Adhesion

E. Barthel

September 2008

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
SAINT-GOBAIN

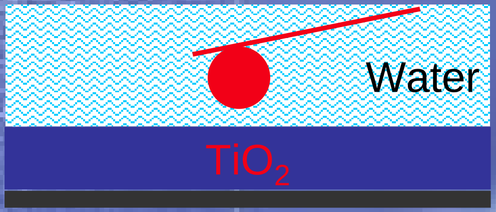
Recent review

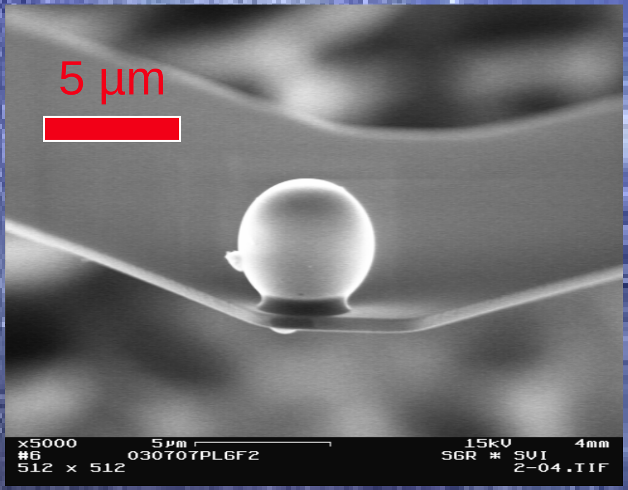
- Adhesive Elastic Contact – JKR and more, E. Barthel, J. Phys. D: Appl. Phys. 41 (2008) 163001

