



Scale invariance associated with smooth plastic flow and PLC effect in an AlMg alloy

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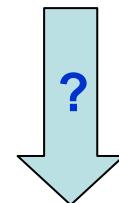
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Chernogolovka, Russia



Objective, motivation

Discontinuous and non uniform process: motion of dislocations



Continuous and uniform plastic flow at macroscale

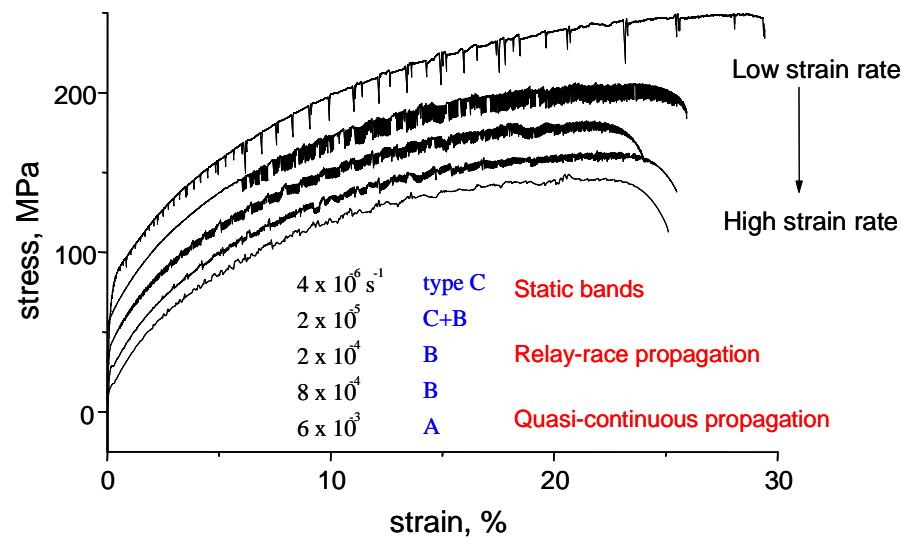
**Intermittency of plastic flow as a
manifestation of self-organization of
crystal defects**

Macroscale: jerky flow

Portevin-Le Chatelier effect

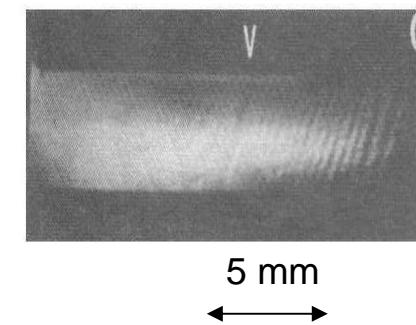
Deformation curves. Al3%Mg polycrystal

M.A. Lebyodkin, Y. Estrin, Acta Mater., 53, 3403 (2005)

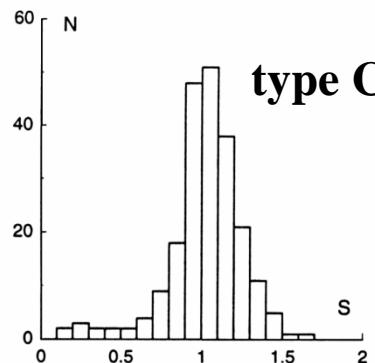


Traces of the PLC bands on the surface
 Al5%Mg

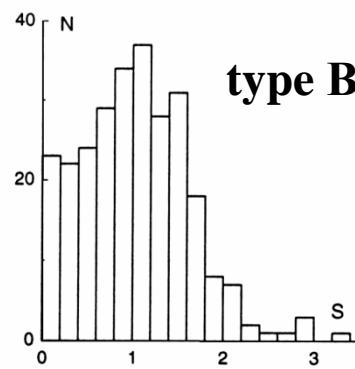
K. Chihab, et al., Scr. Metall., 21, 203 (1987)



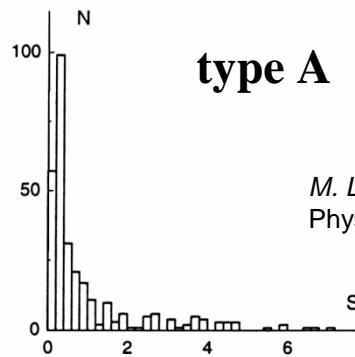
Analysis of stress serrations



type C

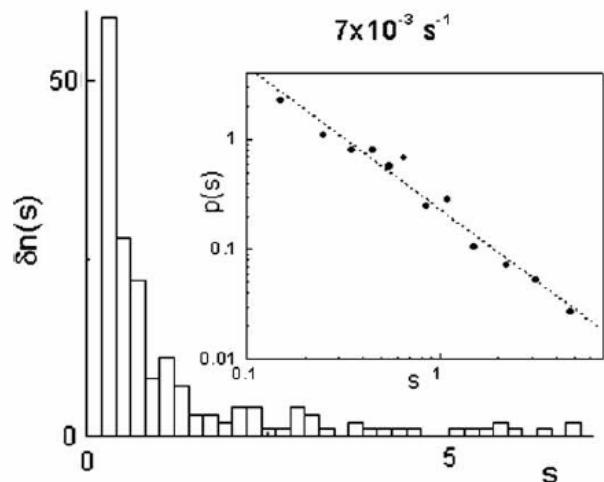


type B



type A

M. Lebyodkin, Y. Bréchet, Y. Estrin, L.P. Kubin,
Phys. Rev. Lett. (1995); Acta Metall. (1996)

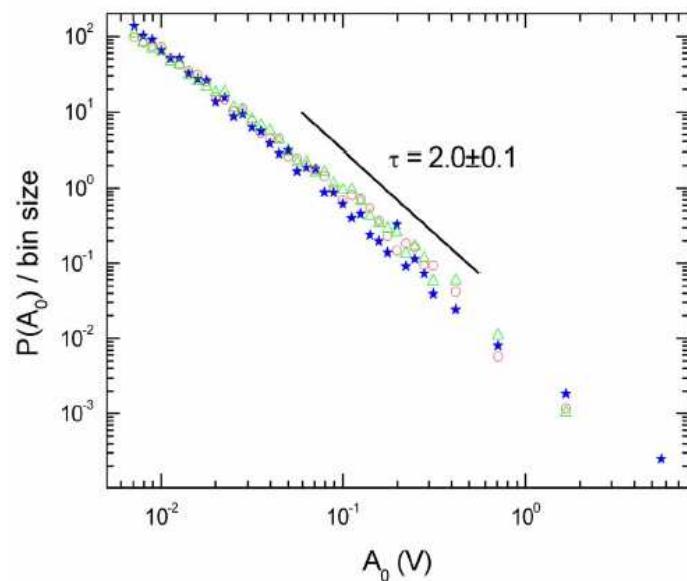


T. Lebedkina, M. Lebyodkin, Acta Mater., 56, 5567 (2008)

- High strain rate: scale-invariant statistical laws
 $P(s) \sim s^{-\alpha}$: $P(ks) \sim (ks)^{-\alpha} \sim s^{-\alpha}$
Self-Organized Criticality
 Infinite number of degrees of freedom
- Lower strain rates: bell-shaped distributions
- Type B: deterministic chaos
 G. Ananthakrishna, S.J. Noronha, C. Fressengeas, and L.P. Kubin, Phys. Rev. E **60**, 5, 5455 (1999).
Scale-invariant chaotic attractor
 Reduced dimensionality
- Scale invariance : fractal dimensions

