EPFL

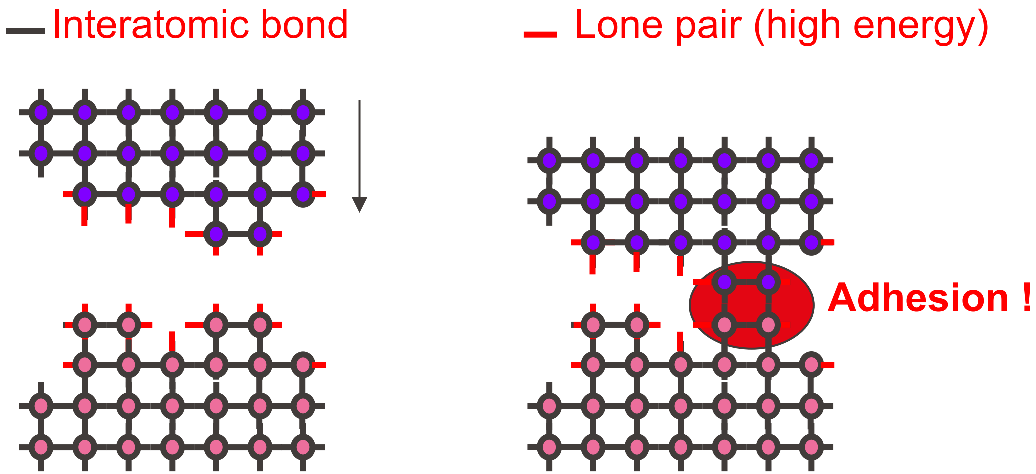
Chapter 2 Contact phenomena

MSE 485 Tribology

1. Adhesion
2. Contact mechanics
3. Surface topography

Adhesion

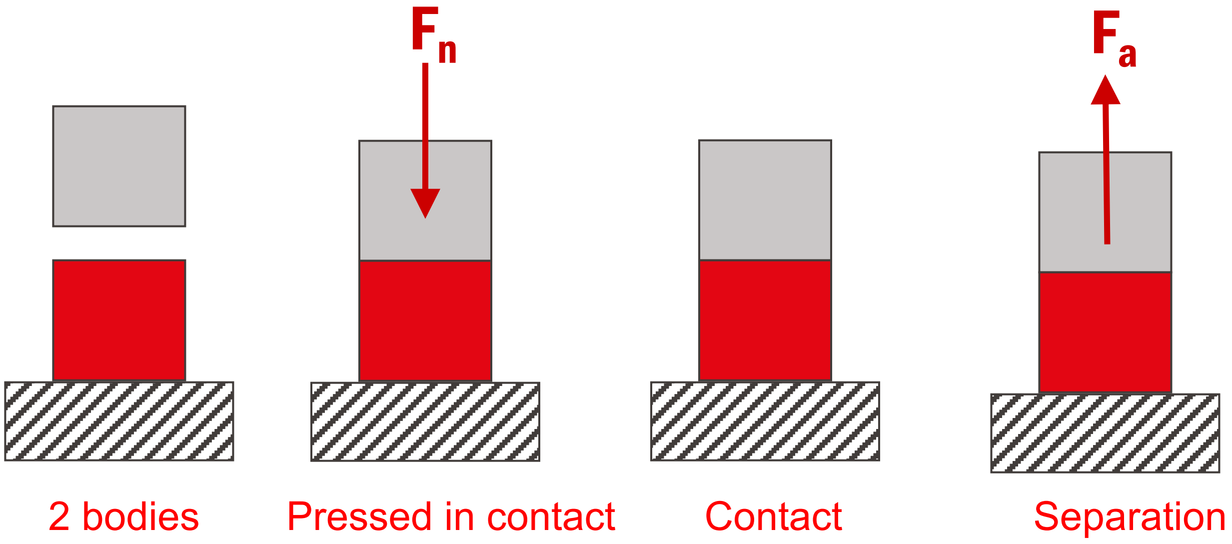
Bonding at the interface between two bodies brought into contact.



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)

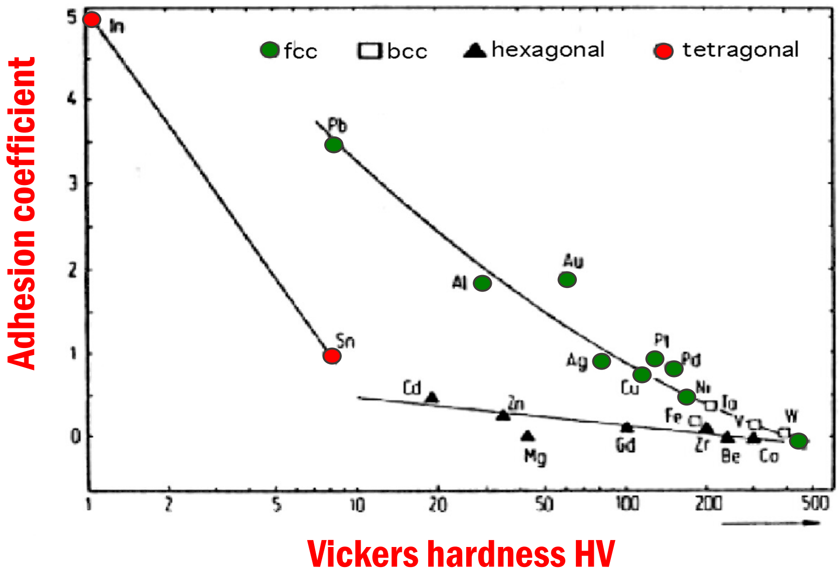
Adhesion test



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

Adhesion coefficient

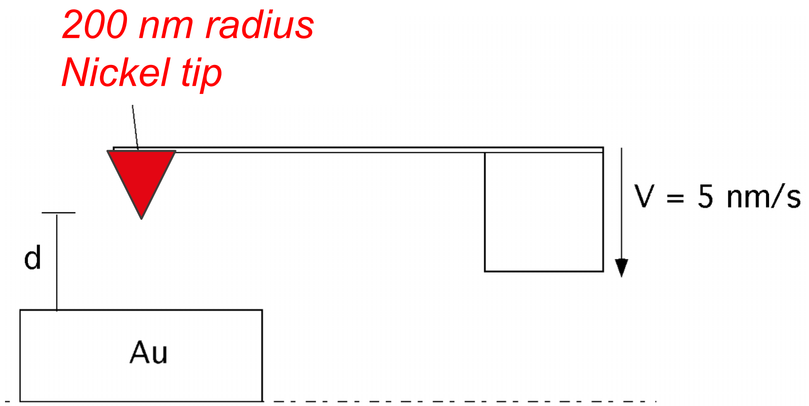
- Adhesion coefficient of pure metals against themselves as a function of **hardness** and **cristalline** structure :



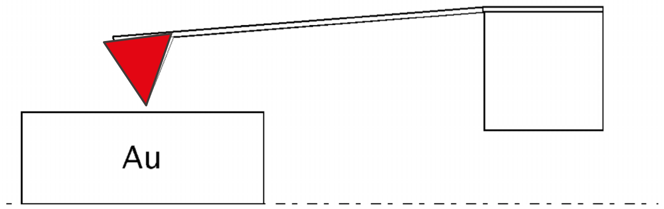
Source : H. Czichos, K.H. Habig, Tribologie Handbuch, Vieweg (1992)

