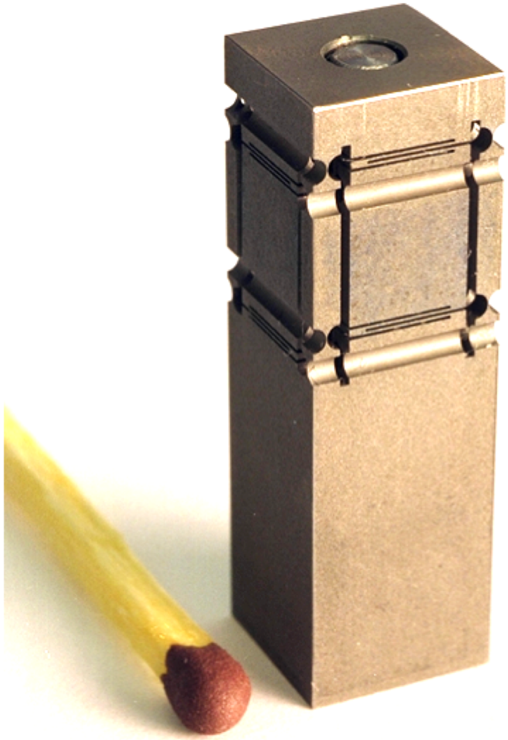
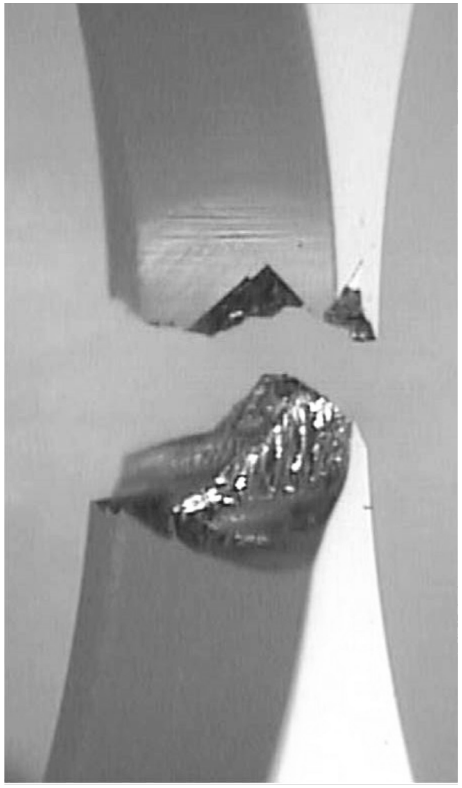
TECHNOLOGICAL ASPECTS





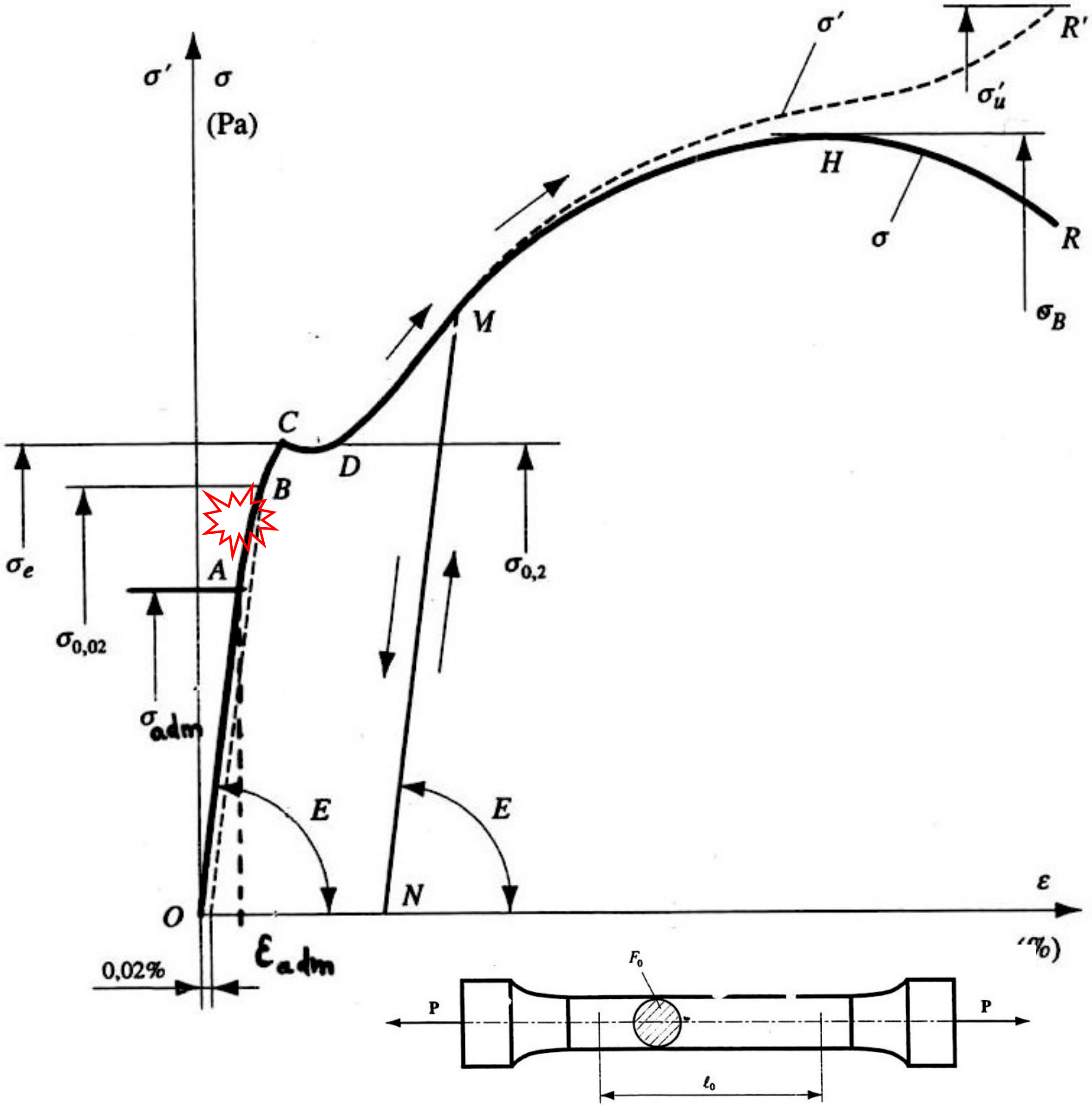
Prof. Simon Henein, Dr. Etienne Thalmann

Material selection

Strain $\varepsilon = \frac{\Delta \ell}{\ell}$

Stress $\sigma = \frac{P}{F}$

Hook’s Law $\varepsilon = \frac{\sigma}{E}$



The stroke of flexures is proportional to:

$$\frac{\sigma_{adm}}{E}$$

← Admissible stress

← Young’s Modulus

« Materials that are good for springs, are good for flexures »

Commonly used metallic alloys

- Spring steels, carbon steels

  e.g. X220CrVMo13-4 (K190), X3NiCoMoTi18-9-5 (W720)
- Spring stainless-steels

  e.g. X10CrNi18-8, N700 ESU (17-4 PH)
- Titanium alloys

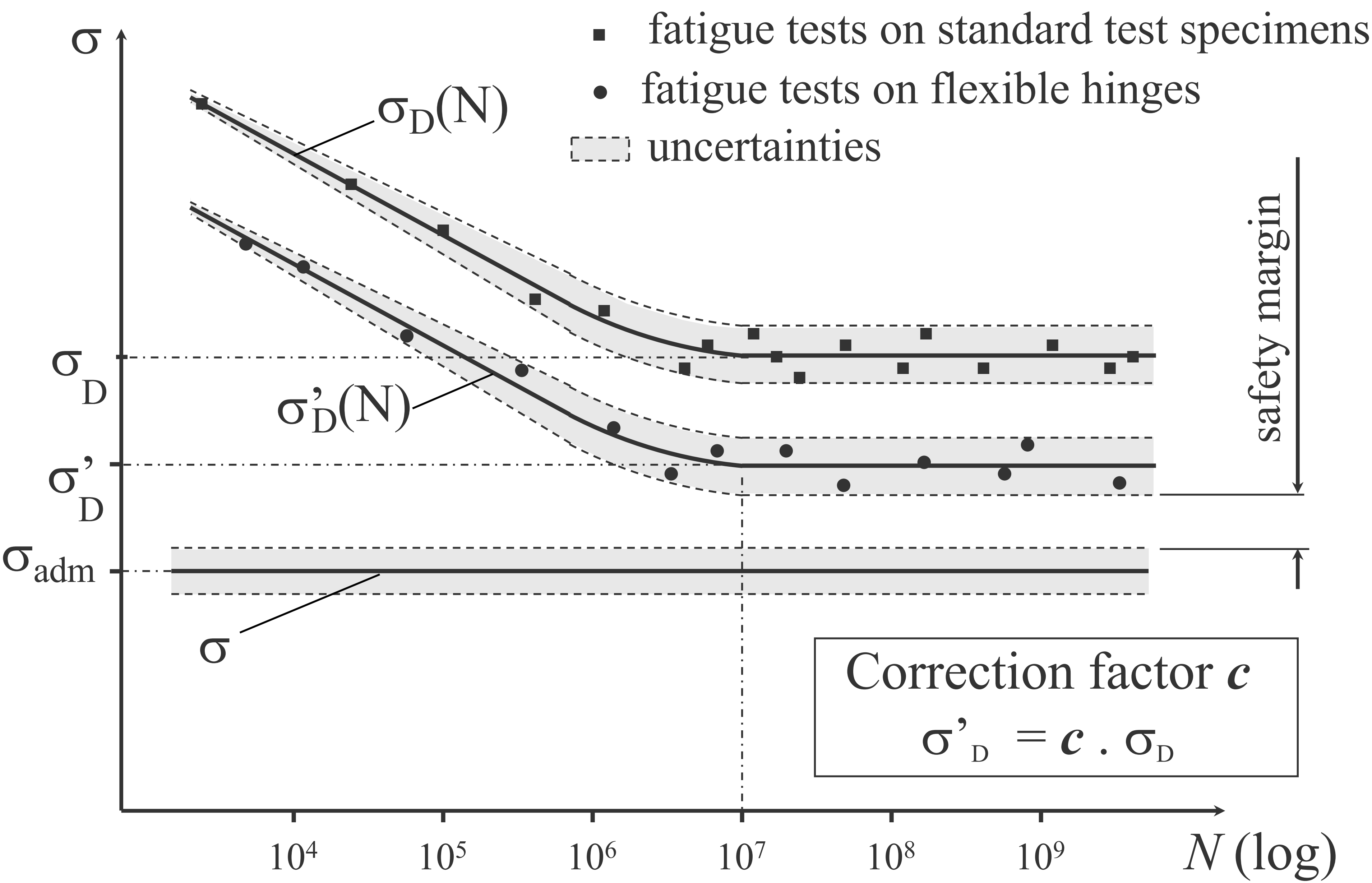
  e.g. Ti Al6 V4
- Copper-beryllium alloys

  e.g. XHMS
- Bronze allows

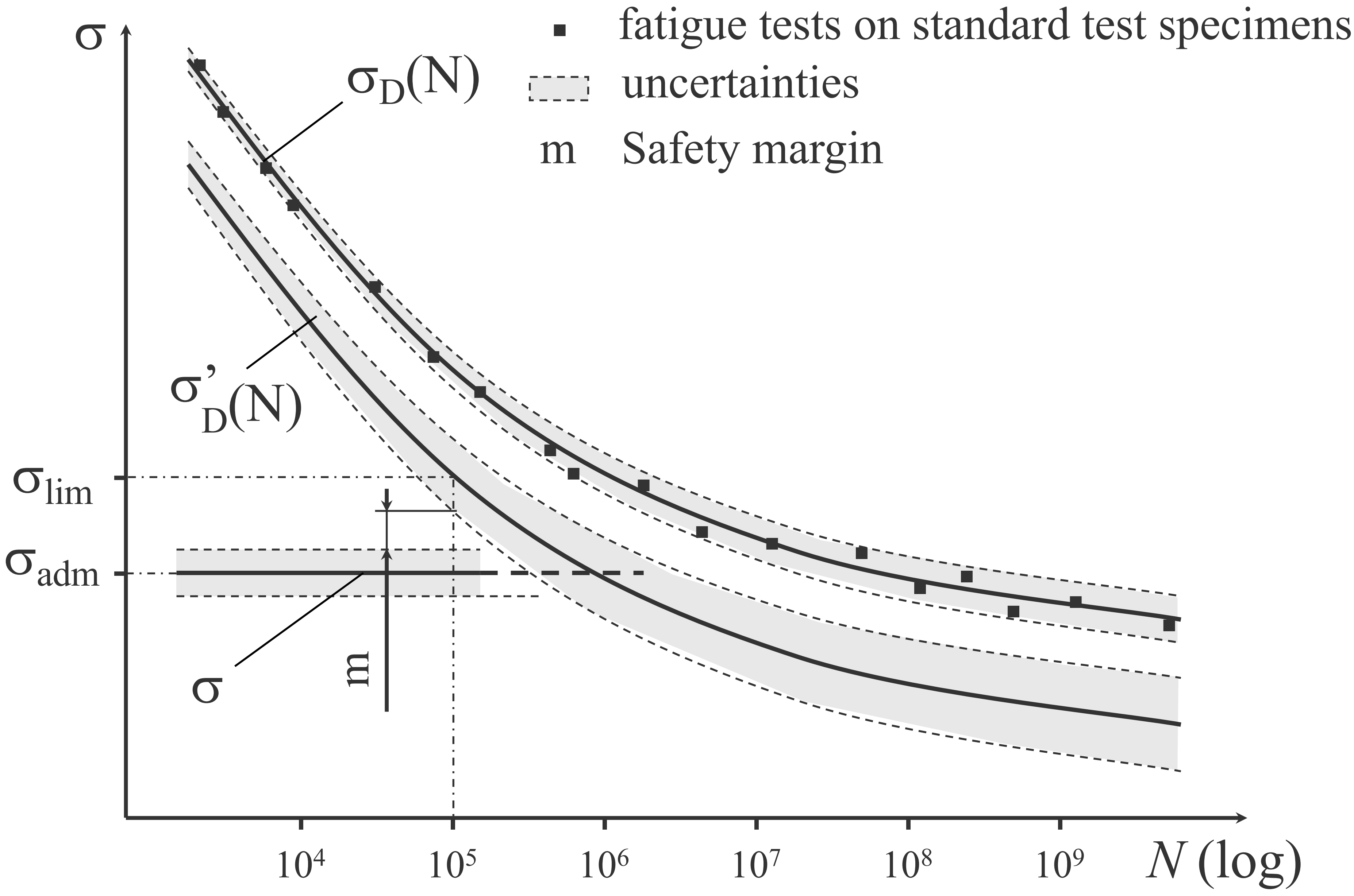
  e.g. Cu Ni 15 Sn 8
- Aluminum alloys

  e.g. AlCuSiMn (Avional), AlZnMgCu1.5 (Perunal)

Fatigue theory



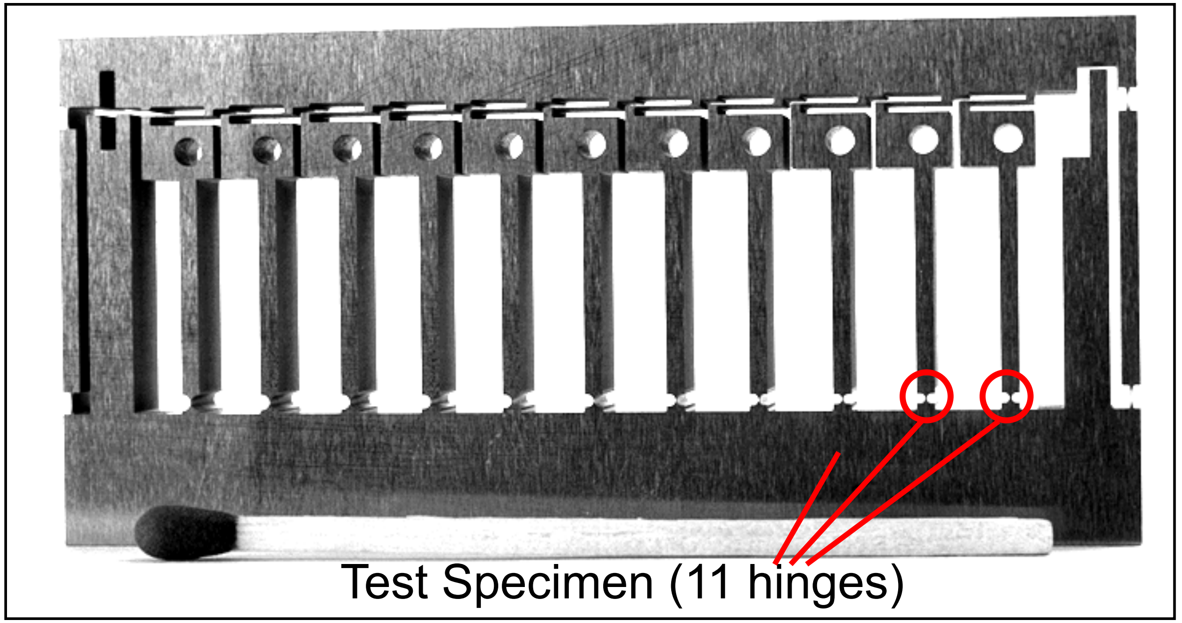
Fatigue of materials without fatigue plateau (e.g. Alu)