Cleaning windows…

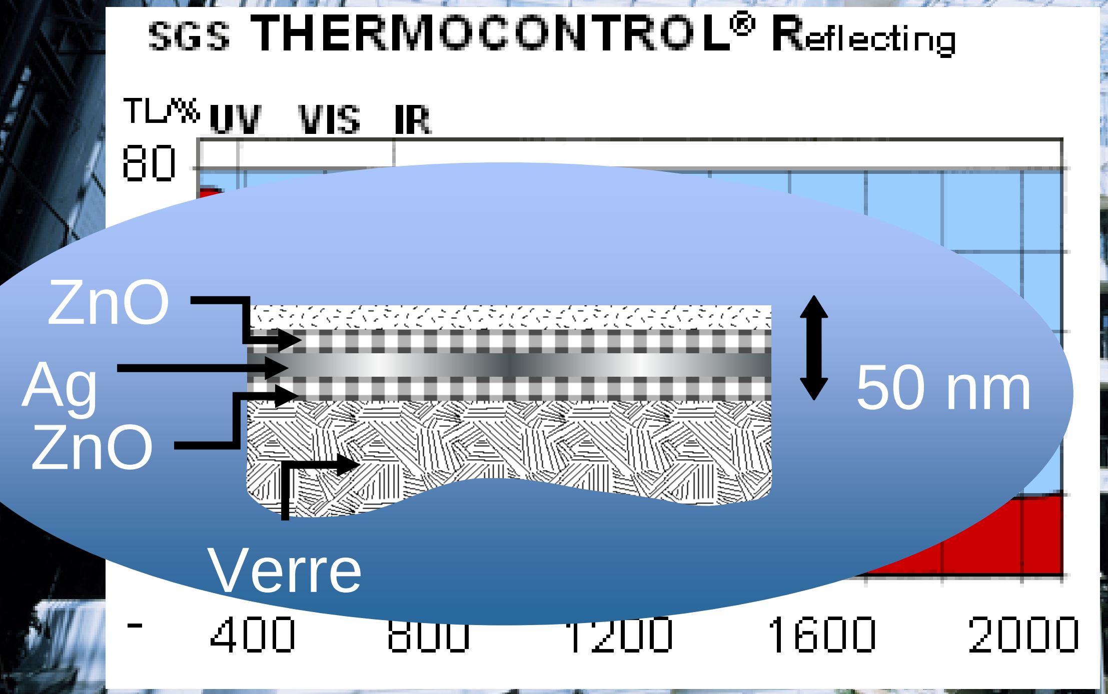
Paris, Quai d'Orsay, August 23, 2008

Self cleaning



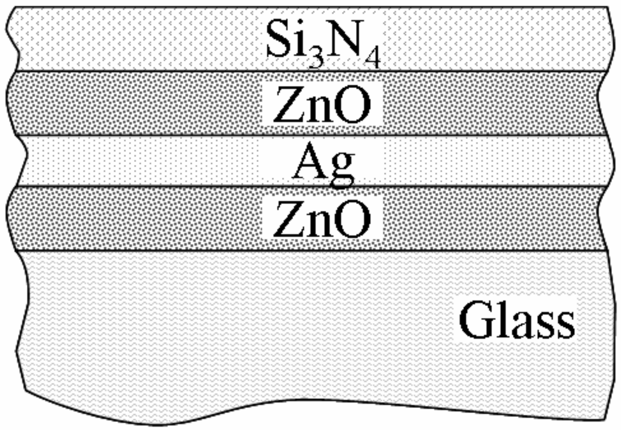


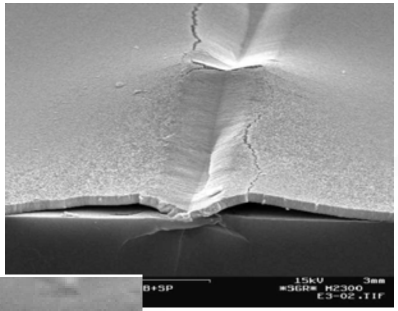
Optical functionalisation

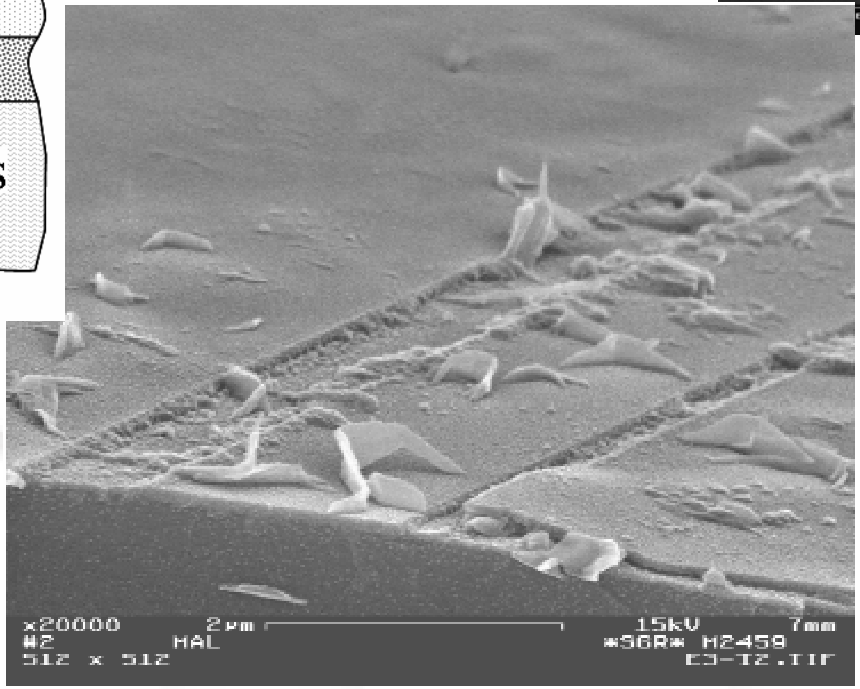


Damage morphology

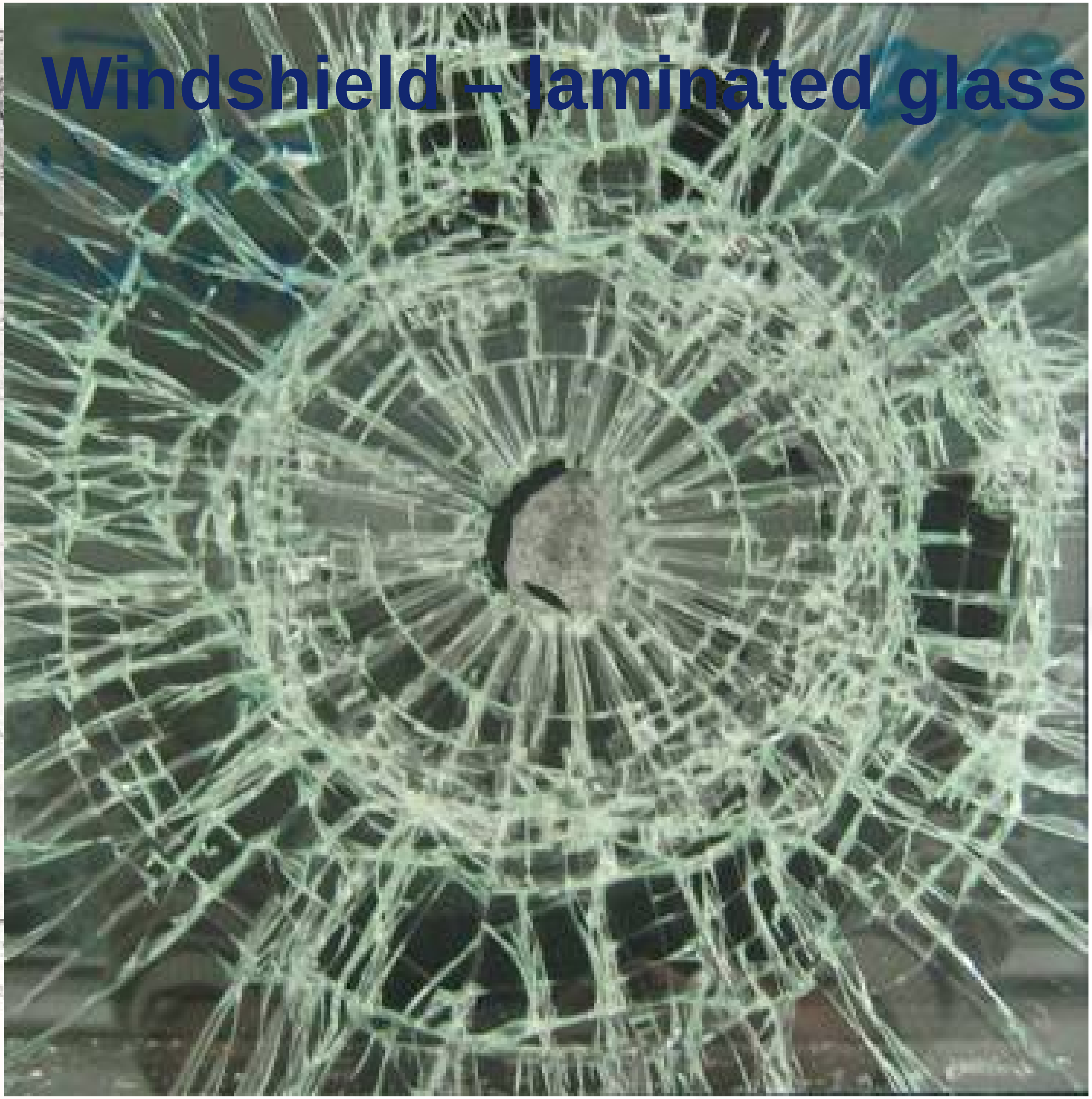
- damage morphology





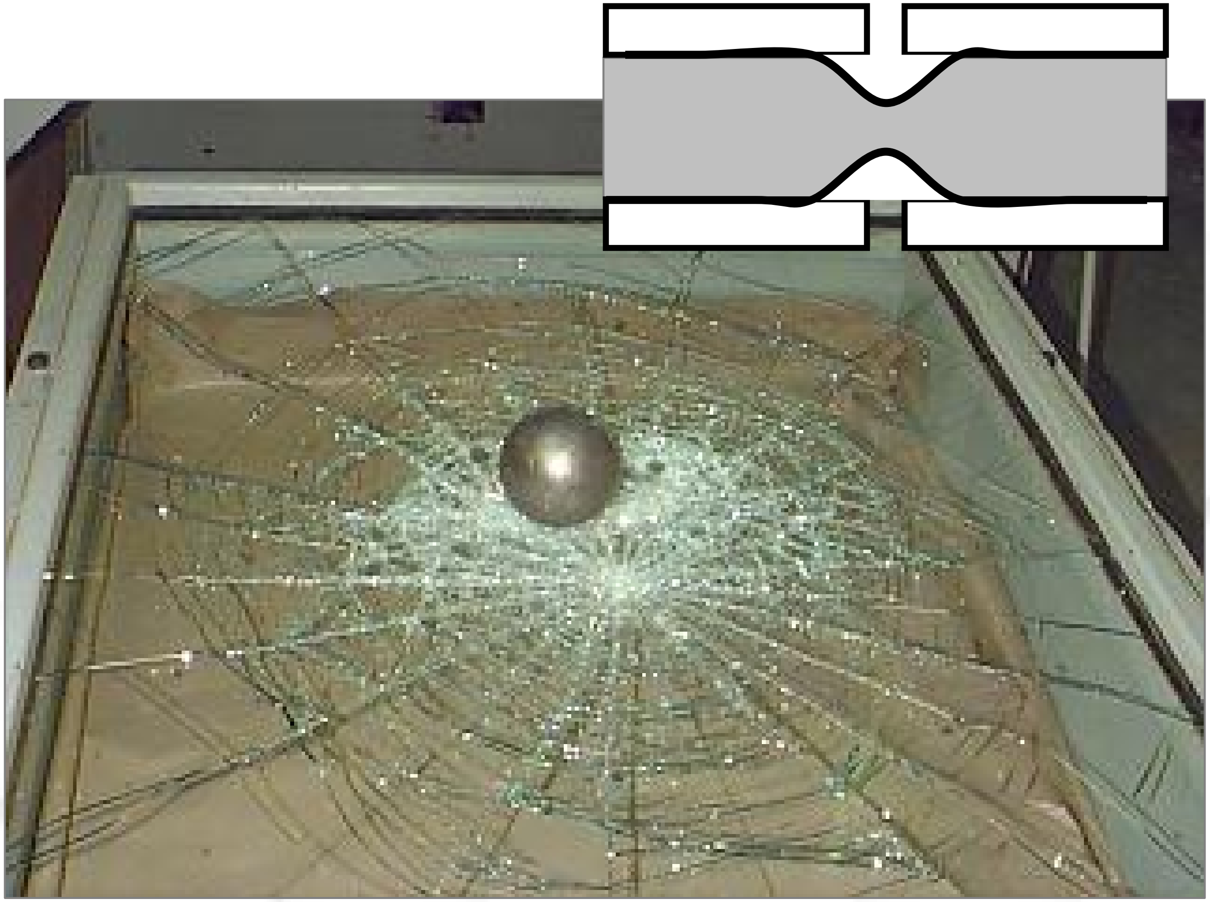


Windshield – laminated glass

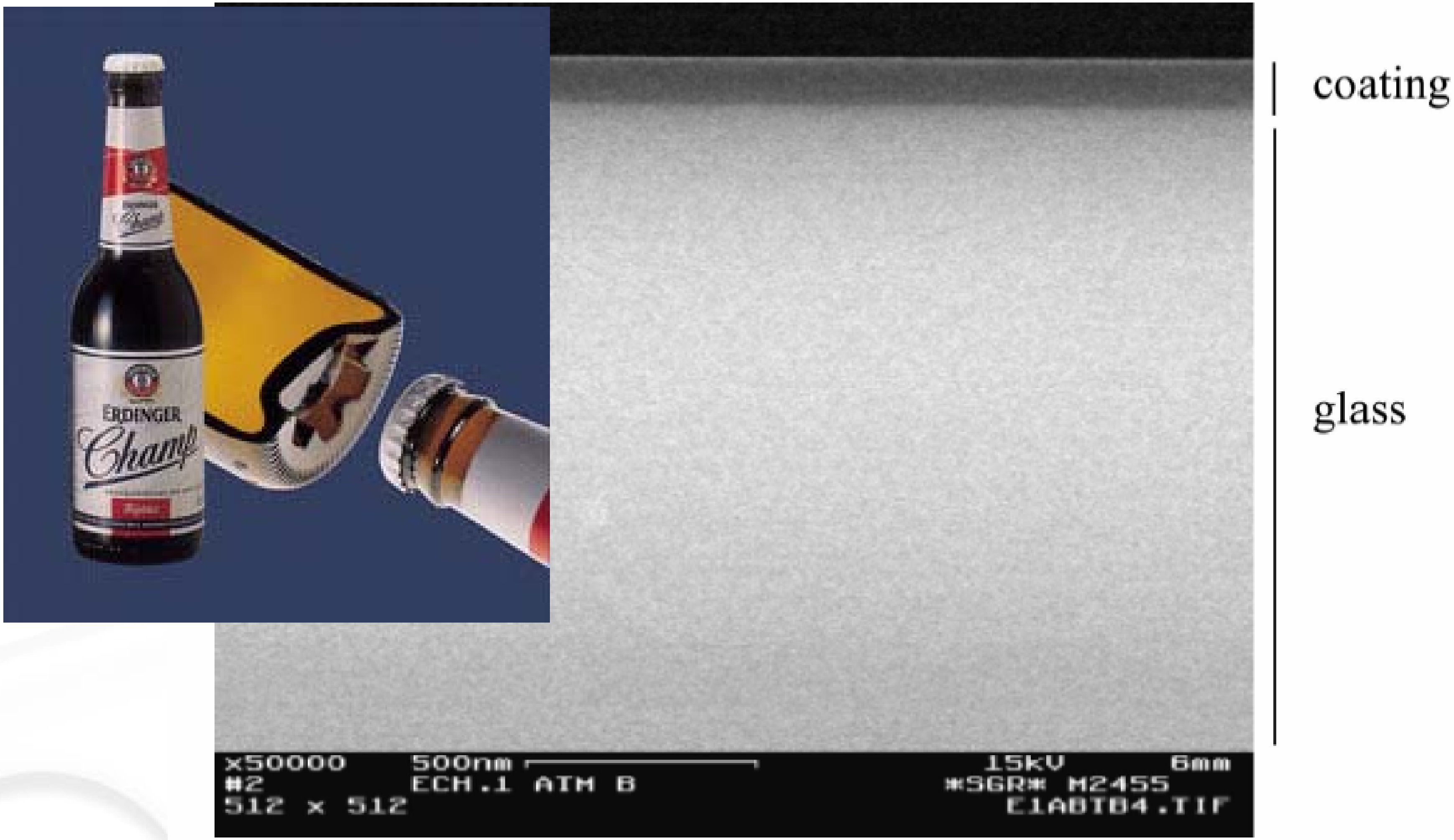


Laminated glass – impact testing

Standard test
EN 356 :
ball 4 kg / 8 m
/ 2 times



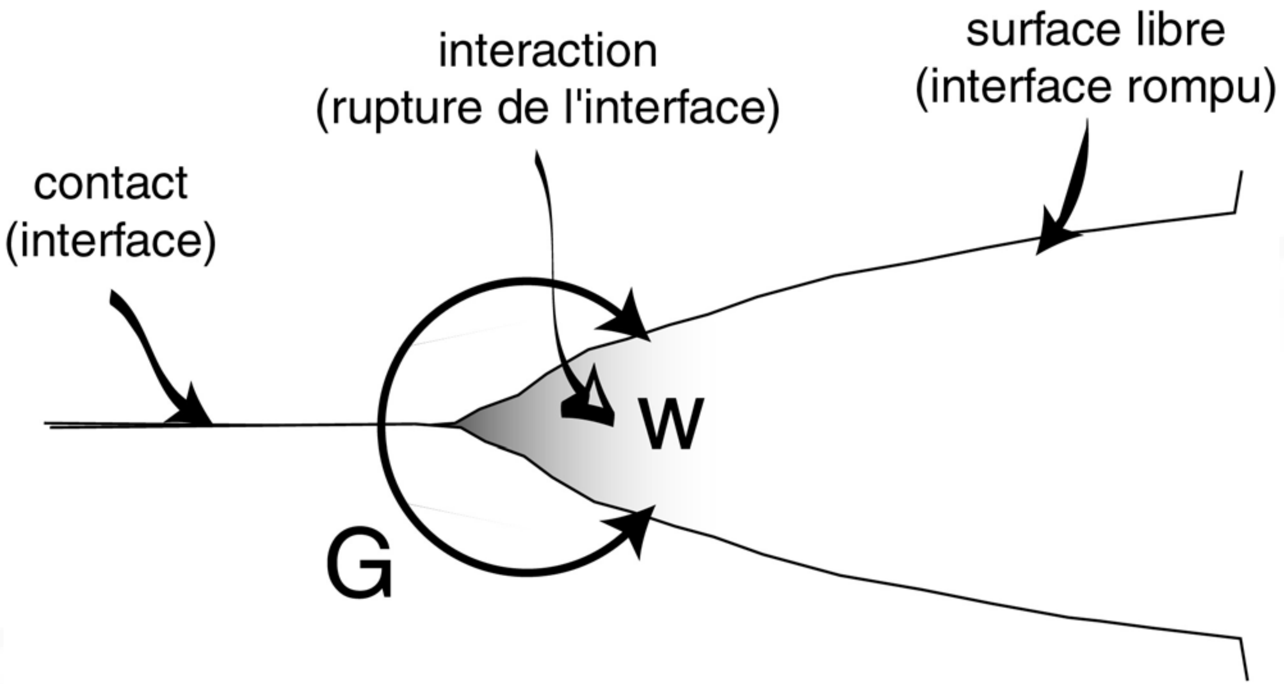
Glass strengthening



Brittleness is fascinating

Afasia 1
Arcangelo Sassolino
Paris, Palais de Tokyo, August 2008

Lengthscales issue



G=w

Outline

- Surfaces and interactions – adhesion
- Mechanics at the local scale – crack tip stresses
- Mechanics at the macroscopic scale – remote loading

