

# Surfaces topography and its effect on interactions with fluids and solids

## Introduction

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# Examples of surfaces

- The way surfaces are machined and the material will control the surface topography
- Two examples of surface roughness on the same sample type below
- **Why controlling surface topography when designing components?**
- **What is the impact of surface topography?**

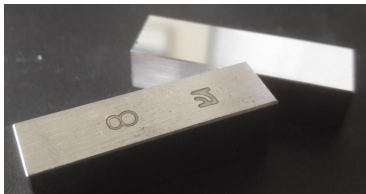
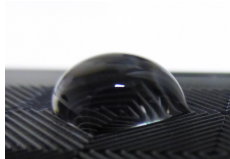
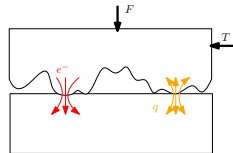


Figure: Examples of surfaces with different surface roughness (smooth and rough)

# Impact of surface topography on physical phenomena

The topography of the surfaces will affect

- light reflexion
- contact area between solids
  - adhesion
  - electricity conduction
  - heat conduction
  - friction
- tactile perception
- liquid spreading on the surface (wettability)



<sup>2</sup>[https://en.wikipedia.org/wiki/Multi-touch#/media/File:Aldea\\_Digital\\_2013\\_01.jpg](https://en.wikipedia.org/wiki/Multi-touch#/media/File:Aldea_Digital_2013_01.jpg)

# Course outline

- ① Solid surfaces: structure and topography
- ② Interaction of two solids surfaces
- ③ Interaction of a liquid with a solid surface

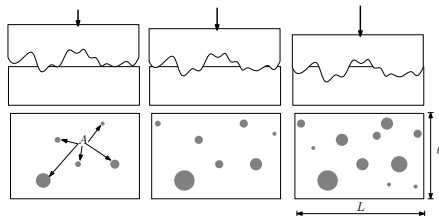


Figure: Contact of surfaces

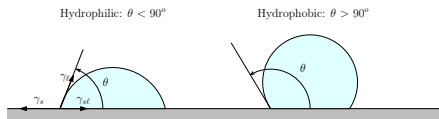


Figure: Wetting of a solid surface



# Surfaces topography and its effect on interactions with fluids and solids

Solids surfaces: structure and topography

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# Outline

- 1 Definition of surfaces
- 2 Structure of surfaces
- 3 Topography of surfaces
- 4 Topography measurement
- 5 Manufacturing process and topography
- 6 Surface properties
- 7 Summary
- 8 Application

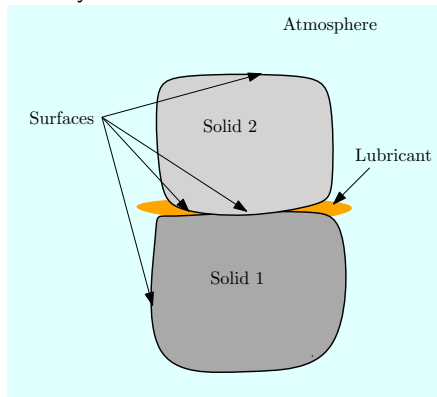
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# Definition of surfaces

"God made the bulk; the surface was invented by the devil"<sup>2</sup>

- **Solid surface:** interface between a solid and another media (gas, liquid, solid).
- The structure of the surface is complex: its depends on its machining process, on the history of the surface et the environments the surface interacted with.



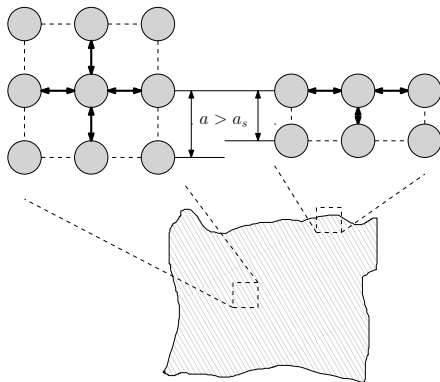
<sup>2</sup>Wolfgang Ernst Pauli (1900-1958), Nobel Prize of Physics 1945

# Outline

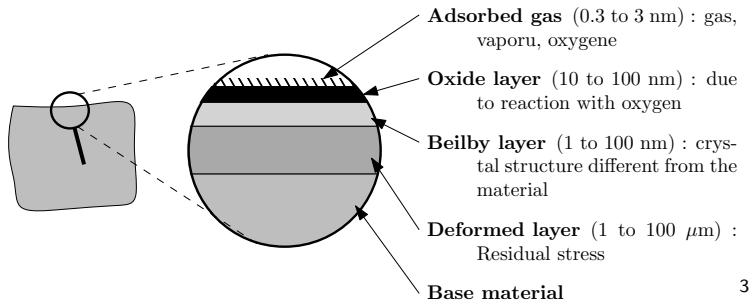
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# Structure of surfaces

- The atoms at the core of the material are in equilibrium under the action of neighboring atoms.
- Surface atoms are only subjected to the forces of atoms below the surface:
  - Interaction with the environment;
  - Particular surface properties.



# Structure of surfaces: Case of metallic materials



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# Structure of surfaces: Case of metallic materials

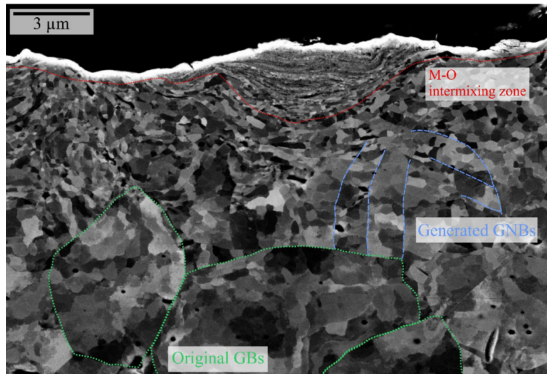


Figure: Cross section of a nickel sample after friction showing the different layers<sup>4</sup>

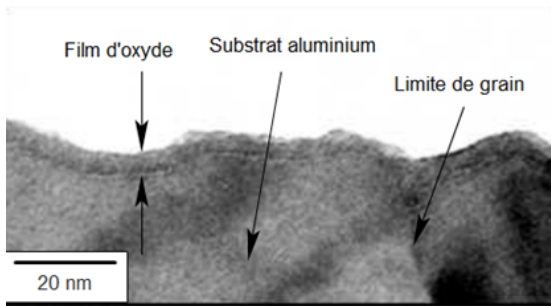
<sup>4</sup>Philipp G Grützmacher et al. "Interplay between microstructural evolution and tribo-chemistry during dry sliding of metals". In: *Friction* 7.6 (2019), pp. 637–650.



# Structure des surfaces: Case of metallic materials

The different layers are usually an asset:

- Surface protection (limits reactions with the environment, galling, etc.)
- Improvement of surface properties (hardness for example);
- Example: the alumina ( $Al_2O_3$ ) formed on the surface protects the aluminum against corrosion and increases the hardness.

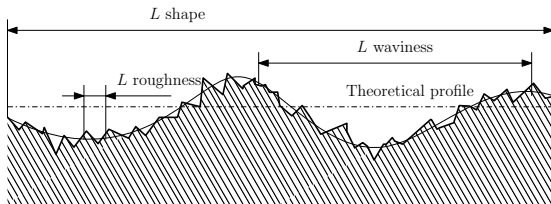


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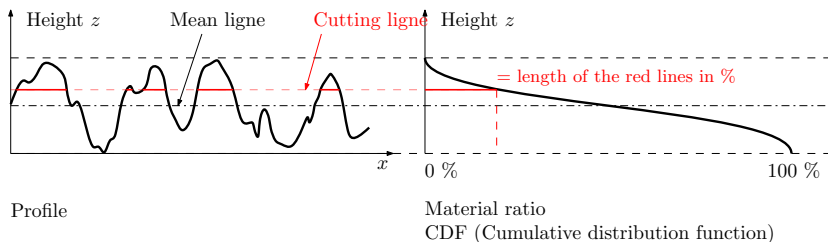
# Topography of surfaces: case of profiles

- Due to the production processes, the conditions of use, the wear, the surfaces exhibit defects which are characterized by deviations in altitude from their theoretical profile;
- Defects are generally identified according to their wavelength  $L$ :
  - $L \sim$  surface size: shape defect
  - $L \sim 0.01$  to  $0.001m$  : waviness
  - $L < 0.001m$  : **roughness**.



# Topography of surfaces: case of profiles

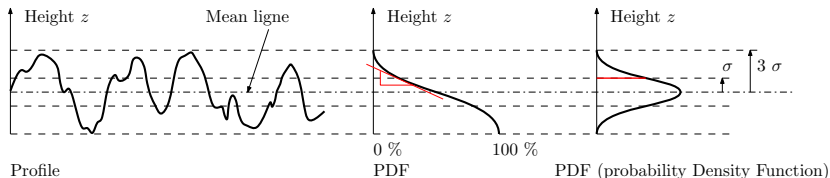
- Profile: height  $z$  as a function of the horizontal length  $x$  ;
- CDF = Cumulative Distribution Function: ratio of material above a cutting line of height  $z$ ;



# Topography of surfaces: case of profiles

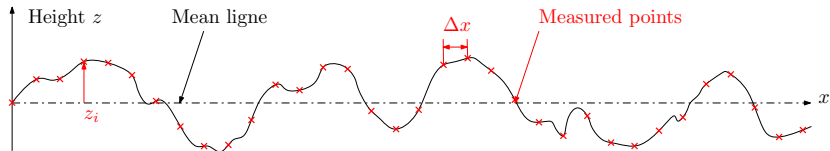
- PDF = Probability Density Function: derivative with respect to  $z$  of the CDF
- For most rough surfaces, the probability density follows a Gaussian law: :  

$$f(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[ -\frac{(z-\mu)^2}{2\sigma^2} \right];$$
- $\mu$  is the mean and  $\sigma$  the standard deviation ( $Rq$  in ISO metrology);
- The profile points are in the range  $-3\sigma$  to  $+3\sigma$ .