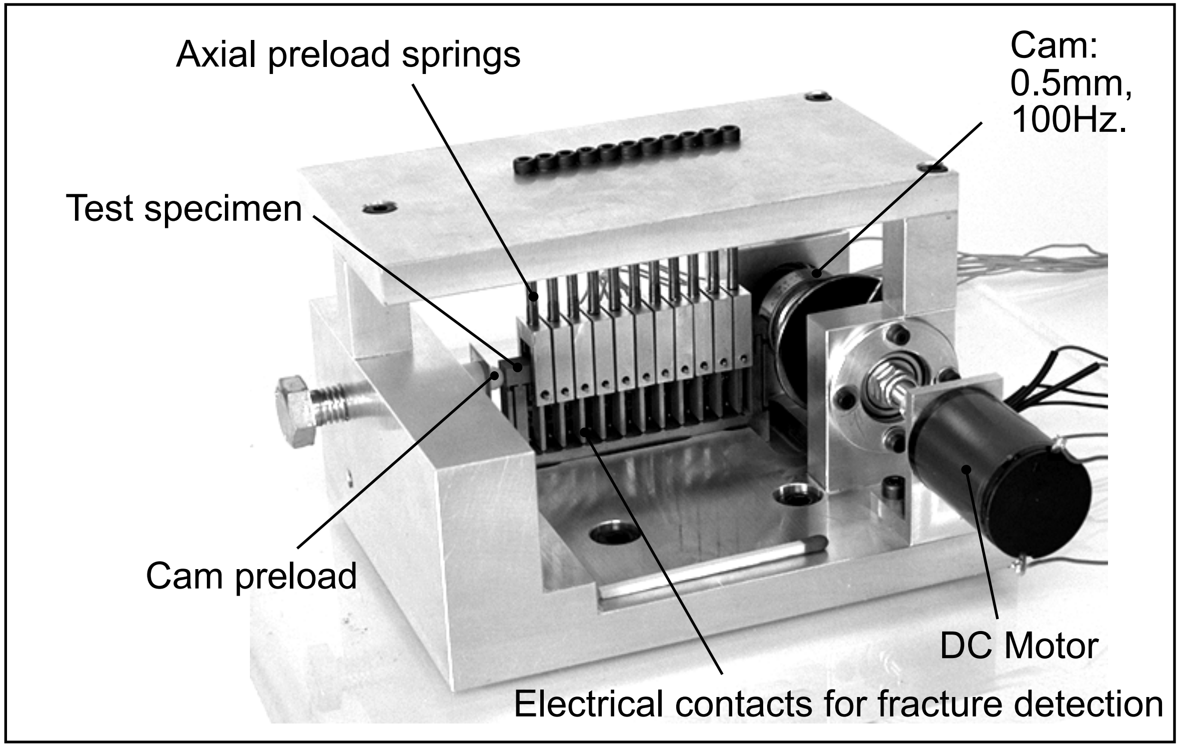


Fatigue tests

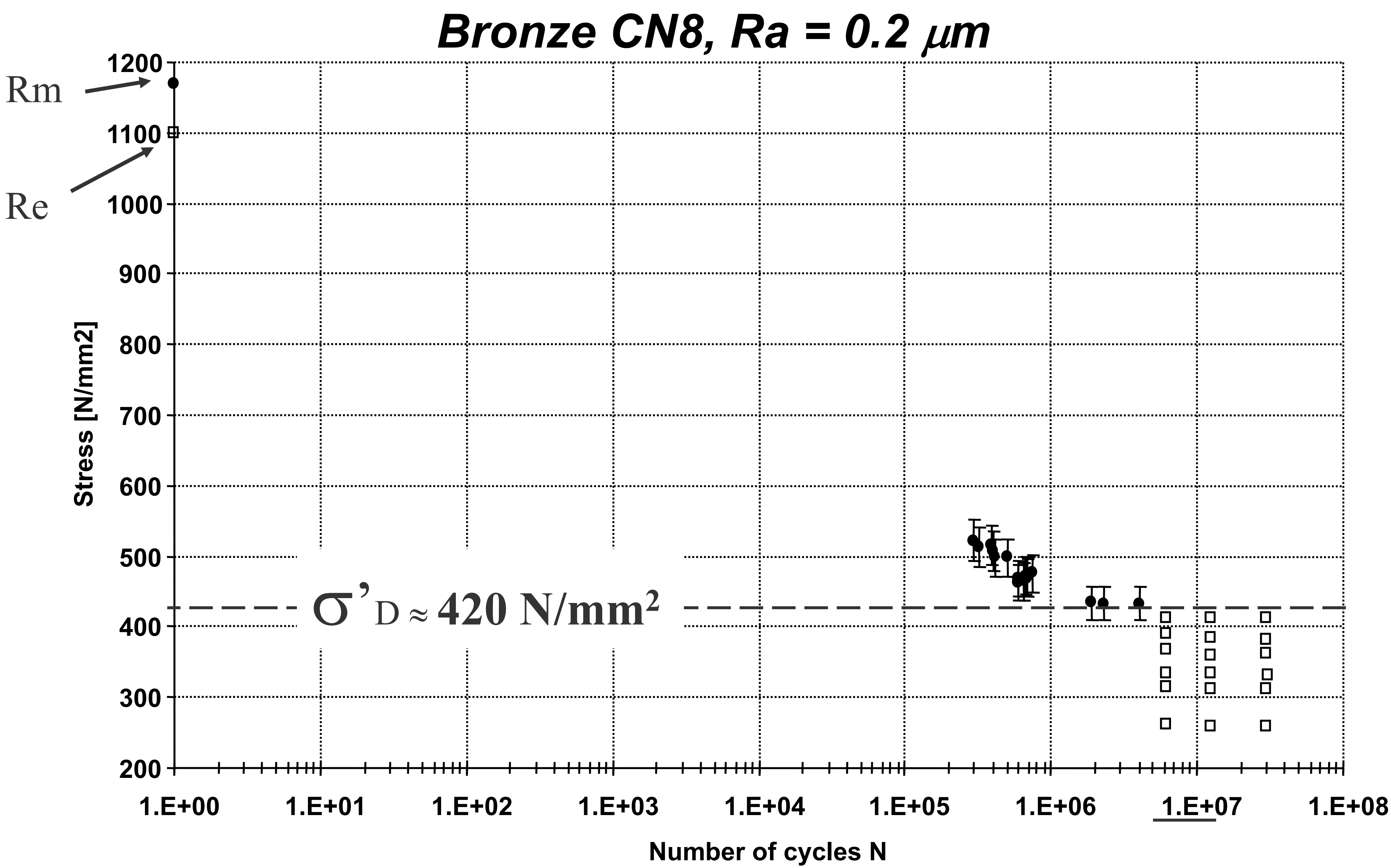
Studied parameters:

- Comparison with data for the bulk material
- Effect of EDM process
- Effect of surface roughness
- Effect of stress concentrations

