

Mechanical structuring

- Mechanical properties of glass
- Precision mechanical machining
- Ultrasonic machining
- Abrasive jet machining
- References

Elastic modulus

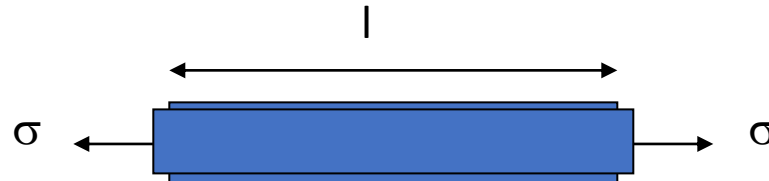
- Elastic modulus : ratio of of the strain, ε , resulting from application of a stress σ :

modulus

E : elastic modulus, Young's

$$\sigma = \frac{E}{1+\nu} \varepsilon$$

ν : Poisson's ratio



$$\varepsilon = \Delta l / l$$

- E is determined by the atomic bonds and by the structure of the network
- Typical value : 10 – 100 GPa

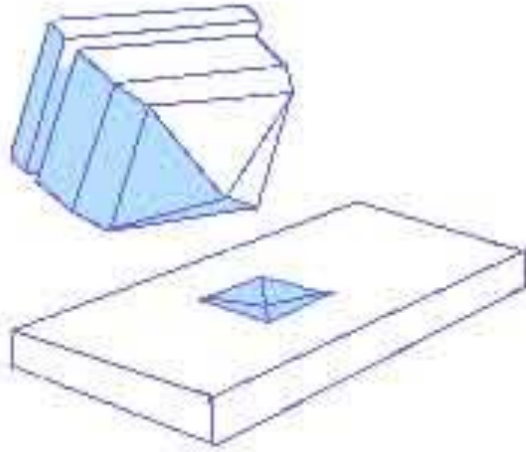
Hardness (i)

Moh's scale (Friedrich Moh, German mineralogist, 1822) :

10	Diamond
9	Corundum
8	Topaz
7	Quartz
6	Feldspar
5	Apatite
4	Fluorspar
3	Calcite
2	Gypsum
1	Talc

Glass : 5 - 7

Hardness (ii)



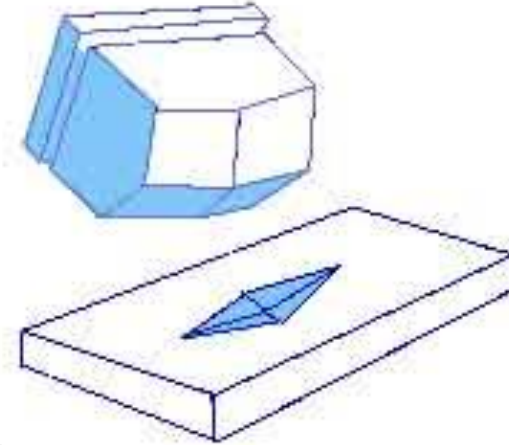
Vickers Test

Opposing indenter faces are set at 136° to each other

$$HV = \frac{1.854F[kgf]}{A[mm^2]}$$

Glass : HV ~ 2–8 GPa

Diamond : HV ~ 100 GPa



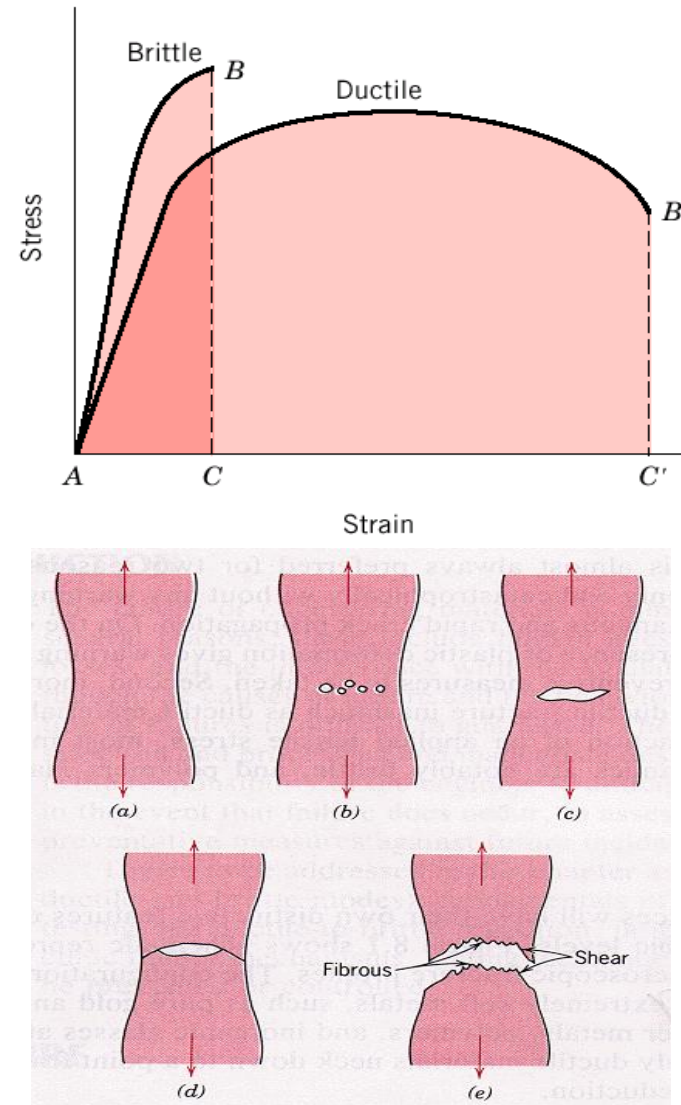
Knoop Test

Long side faces are set at a $172^\circ 30'$ to each other. Short side faces are set at a 130° to each other

$$HK = \frac{14.2F[kgf]}{A[mm^2]}$$

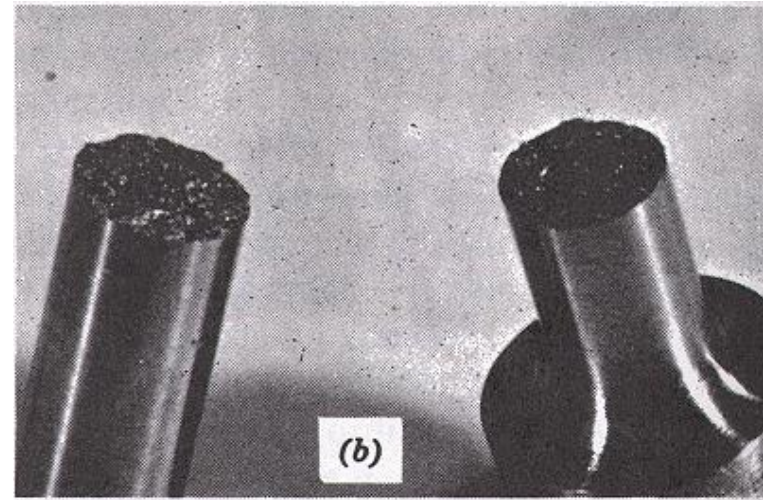
Toughness (metals)

- Toughness: ability to absorb energy in the plastic range up to fracture
- Proportional to area under the strain-stress curve up to fracture
- Units: energy per unit volume, e.g. J/m^3



Fracture (brittle materials)

- Two steps in the process of fracture:
 - Crack initiation
 - Propagation
- Exhibits little or no plastic deformation and low energy absorption before failure
- Crack propagation spontaneous and rapid
- Occurs perpendicular to the direction of applied stress, forming an almost flat fracture surface
- Deemed unstable as it will continue to grow without the aid of additional stresses



Griffith theory of brittle fracture

- The critical stress required for crack propagation in a brittle material is given by:

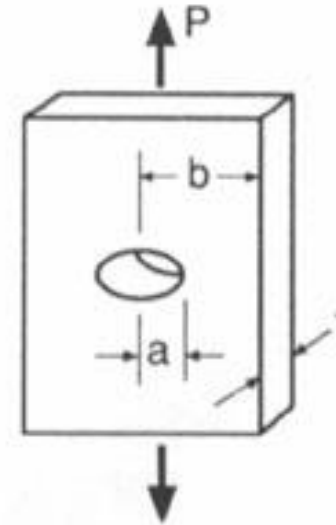
$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

E = modulus of elasticity

γ_s = specific surface energy

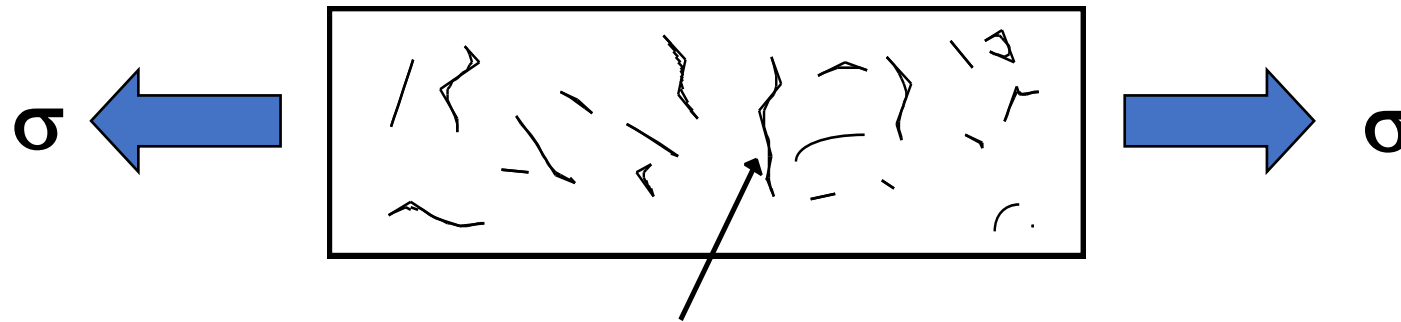
a = half the length of an internal crack

- Applies only in cases where there is no plastic deformation present.



Defect controlled strength

- It is not possible to define the strength of a glass, because the strength is determined by the largest defect (crack) present in a given sample



- Thus strength is determined by a combination of a materials parameter (toughness) and a variable (crack size)

Fracture Toughness

- Stresses near the crack tip of a material can also be characterized by the stress intensity factor, K ,
- A critical value of K exists, similar to the value σ_c , known as fracture toughness given by:

$$K_c = Y\sigma\sqrt{\pi a}$$

- Y is a dimensionless parameter that depends on both the specimen and crack geometries.
- Carries the unusual units of $\text{MPa m}^{1/2}$

Defects

- Fracture toughness is not a variable, so the variation in strength must come from a variation in the size of the biggest defect
- Note that it is the *biggest* defect which is significant, lots of small defects are stressed but do not reach their critical stress for propagation
- Sources of defects
 - Flaws from imperfect sintering
 - Impact, contact and abrasion damage

Size of defects

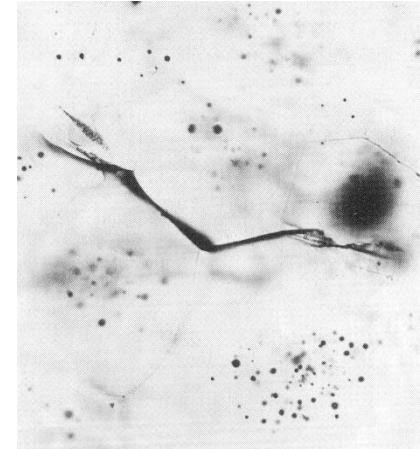
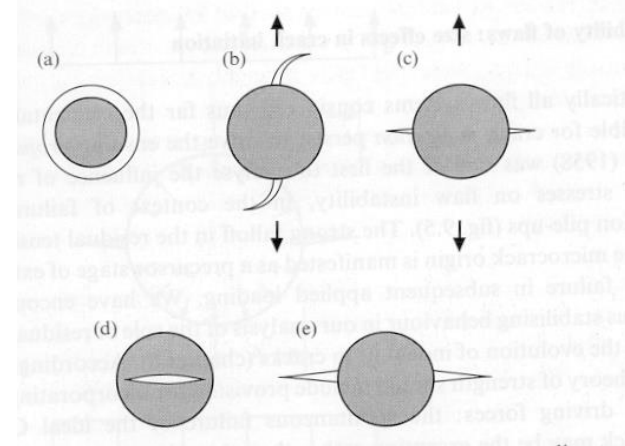
- Most brittle materials have fracture toughness in the range $1 - 5 \text{ MNm}^{-3/2}$
- Thus we can estimate likely critical defect size from the measured fracture stress
- Typical engineering ceramics have critical defects about $1 - 10 \mu\text{m}$

Table 9.1. Typical 'Griffith' flaw sizes and strengths of brittle materials.

Flaw size	Material	Strength
nm	Pristine optical fibres, whiskers Ultra-fine-grain ceramics	10 GPa
μm	As-handled glasses, single crystals Fine-grain polycrystalline ceramics	1 GPa
	Coarse-grain polycrystalline ceramics Composites	100 MPa
mm	Rocks Refractories	10 MPa
	Concretes	
m	Earth's crust, glaciers	1 MPa

Defects from thermal expansion mismatch

- Inorganic impurities (e.g. dust or contaminants) are retained as inclusions
- If they have a different expansion coefficient they will generate internal stress on cooling from sintering temperature
- Also possible if a monolithic material has anisotropic thermal expansion. In which case polycrystals will contain stresses
- Stresses can lead to fracture



Blunt contact defects (i)

- Distinguish between *blunt* and *sharp* contact
- Blunt contacts are approximated to the contact of a sphere
- Contact problem solved by Hertz - Hertzian contact
- Deformation is all *elastic* and the contact region is a circle of radius a

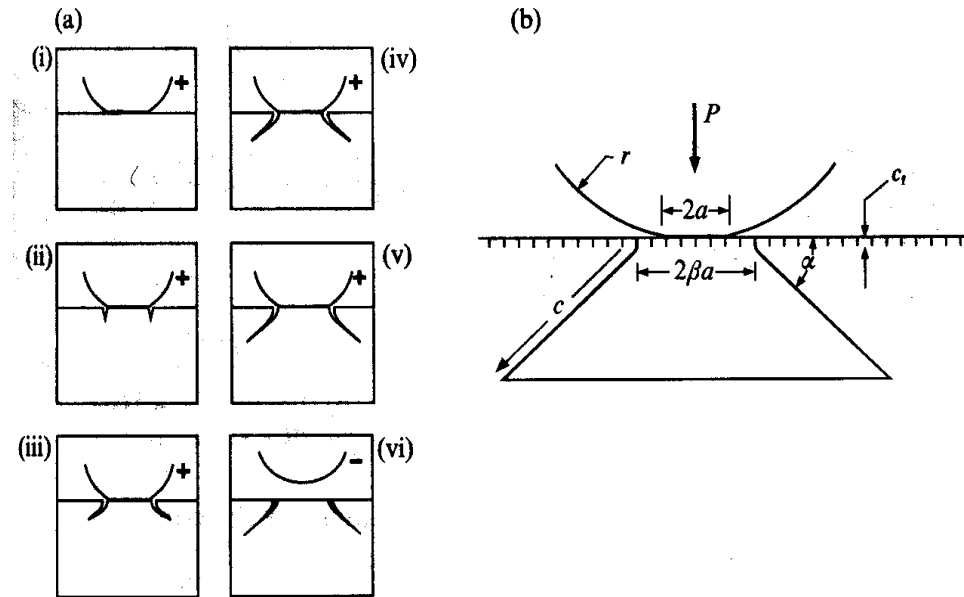


Fig. 8.2. Hertzian cone crack system. (a) Evolution of cone during complete loading (+) and unloading (-) cycle. (b) Geometrical parameters.

Blunt contact defects (ii)

- For a 1 μm ball on glass a force of 2.5 mN will generate a contact pressure of 10 GPa
- Stress beneath contact is compressive, but at surface just outside the contact it is tensile of similar magnitude
- Contact stresses can nucleate cracks. These propagate in a ring around the contact and then travel into the material as a characteristic *cone crack*

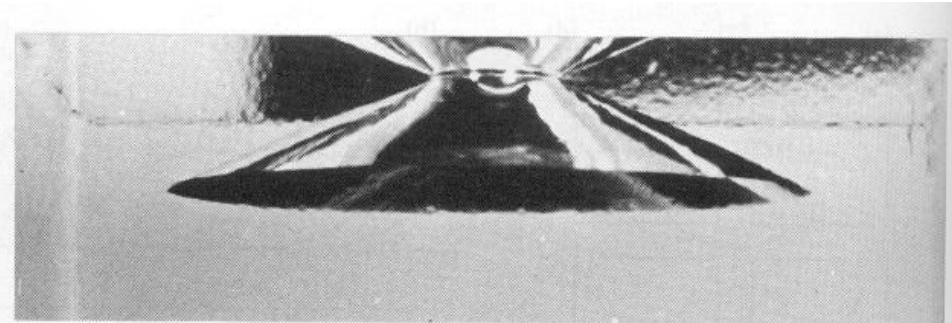
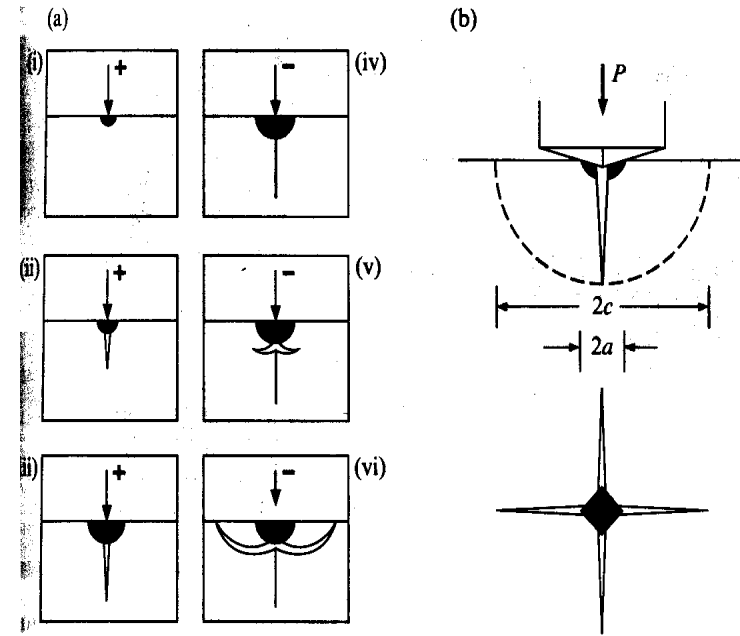


Fig. 8.3. Cone crack in soda-lime glass. Photographed under load ($P = 40 \text{ kN}$) from cylindrical punch, optical micrograph (block edge length 50 mm). Crack makes angle $\simeq 22^\circ$ to free surface. (After Roesler, F. C. (1956) *Proc. Phys. Soc. Lond.* **B69** 981.)

