On the scaling properties of fracture surfaces

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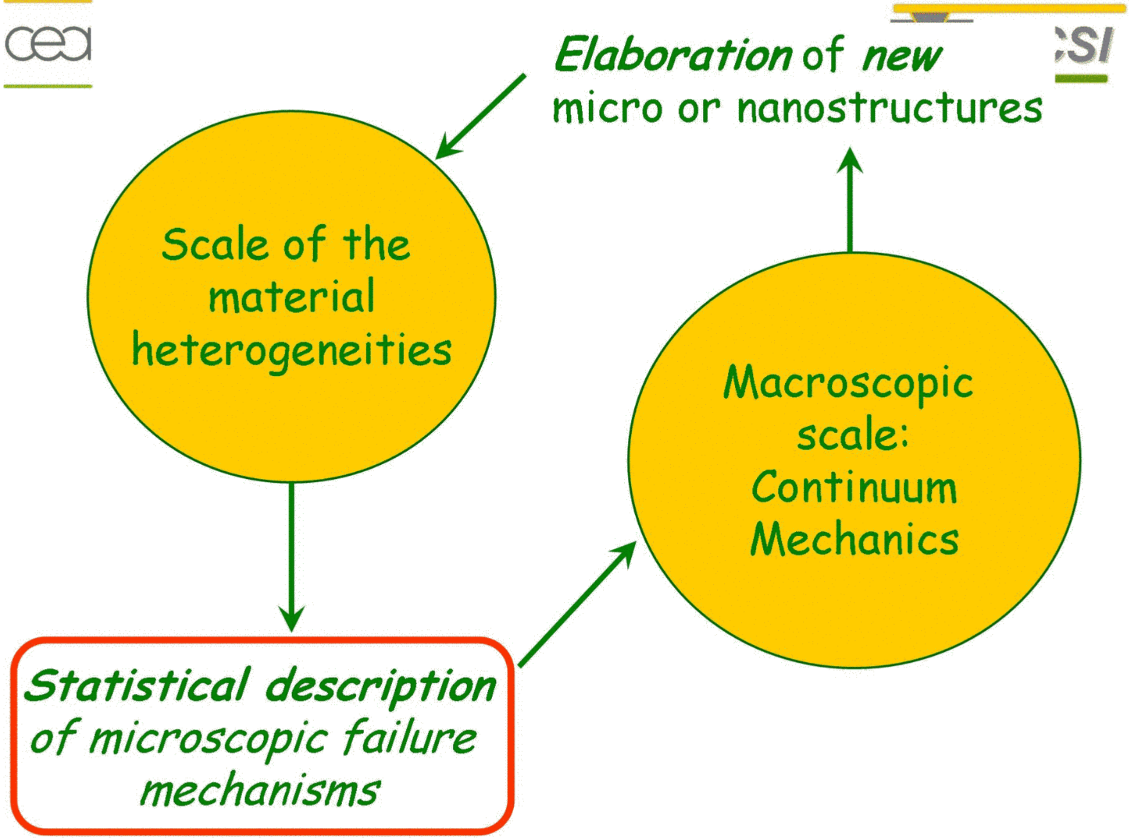