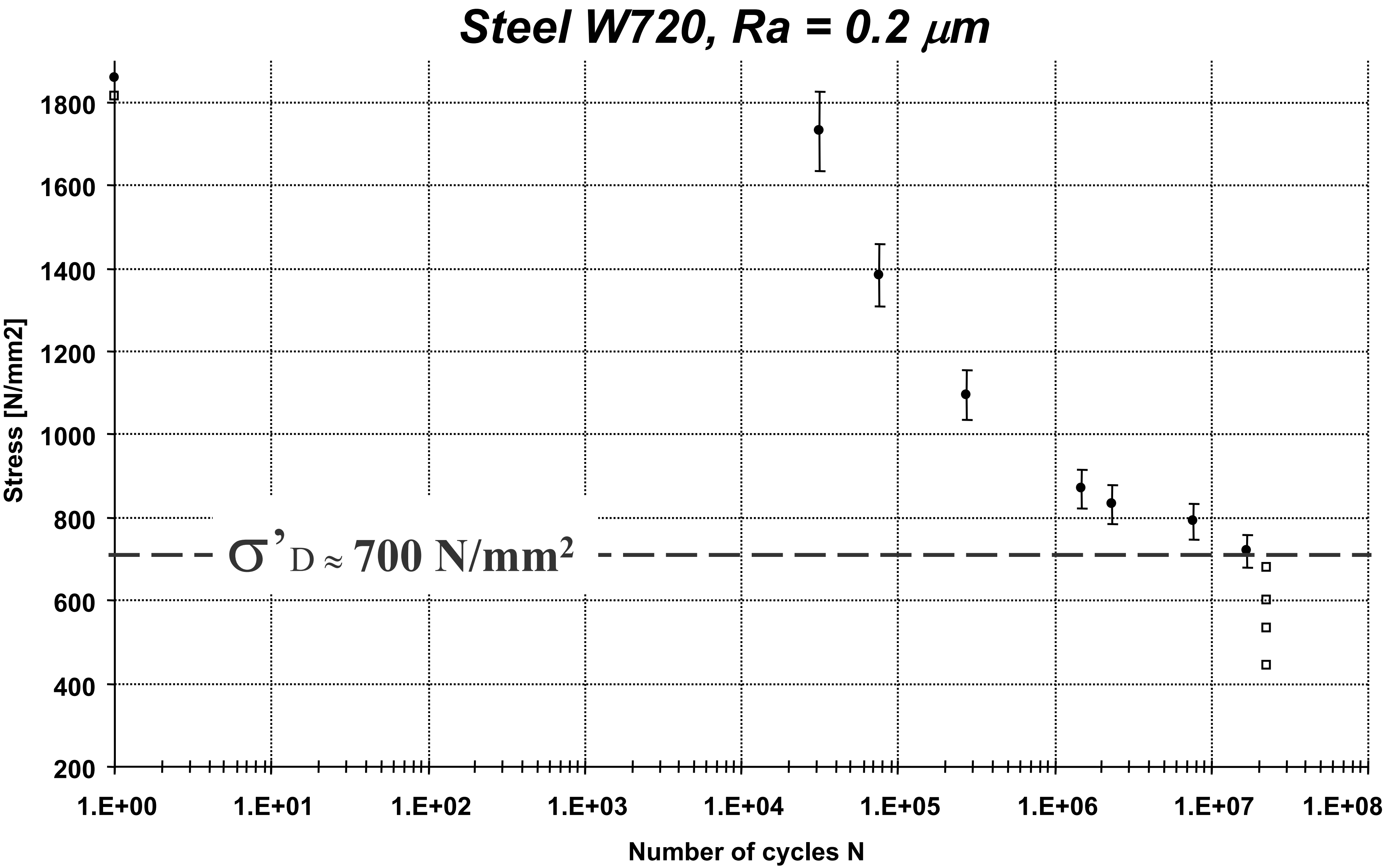




Example of fatigue test results

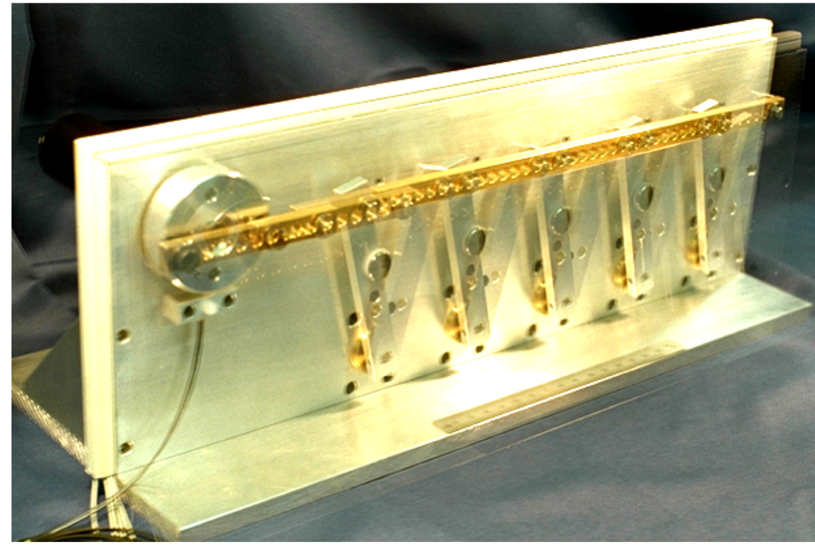


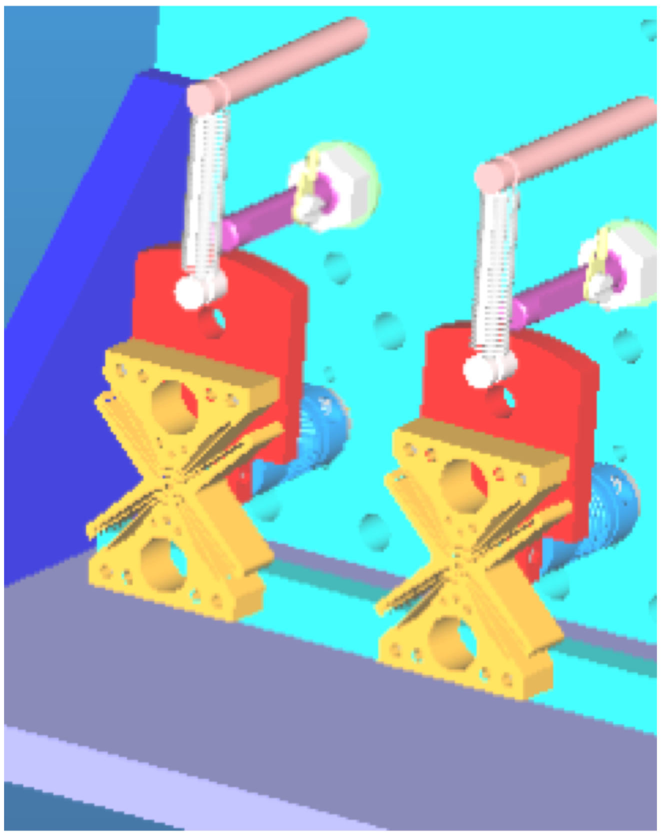
Example of fatigue test results

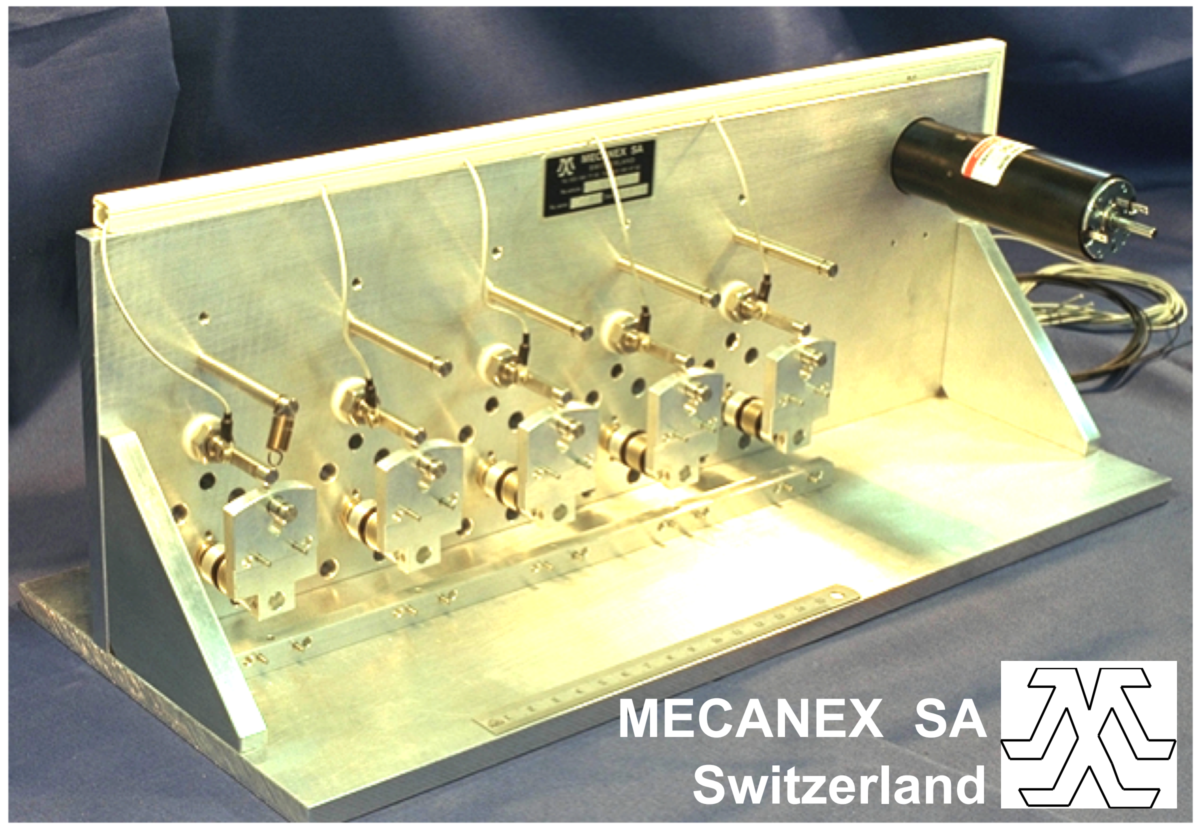


Fatigue tests on real parts

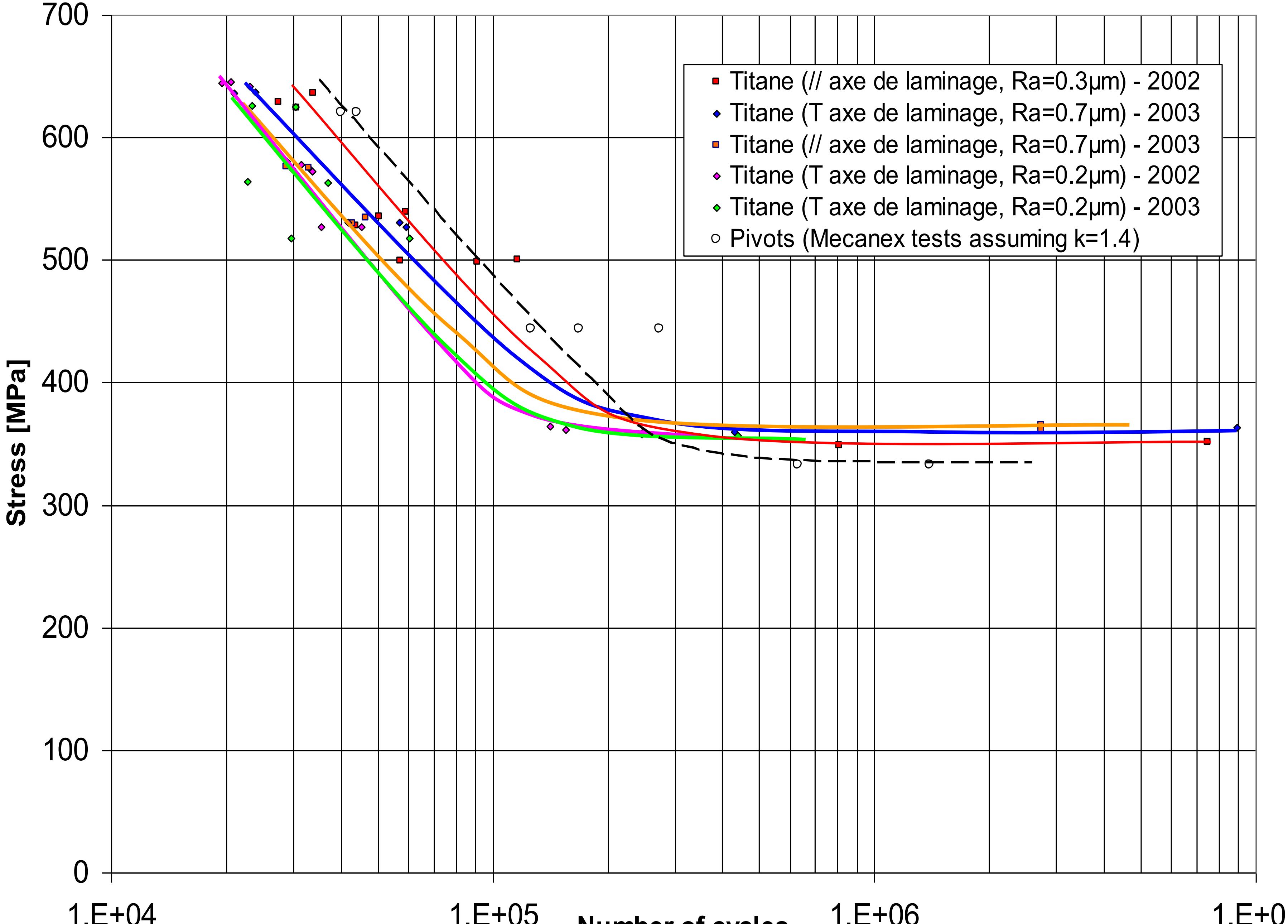
Example of the “Butterfly-Pivot”







Titanium (Ti-6Al-4V) fatigue tests

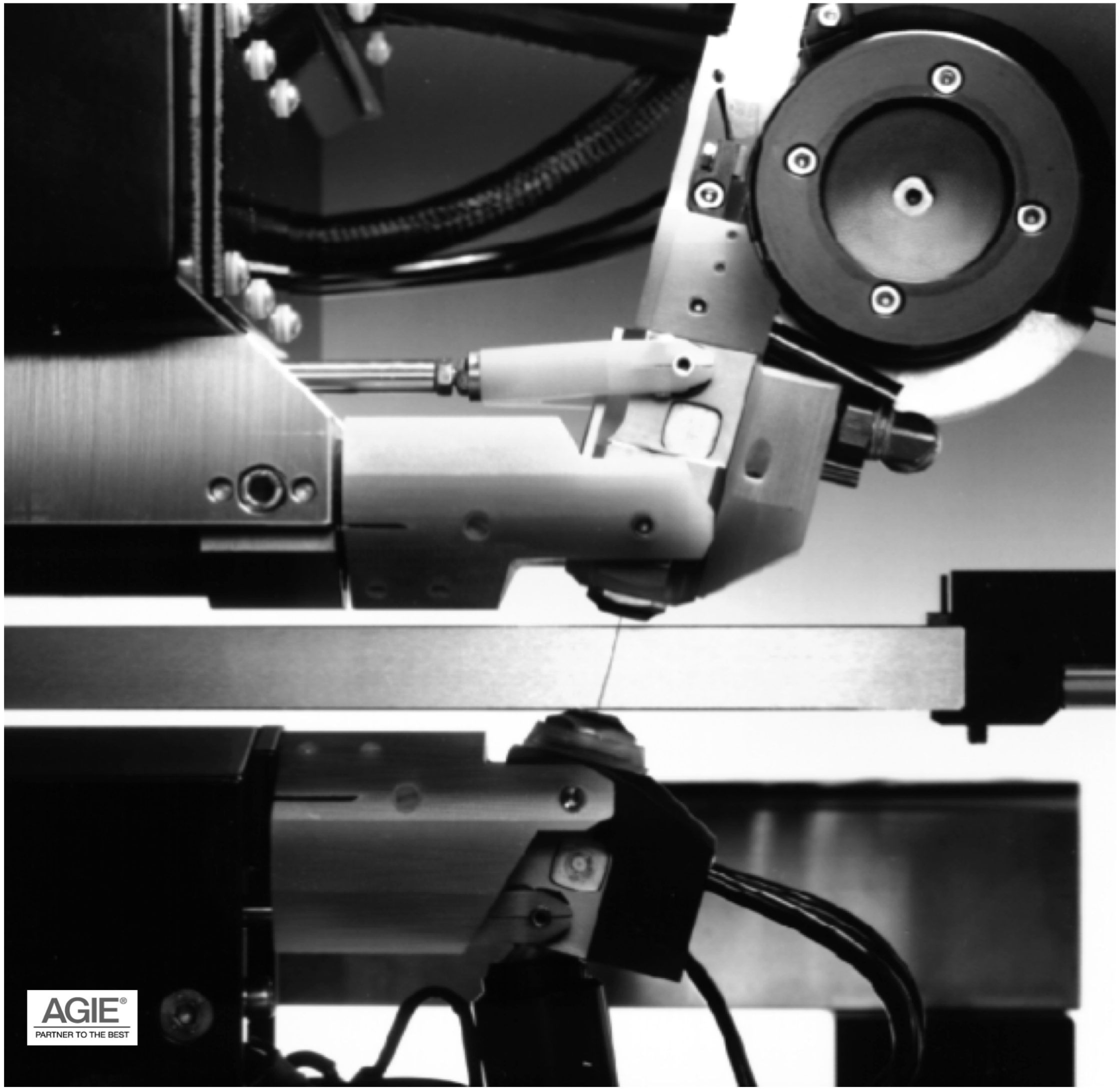


Conclusion of the fatigue experiments

- For roughnesses below Ra=0.2μm, the fatigue data derived from standard fatigue tests appear to be valid for thin (down to 30 microns) flexible hinges machined by wire-EDM.
- Increasing the roughness decreases the fatigue limit and increases uncertainties on the measured thicknesses and the calculated stress inside the flexures.
- For the most demanding applications (e.g. aerospace), fatigue testing of the real parts often cannot be avoided.

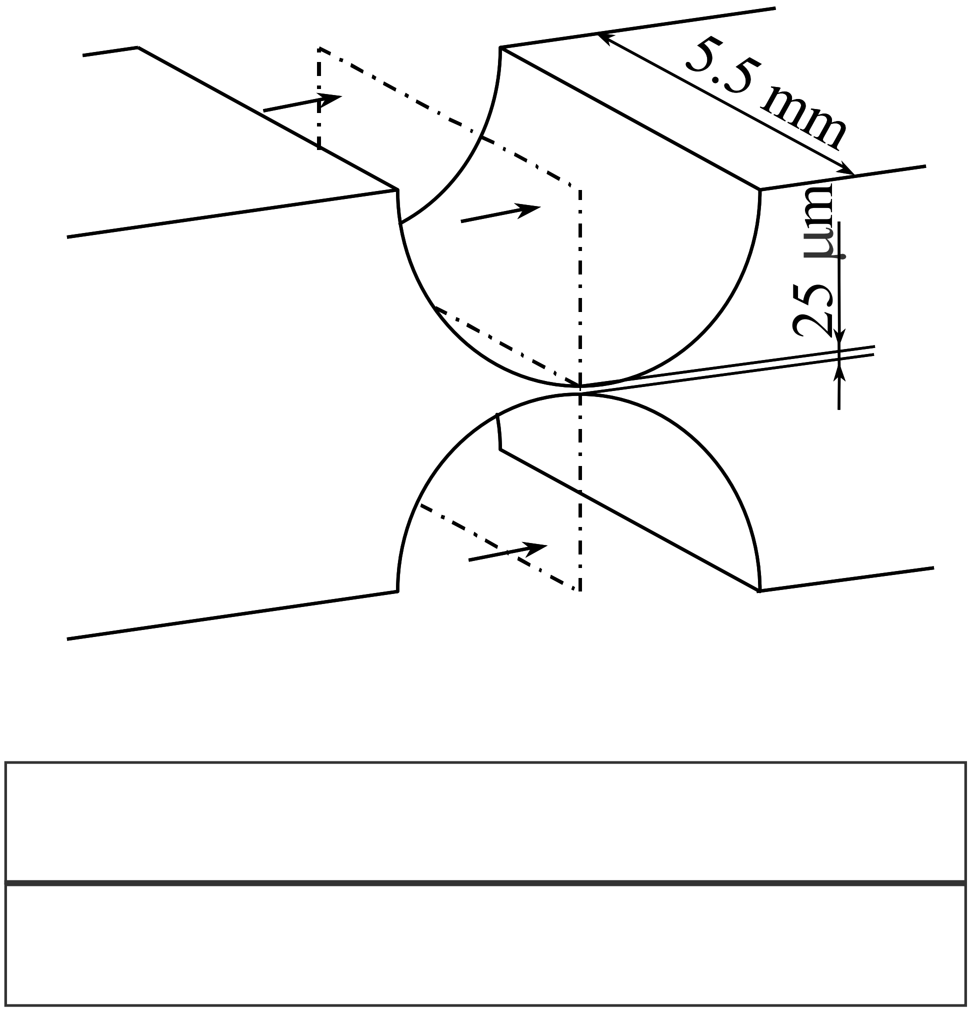
[Henein, S. et al. (1999), Fatigue failure of thin wire-EDM machined flexible hinges, *Proc. SPIE Int. Symp. on Intelligent Systems & Adv. Manufacturing,* Vol 3834, Boston, USA]

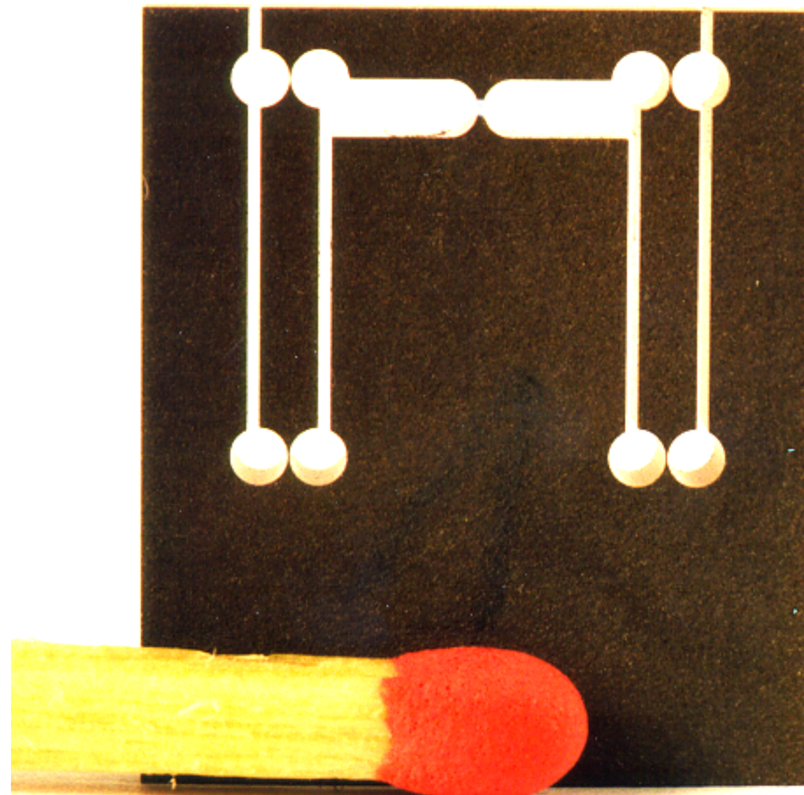
Wire electro-discharge machining



- Very small machining forces
- Insensitivity to hardness
- High aspect ratios
- High precision
- Monolithic machining