Macroscopically smooth plastic flow

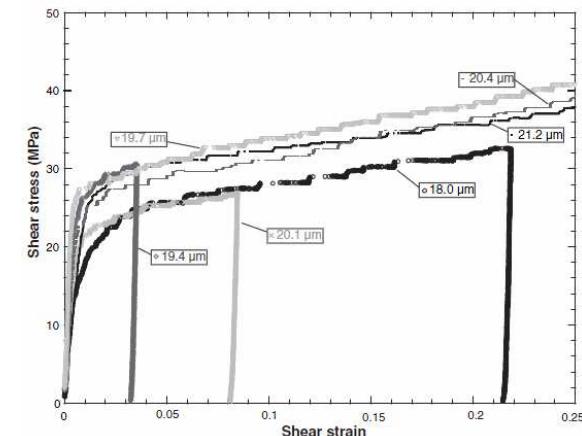
Power-law statistics for acoustic emission (AE)



Ice and Cd single crystals

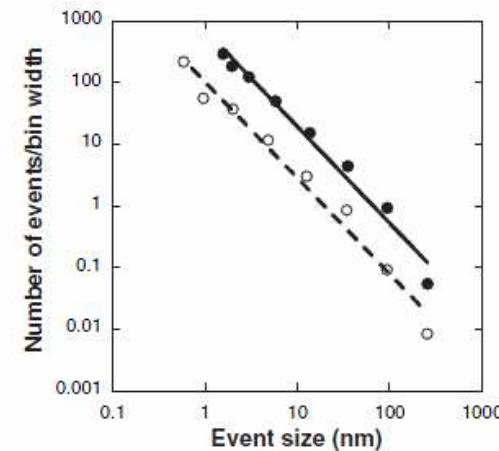
J. Weiss, T. Richeton, et.al., PRB, 76, 224110 (2007)

Power-law statistics for stress jumps in micropillars



Ni single crystals

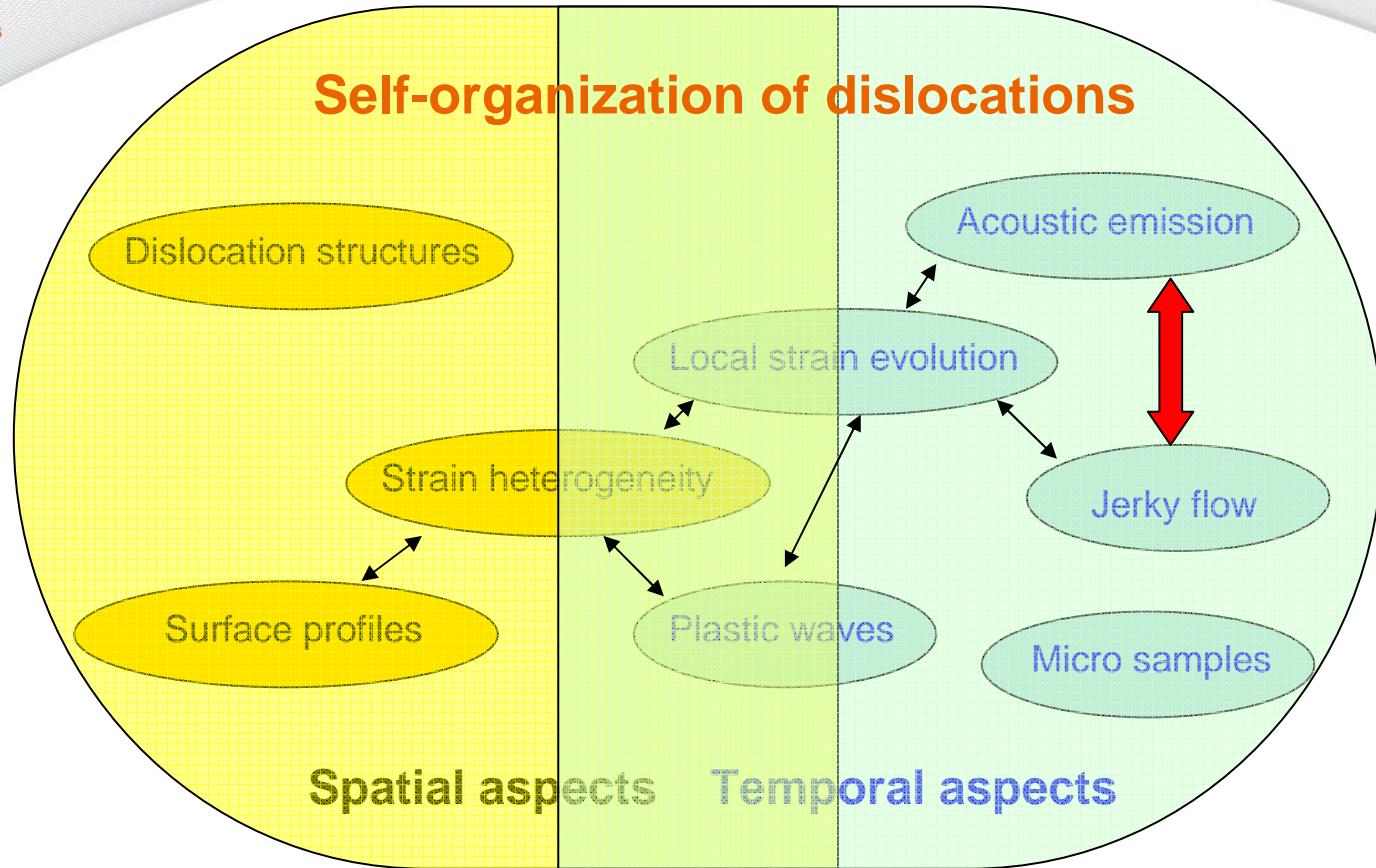
D. Dimiduk, et.al.,
 Science 312, 1188 (2006)