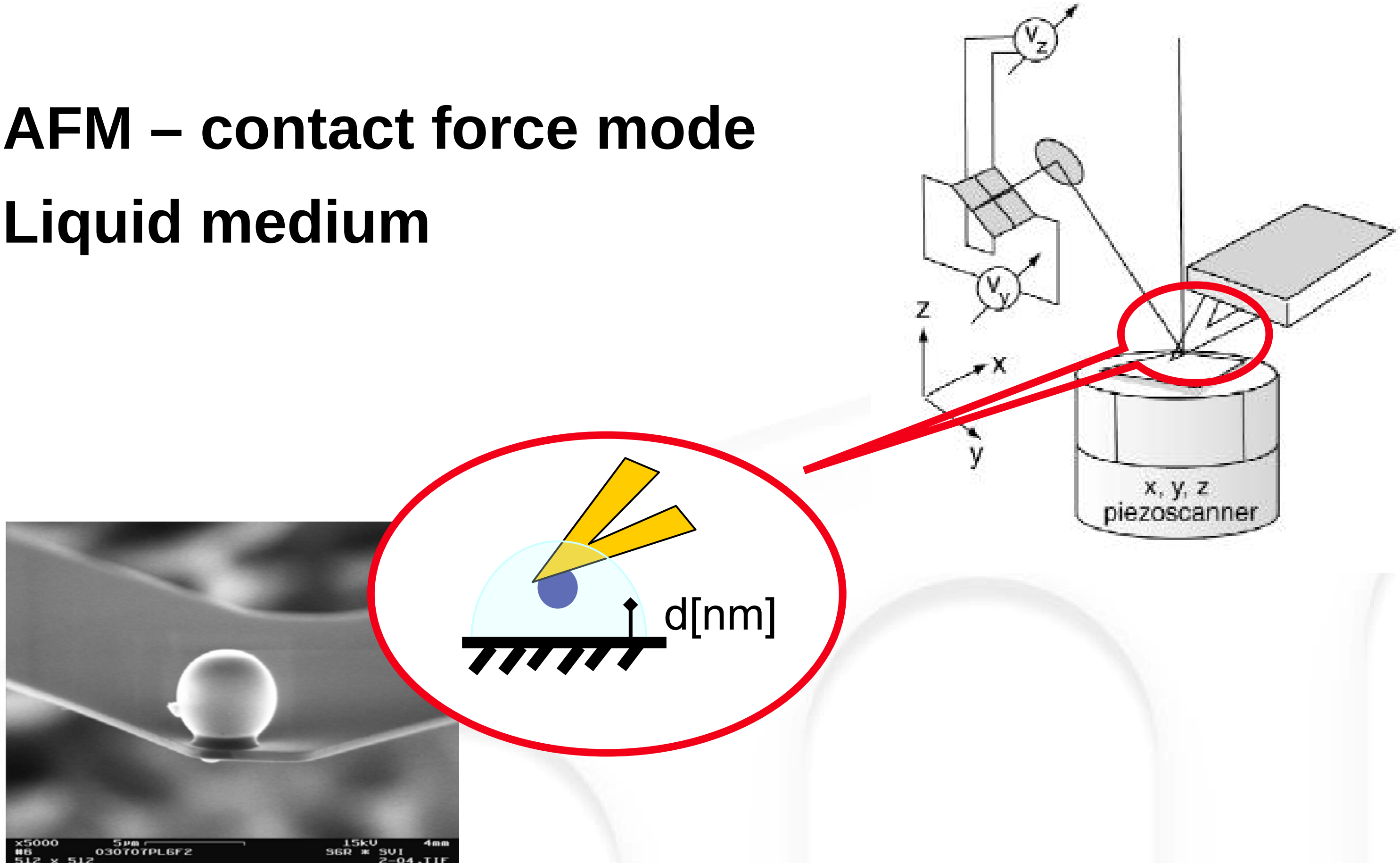
Part I

Part I – Interaction stresses

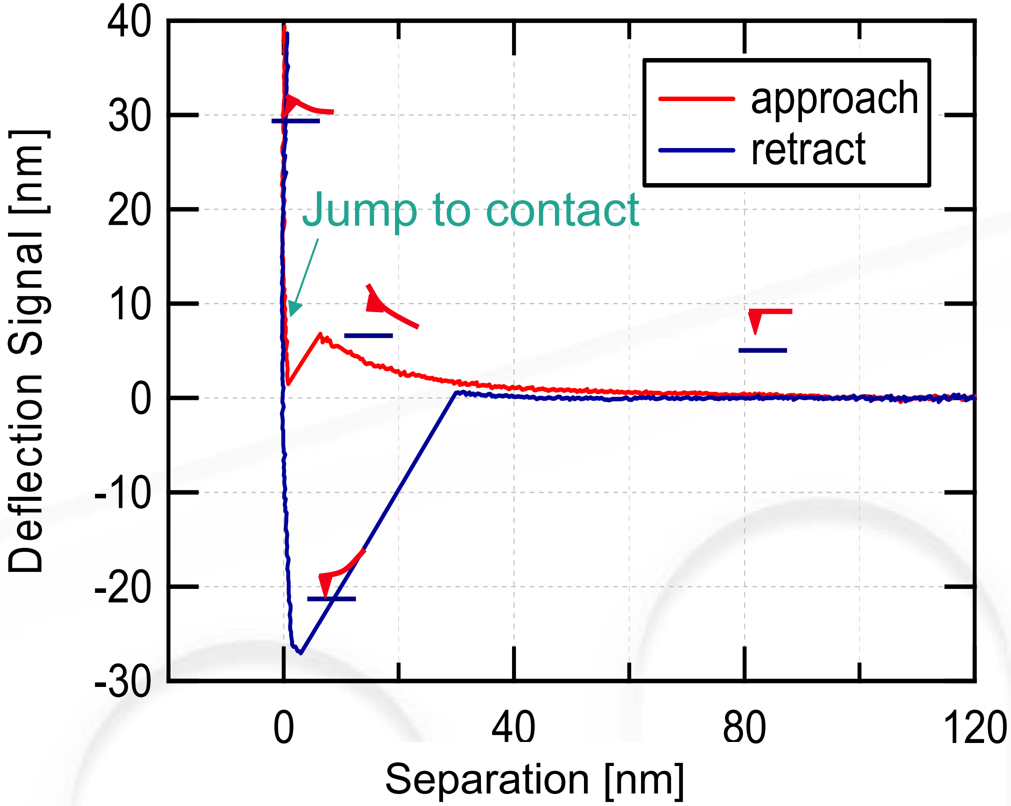
- 1 Measuring the interactions
  - a) Surface forces
  - b) Derjaguin approximation
  - c) Derjaguin approximation – Adhesion
- 2 Interactions and critical stress
  - a) various interactions
  - b) critical (rupture) stress

I.1.a) Surface forces measurement

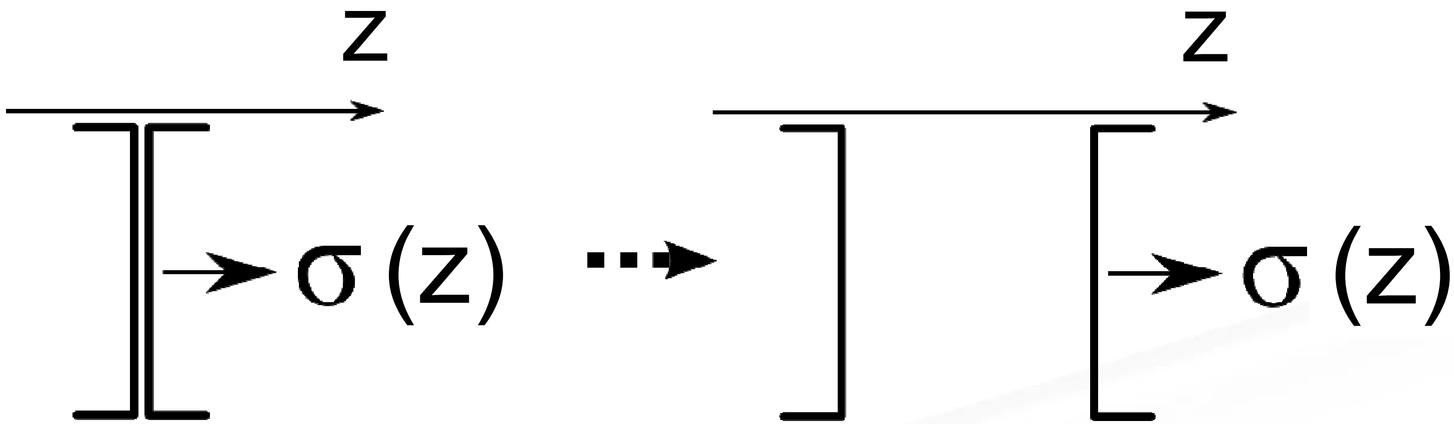
- AFM – contact force mode
- Liquid medium



