

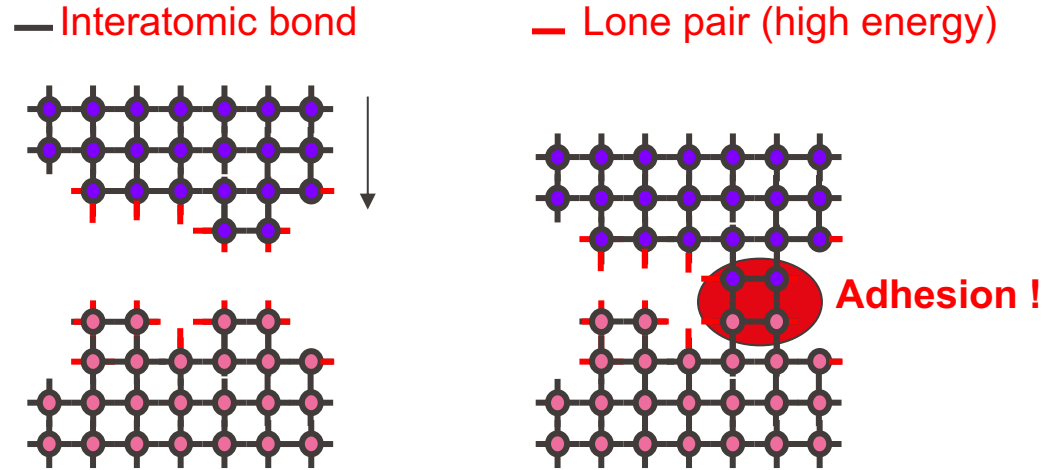
Chapter 2

Contact phenomena

MSE 485
Tribology

1. Adhesion
2. Contact mechanics
3. Surface topography

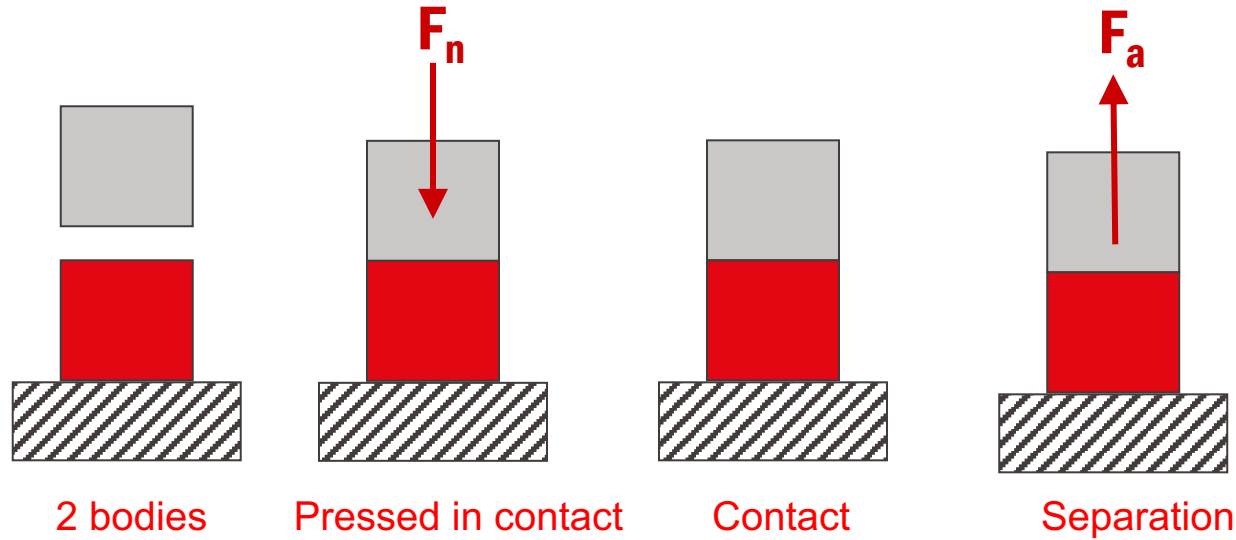
Bonding at the interface between two bodies brought into contact.



The degree of adhesion depends on :

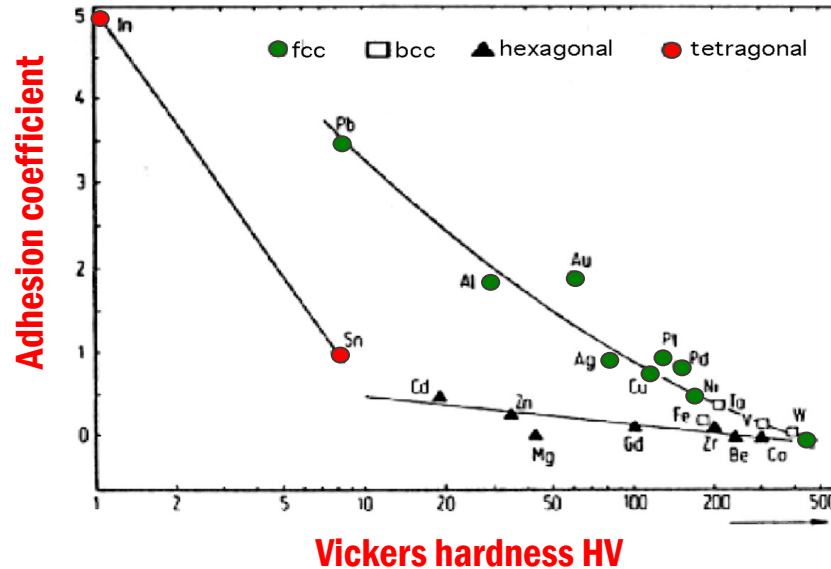
- Type of bonding : ionic, covalent, metallic, Van der Waals (dipoles)
- Malleability of the materials
- Surface roughness, cristallographic orientation
- Contaminants (oxidation, adsorption of molecules)

Adhesion test



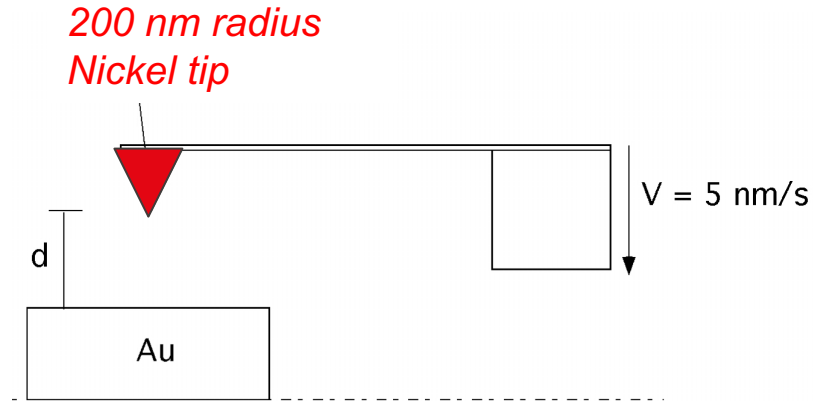
Coefficient of adhesion a :
$$a = \frac{F_a}{F_n} - 1$$

- Adhesion coefficient of pure metals against themselves as a function of **hardness** and **cristalline** structure :

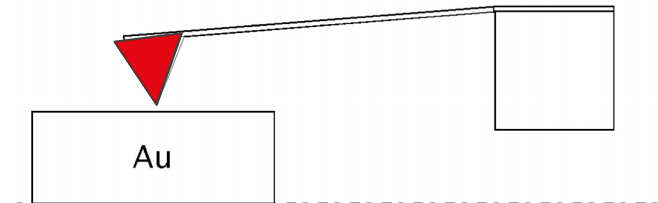


Source : H. Czichos, K.H. Habig, Tribologie Handbuch, Vieweg (1992)