Missing: small scale for the PLC effect



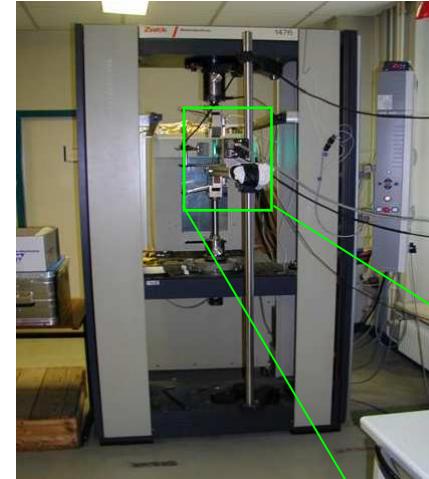
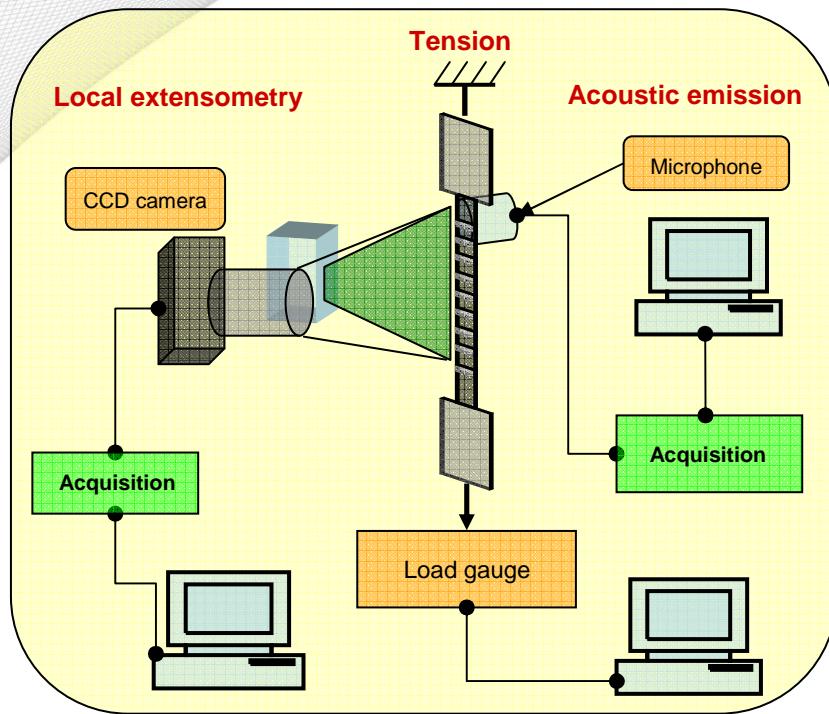
So what?



Attractiveness of the PLC effect

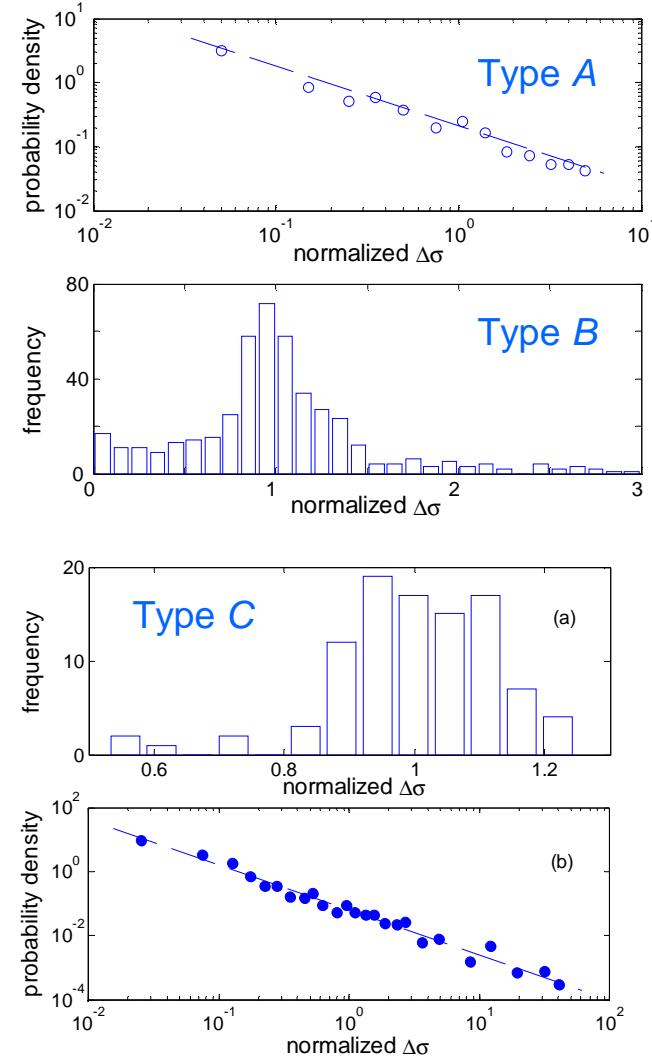
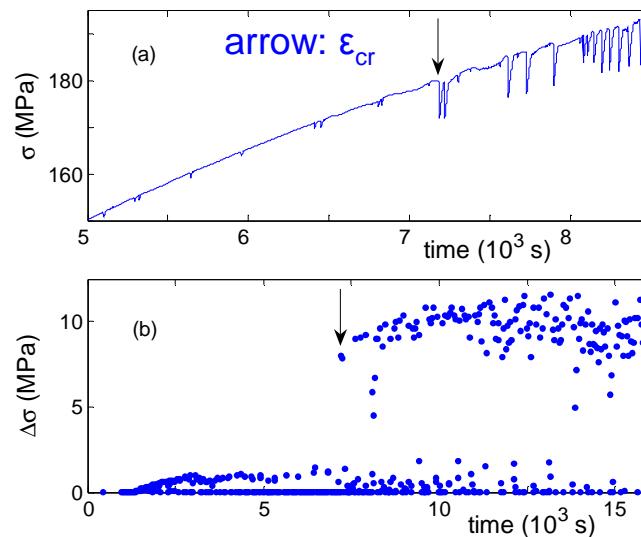
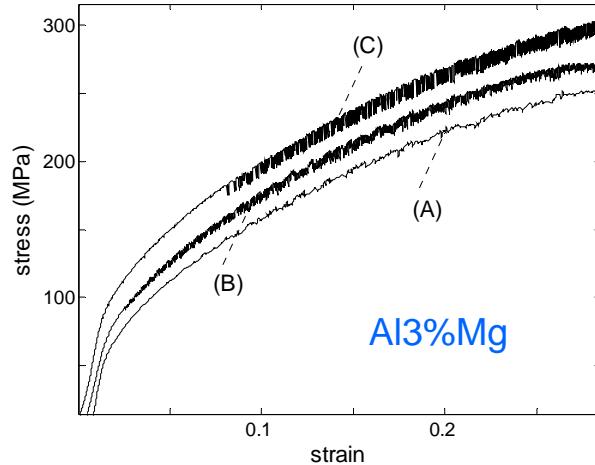
- $\sigma(t)$, AE, $\varepsilon_{loc}(t)$: Access to several scales of the processes in the same test
- ε_{cr} for the onset of the PLC effect: access to quasi-smooth and jerky deformation in the same test