Classical force curve

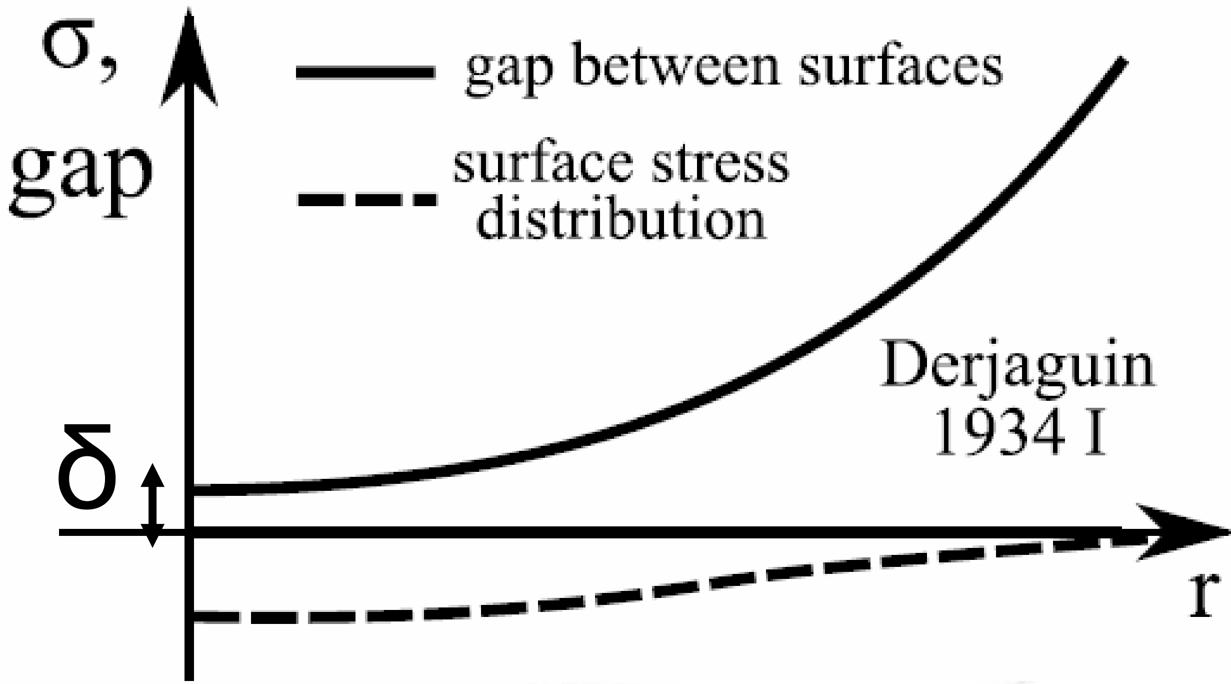


Interaction potential – Interaction stresses



$$\sigma(z) = -\frac{dV}{dz}(z)$$

I.1.b) Derjaguin Approximation

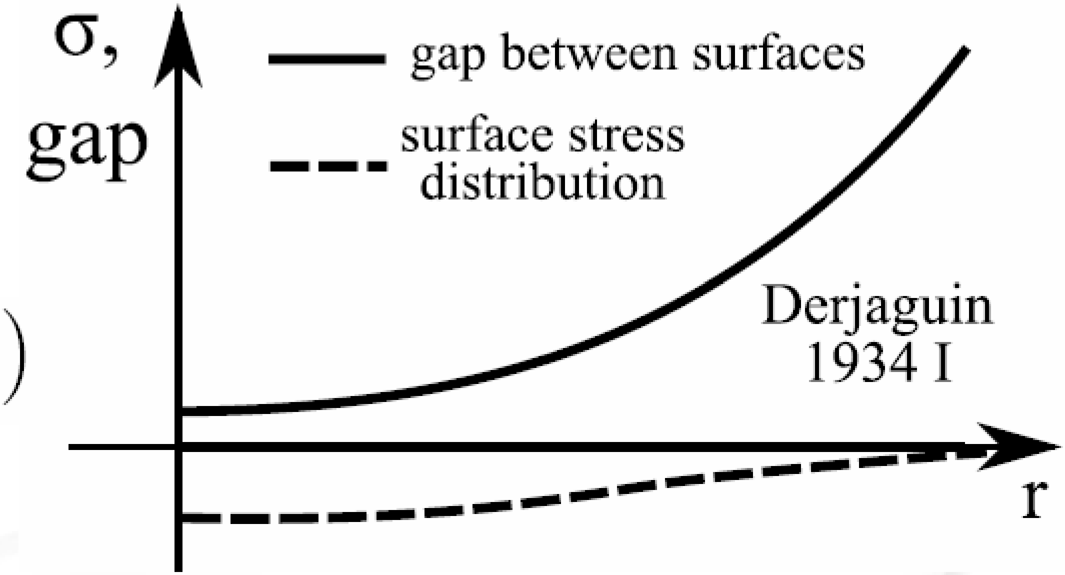


$$F_{ext} = 2\pi \int_0^{+\infty} dr\, r\, \sigma_z(r)$$

$$\boxed{F_{ext}(\delta) = 2\pi R V(\delta)}$$

I.1.c) Derjaguin Approximation – Adhesion

$$F_{ext}(\delta) = 2\pi R V(\delta)$$



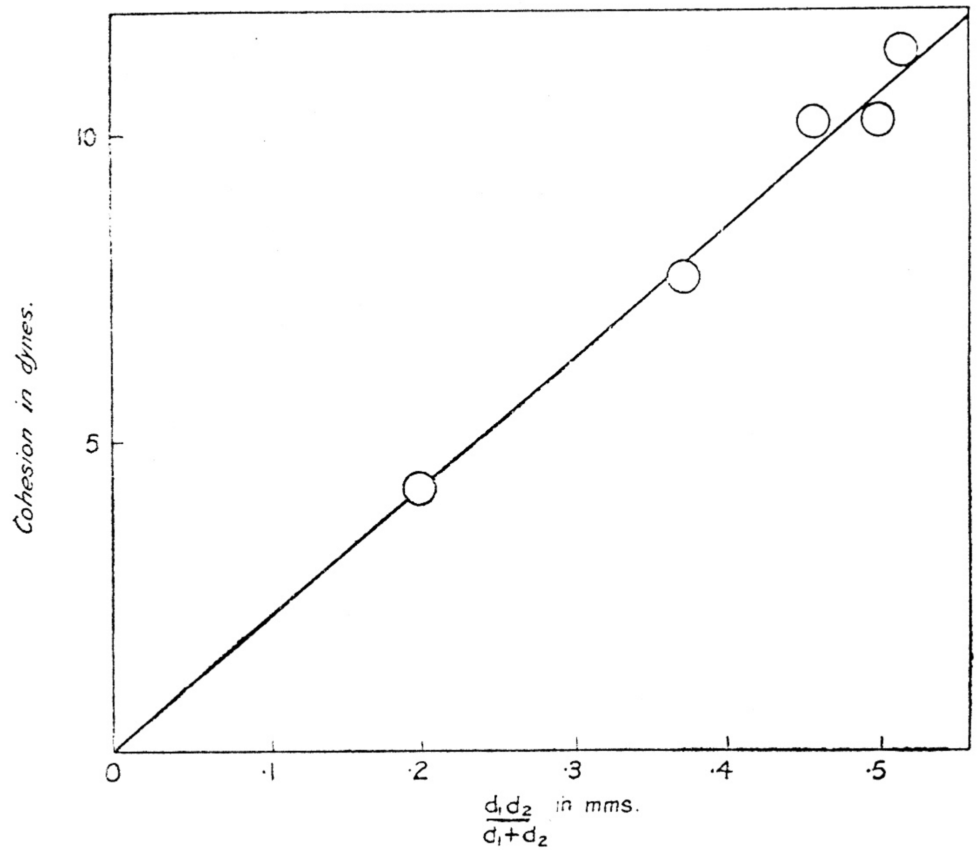
- Pull out force

$$F_{pullout} = -2\pi R w$$

1932 Bradley

Fig. 3.

Fig. 4.

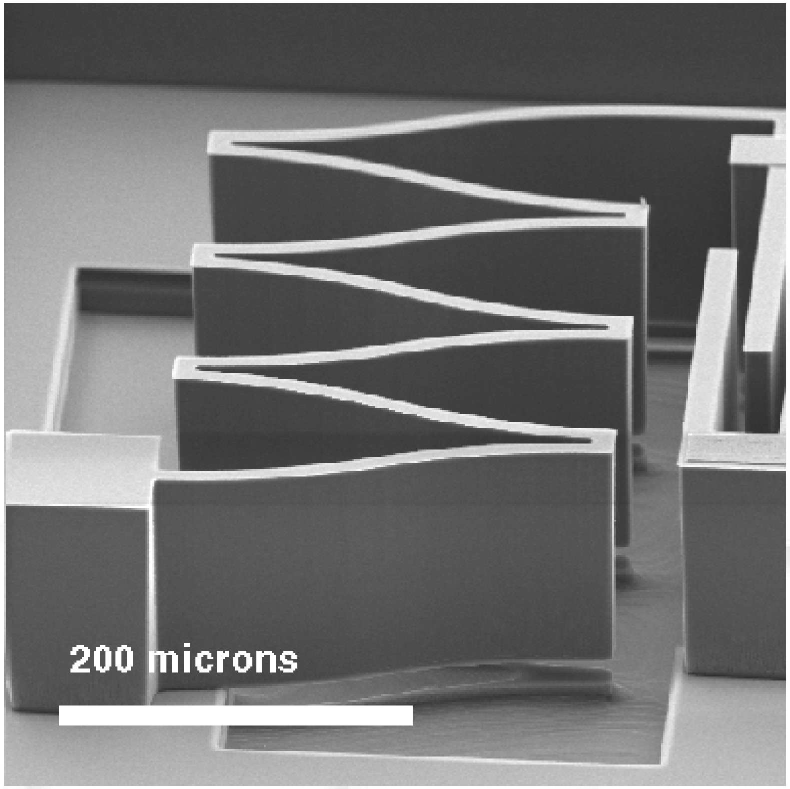


sous vide…
préhistorique

with silica spheres

Scaling issues – small is... sticky

- **macroscopic forces**
  - **gravity** but also
  - inertia
  - aerodynamics
- **surface forces**

