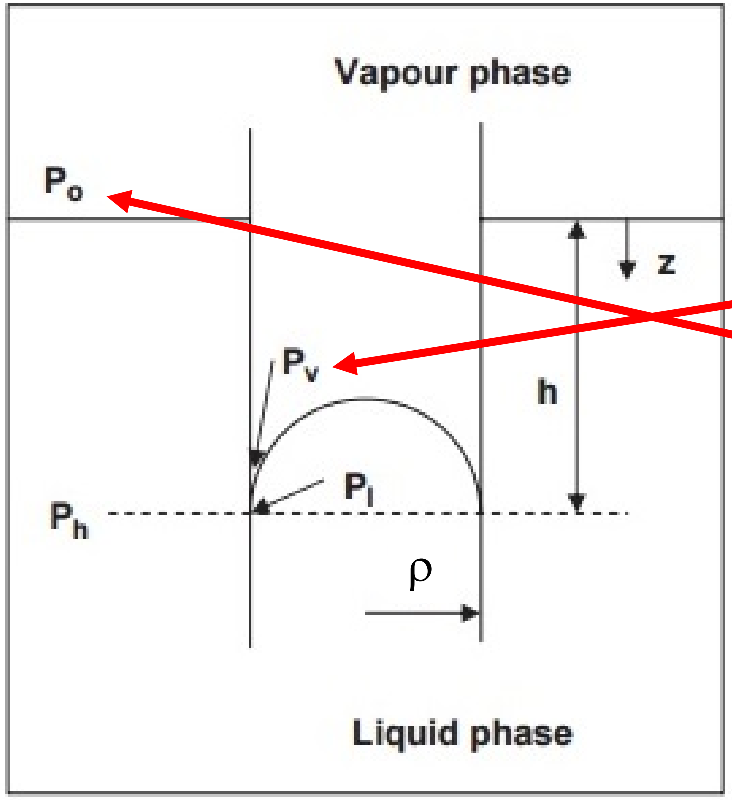


Figure: Fabio, Villa et al. (2014). doi: 10.1615/IHTC15.nmt.009823.

Change in vapor pressure due to contact angles

- Kelvin equation



(source Wiki)

$$\ln \frac{p_v}{p_0} = \frac{2\gamma V_m}{\rho R T}$$

Surface tension

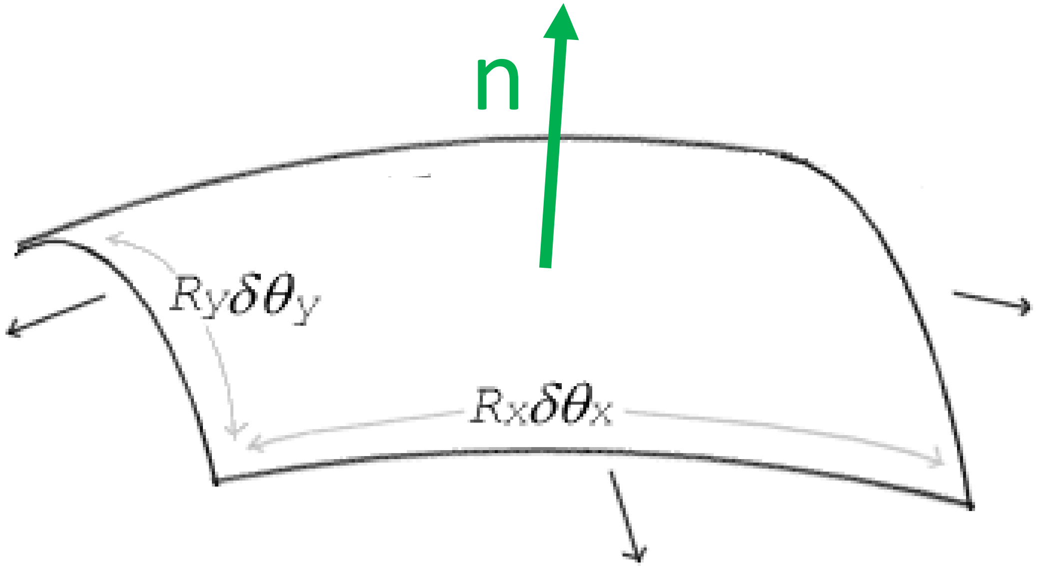
Molar volume

Saturated vapor pressure

Meniscus radius

Universal gas constant

Temperature



Laplace-Young equation

- States the difference of pressure at the interface between a gas and a liquid

$$\Delta p = \gamma\left(\vec{\nabla}\cdot\vec{n}\right) = \gamma\left(\frac{1}{R_x}+\frac{1}{R_y}\right) = 2\gamma H$$

Surface tension

Normal to the surface

Mean curvature

Principal radii

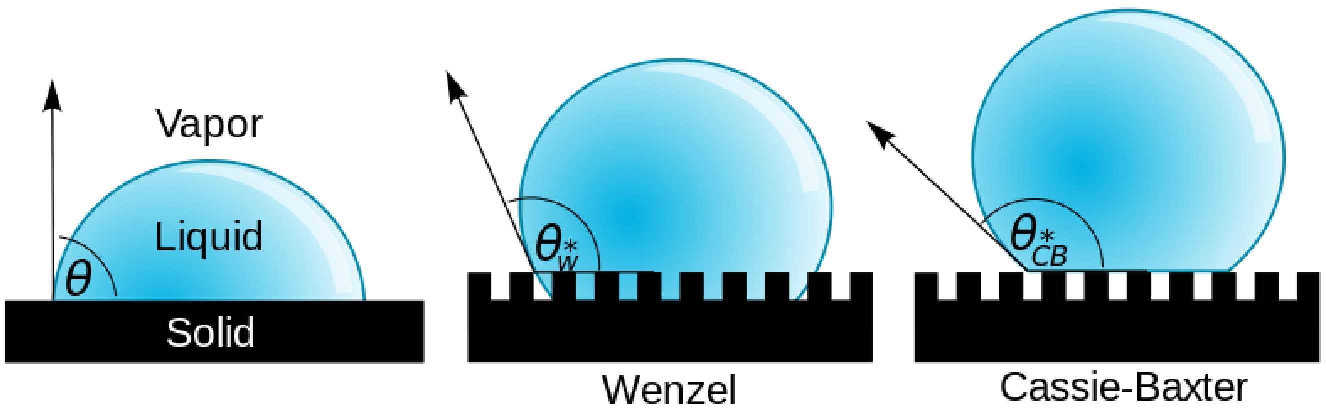
Difference of pressure across the interface

Illustration on how processing can be used to engineering surface at the nano-scale

Walking on water...

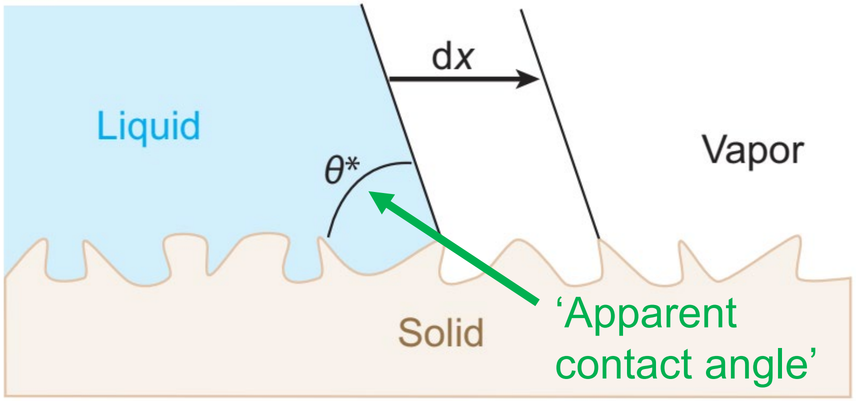
Bush JWM, Hu D, Prakash M. 2008. The integument of waterwalking arthropods: form and function. *Adv. Insect Physiol.* 34:117–92

Engineered hydrophobic surfaces/effect of roughness: how it works?



(source: Vladsinger, Wiki)

*Wenzel: **assume** that the liquid continuously 'wet' the rough surface.*



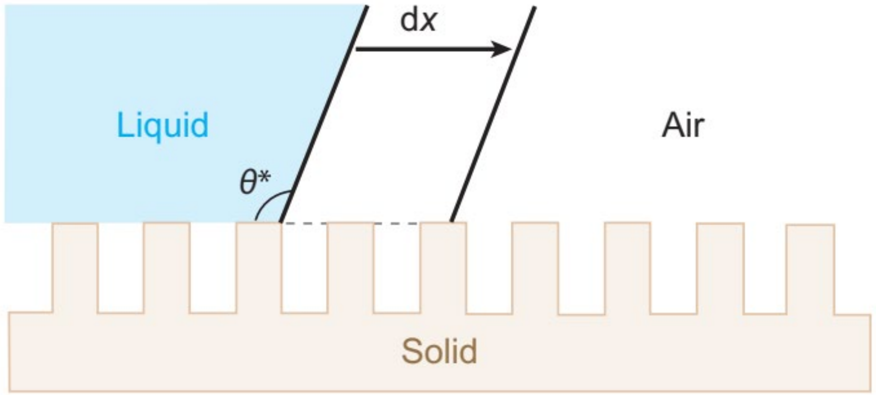
(source: David Quéré, ESPCI)

$$\theta^* \neq \theta$$

$$\cos\theta^* = \mathrm{r}\cos\theta$$

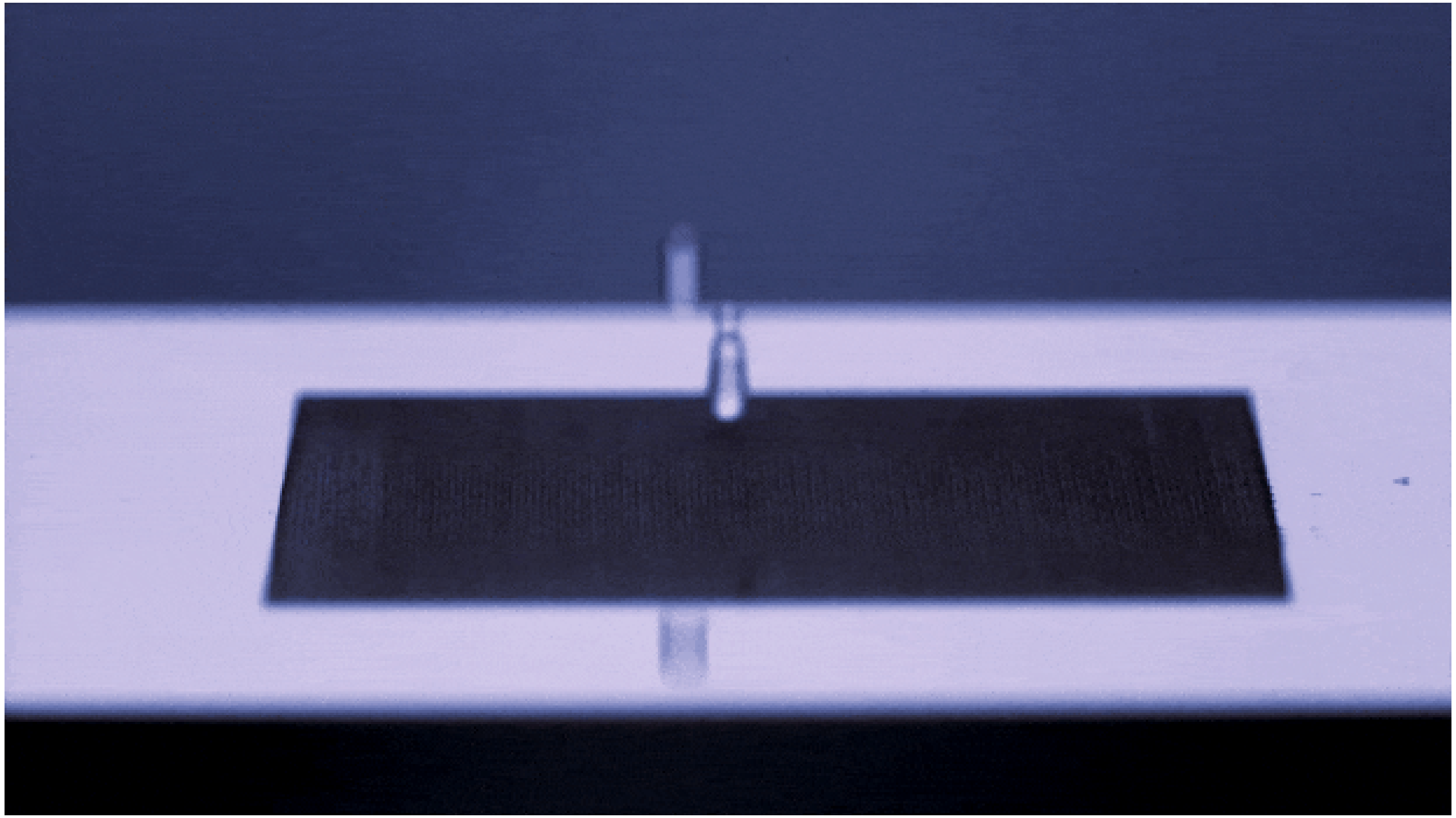
'roughness factor' > 1

*Cassie-Baxter: **assume** that the presence of air-liquid interface.*



(source: David Quéré, ESPCI)

