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Shear banding and hysteresis in complex fluids

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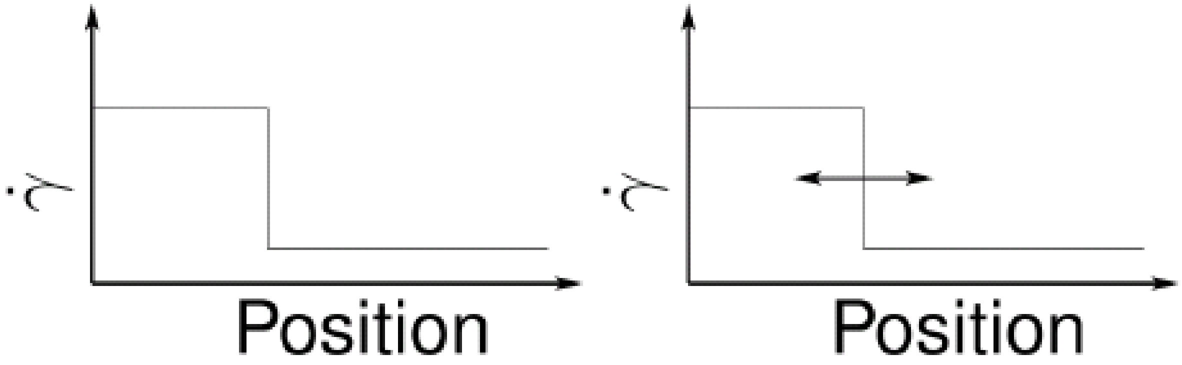
Work done in collaboration with: Antti Puisto, Mikael Mohtaschemi (Aalto), Xavier Illa (Barceolona), …

Outline:

- Comments on shear bands: Couette test case. Particles in flows.
- Hysteresis in fluids?
- Model for the same.
- Conclusions/perspectives.

Shear-banding in complex flows

- Shear banding is a stationary state, where two (or more) different shear rates regimes apppear
- In transient shear banding, as the name suggests, the shear band propagates and vanishes in time