Nanoscopic aspects

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



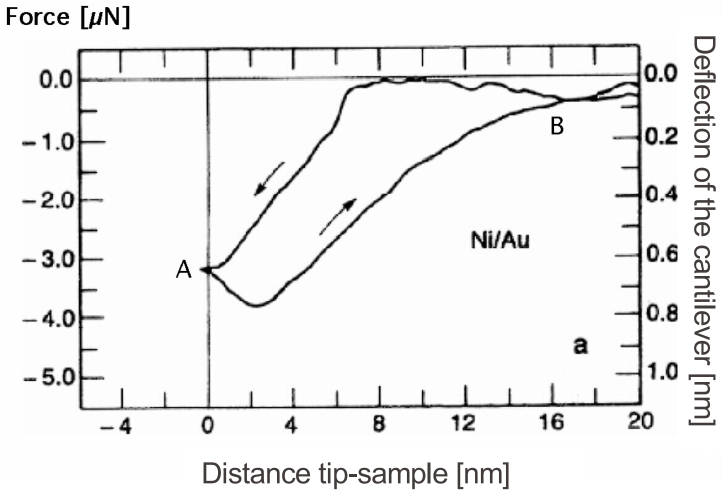
Approach of the Ni tip towards the Au sample at a constant speed.



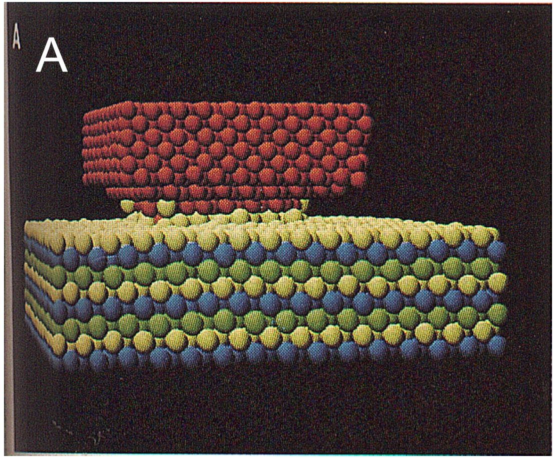
Deflection of the cantilever due to the attractive force between the Ni tip and the Au sample.

Case of a contact without indentation

- Experimental curves: force versus distance:



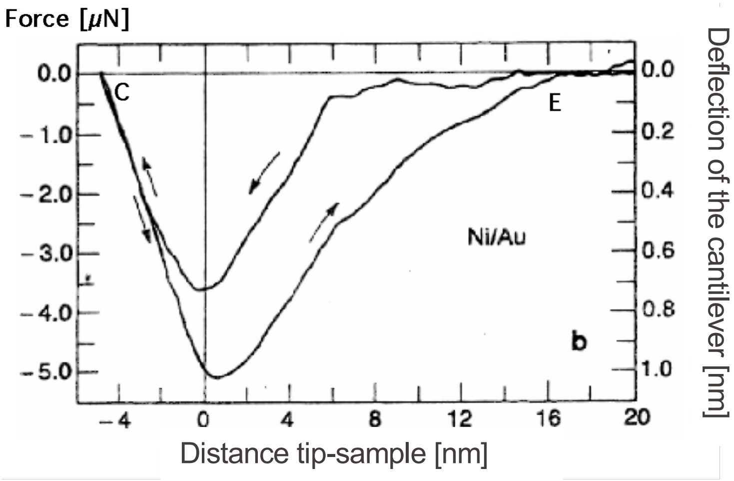
- Numerical simulation :
- (molecular dynamics based on Lennard-Johnes' potential)



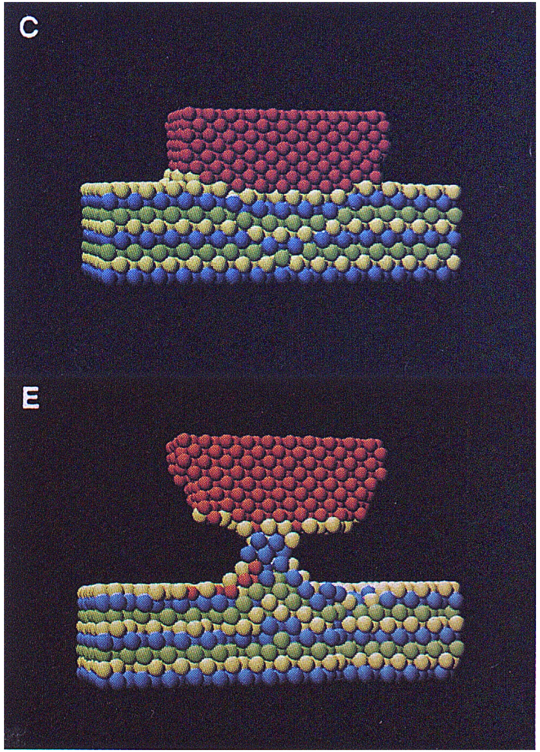
Red : Ni atoms
Yellow/Blue/Green : Au atoms

Case of a contact with indentation

- Experimental curves: force versus distance:



- Numerical simulation :



1. Adhesion

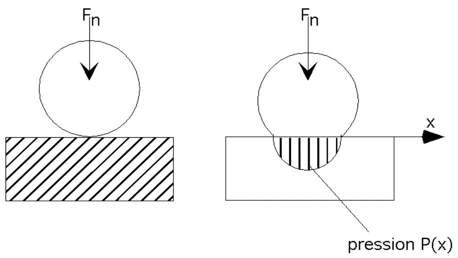
2. Contact mechanics

3. Surface topography

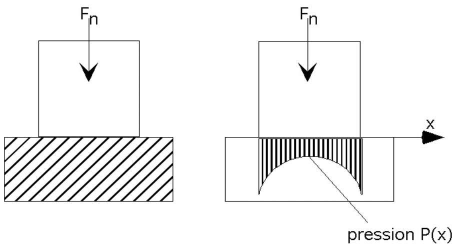
Study of the amplitude and distribution of mechanical stresses in a contact.

- Conformity of the contact

Non-conformal contact :



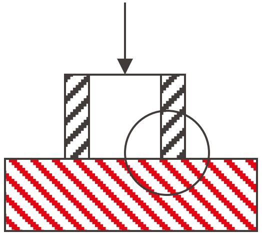
Conformal contact :

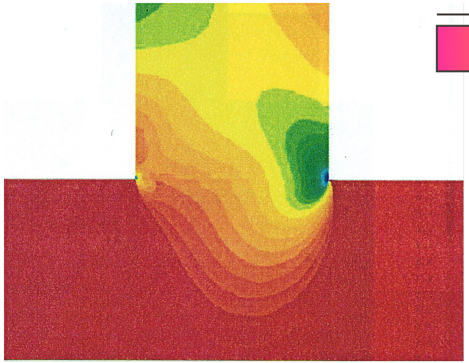


Conformal contact

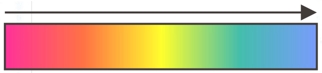
- Example of finite elements calculation of stress distribution in a conformal contact : rings-plane contact

