Plastic deformation and rupture of silicate glasses

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A CRITICAL review of present theories of glass fracture reveals that the understanding of the fracture process is still incomplete.

E. Shand, J. Am. Ceram. Soc. 1961

Mechanical properties of amorphous materials

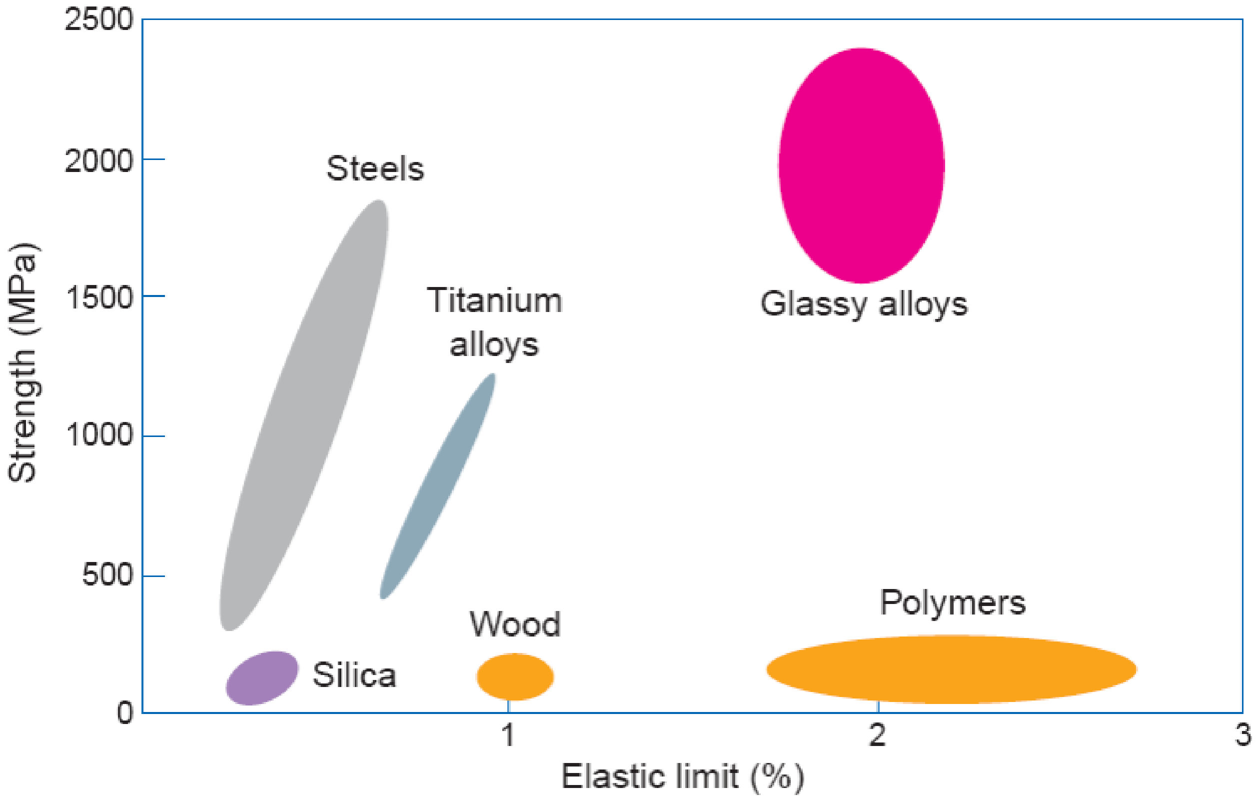

Fig. 3 Amorphous metallic alloys combine higher strength than crystalline metal alloys with the elasticity of polymers.

Telford, Materials Today, March 2004

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Silica glass: a brittle material ?

Intrinsic strength

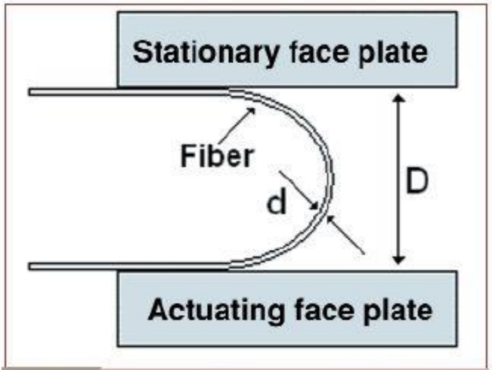
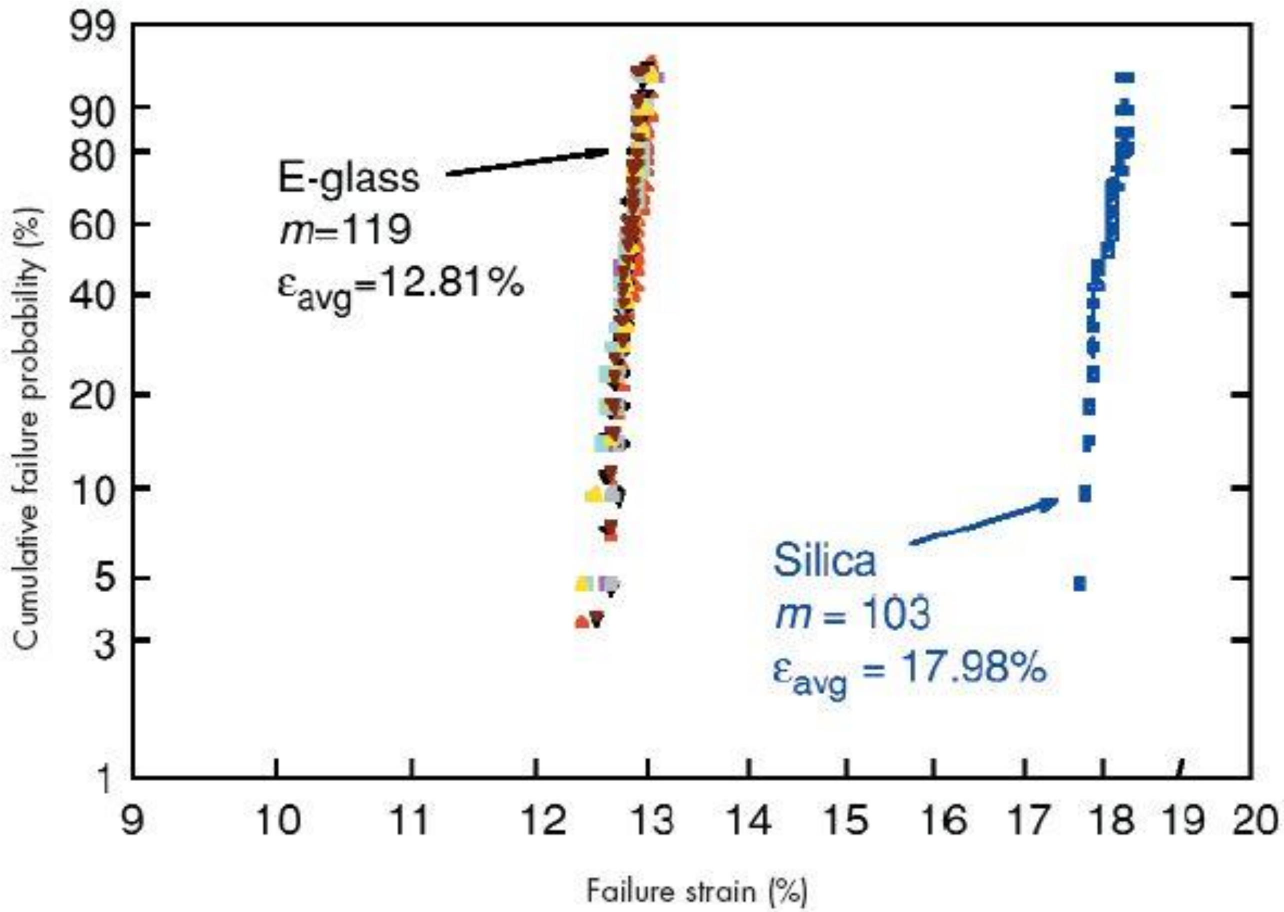


Figure 1 Experimental geometry for the TPB test.