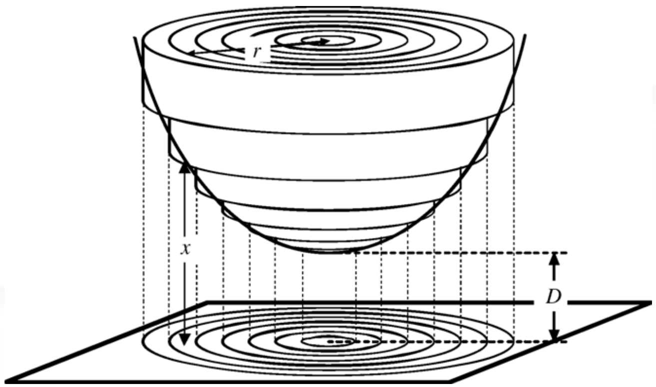


The cut-off distance is about 1 mm !
...equal to a capillary length
...strange

$$R < \sqrt{\frac{w}{\rho g}}$$

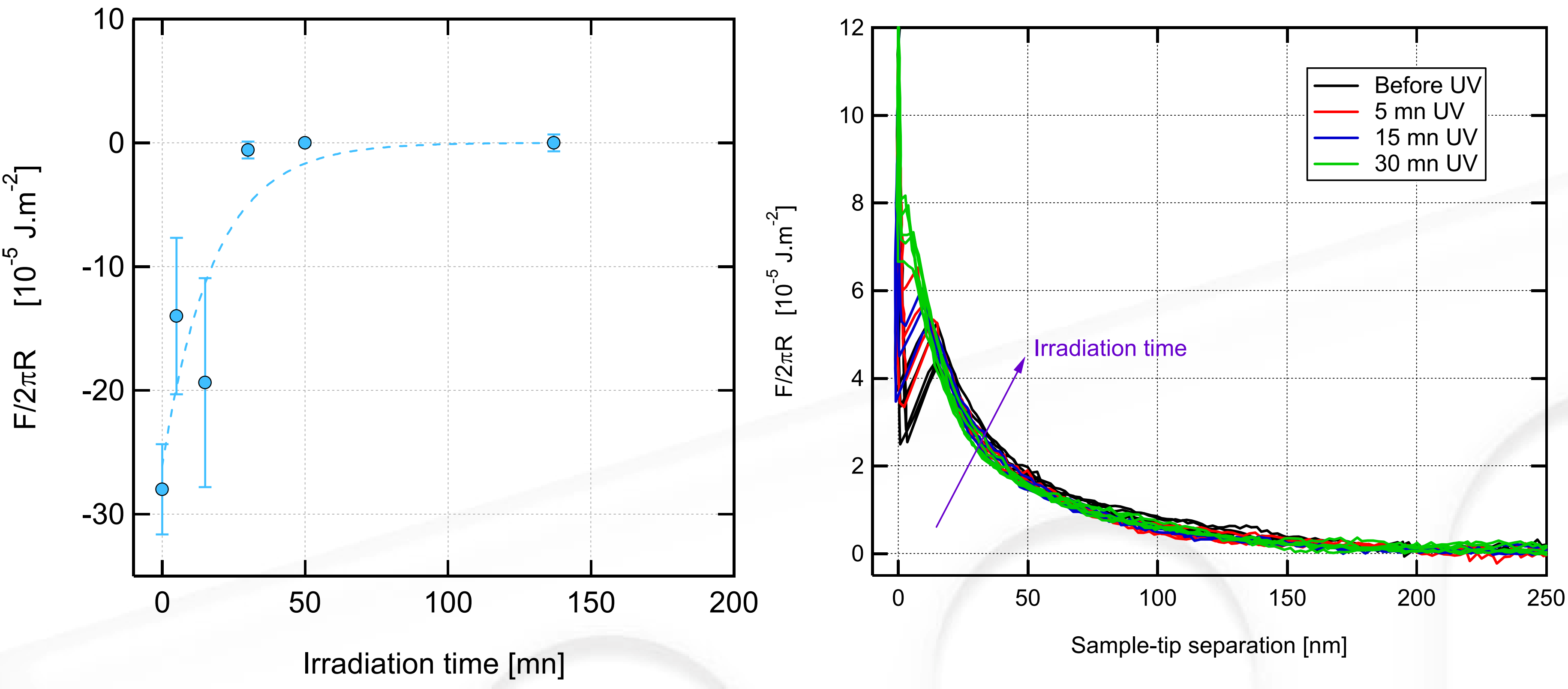
I.2.a) Example: van der Waals forces

$$F = -\frac{A_H}{6\delta^2} R$$



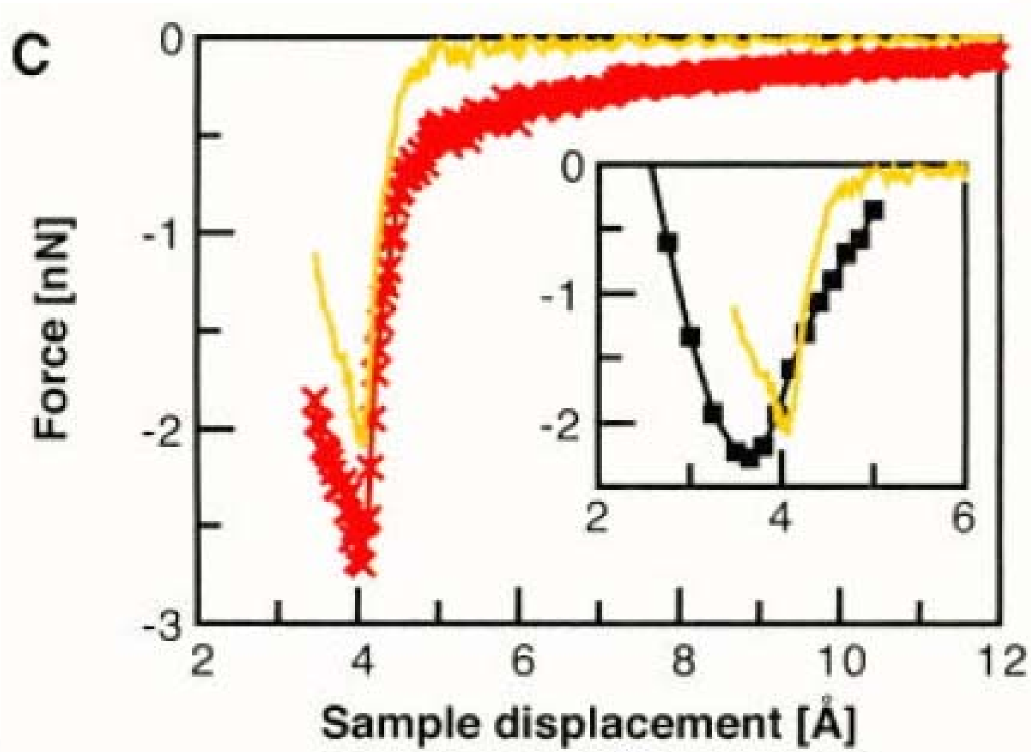
A_H is the Hamaker constant

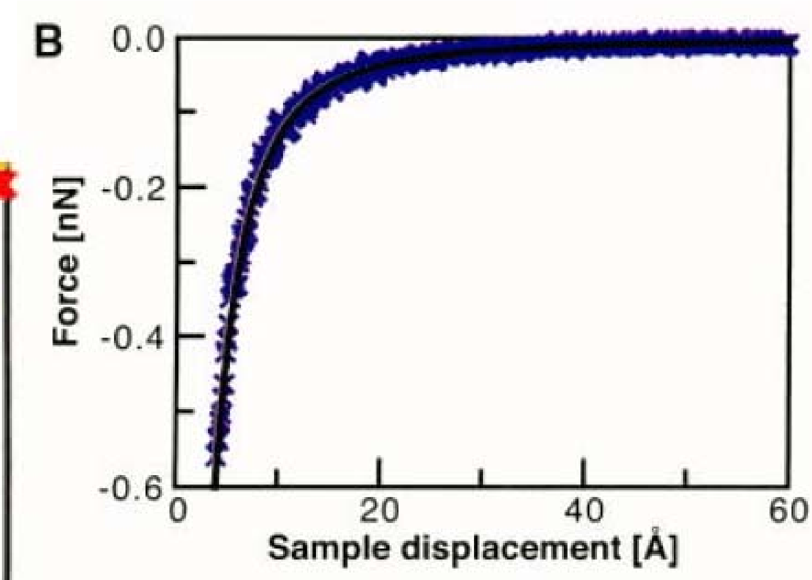
TiO_2 Anatase – UV irradiation

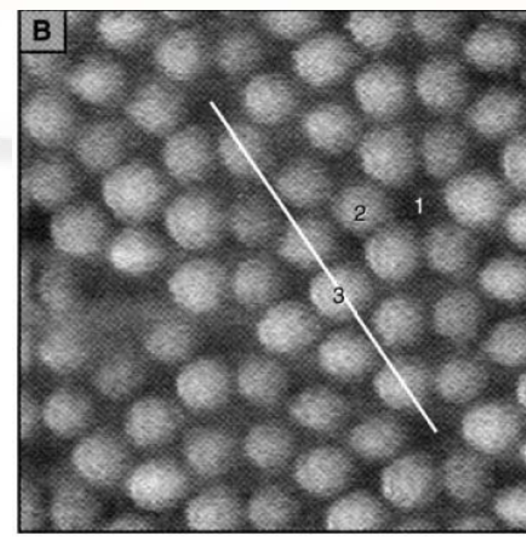


Ramzi Jribi, PhD thesis

Very short range surface forces measurements

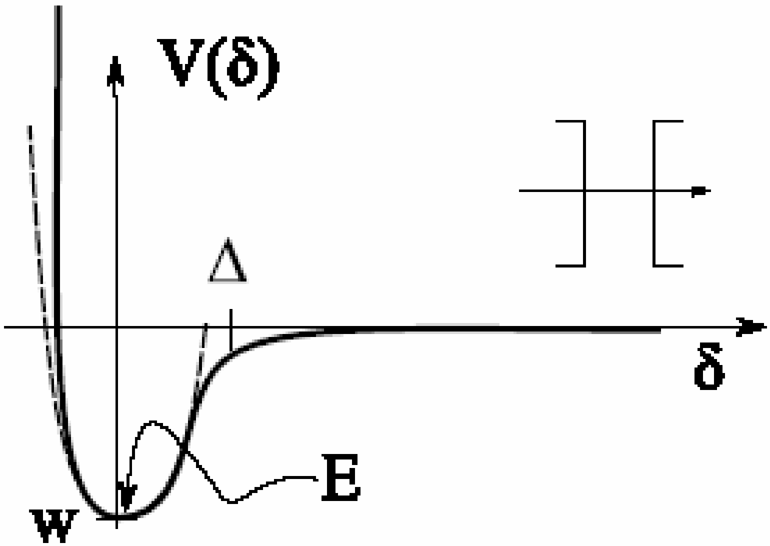






- Lantz, Science,291(2001) 2580

I.2.b) Rupture stress



- Interaction potential

$$V_{el}(\delta) = E\frac{\delta^2}{2\Delta} = \frac{\sigma^2\Delta}{2E}$$

- Rupture

$$V_{el} \simeq w$$

$$\boxed{\frac{\sigma_{crit}^2\Delta}{2E} \simeq w}$$

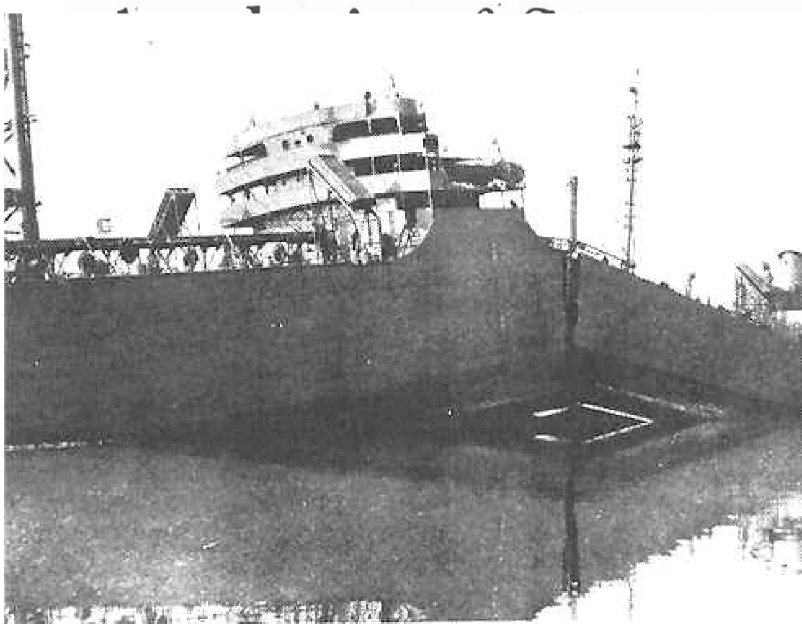
$$\sigma_{crit} \simeq \sqrt{\frac{2Ew}{\Delta}}$$

Orowan
Kohn Sham 1974

orders of magnitude – adhesion energies and critical (rupture) stresses

$$
\begin{aligned}
w &\simeq 1\ \mathrm{Jm}^{-2} \\
\Delta &\simeq 0.2\ \mathrm{nm} \\
E &\simeq 100\ \mathrm{GPa} \\
\sigma_{crit} &\simeq 30\ \mathrm{GPa}
\end{aligned}
$$

$$\text{or } 100 \text{ tons} = 10^6 \text{ N on } 1\times 1 \text{ cm}^2 \text{ !}$$



and Strains Near the Traversing a Plate

WASHINGTON, D. C.

Introduction

d subsequent to the recent World War, investi- fracturing have shared in the general growth mechanics research. Among the fracture failures responsible for interest in this field were those of welded ships, gas-transmission lines, large oil-storage tanks, and pressurized cabin planes. The propagation of a brittle crack across one or more plates in which the average tensile stress was thought to be safely below the yield strength is a prominent feature of these examples.

As a result of these investigations there was a revival of interest in the Griffith theory of fracture strength (1).[2] It was pointed out independently by Orowan (2) and by the author (3) that a modified Griffith theory is helpful in understanding the development of a rapid fracture which is sustained with energy from the surrounding stress field. Expositions of this idea have

J. Appl. Mech. 1957

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Part II – remote loading

- Crack propagation – Energy release rate

1) Linear system
   - a) Peel test and asymmetric vs symmetric peel
   - b) DCB measurement for thin films
   - c) crack deflection

2) Non linear system
   - a) hertzian contact
   - b) adhesion and elastic deformation: Derjaguin 1934 II

Crack propagation – Energy release rate

- Energy release rate

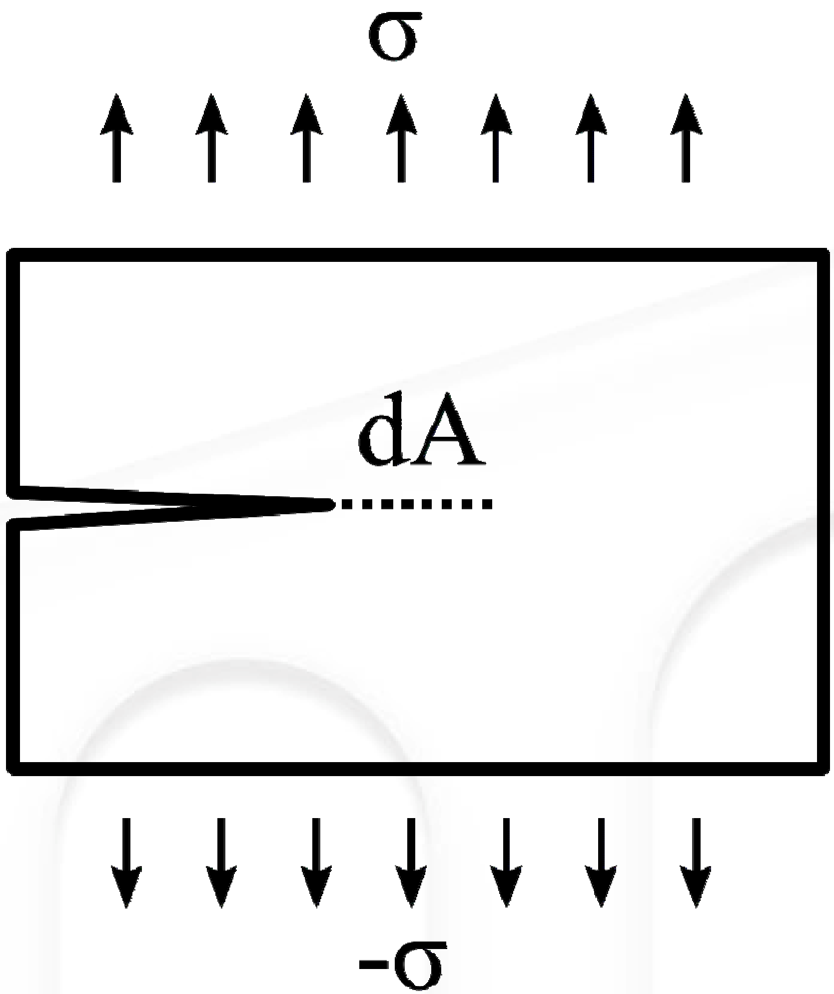
$$\mathcal{G} \equiv -\frac{d\mathcal{E}_{mech}}{dA}$$

A is the *fracture* area

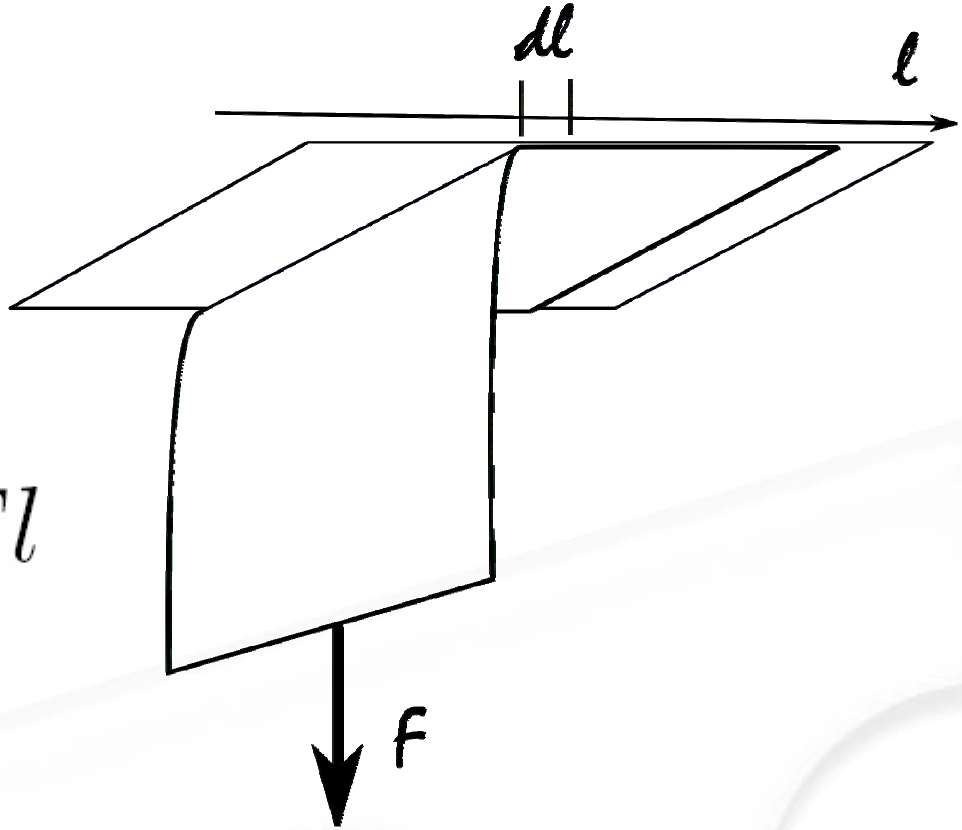
$$\mathcal{E}_{mech} = \mathcal{E}_{elas} + \mathcal{E}_{pot}$$