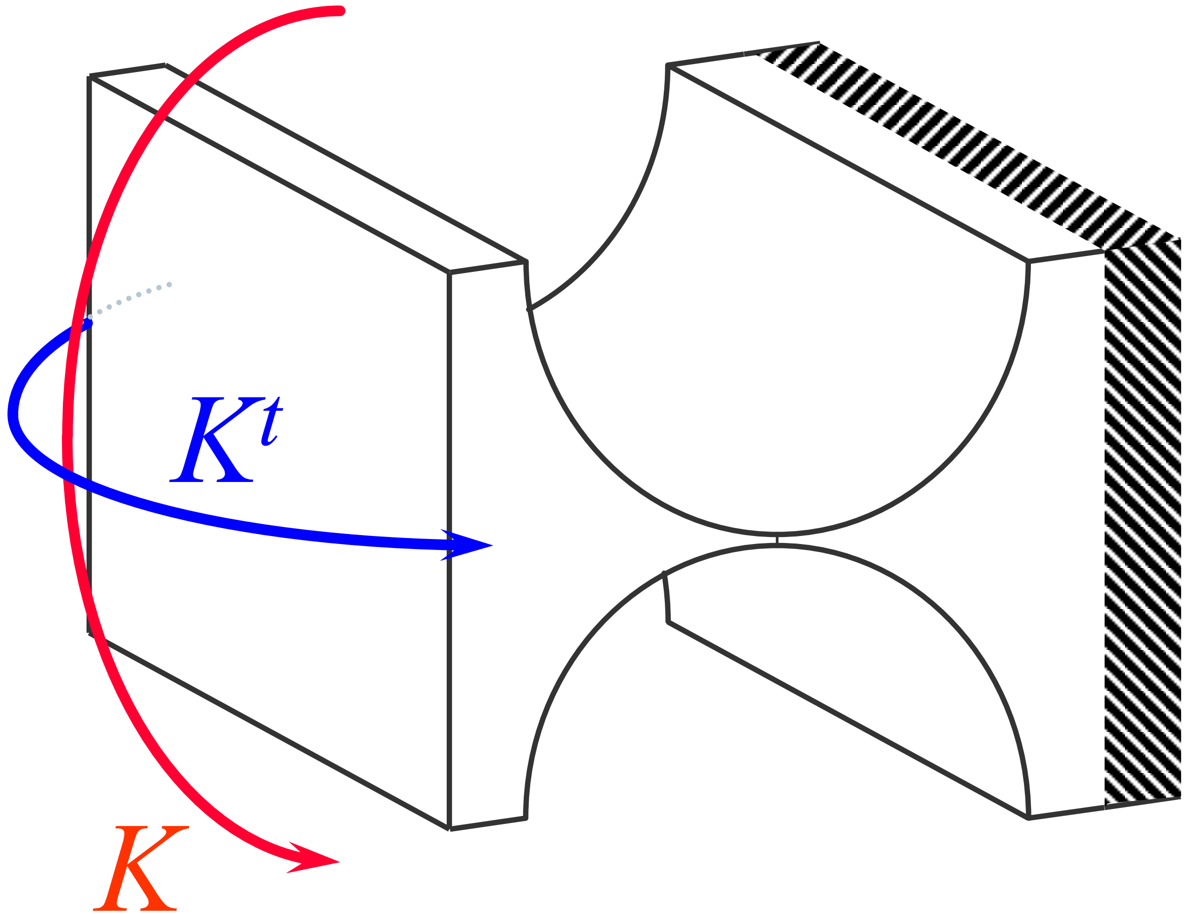
High Aspect Ratios





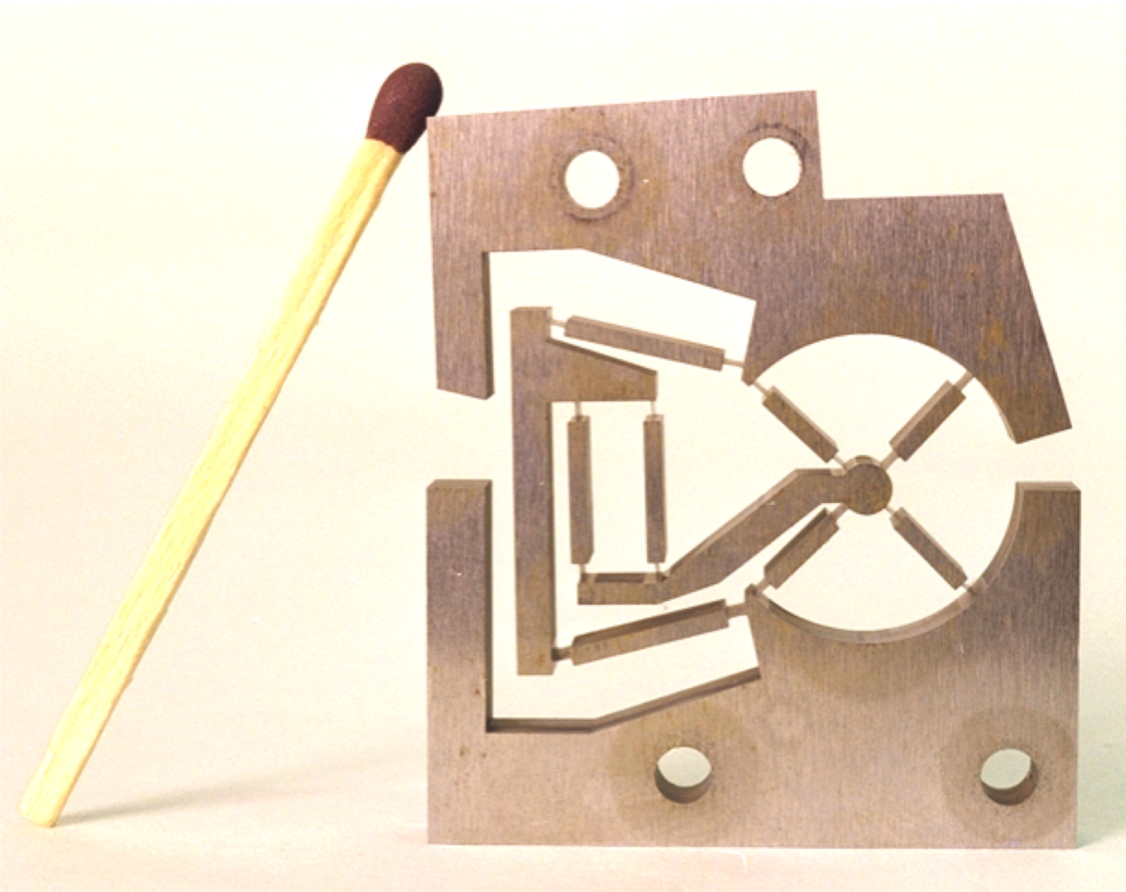
High Stiffness Ratios

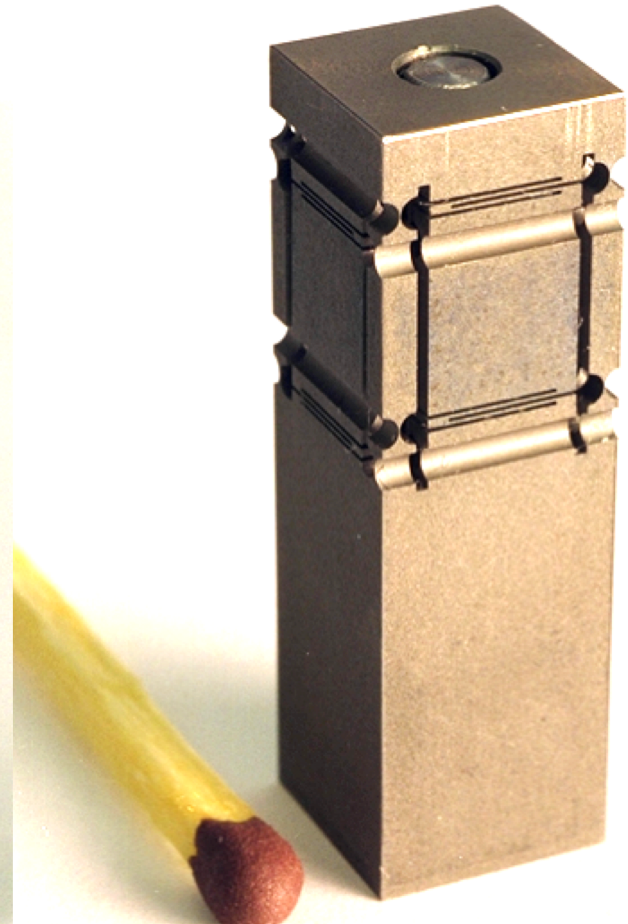
$$\frac{K^t}{K} > 20'000$$



Monolithic manufacturing of complex structures

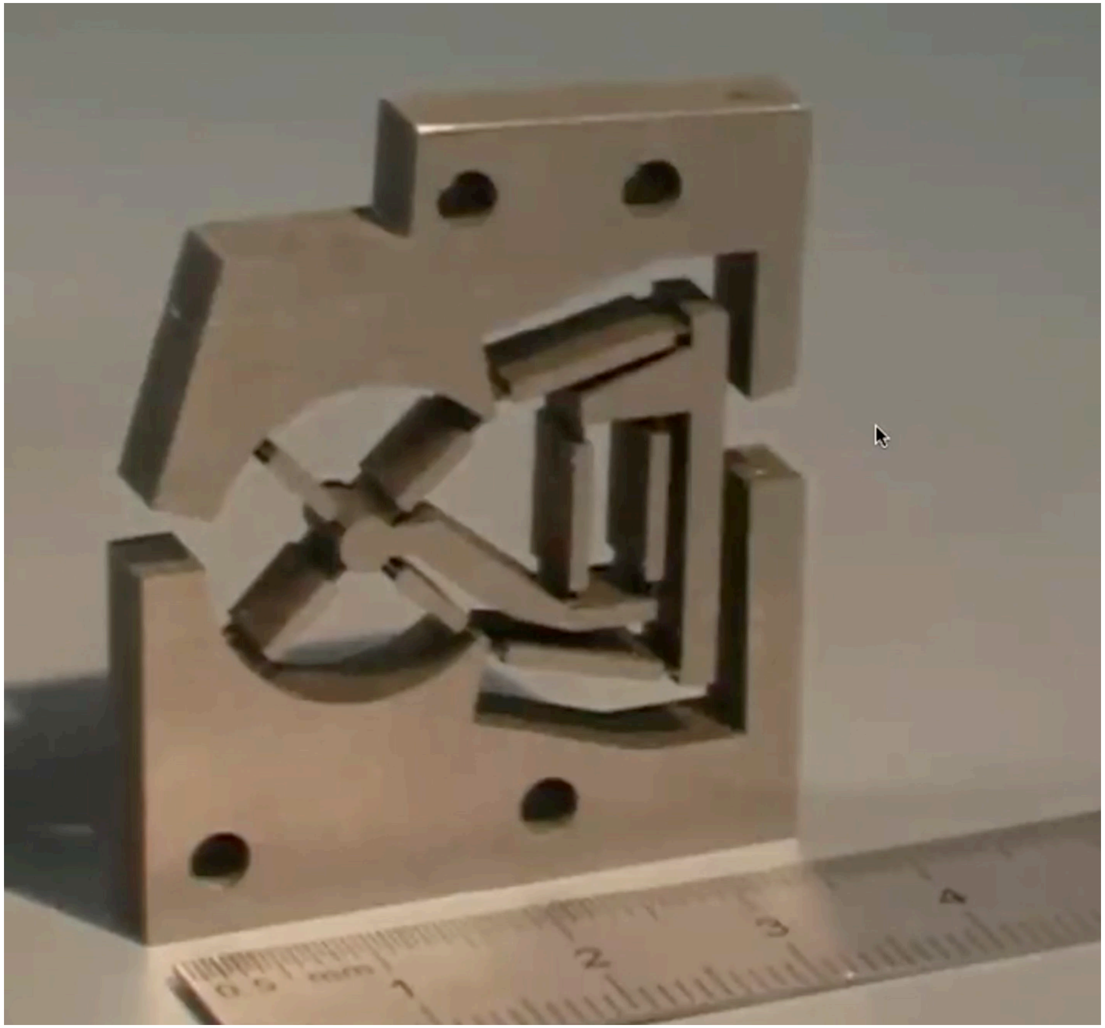
« Design for no assembly »





Monolithic flexure pivot

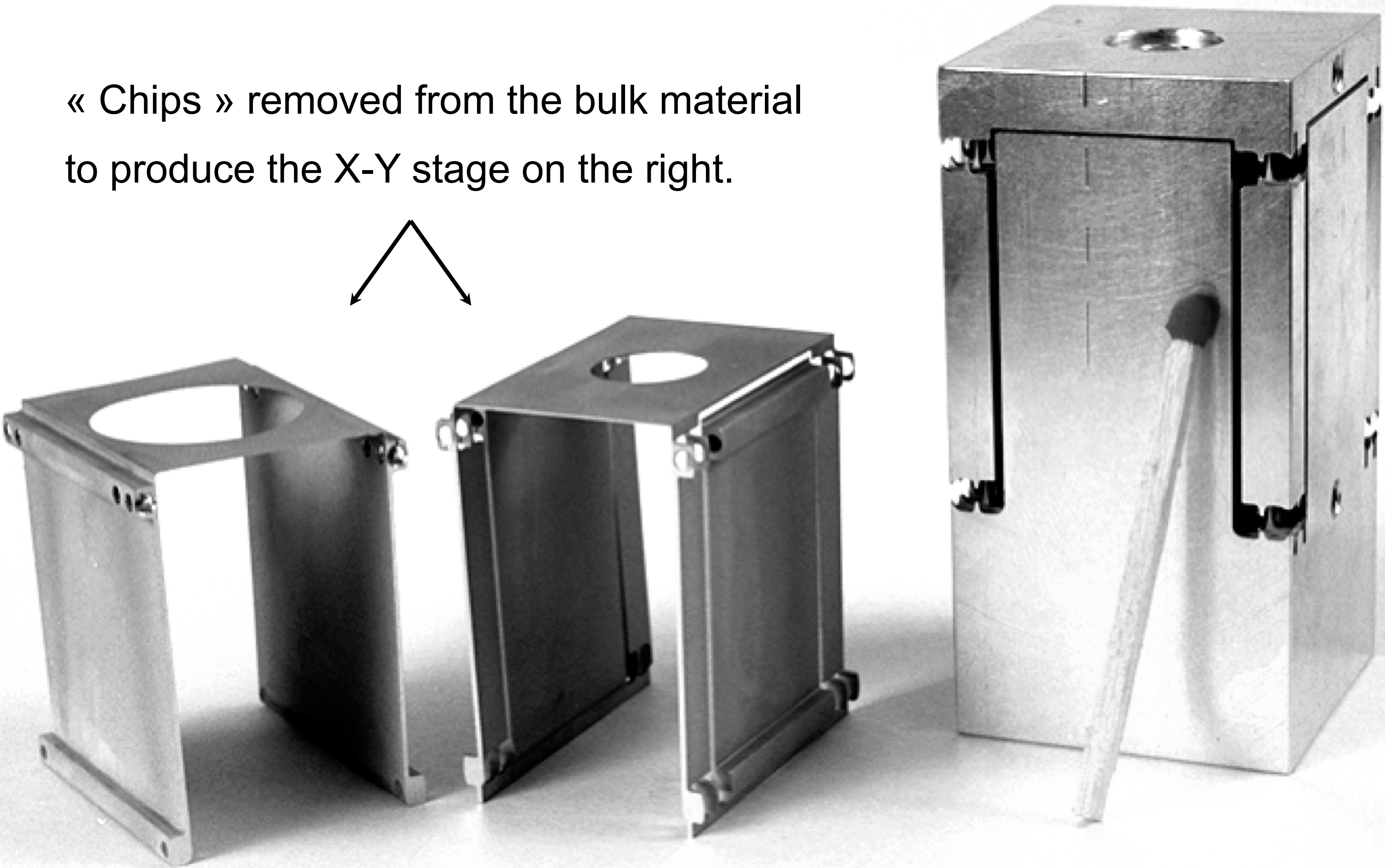
Serial notched RCC pivot with slaving mechanism



Monolithic manufacturing of complex structures

« Chips » removed from the bulk material

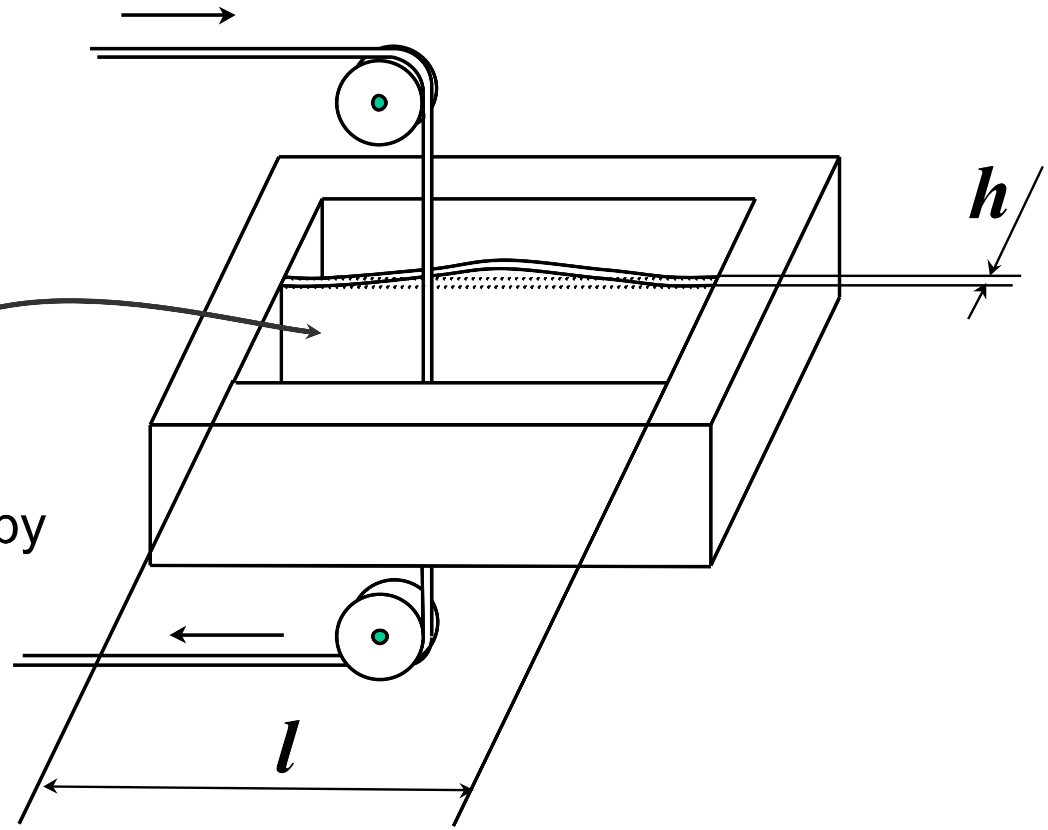
to produce the X-Y stage on the right.