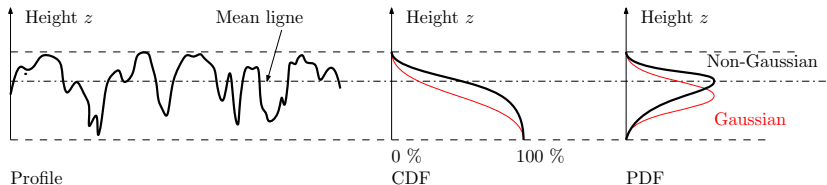
# Height statistical parameters: case of profiles

- The profile is measured by a device which gives a series of  $n$  points  $z_i$  laterally spaced of  $\Delta x$ ;
- Height (m or  $\mu\text{m}$ ): Arithmetic average  $Ra = \frac{1}{n} \sum_1^n |z_i|$
- Height (m or  $\mu\text{m}$ ): Quadratic average  $Rq = \sqrt{\frac{1}{n} \sum_1^n z_i^2}$  is equivalent to  $\sigma$ ;
- Skewness parameter (non-dimensional):  $RSk = \frac{1}{nRq^3} \sum_1^n z_i^3$ ;
- Kurtosis parameter (non-dimensional):  $RKu = \frac{1}{nRq^4} \sum_1^n z_i^4$ ;



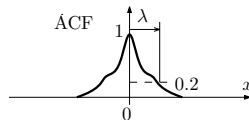
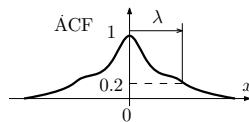
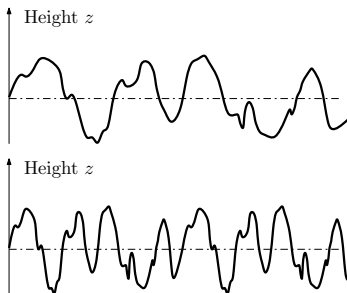
# Height statistical parameters: case of profiles

- Due to the manufacturing process, surfaces can be Non-Gaussian.
- Gaussian surface :  $Rq \approx \sqrt{\frac{\pi}{2}} Ra \approx 1.25 Ra$   $RSk = 0$   $RKu = 3$
- Non Gaussian surface (process with pics removal):  $RSk < 0$  et  $RKu > 3$ .



# Lateral size of asperities: case of profiles

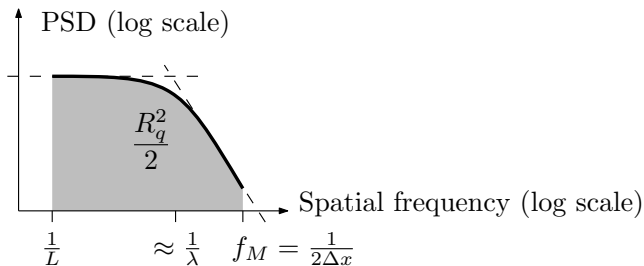
- ACF = Auto Correlation Function: egree of resemblance of a surface to itself shifted by  $x$ ;
- $FAC(x = j\Delta x) = \frac{1}{nRq^2} \sum_1^n z_i \times z_{i+j}$
- For many rough surfaces, it is a decreasing function tending to zero.
- The correlation length  $\lambda$  is the characteristic size of asperities.
- Is it the horizontal distance to reach  $ACF = 0.2$ .





# Roughness characterization: PSD

- PSD = Power Spectrum Density is the Fourier transform of the ACF.
- Distribution of the space frequencies;
- Lowest frequency  $\frac{1}{L}$  where  $L$  is the sample length;
- Highest frequency  $f_M = \frac{1}{2\Delta x}$  where  $\Delta x$  is the sampling length.
- The slope changes occurs at  $\frac{1}{\lambda}$
- The area below the curve corresponds to  $\frac{R_q^2}{2}$



# From profiles to surfaces

The roughness parameters are defined in the ISO standard. Many metrological tools measure the surface (and not the profile). Surface parameters have the same definition but different name:

Parameter	Profile	Surface
Arithmetic average	$R_a$	$S_a$
Quadratic average	$R_q$	$S_q$
Skewness	$RSk$	$SSk$
Kurtosis	$RKu$	$SKu$
Correlation length (lowest value)	$\lambda$	$Sa\lambda$
Correlation length (biggest value)	$\lambda$	$Sa\lambda/Str$

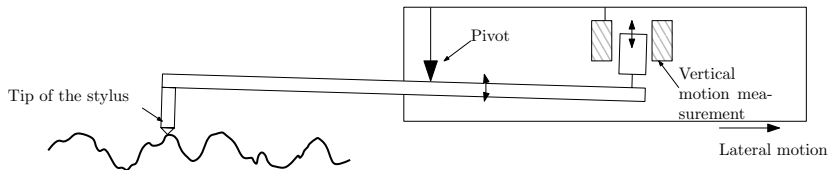
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# Topography measurement

Stylus profiler:

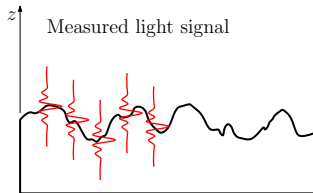
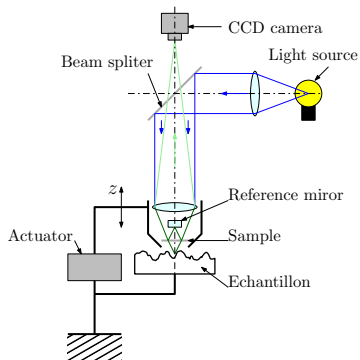
- Vertical resolution  $\Delta z = 1\text{nm}$ ;
- Lateral resolution  $\Delta x = 2\mu\text{m} = \text{curvature radius of the tip}$ ;
- Sample length  $L_x = \text{mm}$ ;
- Requires profile or surface scan (can create scratches in soft materials)



# Topography measurement

White light interferometer:

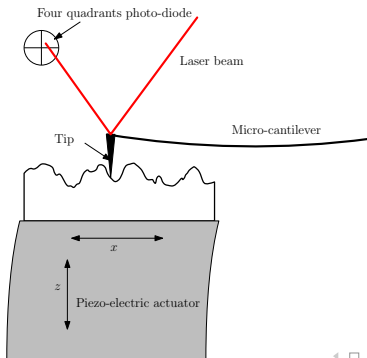
- Vertical resolution  $\Delta z < 0.1nm$ ;
- Lateral resolution  $\Delta x \simeq 0.5\mu m$ ;
- Sample length  $L_x = 1mm$ ;
- Directly measures a surface. Possible outliers due to light reflexion.



# Topography measurement

Atomic force microscope:

- Vertical resolution  $\Delta z < 0.1nm$ ;
- Lateral resolution  $\Delta x \simeq 1nm$ ;
- Sample length  $L_x < 0.1mm$ ;
- Requires profile or surface scan.



# Topography measurement

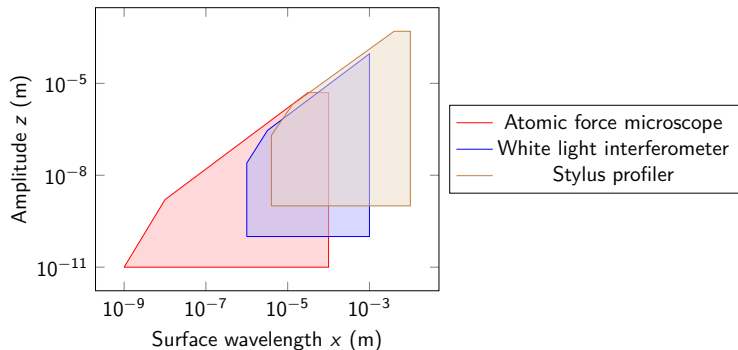
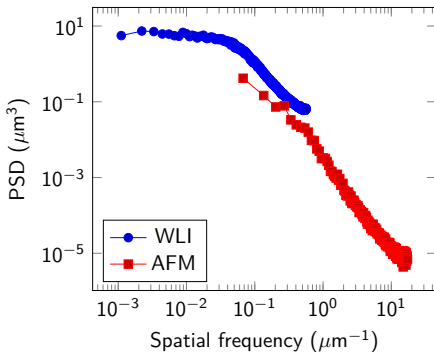


Figure: Comparison of the ranges of measurement of instruments (including slope and radius limits)

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<sup>5</sup>M. Stedman. "Basis for comparing the performance of surface-measuring machines". In: *Precision Engineering* 9.3 (1987), pp. 149–152. ISSN: 0141-6359. DOI: [https://doi.org/10.1016/0141-6359\(87\)90032-8](https://doi.org/10.1016/0141-6359(87)90032-8).

# Comparison of instruments



Necessity to specify the instrument  
(sample length and lateral sampling)  
when giving  $Sq$  values

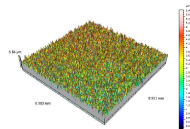


Figure: WLI (White Light Interferometer),  
 $Sq = 0.93\mu\text{m}$ ,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$

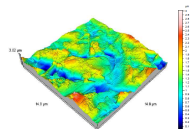


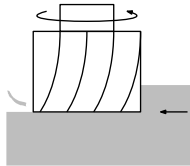
Figure: AFM (Atomic Force Microscope),  
 $Sq = 0.37\mu\text{m}$ ,  $L = 14.8\mu\text{m}$ ,  $\Delta x = 0.029\mu\text{m}$



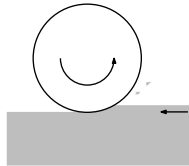
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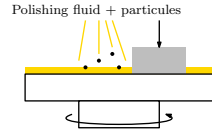
# Usual machining process



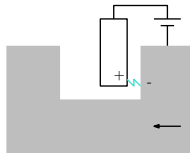
Milling



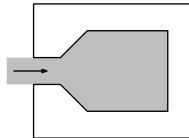
Grinding



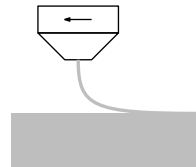
Honing and polishing



Electroerosion



Molding

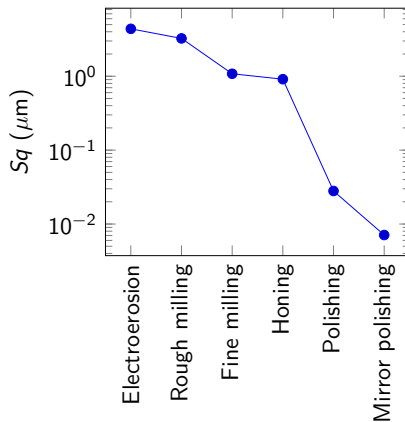


3D printing

Figure: Some usual surfaces production methods

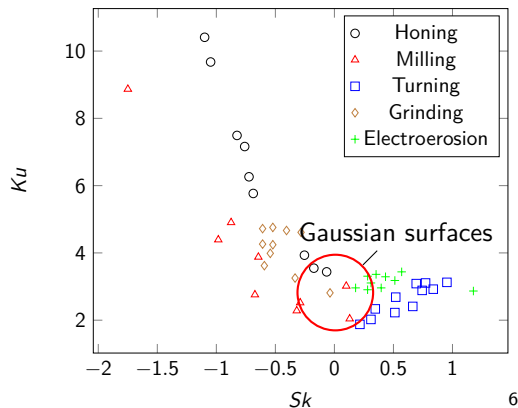
# Impact of machining on topography

Impact of the machining process on the roughness height  $S_q$  (WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ ):



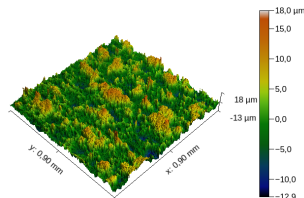
# Impact of machining on topography

Impact of the machining process on the Gaussian nature of the surface:



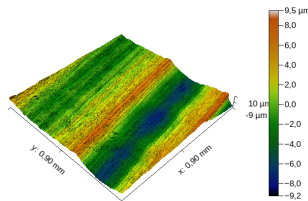
<sup>6</sup>D.J. Whitehouse. *Handbook of Surface and Nanometrology*. IOP Publishing, 2003.