- Equilibrium

$$\mathcal{G} = w$$



II.1.a) 90° Peel test



$$\mathcal{E}_{mech} = \mathcal{E}_{pot} = Fl$$

$$\mathcal{G} = -\frac{F}{b}$$

$$\boxed{|F| = wb}$$

II.1.a’) (A)symmetric peel test – Elastic strip

- ethylene propylene rubber / PMMA + thin EPR film
- 10 cm wide / 12 mN / applied 60 mn
- a: no propagation / b: crack speed 2 µm/s

6. EXPERIMENTAL PROOF THAT STRESS DOES NOT DRIVE CRACKS

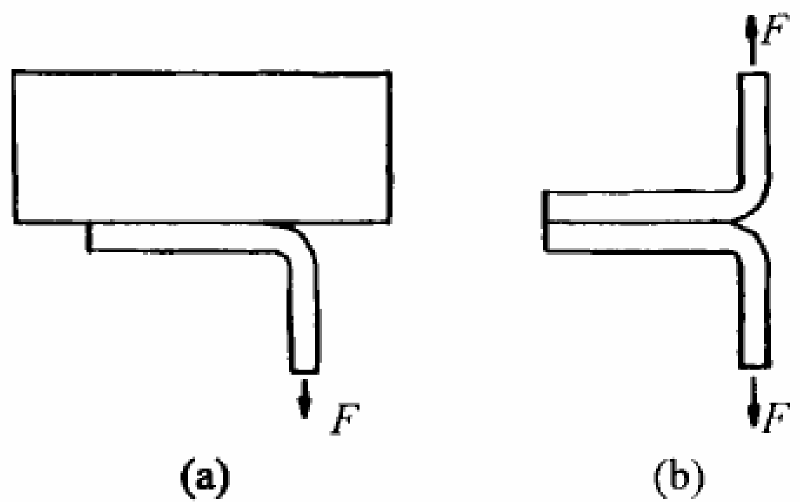
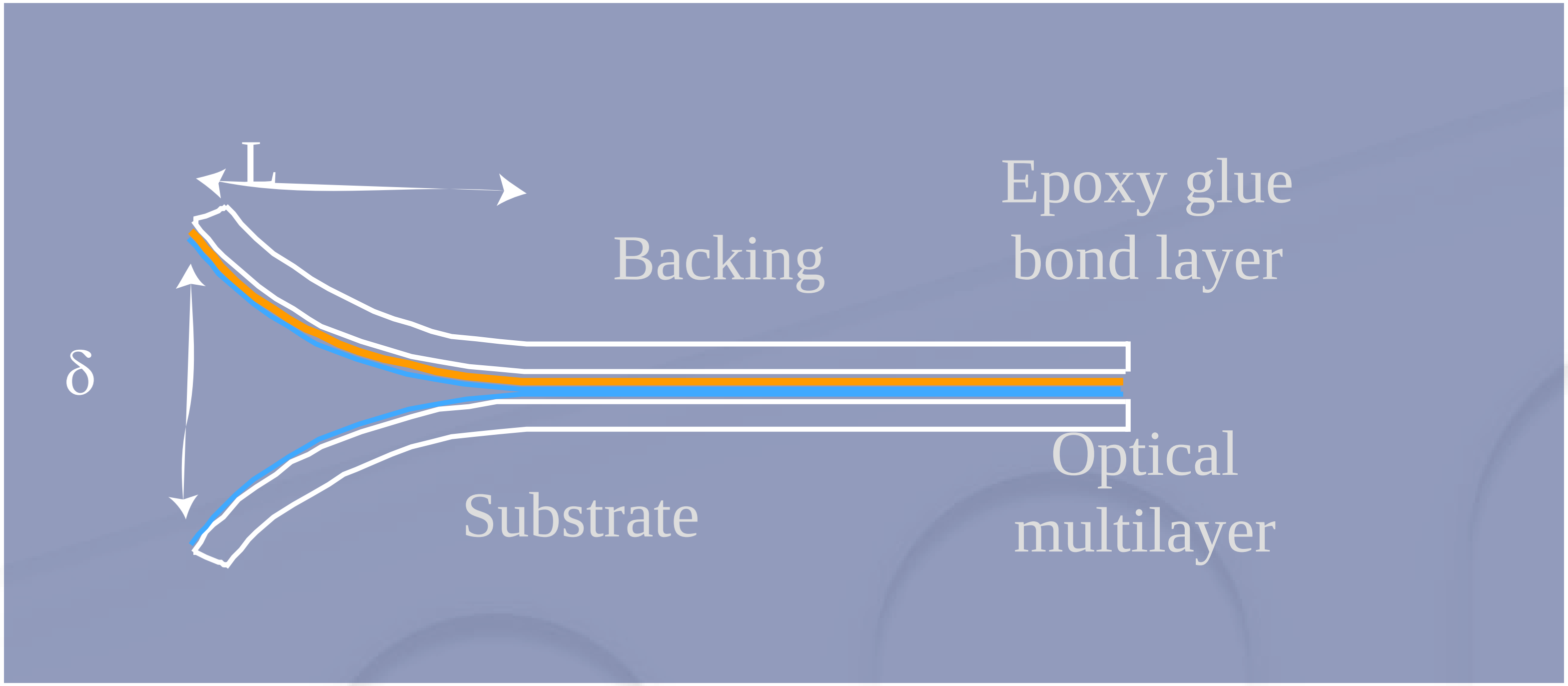


Figure 6. (a) Peel test with F just low enough to prevent cracking; (b) peel test at the same stress now fractures.

- K. Kendall, J Adhes Sci Technol 8 (1994) 1271

II.1.b) The Double Cantilever Beam (DCB)



A1

II.1.b) The Double Cantilever Beam (DCB)

- Linear system

$$F = \alpha\delta \quad \text{with} \quad \alpha = \frac{Eb}{4}\left(\frac{h}{L}\right)^3$$