Technological limitations of wire-EDM
Maximum aspect-ratio of blades

We have experimentally demonstrated that the aspect-ratio of blades machined by wire-EDM is limited to approximately 60

$$\frac{l}{h} \leq 60$$



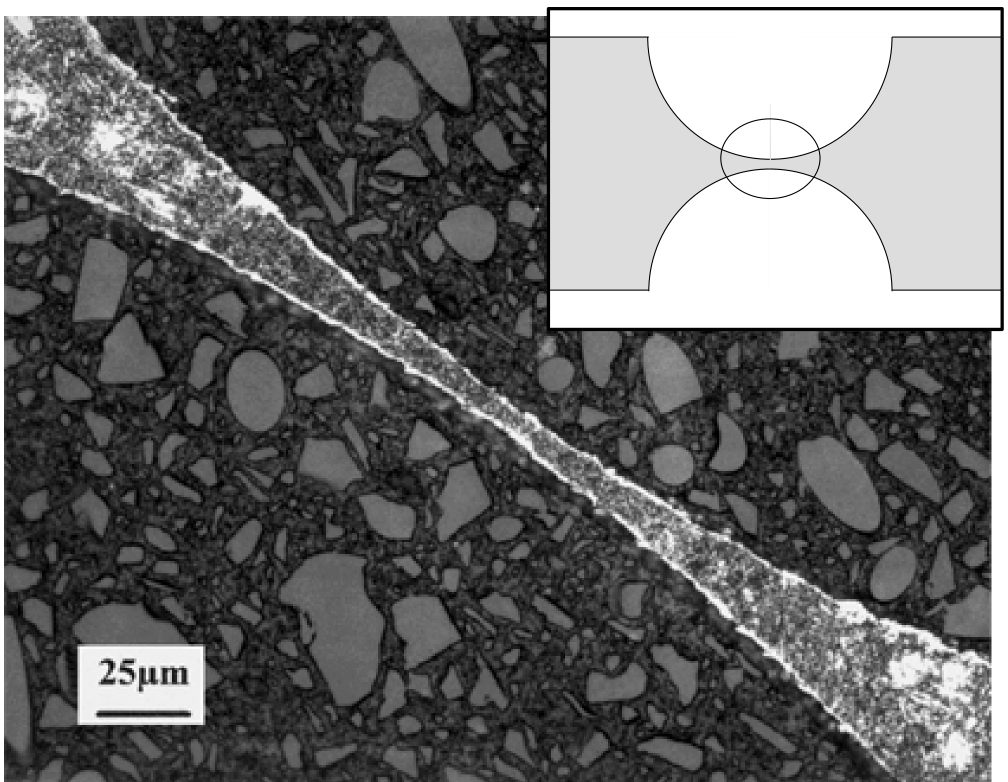
Vibrations of the blade induced by

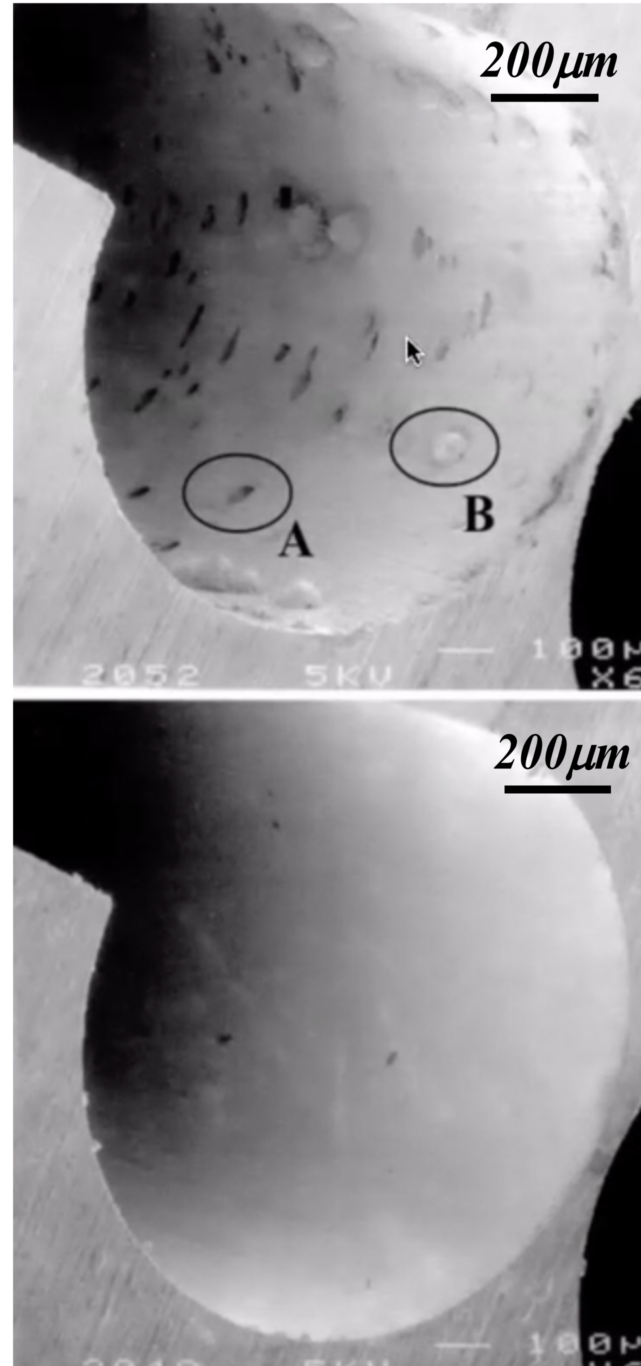
- jet of rinsing water
- electrical arcs and bursts
- electrostatic forces

Technological limitations of wire-EDM

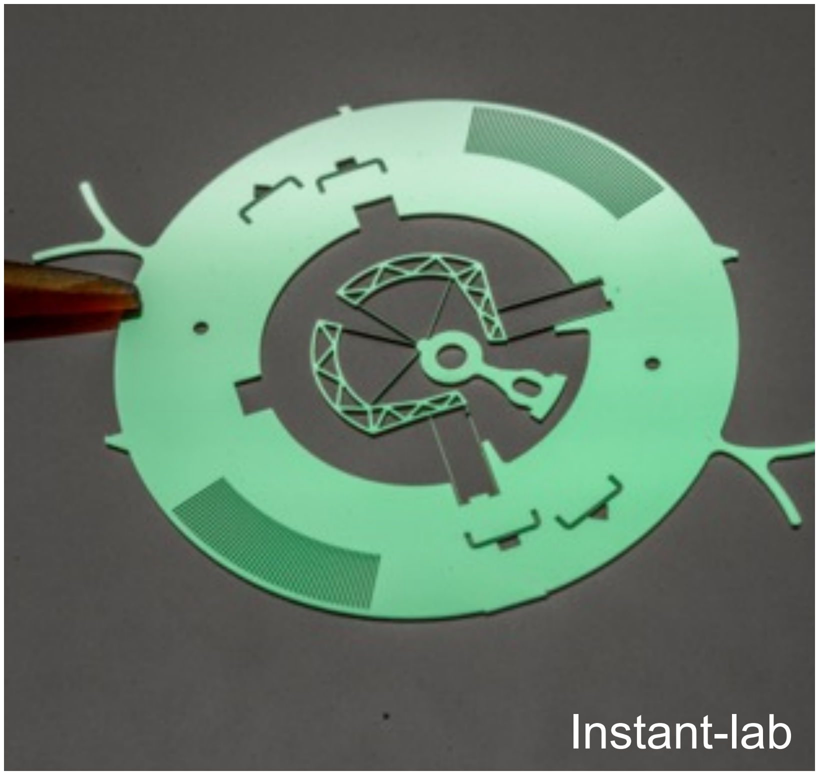
Minimum thickness: typically 30 um

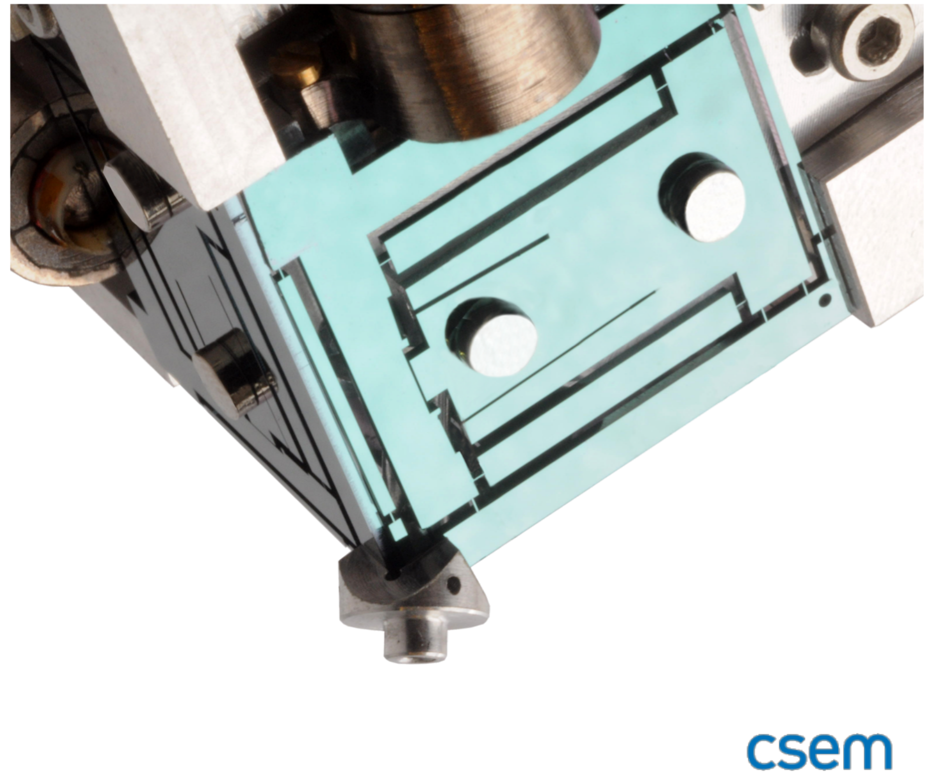
Best surface roughness: typically Ra 0.2 um





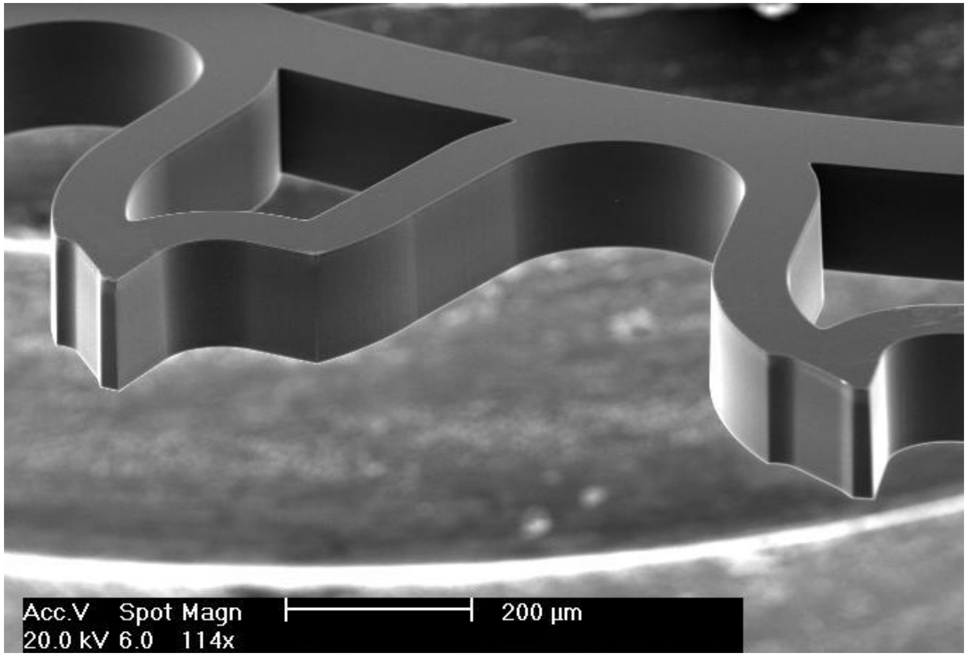
Flexures in Silicon



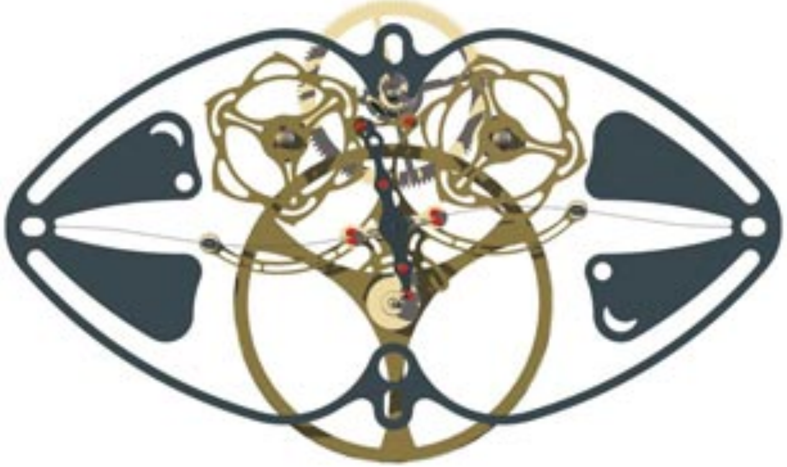


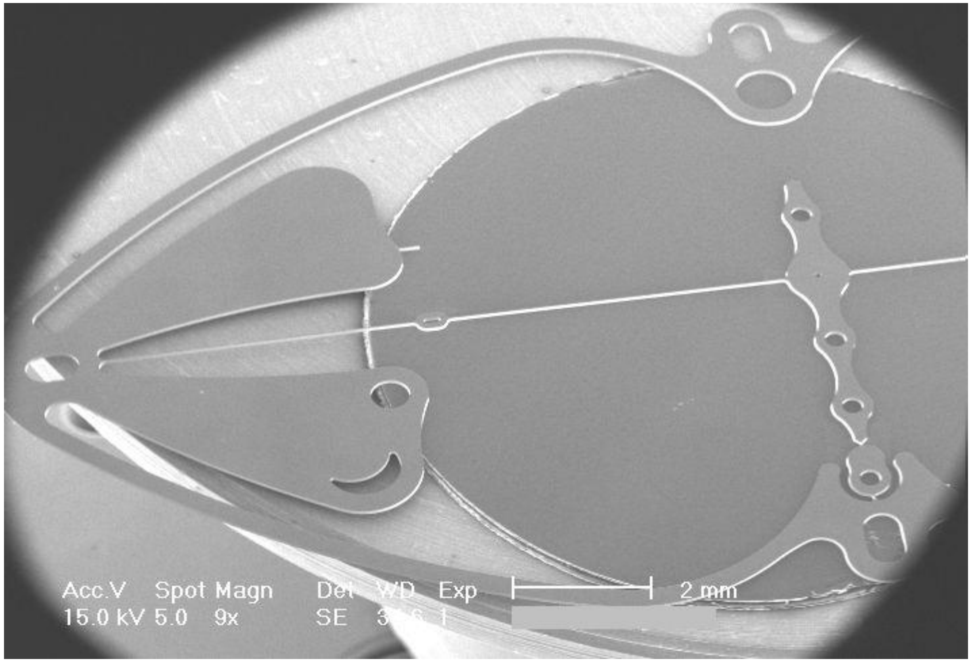
Silicon parts for watches

Escapment wheel (Ulysse Nardin)