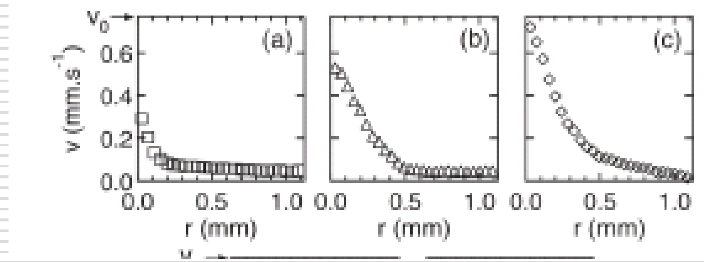


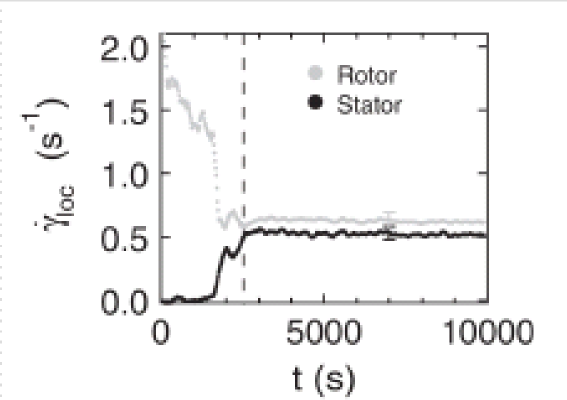
Transient shear banding

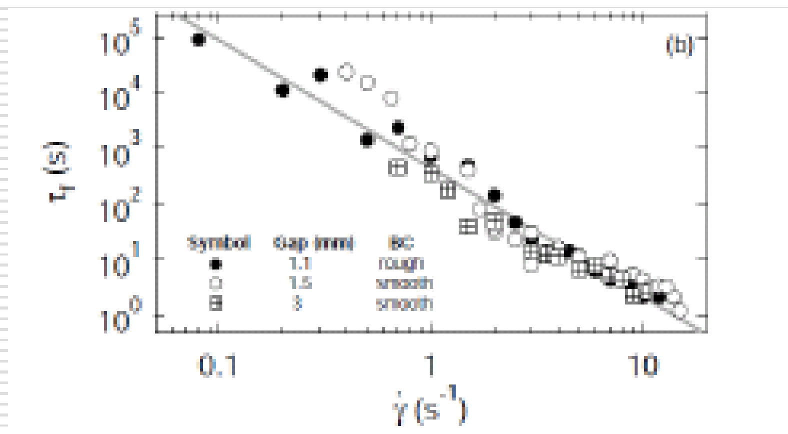
PRL **104**, 208301 (2010)

Couette device,

yield stress fluid ($\sigma = \sigma_c + B\varepsilon_t{}^k$)







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Transient shear banding

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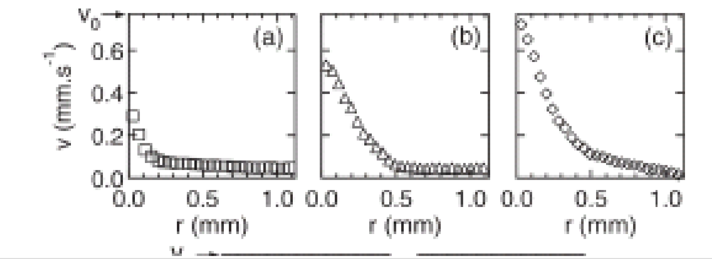
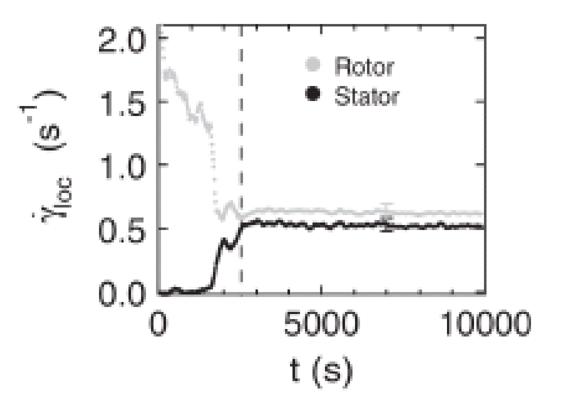
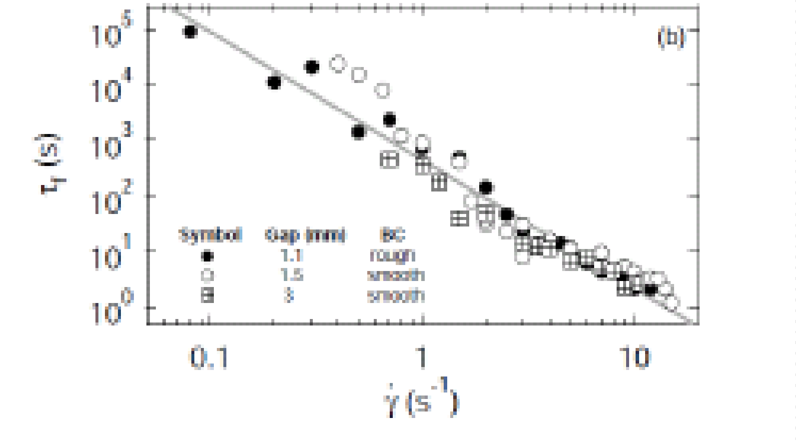
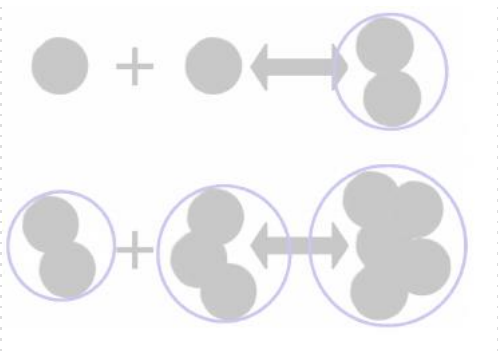






Attractive colloids and (T)SB

Fractal aggregates plus PBE plus effective viscosity:



Lambda-models and other structural models….