- Energy release rate

$$\boxed{\mathcal{G} = \frac{3Eh^3}{8}\frac{\delta^2}{L^4}}$$

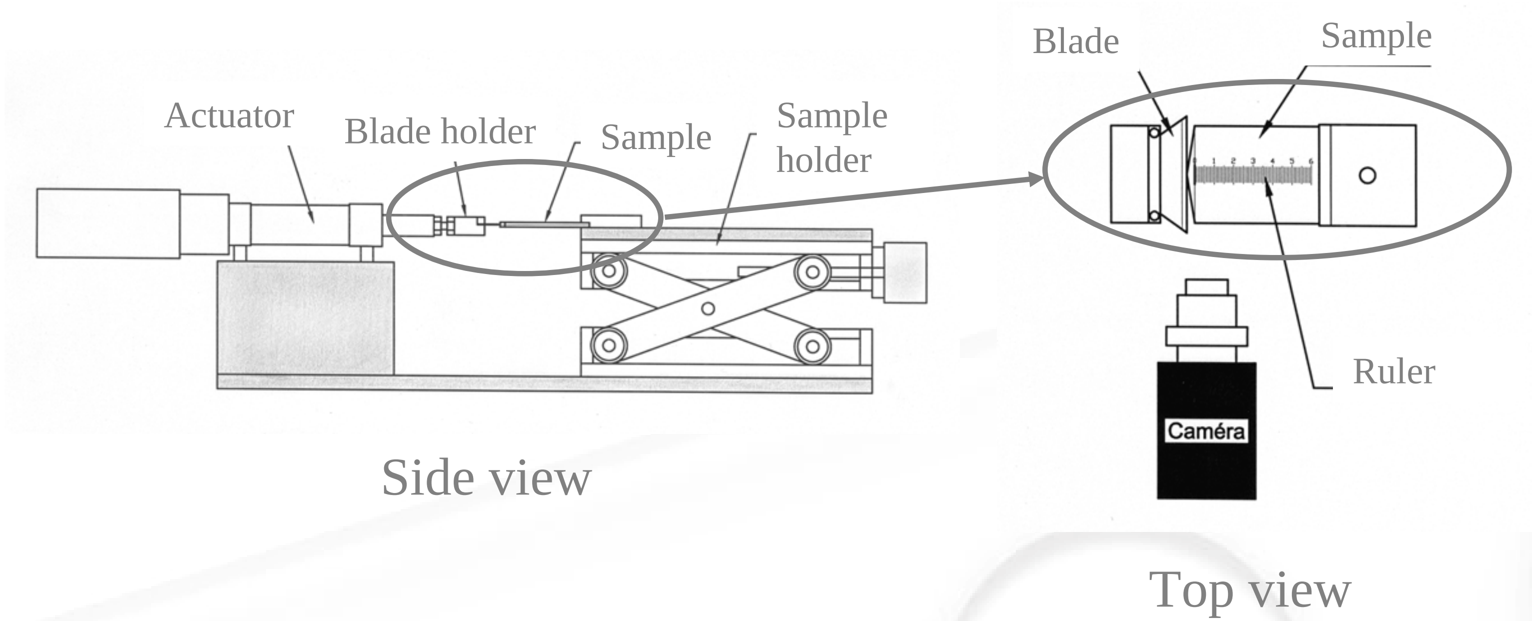
- or

$$\mathcal{G} = \frac{6}{Eh^3}L^2\left(\frac{F}{b}\right)^2$$

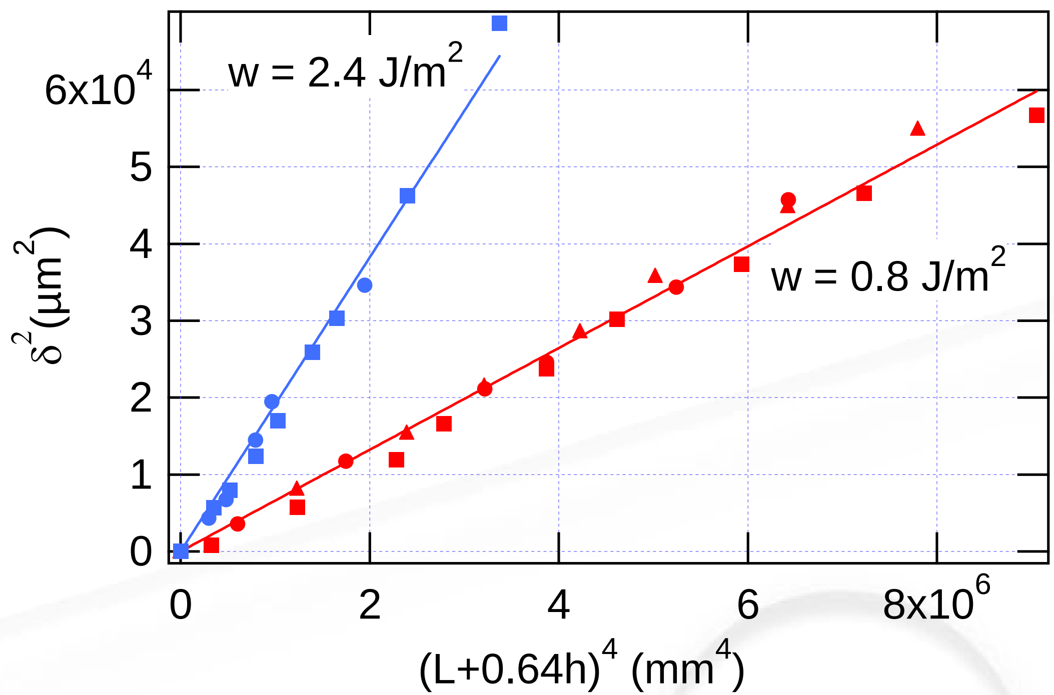
- Impacts the stability

DCB adhesion energy measurement

experimental set-up



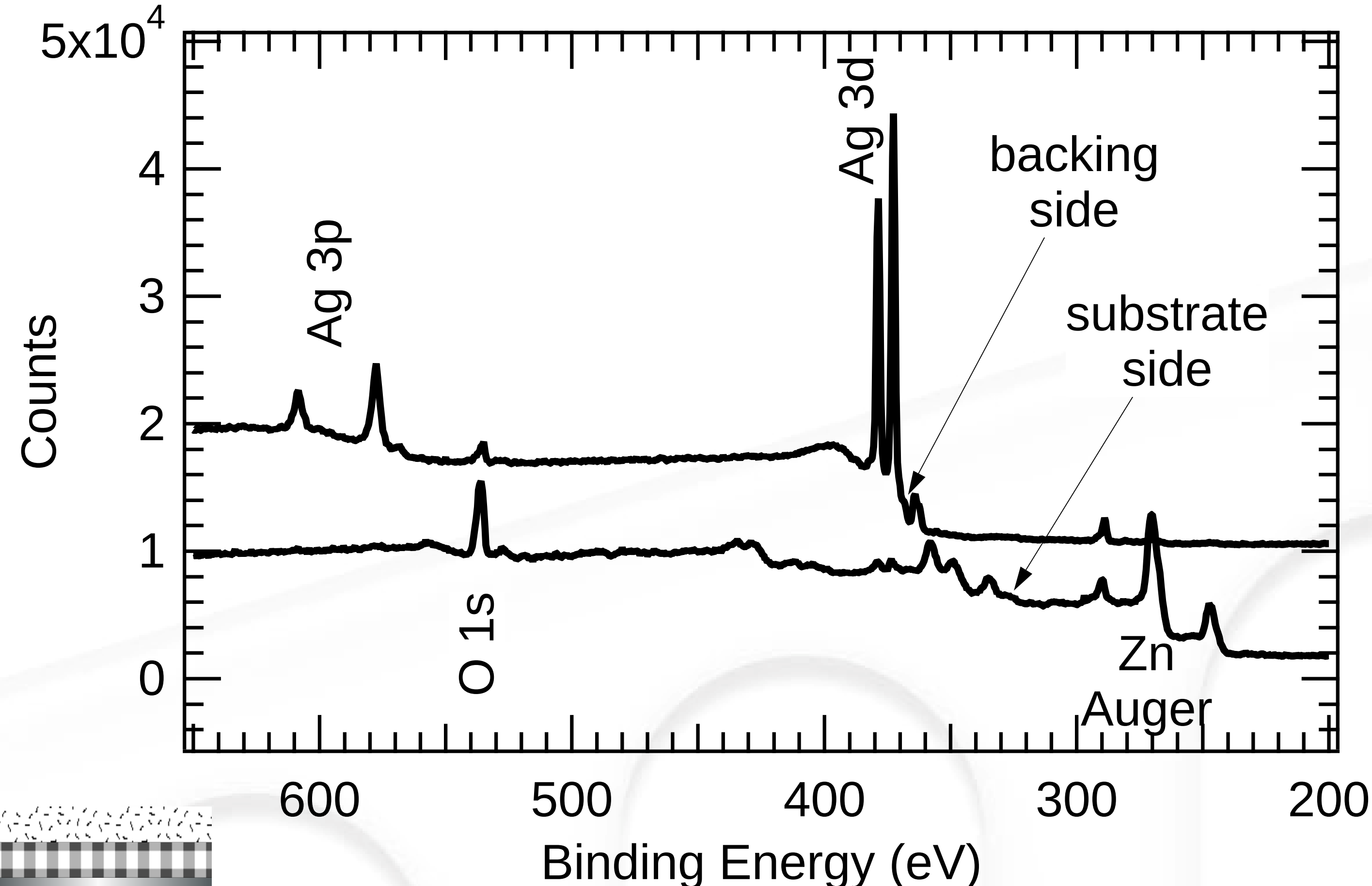
DCB – results

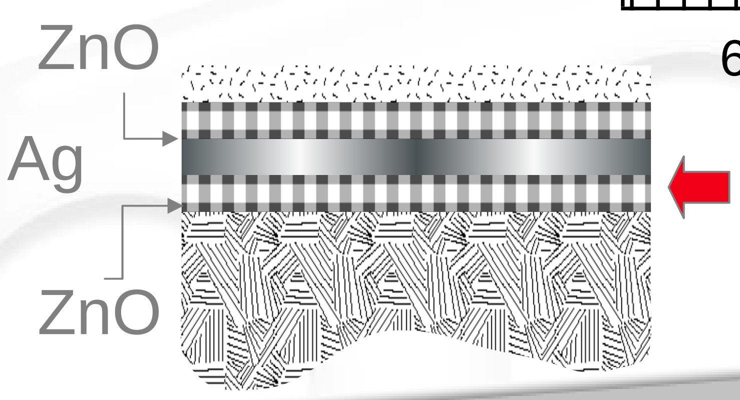


Obreimov, Kanninen

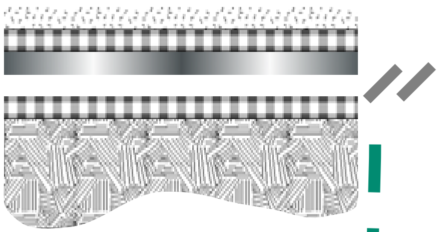
Barthel et al. Thin Solid Films, 2005

Indentification of the interfaces - XPS



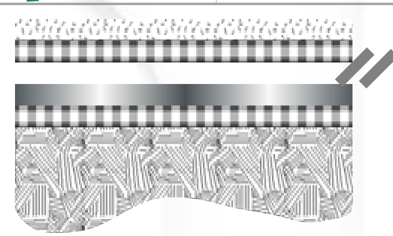


underlayer



// is the locus of failure

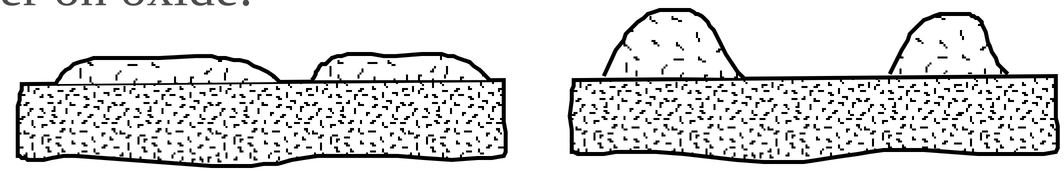
1	Glass / Si_3N_4 // Ag / ZnO	**0,7 J/m²** ± 0,2 (2 s.)
2	Glass / ZnO // Ag / ZnO	**1,5 J/m²** ± 0,2 (2 s.)
3	Glass / TiO_2 / Ag // ZnO	**2,1 J/m²** ± 0,7 (3 s.)
4	Glass / SnO_2 / Ag // ZnO	**2,4 J/m²** ± 0,1 (3 s.)



Results

Deposition is not at equilibrium

Silver on oxide:



Ambiant Temperature

High Temperature

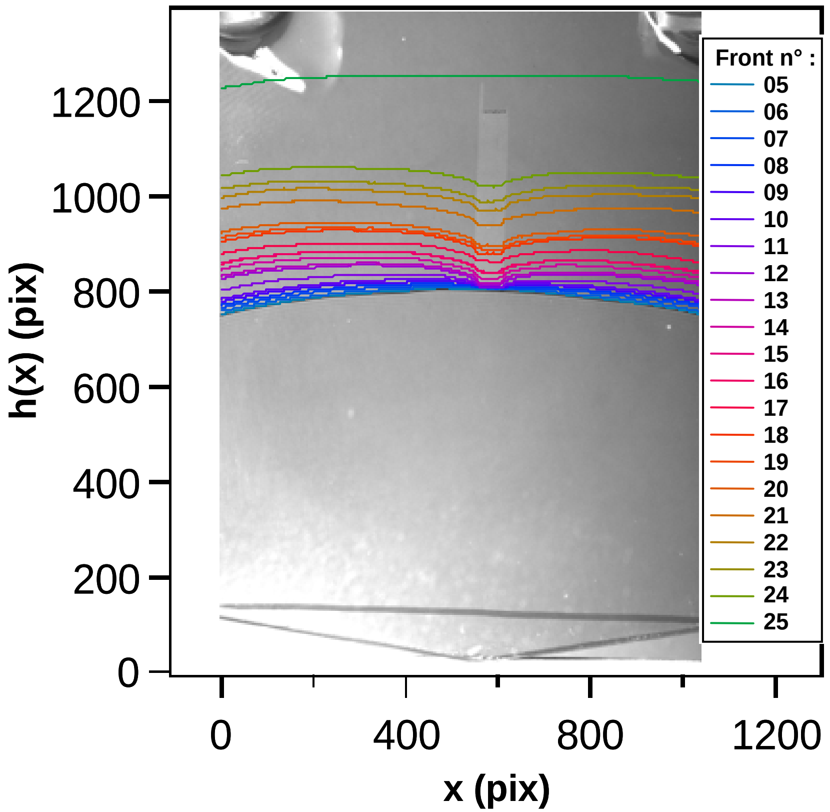
Ag does not wet ZnO; ZnO wets Ag

History matters:

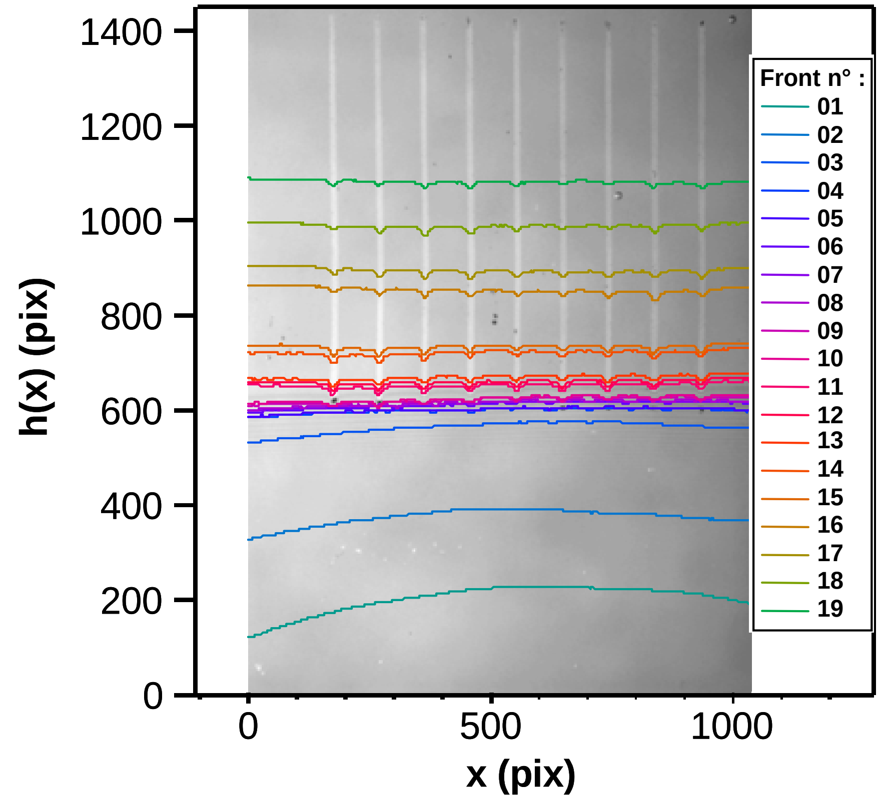
cf also Lin and Bristowe PRB 2007

Adhesion – crack propagation in structured interfaces

Sample A : Single Scratch

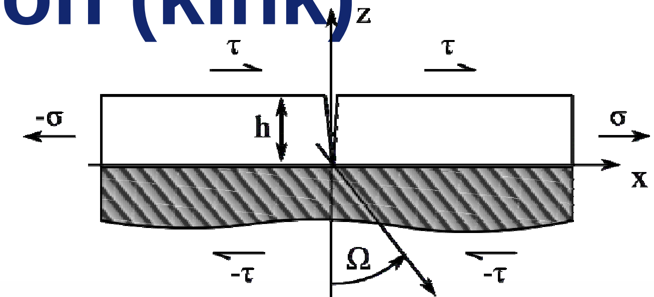


Sample B : Multi scratch

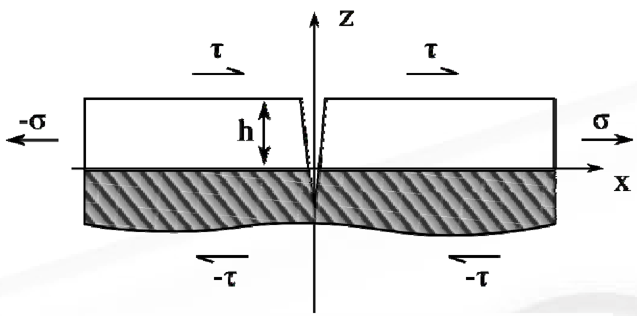


Dalmas et al. 2009

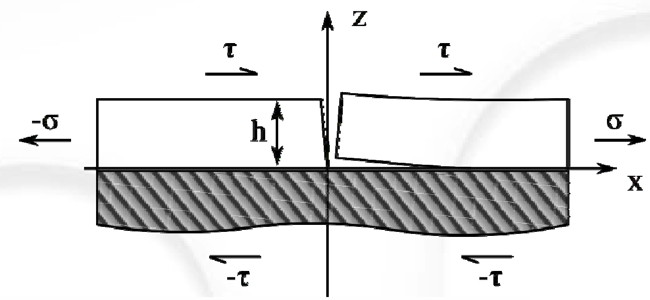
II.1.c) A more complex example crack deflection (kink)



$$w_{coh} < > 4\pi w_{int}$$



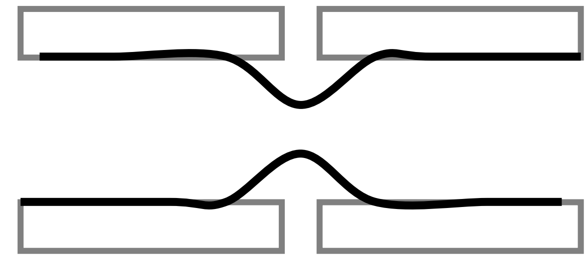
$$\sigma = \sqrt{\frac{E^{\star} w_{coh}}{\pi h}}$$