C. Kurkjian Am. Ceram. Soc. Bull. 84 (2005)

Rupture Strain

Silica and borosilicate glass

tensile strength of silica at room temperature is 6.5 GPa

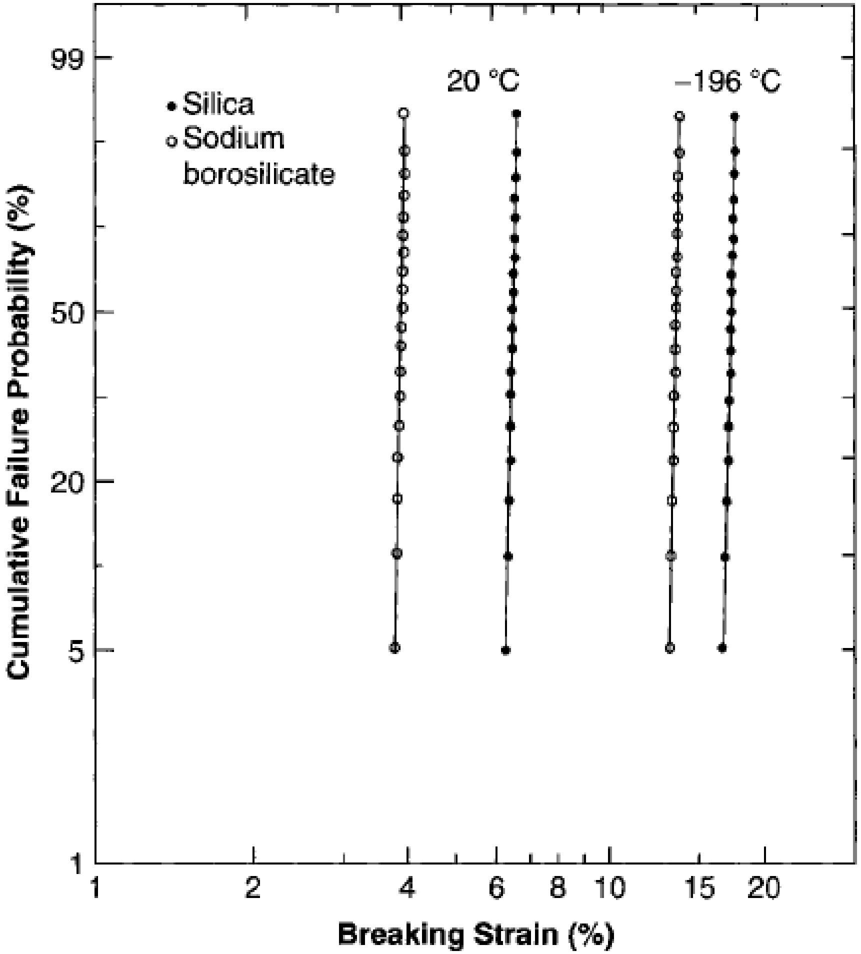
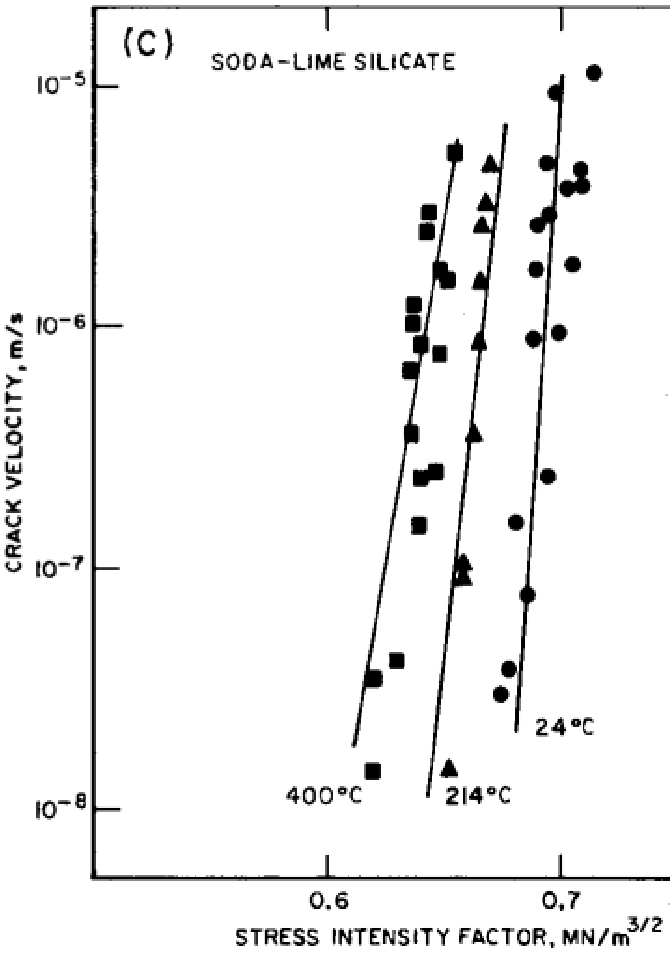
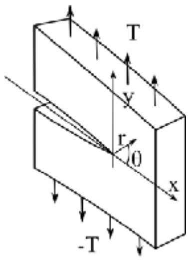


Figure 24.3 Failure strain (measured in two-point bend) of silica (●) and sodium borosilicate (○) glass fibers in liquid nitrogen and at room temperature (used, with permission, from reference [9]).

[9] Duncan, W. J. et al. 1984. The effect of environment on the strength of optical fiber. In: *Strength of Inorganic Glasses* (C. R. Kurkjian, ed.), pp. 309–328. Plenum Press, New York.

Fracture energy of amorphous silicates

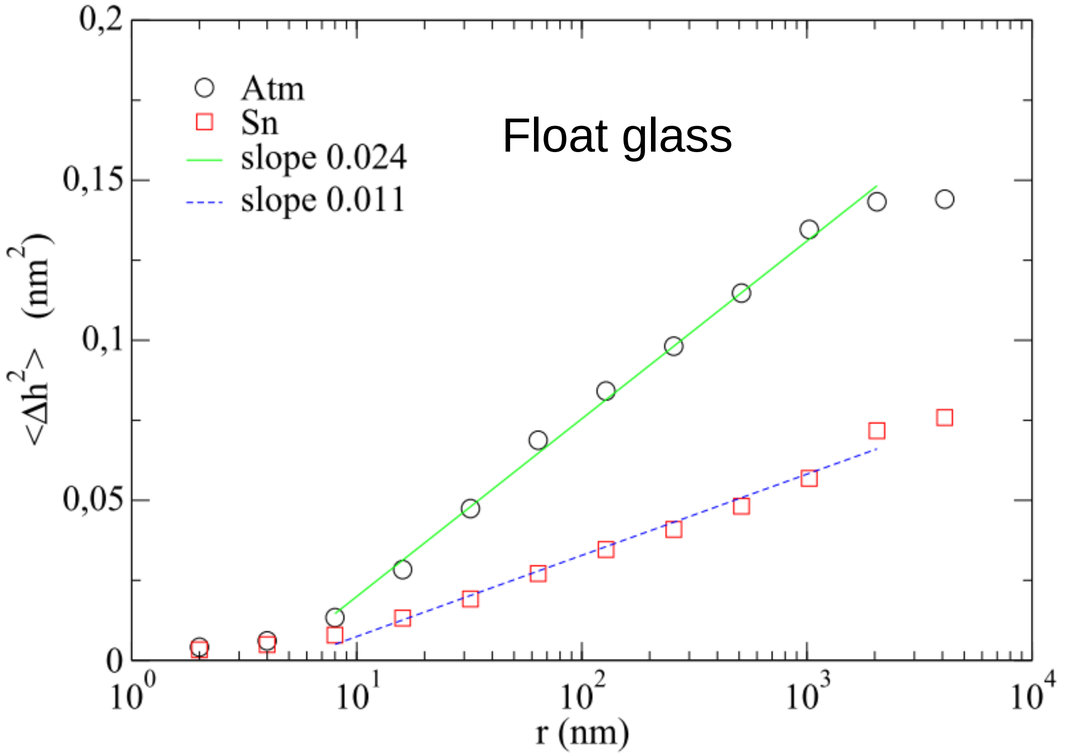


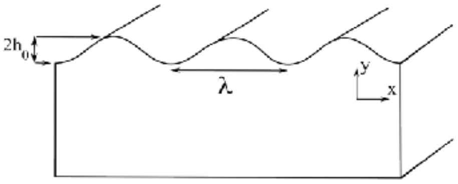


ca. 5 J/m²

Widerhorn & al. 1974

Fracture energy – surface energy





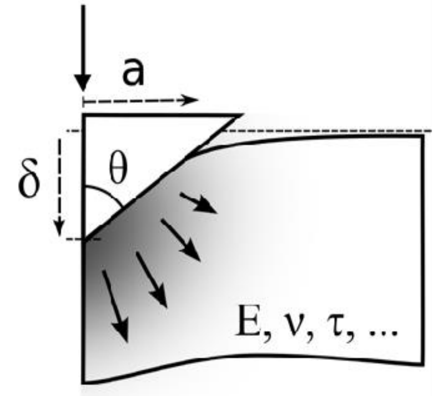
surface energy : *ca.* 0.5 J/m^2

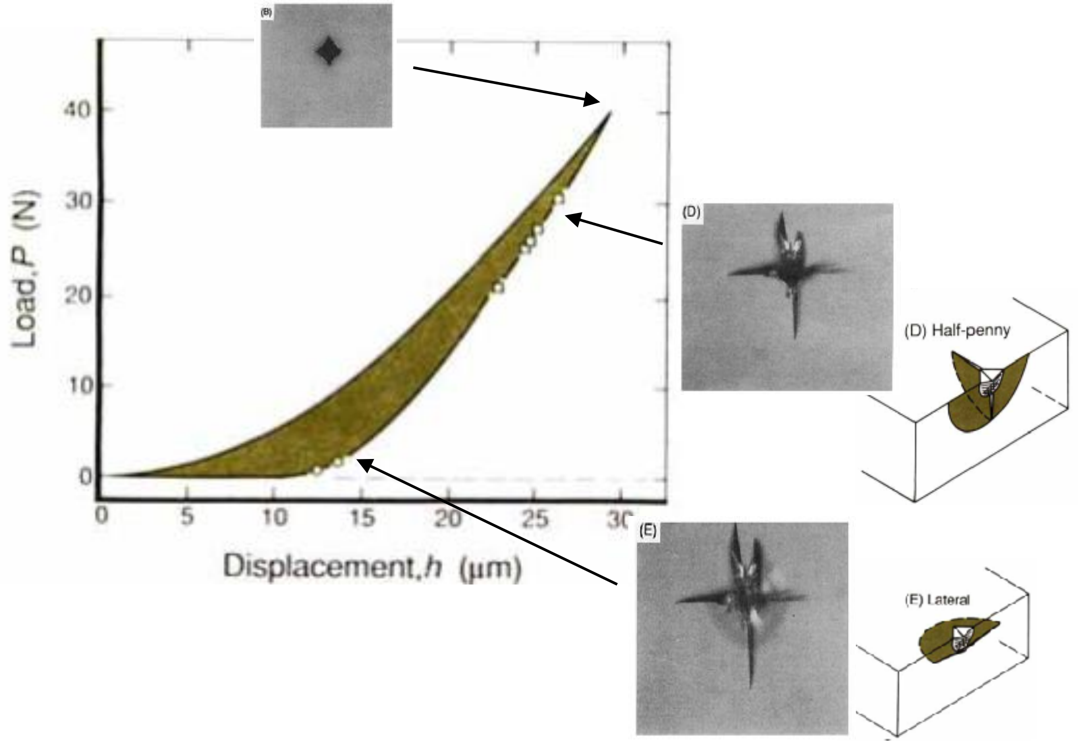
Sarlat et al. European Physical Journal B 54 (11/2006) 121-126

Fracture energy >> surface energy -> brittle ?