- Experience with an AFM type tool : (*Landman et al, Science 248, 454-461, 1990*)



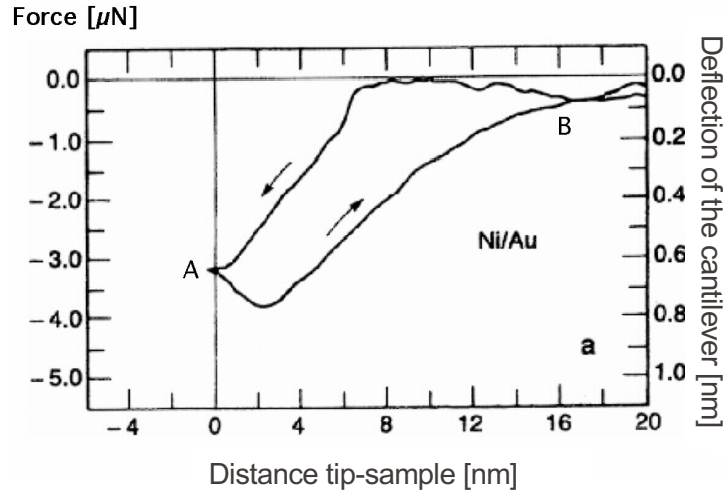
Approach of the Ni tip towards the Au sample at a constant speed.



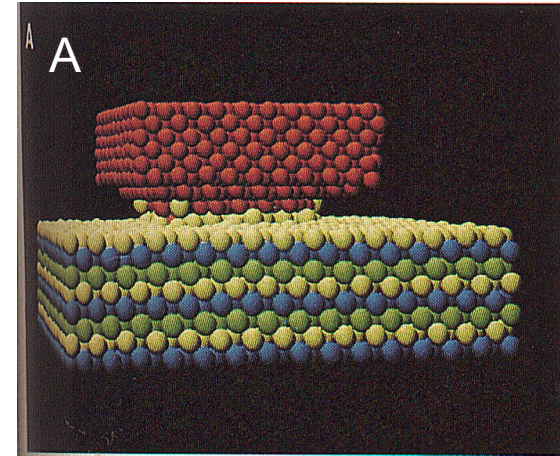
Deflection of the cantilever due to the attractive force between the Ni tip and the Au sample.

Case of a contact without indentation

- Experimental curves: force versus distance:



- Numerical simulation :
- (molecular dynamics based on Lennard-Johnes' potential)

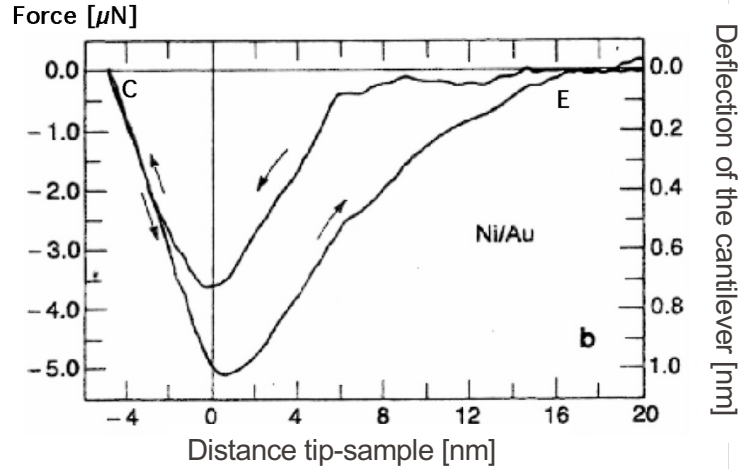


Red : Ni atoms

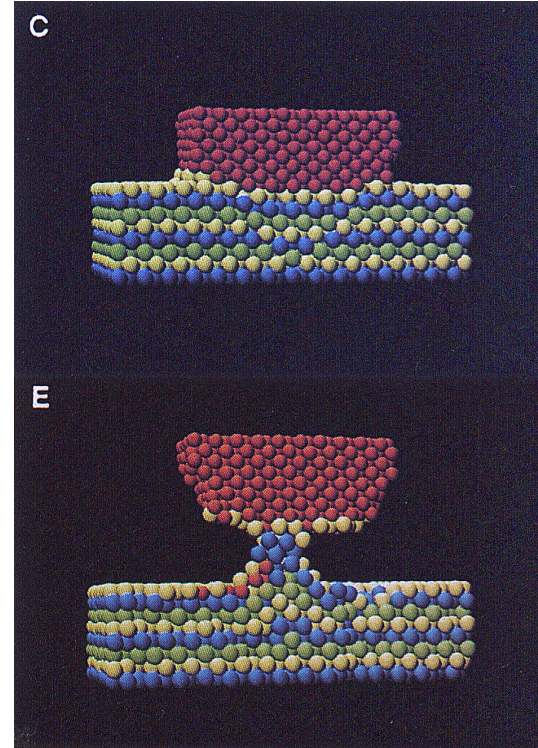
Yellow/Blue/Green : Au atoms

Case of a contact with indentation

- Experimental curves: force versus distance:



- Numerical simulation :



1. Adhesion

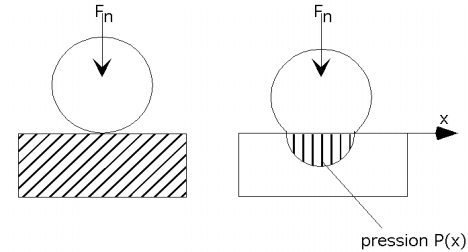
2. Contact mechanics

3. Surface topography

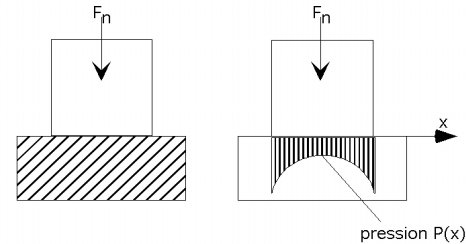
Study of the amplitude and distribution of mechanical stresses in a contact.

- Conformity of the contact

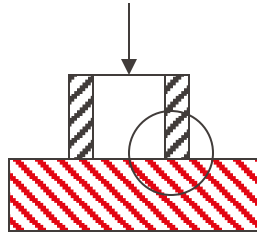
Non-conformal contact :



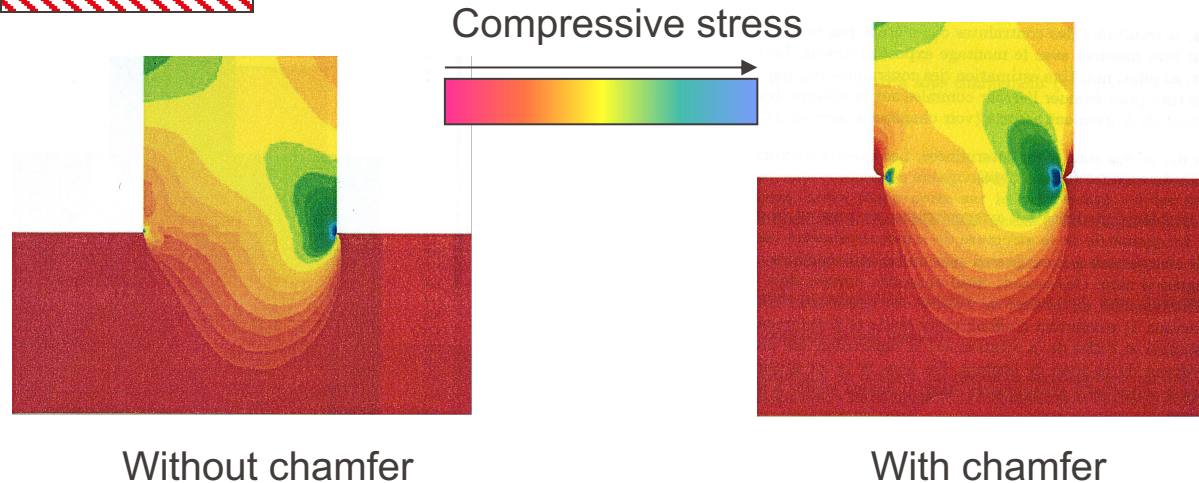
Conformal contact :