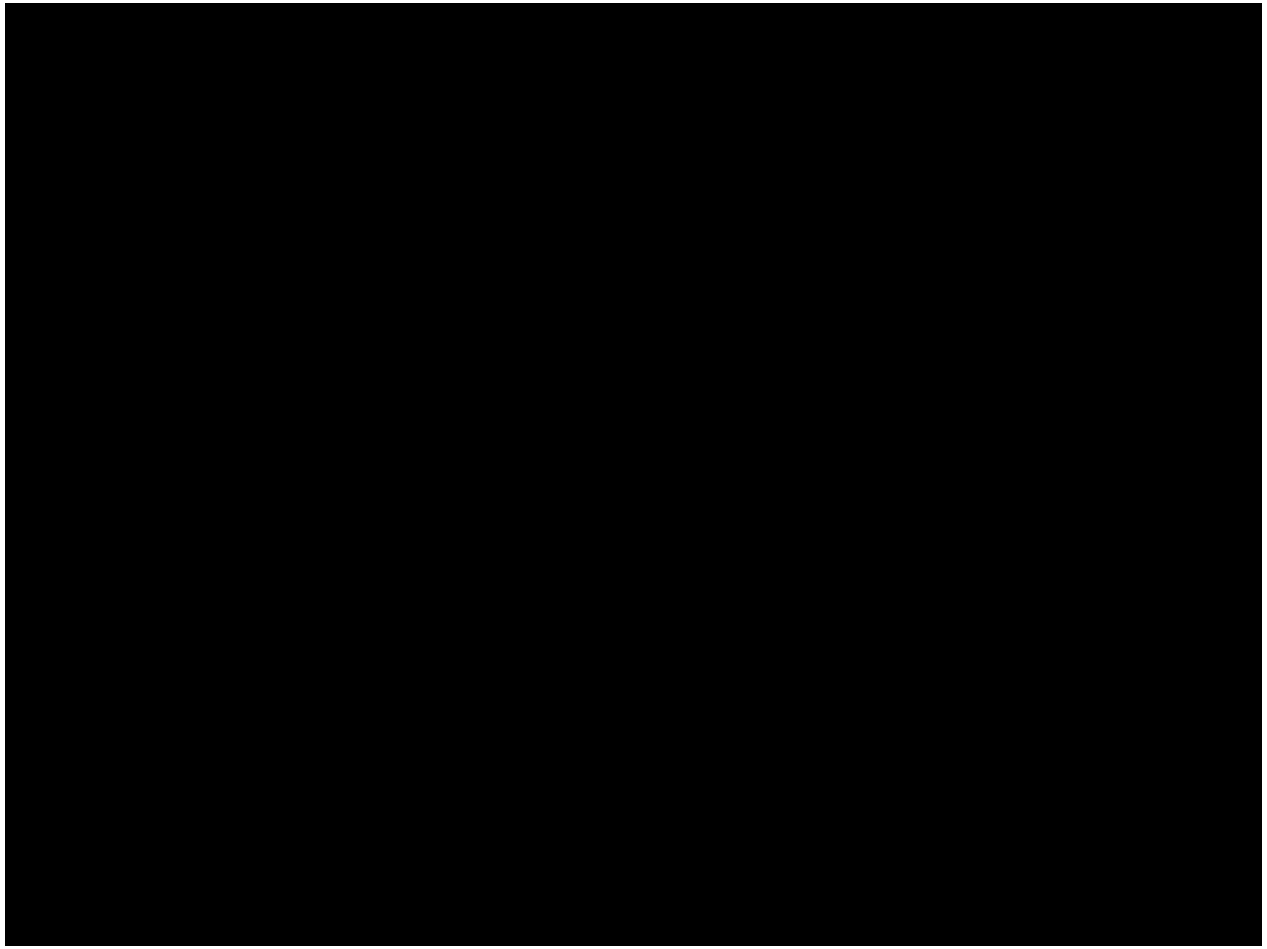
What about manufacturing? Engineered surfaces?



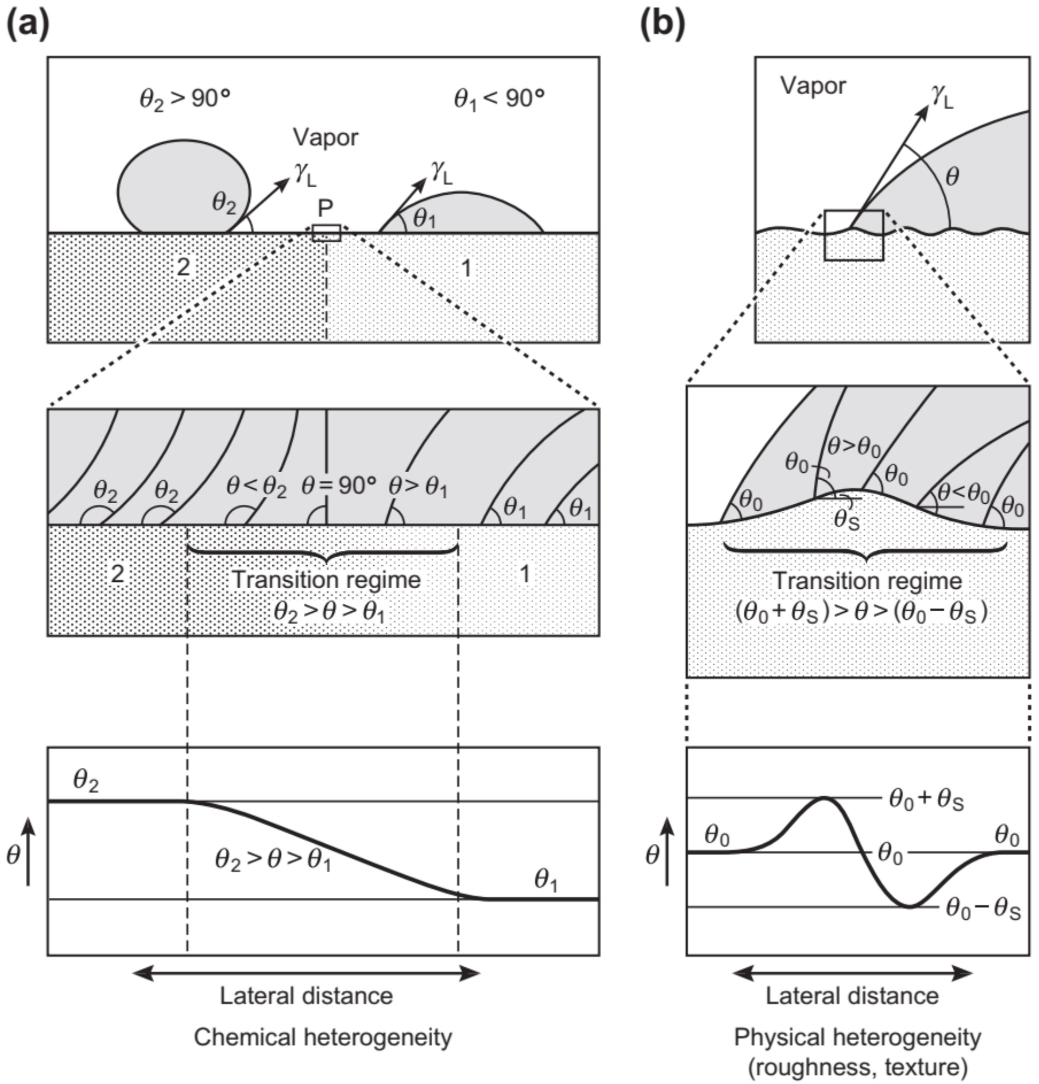
(source: Univ. of Rochester, Prof Guo)

https://youtu.be/FLegmQ8_dHg

Wettability gradient

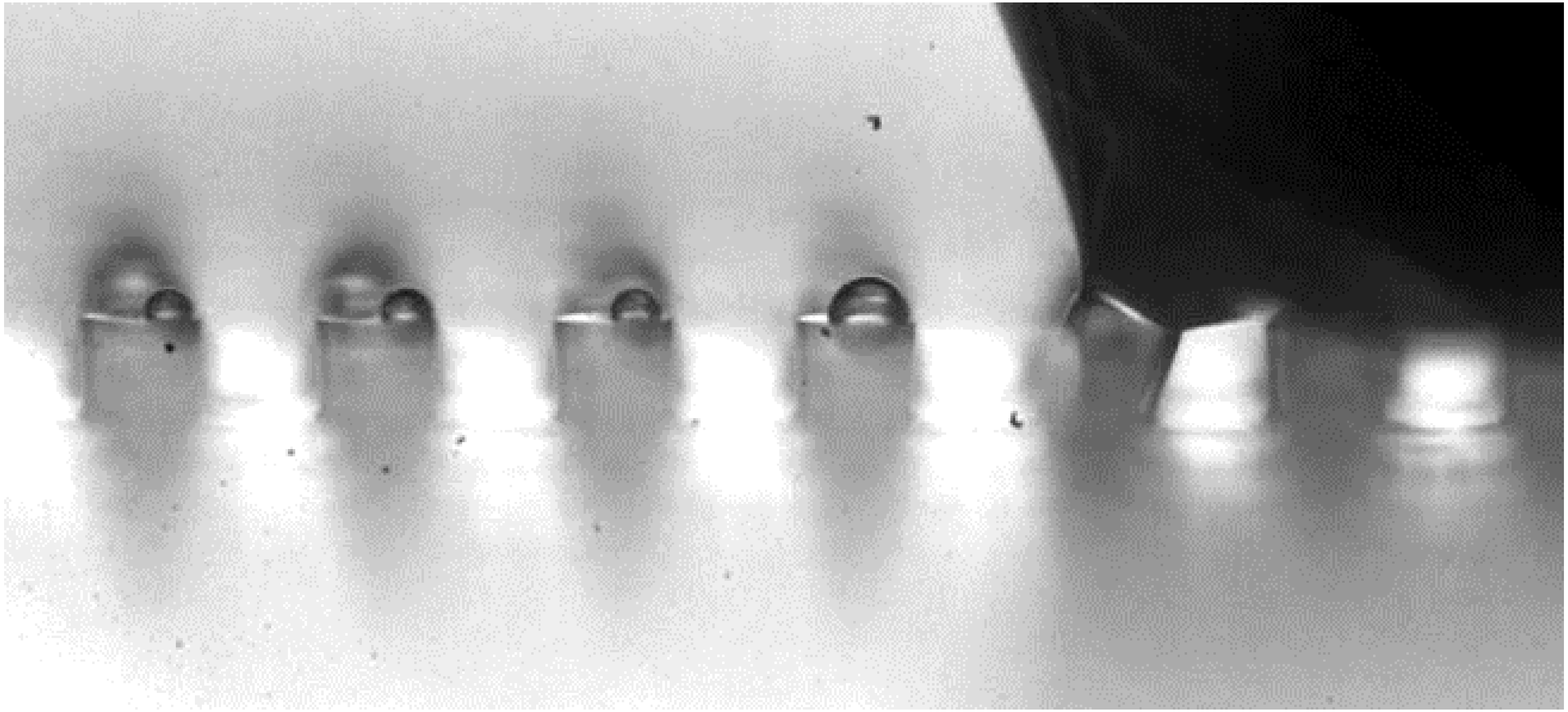


(Source D-MAVT / ETHZ)
https://youtu.be/puYo9w4cuOc



(source: J. Israelachvili, Adhesion and Wetting Phenomena)