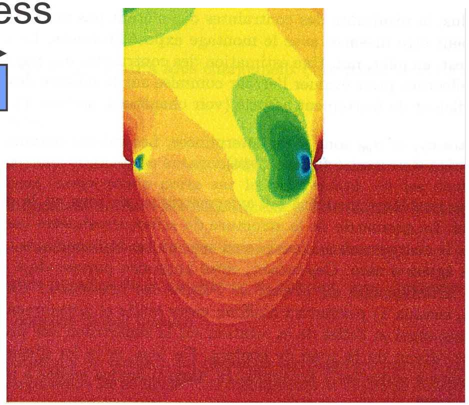
Source: Thèse I. Serre, Ecole Polytechnique Paris (2000)





Without chamfer

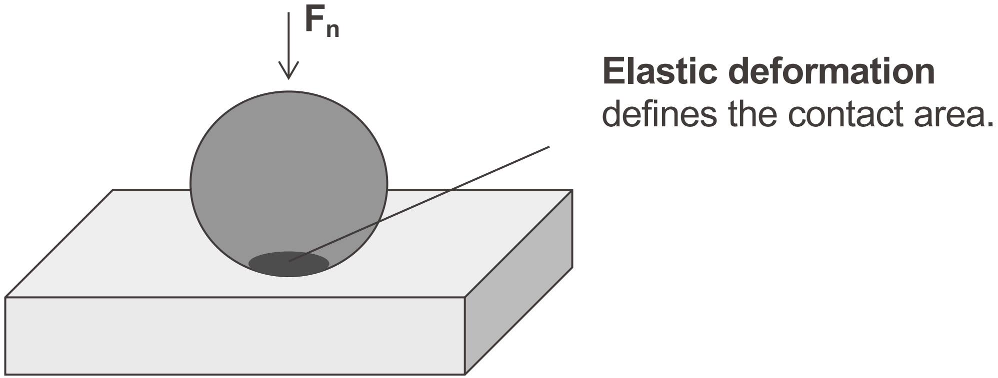




With chamfer

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.



Ball-plane contact

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

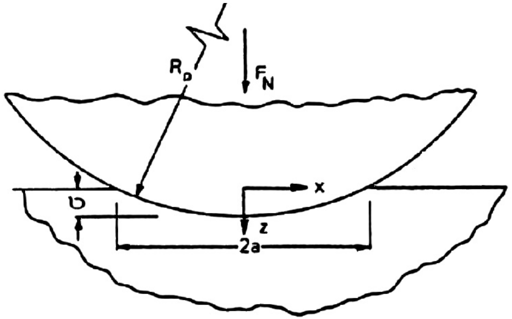
- Radius of contact area (circle) $a = \left(\frac{1.5 F_n R}{E'}\right)^{1/3}$
- Maximum contact pressure $p_0 = \frac{3F_n}{2\pi a^2}$
- Average contact pressure $p_m = \frac{F_n}{\pi a^2}$
- Maximum deflection $w = 1.31\left(\frac{F_n^2}{E'^2 R}\right)^{1/3}$
- Maximum shear stress $\tau_{\max} = \frac{p_0}{3}$
- Depth of maximum shear strength $z = 0.638 \cdot a$

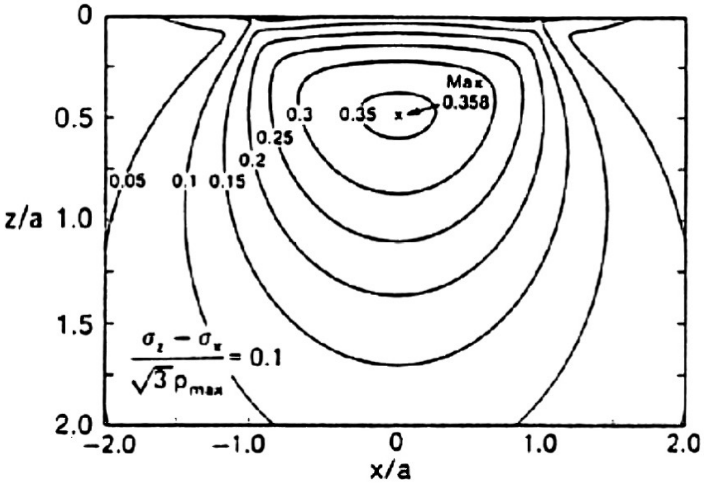
$$\frac{1}{E'} = 0.5\left[\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right]$$

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

Ball-plane contact

- 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

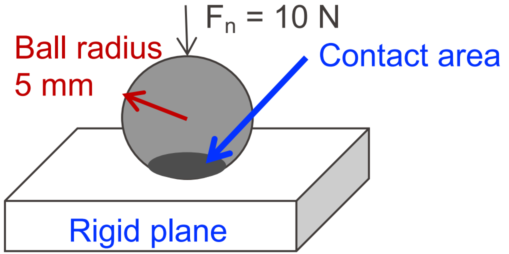
- **Tresca criterion**: plastic deformation occurs when a critical shear stress of YS /2 (YS: Yield strength in uniaxial traction) is reached.

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

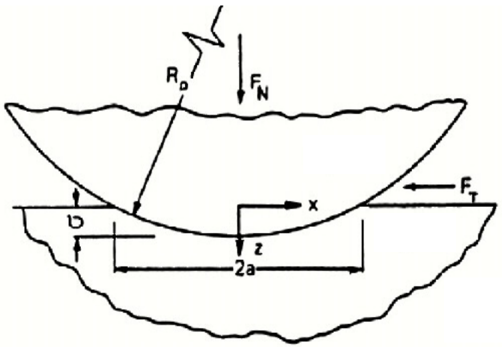


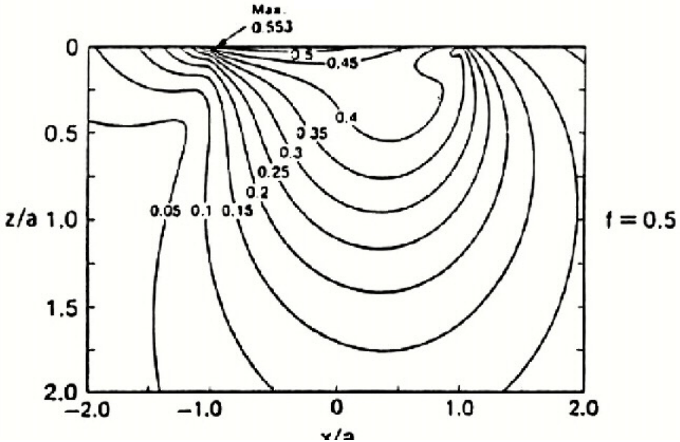
Ball Material	Elastomer	Polymer	Metal	Ceramic	Unit
E Modulus	0.02	1	200	500	GPa
Poisson ratio	0.5	0.5	0.3	0.3	
Radius of contact area	1.121	0.304	0.057	0.043	mm
Average Pressure	**3**	**34**	**995**	**1740**	**MPa**
Yield Strength (σ_Y)	10	20	350	350	MPa
Av. Pressure/σ_Y	0.3	1.7	2.8	5.0	