Sharp contact defects

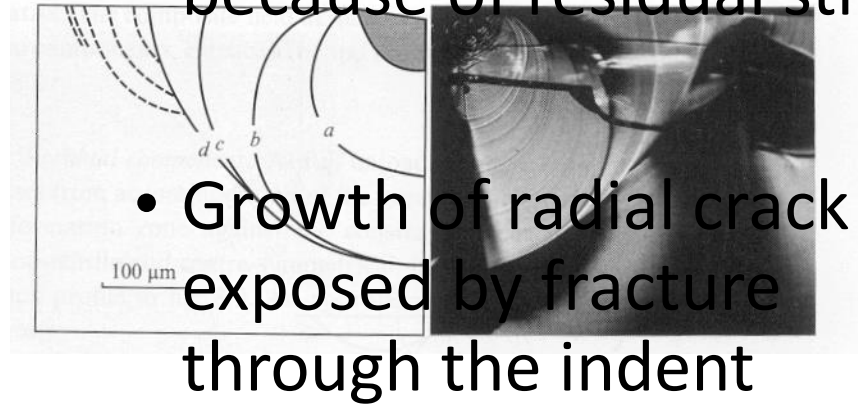
- Indentation by a point contact leads to a singularity in the stress field beneath the contact
- Plastic flow occurs just below the contact point.
- At some critical load defects in the material cause *radial cracks* to form on tensile median planes. These cracks propagate downwards on increased load.
- On *unloading* the *median cracks* close up below the surface but open at the surface as plastic deformation leads to a residual tension.



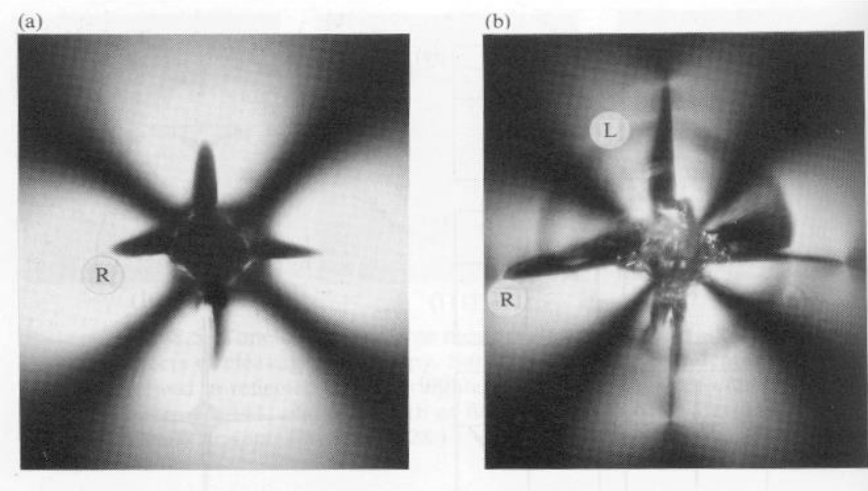
- Finally just before unloading a new set of *lateral cracks* parallel to the surface may be nucleated in the residual tensile field.

Sharp contact

- Radial/median crack system first under load from a pyramid diamond indenter (Vickers)
- Then unload - radial cracks open further because of residual stress

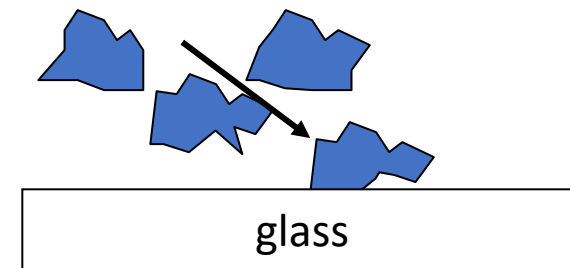
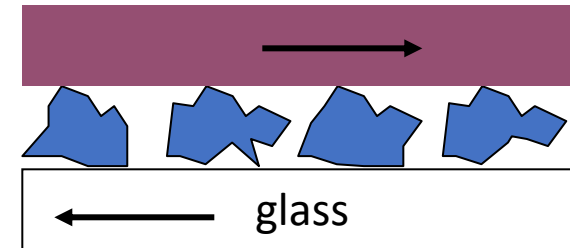
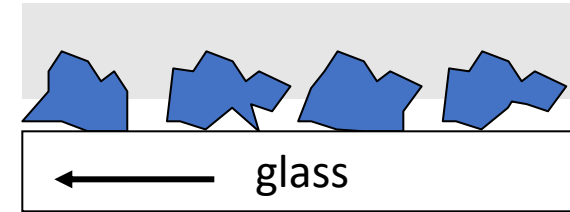


- Growth of radial crack exposed by fracture through the indent



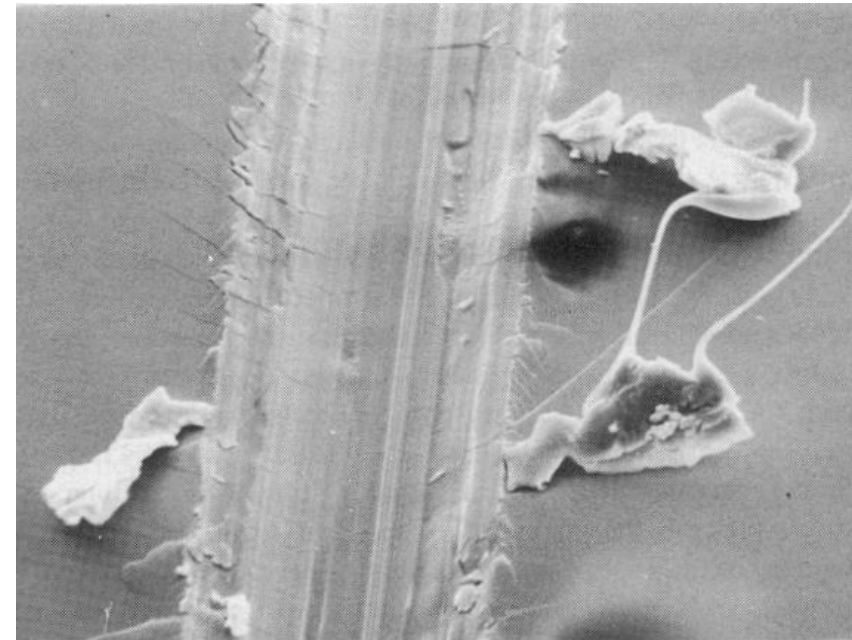
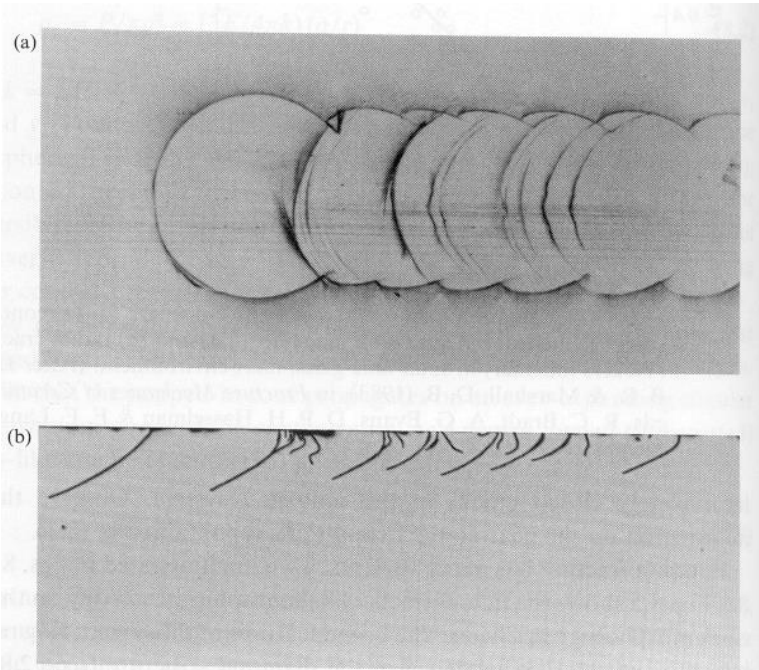
Abrasion and erosion

- Defects and cracks are at the basis of glass micropatterning
- **Grinding or two-body abrasion** : abrasive particles are embedded in adhesive backing → grinding, sawing, precision machining
- **Three-body abrasion** : loose particles in a carrier fluid are contained between workpiece and backing plate → ultrasonic machining
- **Solid particle erosion** : particles in a gas stream strike the glass surface → powder blasting



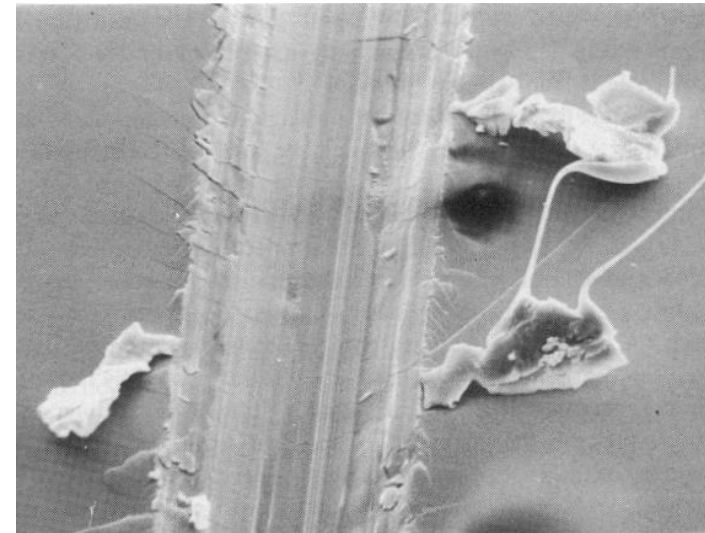
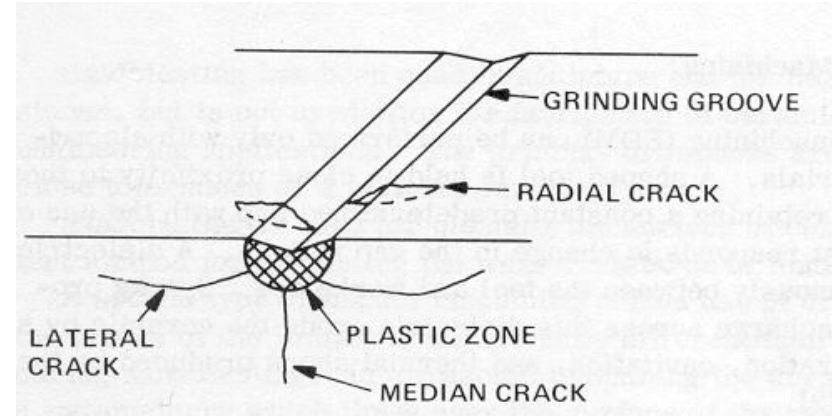
Two-body abrasion

- Repeated cone cracks from a blunt slider
- Sharp slider causes local plastic flow; radial and median crack families will be present



Precision glass machining

- Machining normally in the form of grinding
- Multiple impact and scratching from diamond particles embedded in a wheel
- These leave a large median crack – major strength reduction
- Also radial and lateral cracks – lateral cracks remove material by spalling

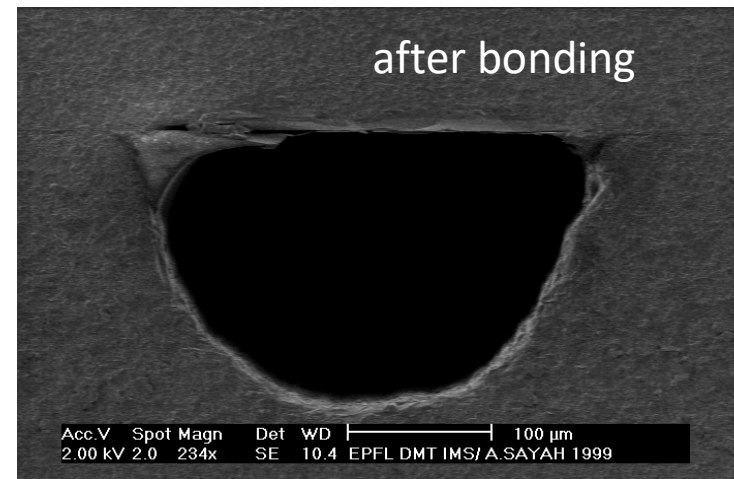
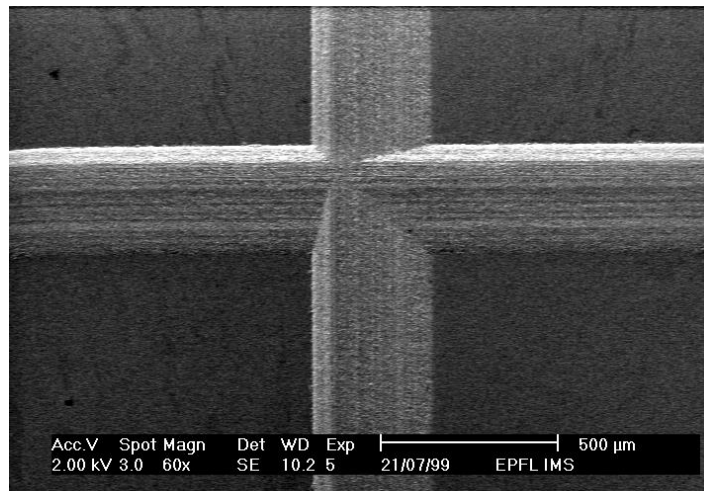


Machining process

- Try and make glass object as “near-net-shape”
- Diamond machining first uses large grit size for efficient material removal
- This introduces large median cracks (scales with particle size)
- Repeated grinding at 90° to the previous grinding direction with finer grit size
- Objective is to completely machine off median defect and replace with a smaller scale version
- Continue with repeated reductions in diamond size until desired finish is achieved

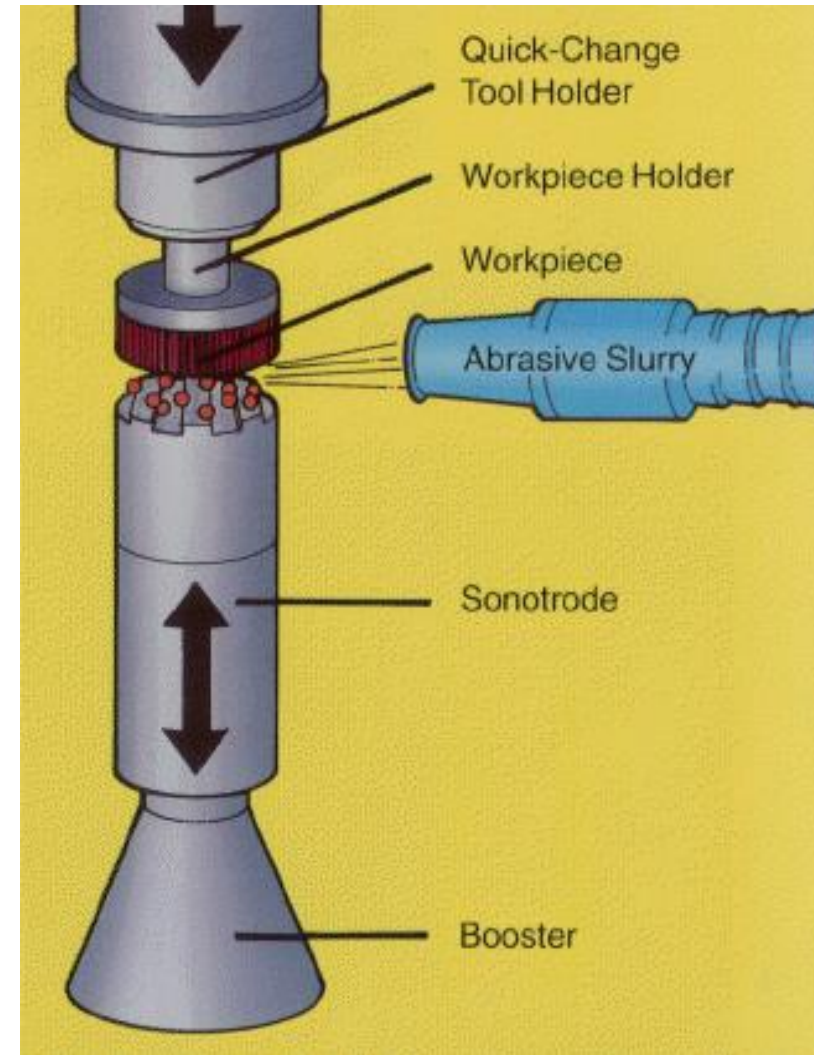
Machining (sawing) microchannels

- Minimum saw blade thickness and channel width is 30 μm .
- Technique has the advantage to be simple and fast
- No mask is necessary and there is no need of clean room environment.
- Only simple straight channels possible



Principle of ultrasonic machining (i)

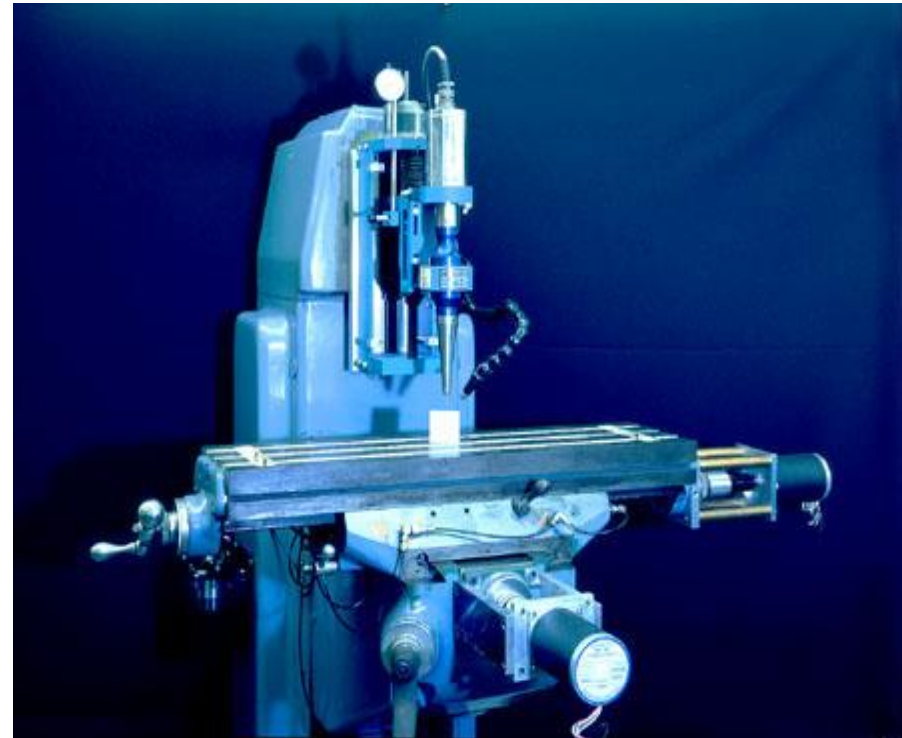
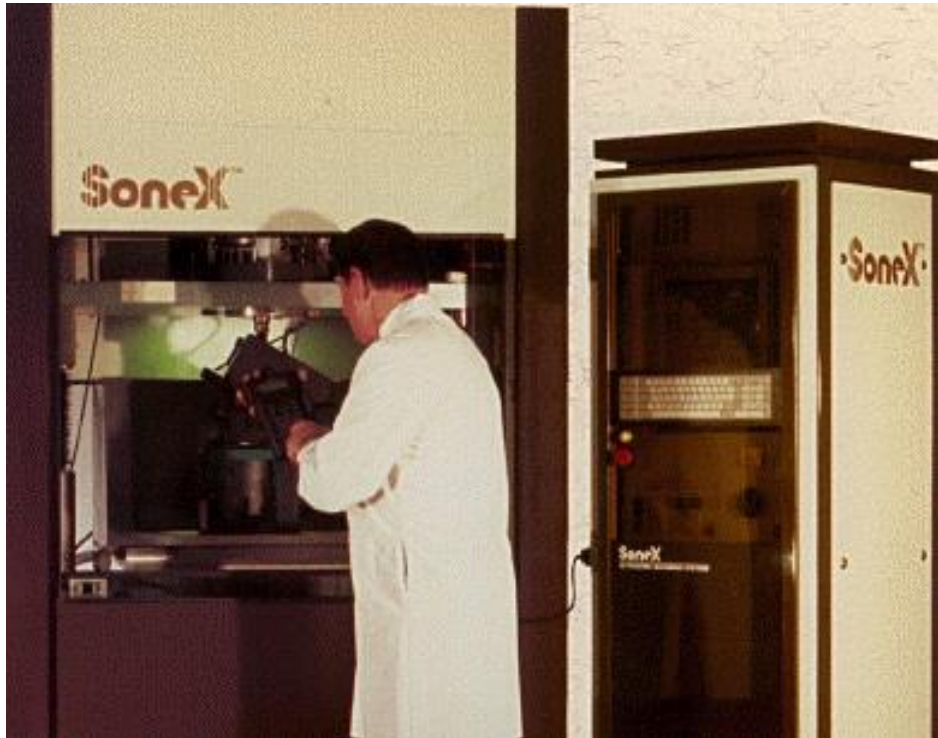
- Material is removed by micro-chipping or erosion with abrasive particles.
- The tool, made of softer material than that of the workpiece, is oscillated by the Sonotrode at a frequency of about 20 kHz
- It forces the abrasive grits, in the gap between the tool and the workpiece, to impact on the work surface, thereby machining the work surface.