Illustration of research at EPFL



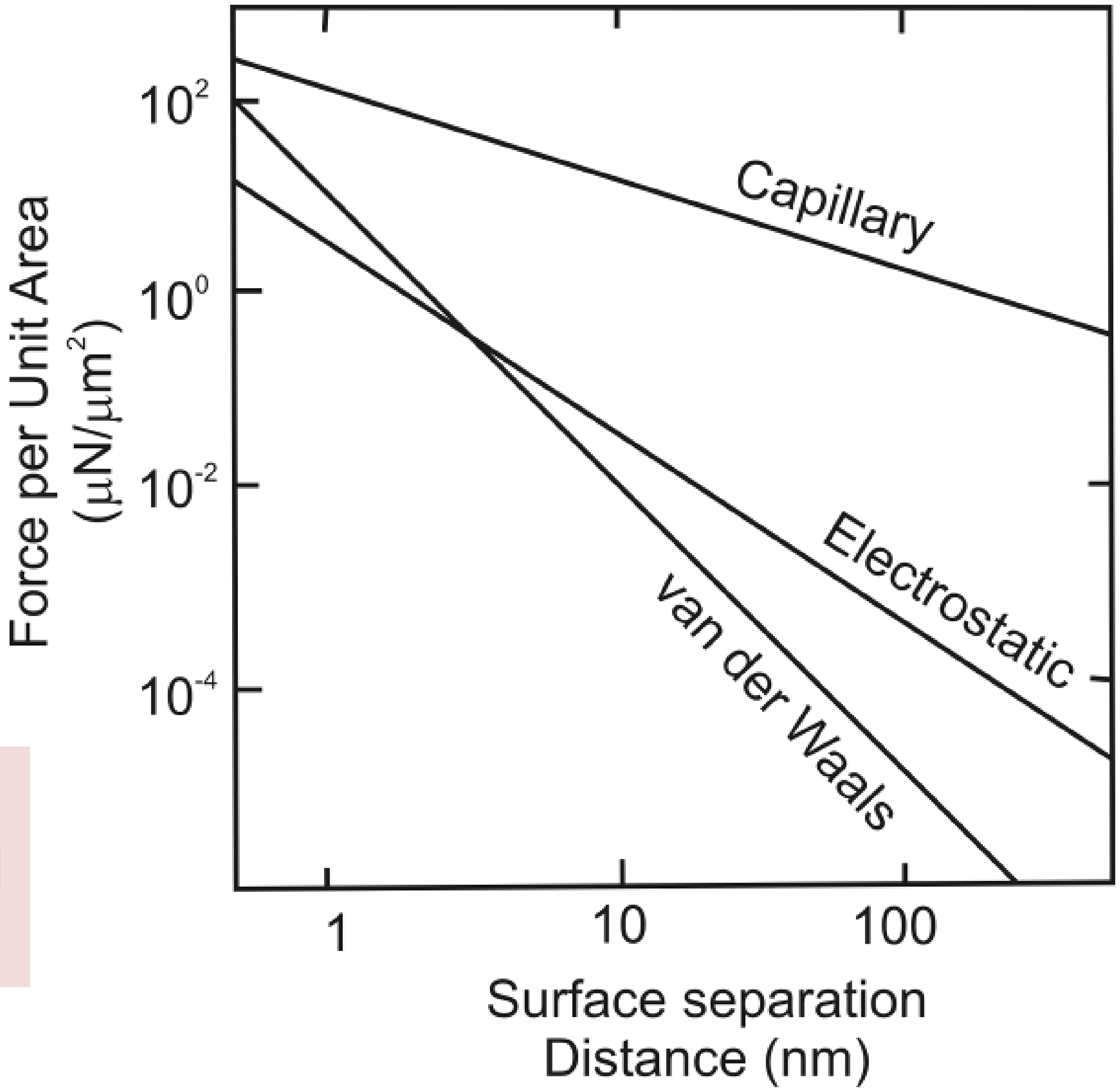
(Courtesy Prof. Kolinsky, EMSI) / PNAS
https://doi.org/10.1073/pnas.2008683117

Illustration of a droplet 'walking on soft pillars' being deformed by surface tension.

Adhesion properties of surfaces

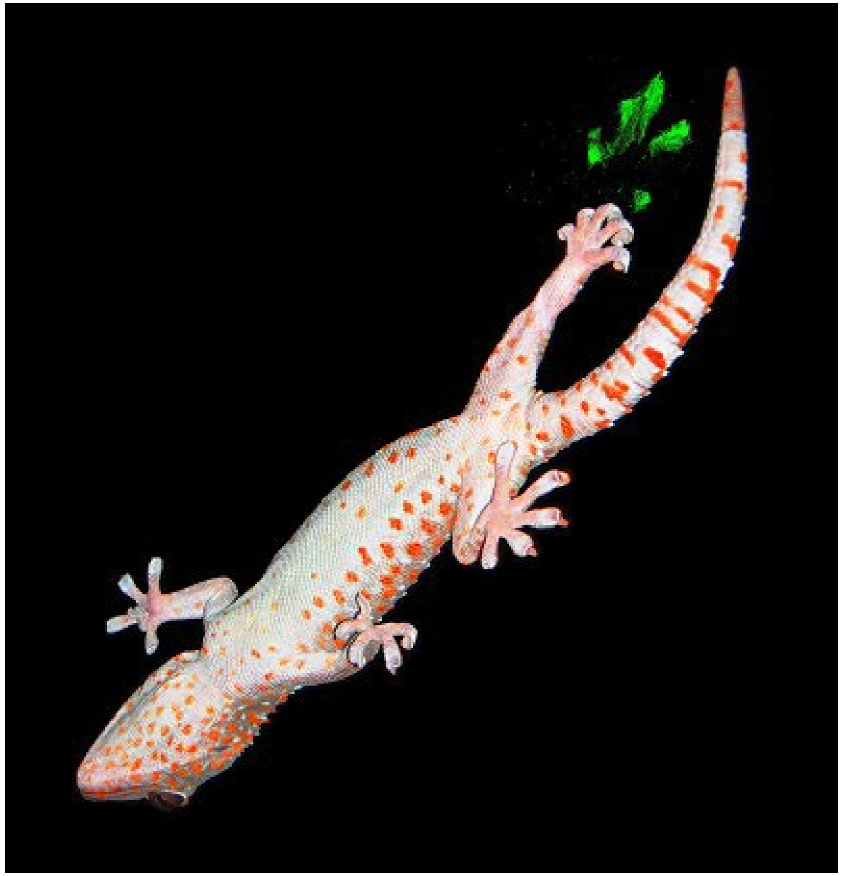
Adhesion force: 'illustrative' comparison

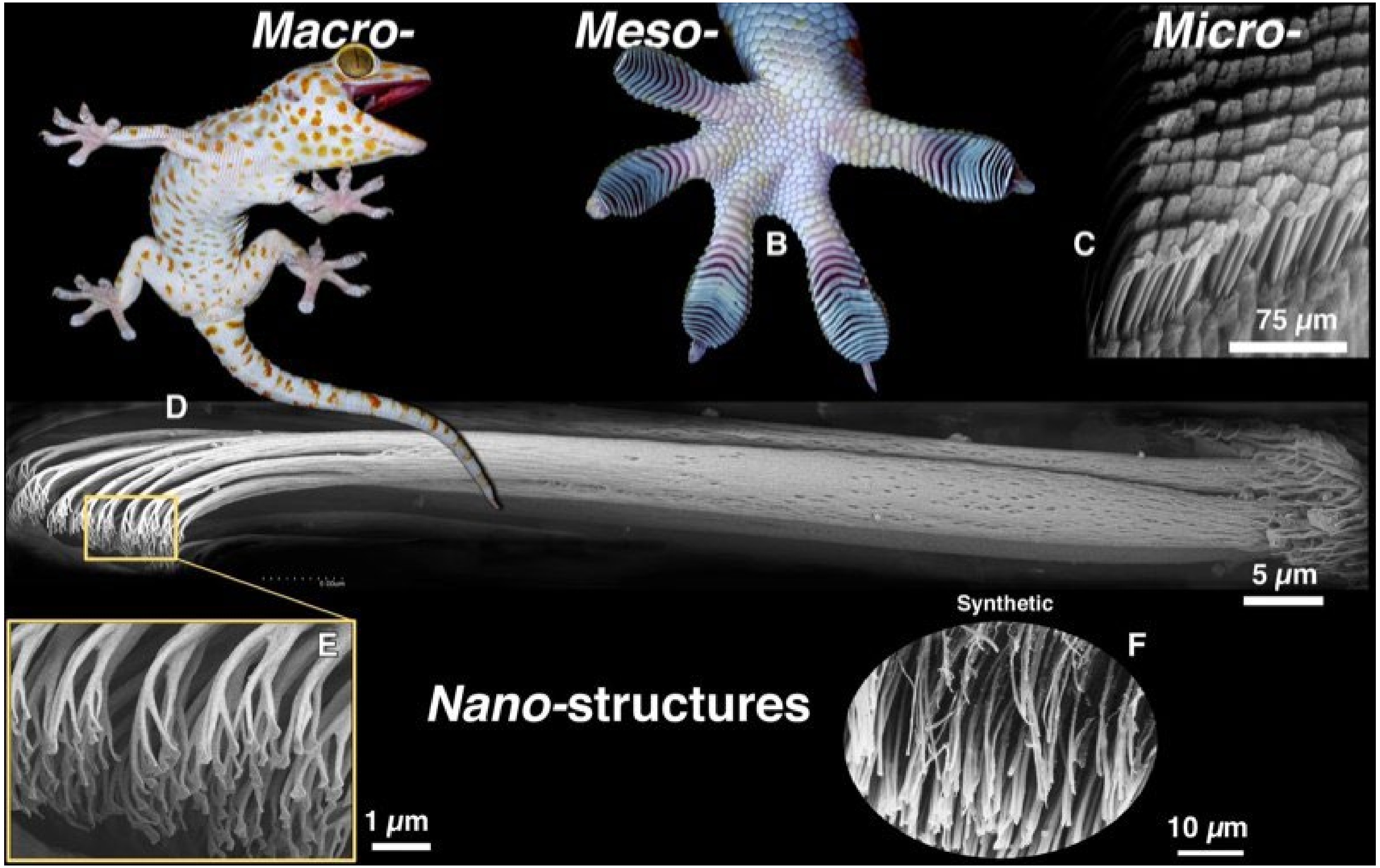
- Example for two SiO_2 surfaces (U=1V, AH = 1.7eV, γ = 73 dyne/cm.)



The nature of the adhesion forces changes with the type of surfaces and the surface separation distance!