Outline

1- Historical results

2- 2D scaling properties of fracture surfaces

3- On the relevant length-scales

4- Conclusion & Work in progress

Outline

1- Historical results

Experimental observations

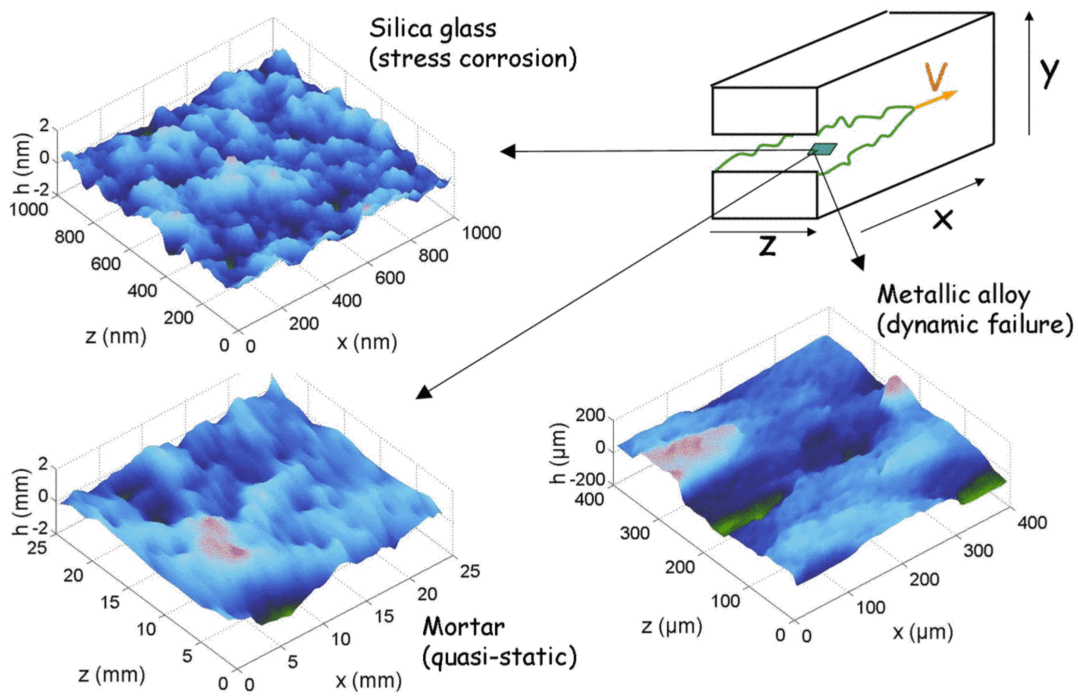
... and Competing models

2- 2D scaling properties of fracture surfaces

3- On the relevant length-scales

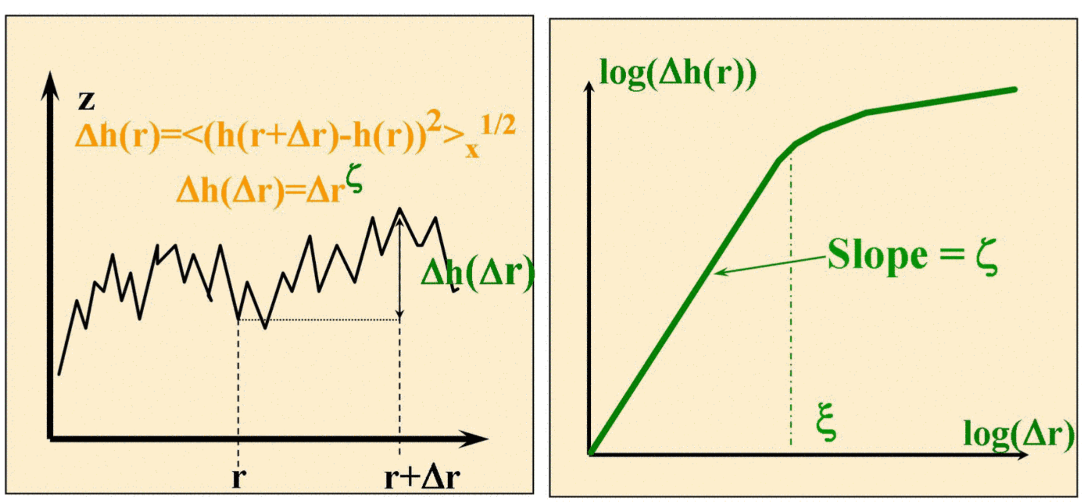
4- Conclusion & Work in progress

1- Fracture surfaces …

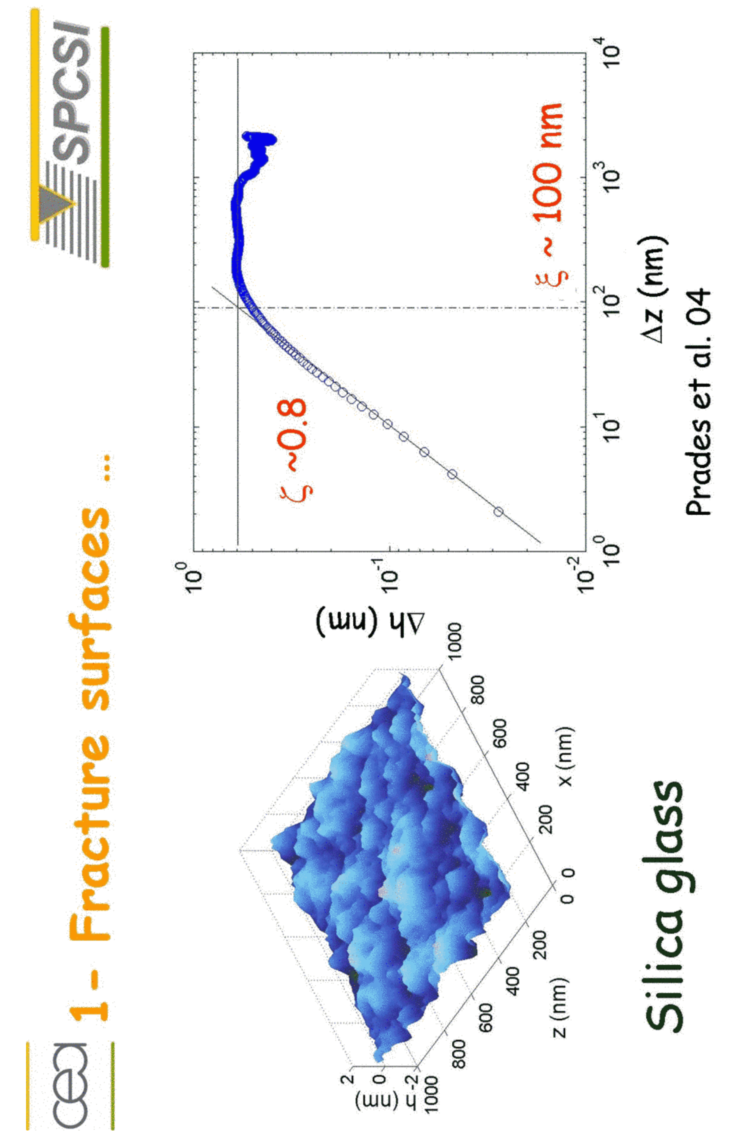


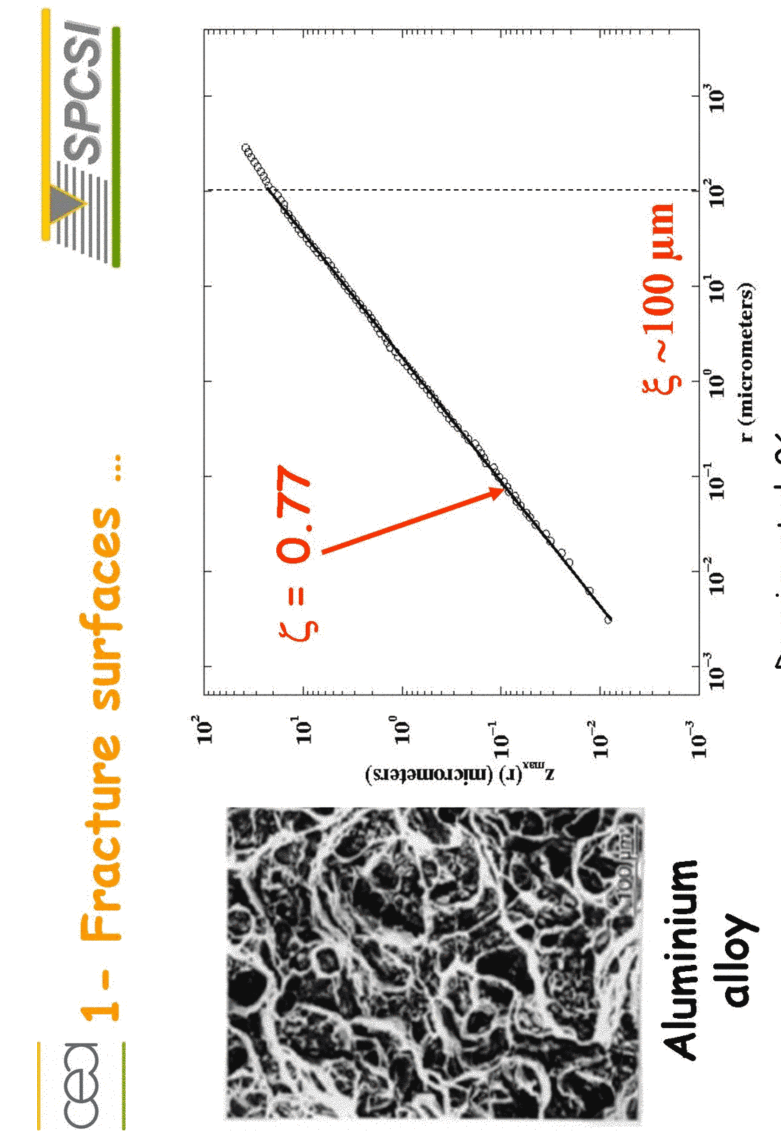
1- Fracture surfaces … … are self-affine

Mandelbrot et al, 84;
Bouchaud et al. 90; Maloy et al. 92

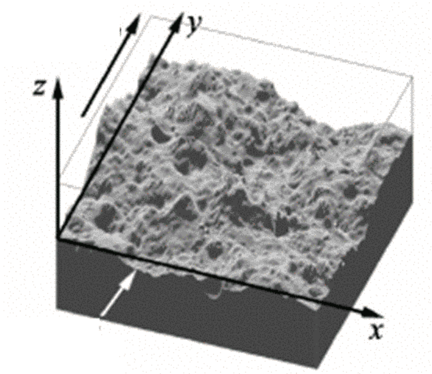


ζ roughness exponent, ξ correlation length

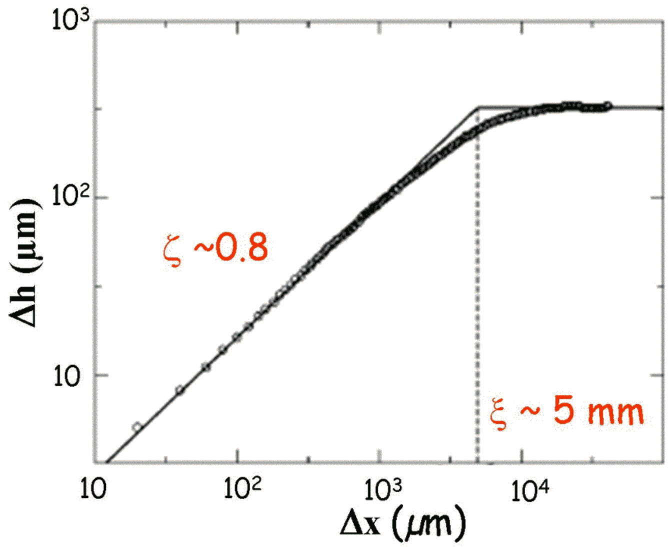

1- Fracture surfaces ...
SPCSI
Silica glass
x (nm)
z (nm)
h (nm)
Δh (nm)
Δz (nm)
ζ ~0.8
ξ ~ 100 nm
Prades et al. 04


1- Fracture surfaces ...
SPCSI
ζ = 0.77
ξ ~100 µm
r (micrometers)
z_max(r) (micrometers)
Daguier et al. 96
Aluminium alloy

1- Fracture surfaces ...