Principle of ultrasonic machining (ii)

- During one strike, the tool moves down from its most upper remote position with a starting speed at zero. It speeds up in this period and finally reaches the maximum at the mean position.
- When the grit size is close to the mean position, the tool hits the grit with its full speed.
- The smaller the grit size, the lesser the momentum it receives from the tool. Therefore, there is an effective speed zone for the tool and, correspondingly there is an effective size range for the grits.

CNC Ultrasonic machines



Sonotrode

- Ultrasonic waves are sound waves of frequency higher than 20 000 Hz
- Ultrasonic waves can be generated using the magnetostrictive effect to convert magnetic energy into ultrasonic energy. This is accomplished by applying a strong alternating magnetic field to certain metals, alloys and ferrites.
- Piezoelectric transducers employ the inverse piezoelectric effect using natural or synthetic single crystals (such as quartz) or ceramics (such as barium titanate) which have strong piezoelectric behavior.

Abrasive slurry

- The abrasive slurry contains fine abrasive grains. The grains are usually boron carbide, aluminum oxide, or silicon carbide ranging in grain size from 100 μm (grit/sieve size 100) for roughing to 5 μm (grit/sieve size 1000) for finishing.
- It is used to microchip or erode the work piece surface and it is also used to carry debris away from the cutting area.

Machinable materials

- As the ratio of hardness of workpiece and tool increases, metal removal rate decreases
- Hard materials like stainless steel, glass, ceramics, carbide, quartz and semi-conductors are machined by this process.
- Brittle materials can be well machined
- Material removal rate = $5.9 f (s/H) R^{0.5} y^{0.5}$

where

f = frequency of oscillations, Hz

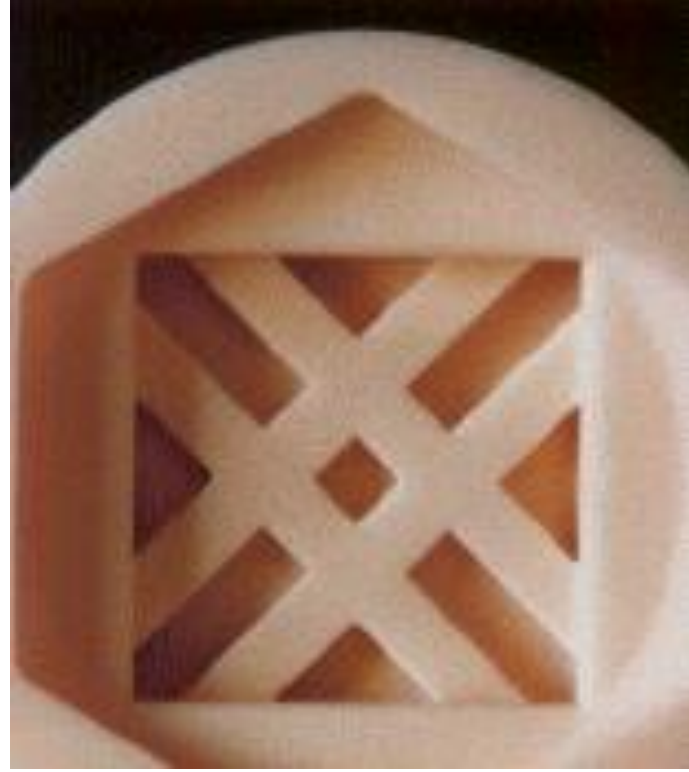
H = surface fracture strength, BHN

s = static stress in tool, kg/mm²

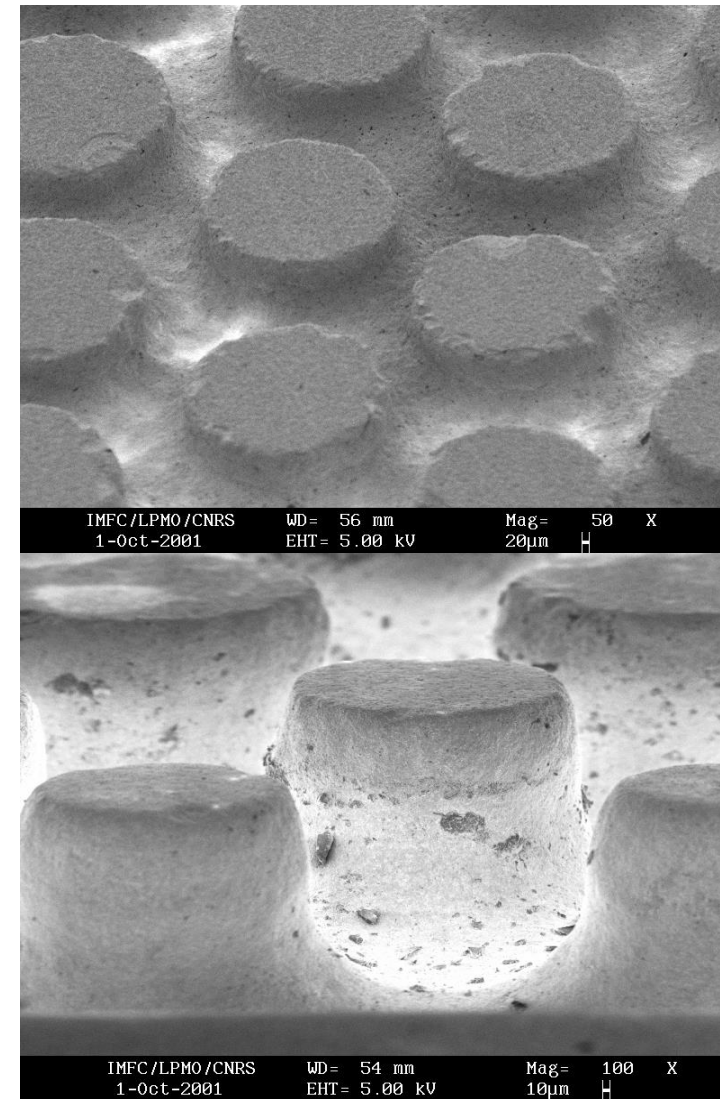
R = mean radius of grit, mm

y = amplitude of vibration, mm

Machining of hard plastics



Micromachining of PZT pillars for ultrasound transducers (Univ. Franche-Comté, Besançon)



Advantages of USM

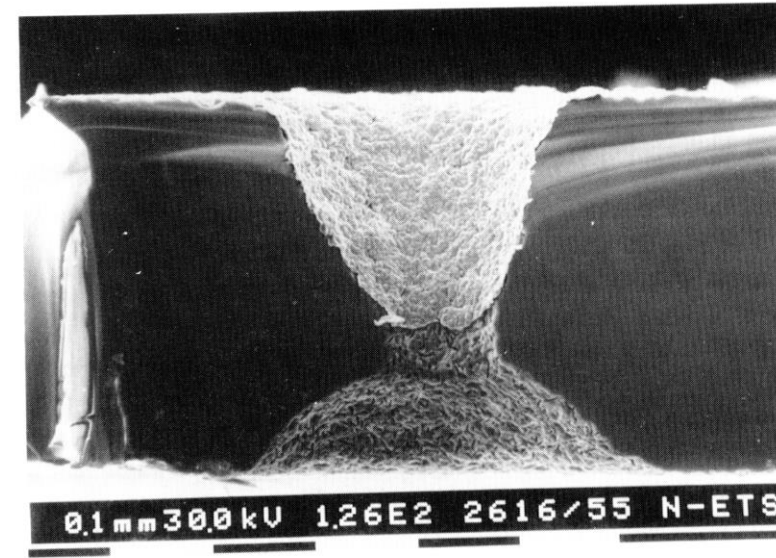
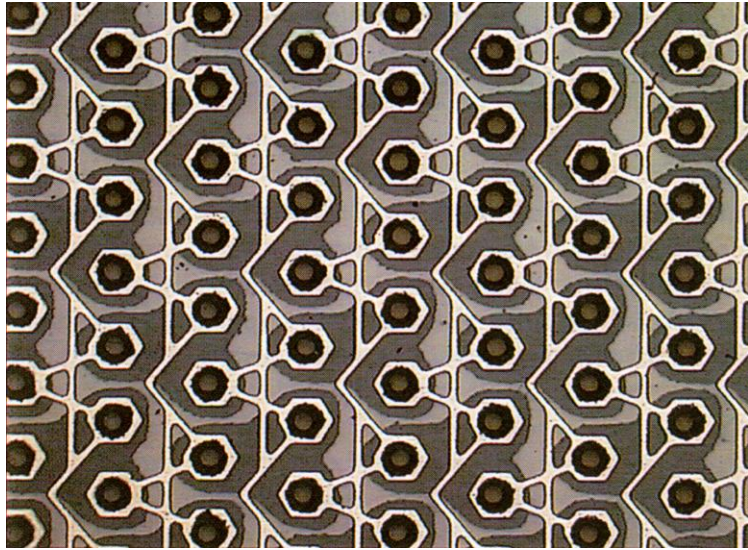
- Machining of any materials, regardless of their conductivity
- USM applies to machining of semi-conductors, such as silicon, germanium etc.
- USM is suitable to precise machining of brittle materials
- USM does not produce electrically, thermally, chemically modified surfaces, because action is not electric, thermal or chemical
- Can drill circular or non-circular holes in very hard materials
- Less stress because of non-thermal characteristics

Disadvantages of USM

- USM has low material removal rate
- Tool wear fast in USM.
- Machining area and depth is restraint in USM.
- Some numbers
 - Under ideal conditions, penetration rates of 5 mm/min can be obtained.
 - Power units give usually 500-1000 watt output.
 - Specific material removal rate of brittle materials is $0.018 \text{ mm}^3/\text{Joule}$.
 - Normal hole tolerances are 0.007 mm and surface finish can be 0.02 - $0.7 \text{ }\mu\text{m}$.

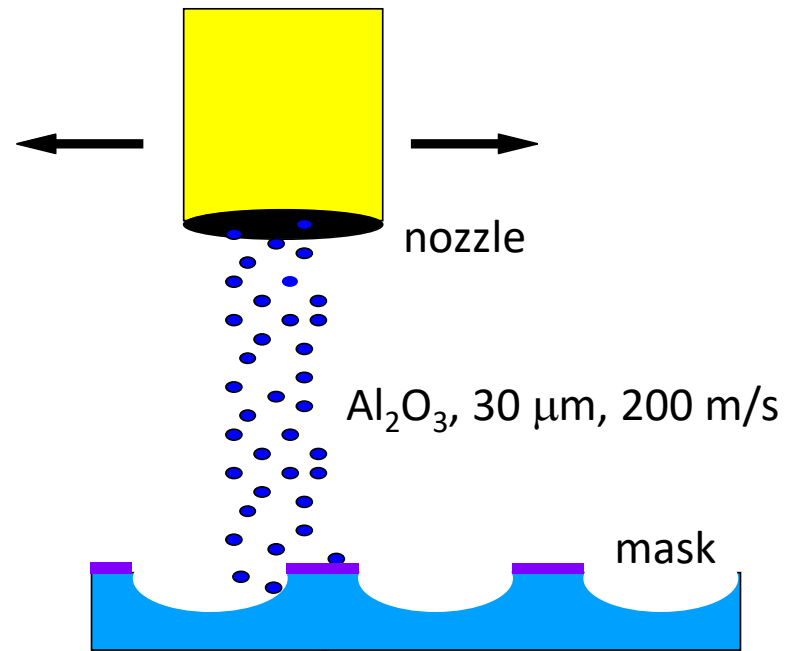
Micro-powder blasting

Powder blasting developed to high level microfabrication technique for flat panel display applications



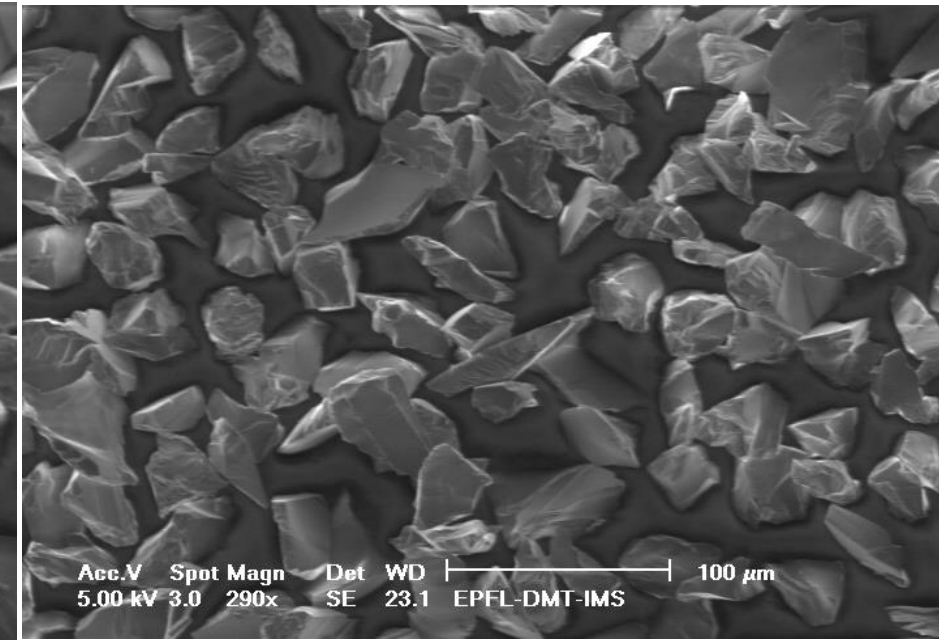
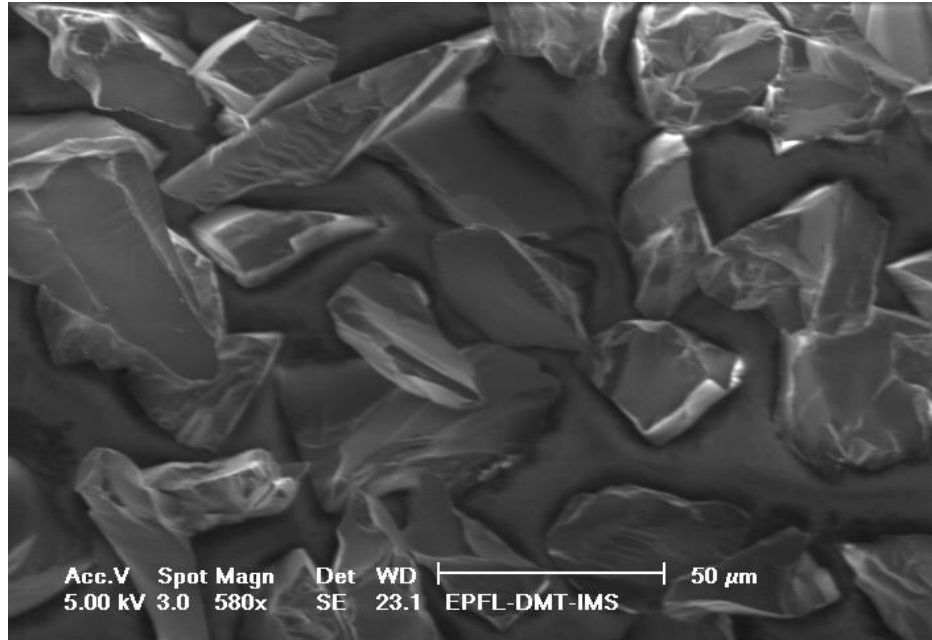
(Philips Research)