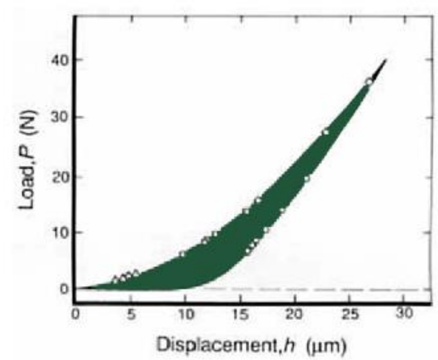
E. Shand, J. Am. Ceram. Soc. 1961, D. Marsh, Proc. Roy. Soc. A 1964,
S. Wiederhorn, J. Am. Ceram. Soc. 1969,…

Cracking sequence - soda-lime silicate





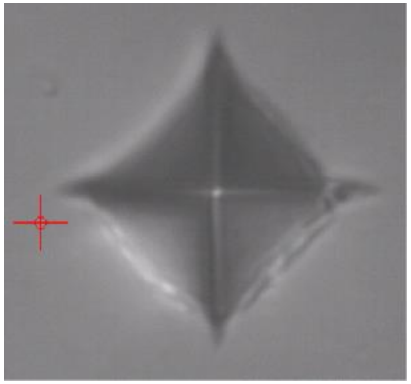
Cook and Pharr J. Am. Ceram. Soc. 1990



amorphous silica

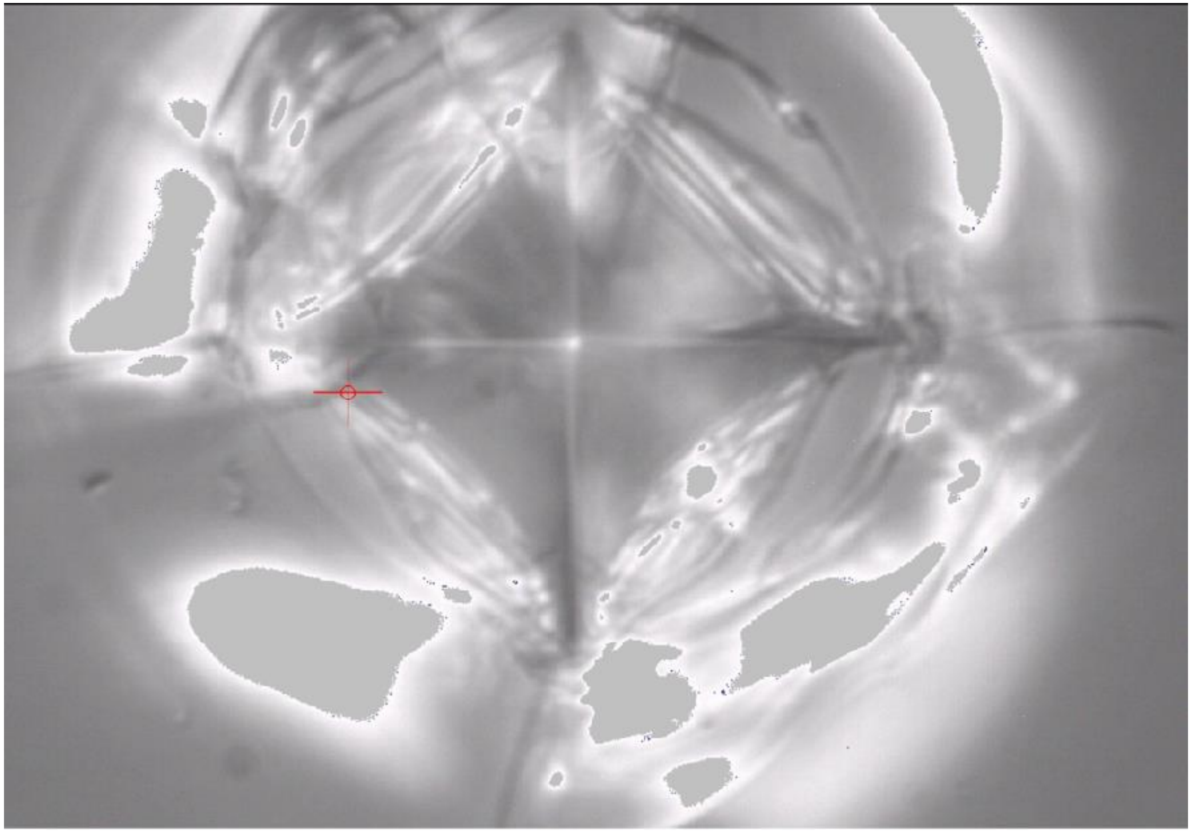
Brittle – ductile transition: lengthscales

20 µm



200 g

20 µm



500 g

silica

w: cohesion energy

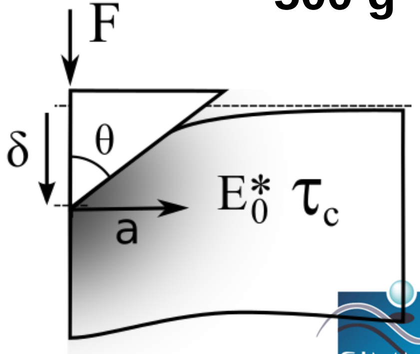
a: spatial extension

σ_y: yield stress

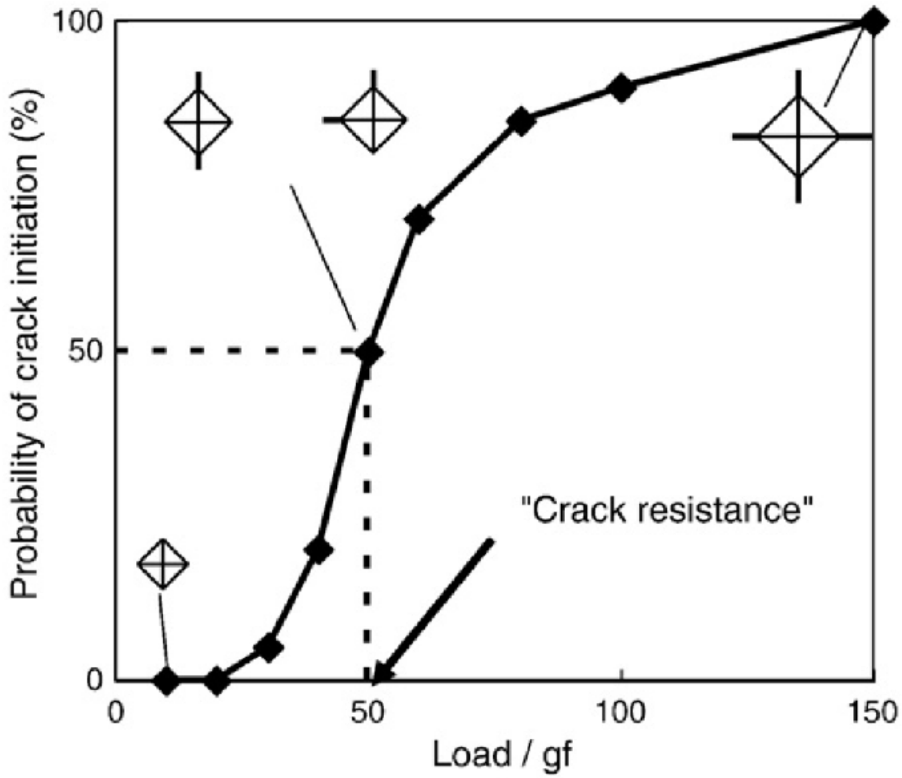
E: elastic modulus

$$wa^2 = a^3 \frac{\sigma_y{}^2}{E}$$

(scaling)



Crack resistance - definition



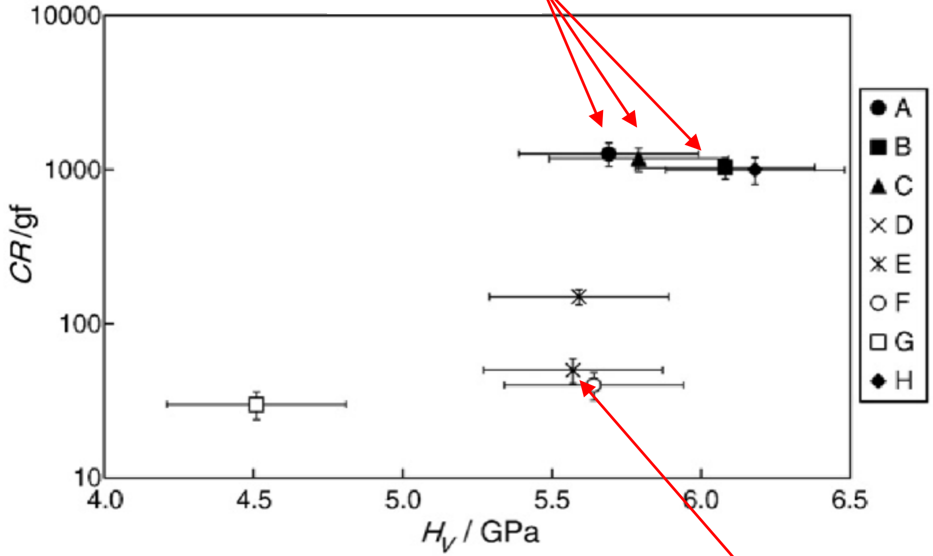
2010 Kato JNCS

There is a size effect ???