- Example of finite elements calculation of stress distribution in a conformal contact : rings-plane contact

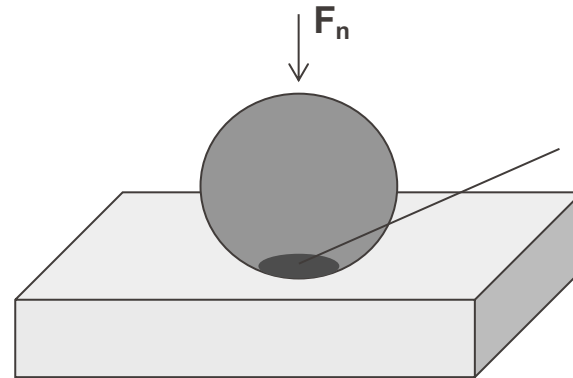


Source: Thèse I. Serre, Ecole Polytechnique Paris (2000)



Analysis of elastic stress fields. Non-conformal contacts

- Hertz mechanics for non-conformal contacts:
 - Calculation of elastic strain and stress in terms of load, geometrical parameters and materials.



Elastic deformation
defines the contact area.

Ball-plane contact

Hertz Contact Mechanics Formalism: example for a ball-plane contact

- Radius of contact area (circle) $a = \left(\frac{1.5 F_n R}{E'} \right)^{1/3}$

- Maximum contact pressure $p_0 = \frac{3 F_n}{2 \pi a^2}$

- Average contact pressure $p_m = \frac{F_n}{\pi a^2}$

- Maximum deflection $w = 1.31 \left(\frac{F_n^2}{E'^2 R} \right)^{1/3}$

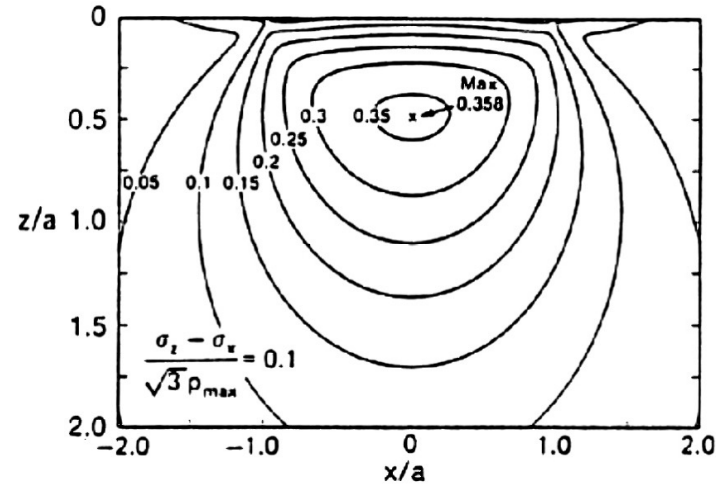
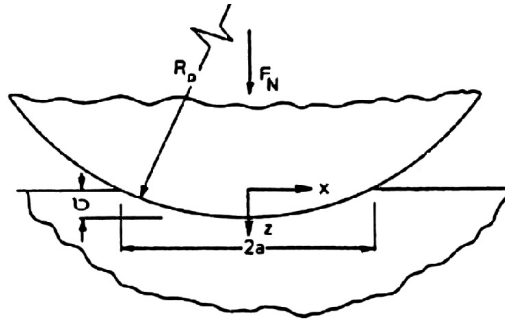
- Maximum shear stress $\tau_{\max} = \frac{p_0}{3}$

- Depth of maximum shear strength $z = 0.638 \cdot a$

$$\frac{1}{E'} = 0.5 \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]$$

E = Young's modulus
 ν = Poisson's ratio

- Distribution of the shear stresses in a ball-plane contact :



The maximum shear stress is located below the surface and corresponds to 1/3 of maximum pressure.

Source : H. Czichos, K.H. Habig, *Tribologie Handbuch*, Vieweg (1992)

Onset of plastic deformation

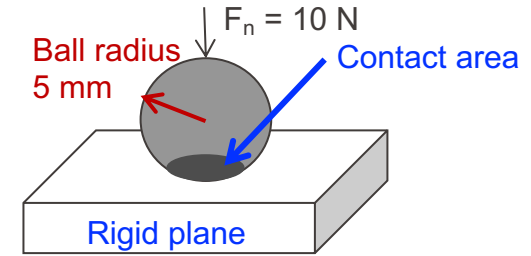
- **Tresca criterion:** plastic deformation occurs when a critical shear stress of $YS / 2$ (YS: Yield strength in uniaxial traction) is reached.

For a ball on plane contact plastic deformation occurs when:

$$P_0 > 1.61 \text{ YS}$$

$$P_m > 1.07 \text{ YS}$$

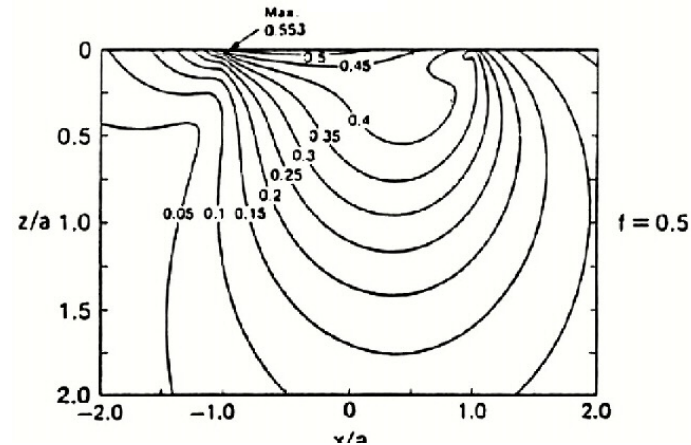
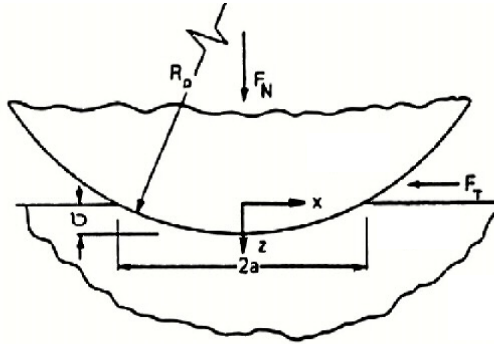
Application to different materials



Ball Material	Elastomer	Polymer	Metal	Ceramic	Unit
E Modulus	0.02	1	200	500	GPa
Poisson ratio	0.5	0.5	0.3	0.3	
Radius of contact area	1.121	0.304	0.057	0.043	mm
Average Pressure	3	34	995	1740	MPa
Yield Strength (σ_Y)	10	20	350	350	MPa
Av. Pressure/ σ_Y	0.3	1.7	2.8	5.0	

Softer but more elastic materials can accommodate contact stresses without plastic deformation