Powder blasting : schematic

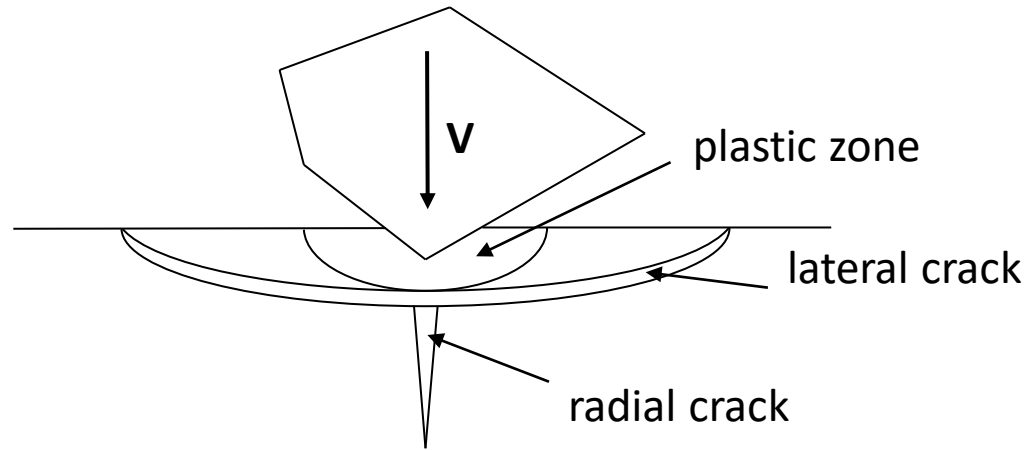


mask :
- steel contact
- soft polymer

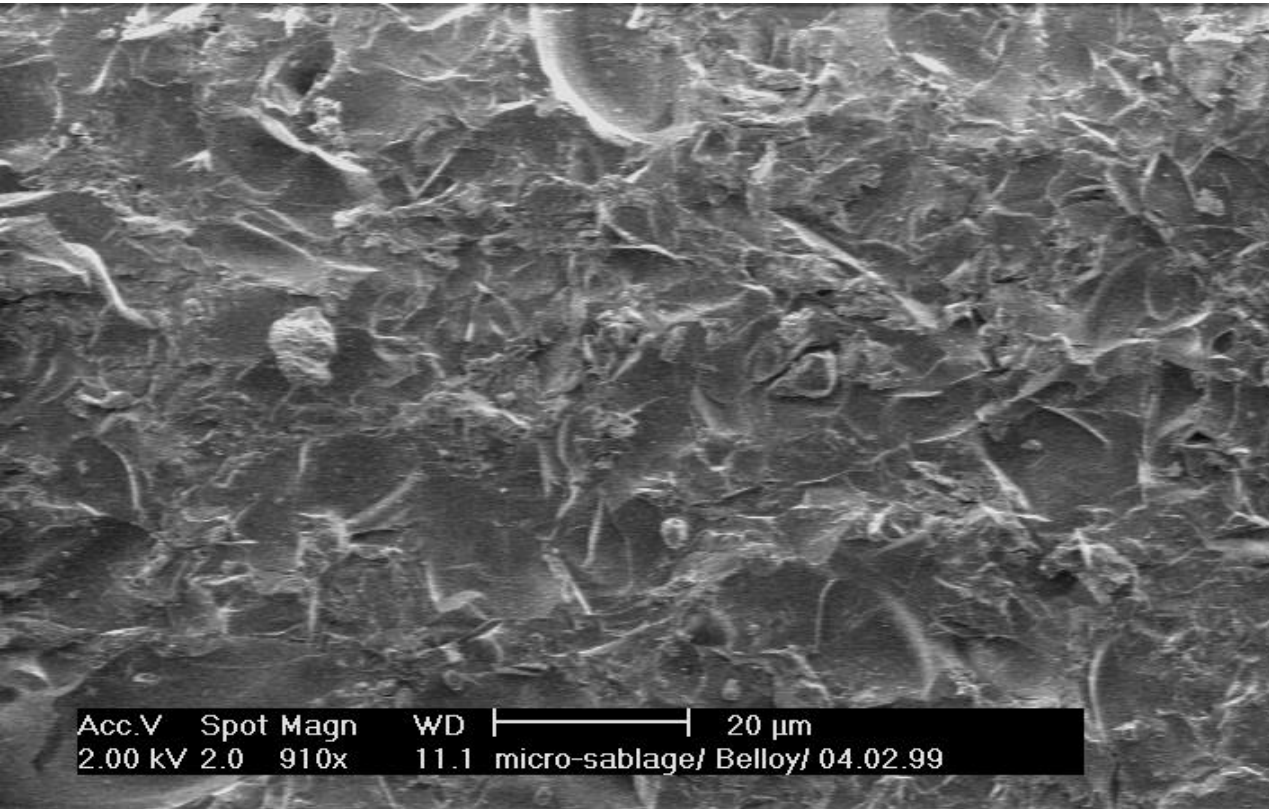
Al_2O_3 powder



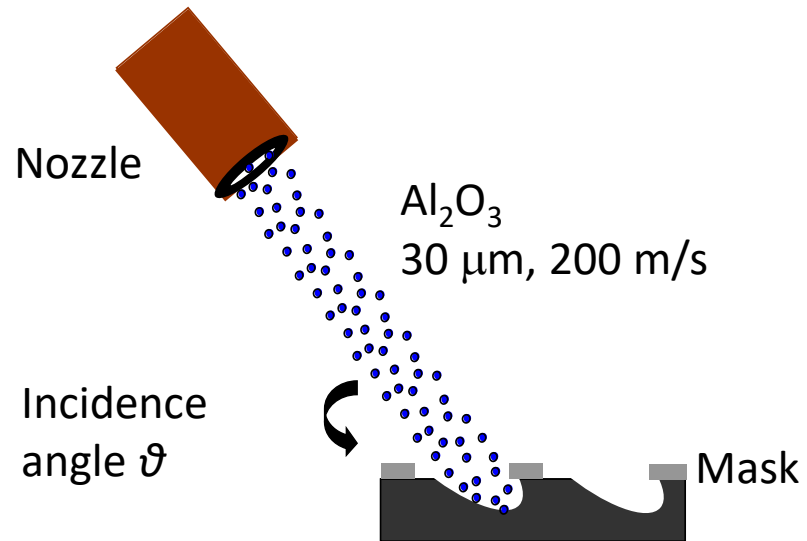
Basic mechanism



Surface roughness : 0.1 – 5 μm



Powder blasting set-up EPFL



Normal vs oblique erosion

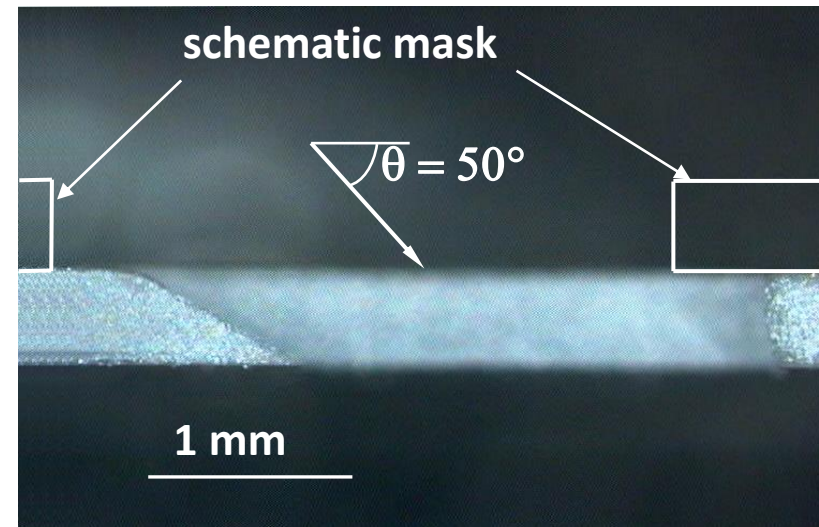
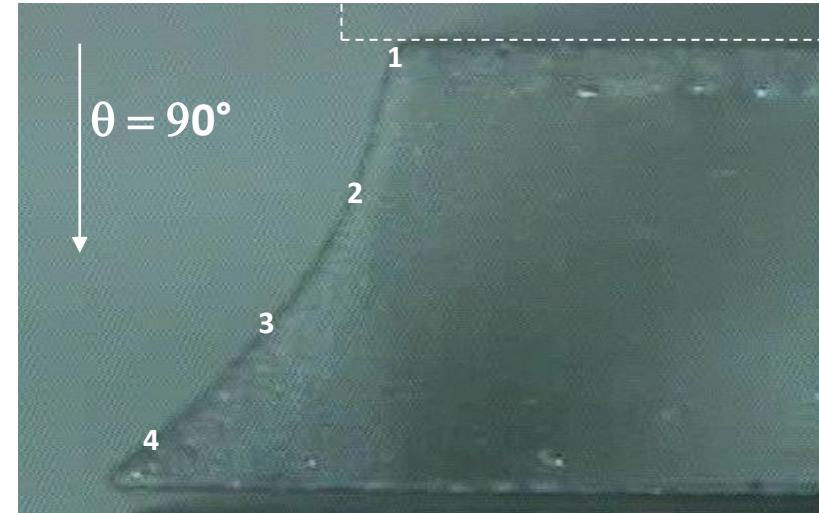
‘Natural’ profile at normal incidence:

finite size particle effects +
normal momentum effect

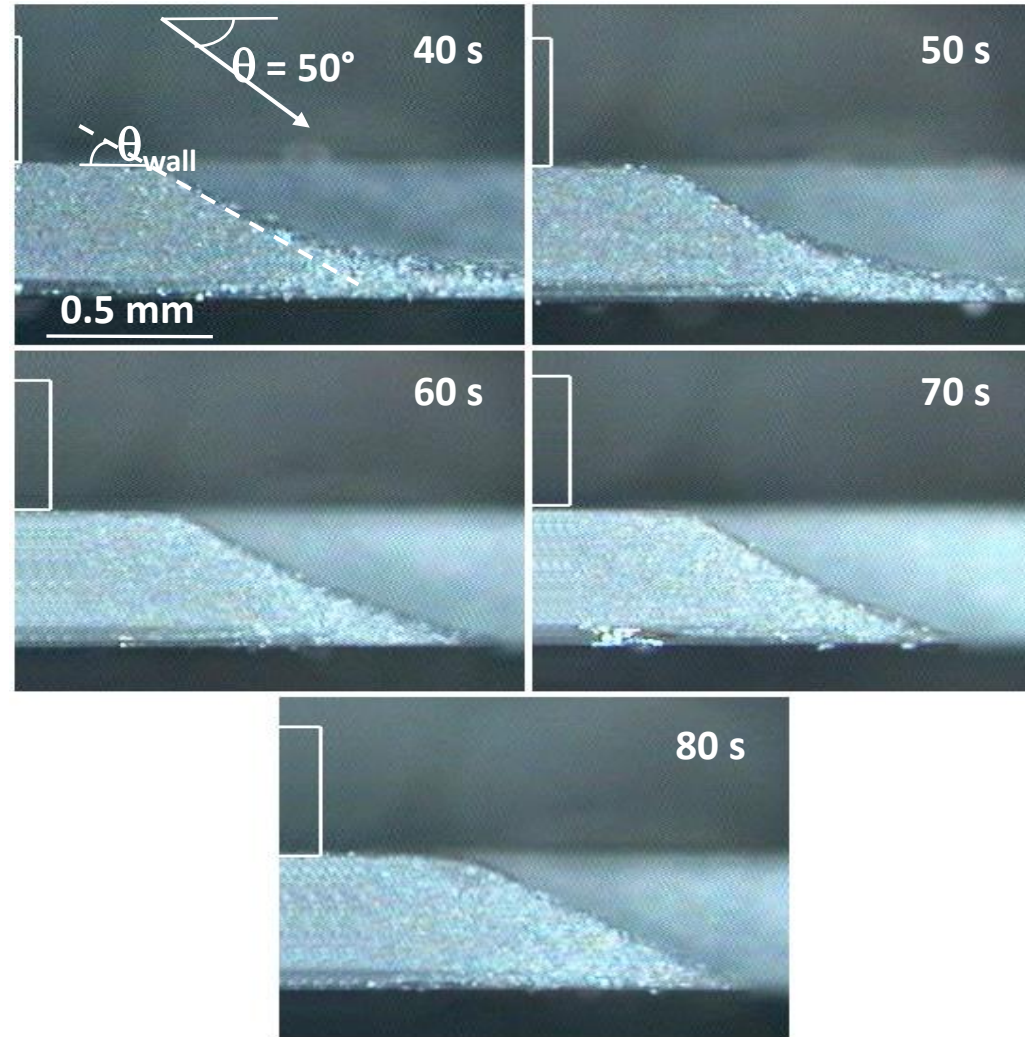
Oblique profile :

left slope $\rightarrow$ primary particles

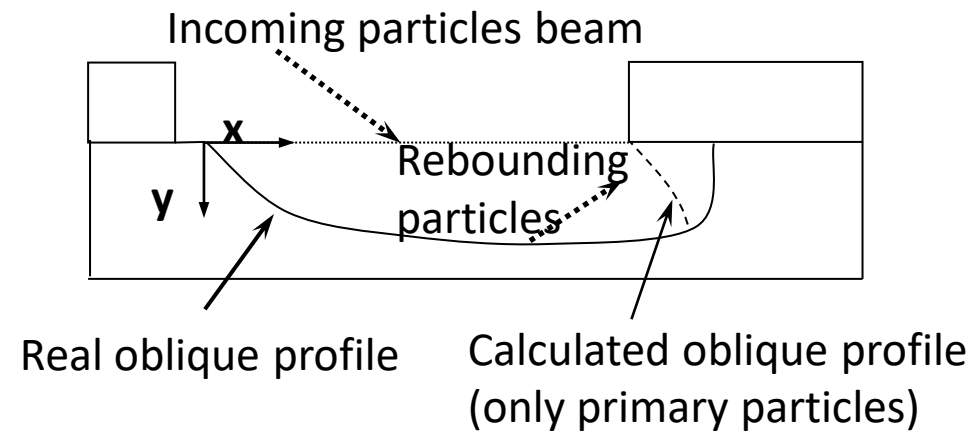
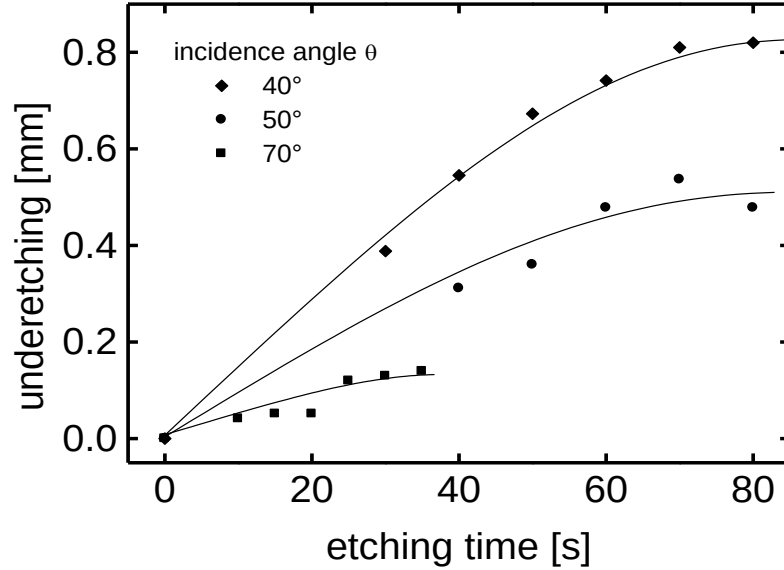
right slope $\rightarrow$ primary +
secondary particles



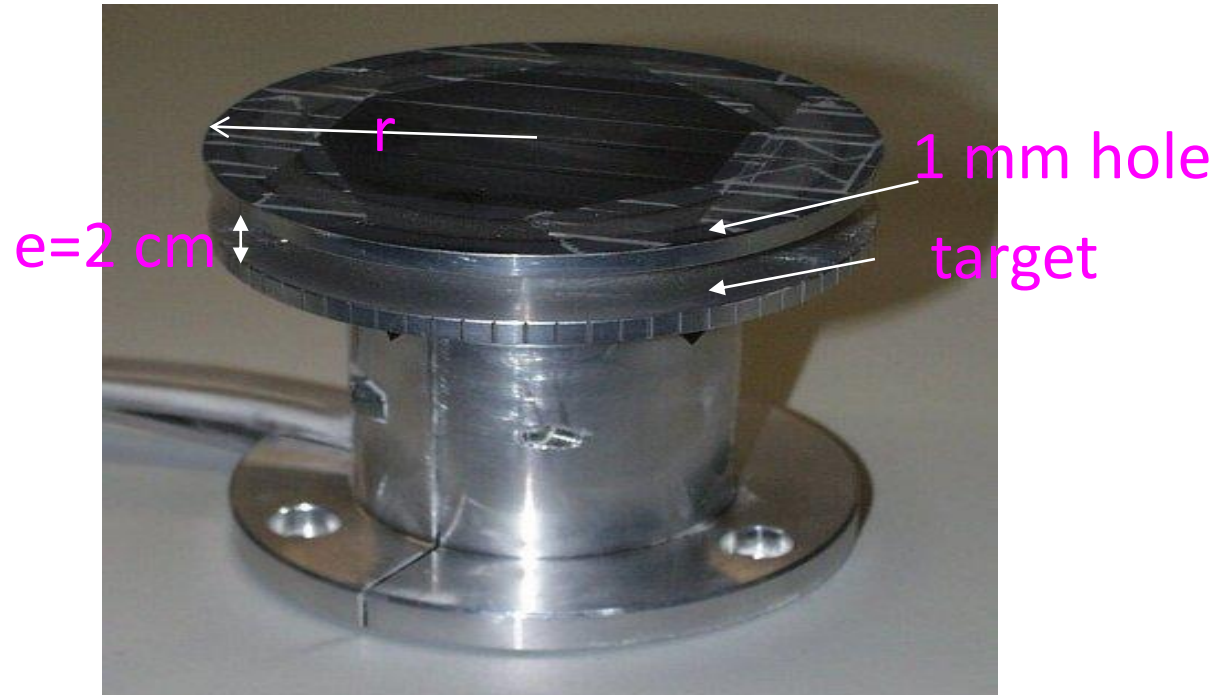
Left wall angle : time evolution



Right-hand slope : underetching



Double-disk system used to determine the particle velocity



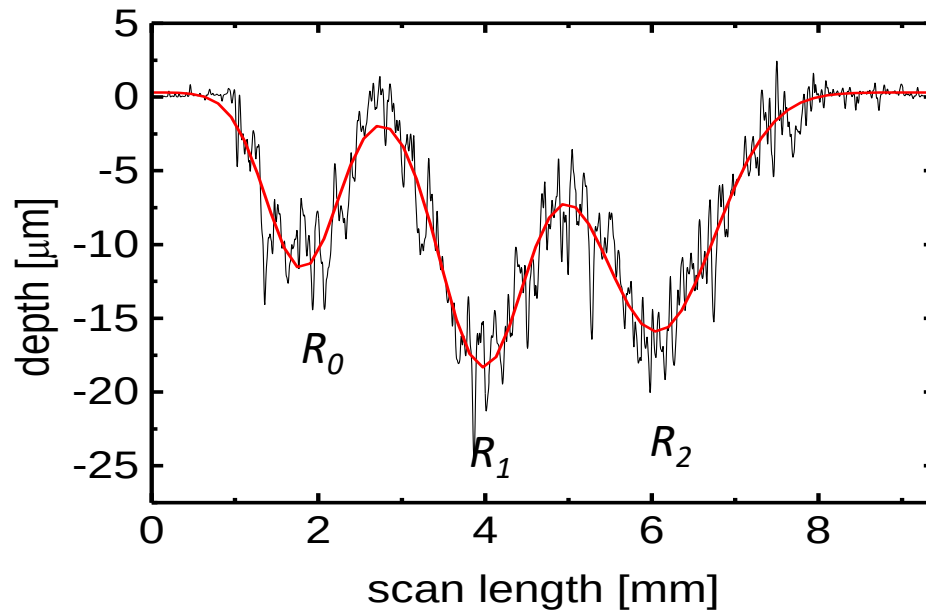
Particle speed v :