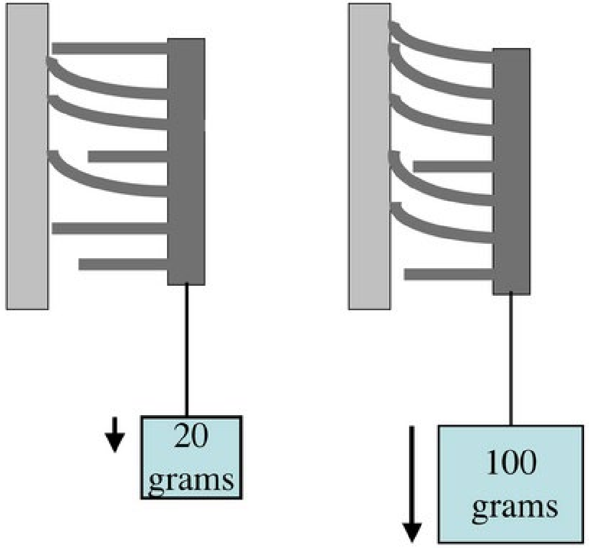
From the Gecko mystery… (a multiscale interaction)



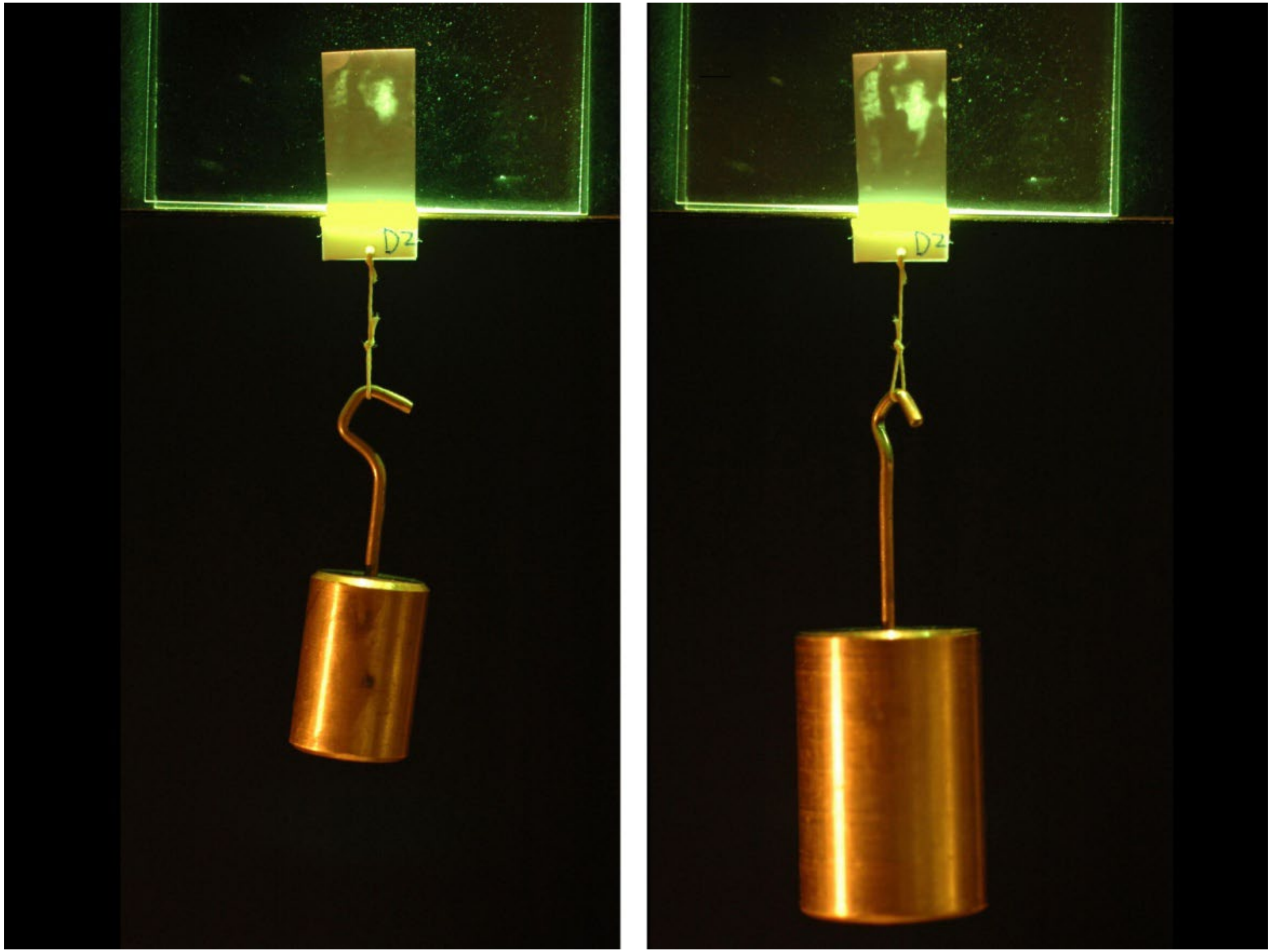


(pictures source: K. Autumn, Lewis & Clark College, USA)

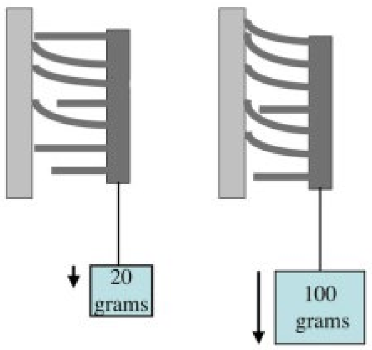
To new adhesive principles….

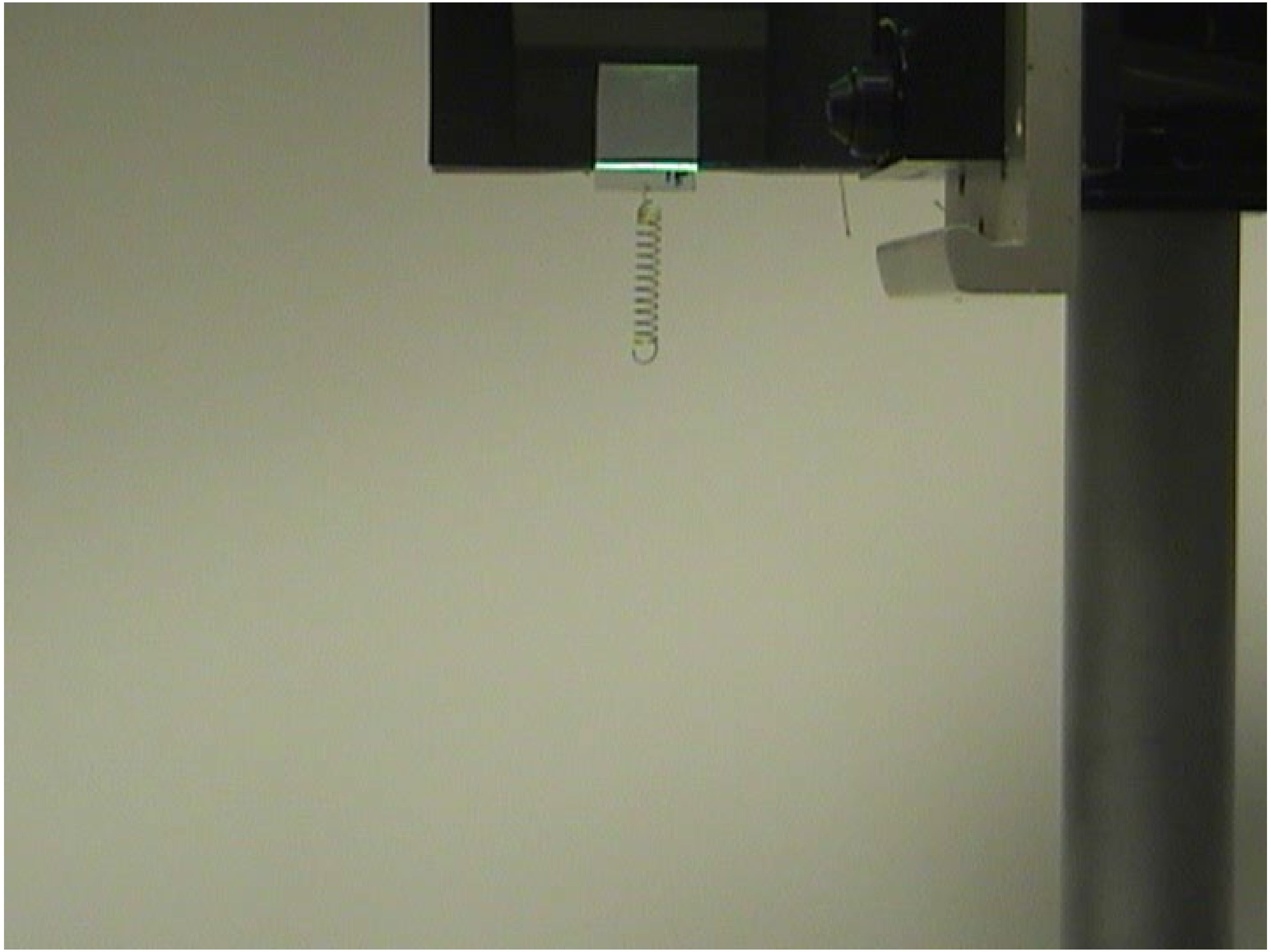


(source: Ron Fearing, UC, Berkeley)



To new adhesive principles….





(source: Ron Fearing, UC, Berkeley)

In industry: The optical contacting method

- Surface are so smooth that van der Waals surfaces prevails

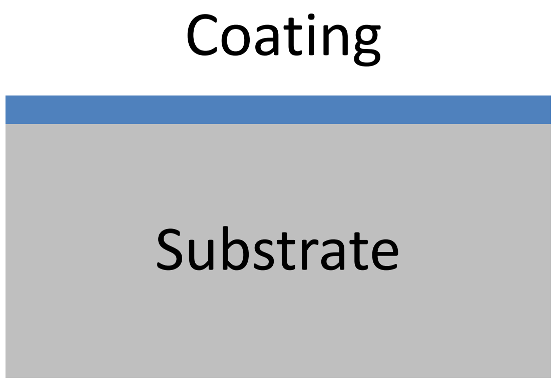
(sub-nm contact distances)

Source:
https://youtu.be/se3K_MWR488
https://youtu.be/hxGMA0nxdEU

A few words about surface treatment

Surface treatments: coatings

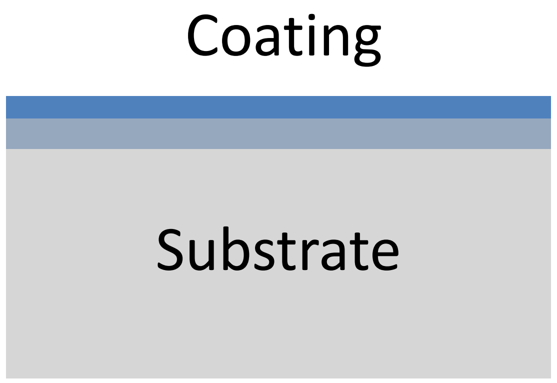
- ✓ **Two separate materials**, the substrate and the coating
- ✓ The coating **does not react** with the substrate
- ✓ Lot of available processes to deposit a coating



- **‘Through a liquid phase’** : Electrolysis, Chemical, Painting, etc.
- **‘Dry method’**: Physical Vapor Deposition, Chemical Vapor Deposition
- **‘Thermal’**: flame, plasma, arc, explosive, etc.
- **‘Beam assisted’**: laser, implantation, etc.
- ... and many others...

Surface treatments: conversion methods / reacting methods)

✓ **Two materials**, the feed-material reacts with the substrate to form a new compound.
✓ Localized chemical reaction



- **‘Electrochemical conversion’** : anodizing of aluminum, titanium, zirconium... / Coloration of steel / Sulfurization in salt bath, etc.
- **‘Chemical conversion’**

Examples

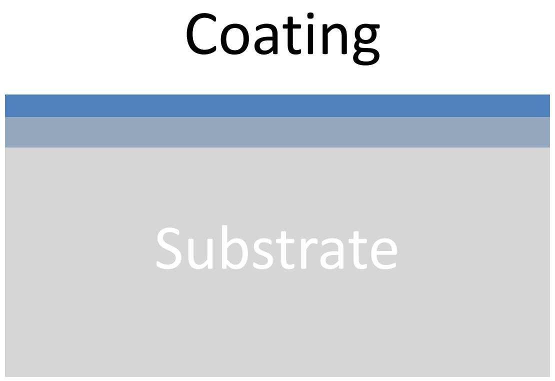
Anodized aluminum

(source Wiki)

Dye + anodization

Surface treatments: thermo-chemical

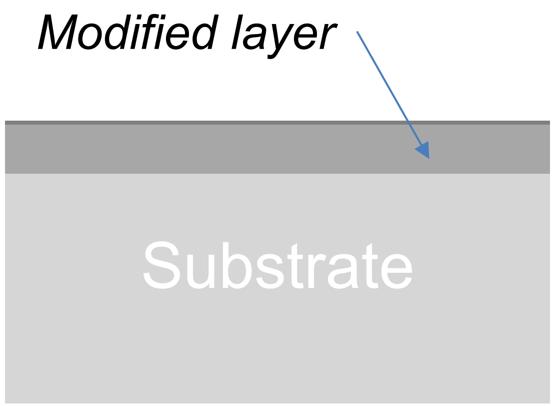
✓ **Two materials**, the feed-material diffuses into the substrates (and may or may not form a new compound).
✓ Diffusion process



- **'Metal/ metalloid diffusion'** : chrome ('chromisation'), tantalum, vanadium, ...; ion mixing, laser-induced mixing,...; cementations, carbonitruration, etc.