# Examples of surfaces



Paramètre	Valeur
$Sq$ ( $\mu m$ )	4.38
$Sa$ ( $\mu m$ )	3.55
$SSk$	0.60
$SKu$	2.793

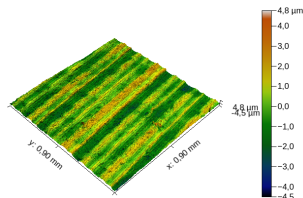
Figure: Surface obtained by electrosion ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ .



Paramètre	Valeur
$Sq$ ( $\mu m$ )	3.25
$Sa$ ( $\mu m$ )	2.63
$SSk$	-0.04
$SKu$	2.51

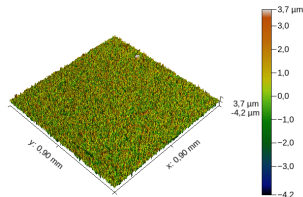
Figure: Surface obtained by rough milling ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ .

# Examples of surfaces



Paramètre	Valeur
$Sq$ ( $\mu m$ )	1.08
$Sa$ ( $\mu m$ )	0.89
$SSk$	0.034
$SKu$	2.49

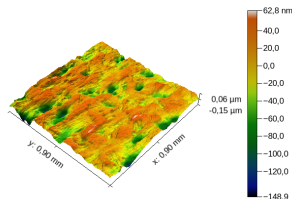
Figure: Surface obtained by fine milling ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ .



Paramètre	Valeur
$Sq$ ( $\mu m$ )	0.912
$Sa$ ( $\mu m$ )	0.709
$SSk$	-0.24
$SKu$	3.93

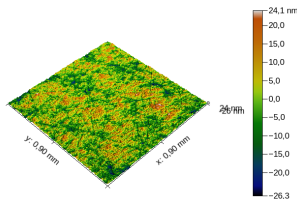
Figure: Surface obtained by honing ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ .

# Examples of surfaces



Paramètre	Valeur
$Sq$ ( $\mu m$ )	0.028
$Sa$ ( $\mu m$ )	0.022
$SSk$	-0.92
$SKu$	4.09

Figure: Surface obtained by polishing ( $z \times 500$ ), WLI,  $L = 0.9mm$ ,  $\Delta x = 0.9\mu m$ .



Paramètre	Valeur
$Sq$ ( $\mu m$ )	0.0071
$Sa$ ( $\mu m$ )	0.0057
$SSk$	-0.09
$SKu$	3.14

Figure: Surface obtained by mirror polishing ( $z \times 500$ ), WLI,  $L = 0.9mm$ ,  $\Delta x = 0.9\mu m$ .

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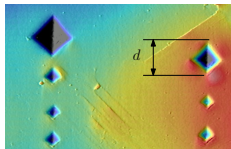
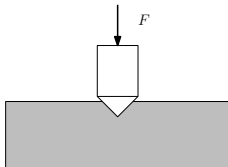
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# Hardness

- Hardness: Ability of a material (and its surface) to resist indentation. There are several types of tests to measure it.
  - Brinell with a ball (HB)
  - Vickers with pyramid (HV)
  - Rockwell with a cone (HRC)
  - Shore (Soft materials: elastomers)
- In the case of Vickers hardness, the hardness value,  $HV$  is expressed:

$$HV \text{ (kgf/mm}^2\text{)} \cong 0.189 \frac{F(N)}{d(mm)^2}$$



# Hardness

- The real hardness  $H$  is the pressure leading to permanent material deformation (plastic flow)
- It is the ratio of the indentation force to the indent area:

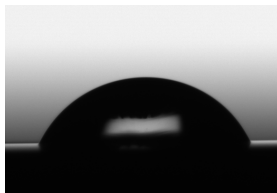
$$H \text{ (MPa)} = 2 \frac{F}{d^2} \cong \frac{2HV}{0.189} \cong 10HV$$

Matériau	$HV \text{ (kgf/mm}^2\text{)}$
Carbon steel	55-120
Stainless steel 316L	140
Martensite (steel with particular crystals arrangement)	1000
Alumina $Al_2O_3$	1800
Silicon carbide $SiC$	2000-3000
Diamond	10000

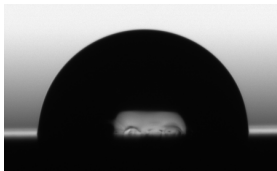
Table: Hardness of usual materials.

# Surface energy

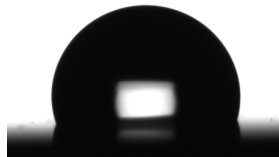
- Surface energy  $\gamma$ : It comes from surface molecules which are free to interact with the environment, unlike those inside the material.
- It affects adhesion and wettability: (From left to right: high  $\gamma$  to low  $\gamma$ ).



a)



b)



c)

Figure: Sessile water drop on a) Stainless steel b) Silicon carbide c) PTFE

# Surface energy

Material	$\gamma$ (mJ/m <sup>2</sup> )
Metals	800-3000
Ceramics	50-120
Polymers	10-30

Table: Surface energy of usual materials<sup>7</sup>.

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<sup>7</sup>R. Gras. *Tribologie - Principes et Solutions Industrielles*. Mécanique et Matériaux. Paris: Dunod, 2008; M.C. Mate. *Tribology on the Small Scale - A Bottom Up Approach to Friction, Lubrication and Wear*. Mesoscopic Physics and Nanotechnology. Oxford: Oxford University Press, 2008.

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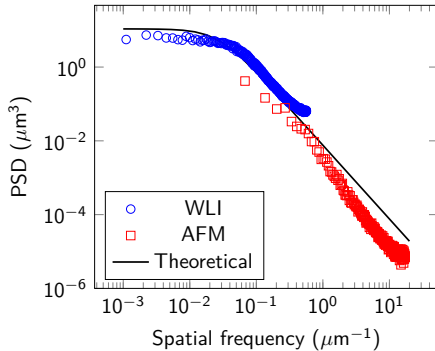
# Summary

- Solid surface = Interface between a solid and another media;
- The surface topography is characterised by  $Rq$  or  $Sq$  (roughness height) and  $\lambda$  (lateral scale of asperities);
- These parameters depend on the measuring instrument;
- The topography is affected by the machining process;
- Surfaces have specific properties :
  - Hardness  $H$ ;
  - Surface energy  $\gamma$ .

# Outline

- 1 Definition of surfaces
- 2 Structure of surfaces
- 3 Topography of surfaces
- 4 Topography measurement
- 5 Manufacturing process and topography
- 6 Surface properties
- 7 Summary
- 8 Application**

# Application



If the ACF is exponential, the PSD can be expressed:  $PSD = \frac{2Rq_0^2\lambda}{1+4\pi^2\lambda^2f^2}$ . Here  $Rq_0 = 0.95\mu\text{m}$  and  $\lambda = 6\mu\text{m}$

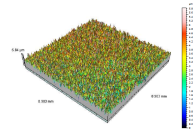


Figure: WLI (White Light Interferometer),  $Sq = 0.93\mu\text{m}$ ,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$

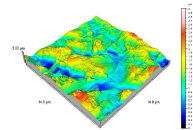
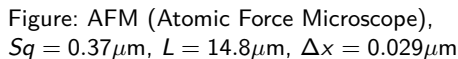
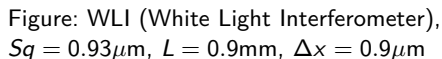


Figure: AFM (Atomic Force Microscope),  $Sq = 0.37\mu\text{m}$ ,  $L = 14.8\mu\text{m}$ ,  $\Delta x = 0.029\mu\text{m}$



- 1 We assume that  $PSD = \frac{2Rq_0^2\lambda}{1+4\pi^2\lambda^2f^2}$
- 2 Express the  $Rq$  value for frequencies in the range  $f_1$  and  $f_2$ . We use:  

$$\frac{Rq^2}{2} = \int_{f_1}^{f_2} PSD df$$
- 3 Calculate the theoretical values of  $Rq$  for the AFM and WLI and compare to the measured values.



# Surfaces topography and its effect on interactions with fluids and solids

Interaction of two solid surfaces

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March 9, 2022



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# Outline

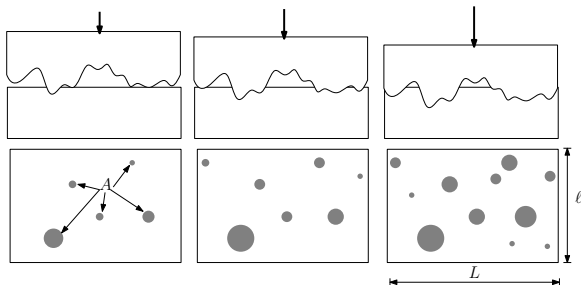
- 1 Introduction
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  - Elastic contact
  - Summary
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  - Definition of surface contact
  - Elastic surface contact
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  - Van der Waals force
  - Work of adhesion
  - Adhesion criteria
  - Summary
- 5 Synthesis and application

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# Objective of the chapter

- Understand the mechanical interactions of two contacting solids and the effect of surface topography
- The main parameter is the real contact area of solids
- How to determine this contact area ?
- Role of materials properties and surface topography
- Case of dry (no liquid, lubricants) elastic contact



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# Definition of the localized contact

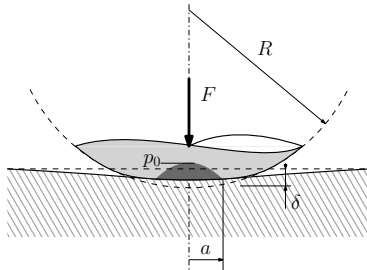
- The localized or non-conforming contact corresponds to the situations where the extent of contact is weak compared to the lateral extent of solids: We speak of linear or point contact;
- The mechanics of rigid solids does not make it possible to obtain information on the behavior of this contact (contact area is zero and contact pressure = force / area  $\rightarrow \infty$ , **Not realistic**);
- It is necessary to consider elasticity and deformation of the solids.