R : rotation speed (rpm)

l : distance between spots

$$v = \frac{2\pi r e R}{60 l}$$

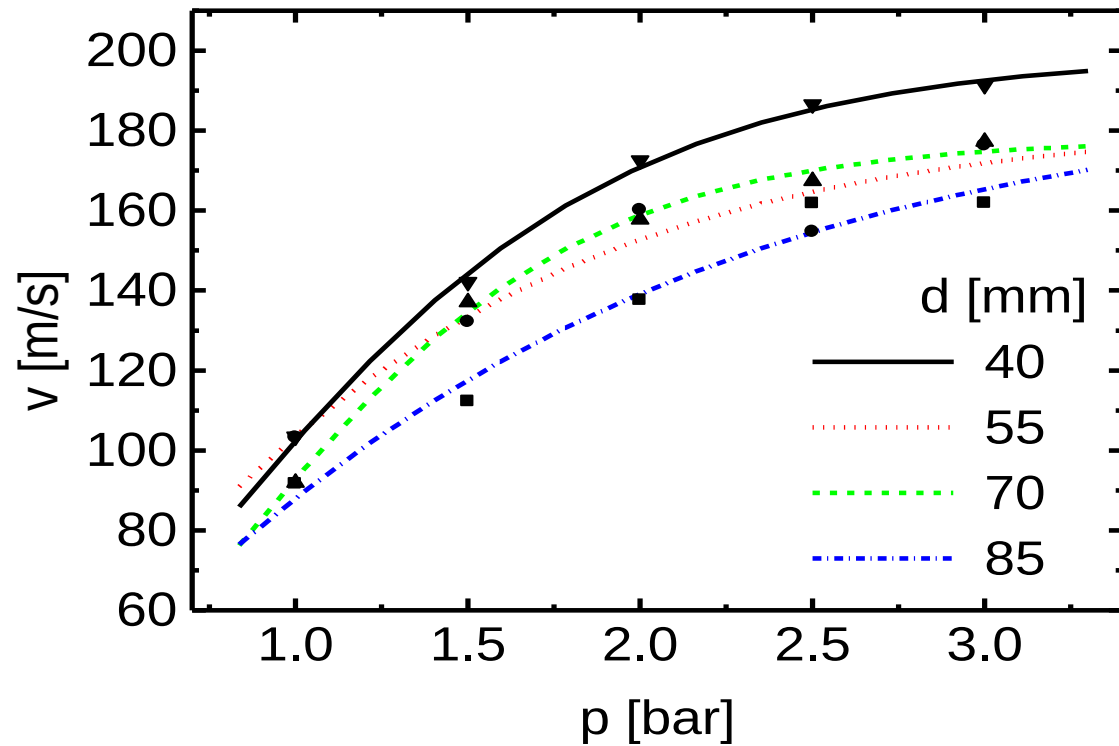
Erosion profiles



$R_0 = 0$ rpm, $R_1 = 6600$ rpm,
 $R_2 = 13200$ rpm

$v = 191$ m/s
for $p = 0.3$ MPa and $d = 4$ cm

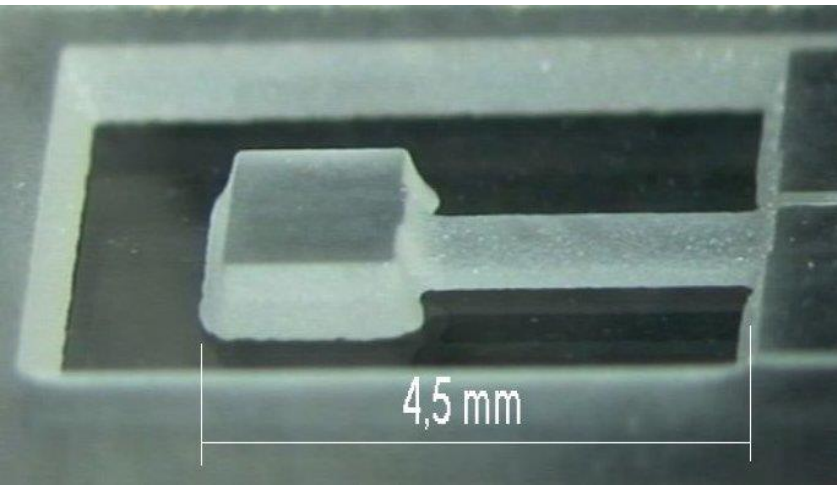
Particle velocity as a function of pressure and nozzle-target distance



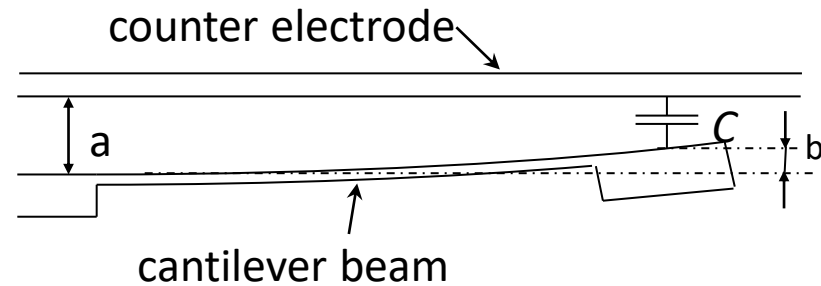
Applications of micro-powder blasting

- Accelerometers
- Cell culture devices
- Fluidic chips for electrophoresis applications
- Miniaturised transformers
- Complex and monolithic suspended structures in glass

Glass accelerometer beam – capacitive read-out



- Mass = 4.87 mg
- Metallic backing plate
- Mechanical actuation
- Quality factor $Q = f_{res}/\Delta f = 100$ in air
- Deflection amplitude = 23 μm at 2856 Hz
- Acceleration amplitude : $A = 4\pi^2 b f_{res}^2 = 755g$

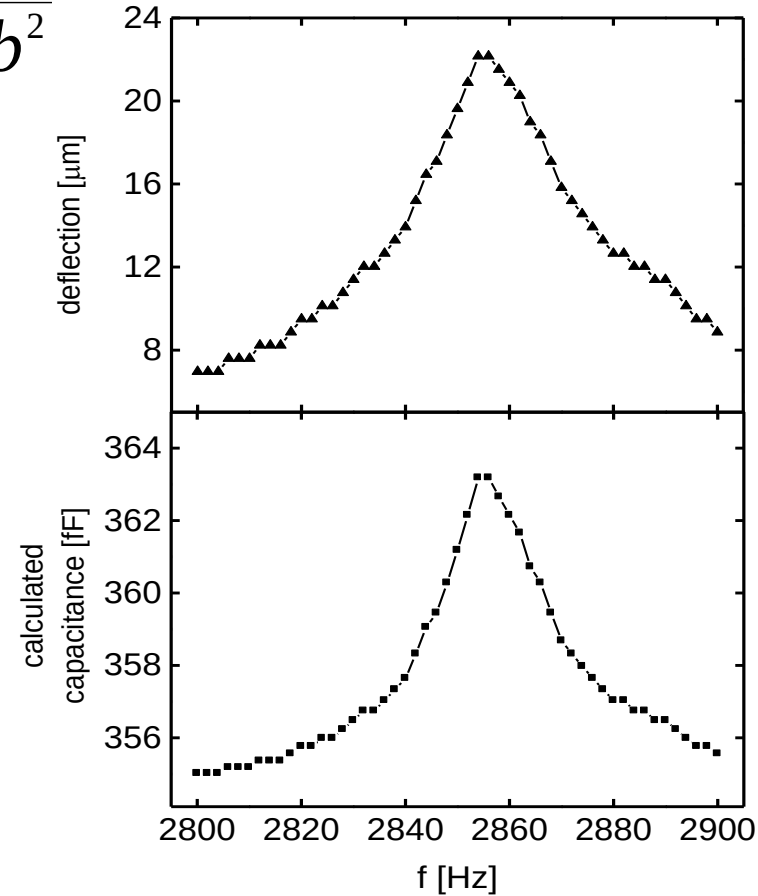


Calculated theoretical capacitance

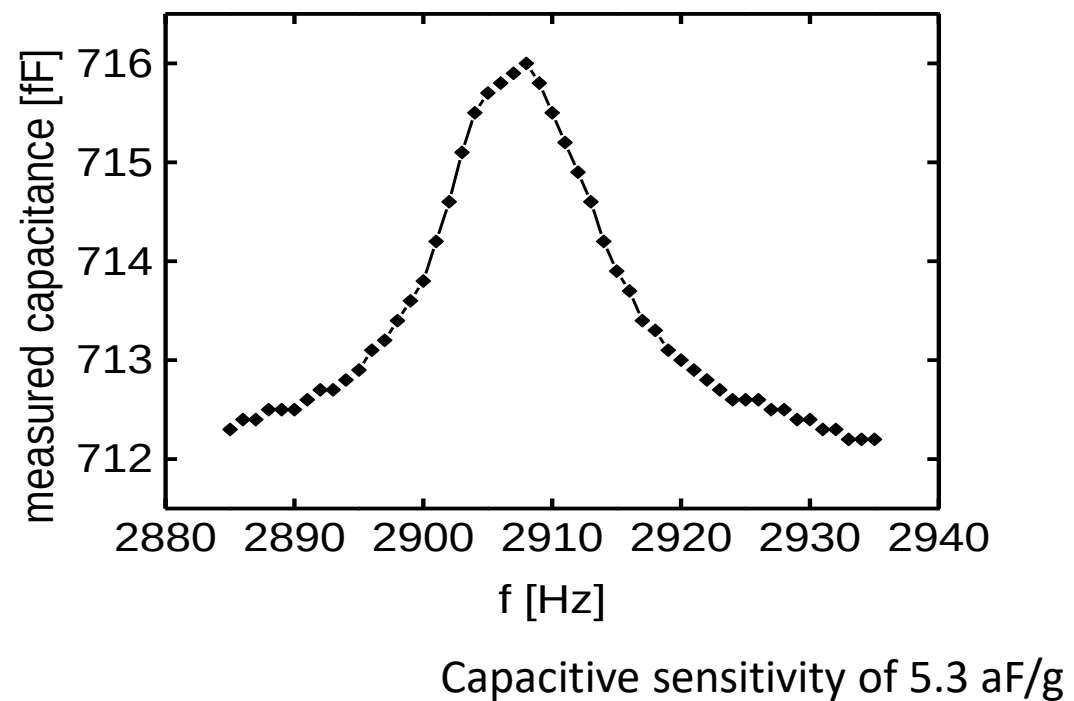
$$C = \frac{1}{\pi_0} \int_0^\pi \frac{\epsilon_0 S}{a + b \cos \alpha} d\alpha = \frac{\epsilon_0 S}{\sqrt{a^2 - b^2}}$$

S : the capacitance surface

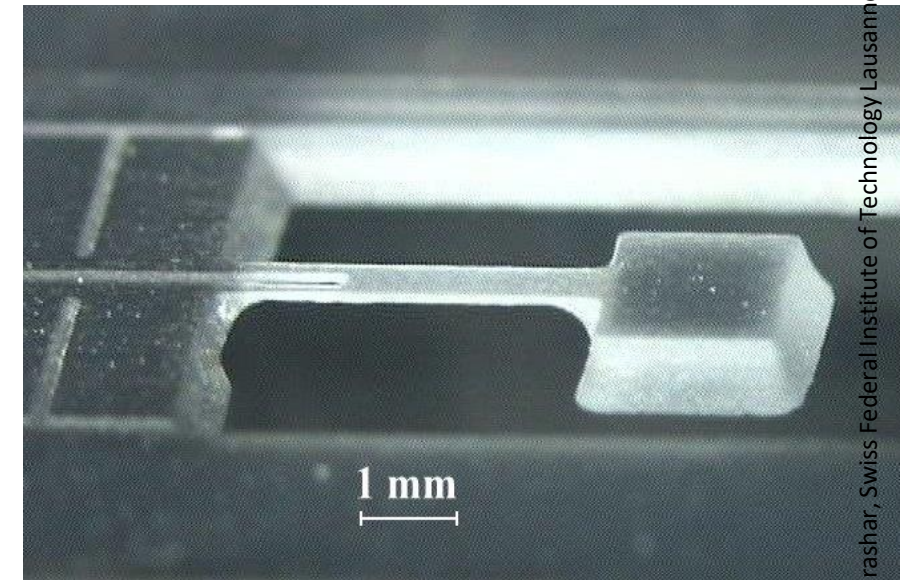
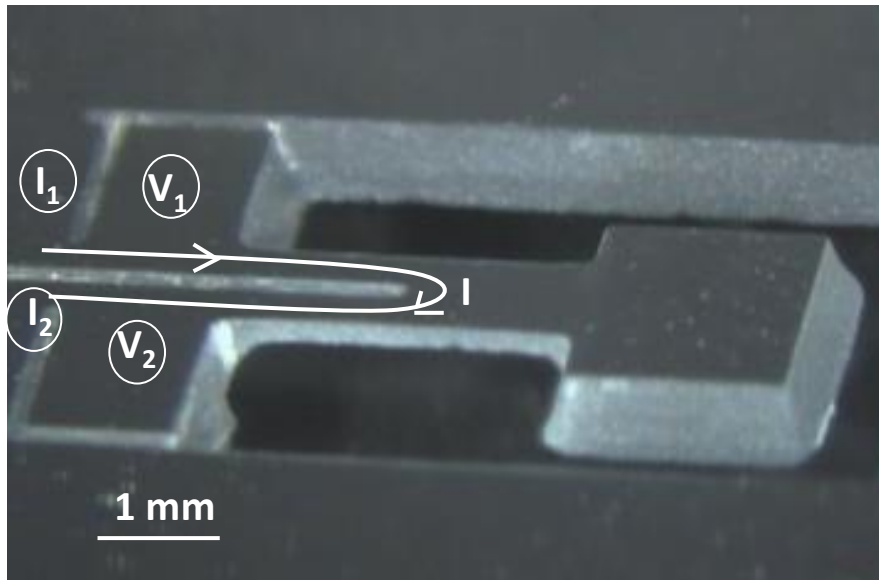
a : static gap



Measured capacitance



Glass accelerometer beam – resistive read-out



$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta s}{s} + \frac{\Delta \rho}{\rho}$$

$$\frac{\Delta s}{s} = -2\nu \frac{\Delta l}{l}$$

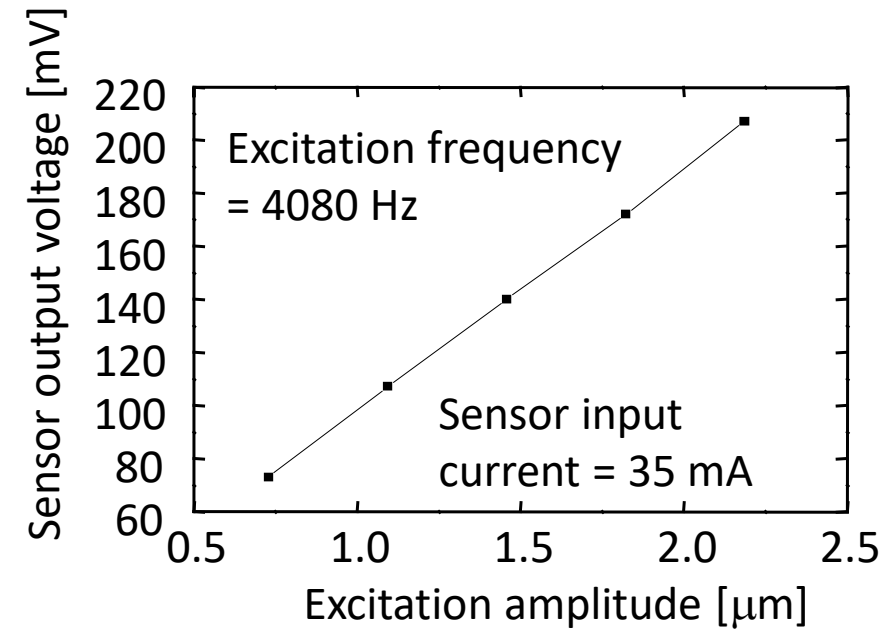
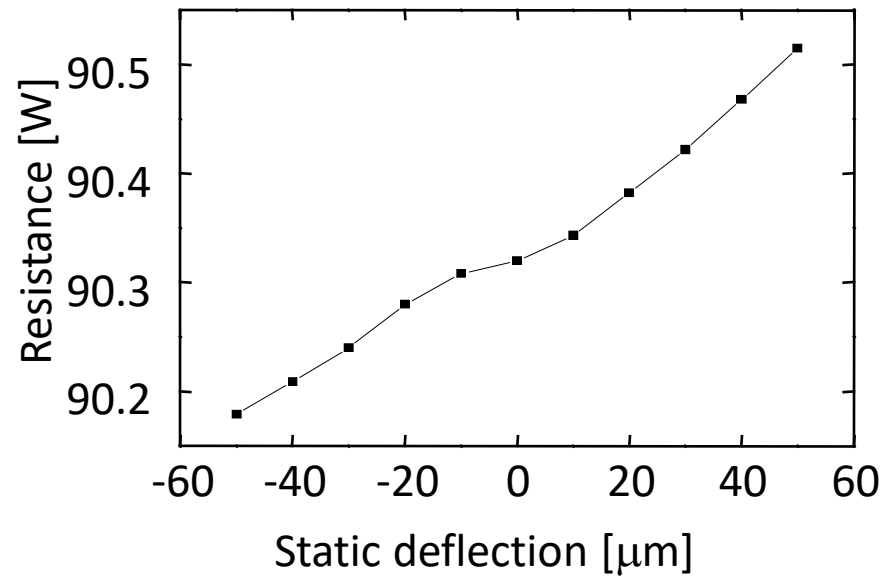
$$\frac{\Delta R}{R} = \left\{ (1 + 2\nu) + C(1 - 2\nu) \right\} \frac{\Delta l}{l} = K \frac{\Delta l}{l}$$