- Ball-plane contact : numerical calculation

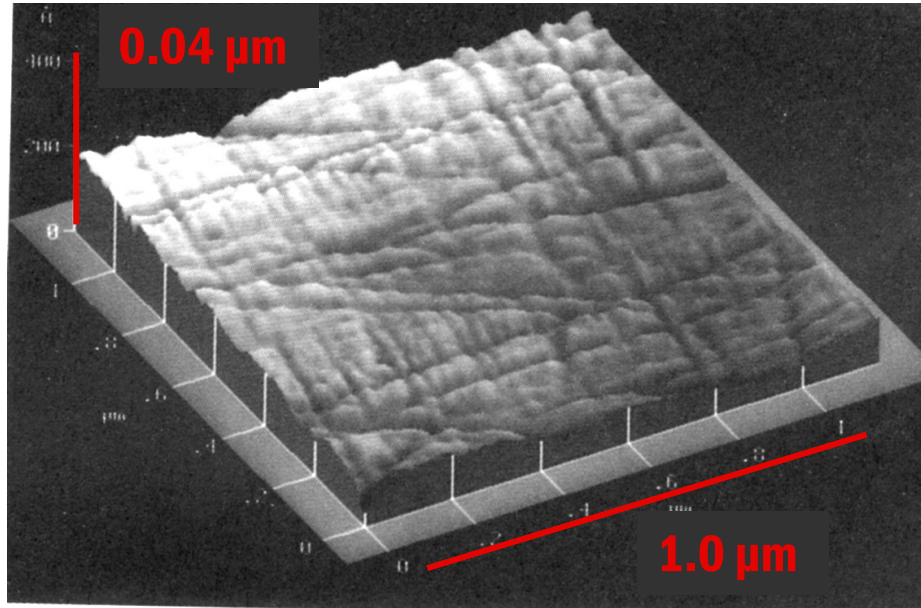


An additional tangential load (friction) yields larger shear stresses and shifts the maximum shear stress towards the surface

1. Adhesion

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3. Surface topography

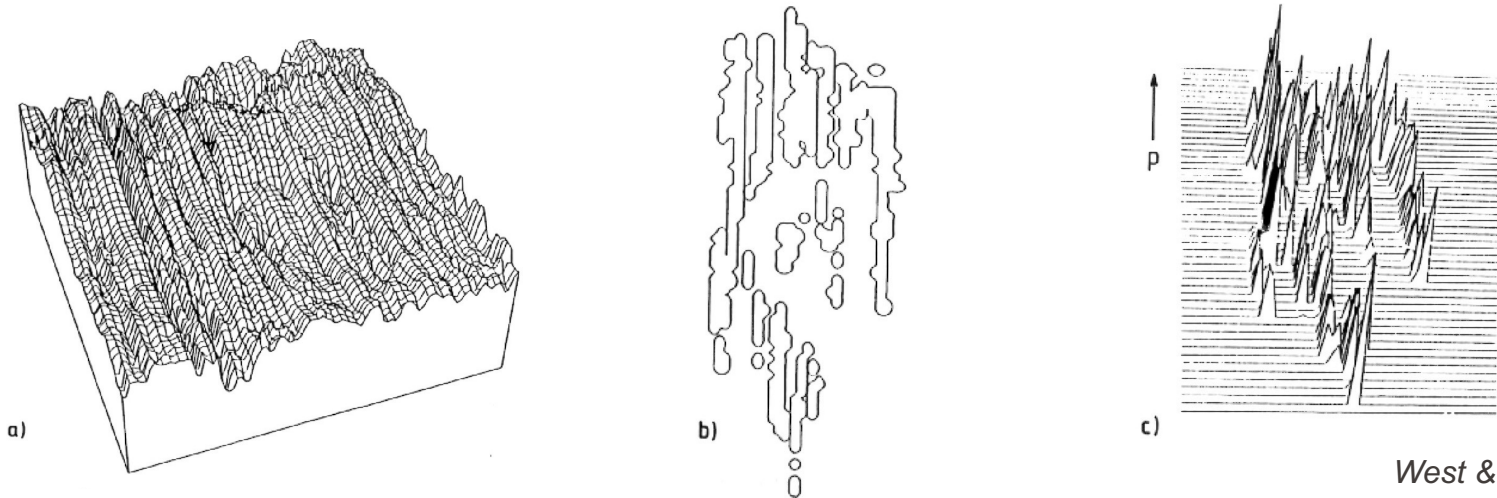


Mirror polished
steel surface (Atomic
Force Microscope image)

*“Putting two solids together is rather like turning Switzerland upside down and standing it on Austria – the area of intimate contact will be small”
F.P. Bowden*

Effect of roughness on local contact pressure

- Numerical simulation of a model Hertzian contact with a rough steel surface ($F_n = 25$ N, $p_0 = 1$ GPa, elliptical contact area : semi-axes 78 μm and 162 μm).
 - a) Representation of the steel surface : area 0.5 mm², maximum relief 4.4 μm)
 - b) Contour of the contact area
 - c) Pressure distribution (maximum value 7 GPa)



West & Sayles, 1988

- Contact between material 1 (rough, soft) and material 2 (smooth, rigid):

(Greenwood & Williamson, 1966)

$$Y = E' H^{-1} \left(\frac{\sigma}{R} \right)^{0.5}$$

Where :

- H = hardness of material 1
- σ = standard deviation of the distribution of the heights of the roughness profile
- R = mean radius of asperities
- $(\sigma / R)^{0.5}$ = mean slope of asperities (< 0.2 for technical surfaces)

- E' is defined as :
$$\frac{1}{E'} = 0.5 \left[\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right]$$

Y < 0.6 : elastic deformation of asperities

Y > 1 : plastic deformation of asperities

- Simplifications : $E_1 = E_2$ $\nu^2 \approx 0$ $(\sigma / R)^{0.5} = 0.2$

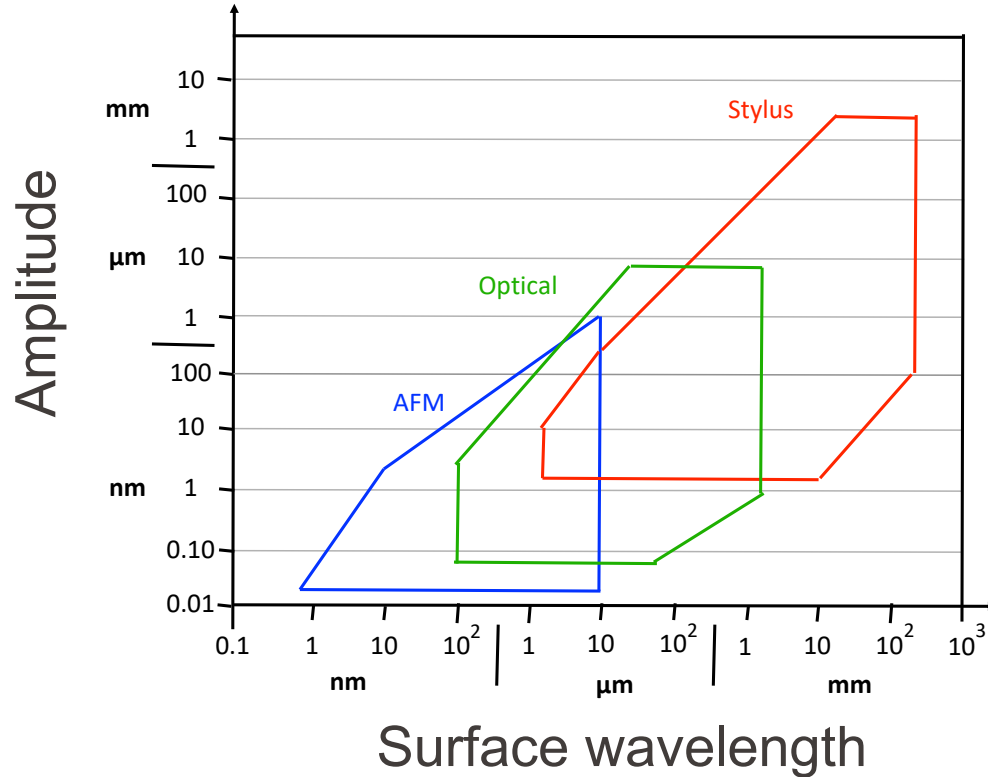
$$Y \approx 0.1 E/H$$

- Approximation for metals :
 - E range from 70 GPa to 200 GPa
 - H range from 1 GPa to 10 GPa

$$Y > 0.7$$

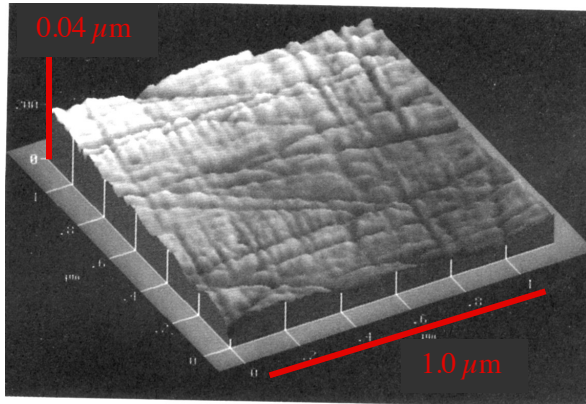
For typical values of surface finish after machining, the deformation of asperities is almost always plastic !