Figure: Examples of localized contacts: a) Ball bearing, b) Roller bearing and gear (Institut Pprime).

# Elastic contact

- In 1881 Hertz<sup>2</sup> proposed a theory to describe this type of contact;
- The hypothesis are:
  - The solids are continuous, smooth and non-conforming (very different radii of curvature); ;
  - The strains and displacements are small;
  - Each solid is a linear elastic infinite half-space;
  - There is no friction in the contact.

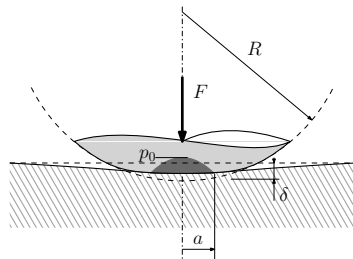


<sup>2</sup>G. Inglebert, T. Da Silva Botelho, and I. Lemaire Caron. "Théorie du contact de Hertz - Contacts ponctuels ou linéiques". In: *Techniques de l'Ingénieur*. □TRI 200, p. 12. ◀ ▶ ≡ ≡ ≡



# Elastic contact

- Contact of a ball on a plane;
- $F$  is the normal force applied to the ball;
- $R$  is the radius of the ball;
- The contact area is circular of radius  $a$ ;
- The interference of the two solids is  $\delta$ ;
- The results depends on the elastic properties of solids  $a$  and  $b$ : 
$$E' = \frac{2}{\frac{1-\nu_a^2}{E_a} + \frac{1-\nu_b^2}{E_b}}$$
- $E$  is the elastic modulus;
- $\nu$  is the Poisson' ratio.



# Elastic contact

- The contact radius  $a$  is expressed:

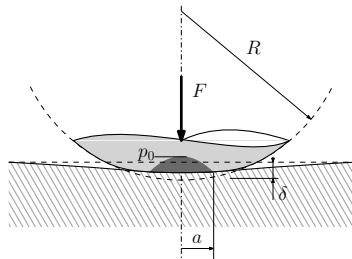
$$a = \left( \frac{3FR}{2E'} \right)^{1/3}$$

- The interference  $\delta$  is:  $\delta = \left( \frac{9F^2}{4RE'^2} \right)^{1/3}$
- The contact pressure  $p$  as a function of the radial coordinate  $r$  is:  $p(r) = p_0 \sqrt{1 - \frac{r^2}{a^2}}$
- The maximum contact pressure is:

$$p_0 = \frac{3F}{2\pi a^2}$$

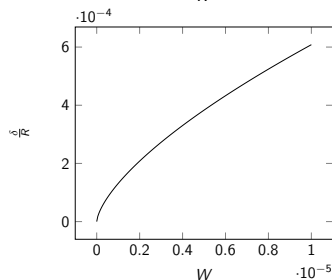
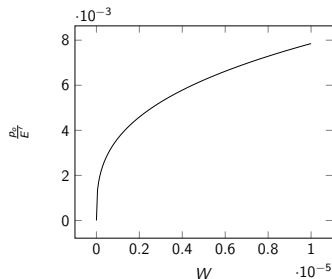
- The average contact pressure is:

$$p_m = \frac{F}{\pi a^2} = \frac{2p_0}{3}$$



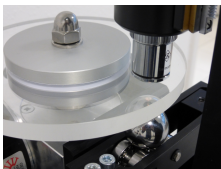
# Elastic contact

- Dimensionless force:  $W = \frac{F}{E' R^2}$
- Contact radius:  $\frac{a}{R} = \left(\frac{3}{2}W\right)^{1/3}$
- Interference:  $\frac{\delta}{R} = \left(\frac{3}{2}W\right)^{2/3}$
- Maximal pressure:  $\frac{p_0}{E'} = \frac{1}{\pi} \left(\frac{3}{2}W\right)^{1/3}$
- Example, ball on plate made of steel  
 $E' = 231 \text{ GPa}$ ,  $F = 200 \text{ N}$  et  $R = 1 \text{ cm}$
- $W = ?$ ,  $a = ?$ ;  $\delta = ?$ ,  $p_0 = ?$

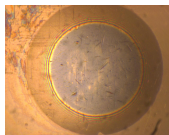
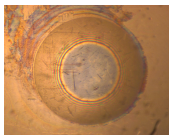


# Elastic contact

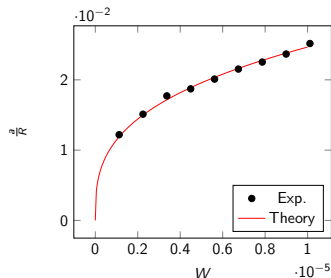
Comparison to experiments, contact between a steel ball and a glass disc (Tribology practical work room, SP2MI)



$$W = 0.225 \times 10^{-5} \quad W = 1.01 \times 10^{-5}$$

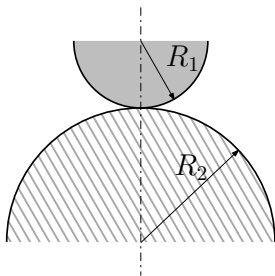


Contact area in dark

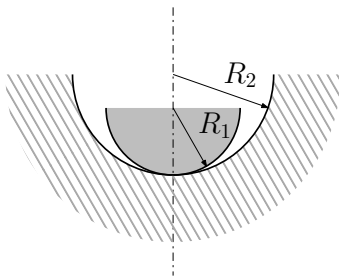


## Case of 2 spheres

The case of two spheres can be reduced to a ball of radius  $R$  in contact with a plane by a geometric transformation:



$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \quad (1)$$



$$\frac{1}{R} = \frac{1}{R_1} - \frac{1}{R_2} \quad (2)$$

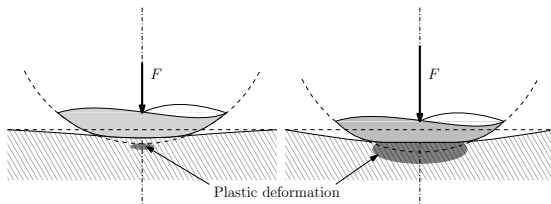
# Elastic limit and plastic deformation

If the applied load  $F$  is too high, plastic areas will appear:

- Maximum stress is below the surface at  $z = 0.5 a$ ;
- Condition for elastic behavior  $p_m < 0.35H$  ( $H$  = hardness)

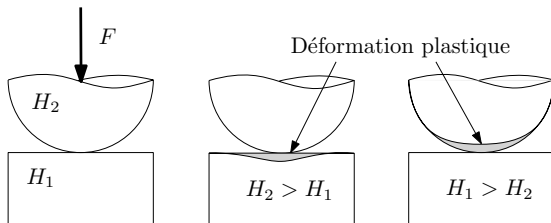
If the load is increased, there will be a full plastic area, it corresponds to a hardness test:

- by definition :  $p_m \simeq H$



# Elastic limit and plastic deformation

- The hardness  $H$  to be considered is that of the softer material (sphere or plane);
- If the sphere is harder, we will have an indentation (like a hardness test);
- If the plane is harder, it is the sphere which will deform plastically. Its radius of curvature will increase.



# Summary

- The contact of one spherical asperity with a plane can be analyzed with the Hertz theory;
- The contact area (and others parameters) depends on
  - elastic properties of the solids;
  - radius of the sphere
  - applied load
- If the load is too high there will be plastic deformation, depending on hardness  $H$ ;
- The contact of two spherical asperities can be transformed to one sphere on a plane.



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# Definition of surface contact

- There are many cases where the contact between solids occurs over a large area;
- In reality, the contact is limited to the tops of the asperities of the surfaces;
- In 1966, Greenwood and Williamson<sup>3</sup> proposed a model based on Hertz theory which allows to calculate the characteristics of surface contacts.



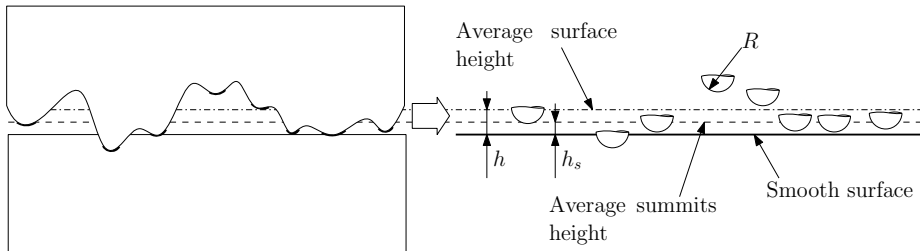
Figure: Examples of surface contact: a) Hip joint prosthesis (credit: NIADDK, 9AO4), b) Mechanical seal (credit: Institut Pprime).

<sup>3</sup>J. A. Greenwood and J. B. P. Williamson. "Contact of Nominally Flat Surfaces". In: *Proceedings of the Royal Society (London)* A295 (1966), pp. 300–319. 

# Elastic surface contact

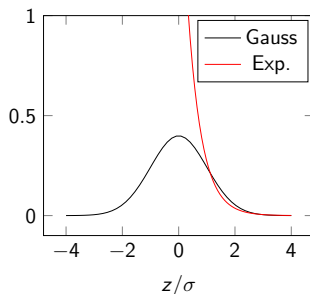
Assumptions used by Greenwood and Williamson:

- The summits of the asperities are spheres of uniform radius  $R$ ;
- The heights of the summits follow a Gaussian distribution, with standard deviation  $\sigma$ ;
- The summits deform independently;
- Each contact is an Hertzian contact;
- As for Hertz contact, it is possible to report all the asperities on one side (each contact is thus a ball on plane).



# Elastic surface contact

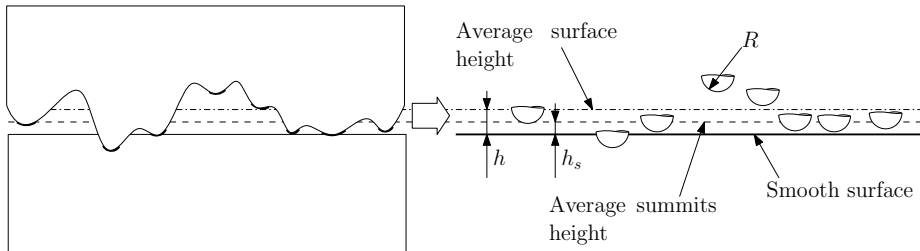
- Additional hypothesis: the contact occurring on the highest summits ( $z > 0$ ), it is possible to approximate the Gaussian curve (PDF of the summits) by an exponential:  $f(z) = 2 \times \exp\left(-2\frac{z}{\sigma}\right)$ ;
- Hypothesis valid if  $z > \sigma$ , which implies a limited loading.