Experimental

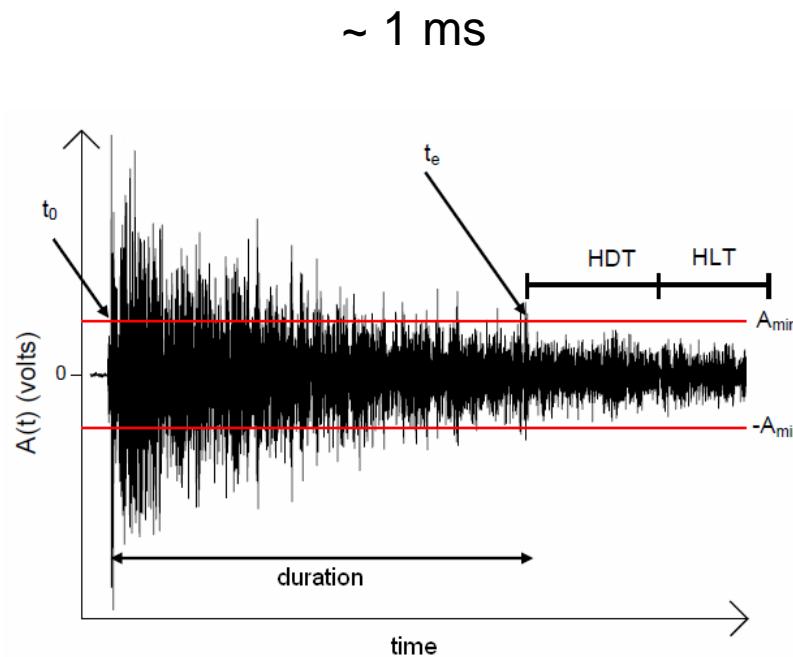


Deformation curves: $10^{-2} - 10^{-1}$ s, bulk, 10^6 dislocations
 AE: 10^{-6} s, bulk, 10^2 dislocations
 CCD camera: 10^{-3} s, surface, 10^4 dislocations