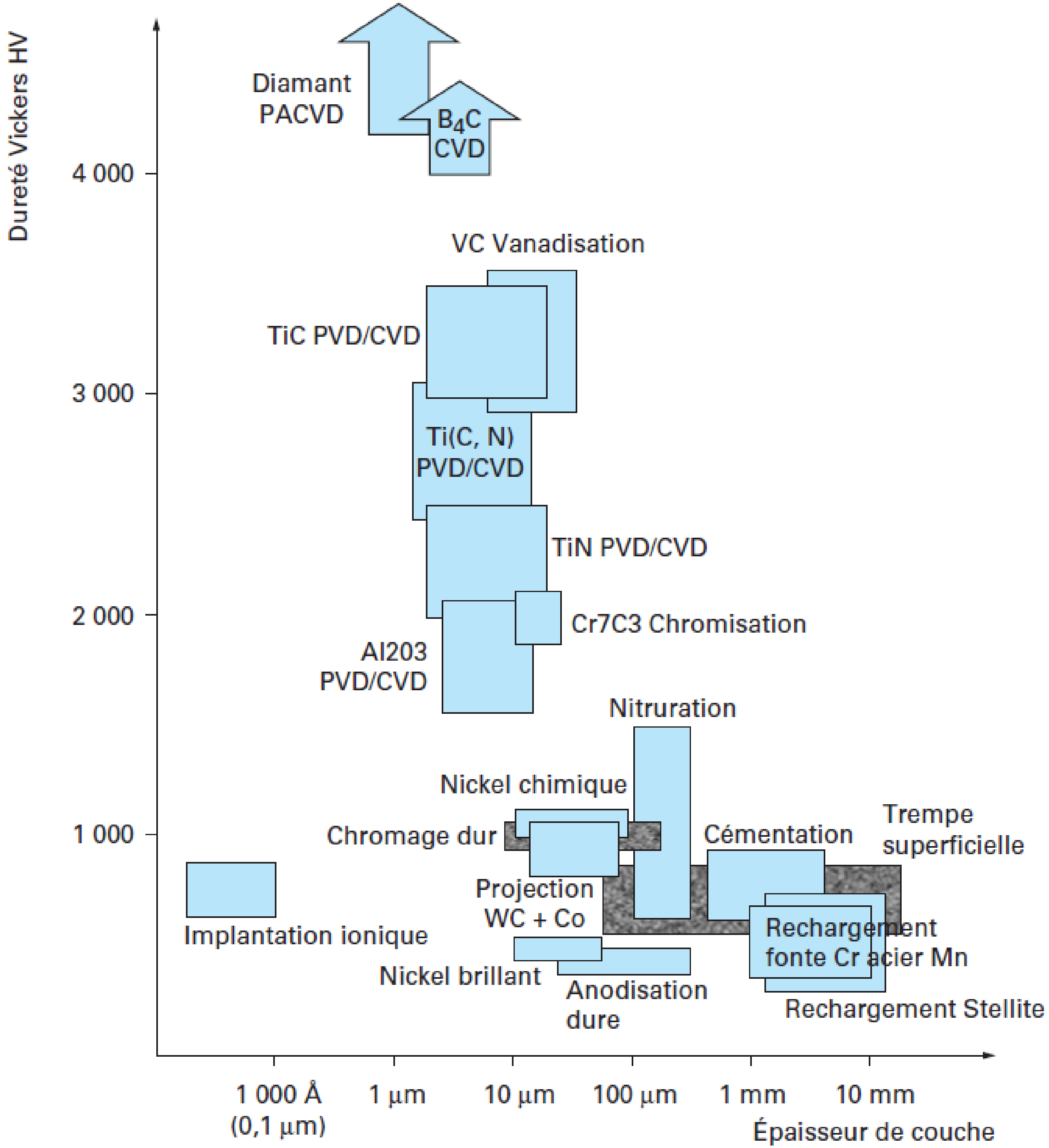
Surface treatments: thermal and mechanical, textured localized transformation

✓ **One material only** - the substrate
✓ **Local** process of mechanical hardening ('écrouissage'), thermal annealing, texturing.



- **Mechanical hardening** : hardening, shock peening ('grenaillage'), laser-shock peening, etc.
- **Localized thermal treatment** : local quenching, flame, laser-annealing, ...
- **Nanoscale texturing:** laser-induced ripples, ...

Surface treatments to improve the hardness



(Source R. Gras, Techniques de l'ingénieur)

Wrap-up

Key points to remember

- Importance of surface topological information and physical properties.
- Relation between surface and functionality
- How topography affects functional properties
- How do we measure the topography surfaces
  - Surface metrology principles
  - Roughness, waviness
  - Abbott-Firestone curves (bearing ratio)
- Role of manufacturing in engineering surfaces

'Lexique manufacturing'

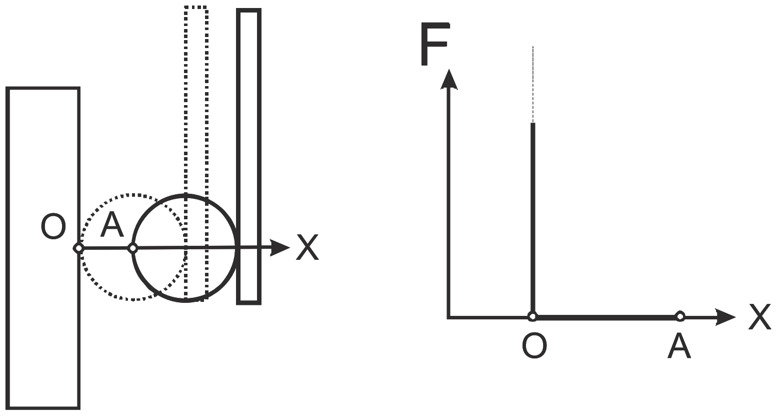
English (UK) > French

- Waviness: *Ondulation de surface*
- Roughness: *Rugosité*
- Toughness: *Tenacité*
- Wear: *Usure*
- Anodized: *~ Eloxé* (néologisme vient de 'Electricly oxidized') / Anodisé*
- Dye: *Colorant*
- Diffusivity: *Diffusivité*
- Scattering: *Lumière diffuse*
- Specular reflection: *Réflexion spéculaire*
- Grazing incidence: *Incidence rasante*
- Coatings: *Couches minces déposées*
- Diamond turning: *Tournage pointe diamant*

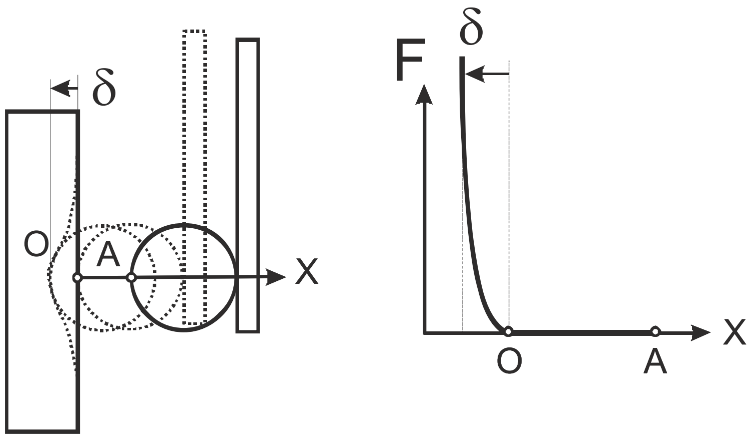
Annex on adhesion properties (to explore the topic further)

Physics of adhesion (introduction)

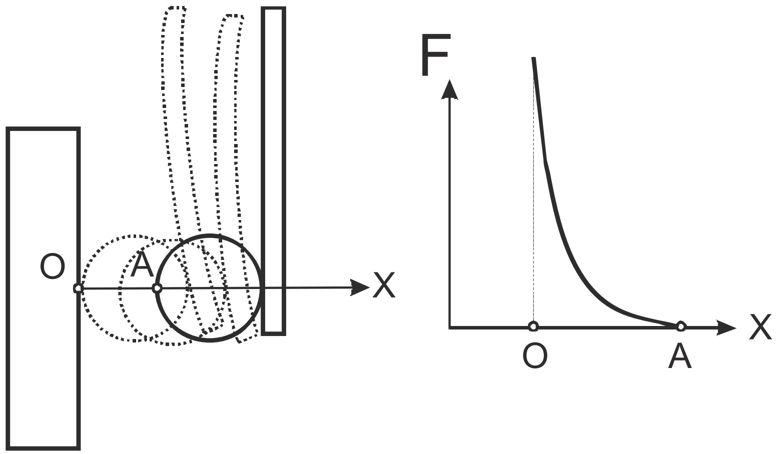
1. *Without surface forces*



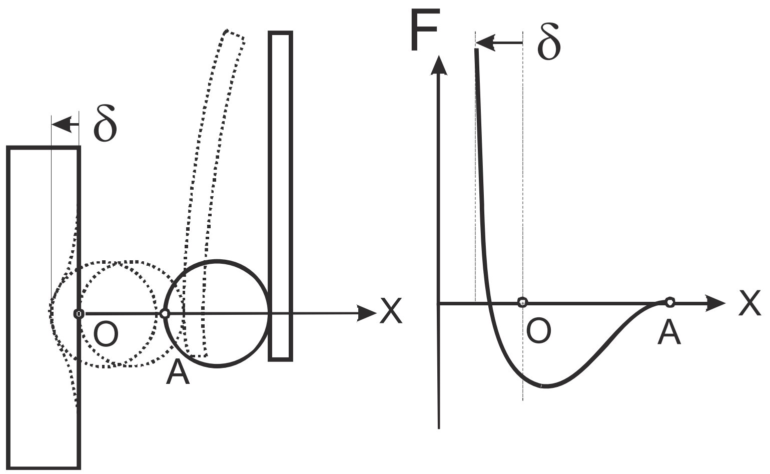
2.