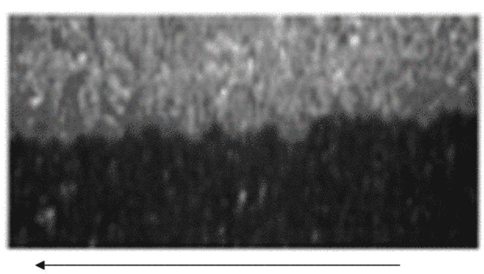
Mortar

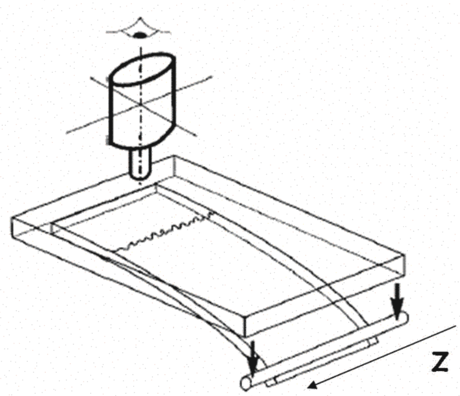


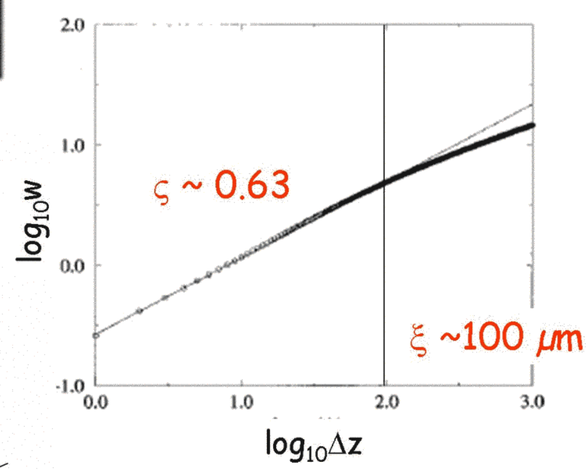
(Mourot & al, 2005)

1- Crack front in interfacial crack

(Delaplace et al., 99)

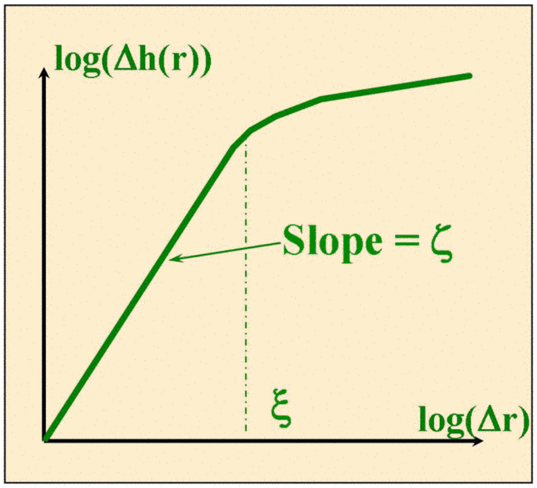


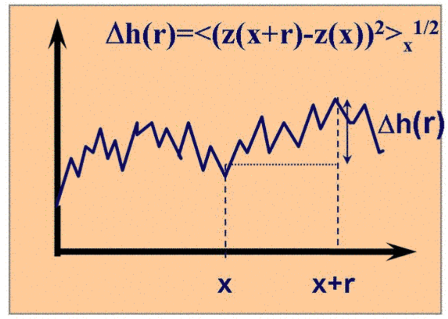




1- Fracture surfaces … … are self-affine

Bouchaud et al. 90; Maloy et al. 92





Roughness exponent:
Universal $\zeta \sim 0.8$ (3D)
$\zeta \sim 0.6$ (2D)

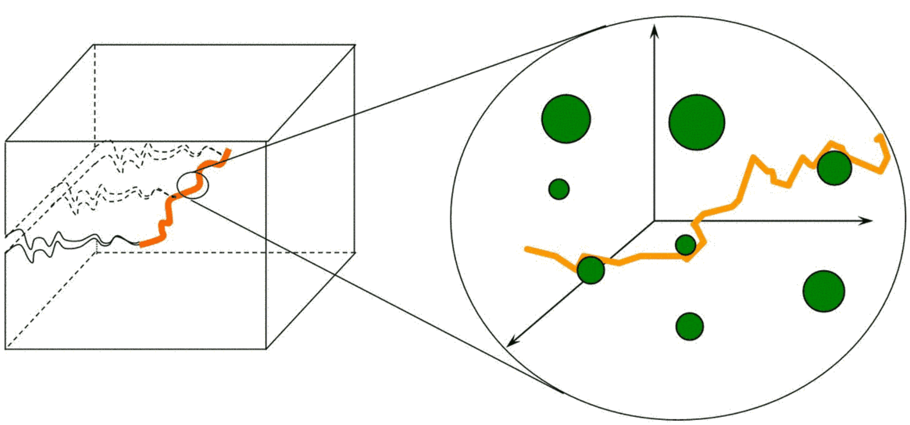
Correlation length ξ : dependent of material, failure mode, crack growth velocity…

1- … and competing models

Crack front = «elastic line» interacting with microstructural pinning obstacles

Fracture surface = trace left behind front

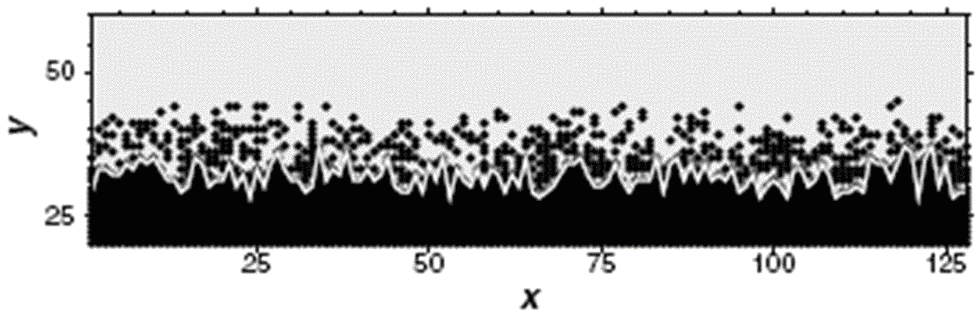
(Bouchaud & Bouchaud, 92; Ramanathan et al. 97; Ertas & Fisher, 97)



General result: self-affine surface
ζ independent of disorder

1- … and competing models

Crack growth = damage coalescence process modelled as a stress-weighted percolation process self induced by the damage gradient
Crack front = continuous path separating the infinite cluster of damage sites from the infinite cluster of sane site
(Roux & Hermann, 90; Schmittbuhl et al; Hansen & Schmittbuhl, 03)