Statistics of stress jumps

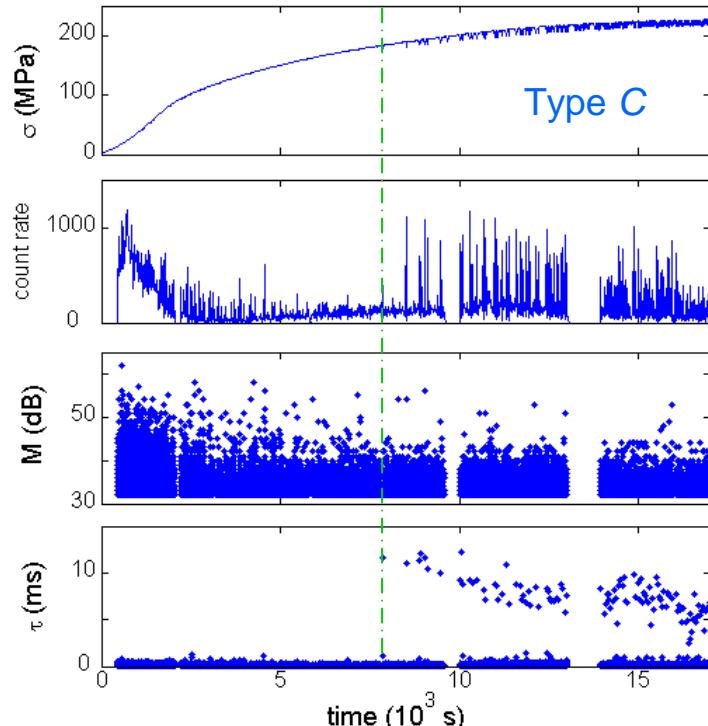


Acoustic emission settings



HDT = 300 μs to 30 μs –40 μs

Global view of AE



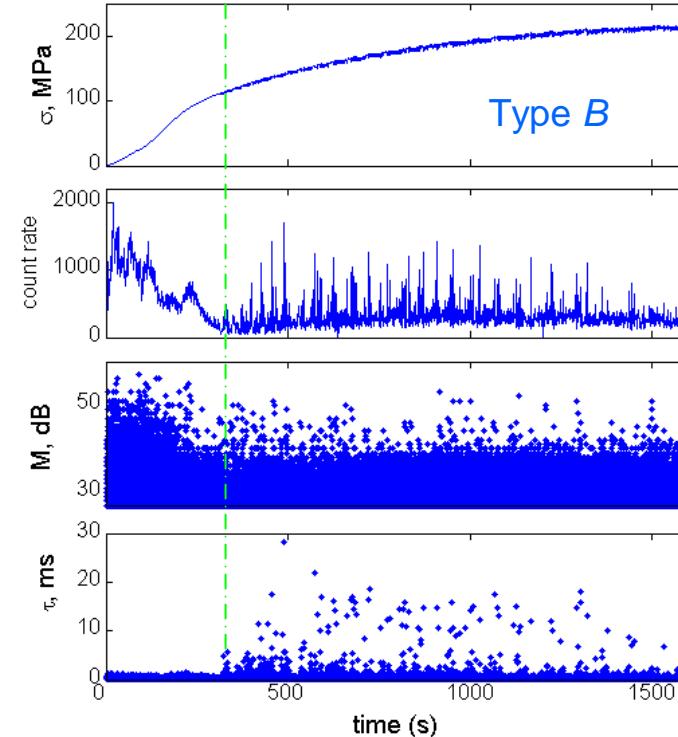
$2 \cdot 10^{-5} \text{ s}^{-1}$

Similar amplitudes
Bursts in durations

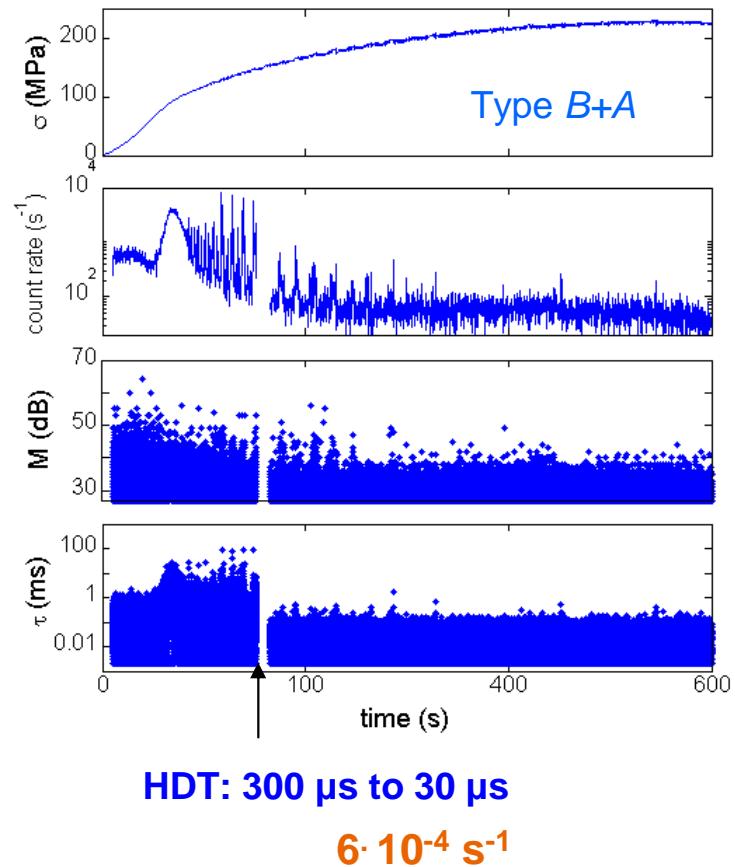
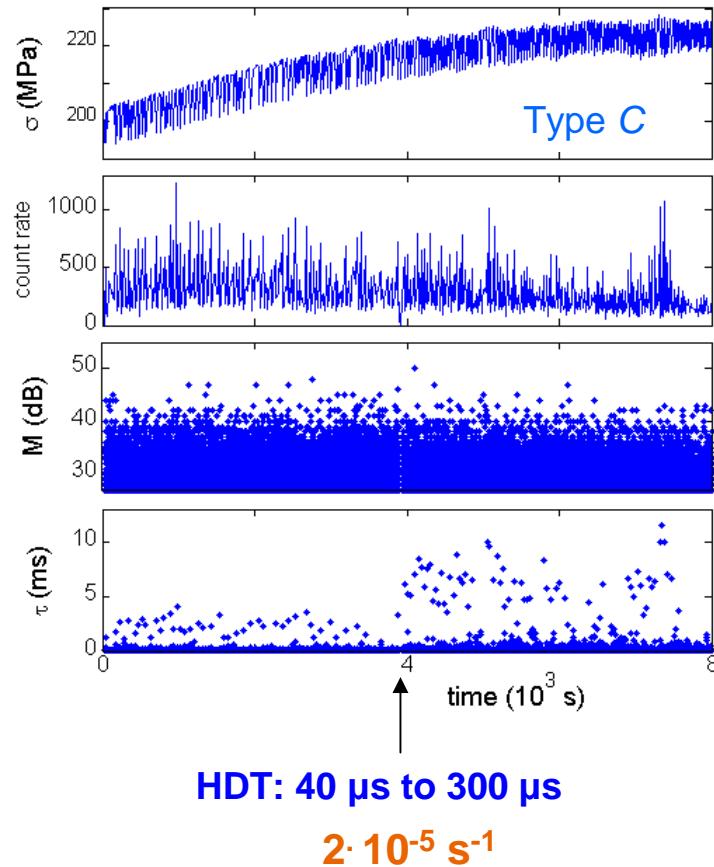
HDT = 300 μs

$2 \cdot 10^{-4} \text{ s}^{-1}$

→ Events merging?

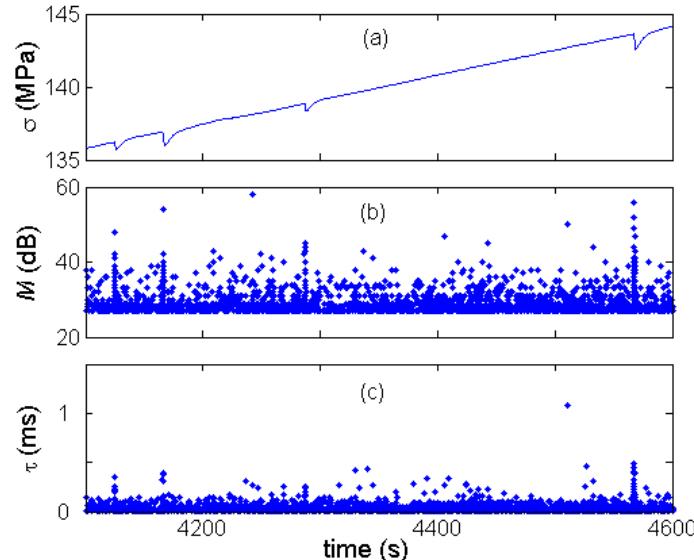


Effect of changing the settings

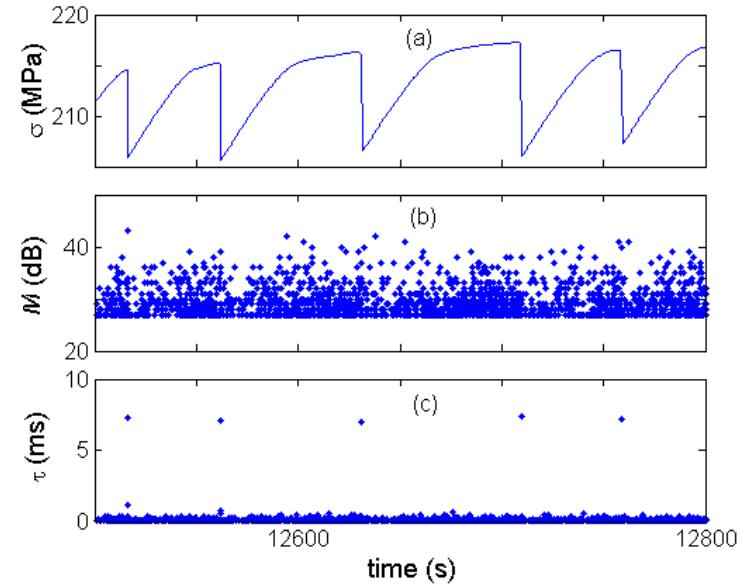


Events merging

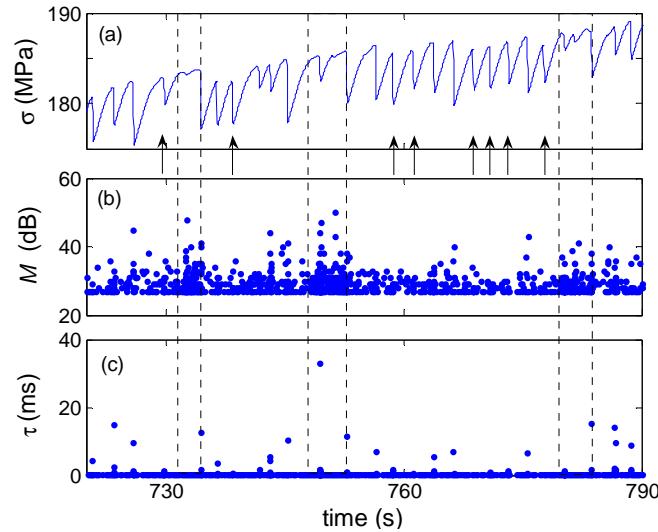
HDT = 300 μ s



$2 \cdot 10^{-5} \text{ s}^{-1}$



$2 \cdot 10^{-4} \text{ s}^{-1}$

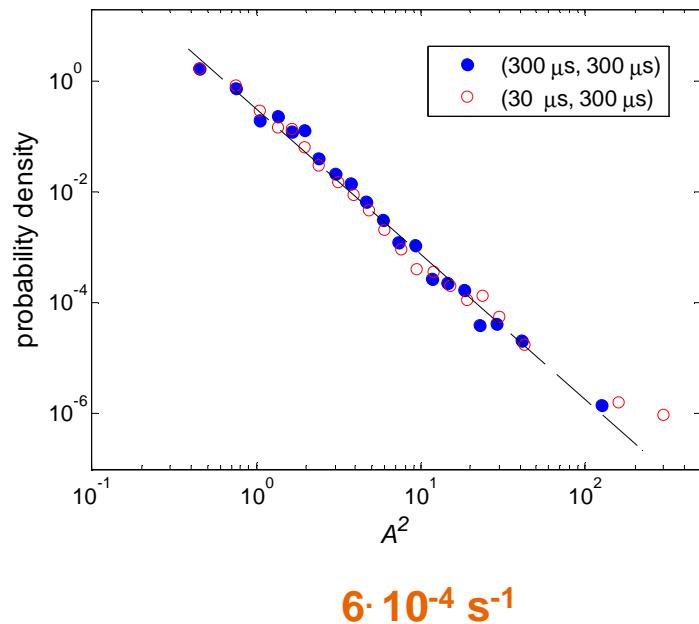


- Arrows: stress drops without burst in duration
- Dashed rectangles: higher activity between type *B* series