3. *With surface forces*

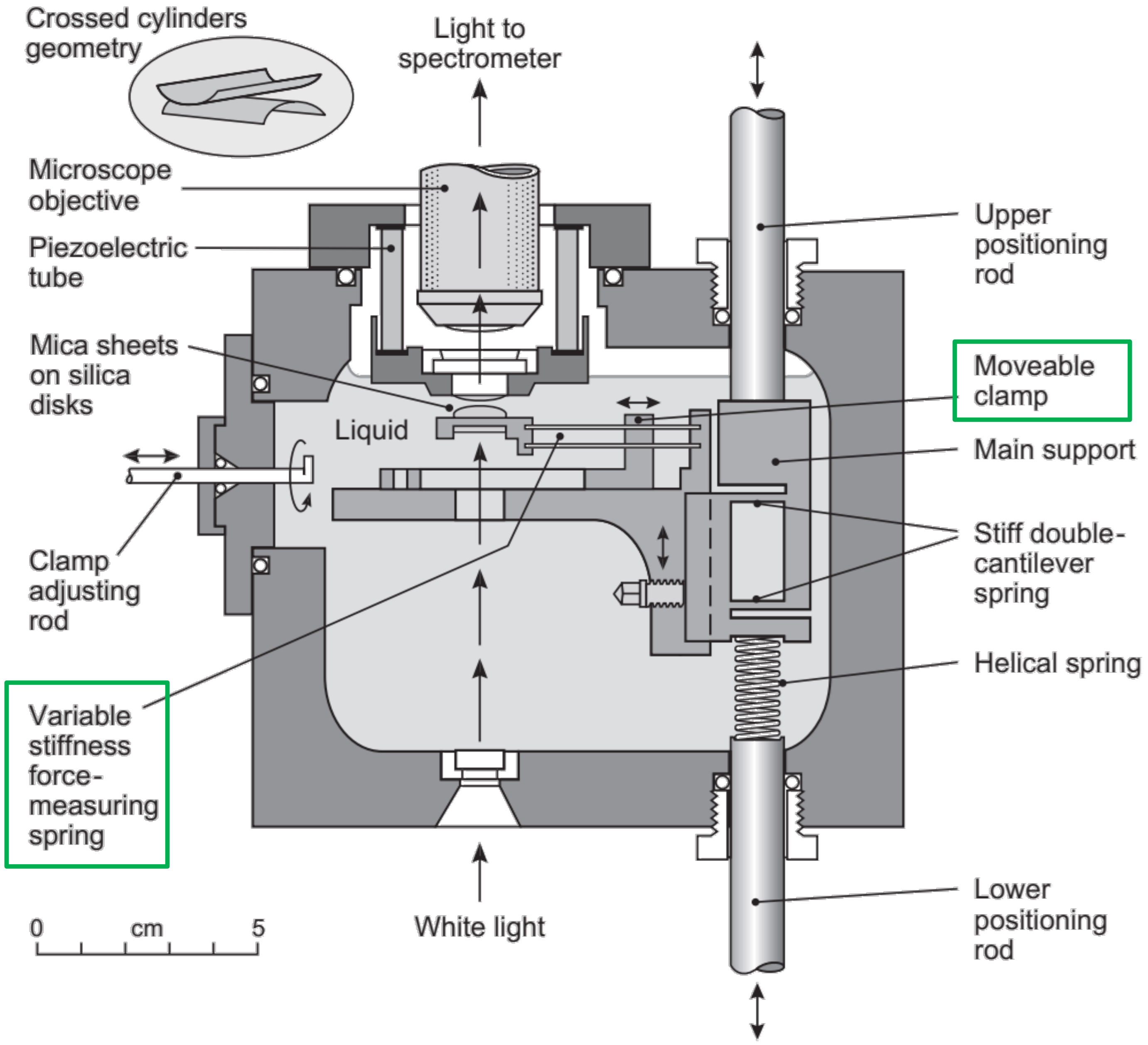


4.



Measuring surface forces

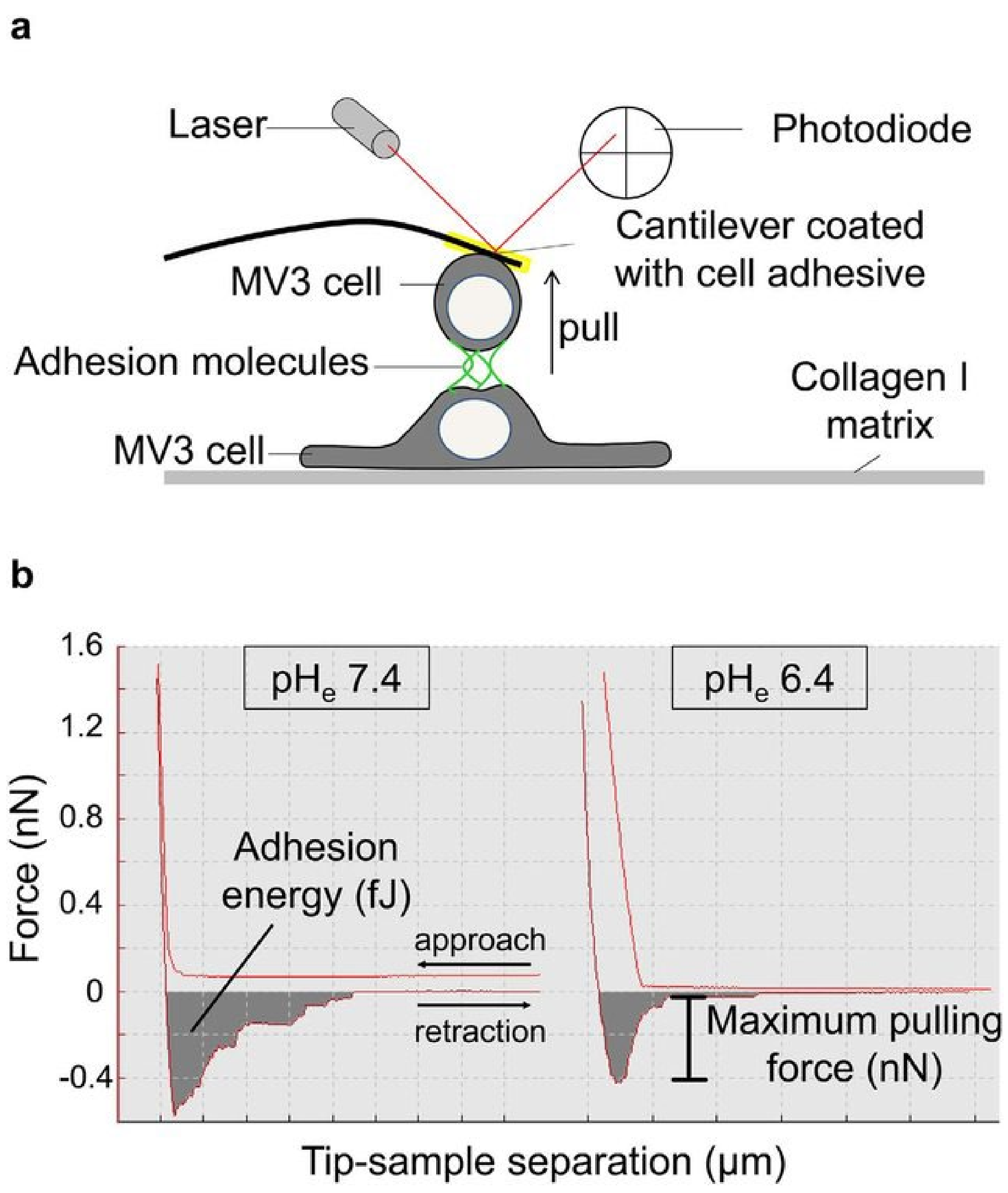
- ‘Large surface’
- Atomically smooth < nm roughness
- Typ. force resolution. 10^{-8} N



(source: J. Israelachvili, Adhesion and Wetting Phenomena)

Illustration of cell-cell adhesion

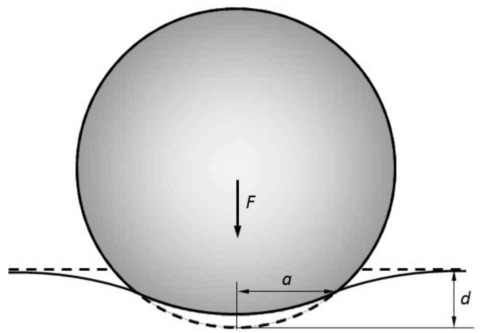
Schematic illustration of cell-cell adhesion analysis using AFM. (a) Single cell force spectroscopy. A single melanoma cell (MV3) attached to a flexible cantilever is brought into contact with another adherent melanoma cell of the same kind seeded on collagen



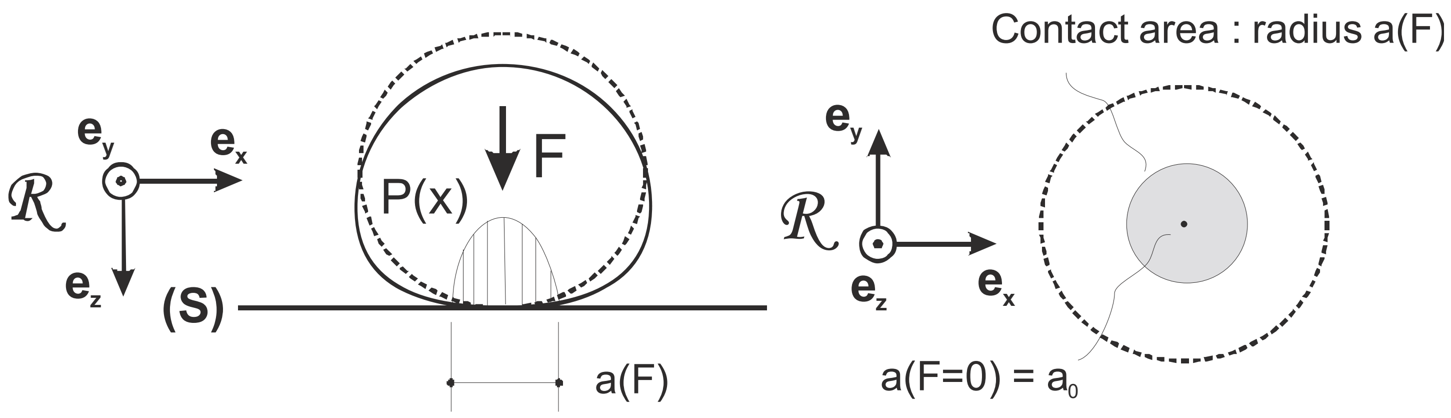
Hofschröer, V., et al. Extracellular protonation modulates cell-cell interaction mechanics and tissue invasion in human melanoma cells. Sci Rep ***7,*** *42369 (2017). https://doi.org/10.1038/srep42369*

Contact surfaces

- Importance in manufacturing => Choice of material in contact areas
- ***Without adhesion forces***
  - Hertz model (sphere on a plane / sphere deforms)
  - [variation: Sneddon model (sphere on a plane / plane deforms)]



(Sneddon model / sphere on a plane, assuming the plane deforms)



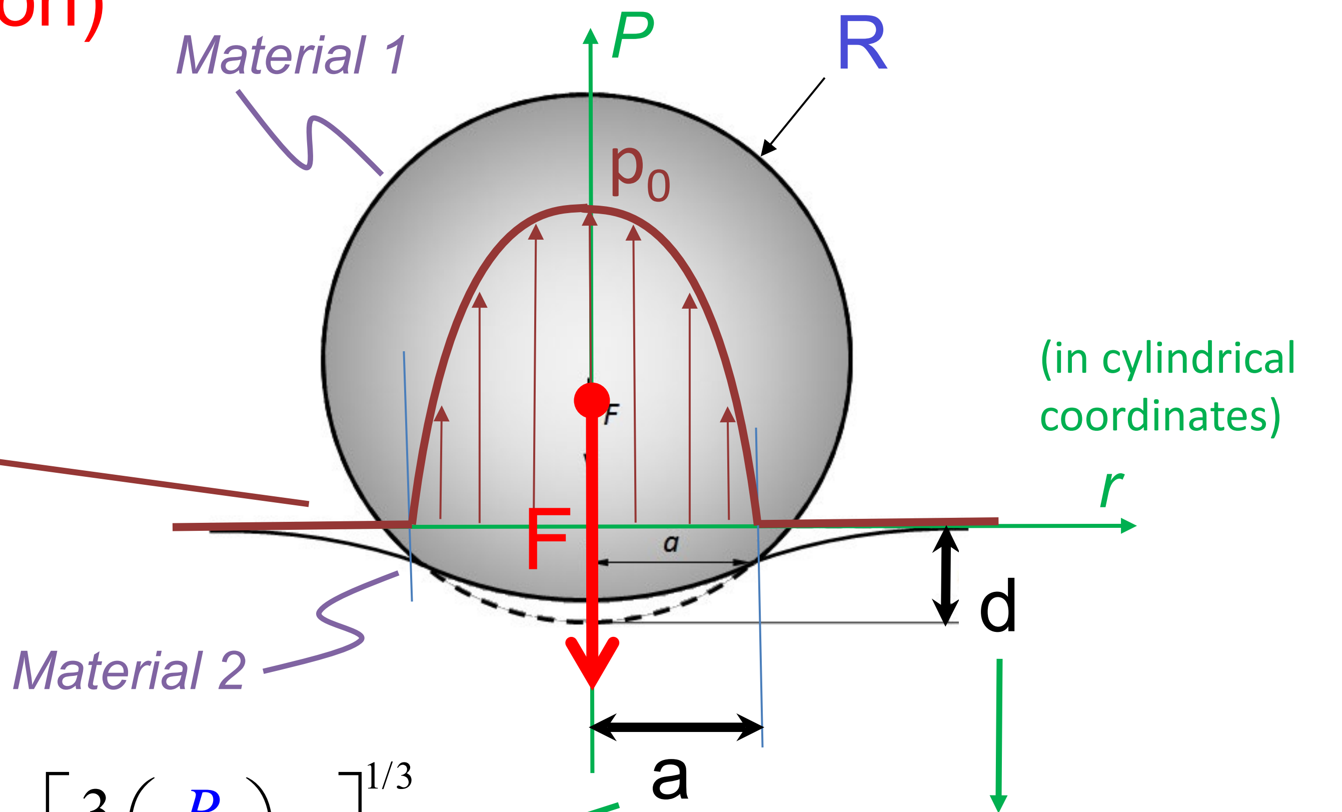
(Hertz model / sphere on a plane, assuming the sphere deforms)