General result: self-affine surface
ζ independent of disorder

Outline

1- Historical results

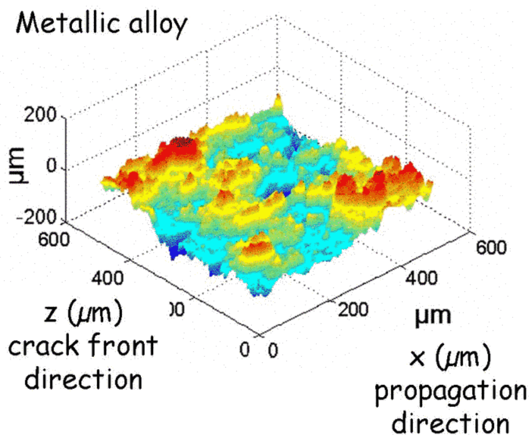
2- 2D scaling properties of fracture surfaces
- Scaling properties in various directions
- 2D height-height correlation function
- Theoretical implications

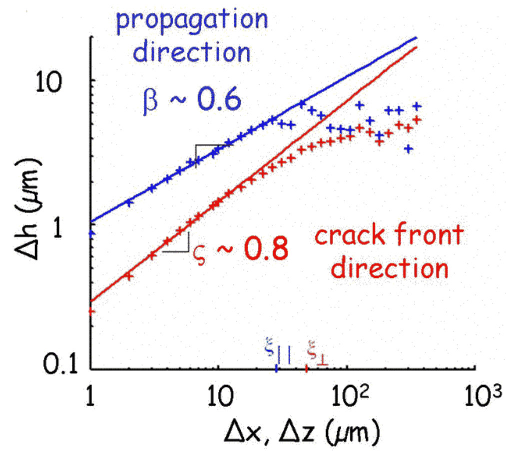
3- On the relevant length-scales

4- Conclusion & Work in progress

2- Self-affine scaling properties in various directions

See also Bouchbinder et al. 05

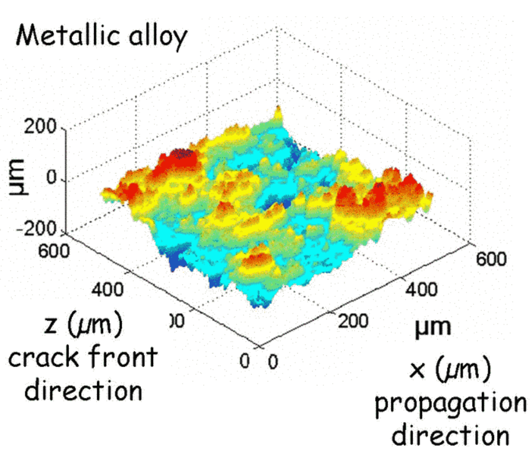


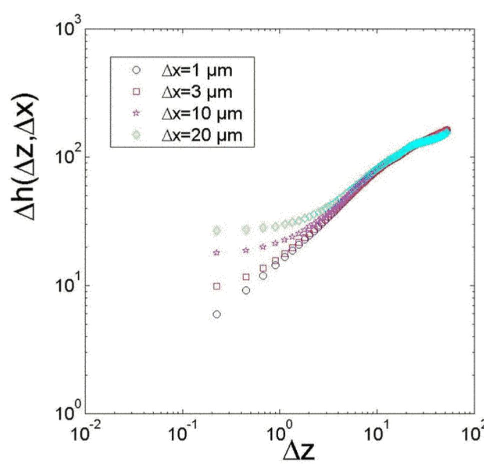


Anisotropy in the correlation length & in the measured roughness exponent

2- 2D height-height correlation function...

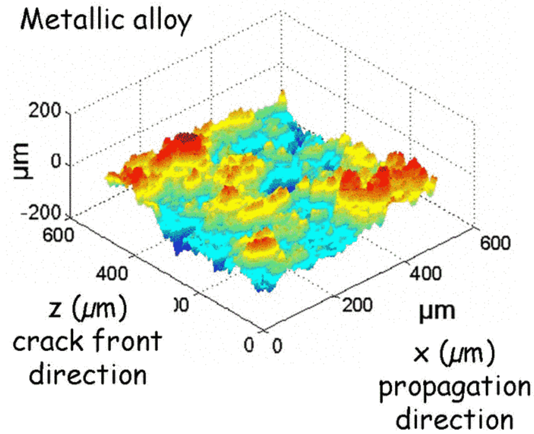
$$\Delta h_{2D}(\Delta z, \Delta x) = (\langle (h(z_A, x_A) - h(z_A+\Delta z, x_A+\Delta x))^2 \rangle_A)^{1/2}$$

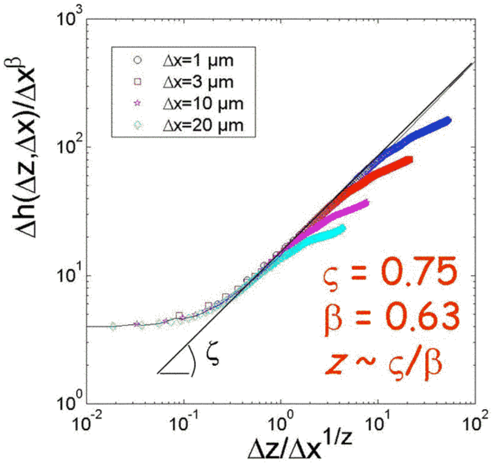




2- 2D height-height correlation function...

$$\Delta h_{2D}(\Delta z, \Delta x) = \left(\left\langle \left(h(z_A, x_A) - h(z_A+\Delta z, x_A+\Delta x)\right)^2 \right\rangle_A\right)^{1/2}$$

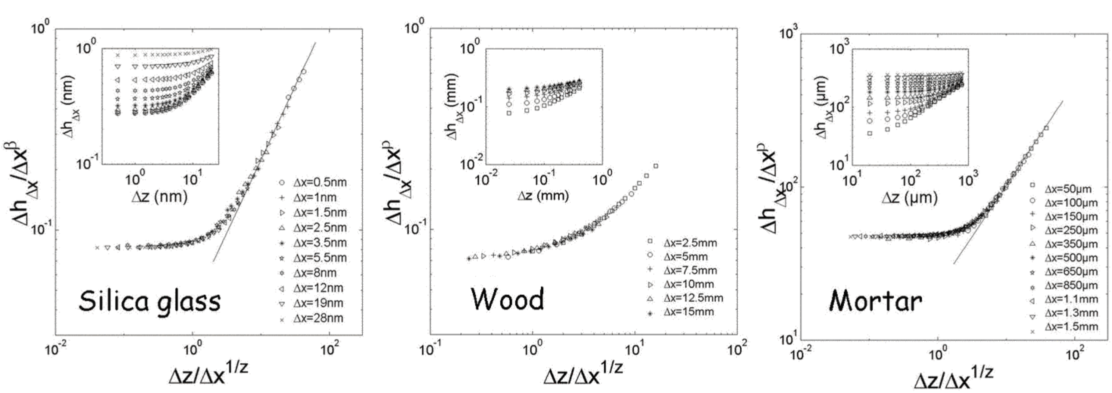




$$\Delta h \sim \Delta x^{\beta} . f\left(\frac{\Delta z}{\Delta x^{1/z}}\right) \quad with \quad f(u) \sim \begin{cases} 1 & if\ u << 1 \\ u^{\varsigma} & if\ u >> 1 \end{cases}$$

2 ind†. exp. : ς , β
1 rel†. exp. $z = \varsigma/\beta$

2- 2D height-height correlation function...