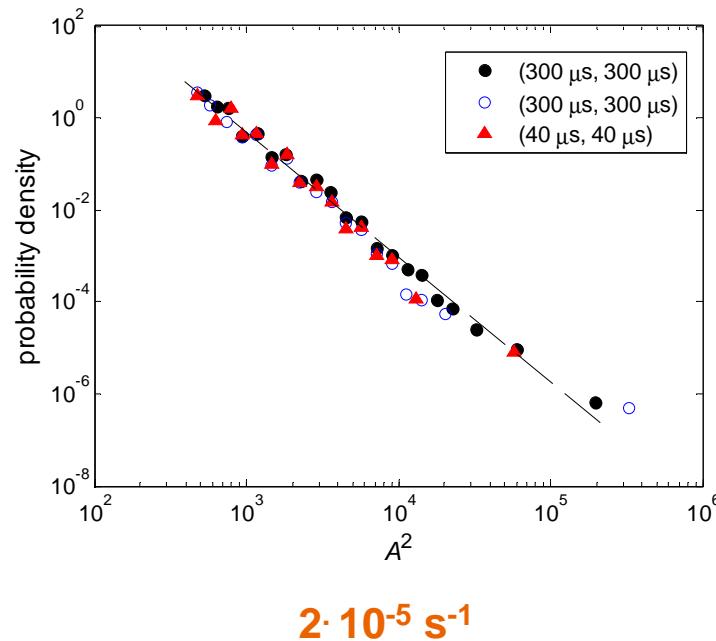
Statistics of the AE events

Power law in all experimental conditions

Effect of changing the settings

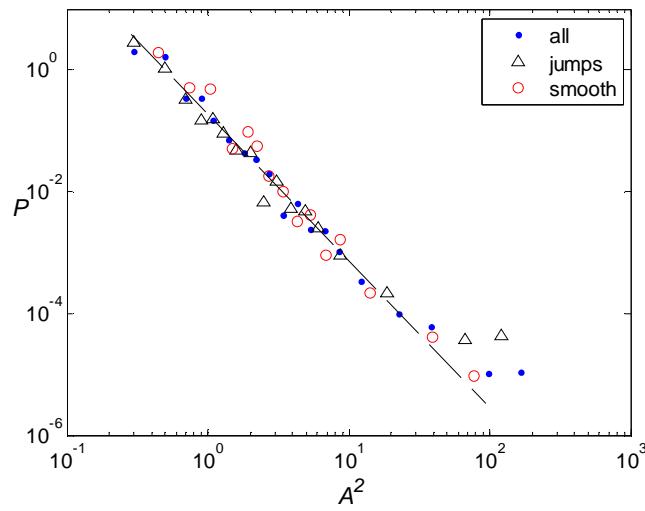
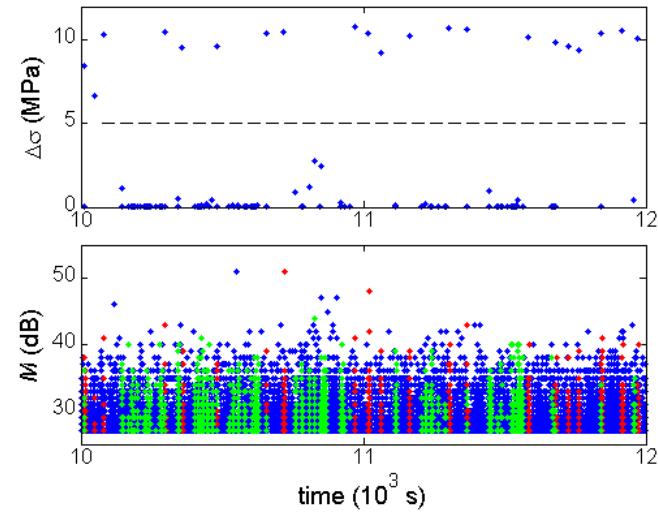
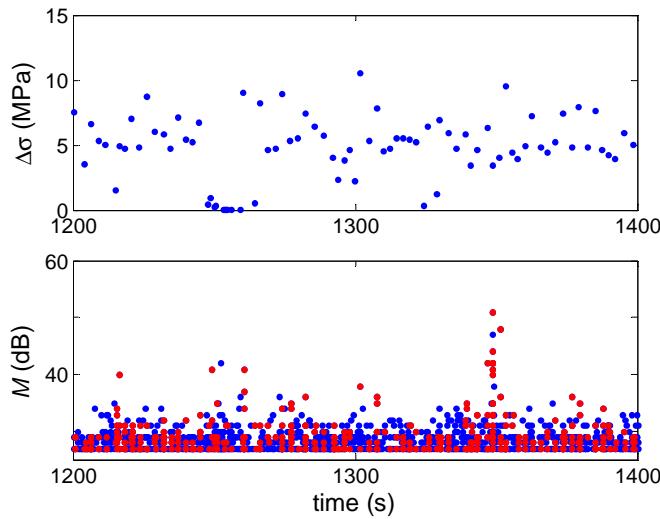