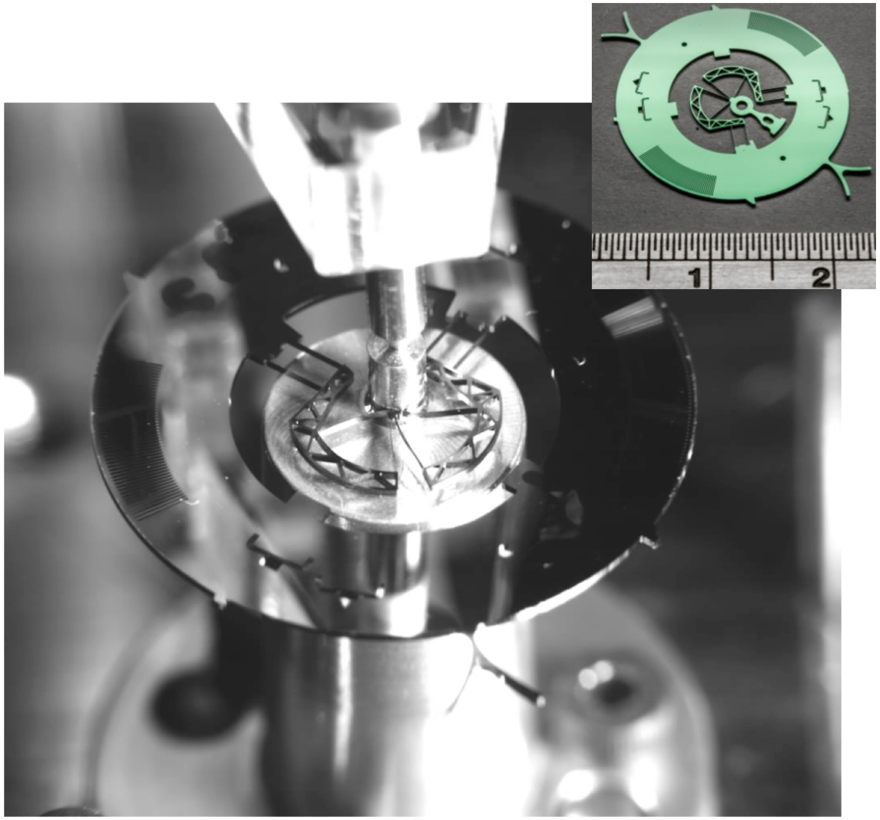


Constant force escapment
(Girard-Perregaux)





Silicon flexure oscillators for watches



1- DOF «co-RCC» flexure oscillator

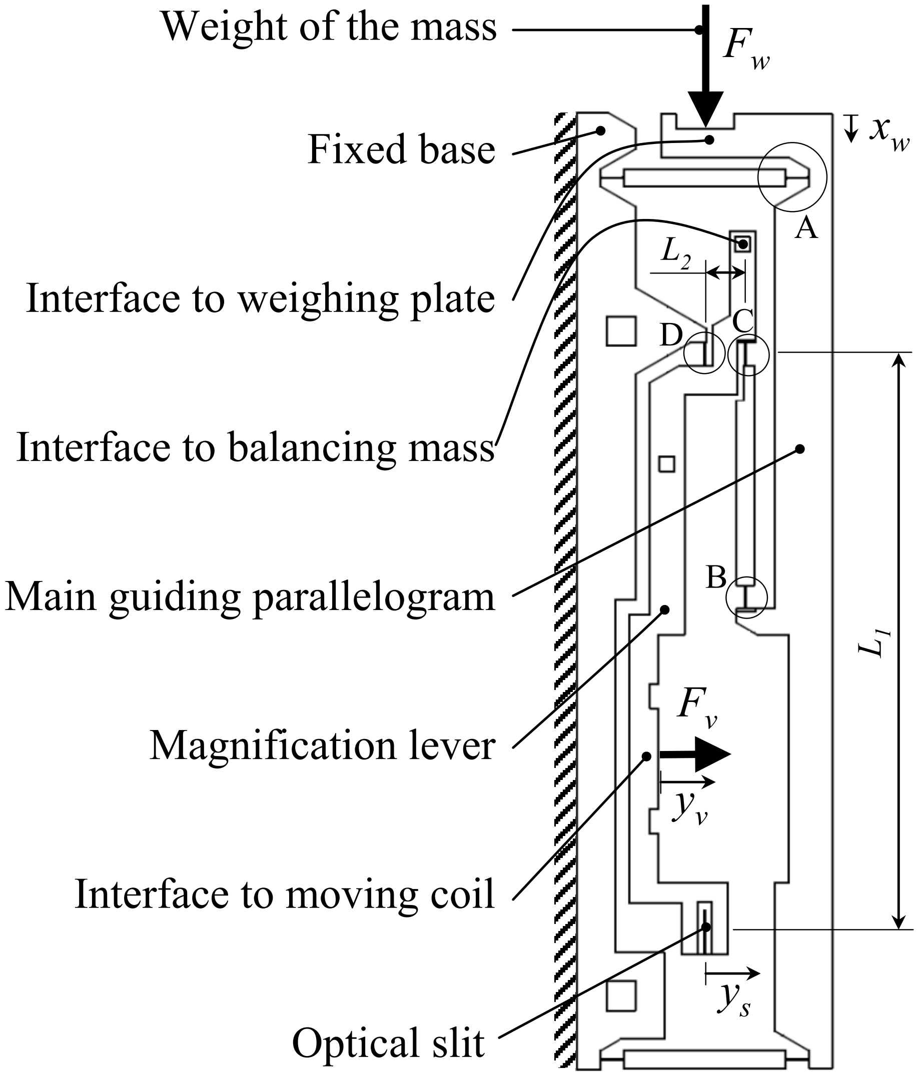
2- DOF «Wattwins» flexure oscillator

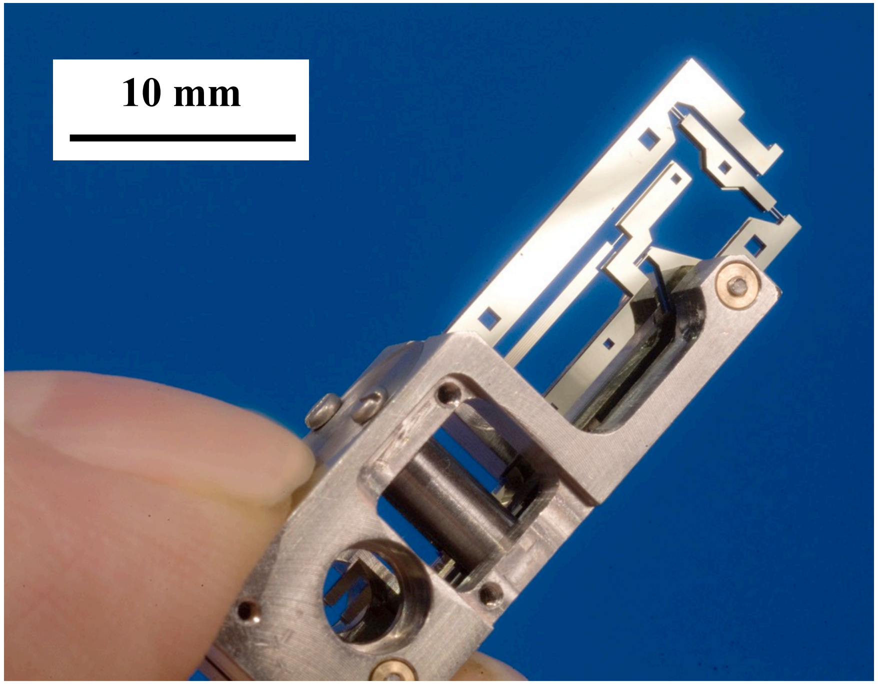
Thalmann, E. (2020). Flexure Pivot Oscillators for Mechanical Watches [EPFL]. https://doi.org/10.5075/epfl-thesis-8802

Schneegans, H., Thalmann, E., & Henein, S. (2021). Shaking force balancing of a 2-DOF isotropic horological oscillator. Precision Engineering, 72,

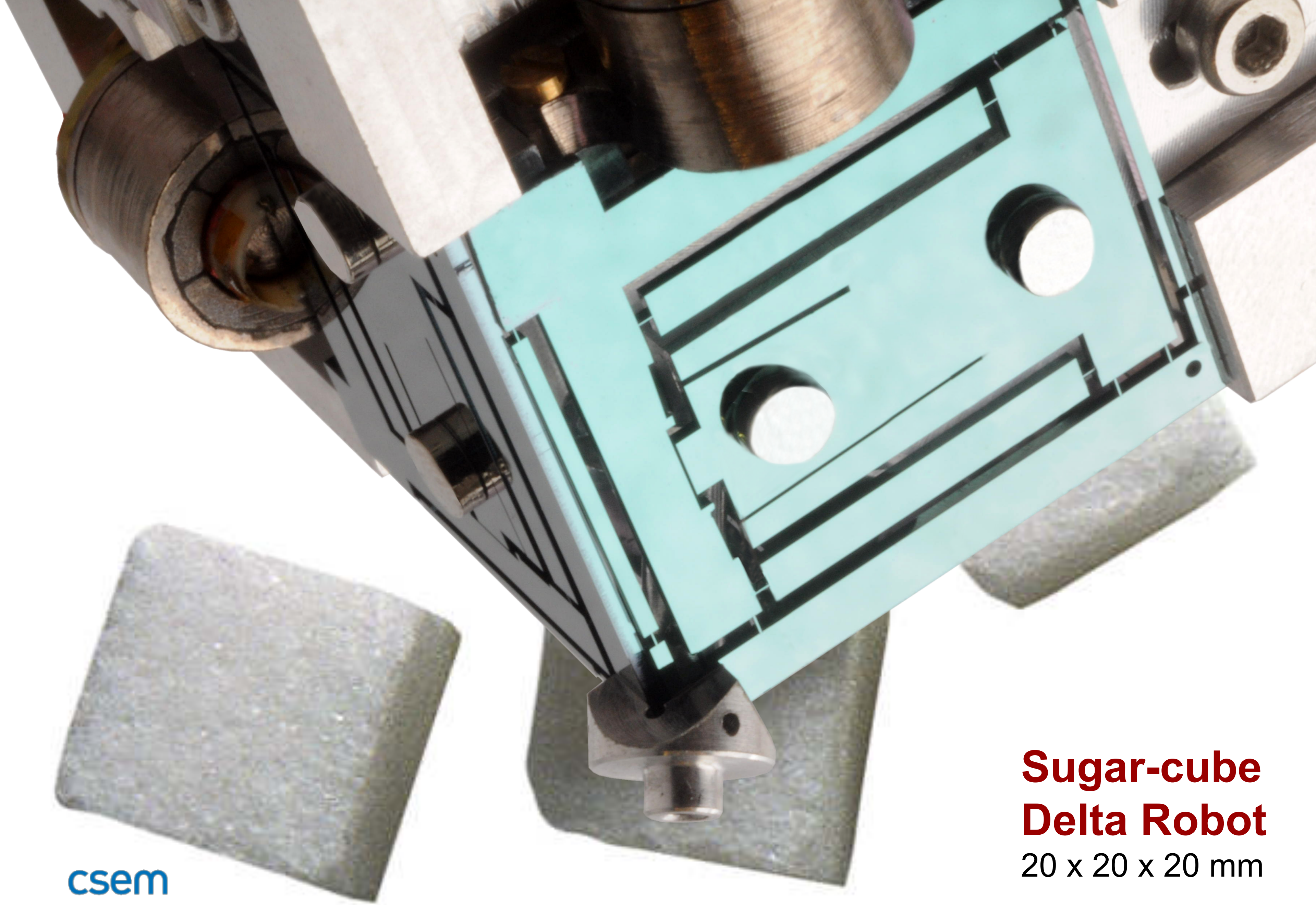
Silicon flexure-based micro-balance

Footprint 9 x 9 mm, suitable for batch weighing processes





S. Henein et al. , Silicon Flexure-Based Micro-Balance for Batch Weighing Processes, Proc. of the euspen Int. Conf., June 2009



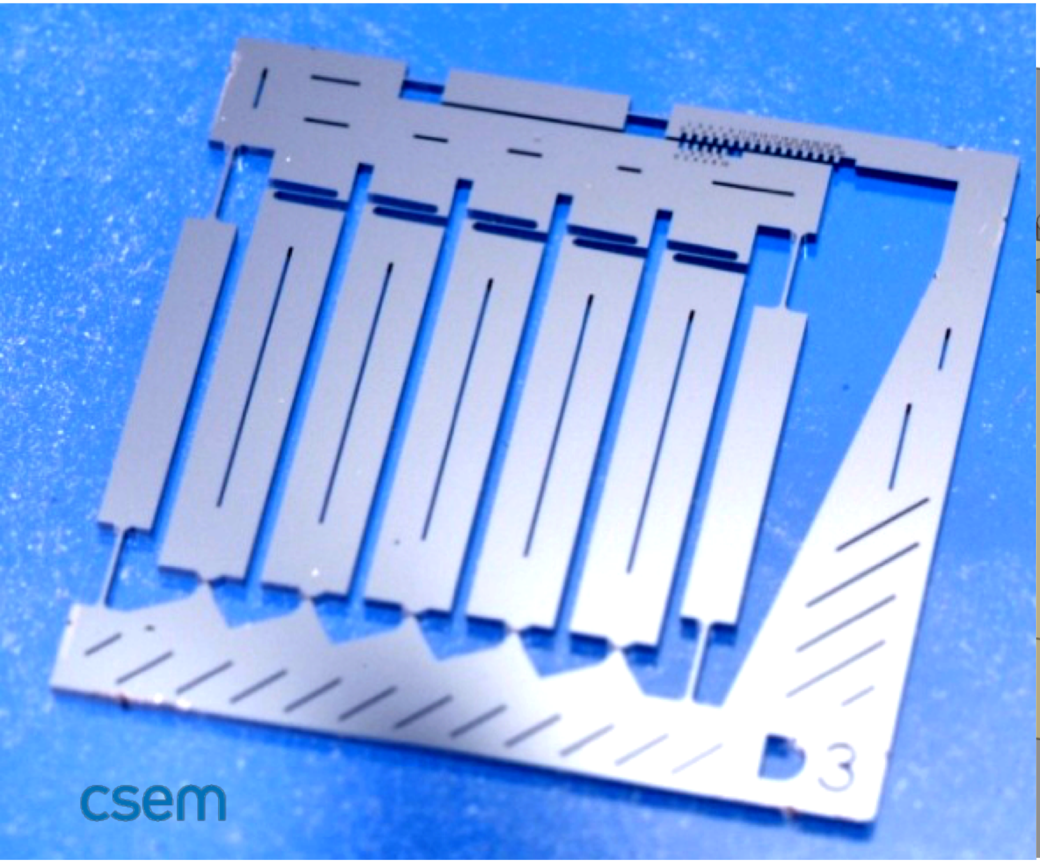
Sugar-cube Delta Robot

20 x 20 x 20 mm

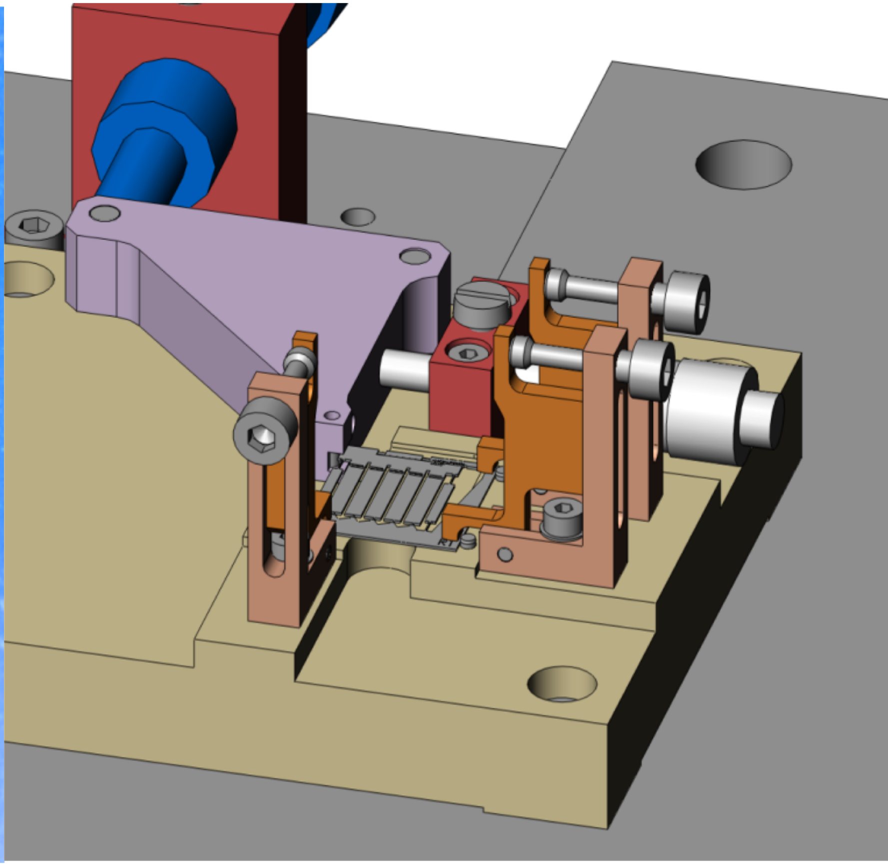
csem

S. Henein et al., Silicon Flexures for the Sugar-Cube Delta Robot, Proceedings of the 11th euspen International Conference, to be published in May 2011