2 universal exponents: $\zeta = 0.75 \pm 0.05$, $\beta = 0.6 \pm 0.05$

1 related exponent: $z = \zeta/\beta \sim 1.3 \pm 0.1$

2- Comparison with models

~~Crack growth = damage coalescence process modelled as a stress-weighted percolation process self induced by the damage gradient~~
~~Crack front = continuous path separating the infinite cluster of damage sites from the infinite cluster of sane site~~
~~(Schmittbuhl et al; Hansen & Schmittbuhl, 03)~~

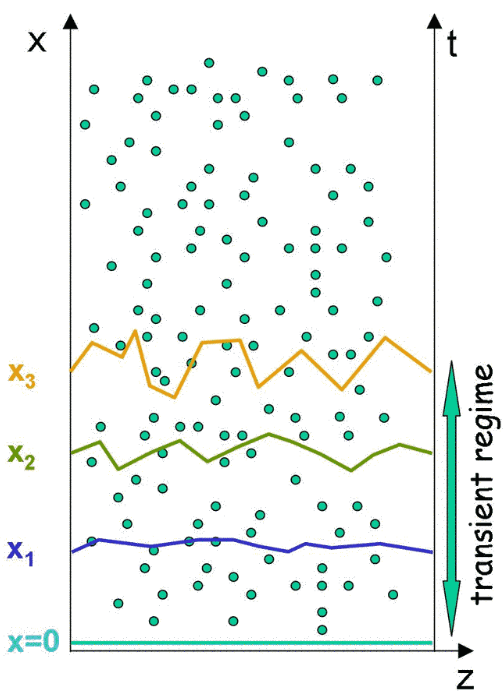
=> no critical scaling properties along crack growth direction

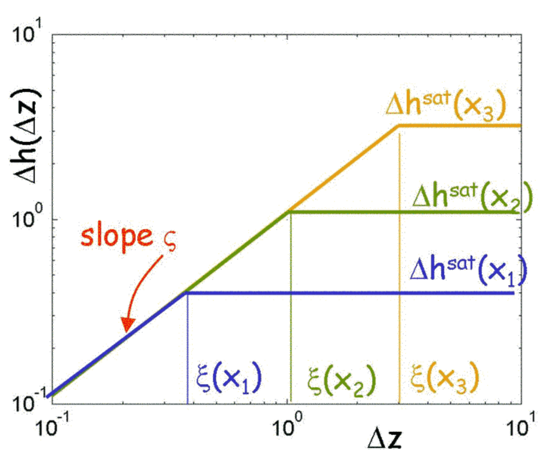
Crack front = «elastic line» interacting with microstructural pinning obstacles
Fracture surface = trace left behind front
(Bouchaud & Bouchaud, 92; Ramanathan et al. 97; Ertas & Fisher, 97)

=> anisotropic critical scaling properties

2- Comparison with elastic line models

A. Barabasi and E. Stanley, 1995

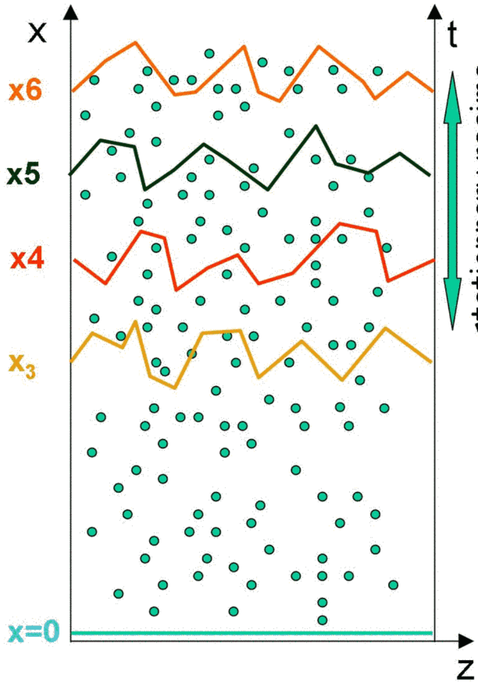


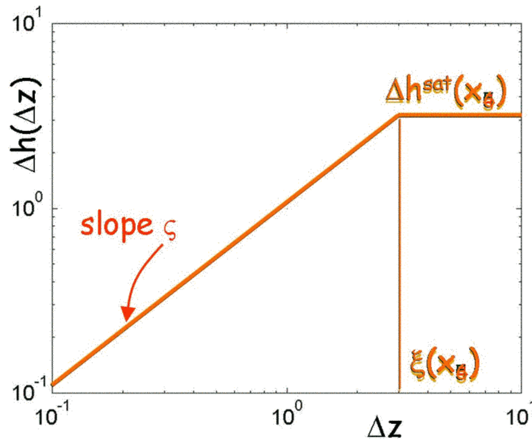


$\xi \sim x^{1/z}$: z *dynamic exponent*
$\Delta h^{sat} \sim x^{\beta}$: β *growth exponent*

2- Comparison with elastic line models

A. Barabasi and E. Stanley, 1995

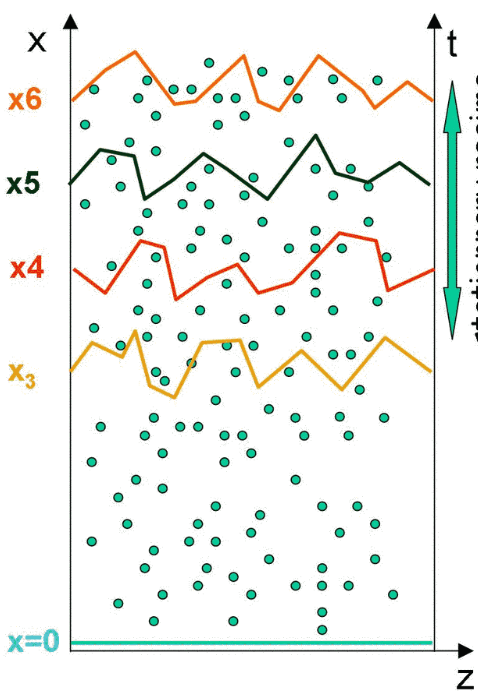




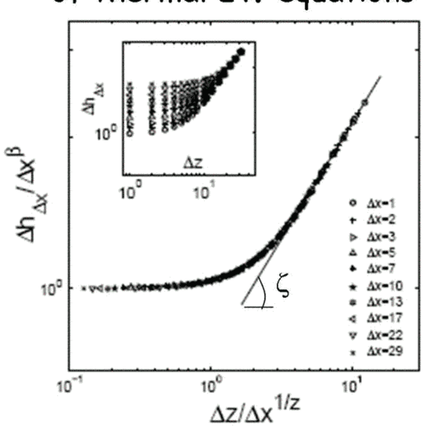
$\xi \sim$ cte
$\Delta h^{sat} \sim$ cte

2- Comparison with elastic line models

A. Barabasi and E. Stanley, 1995



Example of $\Delta h(\Delta z, \Delta x)$ in the steady regime from simulations of thermal EW equations