One sample
 Change during the test

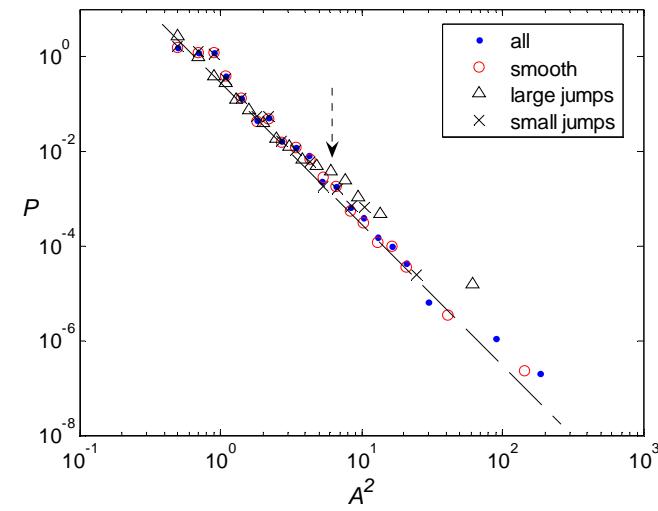


Three samples

Separation of AE events

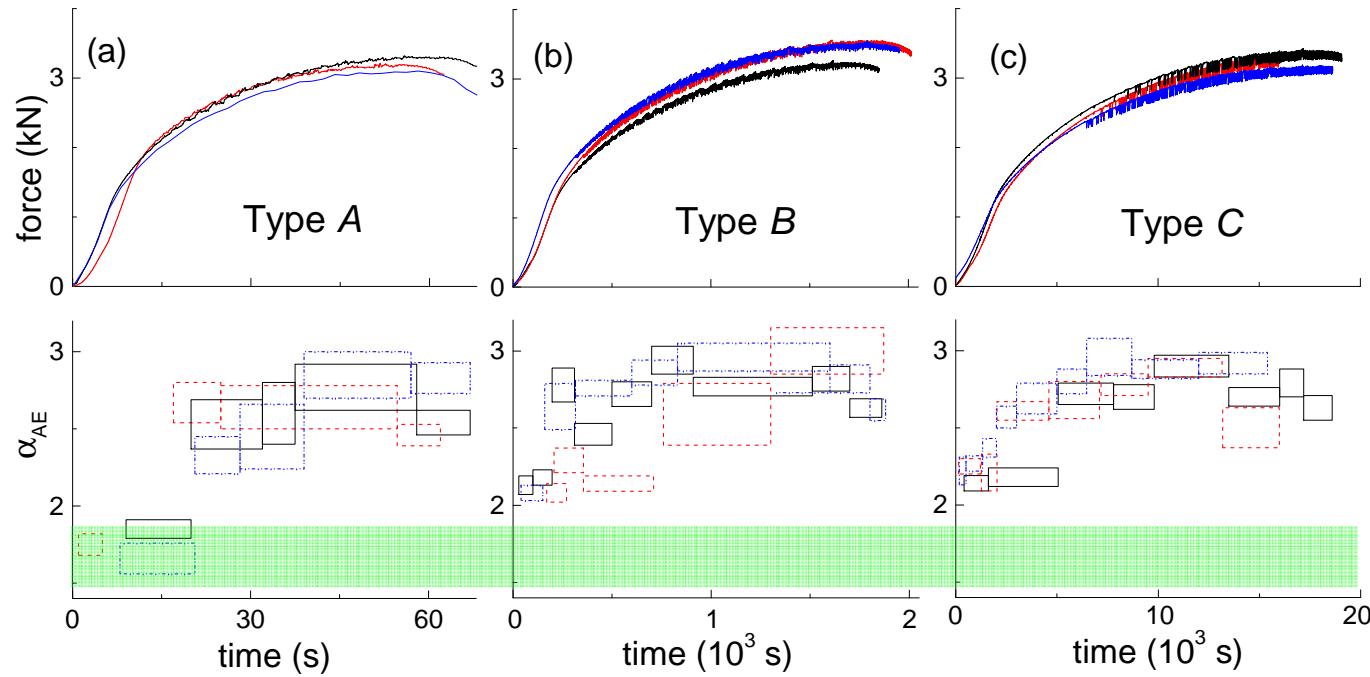


$2 \cdot 10^{-4} \text{ s}^{-1}$



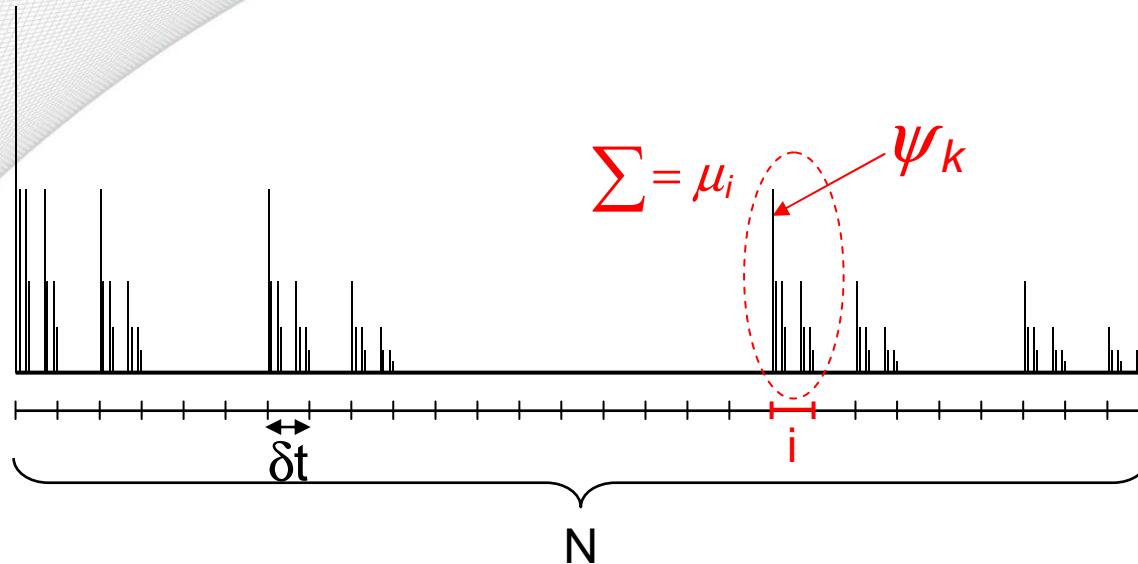
$2 \cdot 10^{-5} \text{ s}^{-1}$

Statistics of the AE: summary



- The exponent changes during deformation: quantitative difference from the case of pure materials. Influence of DSA?

Multifractal analysis



- constant signal

- periodic or stochastic: $\delta t \gg \lambda$

$$\mu_i \sim \delta t, \quad N = 1/\delta t$$

$$Z_q \sim \delta t^q \times 1/\delta t = \delta t^{q-1}$$

local measure:

$$\mu_i(\delta t) = \frac{\sum_{\text{int. } i} \psi_k}{\sum_{N \text{ int.}} \psi_k}$$

$$Z_q = \sum_{i=1}^N \mu_i^q$$

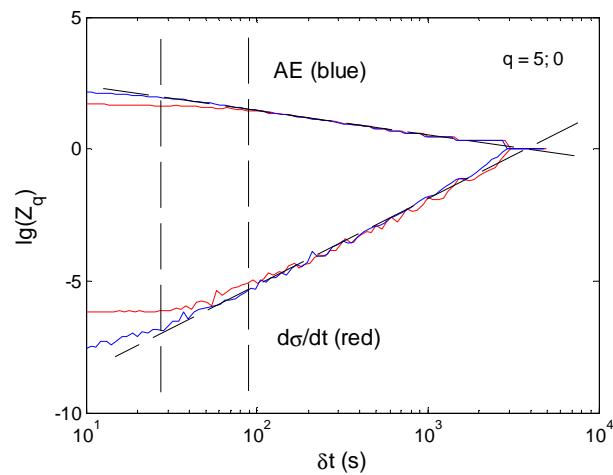
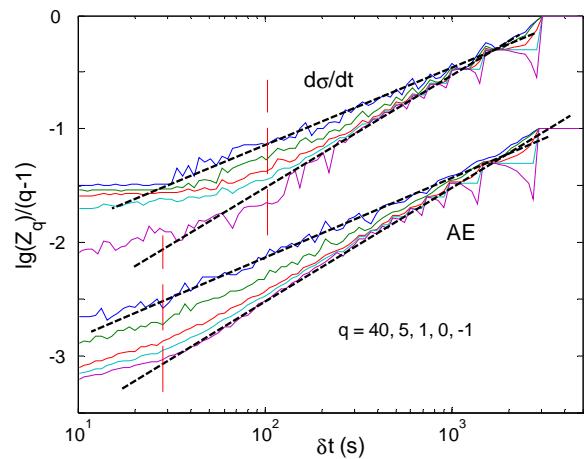
- self-similar signal: $Z_q \sim \delta t^{(q-1)D_q}$
 D_q : generalized fractal dimensions