# Elastic surface contact

List of the parameters:

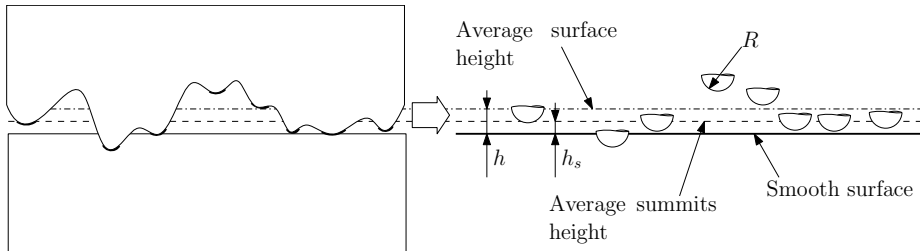
- Summit radius  $R$ ;
- Summit height standard deviation  $\sigma$ ;
- Summit density  $\eta$  = number of summits per unit area;
- Apparent area  $\mathcal{A}$ ;
- The total number of summits is thus:  $N = \eta \mathcal{A}$ ;



# Elastic surface contact

- Probability of contact if the distance between surfaces is  $h_s$ :  

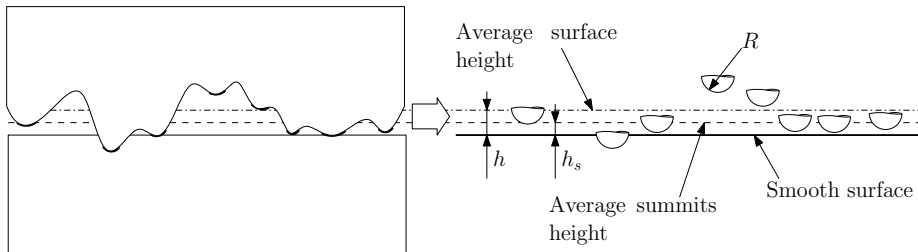
$$P(z > h_s) = \int_{h_s}^{\infty} f(z) dz;$$
- Number of summits in contact:  $n = N \times \int_{h_s}^{\infty} f(z) dz;$
- Contact area of one summit:  $A = \pi a^2 = \pi R^2 \left(\frac{3}{2}W\right)^{2/3} = \pi R \delta$
- The interference of the summit of height  $z$  is  $\delta = z - h_s$
- Total contact area is  $A = N \int_{h_s}^{\infty} \pi R (z - h_s) f(z) dz;$
- The same can be done for the load.



# Elastic surface contact

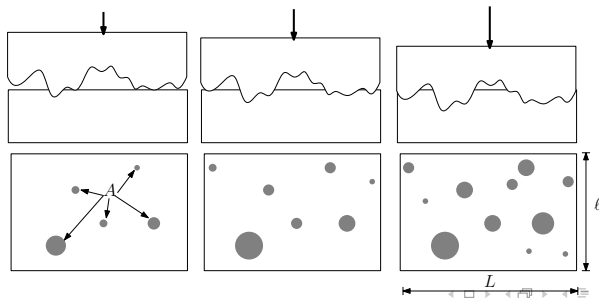
Finally, it is found that

- Number of summits in contact:  $n = \eta \mathcal{A} \exp\left(-\frac{2h_s}{\sigma}\right)$ ;
- Real area of contact:  $A = \pi R \frac{\sigma}{2} \eta \mathcal{A} \exp\left(-\frac{2h_s}{\sigma}\right)$ ;
- Contact force  $F = \eta \frac{E'}{2} \sqrt{\pi R \frac{\sigma^3}{8}} \mathcal{A} \exp\left(-\frac{2h_s}{\sigma}\right)$
- $n$ ,  $A$  and  $F$  increase exponentially as the distance  $h_s$  of surfaces decreases.



# Main results

- The relations indicate that the area  $A$  is proportional to the force  $F$ :  $F \propto A$ ;
- The average pressure is constant (independent of  $F$ ):  $p_m = \frac{F}{A} = \frac{E'}{2} \sqrt{\frac{\sigma}{2\pi R}}$ ;
- For a given summit, the contact pressure increases with  $F$  (Hertz theory);
- As new summits come into contact with weak pressure,  $p_m$  remains constant on average.
- For a given load  $F$  and surface topography, the real contact area  $A$  is independent of  $\mathcal{A} = L \times \ell$ ;

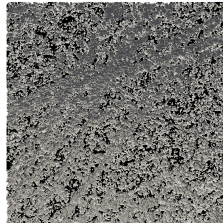
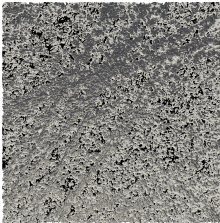
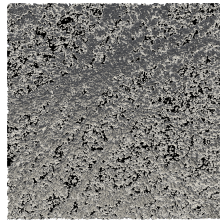
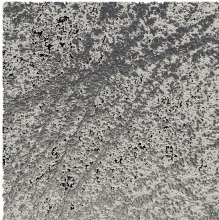




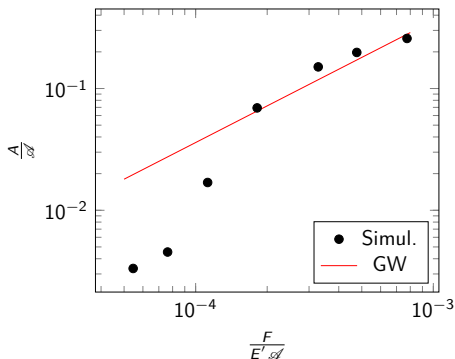
# Comparison to advanced numerical simulations

Contact area (black) for  $\frac{F}{E' \mathcal{A}} = 0.00018$  to  $0.00077$

The simulation was performed with measured surface topography.



# Comparison to advanced numerical simulations

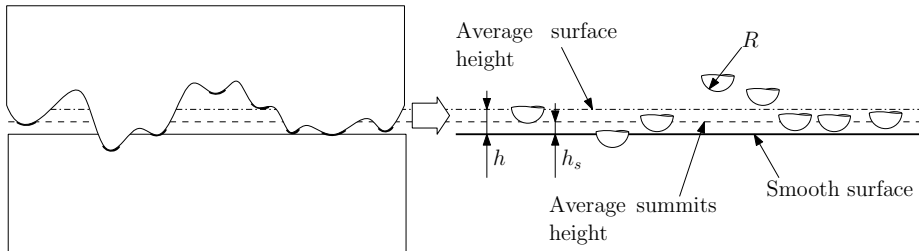


- For real surfaces, the proportionality  $F \propto A$  is observed on a range of force;
- The Greenwood et Williamson model gives a quite good approximation.

# Statistical parameters of the contact

Is it possible to find a relation with surface topography parameters:  $Sq$  and  $\lambda$ , correlation length ?

- Standard deviation:  $\sigma \approx Sq$
- Radius:  $R \approx \frac{\lambda_x \lambda_y}{Sq}$
- Density:  $\eta \approx \frac{1}{4\lambda_x \lambda_y}$
- Case of two rough surfaces:
- $Sq = \sqrt{Sq_1^2 + Sq_2^2}$
- $\frac{1}{\lambda} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$

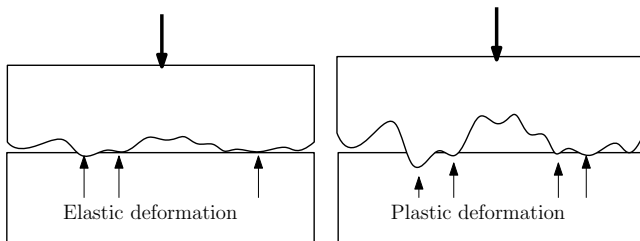


# Elastic limit and plastic deformation

- It is possible to exceed the elastic limit of the material.
- Greenwood and Williamson have defined an index that allows us to assess whether the behavior is elastic:  $\psi = \frac{E}{2H} \sqrt{\frac{\sigma}{R}} = p_m \sqrt{2\pi}$
- If  $\psi > 1$ , fully plastic behavior;
- if  $\psi < 0.6$ , elastic behavior;

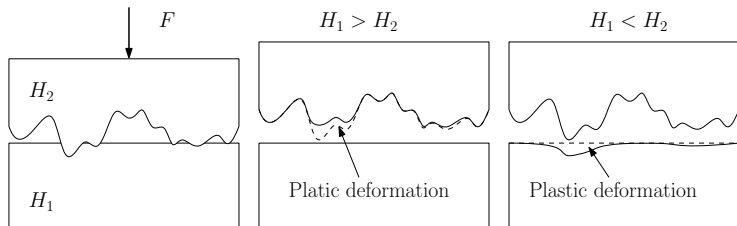
# Elastic limit and plastic deformation

- The plastic criteria is independent on the applied load;
- It depends on materials and surface topography;
- By using  $R \approx \frac{\lambda_x \lambda_y}{Sq}$  and  $\sigma \approx Sq$ , the plasticity index is:  $\psi = \frac{E'}{2H} \frac{Sq}{\sqrt{\lambda_x \lambda_y}}$
- The rougher the surface (high  $Sq$ ), the more plastic the deformation is likely to be.



# Elastic limit and plastic deformation

- The hardness  $H$  to be considered is that of the softer material;
- It is preferable that the harder material is smoother to avoid degrading the surface finish.



# Summary

- The contact of rough plane surfaces can be analyzed with the Greenwood Williamson theory;
- The contact area (and others parameters) depends on
  - elastic properties of the solids;
  - surface topography
  - applied load
- **The contact area is proportional to the load.**
- The average contact pressure is constant.
- A plasticity index  $\psi$ , depending on hardness  $H$  is used to verify if the contact is elastic or plastic;
- Rough surfaces can suffer of plastic deformation.

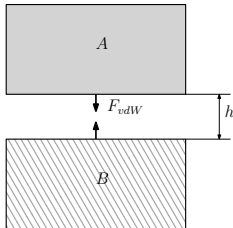
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# Van der Waals force

- 2 material particles are naturally attracted.
- the forces of Van der Waals allow this attraction to be described. In the case of 2 perfectly plane surfaces of area  $S$ , it is expressed:  $F_{vdW} = -S \frac{A}{6\pi h^3}$
- $A$  is the Hamaker constant. It depends on materials.
- It is linked to the surface energy<sup>4</sup>:  $A(J) \approx 2.1 \times 10^{-21} \gamma \text{ (mJ/m}^2\text{)}$

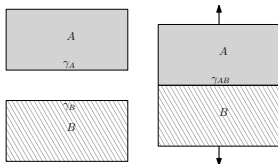


<sup>4</sup>M.C. Mate. *Tribology on the Small Scale - A Bottom Up Approach to Friction, Lubrication and Wear*. Mesoscopic Physics and Nanotechnology. Oxford: Oxford University Press, 2008.