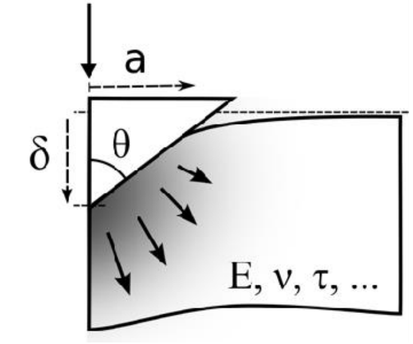
Indentation cracking vs glass properties

Crack resistance

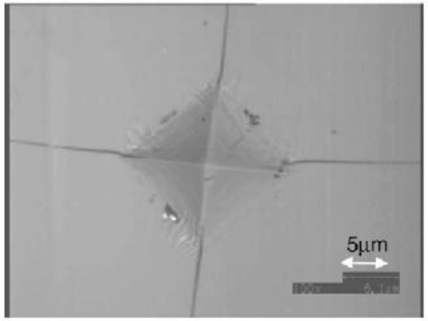
borosilicates



soda lime silicate



Crack resistance



	E (Gpa)	K_c (MPa $m^{0.5}$)
borosilicate A	64	0.73
soda lime silicate	72	0.75

The mechanical properties of silicate glasses are *all very similar except for indentation cracking -> ???*

Kato et al. JNCS 2010

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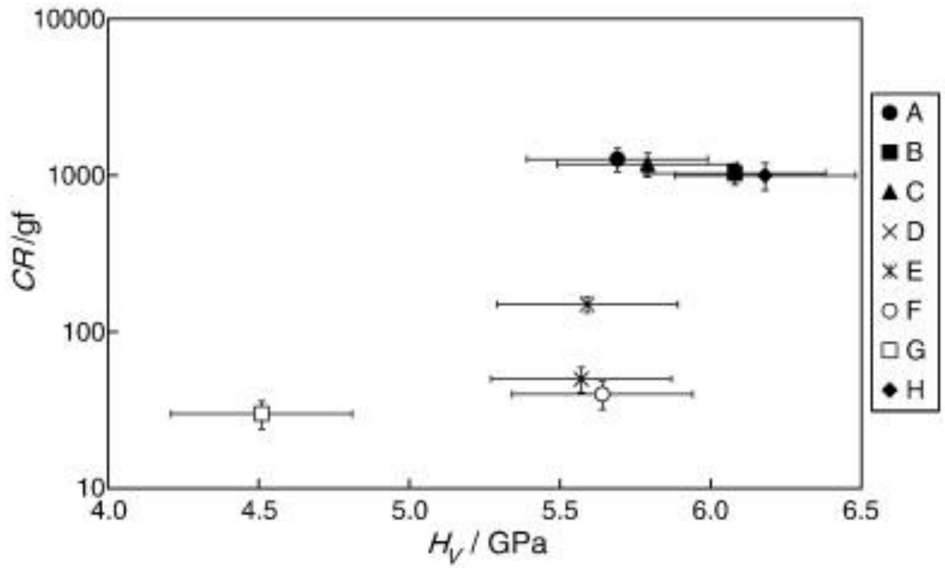
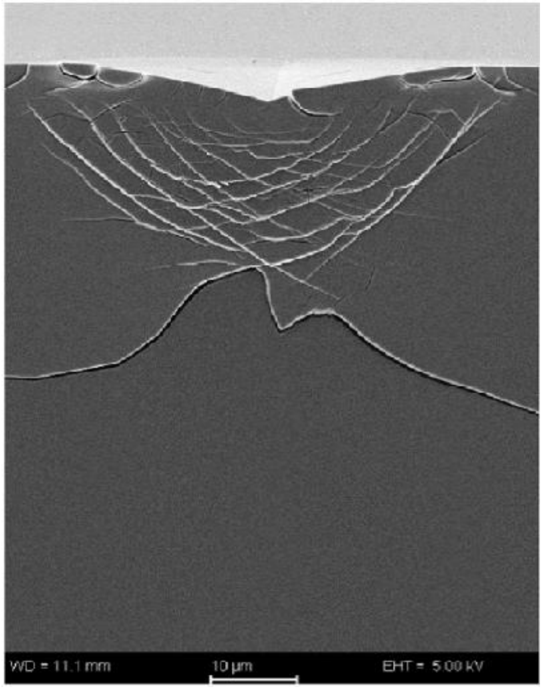
Crack resistance



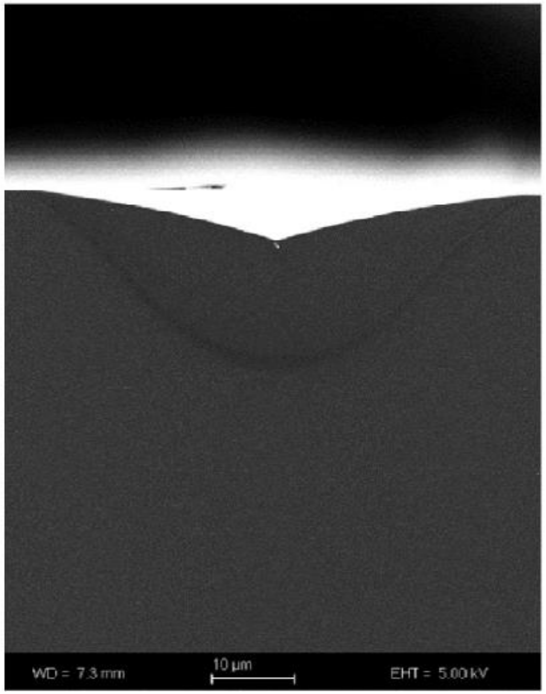
Name	General composition (mol%)	ρ (g/cm^3)	T_g (°C)	K_{IC} (MPa·m$^{1/2}$)	E (GPa)	K (GPa)
A	$70SiO_2 - 20B_2O_3 - 5K_2O$	2.28	500	0.73	64	40
B	$75SiO_2 - 10B_2O_3 - 5Na_2O$	2.36	570	0.76	71	37
C	$70SiO_2 - 10Al_2O_3 - 10B_2O_3$	2.48	710	0.79	70	40
D	$70SiO_2 - 10Na_2O - 10CaO$	2.49	540	0.75	72	47
E	$70SiO_2 - 10Na_2O - 5SrO$	2.76	520	0.71	68	40
F	$70SiO_2 - 5SrO - 5K_2O$	2.81	630	0.73	77	43
G	$60SiO_2 - 25PbO - 5B_2O_3$	4.44	470	0.66	63	44
H	$70SiO_2 - 15Al_2O_3 - 10Li_2O$	2.43	710	0.84	81	39