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

Effect of tangential force

- 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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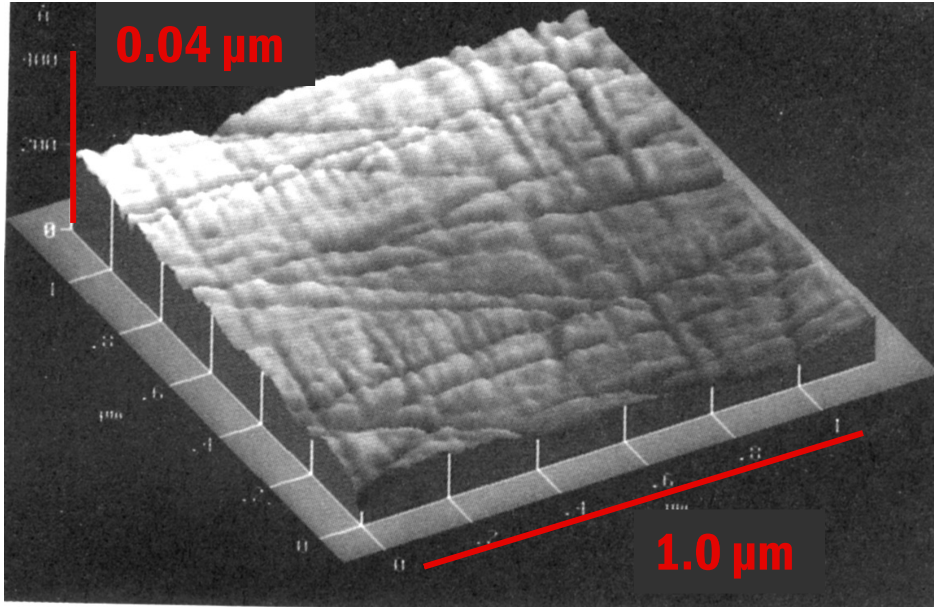
3. Surface topography

Surface roughness

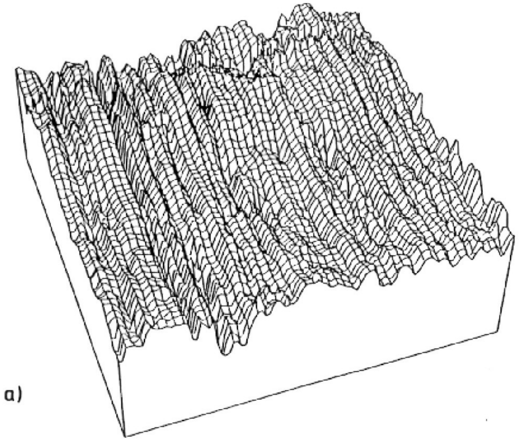


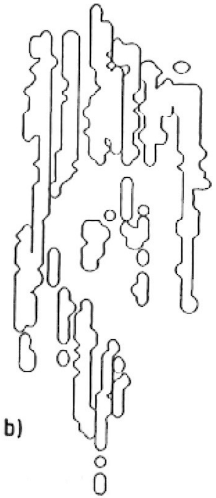
Mirror polished steel surface (Atomic Force Microscope image)

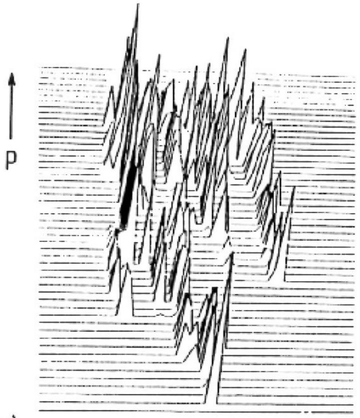
"Putting two solids together is rather like turning Switzerland upside down and standing it on Austria – the area of intimate contact will be small"
F.P. Bowden

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**)


a)


b)



c)

West & Sayles, 1988

Plasticity index Y

- 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
- $\boldsymbol{\sigma}$= standard deviation of the distribution of the heights of the roughness profile
- R = mean radius of asperities
- $(\boldsymbol{\sigma} / \mathrm{R})^{0.5}$ = 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

Application to technical metallic surfaces

- Simplifications : E1 = E2 $\nu^2 \approx 0$ $(\sigma / R)^{0.5} = 0.2$

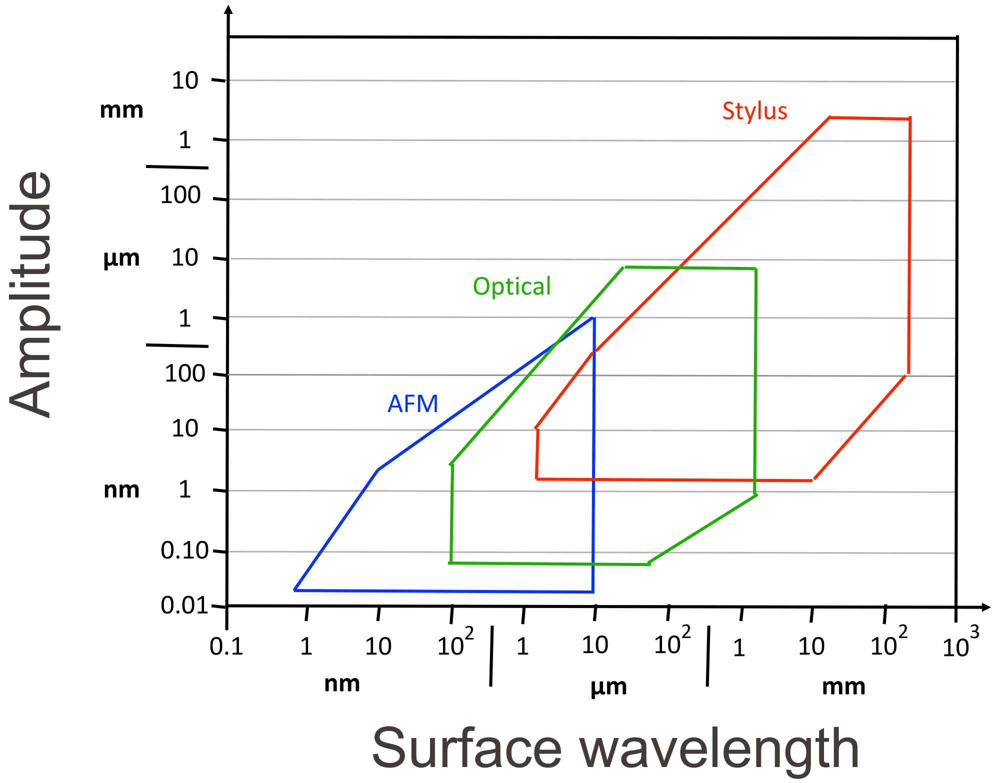
$$Y \approx 0.1\ E/H$$

- 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 !