$$\frac{\log(Z_q)}{q-1} \sim \log(\delta t)$$

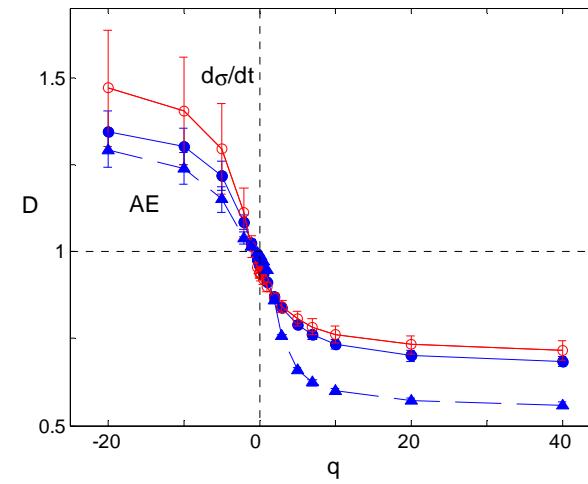
$$\frac{\log(Z_q)}{q-1} \sim D_q \log(\delta t)$$

Results of analysis

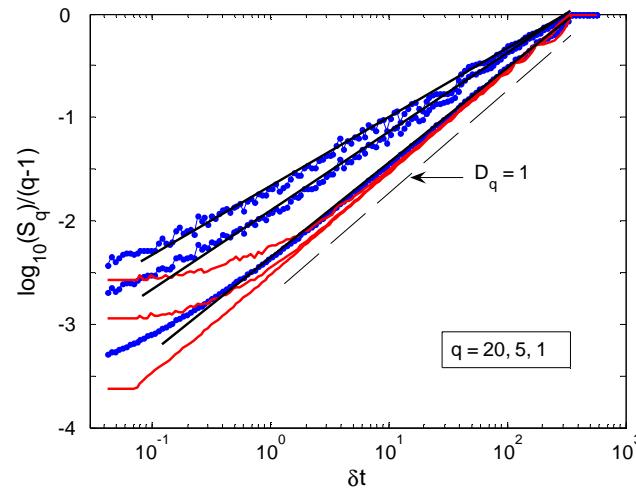
Examples of partition functions



Spectra of generalized dimensions



Surrogate AE series

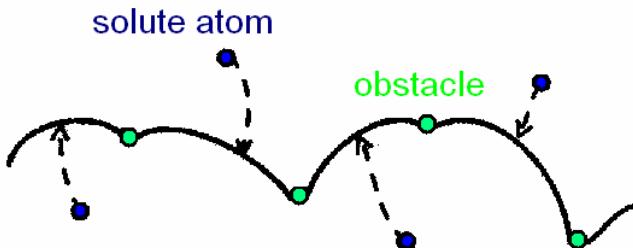


Experimental conclusions

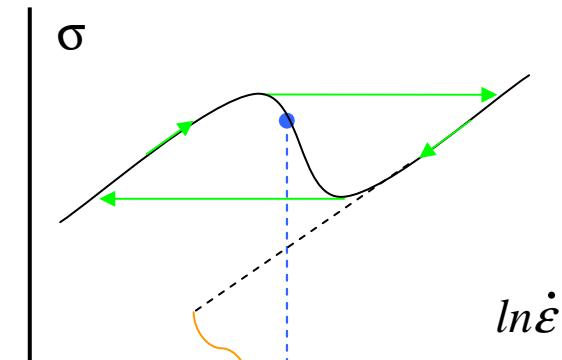
- Similar amplitude scale, similar scaling properties of AE: common nature of dislocation processes in jerky and smooth flow
- Power-law statistics for AE, for small stress jumps: inherently intermittent scale-invariant character of plasticity
 - Why there is no sporadic stress serrations in bulk samples of pure materials?
 - Why there is no AE bursts during PLC stress serrations?
- AE + $\sigma(t)$: dependence of the statistics on the scale of observation. Concurrence between scaling and synchronization: PLC bands as aggregates of dislocation avalanches. The dislocation avalanches themselves are described by scale-free distributions, characteristic scales may characterize stress serrations.

Mechanism of the PLC effect

Additional pinning of dislocations by solute atoms

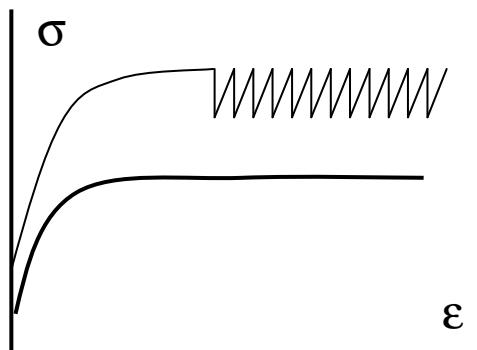


Negative Strain Rate Sensitivity, SRS < 0



Arrhenius equation for thermal activation of dislocations

Relaxation oscillations



- Threshold stress
- Two distinct time scales
- Spatial coupling between defects

Relevant models

- **Self-organized criticality** (classical example: earthquakes)

P. Bak, C. Tang, and K. Wiesenfeld, Phys. Rev. A **38**, 364 (1988).

- **Synchronization** (classical example : fireflies, lucioles)

S.H. Strogatz, Physica D **143**, 1 (2000).

- **Concurrence of scale-invariance and synchronization**

C.J. Pérez, Á. Corral, A. Díaz-Guilera, K. Christensen, and A. Arenas, Int. J. Mod. Phys. B, **10**, 1111 (1996).

- **SOC: strong coupling and weak nonlinearity** (high strain rate)
- **Synchronization: weak coupling and strong nonlinearity** (low strain rate)

- Imposed strain rate \longrightarrow degree of nonlinearity
- Concurrence of the reloading time and the plastic relaxation time \longrightarrow coupling strength

L.P. Kubin, C. Fressengeas, and Ananthakrishna, in *Dislocations in Solids*, Vol. 11, 101-192, Eds. F.R.N. Nabarro and M.S. Duesbery (Elsevier Science BV, Amsterdam, 2002).

Impact on the PLC models

Problem of the critical strain

Basic condition: $SRS < 0$ (L.P. Kubin, Y. Estrin)

Actual experiments: Should the conditions of synchronization be the second necessary condition ?