2010 Kato JNCS

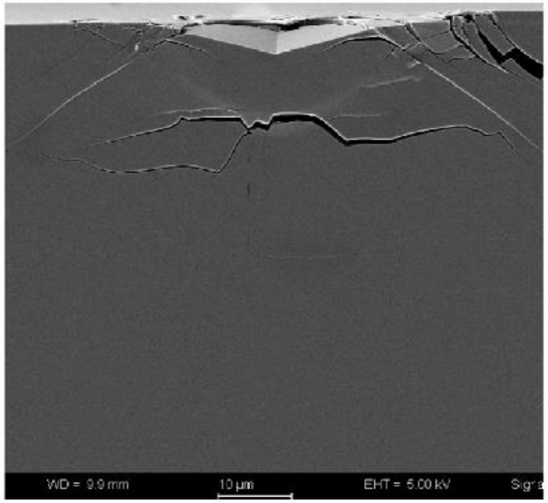
Verres normaux



Soda lime silicate



Calcium alumino
boro silicate



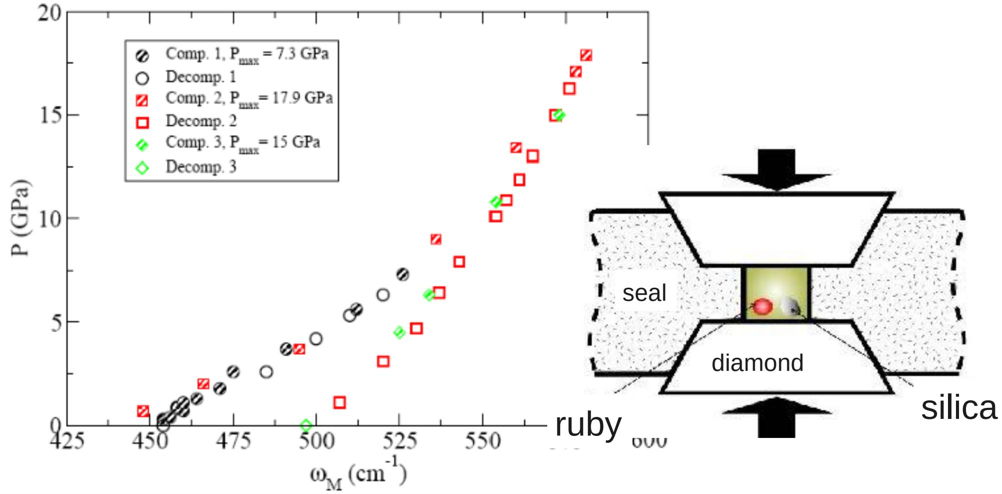
Amorphous silica

Gross et al. JNCS 2018

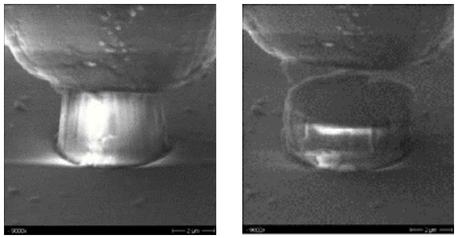
1 kgf Vickers

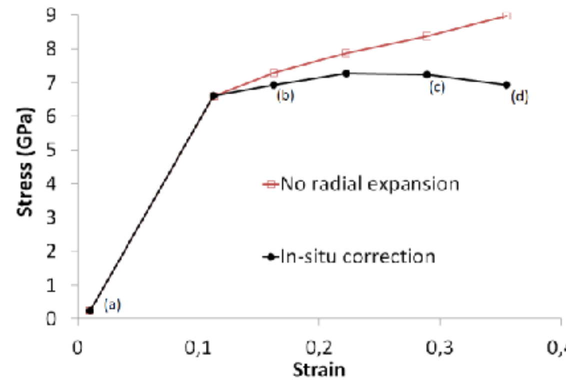
Ductile fragile transition when how why?

Silicate glasses - micromechanics

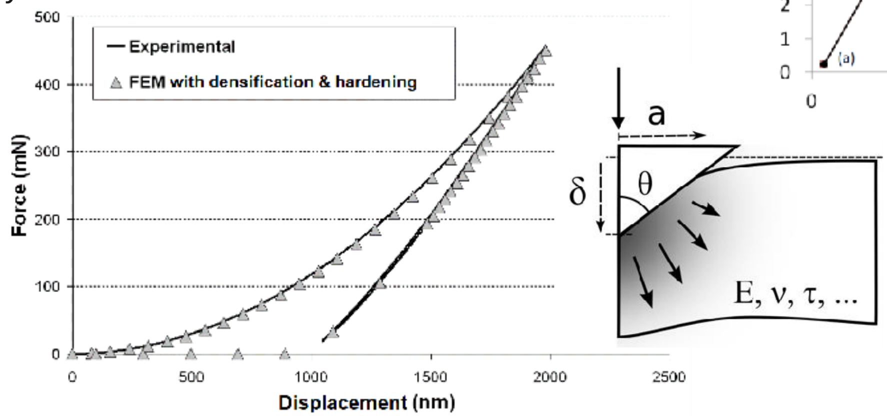


T. Deschamps et al. J. Phys.: Cond. Mat. 2012





Kermouche et al. Acta Mater. 2016



G. Kermouche et al. Acta Materialia 56 (2008) 3222

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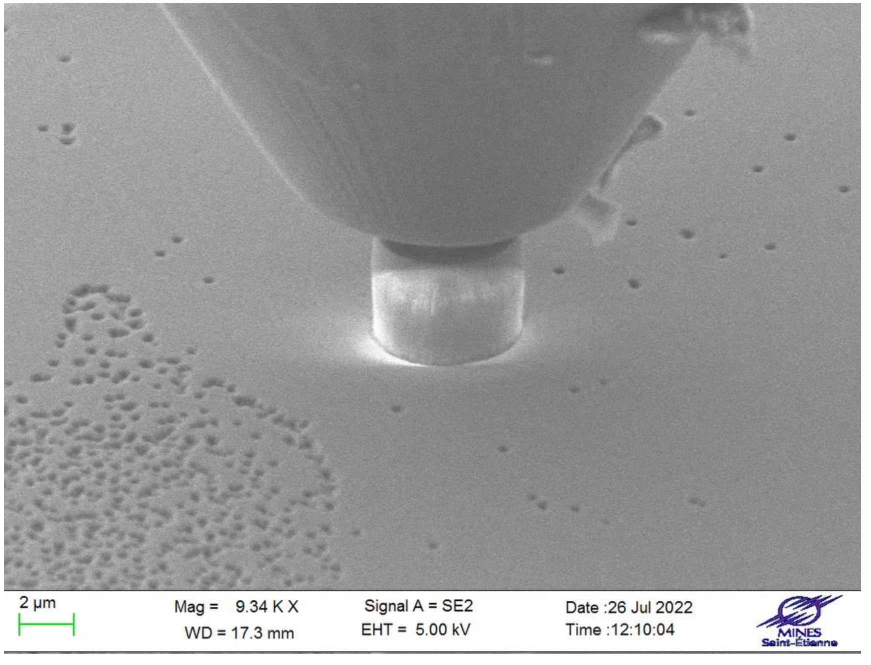
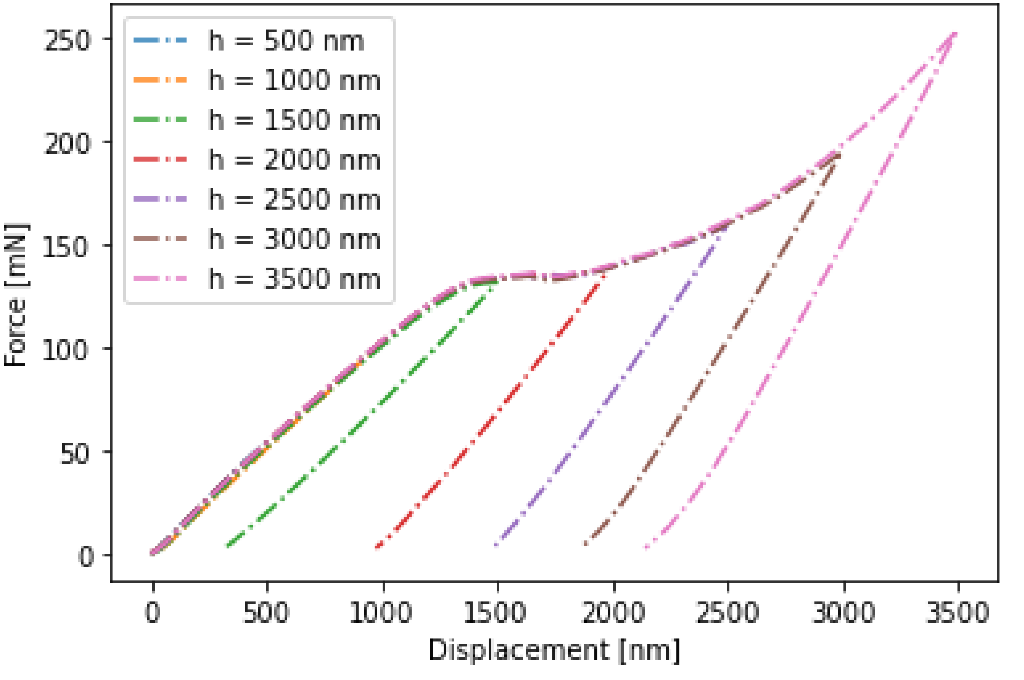
Straining pillars up to different levels

- Micro-compression of a row of silica pillars



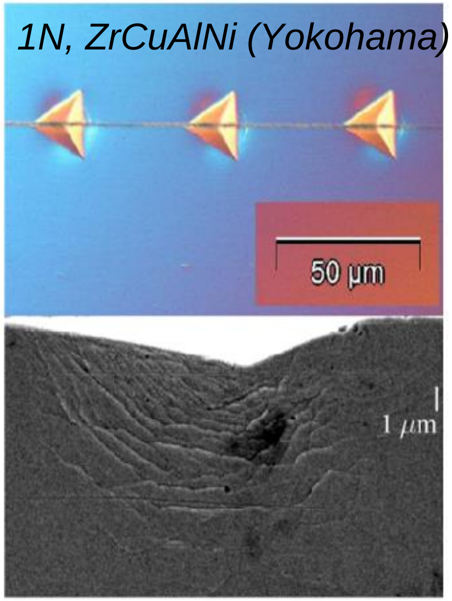


G. Kermouche, coll. NEG-NIMS-ESPCI-MSE
2023 (03/23)

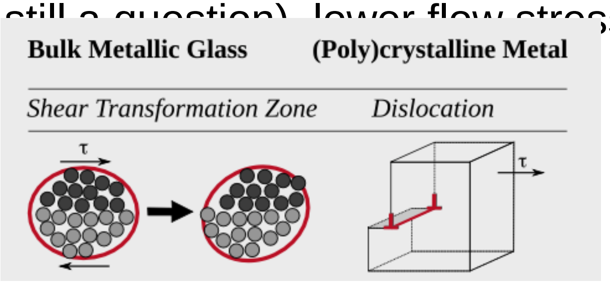
Plasticity, Strain localisation and shear bands: BMGs

- Steif et al. (Acta Mat 1982) for BMG: catastrophic softening with free volume creation localised within the shear band (SB).
  - Pampillo (1972) SB exhibit a higher etching rate than the bulk => agrees with free volume => observation of SB, yes!
  - But composition dependant mechanism
- **Mechanism:** activation of shear transformation zones (STZs), **shear bands** are resulting from the percolation of STZs along a favorable shear path [Deng et al. 1989, Albe et al. 2013].
- Within those shear bands: local disordering (often free volume increase), Tre increase, thickness ≈20 nm (effective thickness still a question), lower flow stress [Greer et al. 2013].