Surface topography: measurement techniques

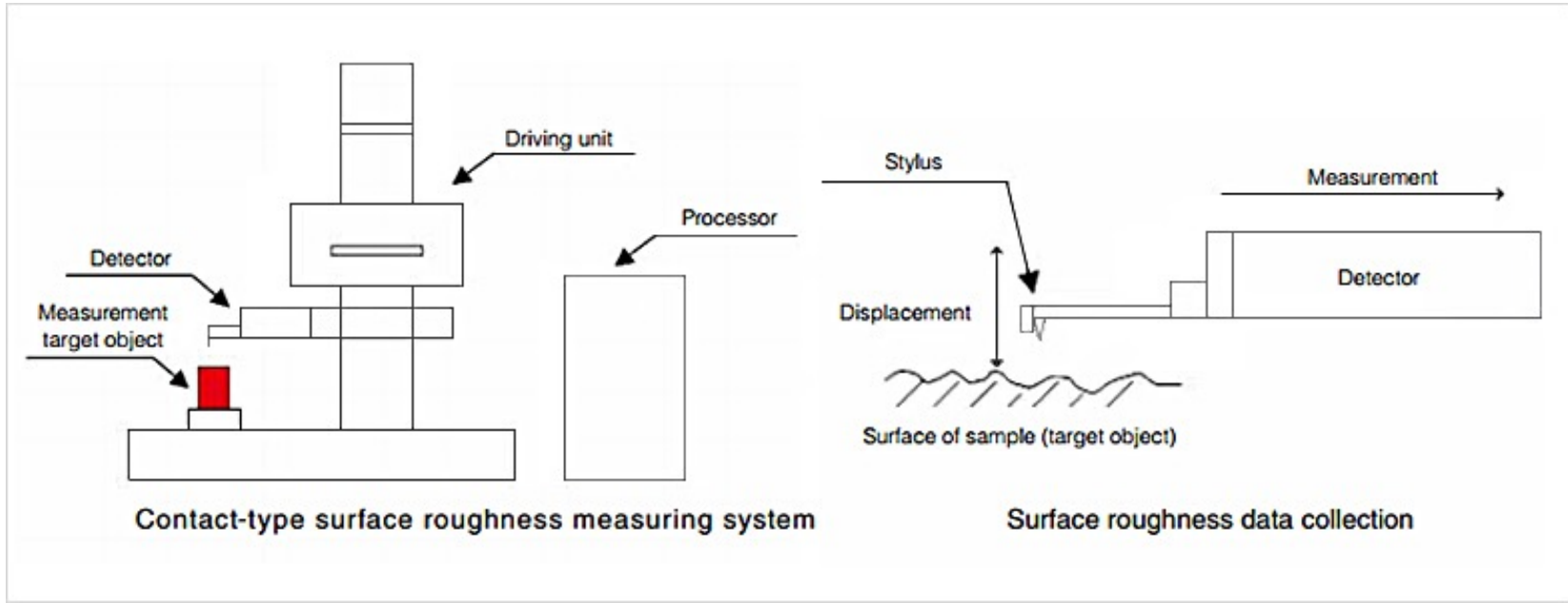


- Resolution

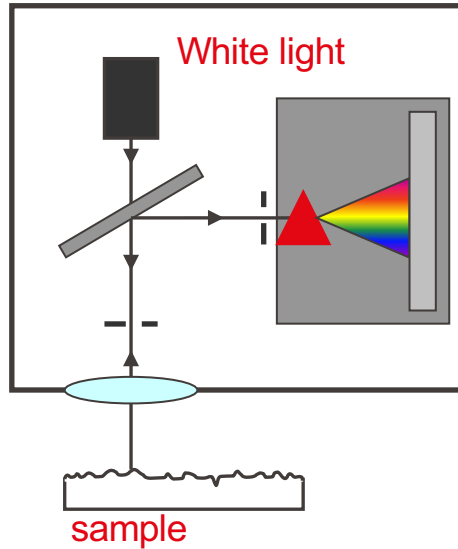
Technique Direction	Profilometer	AFM
Horizontal	1000 nm	10 nm
Vertical	10 nm	0.1 nm



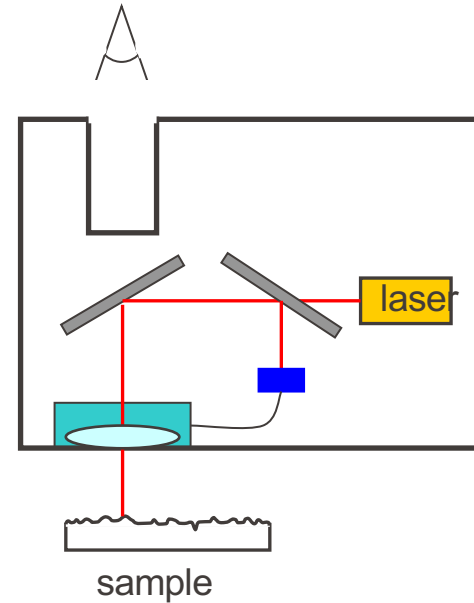
Mirror polished steel surface: AFM image