Fatigue tests on silicon flexures



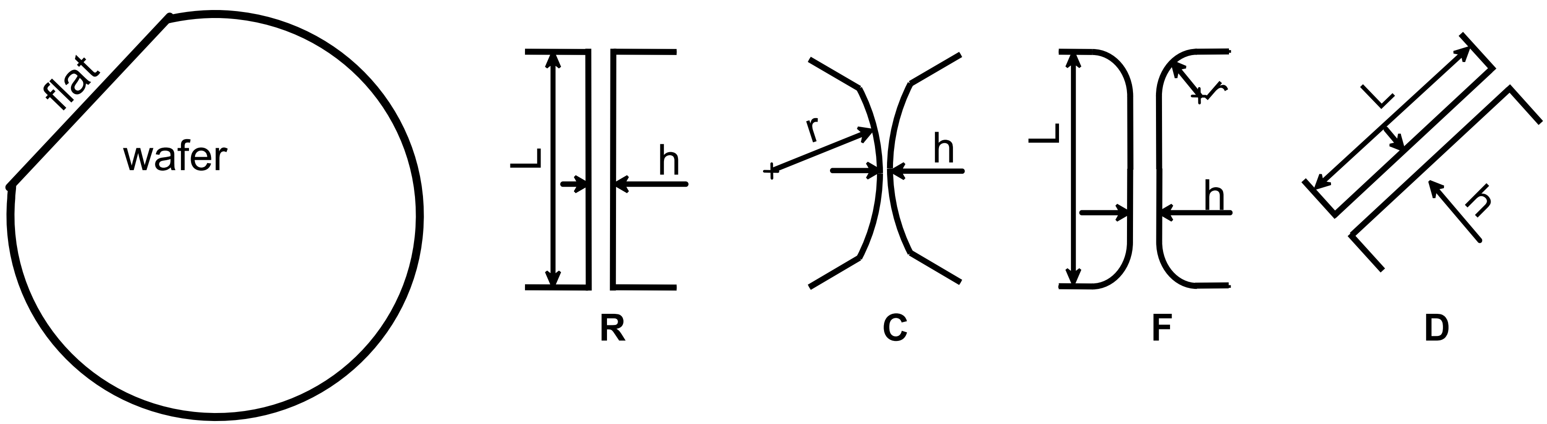
Test specimen



Test bench

S. Henein et al., Silicon Flexures for the Sugar-Cube Delta Robot, Proceedings of the 11th EUSPEN International Conference, to be published in May 2011

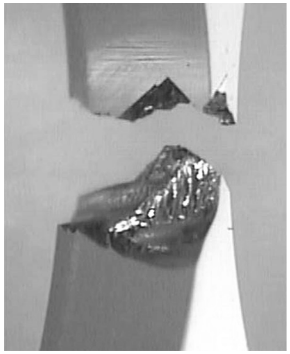
Tested hinge shapes and orientations

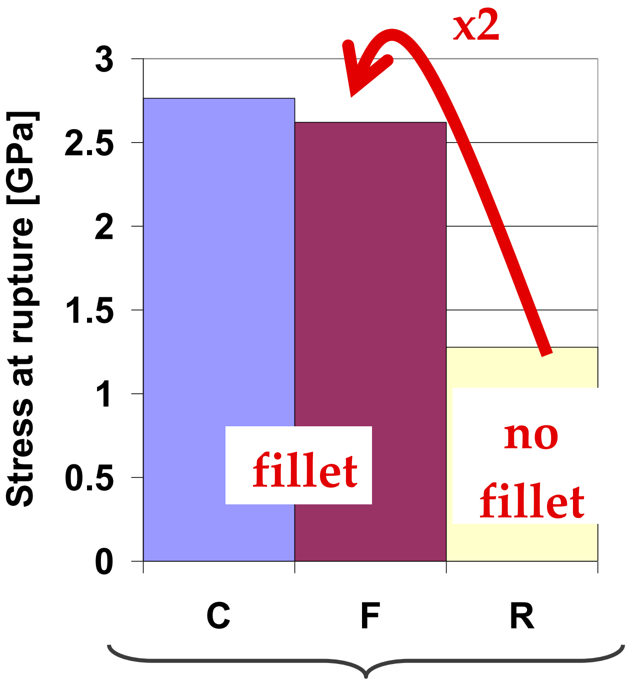


Orientation of tested hinges with respect to the wafer flat

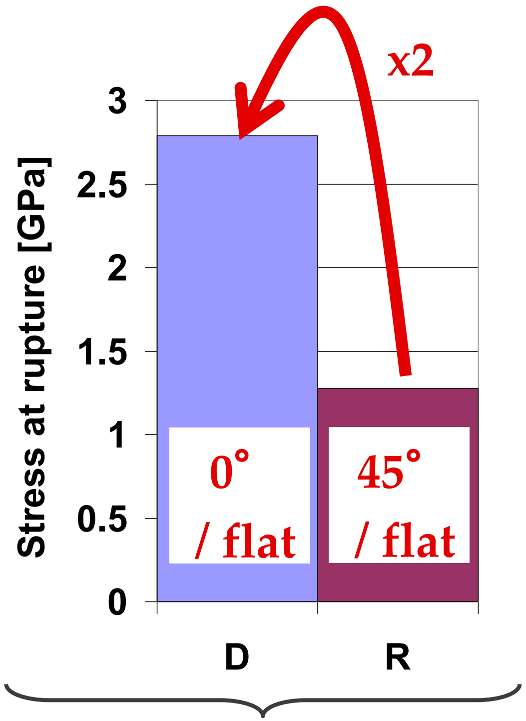
Shape	h [µm]	b [µm]	r [µm]	L [µm]	Number of hinges
C	20 to 100	250 and 350	230 to 1150	-	103
D	10 to 50	250 and 350	-	40 to 200	41
F	10 to 100	250 and 350	10 to 100	40 to 400	116
R	50 to 100	250 and 350	-	200 to 400	73

Synthetic Results of the Fracture Tests

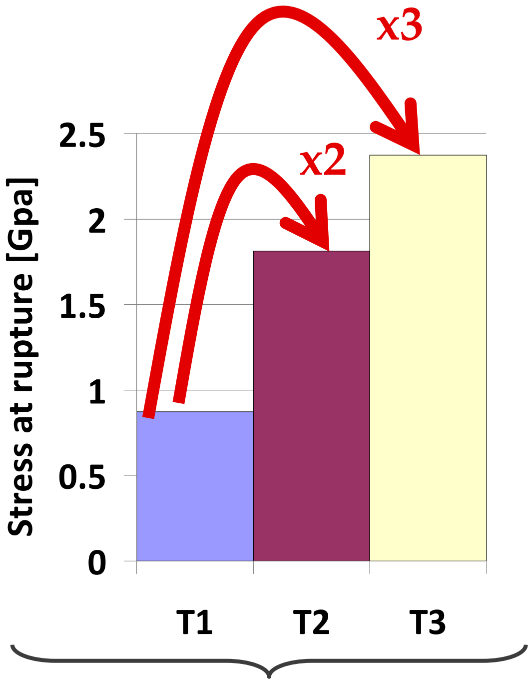




- same orientation w.r.t. the crystal lattice
- with or without fillet

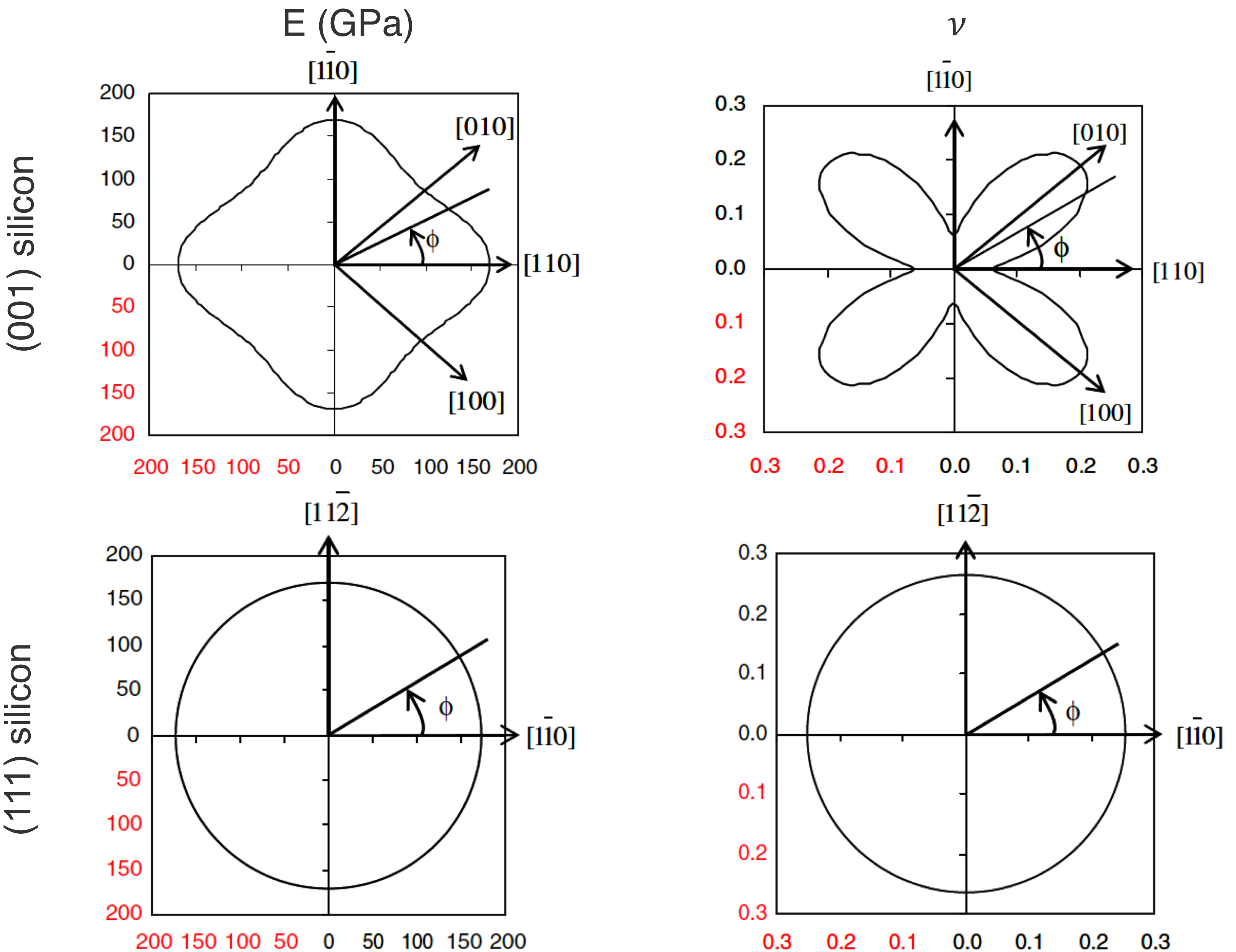


- same shape
- different orientations w.r.t. the crystal lattice



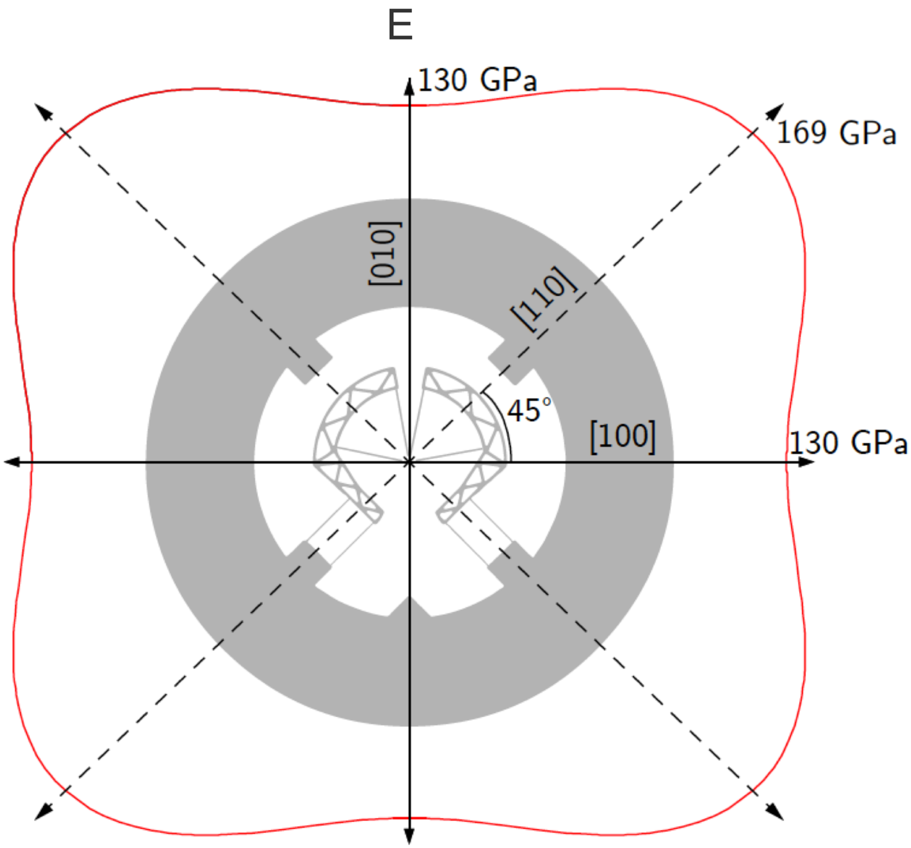
- different surface treatment

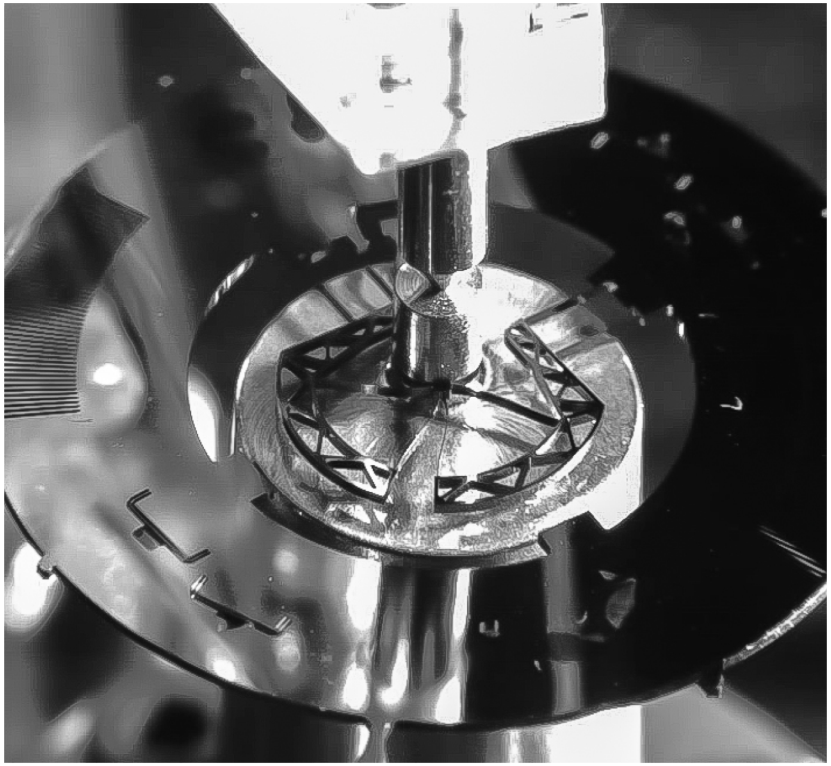
Anisotropy of silicon



Cho, C.-H. (2009). Characterization of Young's modulus of silicon versus temperature using a "beam deflection" method with a four-point bending fixture. *Current Applied Physics*, *9*(2)