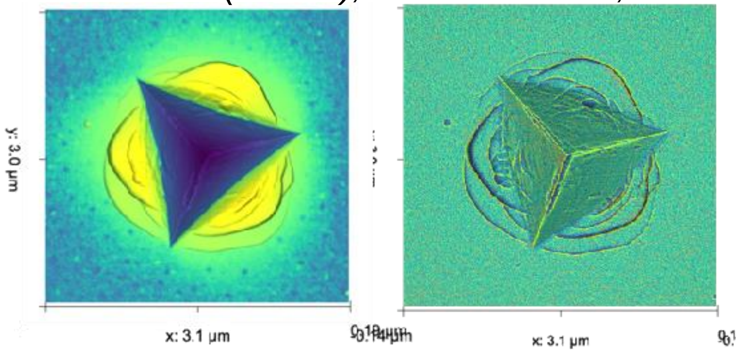
1N, ZrCuAlNi (Yokohama)



Keryvin et al. J. Phys. D: Appl. Phys. 41 (2008)



BMG base Ti (SiMAP), Berkovich 8 mN, AFM



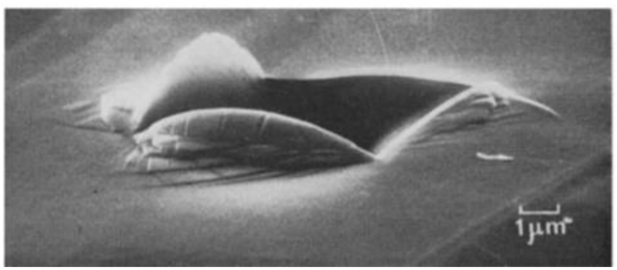
Those are amorphous materials but not “as brittle as” oxyde glasses, they also almost do not densify.

Greer et al. Materials Science and Engineering R 74 (2013) 71–132

Plasticity, Strain localisation and slip lines: Oxyde glasses

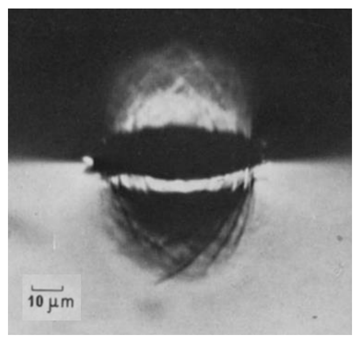
- Peter (1970) **densification occurs** in all glasses but it cannot explain the observation of curls like metal from scratch (even for silica though, see Puttick, Proc. Roy Soc. A 1989), or pile up from indentation => **shear flow** must occur.

Flat glass Pile up

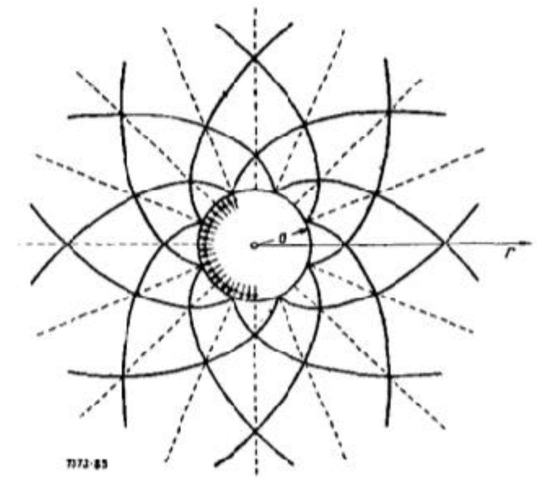


70° 4-sided pyramid indentation, E. Dick (1969).

Slip lines



≈11 N, r=80 µm spherical indentation



Slip line system (τ_{max}= const.) around a circular cylindric tube inside a plastic body caused by normal pressure (internal pressure) on the wall [from Sokolowskij 1955].

Yes for : plate glass (SLSG?), SiNaCa (76/14/10)
No for : SiNa (85/15), SiO2

Important role of glass composition: network modifiers !
Proposed mechanism based on the effect of shear upon local viscosity (Bingham flow equation)

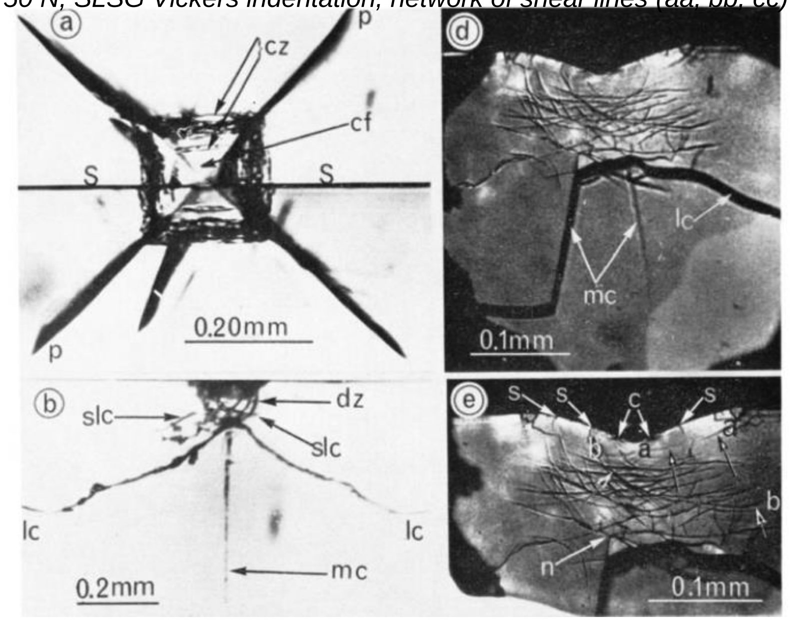
Plasticity, Strain localisation and shear cracks: Oxyde glasses

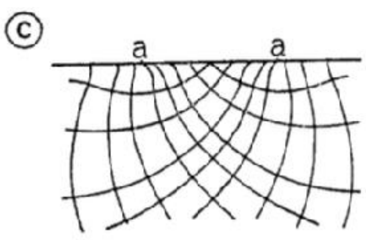
Hagan and Swain (1978)

- General features captured by the elastic contours but the expending cylindrical cavity (Sokolowskij 1955) is better.

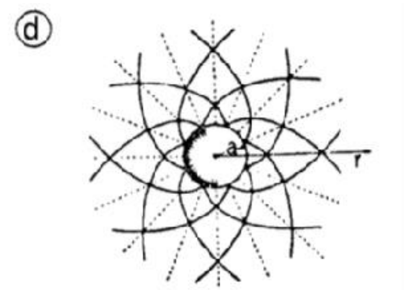
- Mechanism :
  "In glasses, shear deformation in the absence of any long range order is non-constructive and the over-straining of atomic bonds leads to bond breakage and degeneration into **shear cracks** (mode II cracking)" *see Palmer and Rice 1973.*

50 N, SLSG Vickers indentation, network of shear lines (aa, bb, cc)

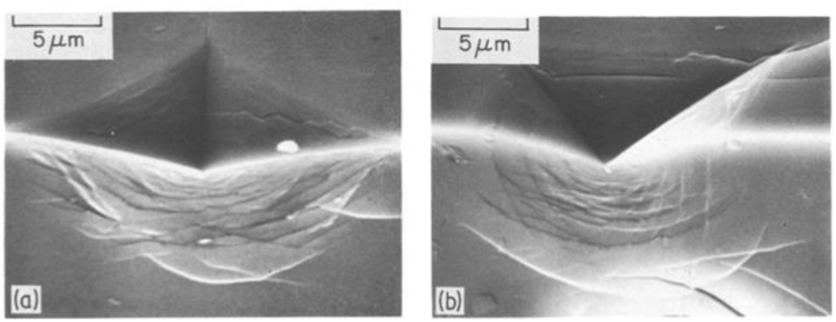




Elastic shear stress trajectories beneath a conical indentation (Sneddon)



Elastic shear stress trajectories about a hemispherical or cylindrical cavity under internal pressure (Hill (1950) Sokolowskij (1955))



SLSG,Vickers, 2N, 90° and 45° observations [Lawn et al. 1983]

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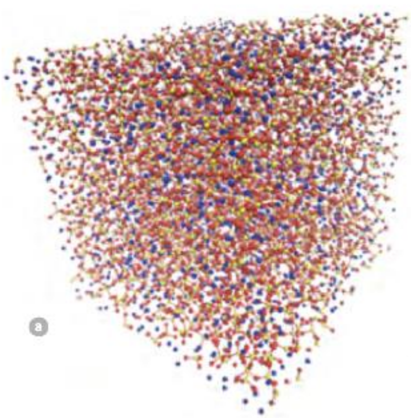
Plasticity, Strain localisation and shear bands: amorphous materials a numerical approach