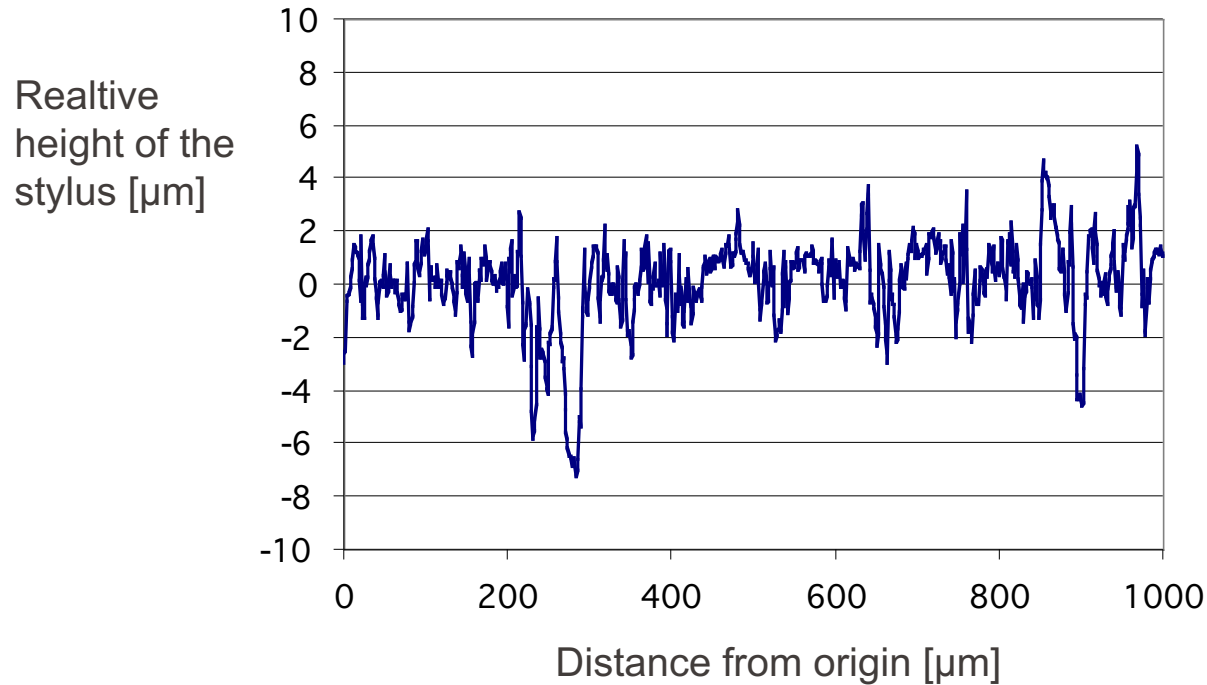
Chromatic confocal



Dynamic focusing



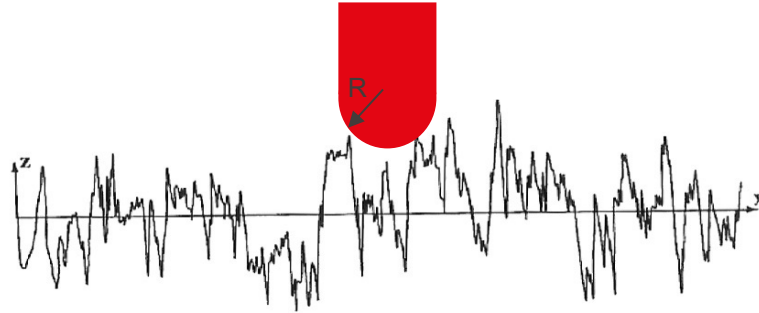
- Two-dimensional topographic measurement:



- Effect of the probe size R on profile measurement :

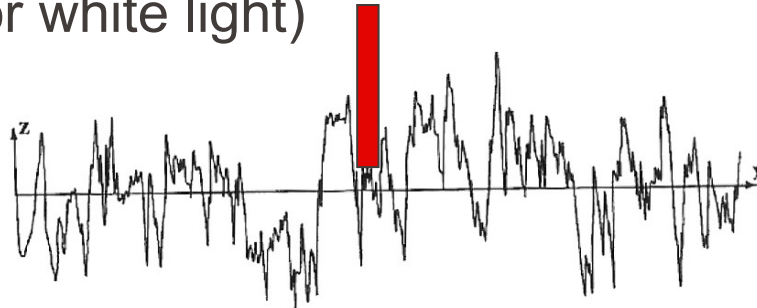
Stylus:

$R = 1\text{-}2.5\ \mu\text{m}$



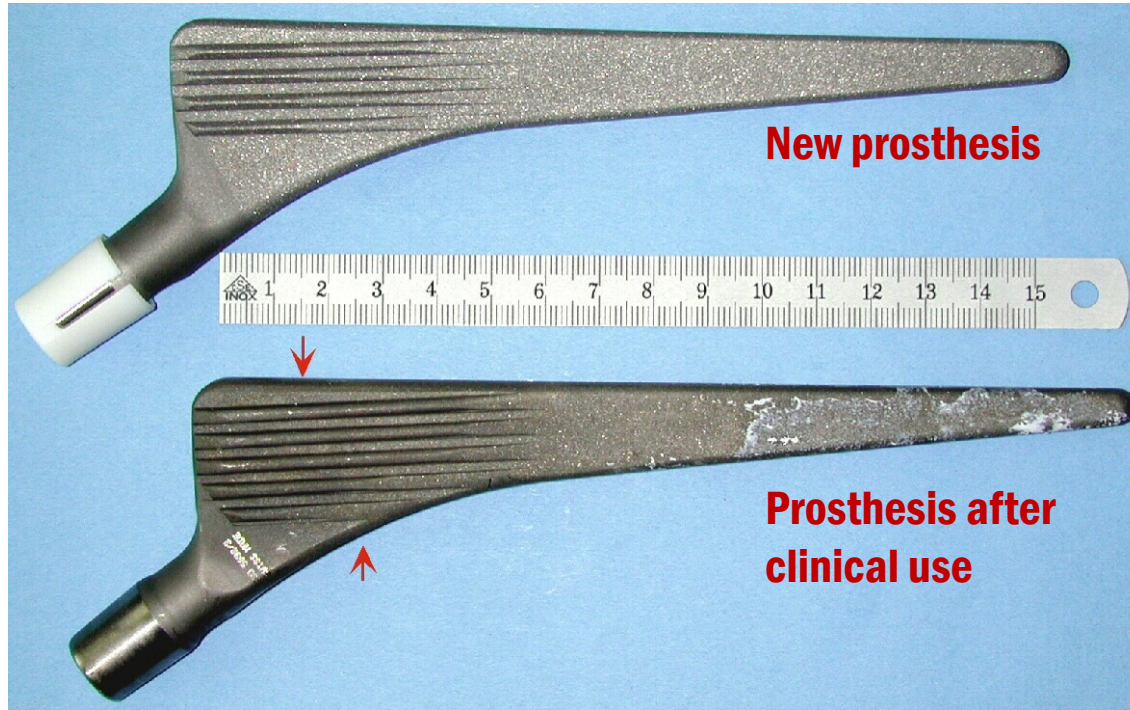
- Optical beam : (laser or white light)