For Pt film : $K = 2$, with $\nu = 0.3$ and $C = 1$

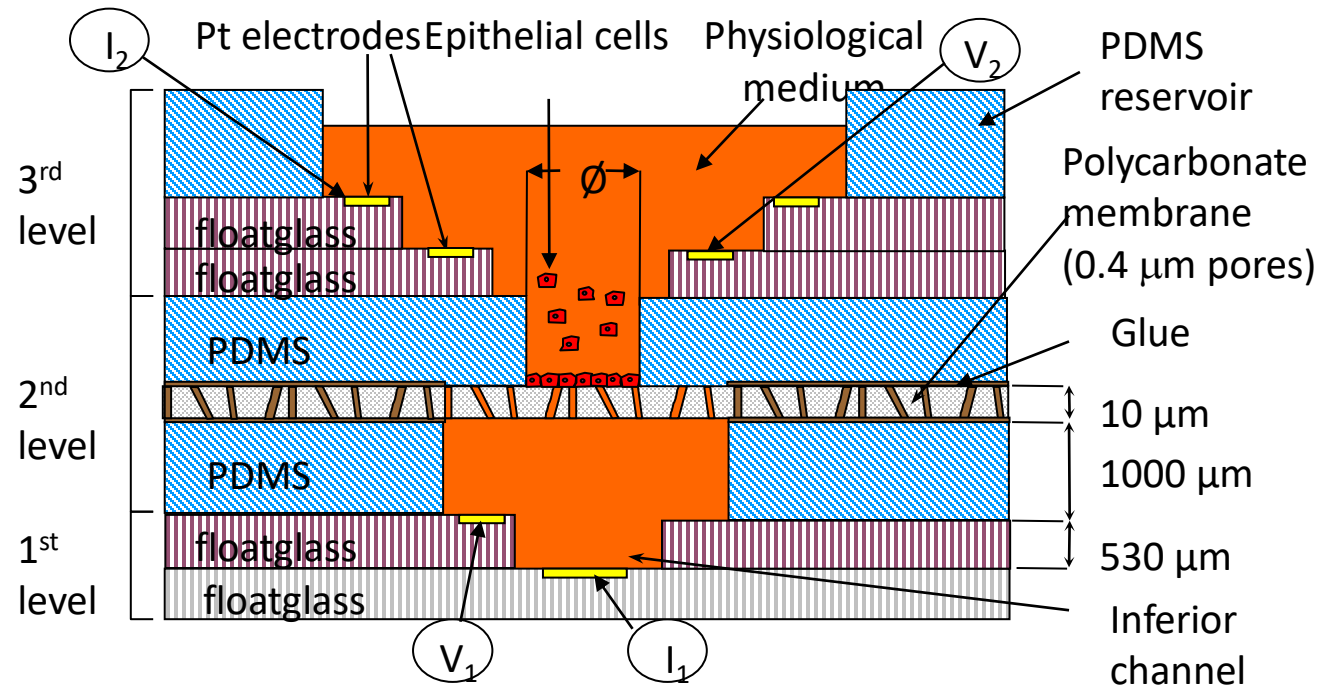


Macroscopic contribution is dominant

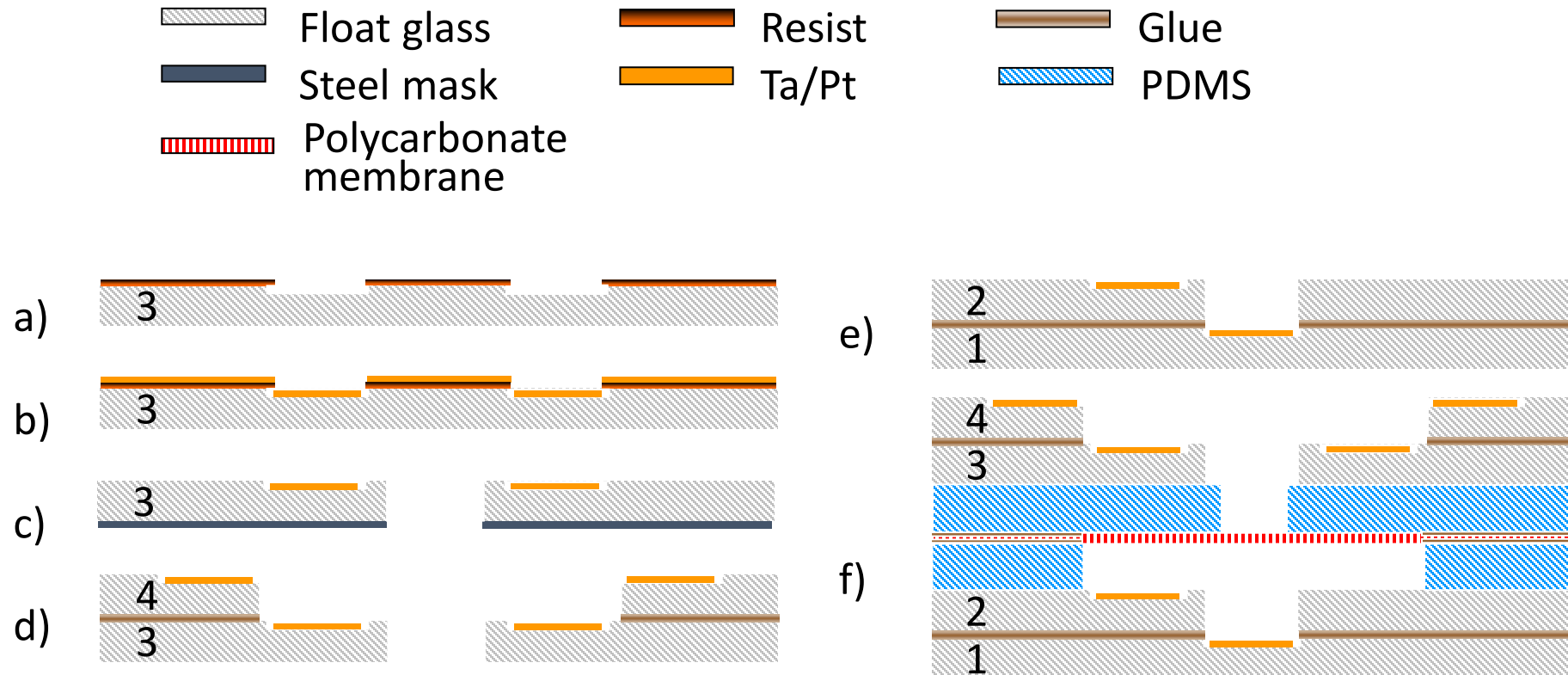
Glass accelerometers - resistive read-out



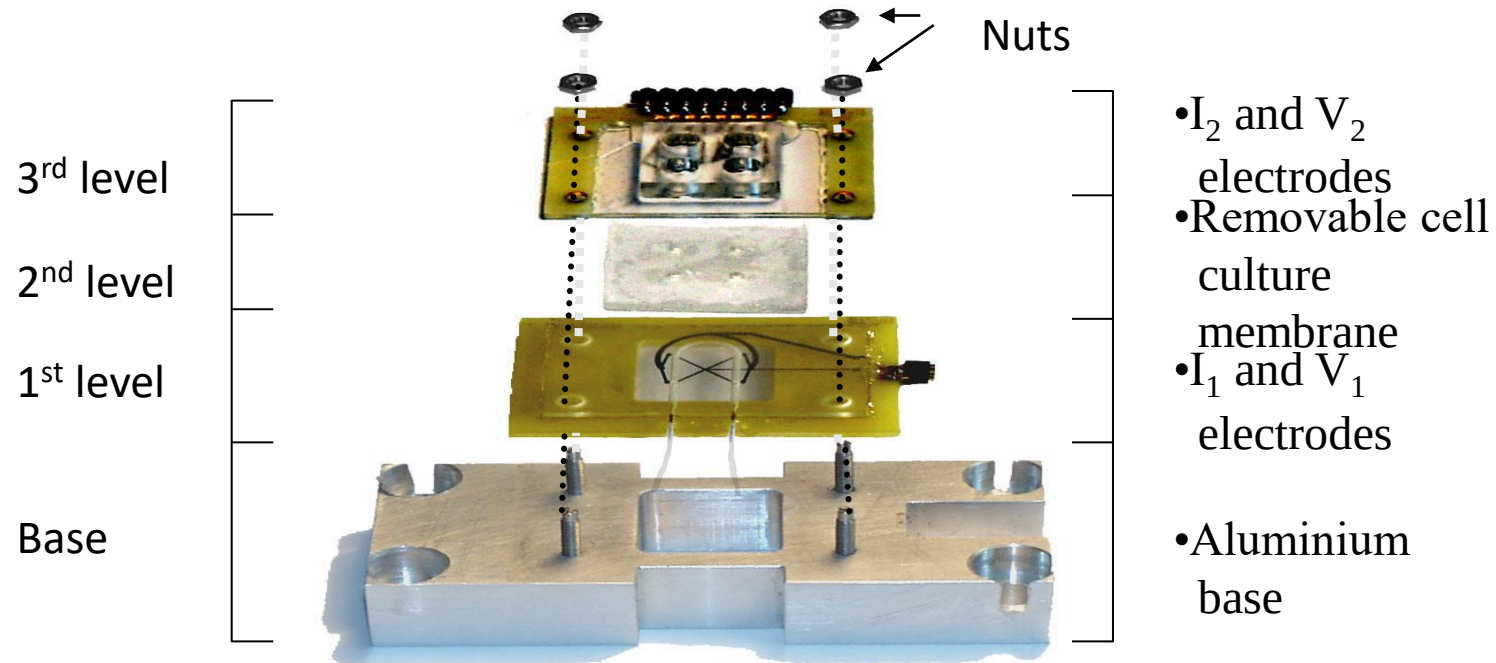
Miniaturised cell culture device

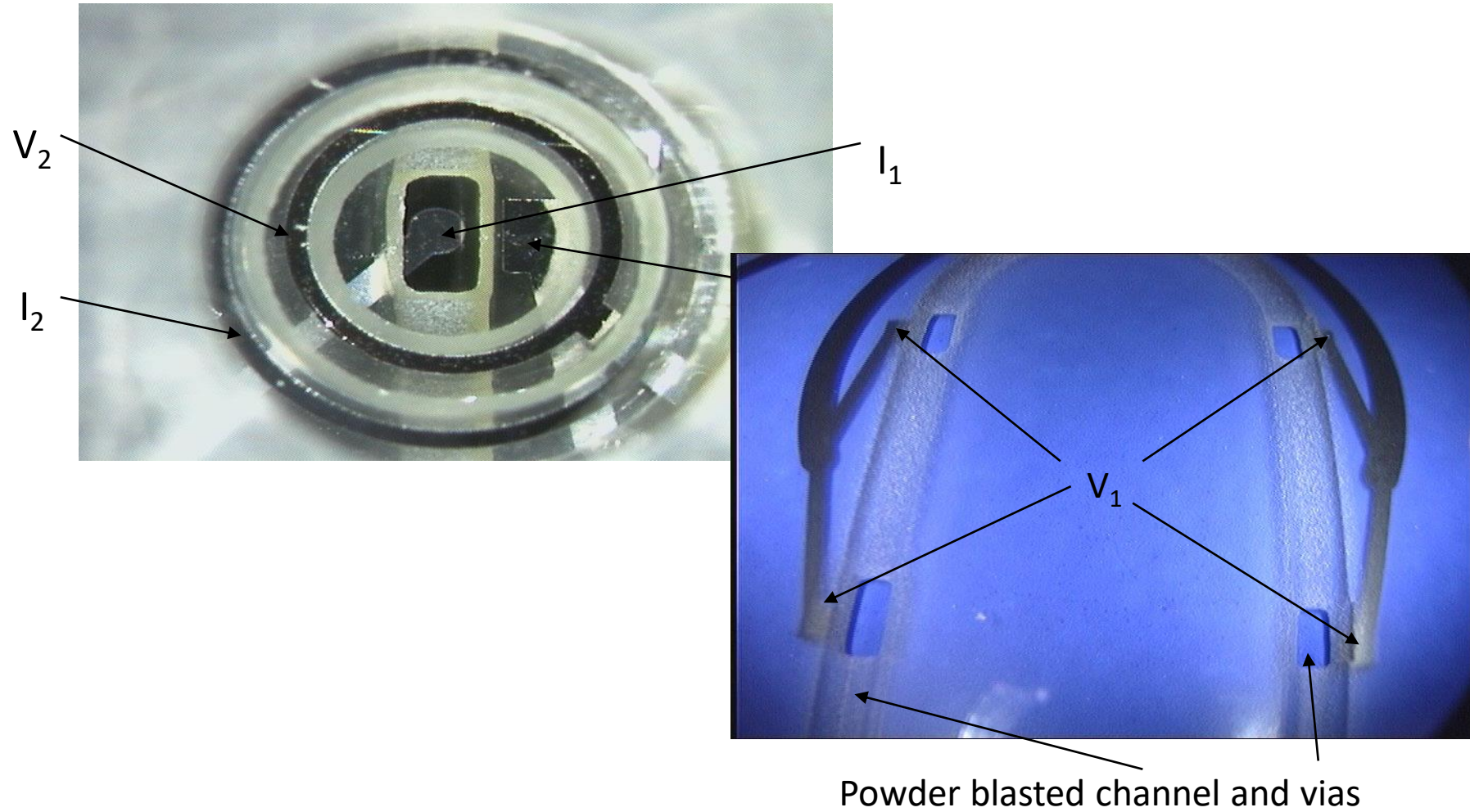


Cell culture device : fabrication

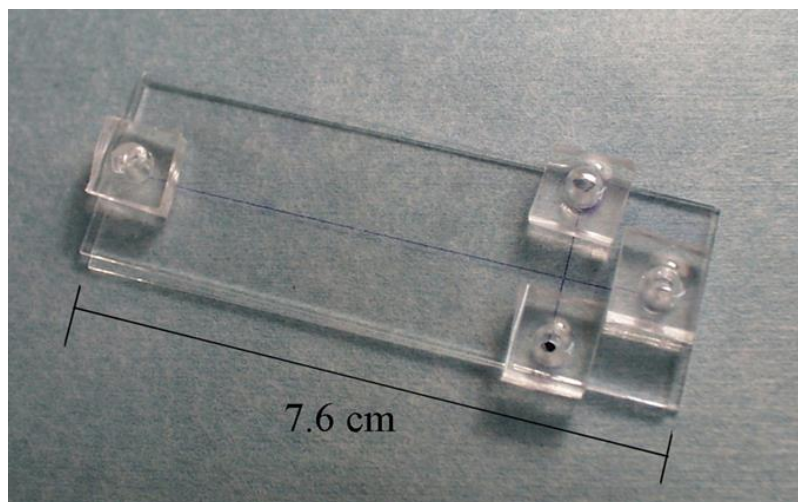


Modular cell culture device

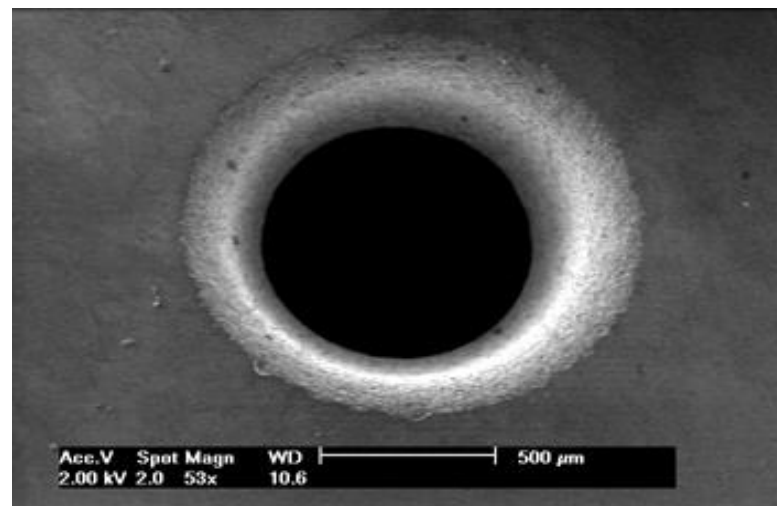
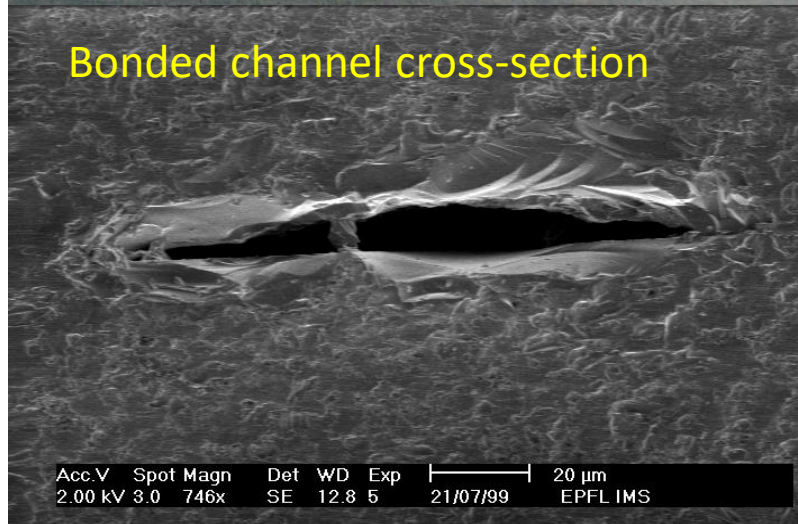