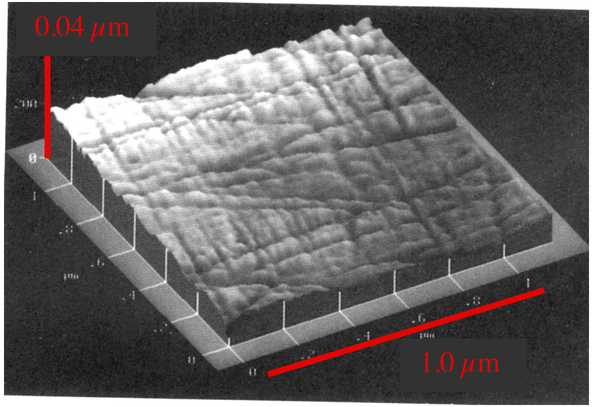
Surface topography: measurement techniques



Profilometry vs Atomic force microscopy

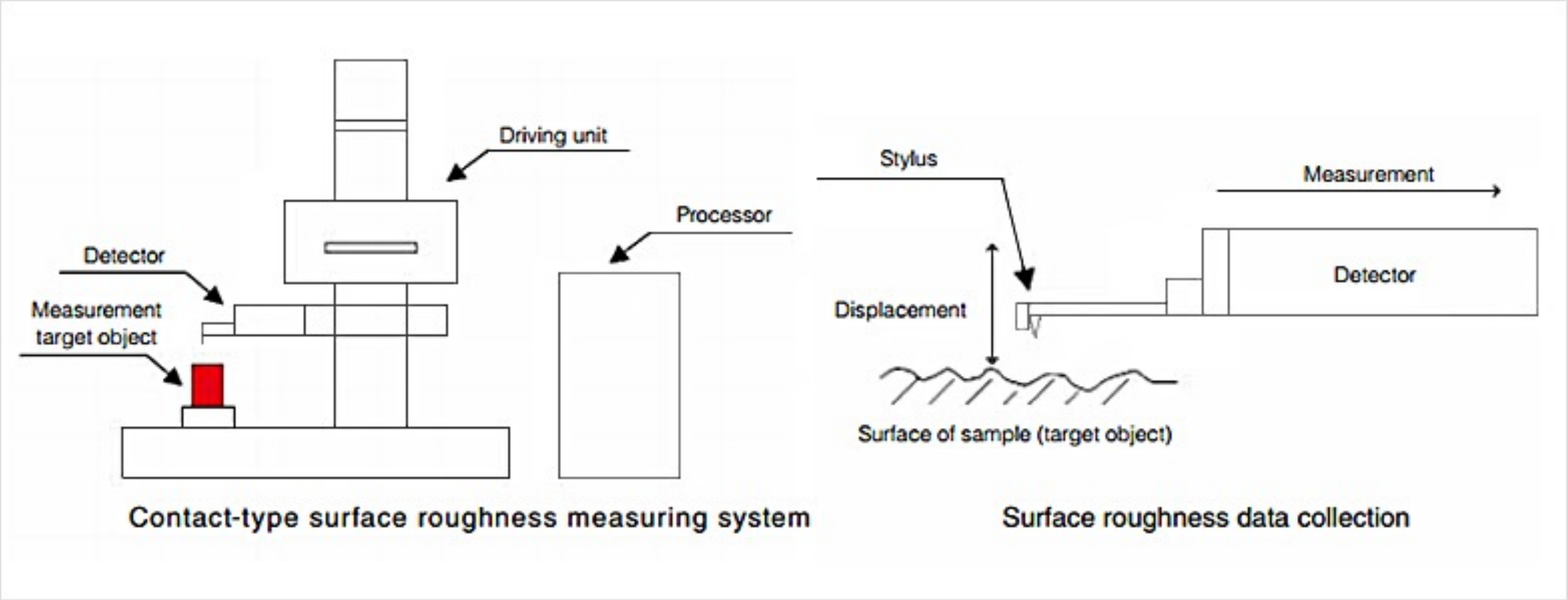
- Resolution

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



Mirror polished steel surface: AFM image

Measurement techniques: stylus profilometer



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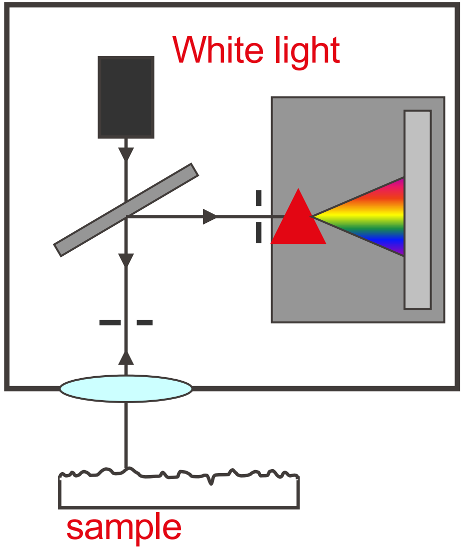
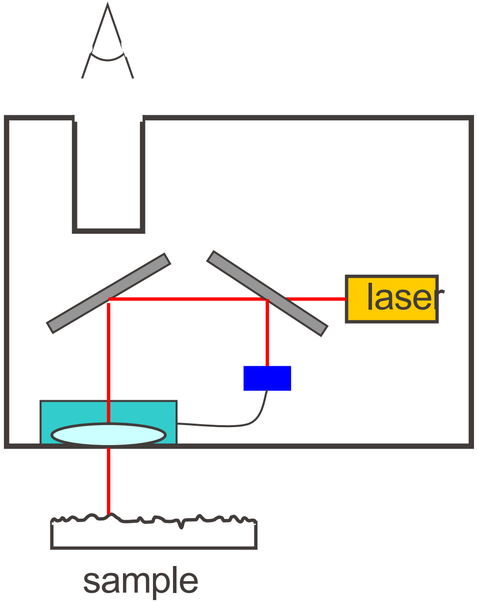
Measurement techniques: non-contact profilometer

Chromatic confocal

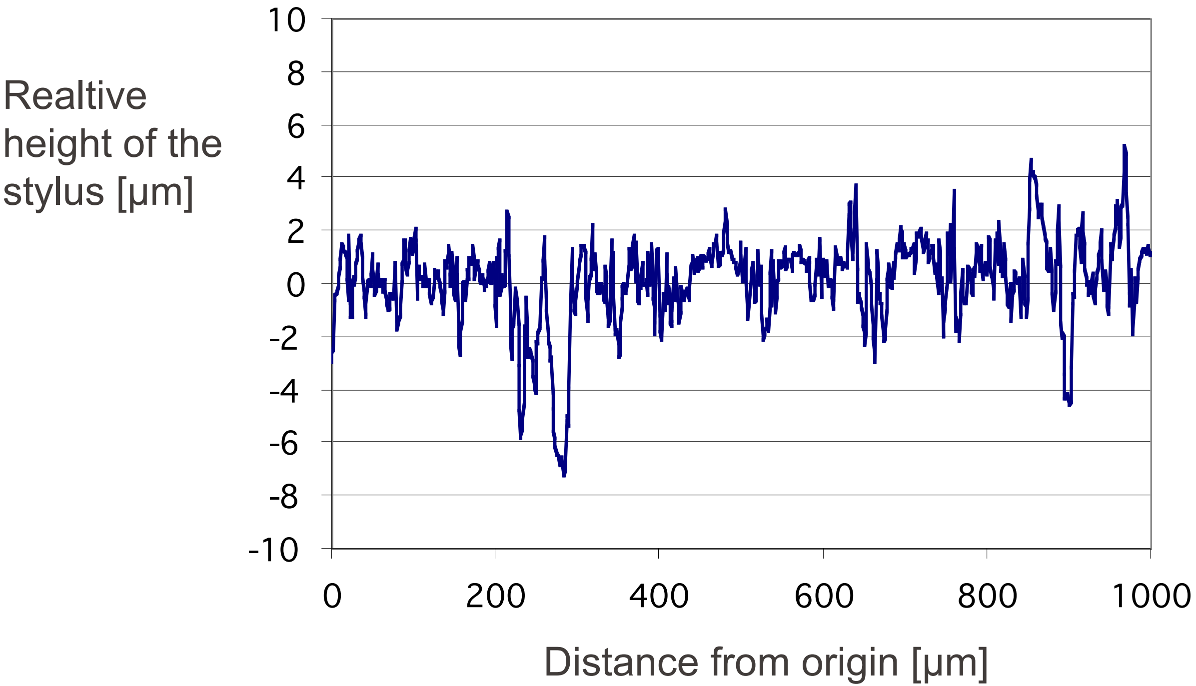


Dynamic focusing



Measurement example

- Two-dimensional topographic measurement:

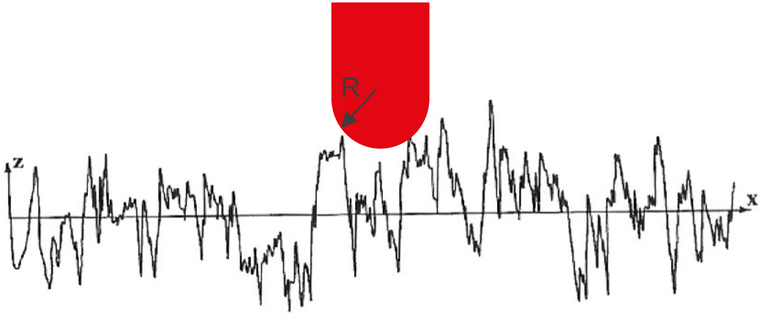


Size of the probe

- Effect of the probe size R on profile measurement :

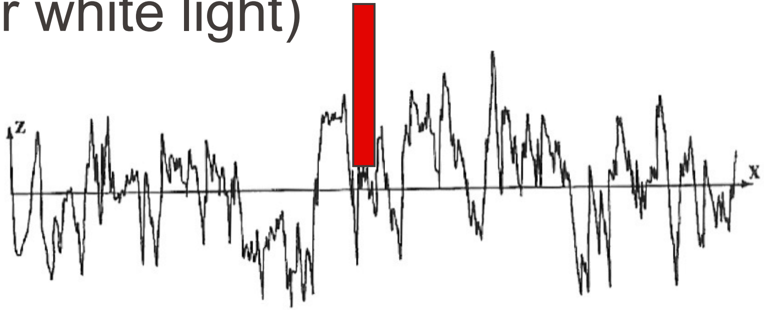
  Stylus:

  R = 1-2.5 μm



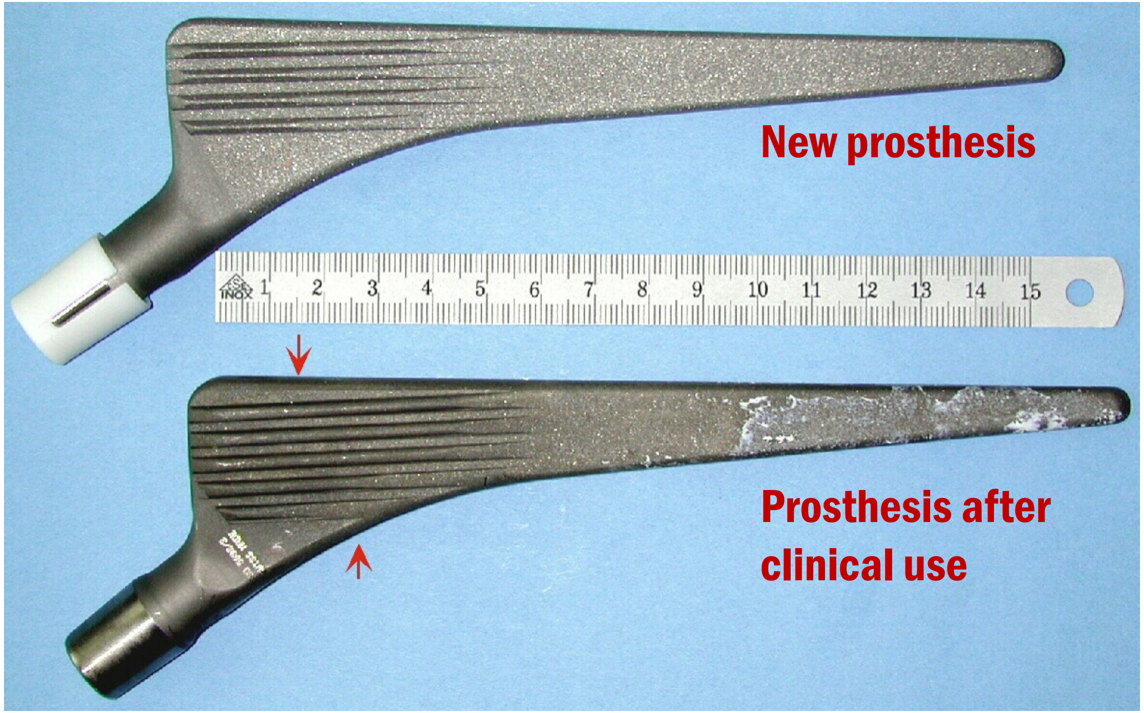
- Optical beam : (laser or white light)