$R = 0.5\text{-}1\ \mu\text{m}$

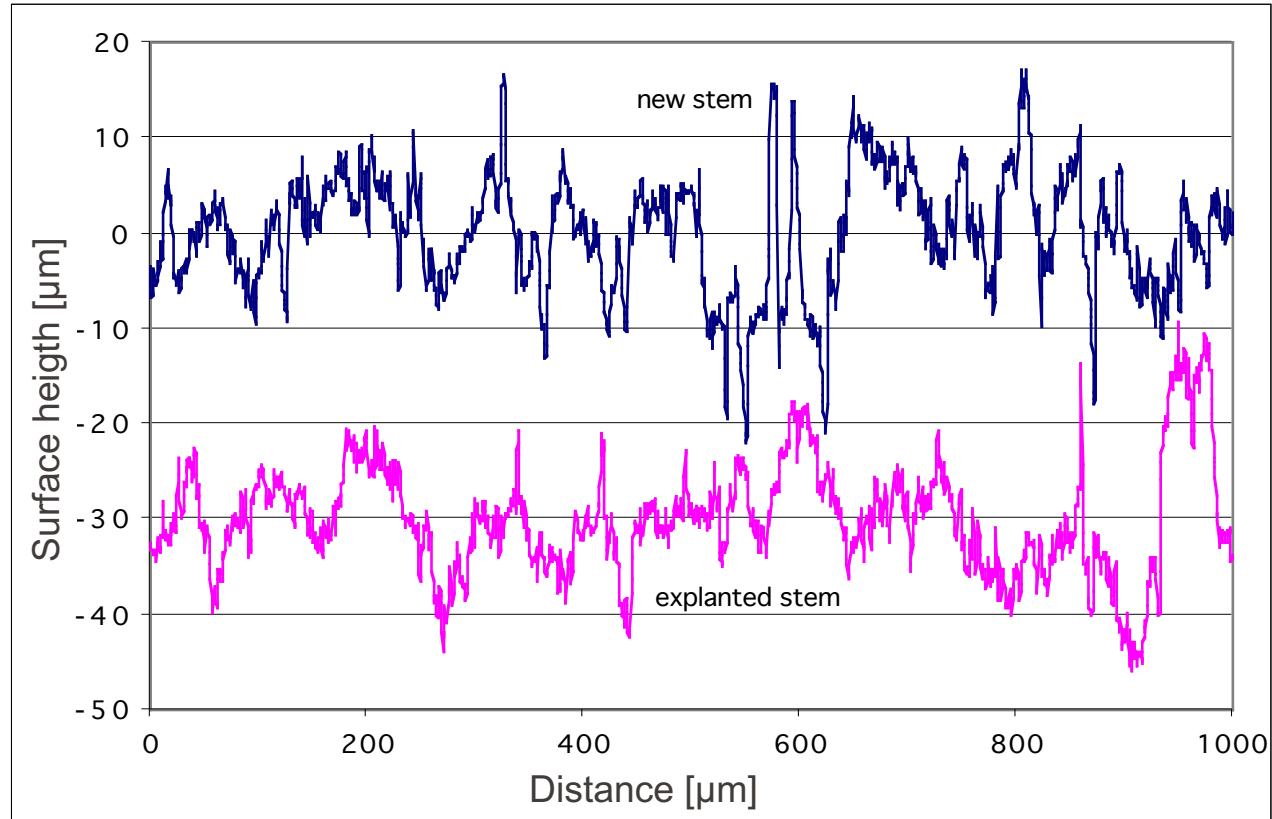


Hip implant stem

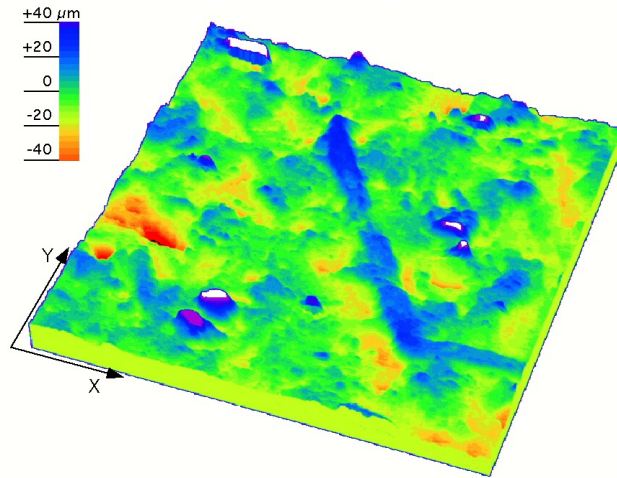
- Comparison : new stem versus stem after 15 years of clinical use (titanium)



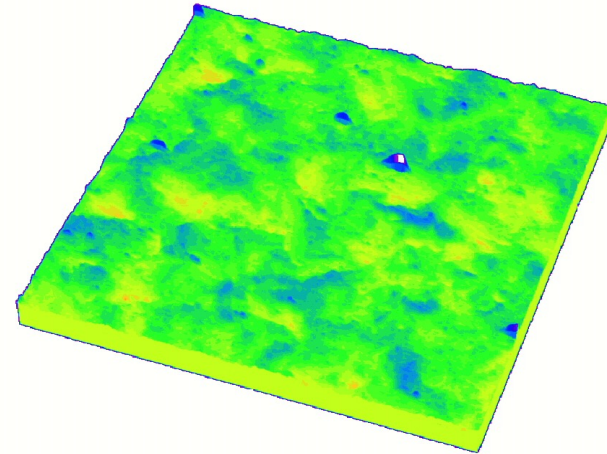
Two-dimensional profilometry



- Analysed surface : $0.5 \times 0.5 \text{ mm}^2$:



New prosthesis



Prosthesis after clinical use

Surface topography: characterization of real surfaces

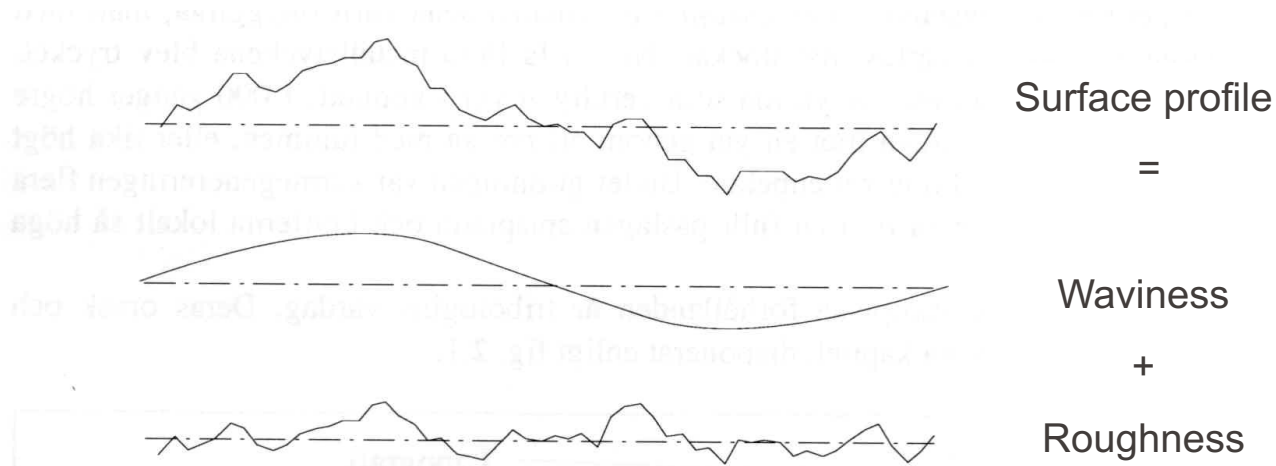


Fig. 2.2 En typisk ytprofil och dess komponenter.

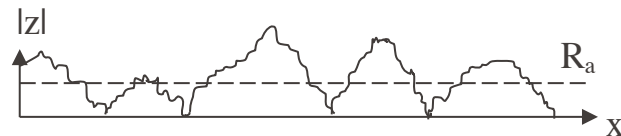
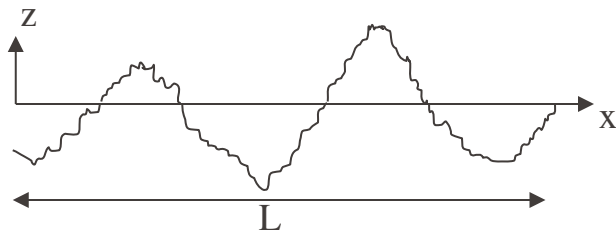
Waviness can be caused by the machining process – a systematic error (vibrations/deflections).

The roughness is a random error produced when material is removed from the surface.

Definition of the most usual parameters : R_a et R_q

- R_a : central line average roughness

$$R_a = \frac{1}{n} \sum_{i=1}^n |z_i|$$



- R_q : root mean square roughness

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n z_i^2}$$

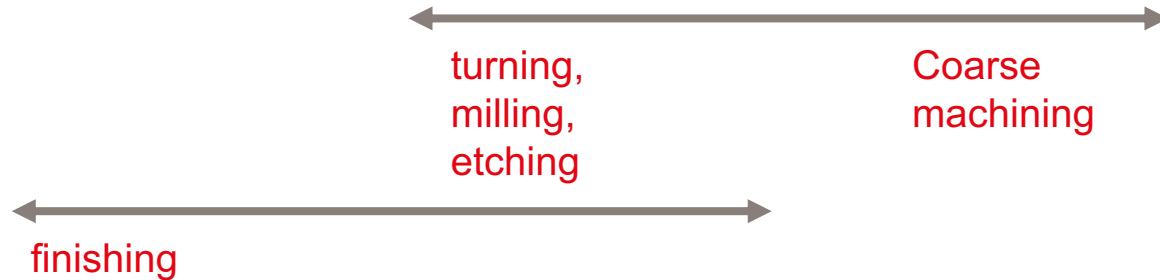
z : height of the profile at position x

n : number of measurement points over the length L

L : measurement length

- The *roughness* of technical pieces is linked to the *machining quality grade* :