# Work of adhesion

- It is the energy that will have to be brought to separate two perfectly plane surfaces in contact;
- This work is expressed as a function of the energy of surfaces (Dupré eq.)  

$$w_{ad}(AB) = \gamma_A + \gamma_B - \gamma_{AB}$$
- If the two materials are identical:  $w_{ad}(AA) = 2\gamma_A$
- In the case of two different materials, we can make the following approximation<sup>5</sup>:  $w_{ad}(AB) \approx 2\sqrt{\gamma_A\gamma_B}$



<sup>5</sup>H-J. Butt, K. Graf, and M. Kappl. *Physics and Chemistry of Interfaces*. Third edition. Weinheim, Germany: Wiley-VCH, 2016.

# Adhesion criteria

- The surfaces will separate if the stored elastic energy  $W_{el}$  is greater than the work of adhesion  $W_{ad}$ :  $\frac{W_{el}}{W_{ad}} > 1$
- Here we assume that work of adhesion is proportional to the contact area:  
 $W_{ad} = A \times w_{ad}$ .
- The elastic energy is:  $W_{el} = \int_{h_s}^{\infty} F dz$  where  $F$  is the applied load and  $h_s$  the final surface distances (rough surface contact).

# Adhesion criteria

- For rough surface contact, it can be shown that:  $\frac{W_{el}}{W_{ad}} = \frac{E'}{w_{ad}} \sqrt{\frac{\sigma^3}{R}} \sqrt{\frac{1}{32\pi}}$
- Gras<sup>6</sup> has defined an adhesion index :  $\alpha = \frac{E'}{2w_{ad}} \sqrt{\frac{\sigma^3}{R}}$  thus  $\alpha \approx 5 \frac{W_{el}}{W_{ad}}$
- There is a risk of adhesion if  $\alpha < 5$

Work of adhesion for different material families<sup>7</sup>:

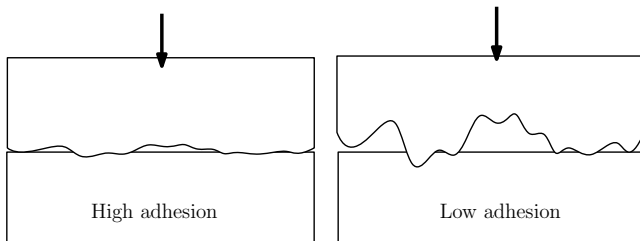
Contact	$w_{ad} \text{ mJ/m}^2$
Metal - Metal	1000-3000
Ceramic - Ceramic	100-500
Polymer - Polymer	< 100
Metal - Polymer	100-200
Metal - Ceramic	200-400
Ceramic - Polymer	50-150

<sup>6</sup>R. Gras. *Tribologie - Principes et Solutions Industrielles*. Mécanique et Matériaux. Paris: Dunod, 2008.

<sup>7</sup>Gras, *Tribologie - Principes et Solutions Industrielles*.

# Adhesion criteria

- The adhesion criteria is independent of the applied load;
- It depends on the material characteristics and the surface topography;
- If  $R \approx \frac{\lambda_x \lambda_y}{Sq}$  et  $\sigma \approx Sq$ , the adhesion criteria is:  $\alpha = \frac{E'}{2w_{ad}} Sq^2 \sqrt{\frac{1}{\lambda_x \lambda_y}}$
- The smoother the surface (low  $Sq$ ), the higher the risk of adhesion.



# Summary

- Adhesion of materials occurs in zones of contact;
- The adhesion intensity is quantified by the work of adhesion;
- By comparing the elastic stored energy and the work of adhesion, it is possible to define an adhesion criteria  $\alpha$ . It depends on
  - elastic properties of the solids;
  - surface topography
  - work of adhesion
- Smooth surfaces can suffer of adhesion.

# Outline

- 1 Introduction
- 2 One asperity localized contact
  - Definition of the localized contact
  - Elastic contact
  - Summary
- 3 Contact of surfaces
  - Definition of surface contact
  - Elastic surface contact
  - Elastic limit and plastic deformation
  - Summary
- 4 Adhesion
  - Van der Waals force
  - Work of adhesion
  - Adhesion criteria
  - Summary
- 5 Synthesis and application

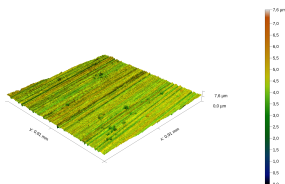
# Synthesis

- Possibility of calculating the contact area  $A$  between two solids;
- One asperity contact described by the Hertz theory;
- Surface contact described by Greenwood and Williamson theory;
- Surface contact: the force  $F$  and the contact area  $A$  are proportional  $F \propto A$ . The average pressure  $p_m$  is constant.
- Surface contact: We define elastic limit criteria  $\psi$  and adhesion criteria  $\alpha$  which depend on the materials  $E'$ ,  $w_{ad}$ ,  $H$  and on the state of surface  $Sq$  and  $\lambda$ .



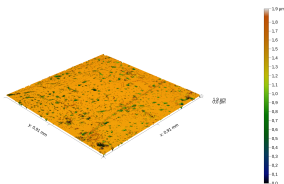
# Application: Study of gauge blocks

- Elastic modulus:  
 $E' = 231\text{GPa}$
- Surface energy:  
 $\gamma = 1\text{ J/m}^2$
- Calculate average contact pressure.
- Check the adhesion criteria



Parameter	Value
$Sq\ (\mu m)$	0.448
$Sal\ (\mu m)$	5.9

Figure: Rough face ( $z \times 10$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu m$ .



Parameter	Value
$Sq\ (\mu m)$	0.0124
$Sal\ (\mu m)$	7.9

Figure: Smooth face ( $z \times 10$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu m$ .

# Surfaces topography and its effect on interactions with fluids and solids

Interaction of a liquid and a solid surface

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March 10, 2022



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# Outline

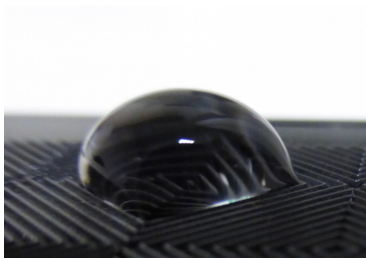
- 1 Introduction
- 2 Surface tension of liquid
  - Definition
  - Experimental evidence and measurement
  - Laplace equation
  - Capillary length
- 3 Wetting of a solid surface
  - Introduction
  - Contact angle
  - Effect of surface topography
- 4 Liquid between two surfaces
  - Introduction
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  - Adhesion / repulsion of two wet surfaces
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# Objectives of the chapter

- Understand the mechanical interactions of a liquid and a solid surface and the effect of surface topography
- One of the main parameter is the contact angle
- Will the liquid spread on the surface?
- How to determine the surface energy of a solid surface?
- Role of materials properties and surface topography
- Cases of a liquid on one surface and between two solid surfaces

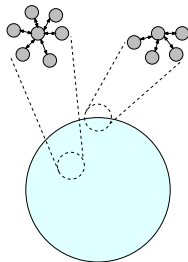


# Outline

- 1 Introduction
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# Definition of the surface tension of a liquid

- The surface tension is a tension force per unit length of a line on the liquid surface. In the case of liquid, it is equivalent to  $\gamma$ , the surface free energy<sup>2</sup>
- This is not true for solids (not discussed in the course)
- The surface tension tends to reduce the surface area of the liquid (or to minimize its energy level)
- It originates from that fact that molecules located on the surface interact only with molecules located in the bulk of the liquid.



<sup>2</sup>E. Bormashenko. *Wetting of Real Surfaces*. Berlin, Boston: De Gruyter, 2013.

# Experimental evidence



Figure: Water strider walking on water surface (By Cory, CC BY-SA 2.1 jp, [commons.wikimedia.org/w/index.php?curid=1242390](https://commons.wikimedia.org/w/index.php?curid=1242390))

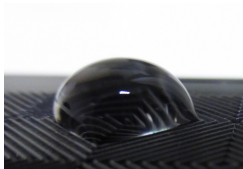


Figure: A water drop keeping its shape



Figure: A metal coin floating on water (By Roger McLassus — Travail personnel, CC BY-SA 3.0, [commons.wikimedia.org/w/index.php?curid=665478](https://commons.wikimedia.org/w/index.php?curid=665478))



# Measurement of liquid surface tension



Figure: The pendant drop methods with contour identification

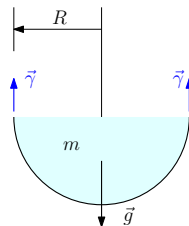


Figure: Force balance

- Surface tension force:  $2\pi R\gamma$
- Weight:  $-mg$
- $2\pi R\gamma - mg = 0$

# Surface tension of liquids

- Surface tension of 'standard' liquids are in the range 20 -70 mJ/m<sup>2</sup>, except for liquid metals
- The surface tension is a decreasing function of  $T$

Surface tension of different liquid in ambient conditions<sup>3</sup>:

Fluid	$\gamma$ mJ/m <sup>2</sup>
Glycerol	64.7
Ethanol	22
Acetone	24
Honey	50 - 60
Water	71

<sup>3</sup>Bormashenko, *Wetting of Real Surfaces*.

# Laplace equation

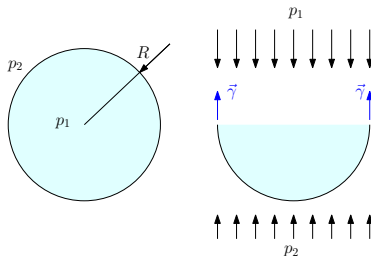


Figure: Axial force balance on a spherical drop or bubble

- External force pressure:  $\pi R^2 p_2$
- Internal force pressure:  $-\pi R^2 p_1$
- Surface tension force:  $2\pi R \gamma$
- Laplace equation:  $\frac{2\gamma}{R} = p_1 - p_2$
- General case with 2 curvature radii:  $\gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) = p_1 - p_2$

# Capillary length

- Hydrostatic pressure due to gravity:  $p_1 + \rho g z_1 = p_2 + \rho g z_2$
- Pressure difference:  $p_1 - p_2 = \rho g (z_2 - z_1) = \rho g h$
- By combining the Laplace equation and the hydrostatic pressure equation, it is possible to define a length scale (the capillary length) :  $\ell_c = \sqrt{\frac{\gamma}{\rho g}}$
- If the radius of a drop is smaller than  $\ell_c$  it will remains spherical, if not, the gravity will deform the drop.