Sphere on a plane (Hertz/Sneddon)

- *Assumes elastic deformation*
- *Small deformation*

Pressure distribution

$$p(r) = p_0\left[1-\left(\frac{r}{a}\right)^2\right]^{\frac{1}{2}}$$



Effective Young modulus of the elastic interface:

$$\frac{1}{E^*} = \left(\frac{1-\nu_1^2}{E_1}\right) + \left(\frac{1-\nu_2^2}{E_2}\right)$$

Material 1 *(E_1, ν_1)*

Material 2 *(E_2, ν_2)*

(ν Coefficient de Poisson)

$$a \simeq \left[\frac{3}{2}\left(\frac{R}{E^*}\right)F\right]^{1/3}$$

$$d \simeq \frac{a^2}{R} = \left[\left(\frac{2}{E^{*2}R}\right)F^2\right]^{1/3}$$

$$F = \frac{4}{3}E^* R^{\frac{1}{2}} d^{\frac{3}{2}}$$

Sphere on a plane (Hertz/Sneddon)

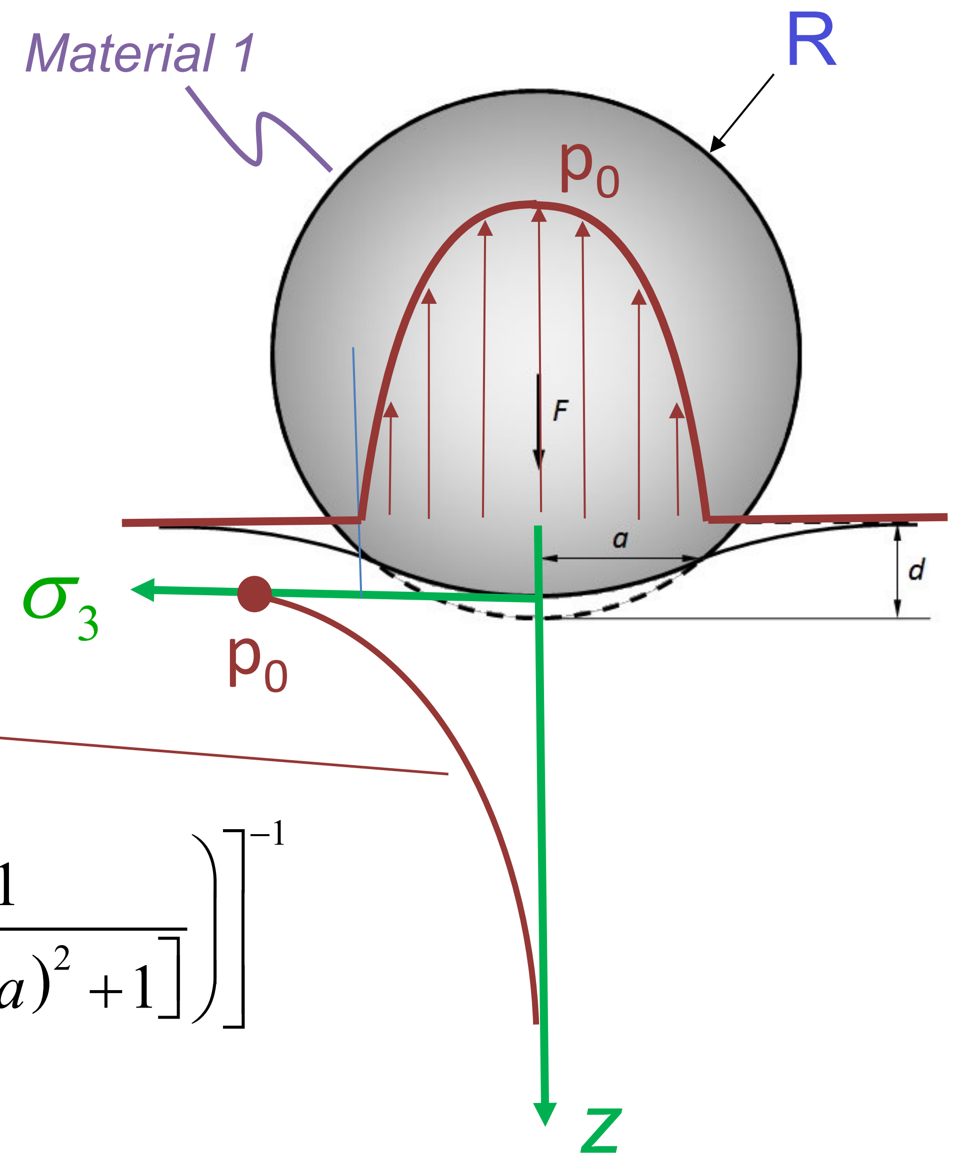
Principal stress (symmetric = cylindrical geometry)

$$\boldsymbol{\sigma} = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} = \begin{pmatrix} \sigma_\perp & 0 & 0 \\ 0 & \sigma_\perp & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix}$$

$$\sigma_3 = \sigma_\parallel(z) = -p_0 \left[1 + \left(\frac{z}{a} \right)^2 \right]^{-1}$$

$$\sigma_1 = \sigma_2 = \sigma_\perp(z) = -p_0 \left[(1+\nu_2)\left(1 - \left| \frac{z}{a} \right|^2 \tan^{-1}\left(\left| \frac{z}{a} \right| \right) - \frac{1}{2\left[(z/a)^2 + 1 \right]} \right) \right]^{-1}$$

Principal shear stresses: $|\tau_1| = |\tau_2| = \tau_{max} = \left| \frac{\sigma_\perp - \sigma_\parallel}{2} \right|$

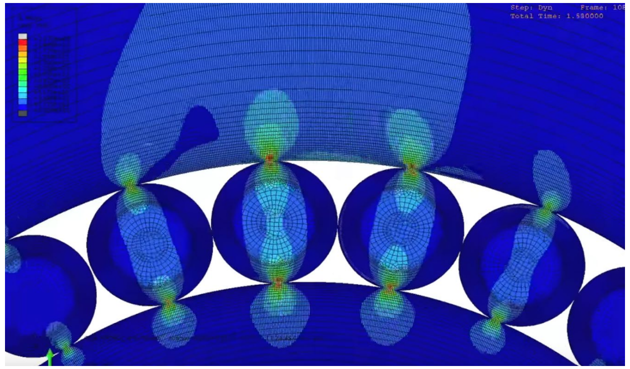


Similar models exist for other contact configuration (cylinder on a plane, sphere on a sphere, etc.)

Importance in manufacturing: choice of materials/design for minimizing wear/high-contact force effects

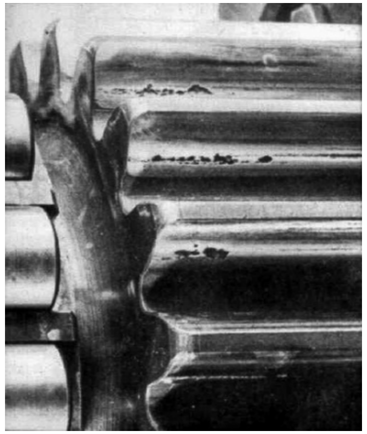
Roller bearing

(source SKF)



Source: https://youtu.be/20exjzKSzB8

Pressure on gear trains



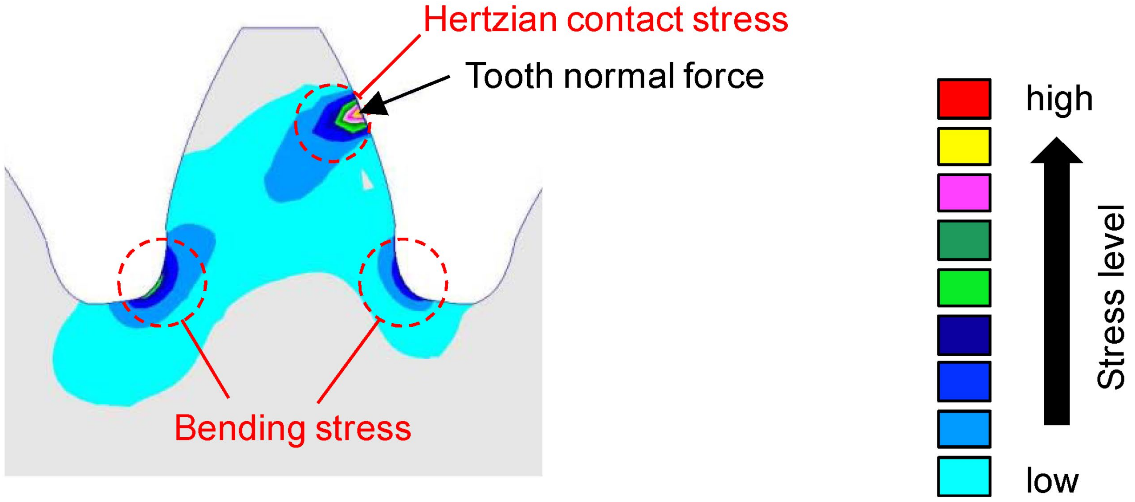
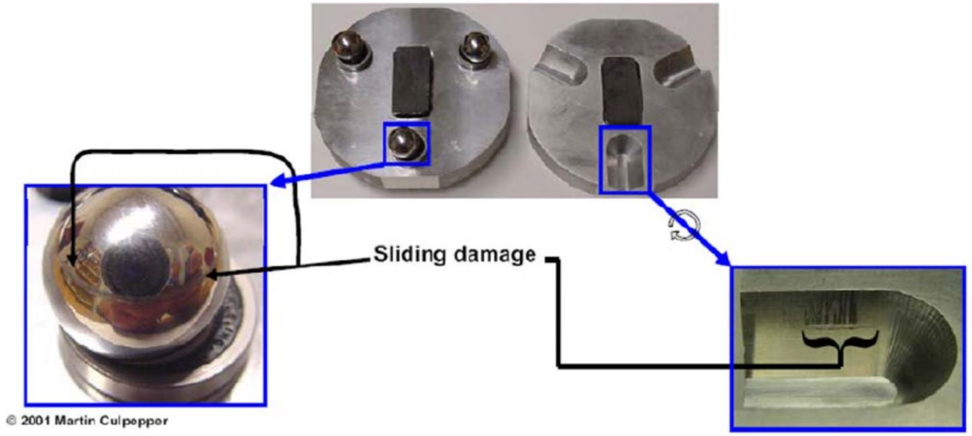


Illustration source: Tobie Thomas, et al. 2017. "Optimizing Gear Performance by Alloy Modification of Carburizing Steels" *Metals* 7, no. 10: 415. https://doi.org/10.3390/met7100415

Pressure on high precision reference elements

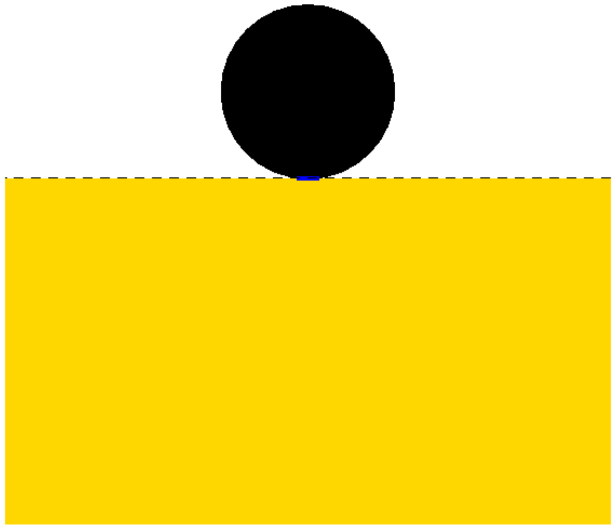


(source Martin Culpepper, MIT)

Models of adhesion forces

Hertz contact theory assumes no contact forces. The presence of adhesion forces modifies the contact area and hence, how the stress is distributed and evolves.