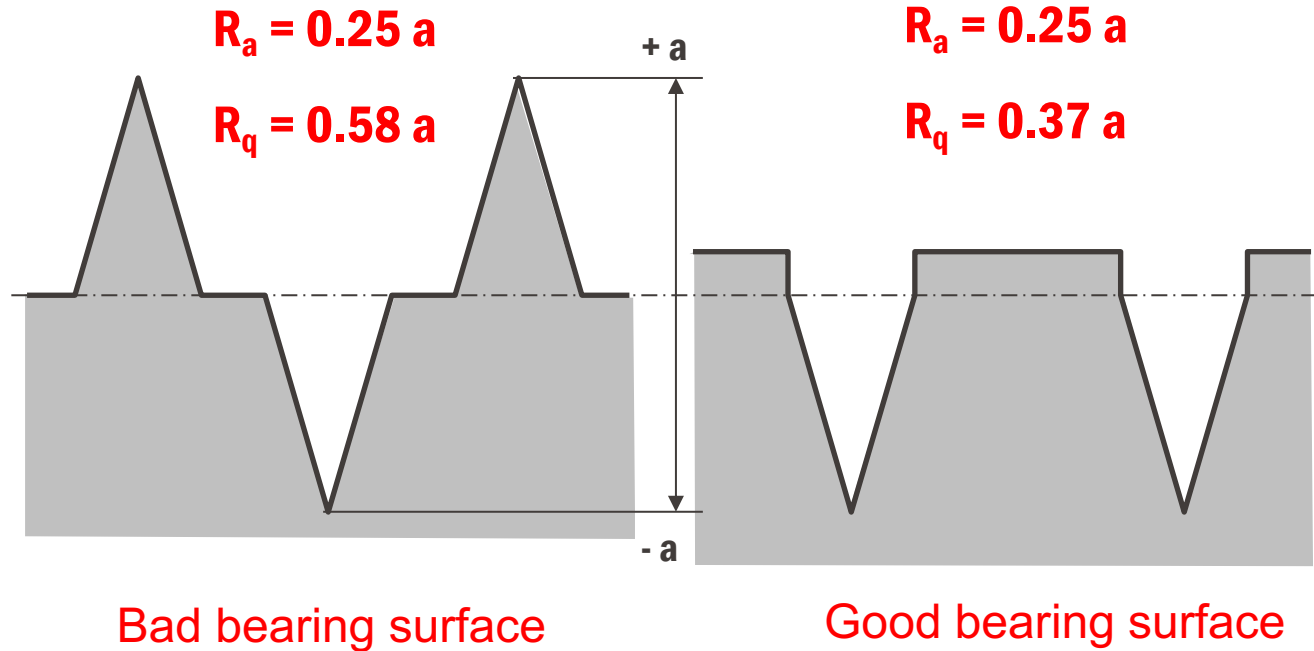
Grade	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12
R_a μm	0.025	0.05	0.1	0.2	0.4	0.8	1.6	3.2	6.3	12.5	25	50



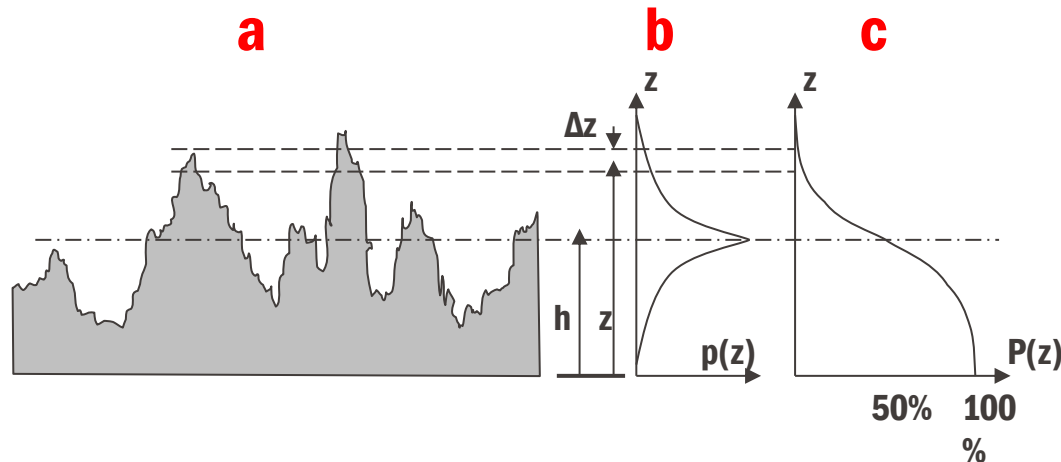
for $R_a < 0.025 \mu\text{m}$: polishing

Limitations of height parameters

- Different surface qualities yield the same R_a value :



- a) Surface profile
- b) Height density of probability function (probability of finding a point of the surface in within a Δz interval and at a height z from the central line)
- c) Cumulative probability function (probability of finding a point of at a height higher than z)



- S_k :Skewness (asymmetry) of the distribution profile $p(z)$

$$S_k = \frac{1}{n} \sum_{i=1}^n \frac{z_i^3}{R_q^3}$$

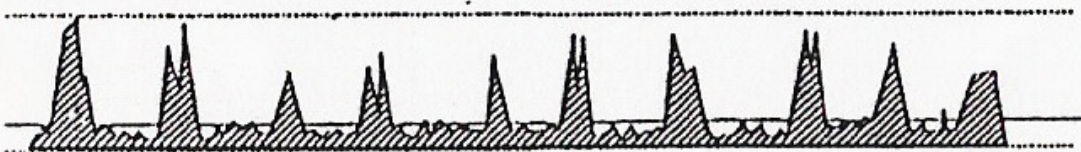
$S_k < 0$



$S_k = 0$



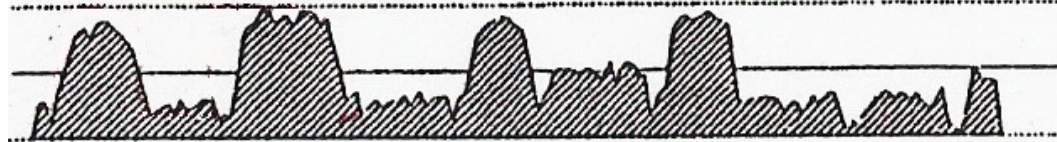
$S_k > 0$



- K: Kurtosis (sharpness) of the distribution profile $p(z)$

$$K = \frac{1}{n} \sum_{i=1}^n z_i^4 / R_q^4$$

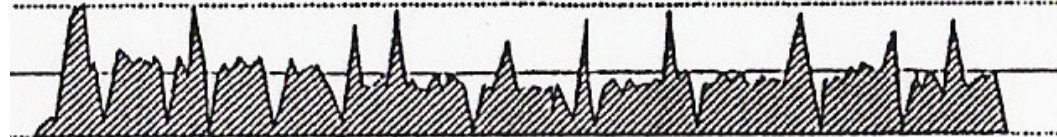
K < 3



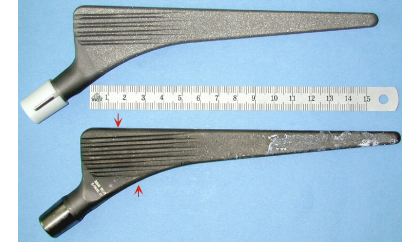
K = 3



K > 3



Case of the hip prosthesis stem



- Mean and standard deviation over five profiles :

	Implant neuf	Implant après utilisation
R_a	4.8 ± 0.6	2.7 ± 0.2
R_q	6.1 ± 0.7	3.5 ± 0.2
R_z	26 ± 2	16 ± 1
S_k	0.1 ± 0.4	0 ± 0.2
K	3.2 ± 0.6	3.5 ± 0.6