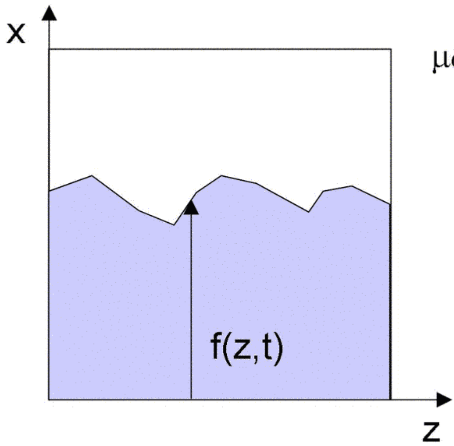
$\zeta = 0.5$
$\beta = 0.25$
$z = 2$

compatible with experimental observations

2- elastic line models…
… as expected from LEFM

Interfacial crack case

See also Schmittbuhl et al. 95



$$\mu \partial_t f = K^0_I(1+G(z,\{f\})) - K^0_{Ic}(1+\eta(z,f(z)))$$

$G_F(k,\{f_F\}) \propto -|k| f_F$ (Gao & Rice 89)

long range elasticity

V<<1 (quenched disorder)

$\varsigma \sim 0.4$, $z \sim 1.4$, $\beta \sim 0.3$

(Rosso & Krauth 02, Tanguy et al 98)

V>>1 (thermal disorder)

$\varsigma \sim 0$, $z \sim ?$, $\beta \sim 0$

(Ramanathan et al. 97)

Experiment: $\varsigma \sim 0.63$???

2- elastic line models…
… as expected from LEFM

3D case:

See also Ramanthan, et al. 97

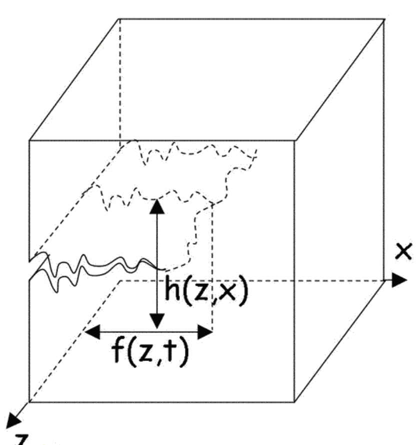
$$\mu \partial_t f = K^0_I(1+G) - K^0_{Ic}(1+\eta(z,f(z,t)))$$

$$\mu \partial_x h(z,x=f(z,t)) = -2K_{II}(z,\{f\},\{h\})/K^0_I + \eta(z,x=f(z,t), h(z,t))$$

Cottrell & Rice, 80

$K_{IIF}(k,\{h_F\},\{f\}) \sim -|k| h_F$ (Barralde & Ball 95)

long range elasticity



V<<1 (quenched disorder)

$\varsigma \sim 0.4$, $z \sim 1.4$, $\beta \sim 0.3$

(Rosso & Krauth 02, Tanguy et al 98)

???

V>>1 (thermal disorder)

$\varsigma \sim 0$, $z \sim ?$, $\beta \sim 0$

(Ramanathan et al. 97)

Experiment:

$\varsigma \sim 0.75$, $z \sim 1.2$, $\beta \sim 0.6$

Outline

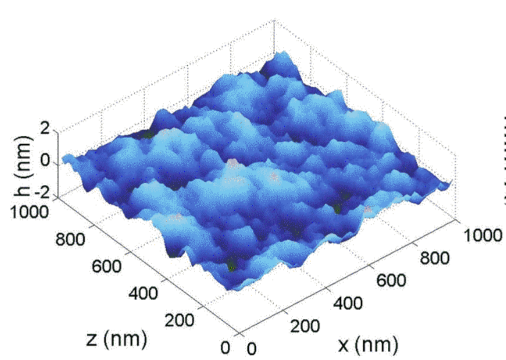
1- Historical results

2- 2D scaling properties of fracture surfaces

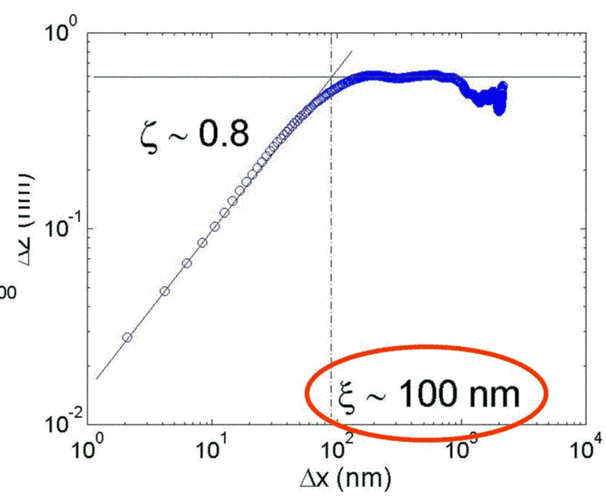
3- On the relevant length-scales
   Origin of correlation length
   Implications on models

4- Conclusion & Work in progress

3- Fracture surfaces …

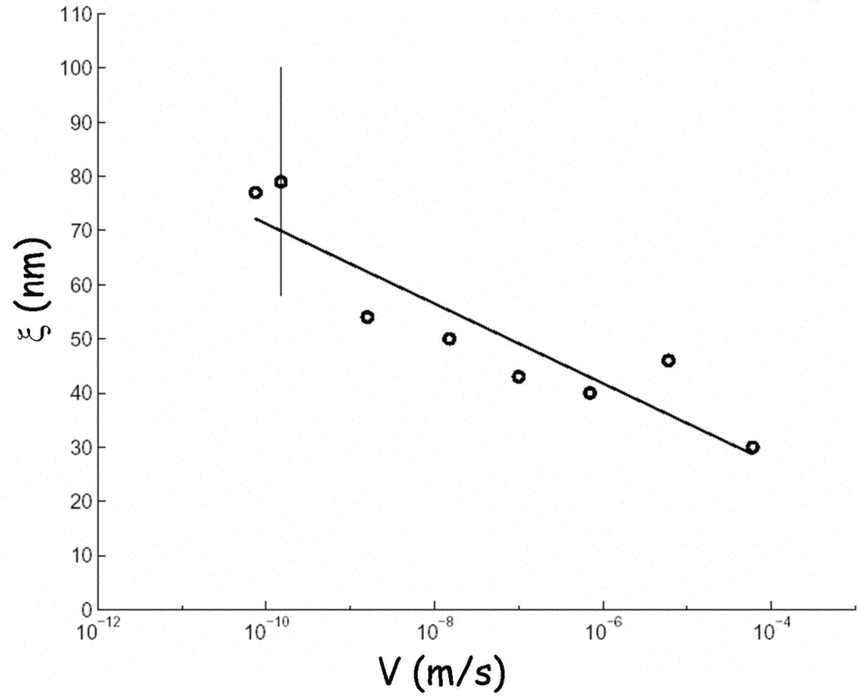


Silica glass



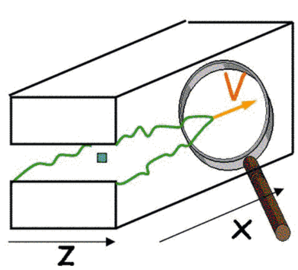
Prades et al. 04

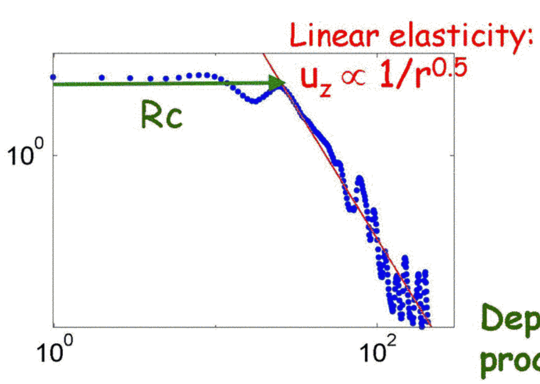
3. Correlation length ξ as a function of crack velocity V