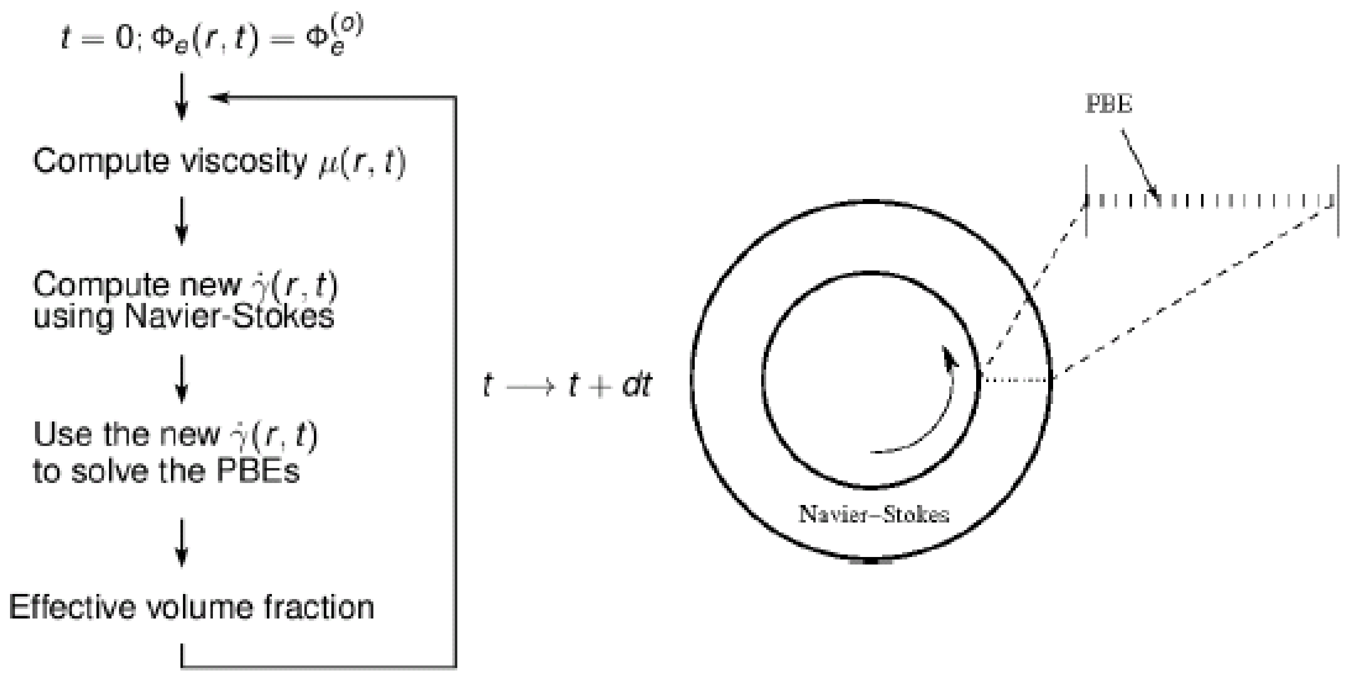
Particle Balance Equations… viscosity equation, cluster swelling (fractal dimension).