Is that it? Of course not

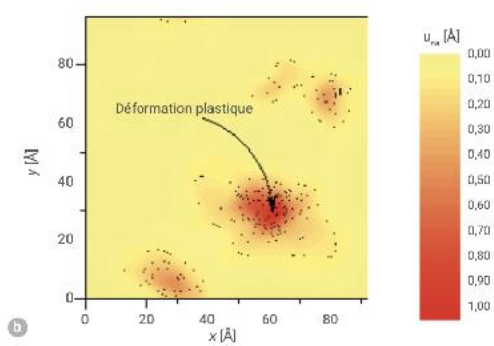
A low scale approach through **numerical simulations**:

Plastic deformation occurs through series of local reorganisations modelled as local slip events. Local yield stresses are randomly distributed in space. Each event induces a Eshelby like elastic stress redistribution [Talami et al. 2012]

SL glass



Local yielding

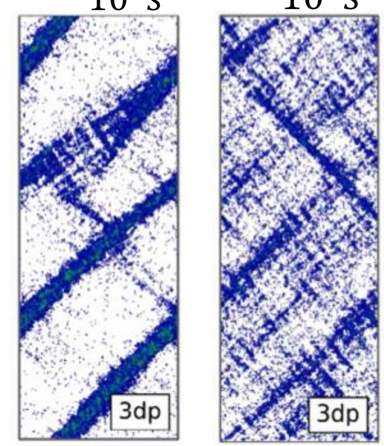


Molinar G. et al. Phys Rev E (2017)

$\epsilon \uparrow$

Then shear banding f($\dot{\epsilon}$, T)

$10^7 s^{-1}$ $10^8 s^{-1}$



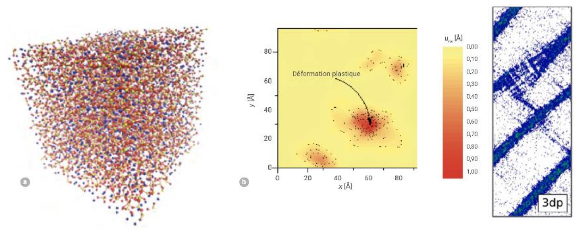
Albe et al 2013, for BMG

Ref et lecture :
Talami et al. C. R. Mécanique 340 (2012)
Tanguy A. C. R. Physique 22 S3 (2021)
Nicolas A. Et al. Rev Mod Pays 90 (2018)
Xiao H. Et al. PNAS 2023
Barthel E. Et al. Reflets de la physique 74 (2022)

Plasticity, Strain localisation and slip lines: Oxyde glasses

Bridging the gap?

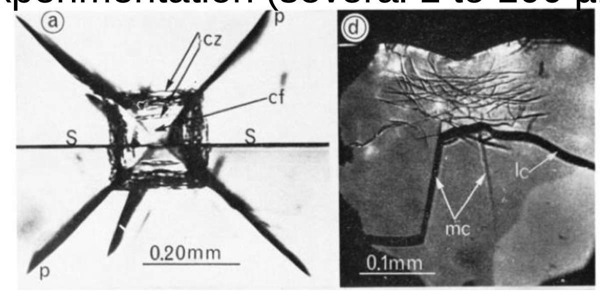
Numerical modeling≈ nm to 100 nm



Plastic shear banding

µ pilars ?
Nanoindentation?
Other tech?

Experimentation (several 1 to 100 µm)



Depending on interpretations shear flow (Peter) or mode II cracks (Hagan, Swain)= slip lines

- When does occur the ductile / brittle transition (i.e. when does the plastic shear band becomes a shear crack)?
- Effective thickness of the plastic shear band?
- Effects of composition.
- Important needs for experimental results at the proper scale too ! (Not simple!)

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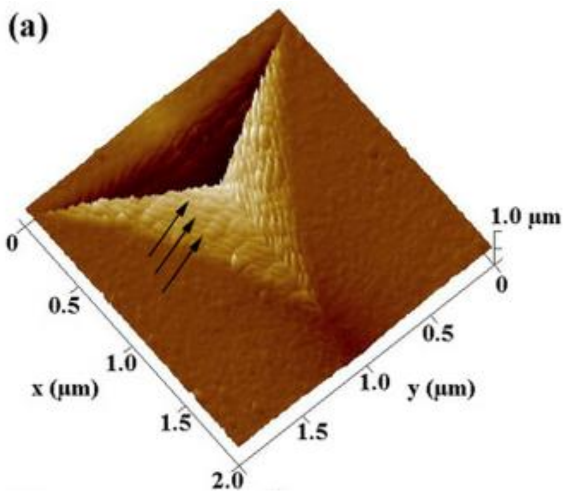
Plasticity, Strain localisation and slip lines: Oxyde glasses

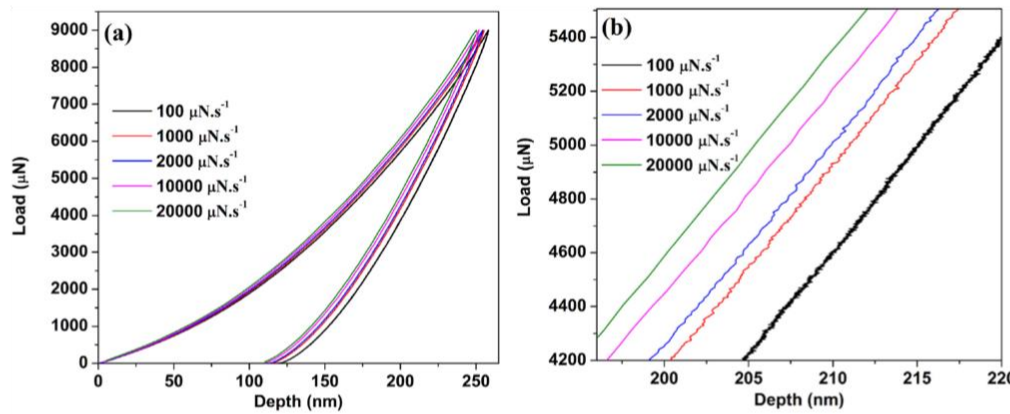
Li et al. (2018)

Aluminosilicate glass: Berkovich 9 mN



Residual imprint: observation flow lines

Li et al. Journal of Non-Crystalline Solids 491 (2018) 79–88



Load-displacement curve : observation of many discrete bursts of rapid displacement at nearly constant load called serration

Pretty much like what is observed for BMGs!

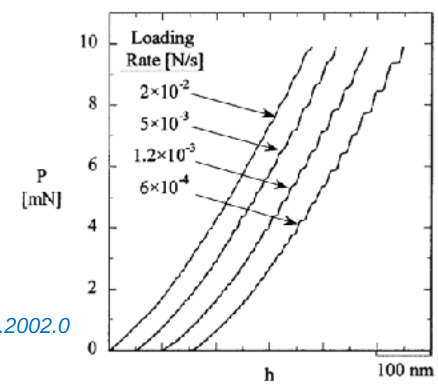


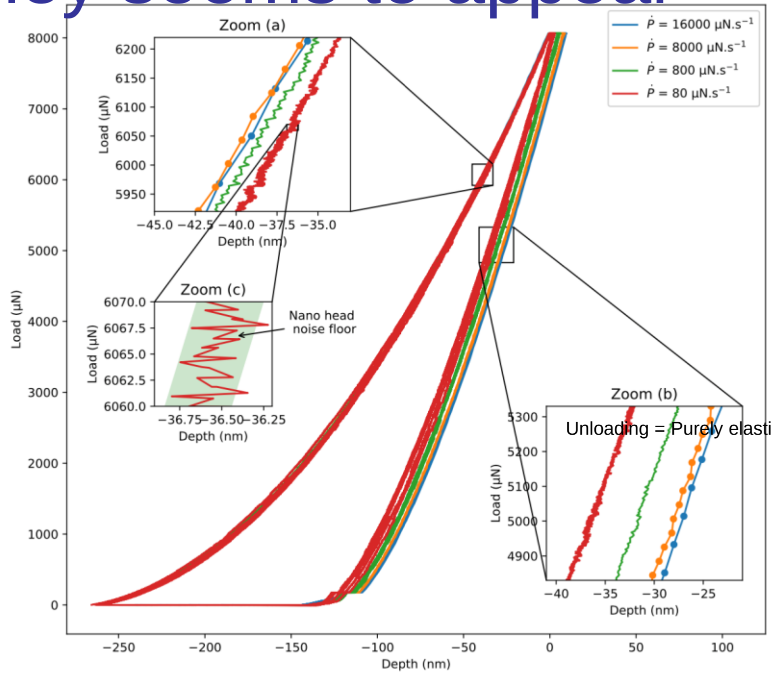
FIG. 1. Load (*P*) plotted against indentation depth (*h*) for the loading segment of four indents on Pd–40Ni–20P with different loading rates.

https://doi.org/10.1557/JMR.2002.0243

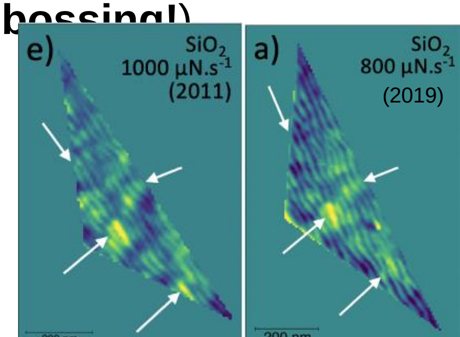
Things a not as simple as they seems to appear

Trenvouez et al. (2020)

1. Bursts appearance and disappearance with loading rate results from the combination of the noise floor sensitivity of the system and of a constant data sampling rate.