  R = 0.5-1 μm

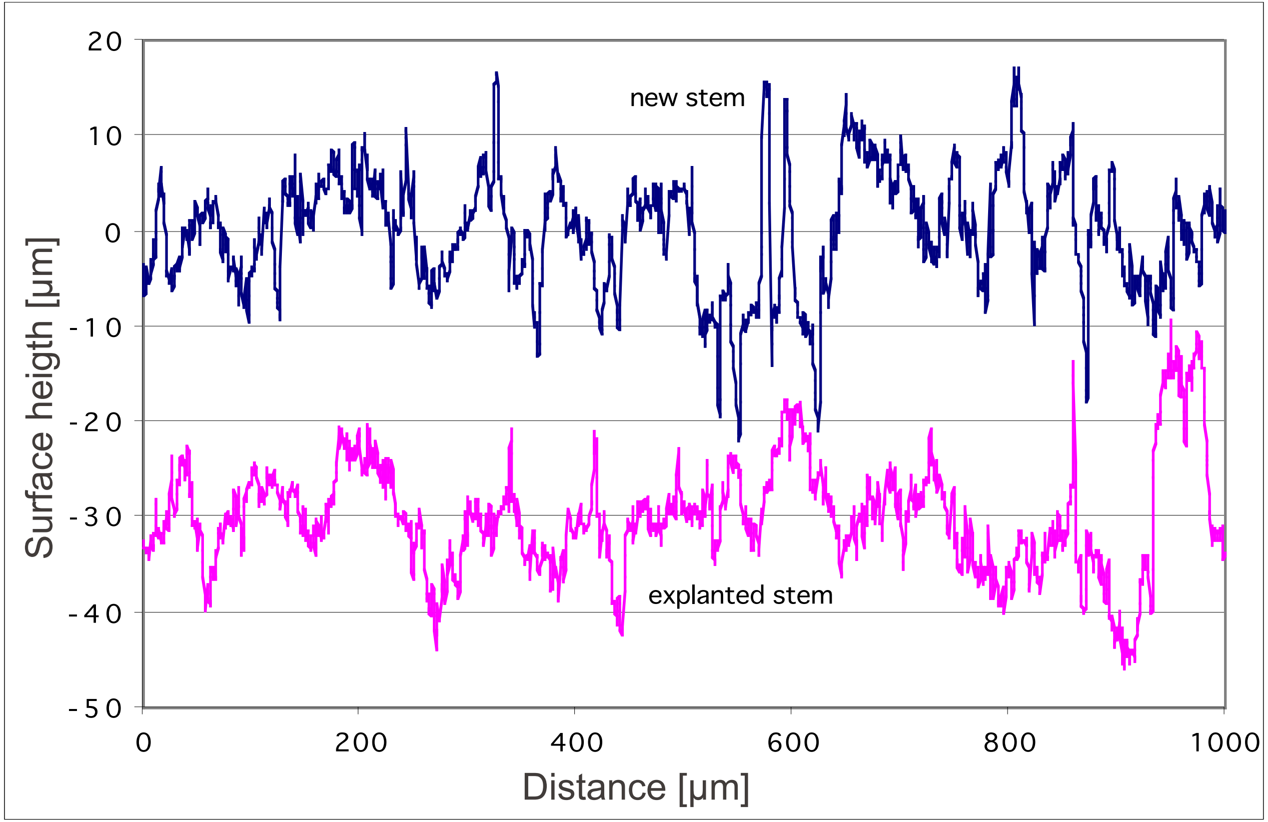


Hip implant stem

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

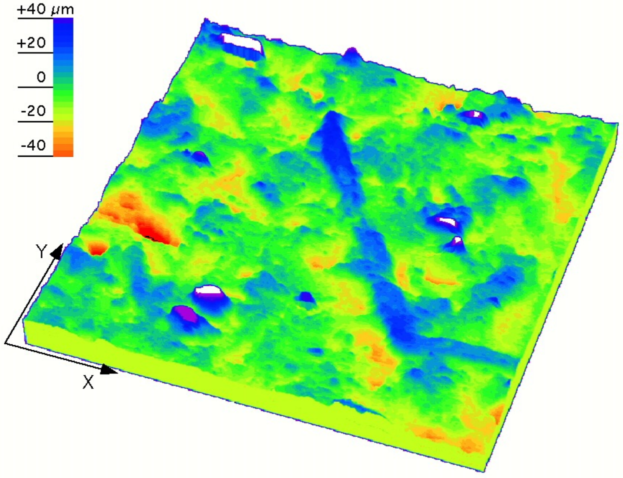


Two-dimensional profilometry

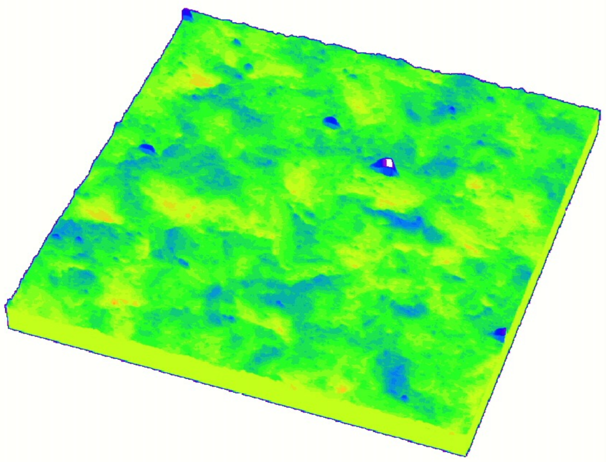


Tri-dimensional profilometry

- Analysed surface : 0.5 x 0.5 mm^2:



New prosthesis



Prosthesis after clinical use

Surface topography: characterization of real surfaces

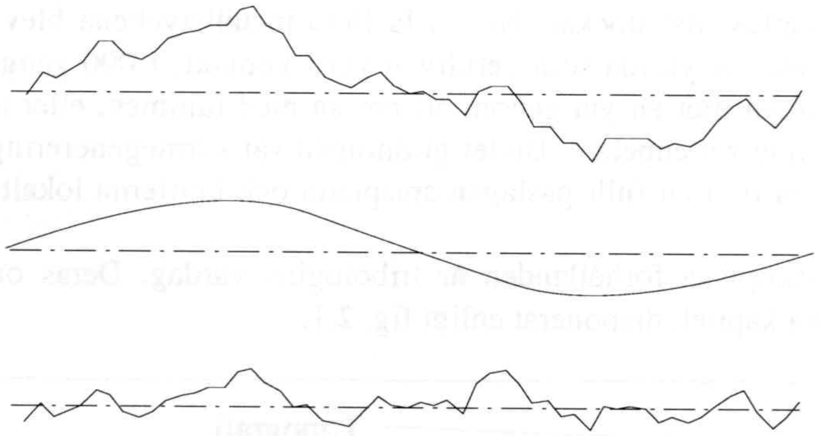


Fig. 2.2 *En typisk ytprofil och dess komponenter.*

Surface profile

=

Waviness

+

Roughness

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

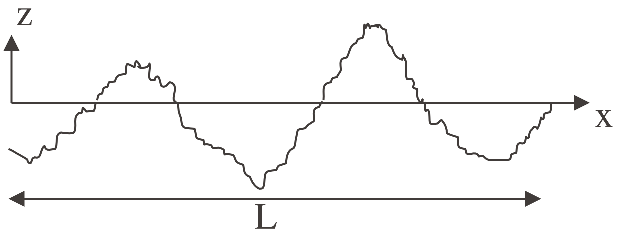
The roughness is a random error produced when material is removed from the surface.

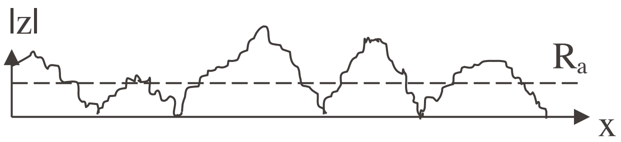
Height parameters

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

Technological aspects

- 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

turning, milling, etching

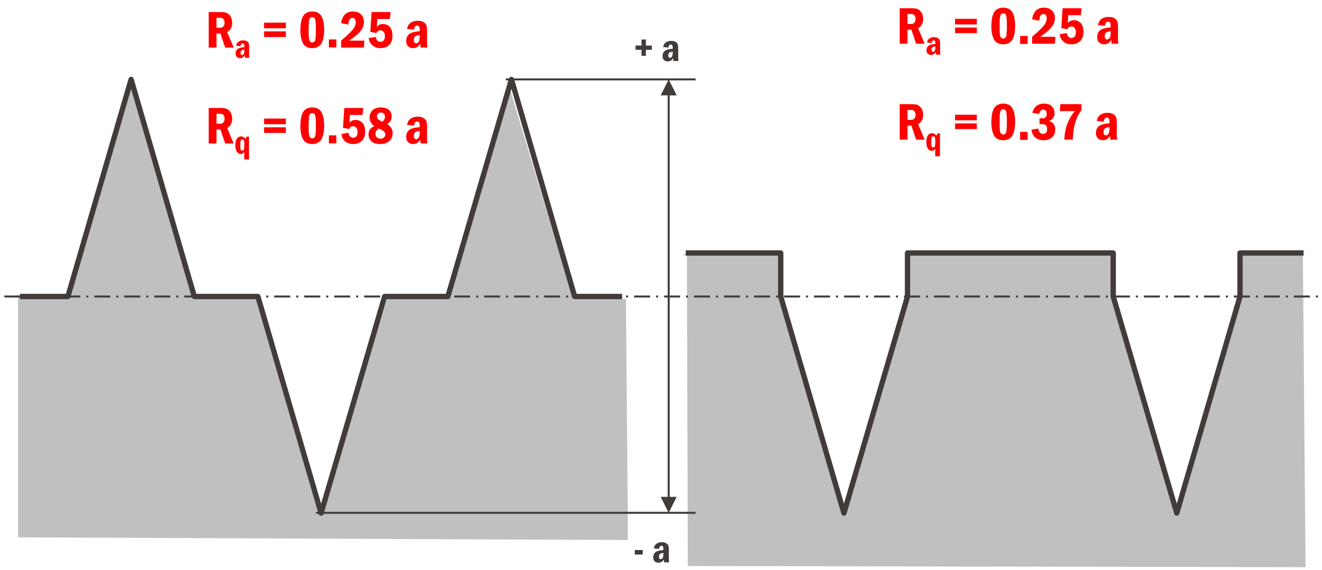
Coarse machining

finishing

for R_a<0.025 µm : polishing

Limitations of height parameters

- Different surface qualities yield the same R_a value :