Krieger-Dougherty equation

$$\mu_s = \mu_0 \left(1 - \frac{\Phi_e}{\Phi_m}\right)^{-\lambda}$$

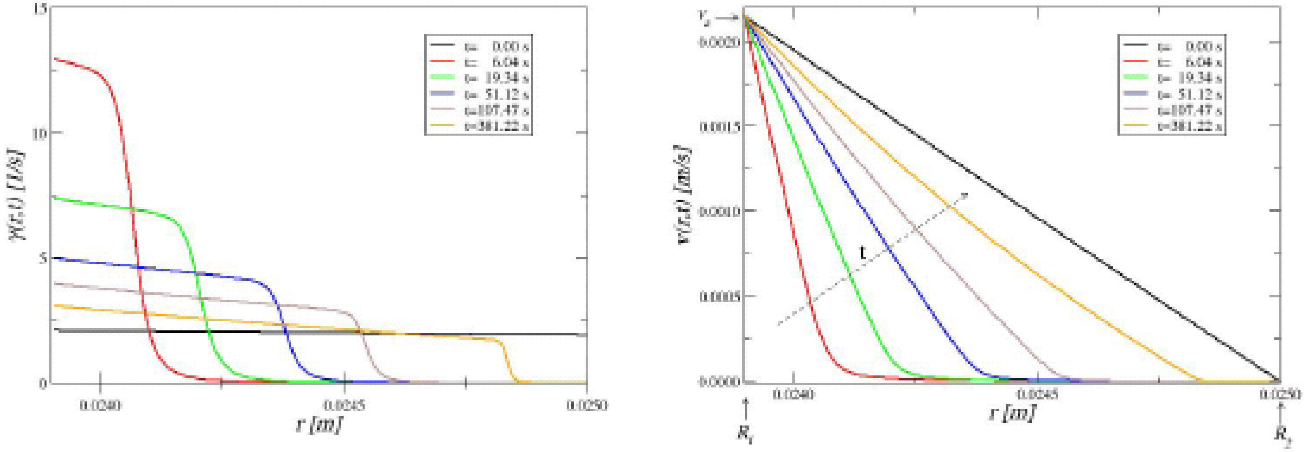
$$k^{(a)}(i,j) = \frac{4}{3} C_e \dot{\gamma} (r_i + r_j)^3, \quad k^{(b)}(i) = \dot{\gamma} \exp\left(-\frac{F_c}{F_h}\right)$$

Virtual rheometer



TSB - results

- Transient Shear Banding seen with a substance with **high initial viscosity**, and **small average bond force**



Role of cohesion, volume fraction, shear rate…

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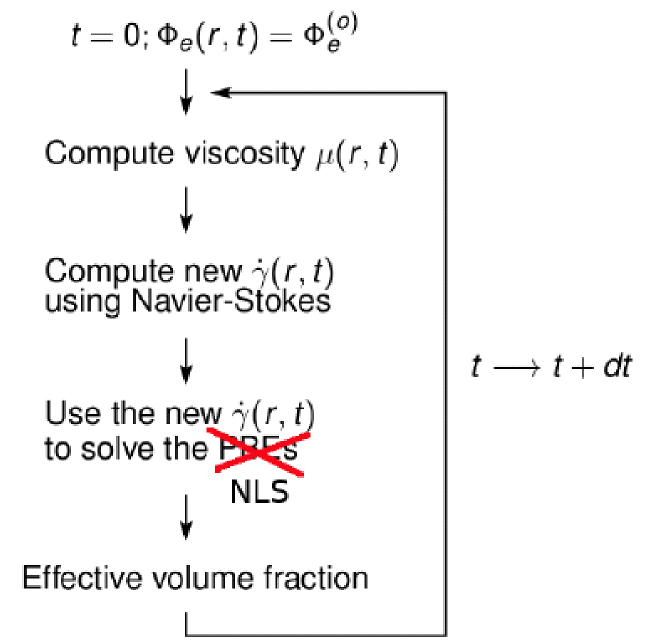
Non-Linear Structural Model