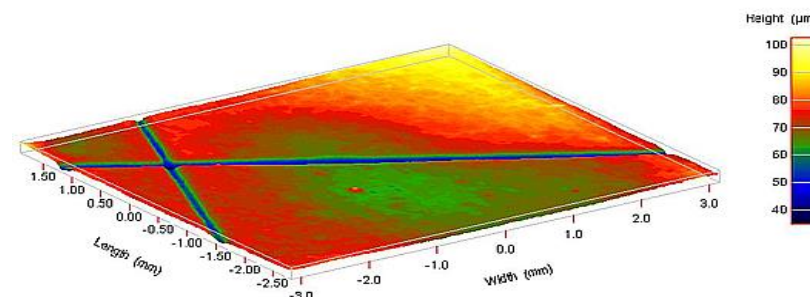
Capillary electrophoresis μ -chips



Bonded channel cross-section

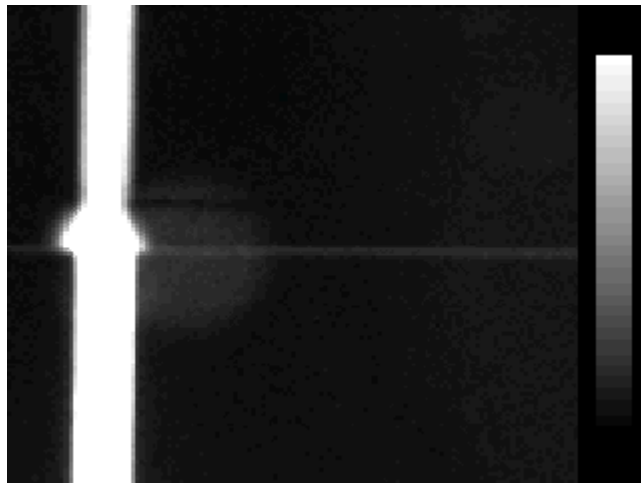


A. Sayah, D. Solignac, T. Cueni, M. Gijs, Sens. & Act. A 84, 103 (2000)

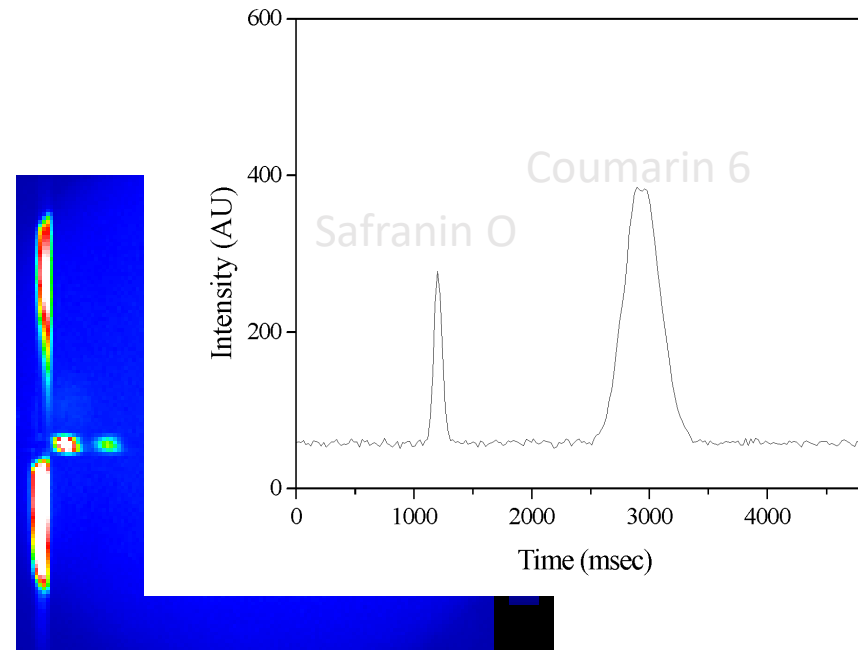


Capillary electrophoresis and electrochromatography

Pinched electrokinetic injection
Borate buffer (10 mM; pH=9.2) +
fluorescein (20 μ M)

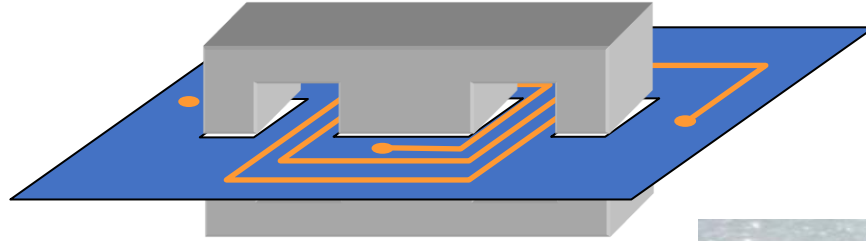


D. Solignac, A. Sayah, S. Constantin, R. Freitag, M. Gijs, Sens. & Act. A 92, 388 (2001)
S. Constantin, R. Freitag, D. Solignac, A. Sayah, M. Gijs, Sens. & Act. B 78, 267 (2001)



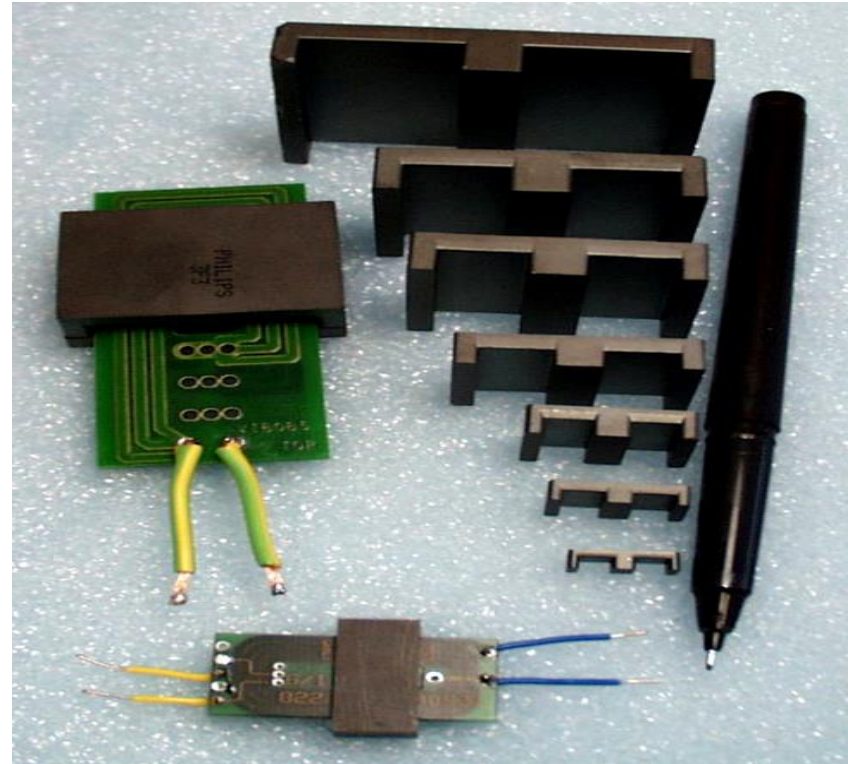
Separation of fluorescent dyes coumarin 6
(30 μ M) and safranin O (30 μ M) in
[ethanol 90% + borate buffer (10 mM)
10%]

Mini-transformers



Combination of
E-shaped ferrite cores
with

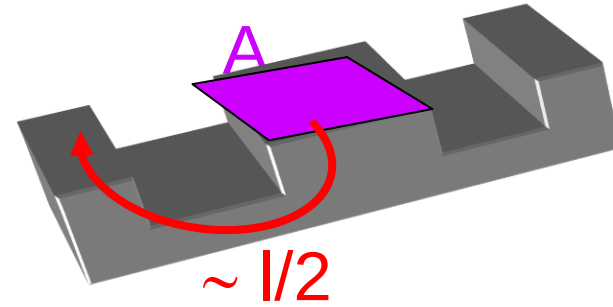
**windings realised in
Printed Circuit Board
technology**



Miniaturisation of inductive devices

'Simple' inductance formula :

$$L = \mu_0 \mu_r \frac{A}{l} N^2$$



Scaling down A and l with the same factor keeps L constant, but

saturation of the magnetic core needs to be avoided

$$\Phi_{\max} = LI_{\max} = NAB_{\max}$$

with $B_{\max} \sim 0.2$ Tesla

'Extreme' (mm) miniaturisation of inductive components

- **Applications**

- Distributed, low power applications (0.1 - 1 Watt)
- Antennas
- Magnetic sensors

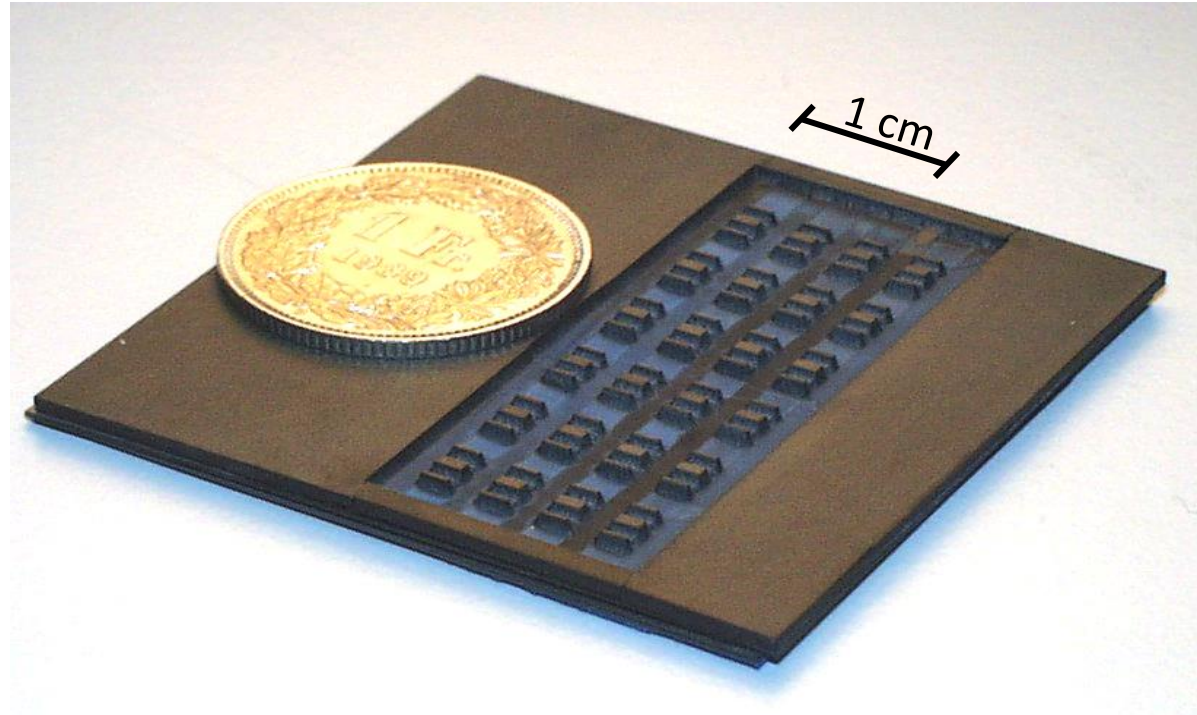
- **Issues**

- Manufacturing of magnetic cores
- Handling and assembly

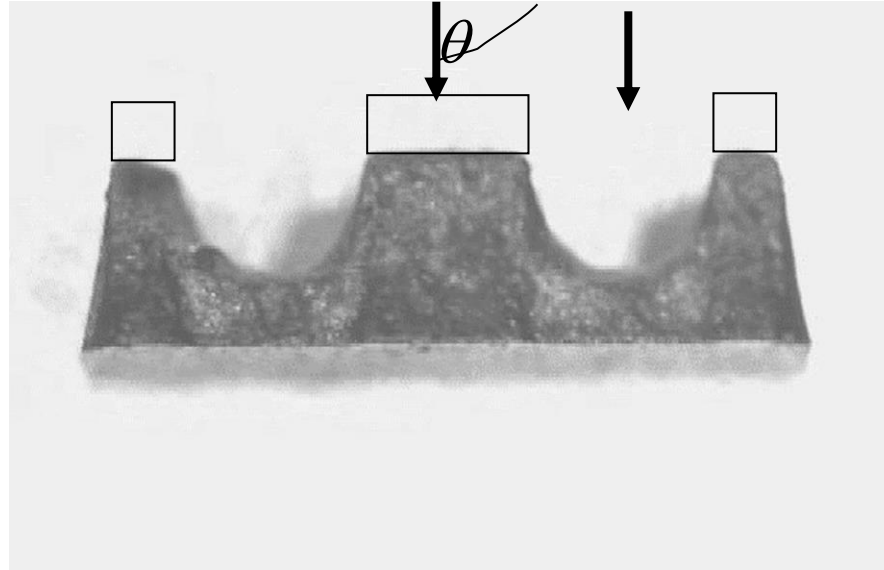
- **Our solution : batch-type technology**

- Hybrid magnetic core - PCB technology
- 3-dimensional microstructuring of ferrite wafers by powder blasting
- Wafer level handling and assembly of devices

Powder blasting of ferrite wafers



'Natural' core profile

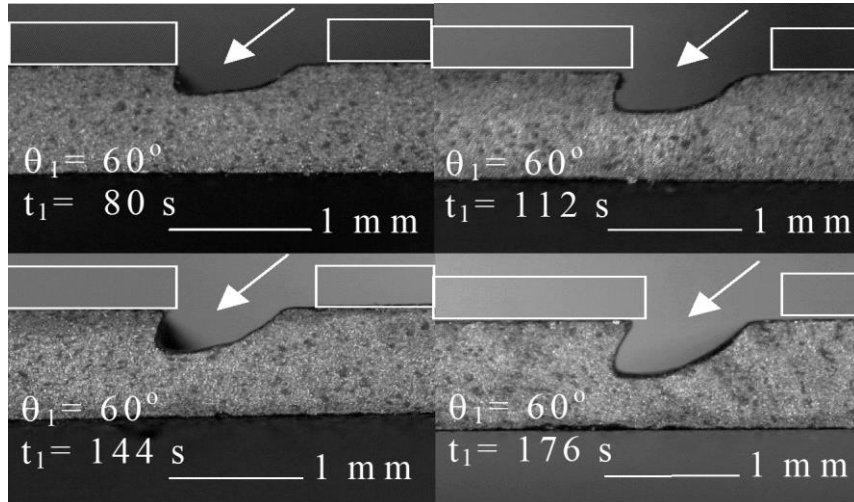


Powder jet at normal incidence ($\theta = 90^\circ$)

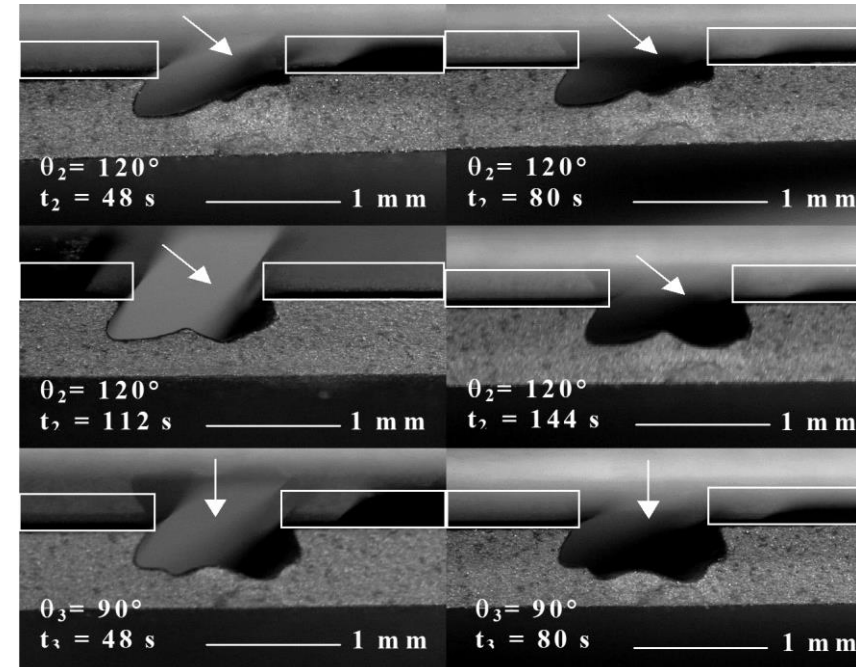
Profile is result of:

- particle finite-size effects
- angle-dependent erosion efficiency

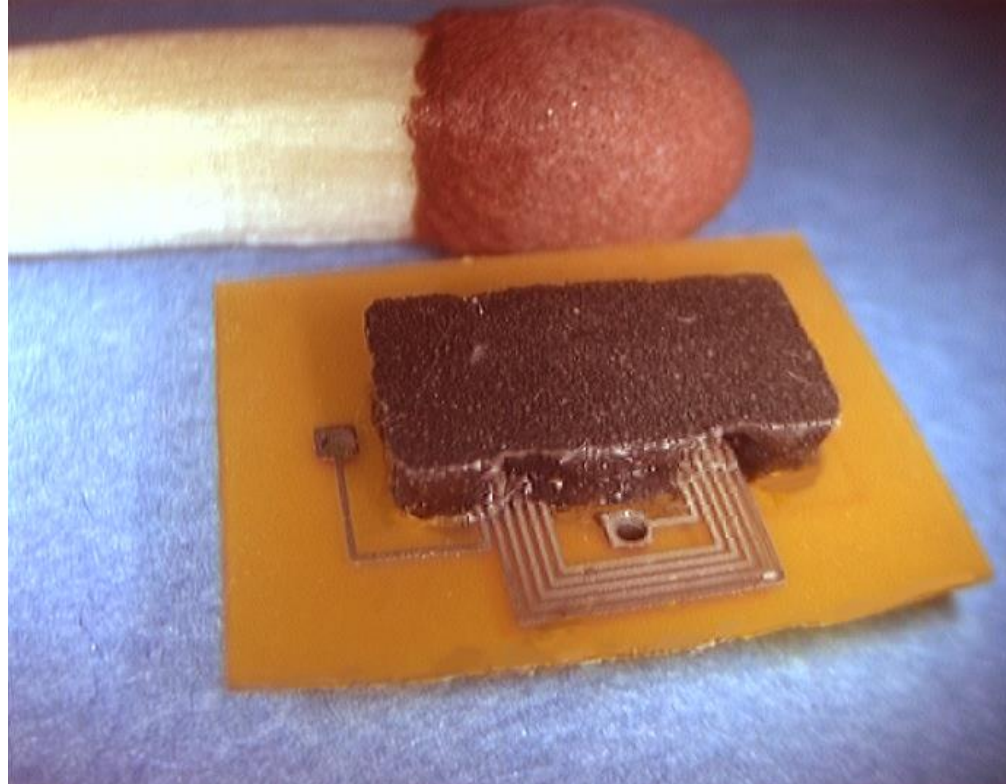
'Tuning' the core profile



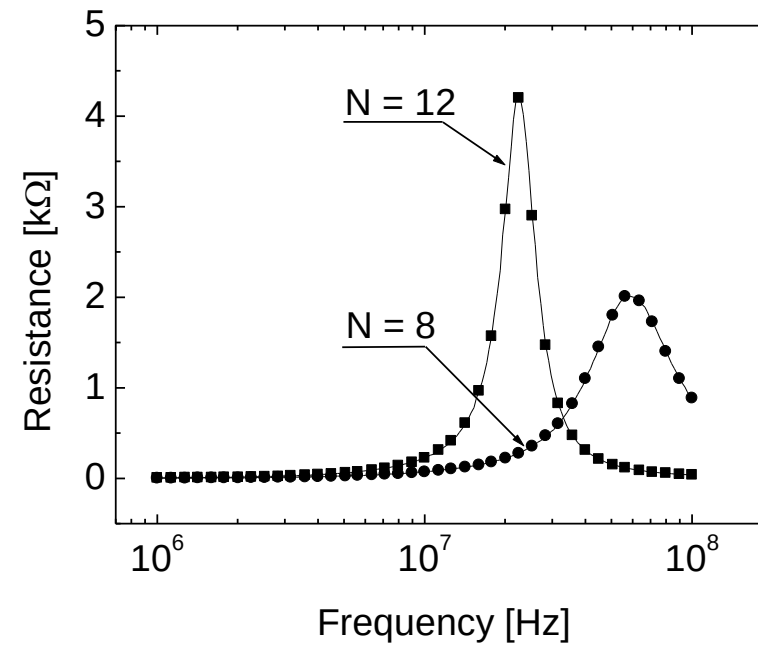
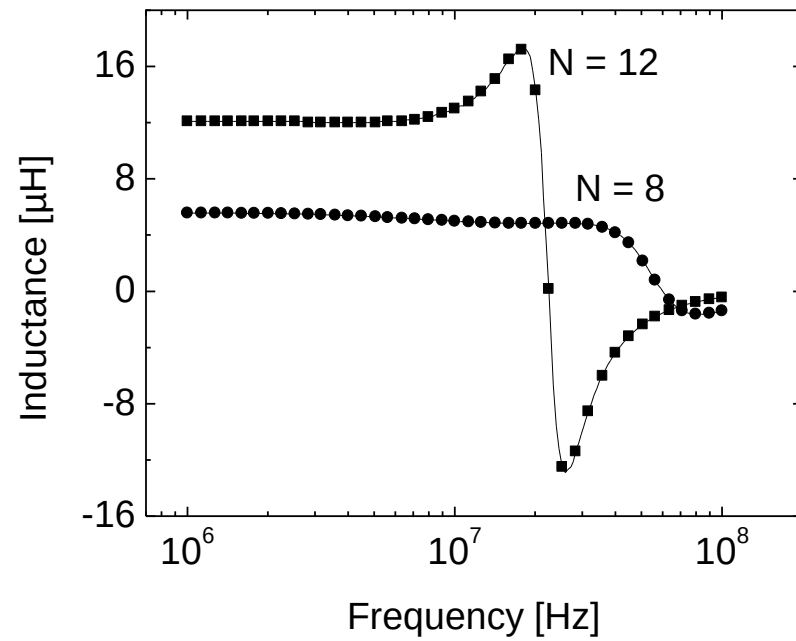
Powder jet at non-normal incidence