Bad bearing surface

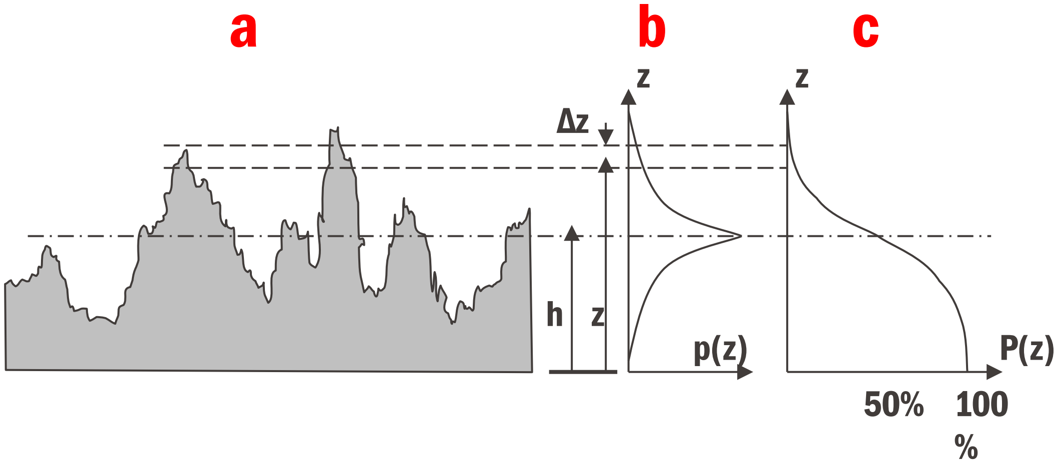
Good bearing surface

Statistical parameters

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)



Statistical parameters

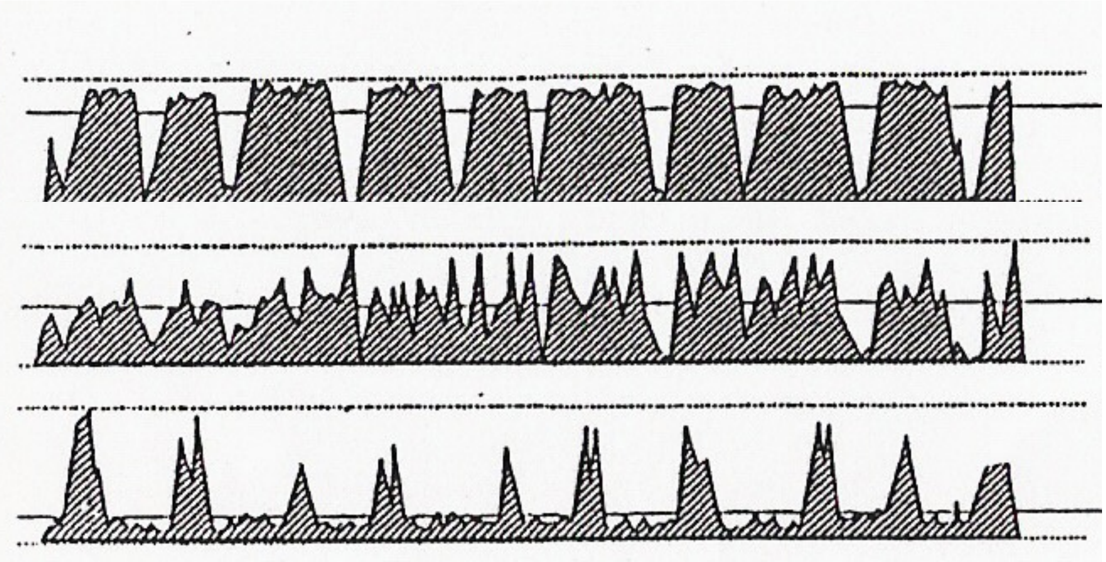
- Sk :Skewness (asymmetry) of the distribution profile p(z)

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

$S_k < 0$

$S_k = 0$

$S_k > 0$



Statistical parameters

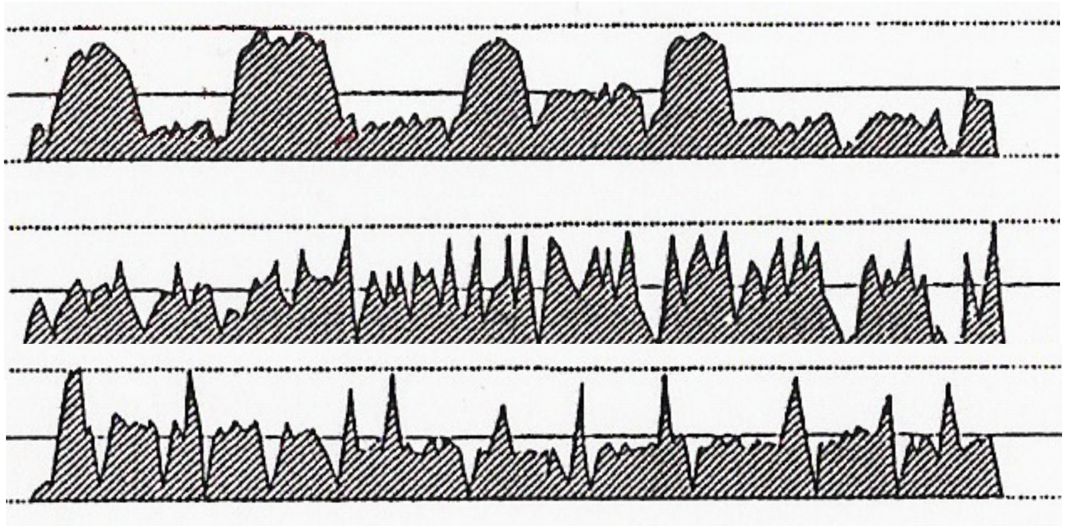
- K: Kurtosis (sharpness) of the distribution profile p(z)

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

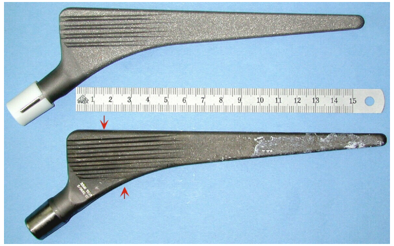
K < 3

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