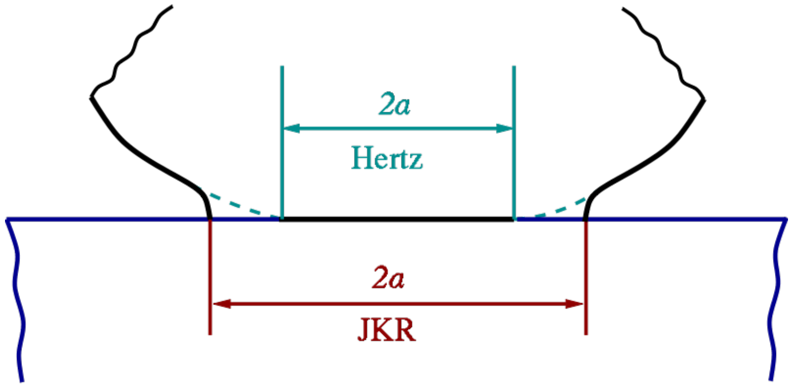
- Johnson-Kendall-Roberts (JKR)
  - Contact area (with adhesion forces **in** the contact area only)
- Derjaguin-Müller-Toporov (DMT)
  - Contact area (with uniform adhesion forces)
- Maugis / Dugdale
  - Contact area (with annular adhesion forces)

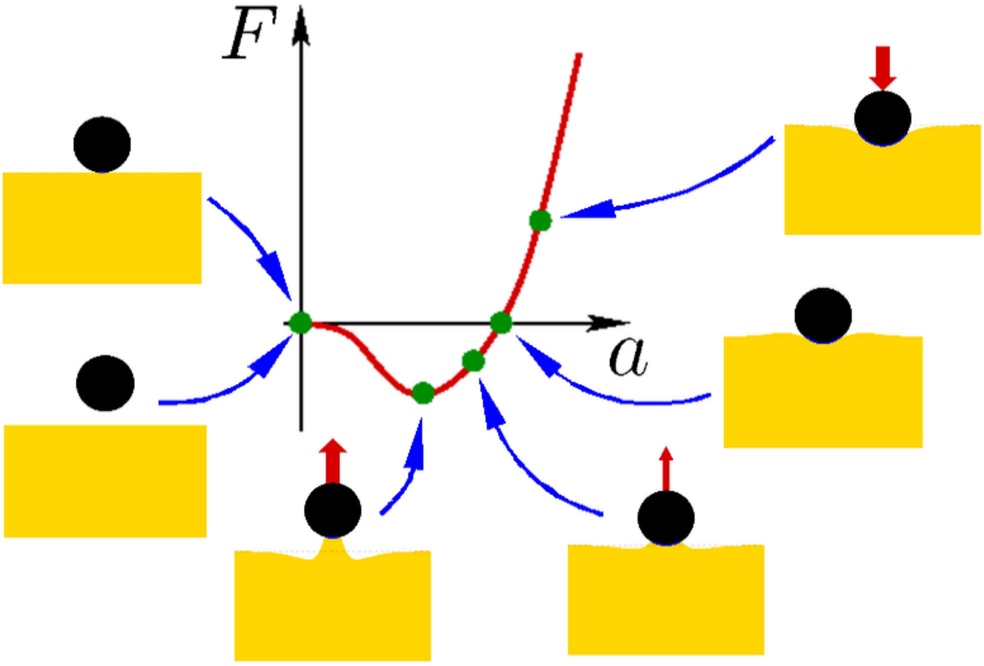


(illustration Wikipedia)

Johnson-Kendall-Roberts (JKR) model

- Adhesion in the contact area only





(source Wikipedia)

Surface energy

$$a^3 = \frac{3R}{4E^*}\left(F + 6\pi\gamma R + \sqrt{12\pi\gamma RF + (6\pi\gamma R)^2}\right)$$

Hertz mode (sphere-sphere)

Effect of adhesion forces

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

(for two spheres R_1 and R_2)

When no force is applied (F=0):

$$a^3 = \frac{9R^2\pi\gamma}{4E^*}$$

Pull-off force: $F_c = -3\gamma\pi R$

Nature of the adhesion forces

- Capillary forces → *Due to the presence of water (moisture in the atmosphere)*
- Electrostatic → *Due to the presence of electrostatic forces*
- Van der Waals → *Interaction at the near atomic scale*

Capillary forces

- Vapor pressure is smaller on curve surface (Kelvin equation)

➢ Formation of liquid meniscus at interface
➢ Pressure difference vapor/liquid => Attractive force

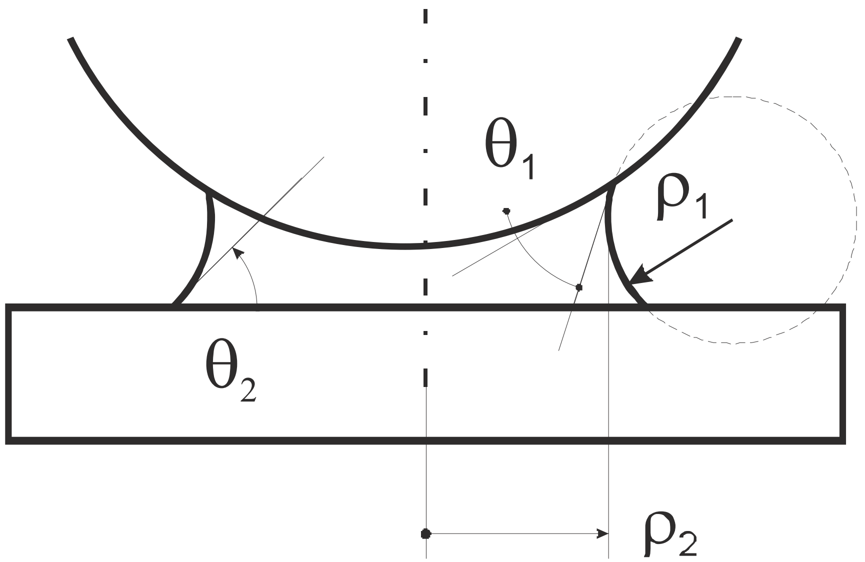


Illustration of capillary forces

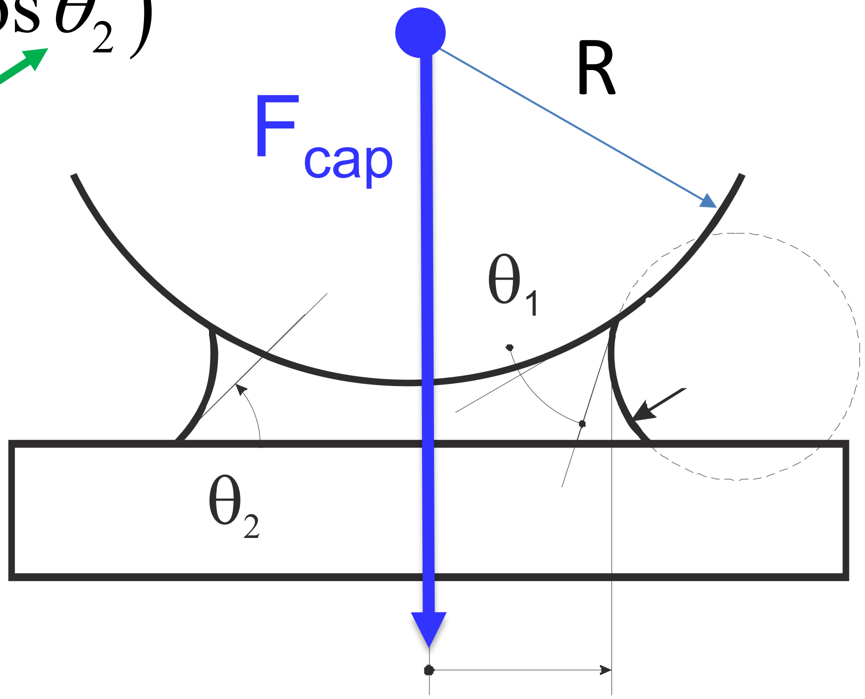
- Example of a water meniscus that pulls a sphere towards a plane

Sphere radius

$$F_{cap} = \gamma (2\pi R)(\cos\theta_1 + \cos\theta_2)$$

Surface tension of the liquid meniscus

Contact angles



Electrostatic forces

- Due to presence of surface charges
- Example: force due to a uniformed density of charges on a flat surface (from Gauss theorem)

$$F_{elec,z} = qE_z = \frac{(\sigma_s S)^2}{4\pi\varepsilon}\left(\frac{1}{r^2}\right)$$

Density of charge (C/m²) → σ_s

Distance to the plane → r

Dielectric constant → ε

- Pressure induced

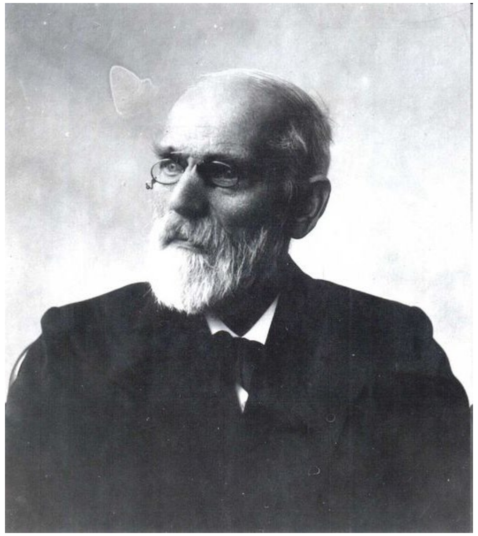
$$p = \left(\frac{\sigma_S^2}{2\varepsilon}\right)$$

Electrostatic forces

Orders of magnitude

Air	$\sigma_s = 3\ 10^{-5}$ C/m^2	p ≈ 50 Pa (gap typ. 1μm)
Good insulator	$\sigma_s = 10$ mC/m^2	p ≈ 1 MPa (gap typ. 1μm)

Van der Waals forces



Johannes Diderik van der Waals (1837 – 1923)

- Present in any solids
- Interaction between dipole moments of atoms
- Three components:
  - Keesom: dipole-dipole (C_K)
  - Debye: dipole-dipole induced (C_D)
  - Dispersion: instantaneous dipole-dipole induced (C_L)

van der Waals Potential:

$$U_{vdW} = -\frac{C_K + C_D + C_L}{\boxed{r^6}}$$

Short distance interaction ! (rapidy decay)

Van der Waals forces (integrated forms for various geometries)

Geometry	Force
Two flat surfaces (per unit area dS)	$F = f \cdot dS \quad \text{with} \quad f = -\frac{A_H}{6\pi D^3}$
Two spheres (diameters R_1 and R_2)	$F = -\frac{A_H}{6D^2}\frac{R_1 R_2}{R_1 + R_2}$
Sphere (diameter R) – flat surface	$F = -\frac{A_H R}{6D^2}$
Cylinder (diameter R) – flat surface	$F = -\frac{A_H R^2}{6D^3}$

A_H is the Hamaker constants (material dependant)