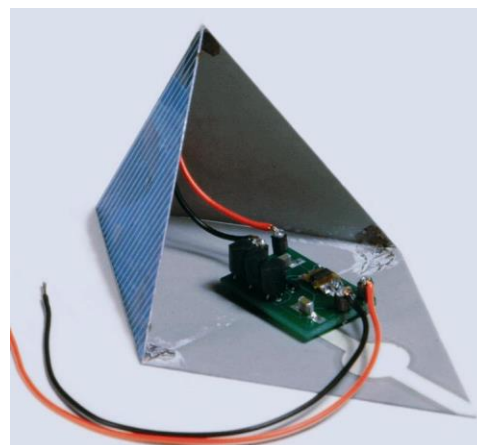
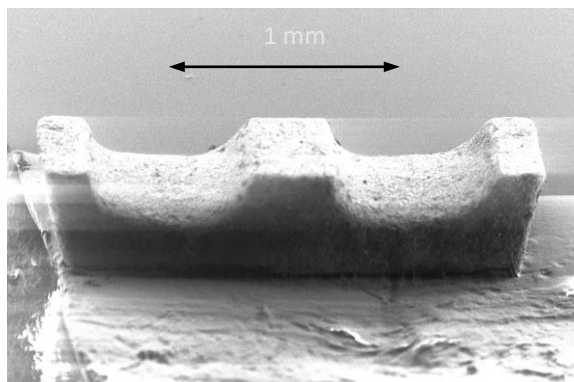
Assembled mini-transformer



Inductance and resistance

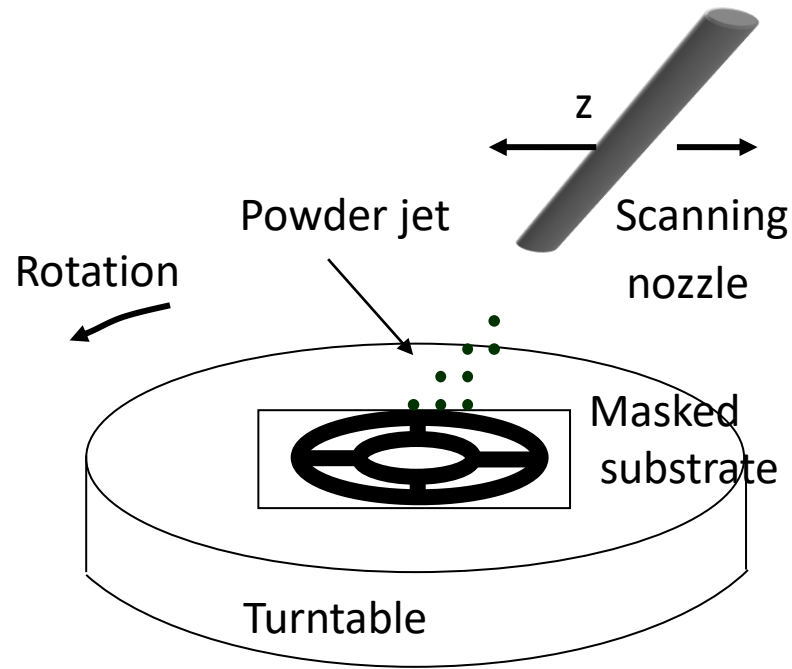


Representation of EPFL at the Hannover Messe 2002

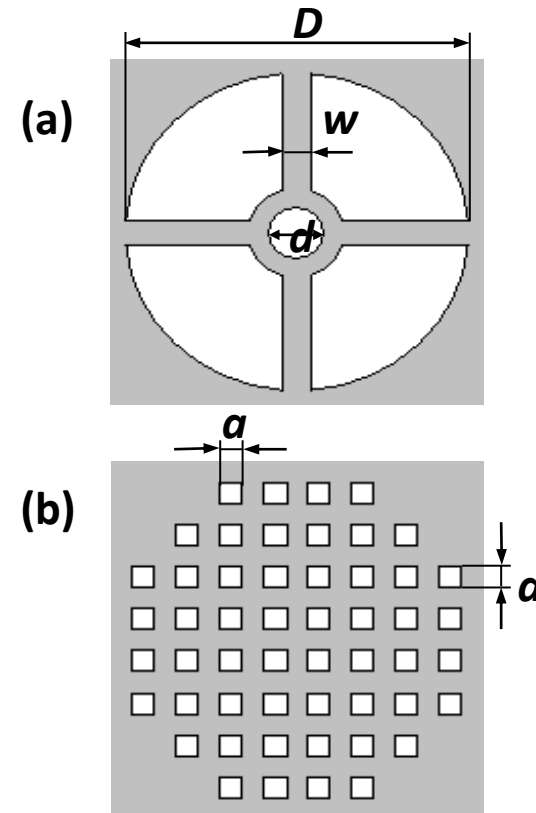


April 2002

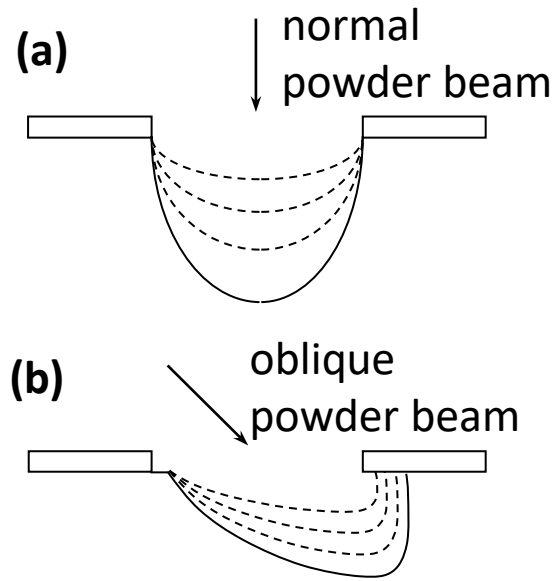
Monolithic suspended structures in glass



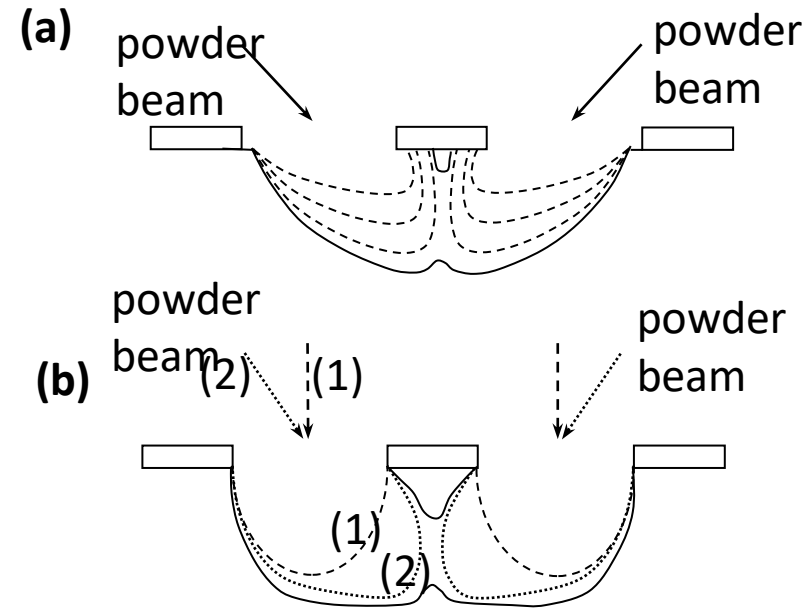
Experimental set up for the rotating mode of the powder blasting micro-erosion process



Mask sample design for the realization of (a) complex three-dimensional and (b) grid structures.

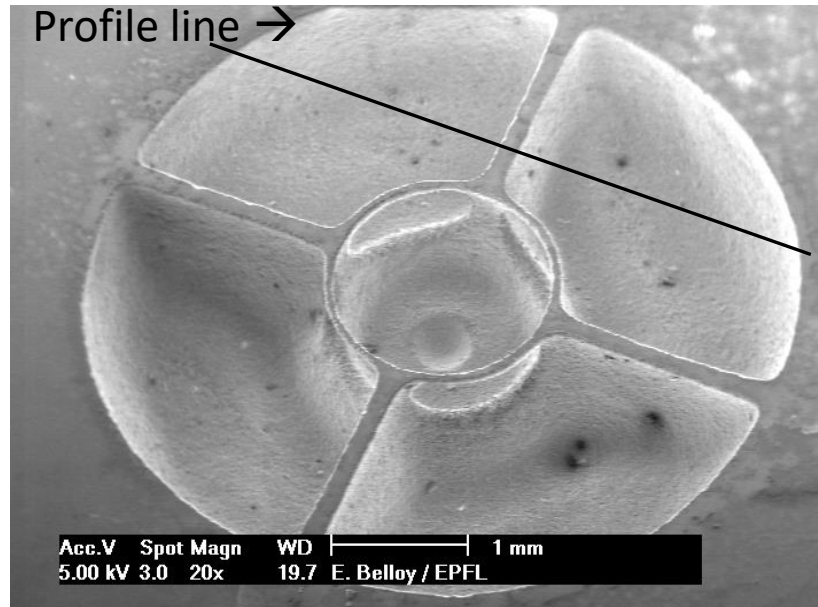


Schematic view of (a) a symmetrical hole obtained with a normal powder beam incidence and (b) a hole shape resulting of an oblique incidence of the eroding particles.

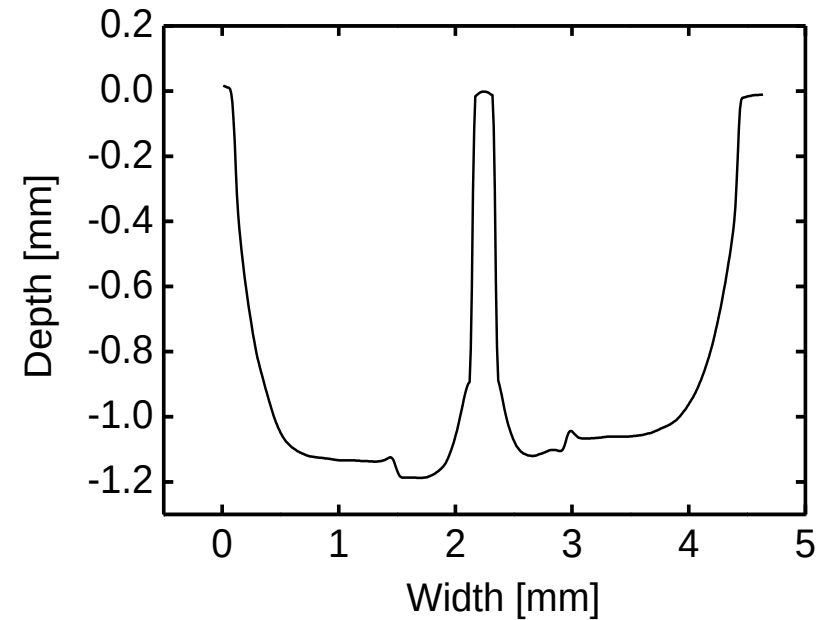


Schematic view of (a) suspended structure realised by one angle of incidence; (b) suspended structure obtained by alternatively using a normal and an oblique powder beam, which minimises the mask underetching effect.

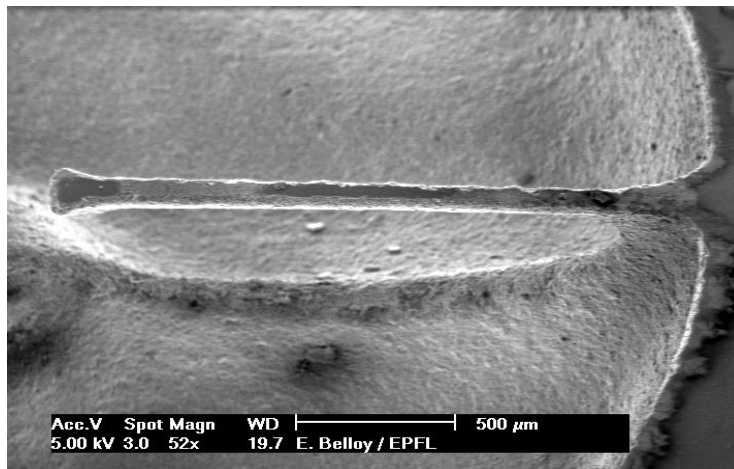
High aspect ratio



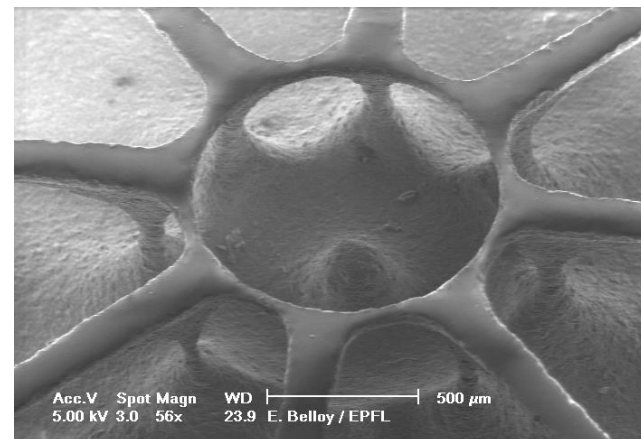
Scanning Electron Microscope (SEM) picture of a connected ring glass structure.



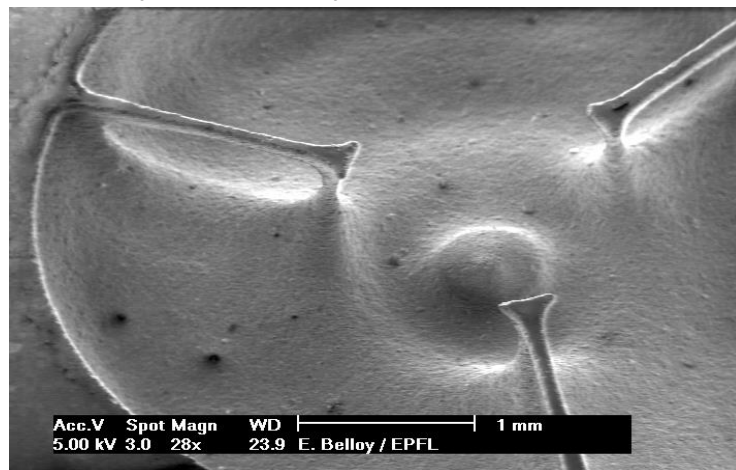
Profile of a high aspect ratio structure obtained using an optical profilometer. The structure width is 0.17 mm giving an aspect ratio of 7.



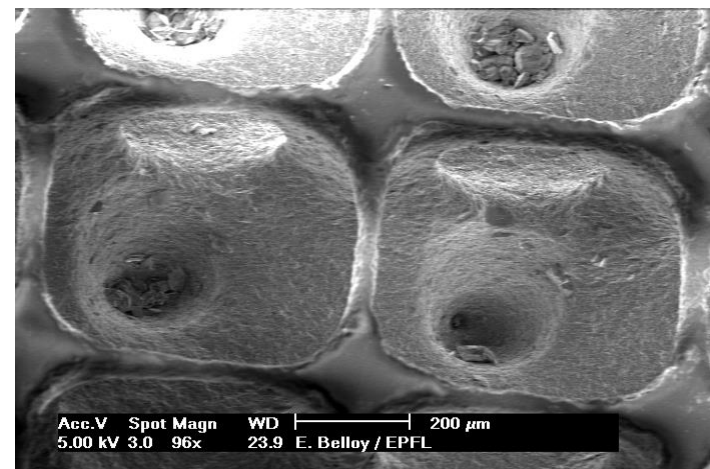
SEM picture of a 115 μm wide and 2 mm long suspended glass cantilever beam. (90° & 50°)



SEM picture of a complex three-dimensional monolithic structure. (60° & 50°)



SEM picture of cantilever beams connected to the substrate on their extremity. (60°)



SEM picture of a monolithic grid structure. (90° & 60°)

References

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- <http://www.umist.ac.uk/MatSci/teaching/year3/ml352>
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- P.J. Slikkerveer, Mechanical etching of glass by powder blasting, Ph.D. thesis Eindhoven University of Technology (1999)
- E. Belloy, A. Sayah, M. Gijs, Sens. & Act. A 86, 231 (2000); E. Belloy, S. Thurre, E. Walckiers, A. Sayah, M. Gijs, Sens. & Act. A 84, 330 (2000); E. Belloy, A. Sayah, M. Gijs, J. Microelectromechanical Syst. 11, 85 (2002)