# Capillary length

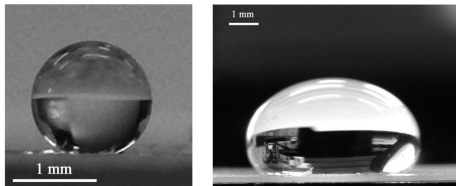


Figure: Effect of volume of water drop on its shape: left  $V = 10 \mu\text{l}$ , right  $V = 200 \mu\text{l}$ <sup>4</sup>

- Capillary length of water:  $\ell_c = \sqrt{\frac{\gamma}{\rho g}} = ?$
- Comparison to the images

<sup>4</sup>Bormashenko, *Wetting of Real Surfaces*.

# Summary

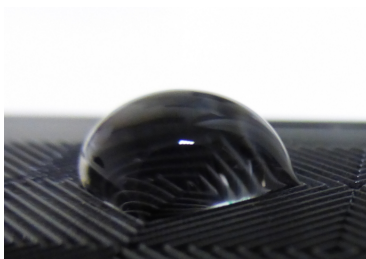
- Liquid surfaces have a surface tension (or surface energy)
- It can be measured using the pendant drop method
- Due to surface tension, the pressure on both sides of the interface can be different (laplace equation)
- There exists a capillary length. This a characteristic size below which surface tension effect are dominant on gravity effect.
- A liquid drop having a size below the capillary length will keep a spherical shape.

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# Introduction

- When a liquid drop is deposited on a surface it will spread to a certain extent
- What are the mechanisms controlling spreading ?
- What is the effect of surface topography ?





# Contact angle: Mechanical approach

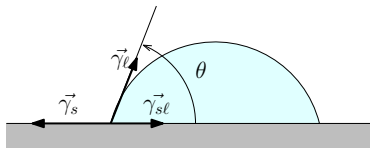


Figure: Sessile drop on a solid flat surface

- Liquid surface tension  $\gamma_\ell$
- Solid surface tension (or surface energy)  $\gamma_s$
- Solid liquid interfacial tension  $\gamma_{sl}$
- Contact angle  $\theta$
- Force balance in the horizontal direction:  $\gamma_{sl} + \cos\theta\gamma_\ell - \gamma_s = 0$
- Young equation:  $\cos\theta\gamma_\ell = \gamma_s - \gamma_{sl}$

# Contact angle: Energetic approach

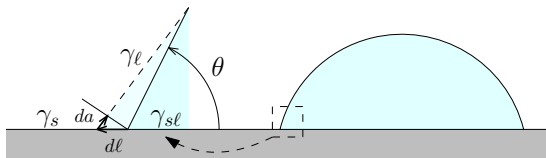


Figure: Energy balance at equilibrium

- Liquid surface energy variation  $da\gamma_\ell$
- Solid surface energy variation  $-dl\gamma_s$
- Solid liquid interfacial energy variation  $d\ell\gamma_{sl}$
- At equilibrium the energy is minimized, small variation must vanish
- $da\gamma_\ell + d\ell\gamma_{sl} - dl\gamma_s = 0$
- Geometric relation:  $da = \cos\theta dl$
- Young's equation:  $\gamma_\ell \cos\theta = \gamma_s - \gamma_{sl}$

# Different surface types

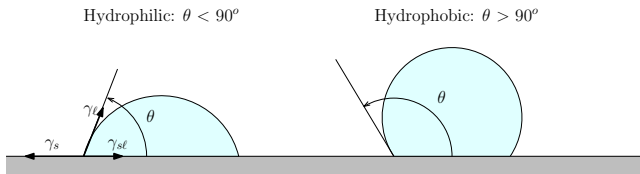
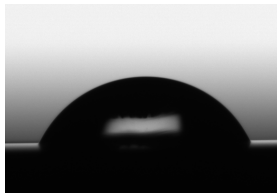


Figure: Surfaces classifications

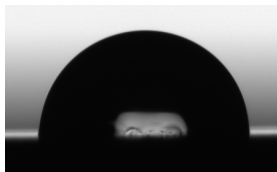
- The angle characterizes the affinity of the solid and liquid;
- Small angle corresponds to a good affinity;
- High surface energy solids (high  $\gamma_s$ ) are generally hydrophilic;
- Low surface energy solids (low  $\gamma_s$ ) are generally hydrophobic;
- If  $\gamma_s > \gamma_{sl} + \gamma_l$ , the fluid totally spreads (no remaining drop).

# Surface energy and wetting

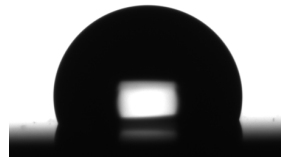
- Examples of contact angle on solids of decreasing surface energy.



a)



b)



c)

Figure: Sesille water drop on a) Stainless steel b) Silicon carbide c) PTFE

# Wetting of a rough surface

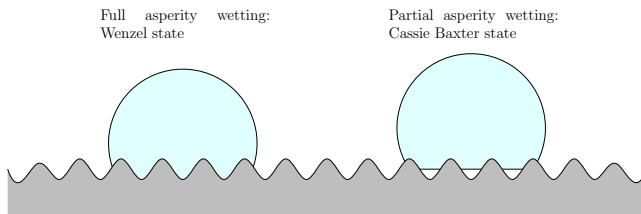


Figure: Different wetting regimes of a rough surfaces

- Different wetting regimes of a rough surface
- Wenzel state: the asperities are fully wetted
- Cassie-Baxter state (or fakir state): partial wetting of the asperities
- The most energetically favorable state will be reached

# Wenzel regime

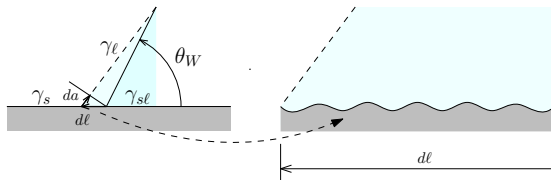


Figure: Energy balance at equilibrium

- Liquid surface energy variation  $da\gamma_l$
- Solid surface energy variation  $-d_r\ell\gamma_s$
- Solid liquid interfacial energy variation  $d_r\ell\gamma_{sl}$
- The real length is linked to the linear length by  $d_r\ell = Rdl$
- $R$  is a roughness factor  $\geq 1$ .
- Young equation:  $\cos\theta_W\gamma_l = R(\gamma_s - \gamma_{sl})$
- Wenzel relation:  $\cos\theta_W = R\cos\theta$
- Hydrophilic ( $\cos\theta > 0$ ) :  $\theta_W < \theta$
- Hydrophobic ( $\cos\theta < 0$ ) :  $\theta_W > \theta$

# Cassie-Baxter regime

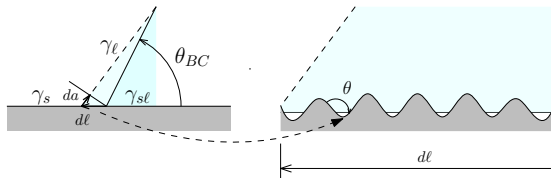


Figure: Energy balance at equilibrium

- Liquid surface energy variation  $da\gamma_\ell$
- Solid surface energy variation  $-d_r\ell\gamma_s$
- Solid liquid interfacial energy variation:  $fd_r\ell\gamma_{sl} + (1-f)d\ell\gamma_\ell + (1-f)d_r\ell\gamma_s$
- The real length is linked to the linear length by  $d_r\ell = R d\ell$
- $R$  is a roughness factor  $\geq 1$ .
- $f$  is fraction of solid wetted by the liquid.
- Energy balance:  $\cos\theta_{BC}\gamma_\ell + fR(\gamma_{sl} - \gamma_s) + (1-f)\gamma_\ell = 0$
- Cassie-Baxter relation:  $\cos\theta_{BC} = fR\cos\theta + f - 1$

# Example of contact angle on rough surfaces<sup>5</sup>

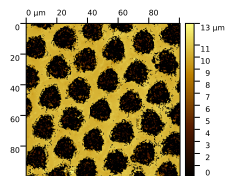
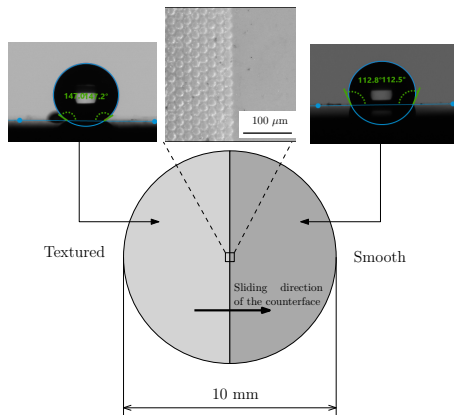


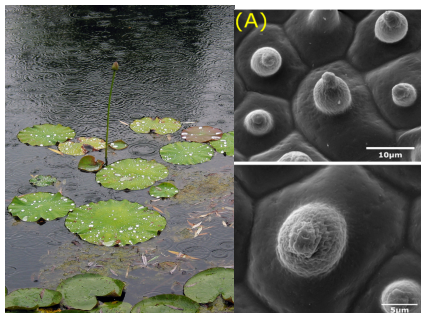
Figure: Topography of the rough surface

Figure: Increase of contact angle by surface texturing

<sup>5</sup>Hiba Jendoubi, Olga Smerdova, and Noël Brunetière. "Unexpected Frictional Behavior of Laser-Textured Hydrophobic Surfaces". In: *Lubricants* 9.3 (2021). ISSN: 2075-4442. DOI: 10.3390/lubricants9030031. URL: <https://www.mdpi.com/2075-4442/9/3/31>



# Natural superhydrophobic surfaces<sup>6</sup>



## Lotus leaf

Low surface energy material combined with surface roughness leads to superhydrophobic behavior !

<sup>6</sup>Floris Honig et al. "Natural Architectures for Tissue Engineering and Regenerative Medicine". en. In: *Journal of Functional Biomaterials* 11.3 (Sept. 2020), p. 47. DOI: 10.3390/jfb11030047. (Visited on 11/23/2020).

# Wetting of a rough surface

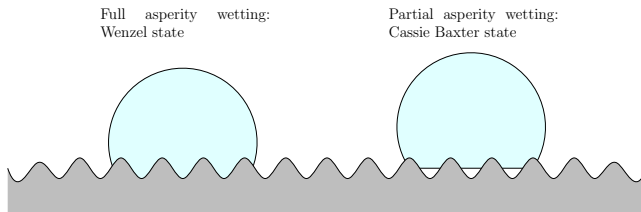


Figure: Different wetting regimes of a rough surfaces

- What will be the wetting regime ?
- The most energetically favorable state will be reached.
- It corresponds to the lowest contact of the two regimes:
- If  $\theta_{BC} < \theta_W$ , it will be the partial wetting;
- If  $\theta_{BC} > \theta_W$ , it will be the full wetting.