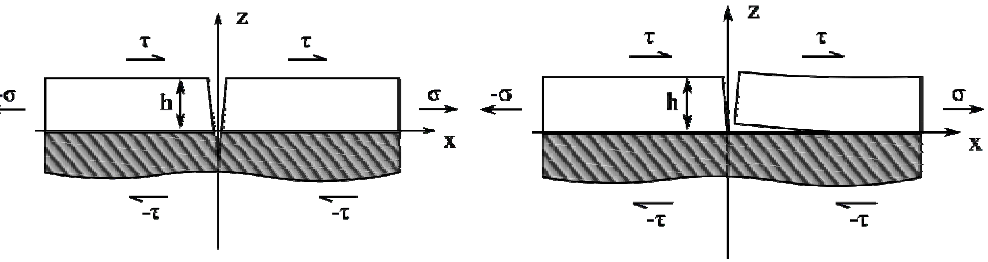


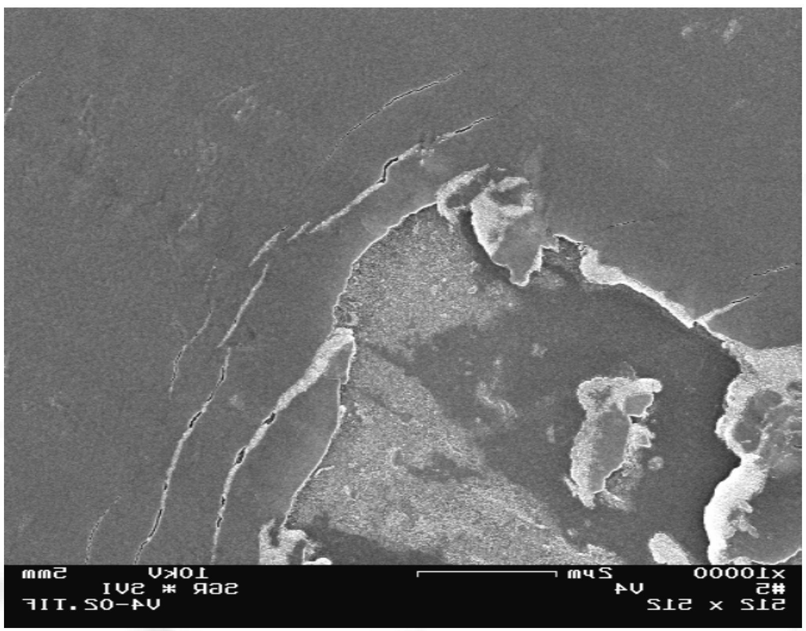
$$\sigma = \sqrt{\frac{4 E w_{int}}{h}}$$

Cook-Gordon 1964, Kendall 2004

Thin film – instability under sliding contact

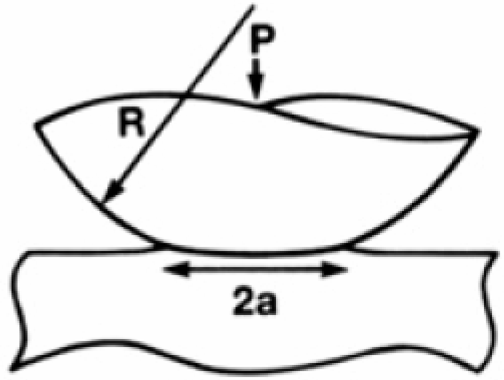




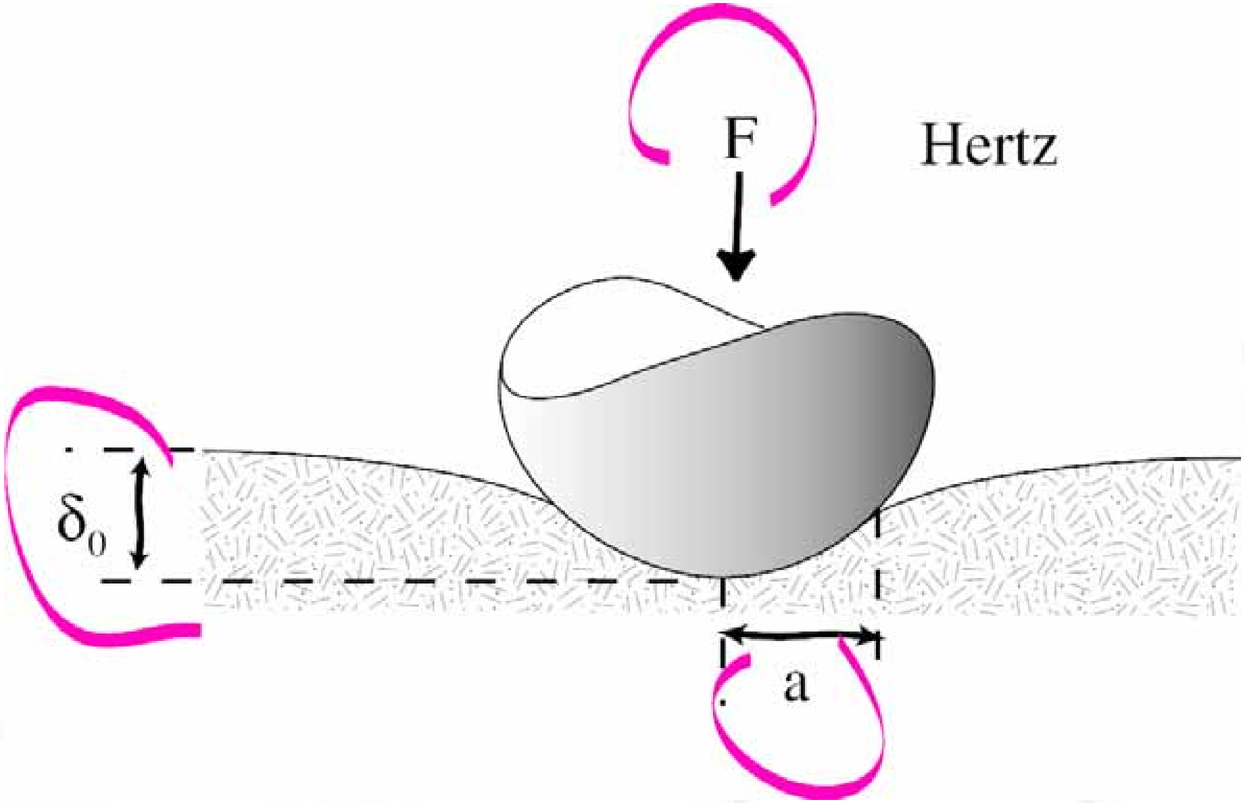


X. Geng, PhD

II.2) Adhesive contact

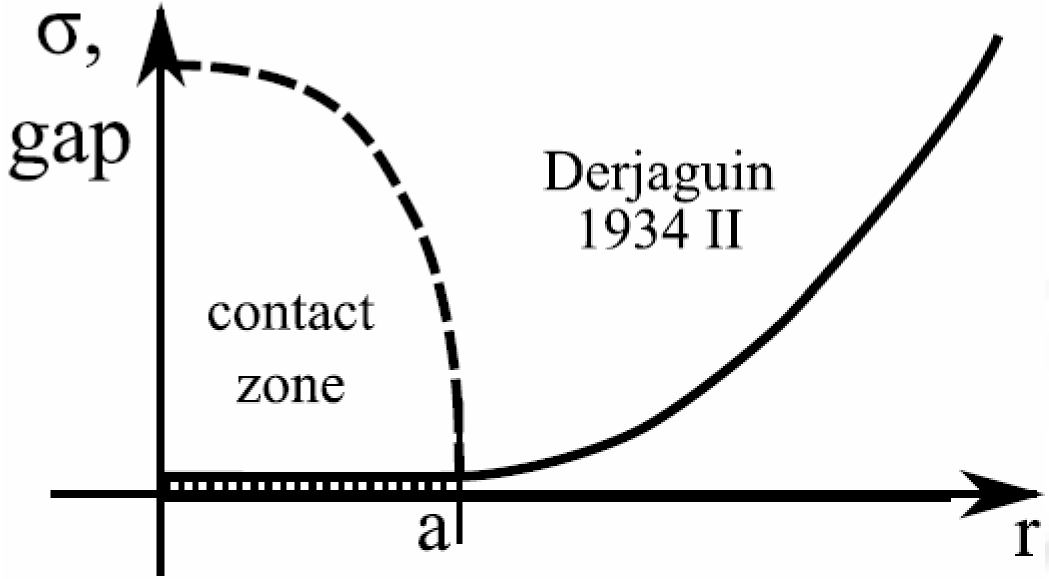


II.2.a) Hertz contact



$$\delta_{\mathrm{H}}(a) = \frac{a^2}{R} \qquad F_{\mathrm{H}}(a) = \frac{4E^{\star}a^3}{3R}$$

II.2.b) Derjaguin 1934 Part II



- Energy

$$\mathcal{E}(\delta) = \mathcal{E}_H(\delta) - w(\pi a^2)$$

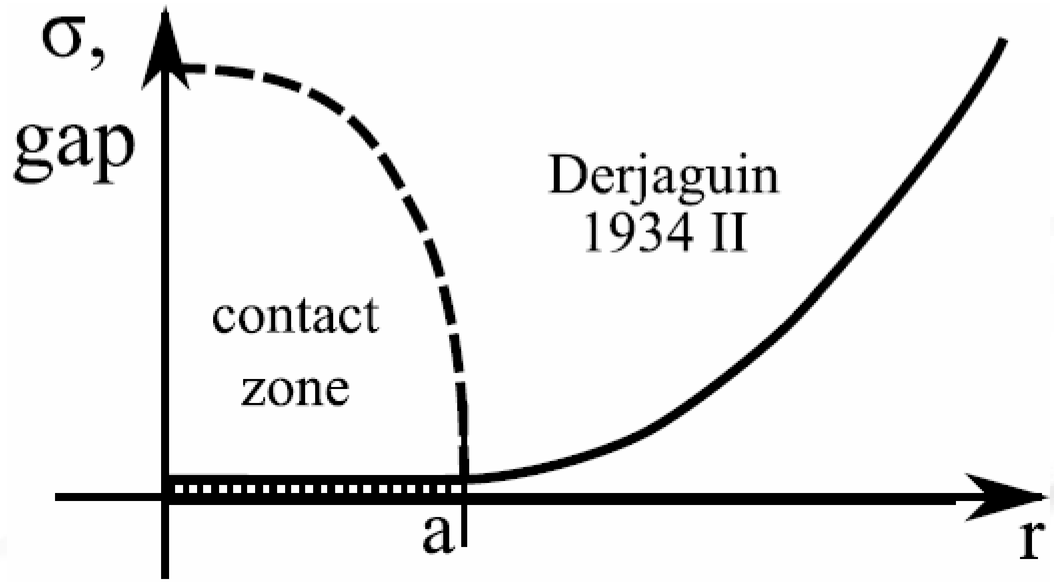
- Penetration and force

$$\delta_D = \delta_H(a)$$

$$F_D = F_H(a) - \pi R w$$

Derjaguin,
Kolloid Z., 69, 155 (1934)

Derjaguin 1934 Part II



- Pull out force

$$F_{pullout,D} = -\pi R w$$

Part III