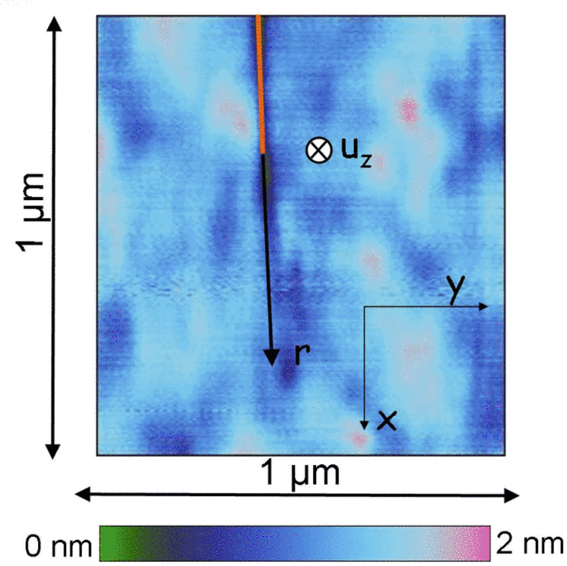


3. Process zone size within amorphous Silica under stress corrosion

Elisabeth's talk, Cindy' s talk

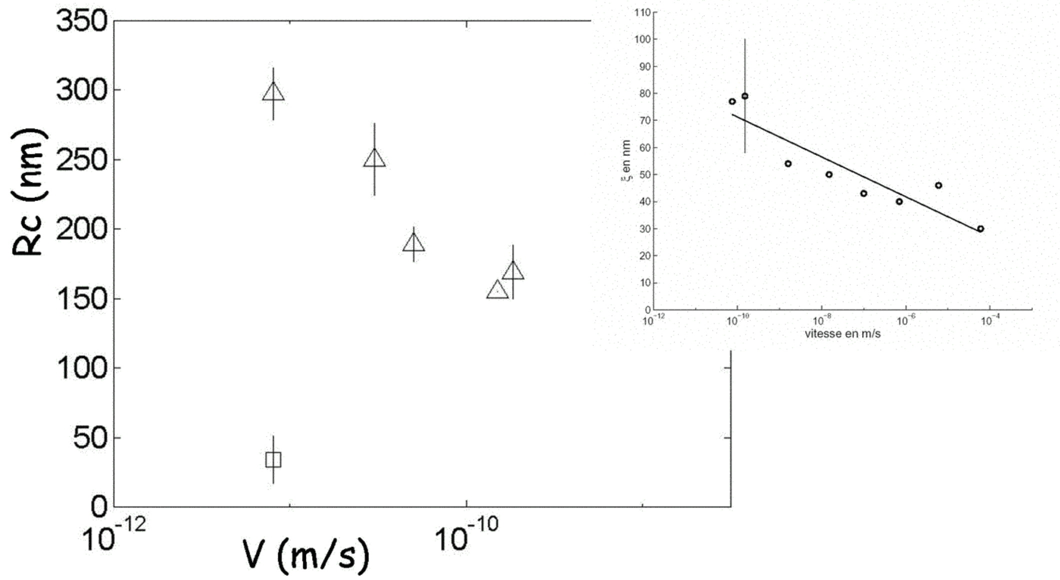






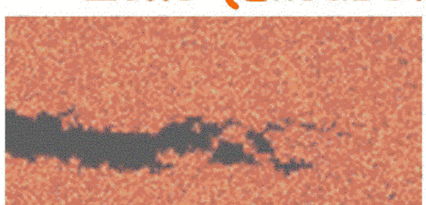
Departure from linear elasticity ~ process zone size Rc ~ 100nm

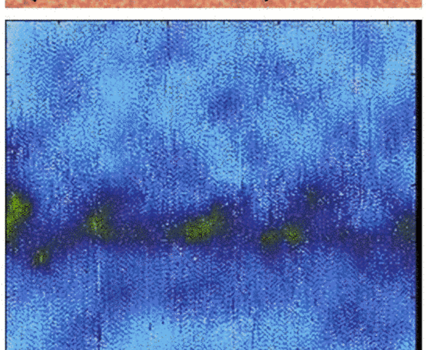
3. Process zone size Rc as a function of crack velocity V (E. Bouchaud's talk)

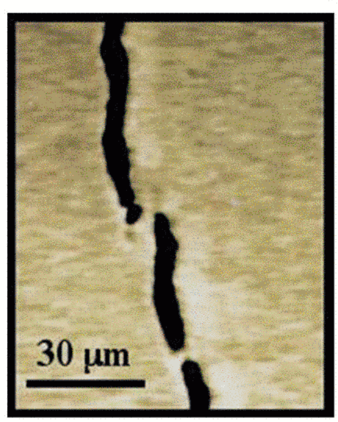


- ξ and Rc behaves the same ⇨ $\xi \sim Rc$!

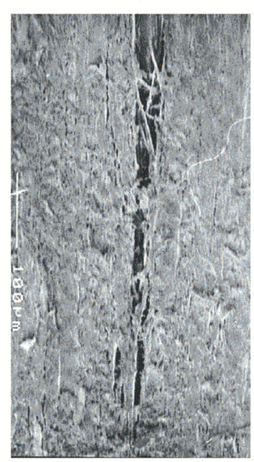
3-Failure mechanisms within the process Zone (Elisabeth's talk; Cindy's talk)


Silica glass, dynamic failure (C. Rountree et al.)


Aluminosilicate glass, stress corrosion (F. Celarie et al.)

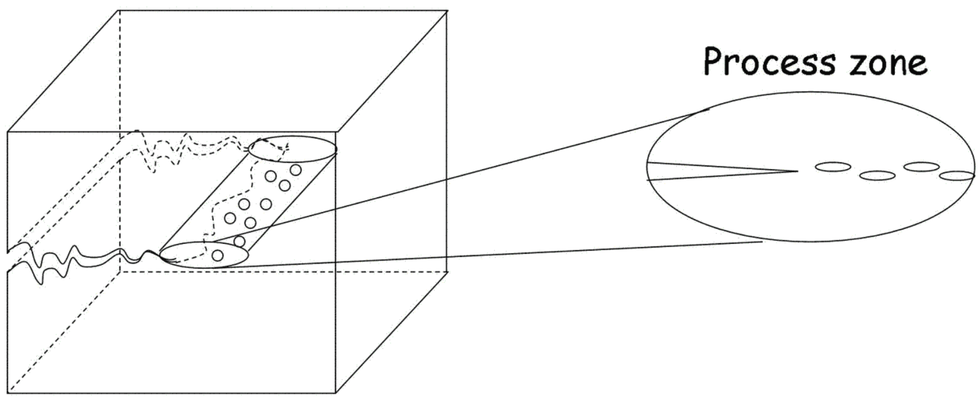


Metallic alloy, E. Bouchaud


Wood, E. Landis et al.