- Shear Thinning
- Characteristic relaxation time

Quemada, Appl. Rheol. **18** 53298 (2008)

$$\Phi_e = (1 + CS)\Phi$$

$$\frac{dS}{dt} = \kappa_F(1 - S) - \kappa_D S$$



$$\kappa_D(t) = k_c \dot{\gamma}(t)$$

$$\kappa_F(t) = \frac{k_A}{\mu_s(t)}$$

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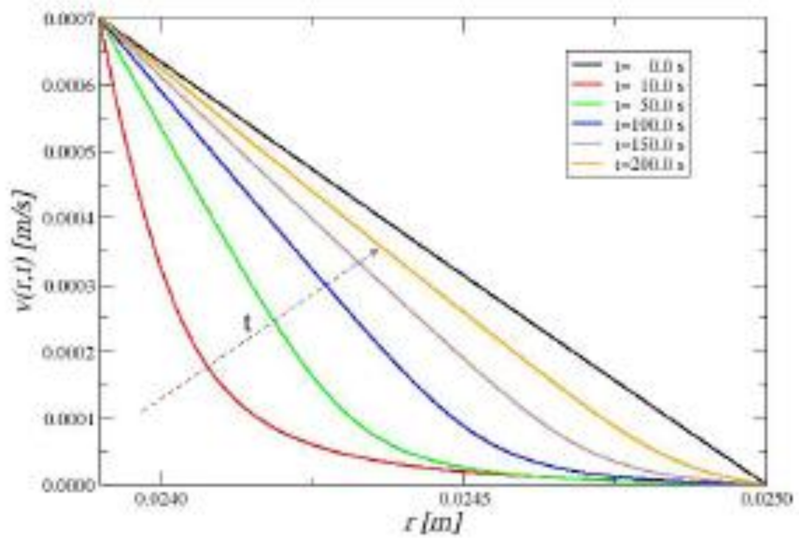
NLS behavior



- Shear thinning…
- TSB… (Puisto et al. PRE 2013, see also talk last week and Soft Matter 2014, PBE)

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Shear thinning model

- Simplest relaxation equation with the basic ingredients (shear thinning, characteristic time)

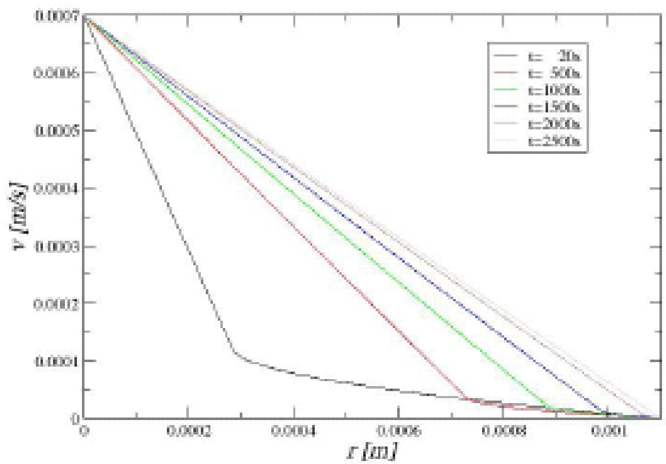
$$\frac{\partial \Phi}{\partial t} = -c\dot{\gamma}^{\kappa}\Phi(r,t)$$

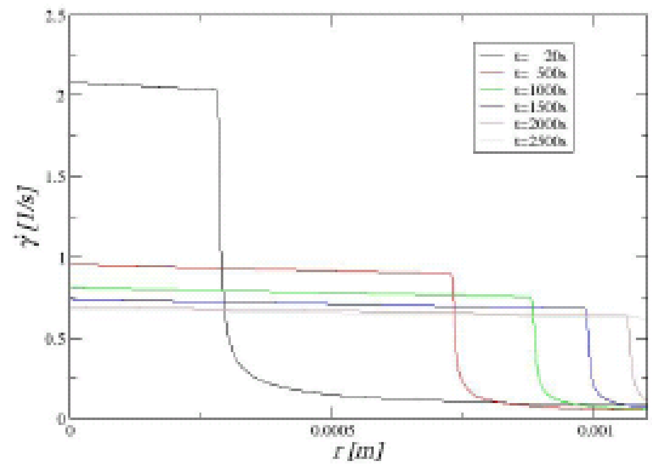
- Viscosity from volume fraction

$$\mu_s = \mu_0 \left(1 - \frac{\Phi}{\Phi_m}\right)^{-\lambda}$$

Simple model: results

- Transient shear banding with the simple model
- The model parameters are adjusted to produce the experimental timescales





A little stop

The previous story: even ”Simple Yield Stress Fluids” have shear bands in typical experiments.