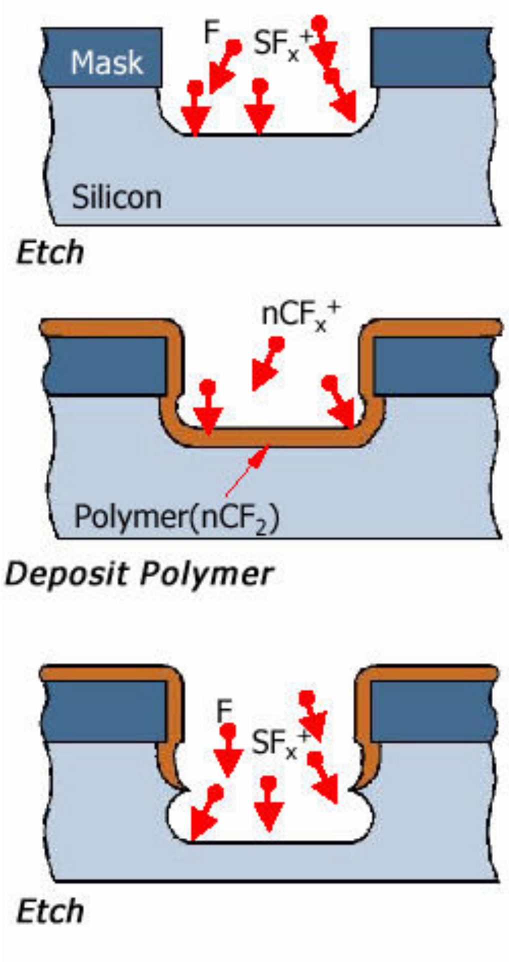
Taking anisotropy into account for design

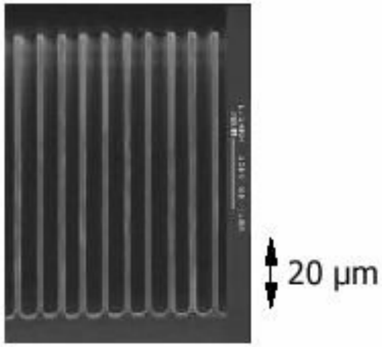




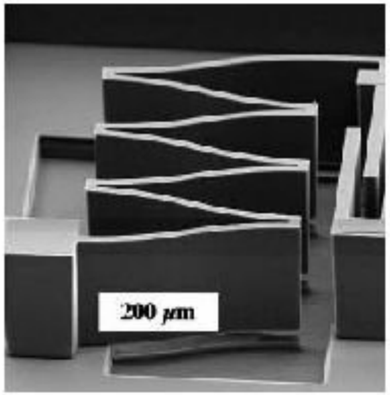
Thalmann, E. (2020). *Flexure Pivot Oscillators for Mechanical Watches* [EPFL Thesis].

DRIE





Trenches - *Surface Technology Systems*



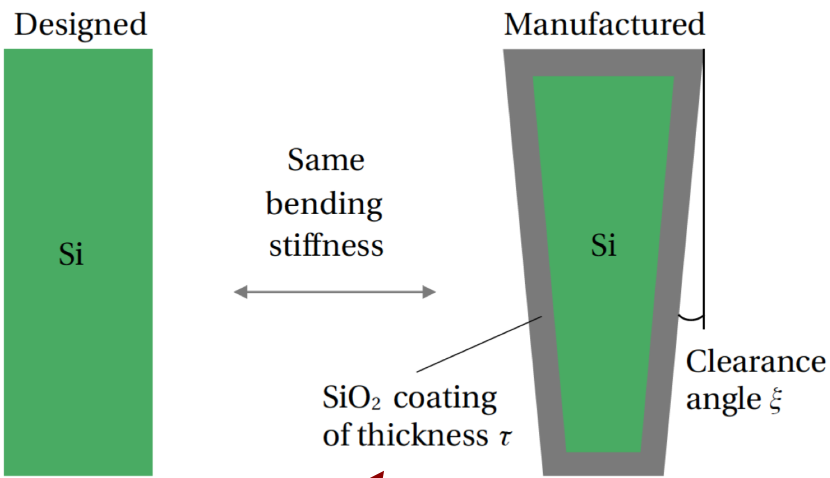
Spring - Klaassen, *et al*, 1995

- High aspect ratios (b/h and L/h)
- High precision
- Micro-scale
- Monolithic fabrication
- Batch manufacturing
- ⚠ Scalloping
- ⚠ Clearance angle

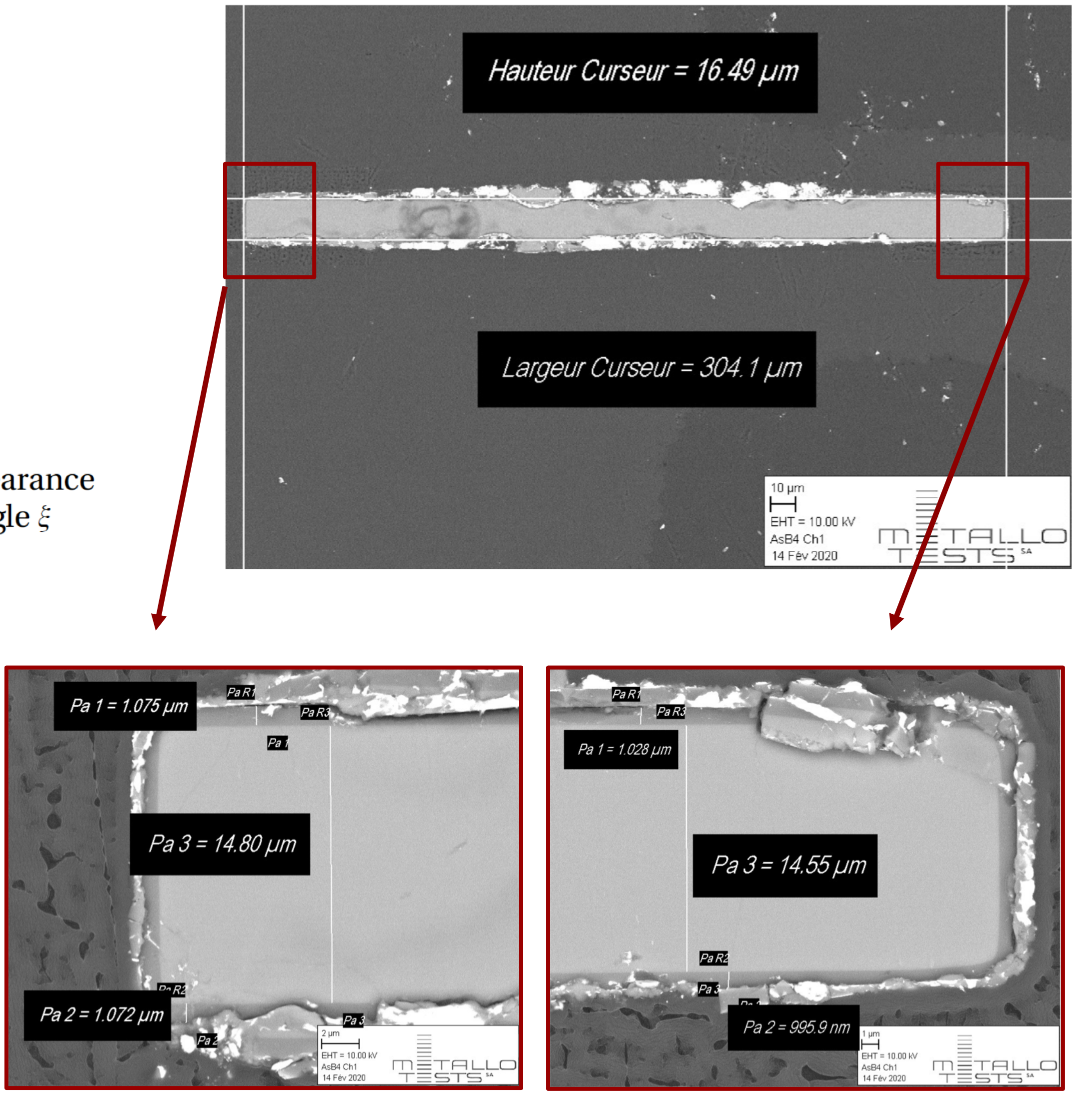
https://www.researchgate.net/figure/Deep-Reactive-Ion-Etching-Microfabrication-Process-2_fig2_242139877

Taking into account clearance angle and oxide layer

$$E_{\mathrm{Si}} I_{\mathrm{rect}} = E_{\mathrm{Si}} I_{\mathrm{Si}} + E_{\mathrm{ox}} I_{\mathrm{ox}}$$



Thermal compensation



Thalmann, E. (2020). *Flexure Pivot Oscillators for Mechanical Watches* [EPFL Thesis].

Musy, J.-P., Maier, F., & Krüttli, A. (2008). *Echappement et spiral réalisés en Silinvar®.* Journée d'Etude de la SSC 2008.

Mechanical properties of silicon

Comparison with steel

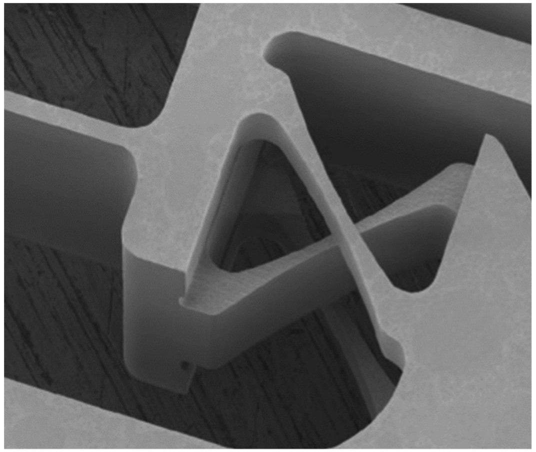
	Si	Steel	Units
Thermal expansion coefficient	**2.6**	12.0	10^{-6} /K
Density	**2.33**	8	g/cm^3
Young's Modulus (E)	**170***	210	GPa
Poisson coefficient	**0.42***	0.30	
Shear coefficient	**67***	80	GPa
Micro-hardness	**~1200***	300-1000	kg/mm^2
Maximal stress	**1000-2500***	500-2000	MPa

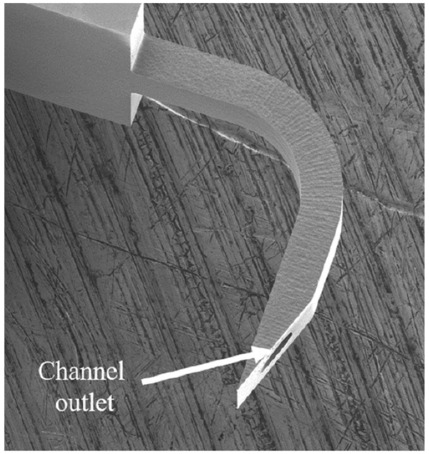
*** values depending on the crystalline orientation**

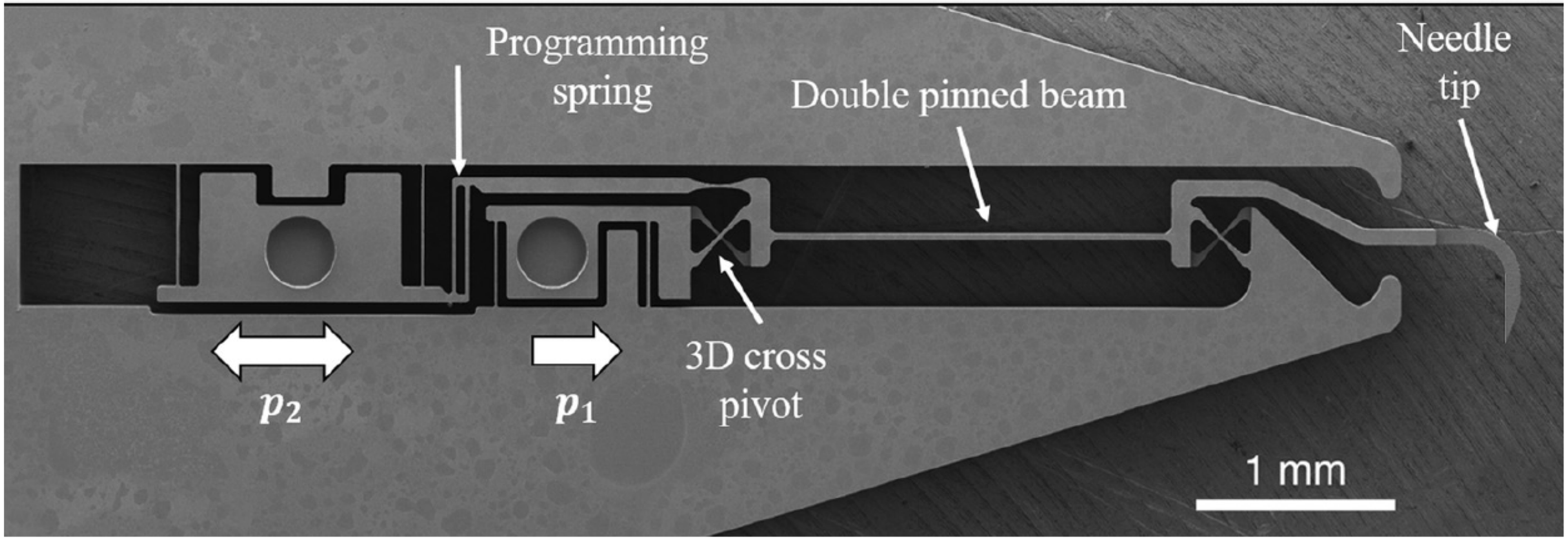
Flexures in glass
Femto-laser etching

Min flexure thickness $\approx 20\ \mu m$

Tolerance on thickness: $\pm 2\mu m$





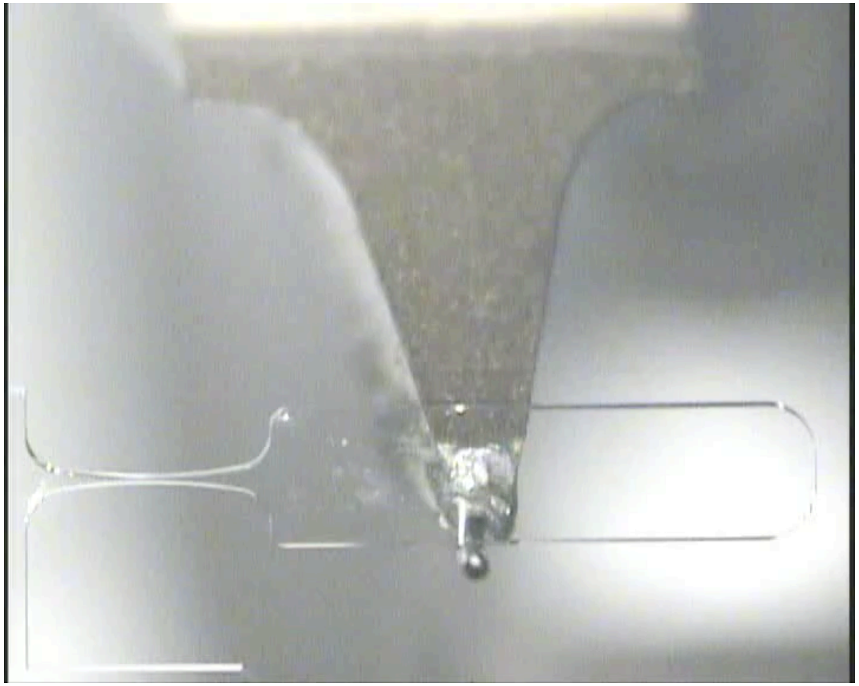


Zanaty, M., Fussinger, T., Rogg, A., Lovera, A., Lambelet, D., Vardi, I., Wolfensberger, T. J., Baur, C., & Henein, S. (2019). Programmable Multistable Mechanisms for Safe Surgical Puncturing. Journal of Medical Devices, 13(2), 021002.

Material properties

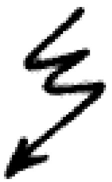
Fused silica

- $E = 74\,Gpa$
- $\sigma_{adm} \approx 1\,GPa$
- $\nu = 0.17$
- $\rho = 2200\,kg/m^3$



Bellouard, Y. (2011). On the bending strength of fused silica flexures fabricated by ultrafast lasers. *Optical Materials Express*, *1*(5)

Technological aspects : summary



- Wire-EDM
  - Maximum aspect-ratio ≈ 60
  - Effect of roughness on fatigue and stiffness

- Silicon : “Macro-MEMS” (2D-2.5D)

- Glass : Promising new material (3D structures).