Crack progresses through growth and coalescence of damage cavities, even in bittle materials

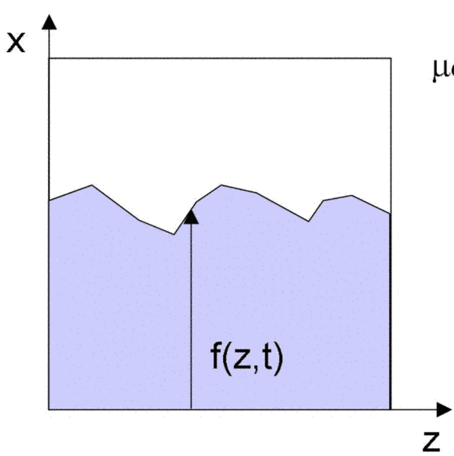
3. Possible interpretation of the anomalous exponents of fracture surfaces



- Correlation length ξ ~ process zone R_c
- Roughness exponent ζ ⇦ nanocavitation process

2- elastic line models…

Interfacial crack case



$$\mu\partial_t f = K^0_I(1+G(z,\{f\})) - K^0_{Ic}(1+\eta(z,f(z)))$$

~~$G_F(k,\{f_F\}) \propto -|k| f_F$~~ Screening due to damage

~~Long~~ short range elasticity

V<<1 (quenched disorder)
ς ~ 0.63, z~1, β ~ 0.63
(Rosso & Krauth 03, our simulations)

V>>1 (thermal disorder)
ς = 0.5, z=2, β =0.25
(Edwards Wilkinson eq.)

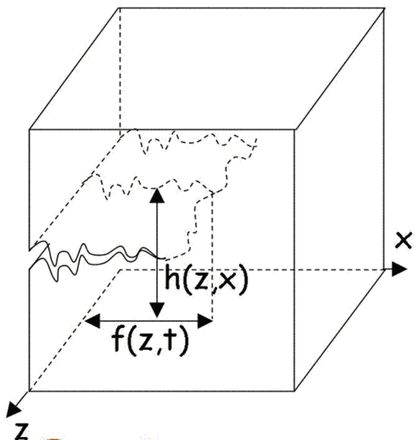
Experiment: ς ~ 0.63

2- elastic line models...

3D case:

$$\mu\partial_t\vec{r} = \mu\partial^2_x\vec{r} + \eta(z,\vec{r}(z,t)) + F$$

$$\vec{r}(z,t) = \begin{cases} f(z,t) \\ h(z,f(z,t)) \end{cases}$$



Experiment:
$\varsigma \sim 0.75$, $z \sim 1.2$, $\beta \sim 0.6$

Screening due to damage

short range elasticity

V<<1 (quenched disorder)
$\varsigma \sim 0.75$, $z \sim ?$, $\beta \sim ?$
(Kardar 98)

V>>1 (thermal disorder)
$\varsigma \sim 0.72$, $z \sim ?$, $\beta \sim ?$
(Ertas & Kardar 92)

4 - Conclusion

- Scaling properties of fracture surfaces accounted qualitatively by elastic line models
  - 2D Height-height correlation function compatible with elastic line models predictions
  - Measured critical exponents $\zeta=0.75$, $\beta=0.6$ and $z=\zeta/\beta \sim 1.2$.
- Damage should be taken into account
  - Correlation length ~ process zone size
  - Exponents incompatible with long range elasticity as predicted by LEFM
  - Exponents compatible with short range elasticity Screening due to damage?

4 - Work in progress

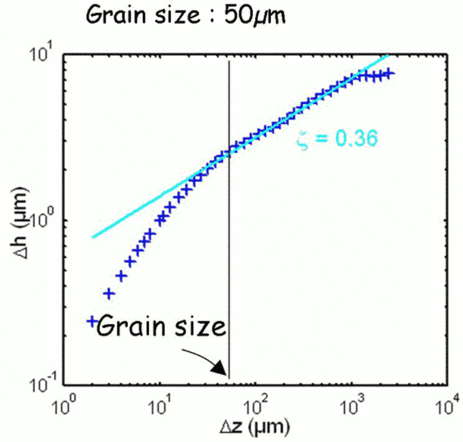
- Fracture surfaces in materials where microstructure scale >> process zone size

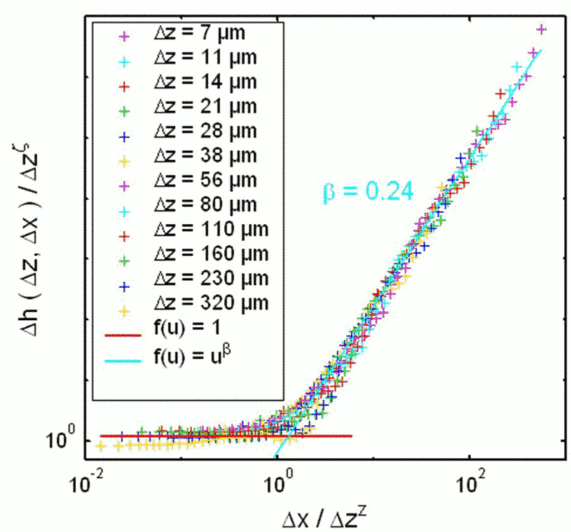
4 - Work in progress

Glassy ceramics

Coll: N. Bonn and P. Vie, LCPC, France

Glassy ceramics
Porosity: 3%
Grain size : 50μm





$\zeta=0.36 \pm 0.03$ $\beta=0.25 \pm 0.02$ $z=1.4 \pm 0.2$

Compatible with LEFM long range elastic predictions

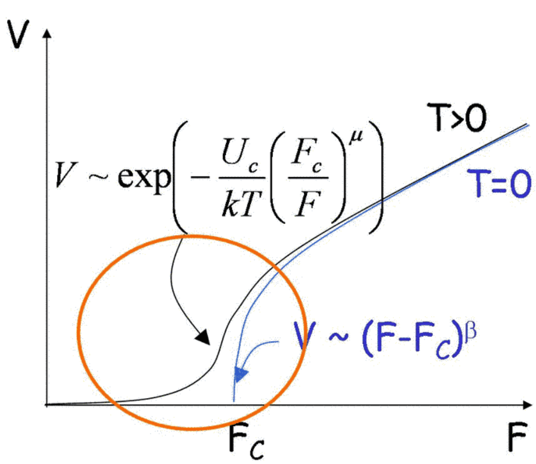
4 - Work in progress

- Fracture surfaces in materials where microstructure scale >> process zone size
- Fracture surfaces in glasses at lengthscales >> process zone size
- Determination of the critical exponents in Elastic line models through numerical simulations
- Signature of Elastic lines models in $V(K_I)$ curves

4 - Work in progress

See also Daguier et al., 97 for related discussion

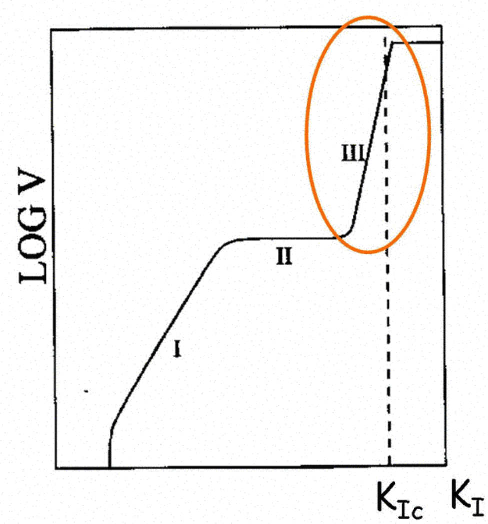
Elastic line models



$\mu(\zeta,z,\sigma)$ $\sigma=1$ (LRE)

$\beta(\zeta,z,\sigma)$ $\sigma=2$ (LRE)

Glass Stress Corrosion



4 – Work in progress

- Fracture surfaces in materials where microstructure scale >> process zone size
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