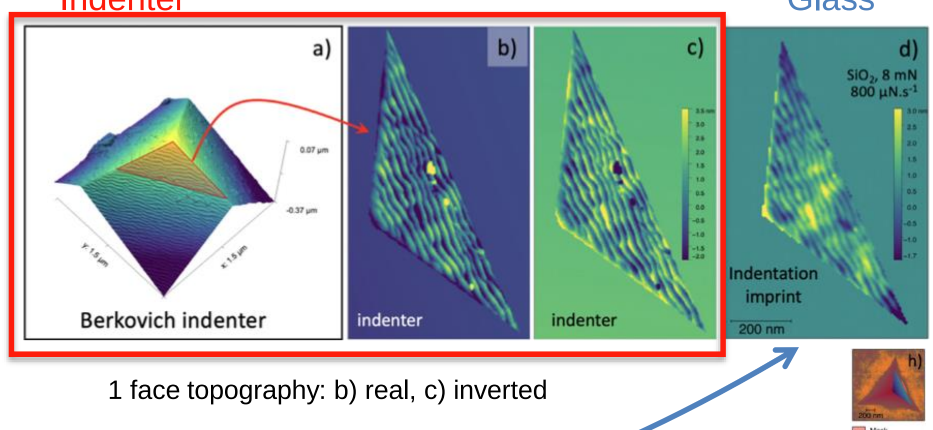
2. Flow lines within the residual imprint are in fact a pre-existing nano pattern on the indenter surface that is transferred to the glass surface upon indentation test (**nano embossing!**)



See Trenvouez et al. J. Non-Cryst. Solids 528 (2020)

Indenter

Glass



1 face topography: b) real, c) inverted

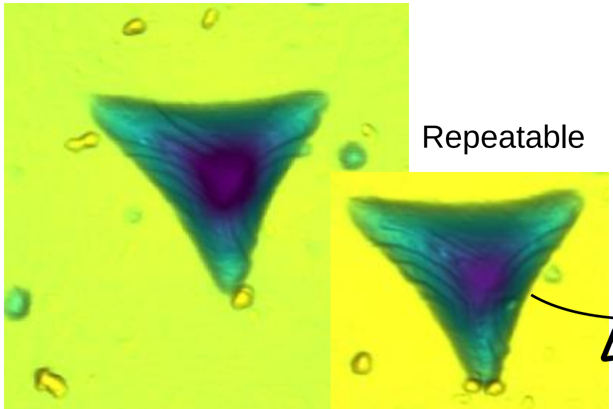
Transferred nano pattern within the indentation imprints

Plasticity, Strain localisation and slip lines: Oxyde glasses

Nano shear cracks beneath the surface at nano indentation site:

- SLSG (yes), silica None!

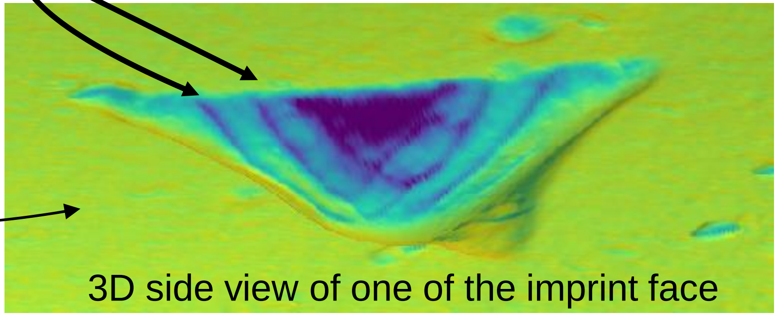
Slip lines underneath the original imprint



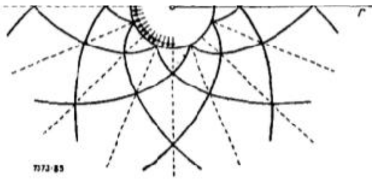
Repeatable

From Han and Trenvouez Thesis , ANR Quic Glass

Slip lines 50 to 60 nm away from each others



Out in 2024!



[from Sokolowskij 1955].

Those slip lines are pure shear cracks although the actual load is divided by about 10000 when compared to Hagan’s work.

Conclusion: an opening for questions

Quite not there yet, but this would the goal!
Silica do deform plastically under shear conditions
=> formation of ribbons during scratch

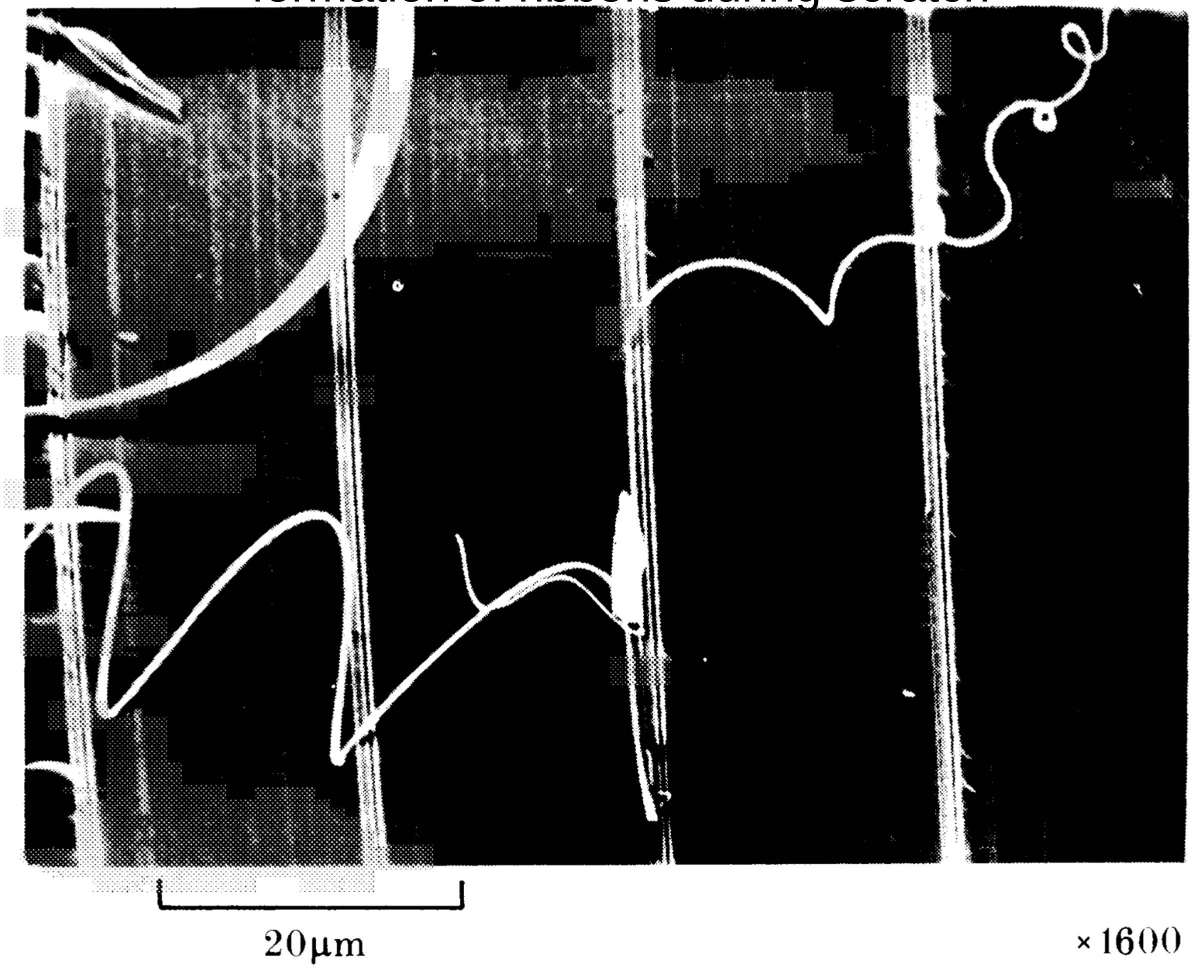
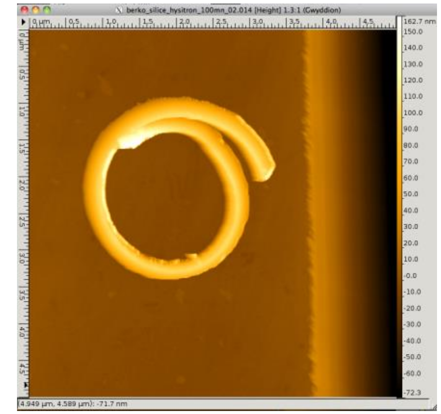


FIGURE 12. Detail of detachment of spiral ribbons from single pass machined grooves in Spectrosil.

Puttick Proc. Roy Soc. A 1989



100 nm thick silica ribbon from scratch

Institut de Physique de Rennes

SIMM

Merci !

Wanted: PhD student for funded PhD position 10/2024 @ IPR Rennes
Topic: Reinforcing materials with water: investigation of the influence of hydration on mechanical properties of oxide glasses.
Contact: maxime.vassaux@cnrs.fr, or me jean-pierre.guin@univ-rennes.fr