# Roughness parameters of engineered surfaces

- $R = S_r \text{ real area} / S \text{ projected surface}$   
(along  $x, y$ )
- ISO parameter:  $Sdr = \frac{S_r - S}{S} = R - 1$
- Electro-eroded surface:  $Sdr = 0.49$ ,  
 $R = 1.49$
- Significant impact of roughness on wetting

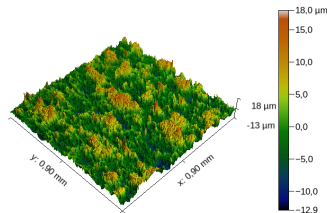


Figure: Surface obtained by electrorosion ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ ,  $Sq = 4.38\mu\text{m}$ .

# Roughness parameters of engineered surfaces

- $R = S_r \text{ real area} / S \text{ projected surface}$   
(along  $x, y$ )
- ISO parameter:  $Sdr = \frac{S_r - S}{S} = R - 1$
- Milled surface:  $Sdr = 0.099$ ,  $R = 1.099$
- Moderate impact of roughness on wetting

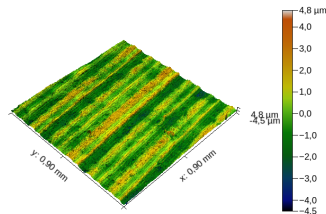


Figure: Surface obtained by fine milling ( $z \times 5$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ ,  $Sq = 1.08\mu\text{m}$ .

# Roughness parameters of engineered surfaces

- $R = S_r \text{ real area} / S \text{ projected surface}$  (along  $x, y$ )
- ISO parameter:  $Sdr = \frac{S_r - S}{S} = R - 1$
- Milled surface:  $Sdr = 0.00$ ,  $R = 1.00$
- No impact of roughness en wetting

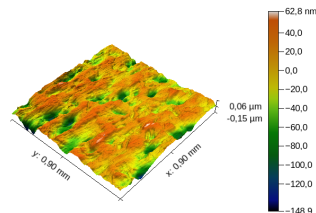
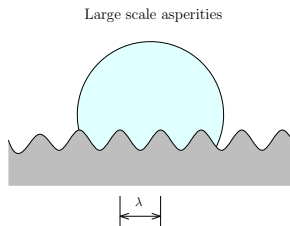
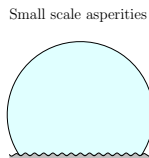


Figure: Surface obtained by polishing ( $z \times 500$ ), WLI,  $L = 0.9\text{mm}$ ,  $\Delta x = 0.9\mu\text{m}$ ,  $Sq = 0.028\mu\text{m}$ .

# Impact of roughness lateral scale



a)



b)

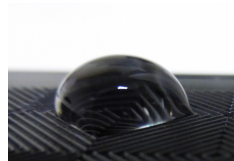


Figure: a) Effect of roughness lateral scale - b) Example of large scale asperities

- The Wenzel and Cassie Baxter equations work if:
- The lateral scale is small  $\lambda$  is small compared to the drop radius.
- More accurately  $\lambda \ll \ell_c$ , the capillary length.
- The equations are not relevant for figure b)

# Summary

- The wetting of solid surfaces is controlled by the surface tension (or surface energy) of the liquid and the solid
- The wetting is characterized by the contact angle: low contact angle = better wetting
- The contact angle is given by the Young equation.
- A high surface energy material is generally hydrophilic
- A low surface energy material is generally hydrophobic
- The surface roughness can have a significant impact on wetting
- In this case, the contact angle is obtained from the Wenzel or Cassie Baxter equation
- Surface roughness + low surface energy can lead to a super-hydrophobic behavior (like lotus leaf)

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- 5 Synthesis and application



# Introduction



a)



b)



c)



d)

Figure: Examples of lubricated contacts: a) ball bearing b) gear and roller bearing c) mechanical seal d) Artificial hip joint<sup>8</sup>

- Many solids contacts are lubricated by a fluid;
- The way the fluid will interact with surfaces is important;
- It can help spreading the lubricant.

<sup>8</sup>

Par X-ray Image ID: 3684. Photographer: Unknown. - from NIH Here. Credit: NIADDK, 9A04 (Connie Raab-contact); NIH., Domaine public, <https://commons.wikimedia.org/w/index.php?curid=789996>

# Capillary force

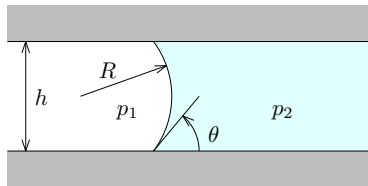


Figure: 2 identical surfaces wet with a wetting liquid ( $\theta < 90^\circ$ )

- Case of two flat surfaces of the same material separated of  $h$
- A liquid having affinity ( $\theta < 90^\circ$ ) is placed between the surfaces
- A meniscus will be formed with :  $h = 2R \cos \theta$
- If the meniscus is cylindrical, the Laplace equation gives:  $\frac{\gamma_\ell}{h} \cos \theta = p_1 - p_2$
- If initially  $p_1 = p_2 = p_{atm}$ , the meniscus will move to the left until  $p_2$  decreases enough to reach equilibrium.
- The meniscus is moved by the capillary force per unit area:  $\frac{\gamma_\ell}{h} \cos \theta$
- The fluid will naturally cover the surfaces, interesting for lubrication !!

# Capillary force

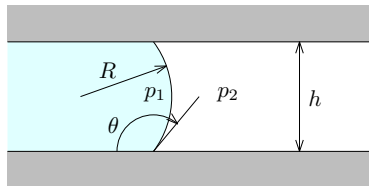


Figure: 2 identical surfaces wet with a non-wetting liquid ( $\theta > 90^\circ$ )

- Case of two flat surfaces of the same material separated of  $h$
- A liquid having low affinity ( $\theta > 90^\circ$ ) is placed between the surfaces
- A meniscus will be formed with :  $h = -2R \cos \theta$
- If the meniscus is cylindrical, the Laplace equation gives:  $-\frac{\gamma_\ell}{h} \cos \theta = p_1 - p_2$
- If initially  $p_1 = p_2 = p_{atm}$ , the meniscus will move to the left until  $p_1$  is high enough to reach equilibrium.
- The meniscus is moved by the capillary force per unit area:  $-\frac{\gamma_\ell}{h} \cos \theta$
- The fluid will naturally repel from the surfaces.
- In the case of sealing surfaces, it could be useful!!

# Adhesion / repulsion of two wet surfaces

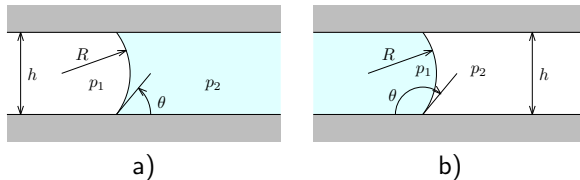


Figure: a) Case of two hydrophilic surfaces - b) Case of two hydrophobic surfaces

- When the meniscus has reached equilibrium position, there will be a pressure differential:
- Hydrophilic case: sub-ambient pressure in the liquid  $-\frac{\gamma_\ell}{h} \cos \theta$
- It will create an adhesion force making the separation of solids difficult
- Hydrophobic case: over-ambient pressure in the liquid  $-\frac{\gamma_\ell}{h} \cos \theta$
- It will create a repulsion force tending to separate the surfaces
- This force is proportional to the wet area and inversely proportional to  $h$  and can thus be very high!

# Summary

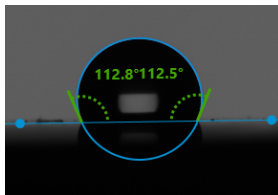
- In many applications, a liquid is placed between two surfaces (lubrication, sealing system, human body)
- Depending on the wetting properties of the surface, different behavior are found:
- For hydrophilic surfaces, the liquid will tend to spread in the gap and create an adhesion force.
- For hydrophobic surfaces, a pressure is needed to spread the liquid, it will create a repulsion force.

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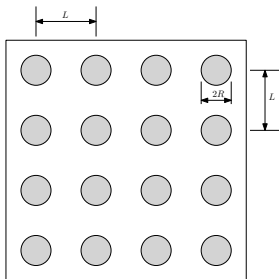
# Synthesis

- The interaction of liquid and a solid surface is controlled by their respective surface energy or surface tension.
- The wetting of the surface or spreading of the liquid is characterized by the contact angle
- Hydrophobic:  $\theta > 90^\circ$  and hydrophilic:  $\theta < 90^\circ$
- The surface topography can modify the contact angle
- The surface tension of the liquid creates a pressure differential (Laplace pressure)
- This pressure controls the wetting of a gap between two surfaces
- It can create an adhesion or a repulsion depending on the surface affinity with the liquid (hydrophobic or hydrophilic)



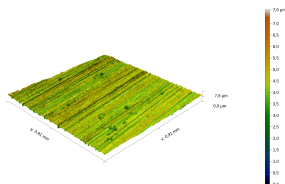
# Application

- A flat plate with cylindrical cavities of depth  $h$ .
- Express the contact angle in the Cassie-Baxter and Wenzel regime
- Application to PTFE and water:  $\theta = 110^\circ$ ,  $R = 4\mu\text{m}$ ,  $L = 10\mu\text{m}$ ,  $h = 1\mu\text{m}$  and  $10\mu\text{m}$



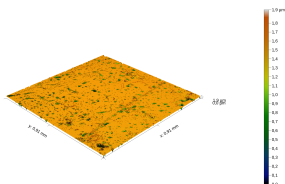


# Study of gauge blocks



Paramètre	Valeur
$Sq$ ( $\mu m$ )	0.448
$Sal$ ( $\mu m$ )	5.9
$Sdr$	0.023

Figure: Rough face ( $z \times 10$ ), WLI,  $L = 0.9mm$ ,  $\Delta x = 0.9\mu m$ .



Paramètre	Valeur
$Sq$ ( $\mu m$ )	0.0124
$Sal$ ( $\mu m$ )	7.9
$Sdr$	0.007

Figure: Smooth face ( $z \times 10$ ), WLI,  $L = 0.9mm$ ,  $\Delta x = 0.9\mu m$ .

- Calculate Wenzel contact angle with water  
 $\theta = 30^\circ$
- Adhesion force if  
 $h = 2Sq$