They thus appear to be thixotropic in spite of a unique steady-state…

What happens if you vary stress/shear rate systematically…?

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Experiments

Wait a second: fluids exhibit hysteresis in the effective flow curve - stress vs. shear rate, $\sigma(\varepsilon_t)$ at finite rates.

What is the reason?

PRL 110, 018304 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Rheological Hysteresis in Soft Glassy Materials

Thibaut Divoux, Vincent Grenard, and Sébastien Manneville

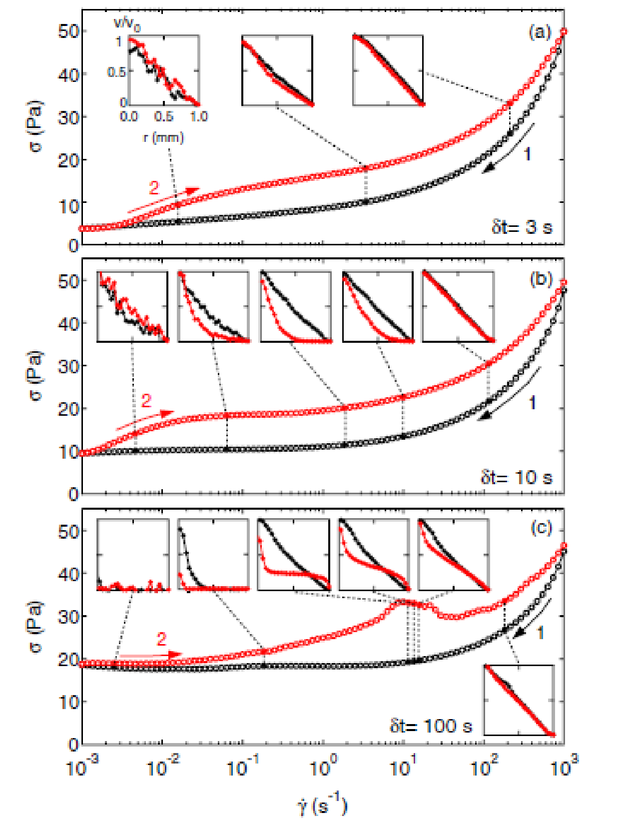
Université de Lyon, Laboratoire de Physique, École Normale Supérieure de Lyon, CNRS UMR 5672, 46 Allée d'Italie, 69364 Lyon cedex 07, France

(Received 17 July 2012; published 2 January 2013)

Case: Laponite

The main parameter of a rheological test: Waiting time at a given shear rate or applied stress.

Shear bands appear…



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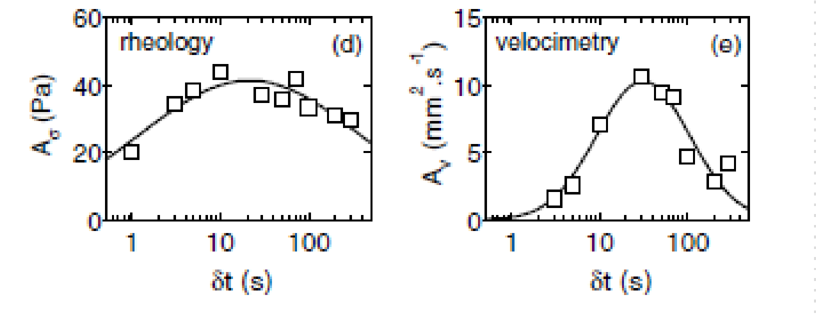
Hysteresis loop area

Measure both the flow curve and use US Velocimetry.



$$A_\sigma \equiv \int_{\dot{\gamma}_{\min}}^{\dot{\gamma}_{\max}} |\Delta\sigma(\dot{\gamma})| d(\log \dot{\gamma}),$$

A peak: classical Dynamical Hysteresis

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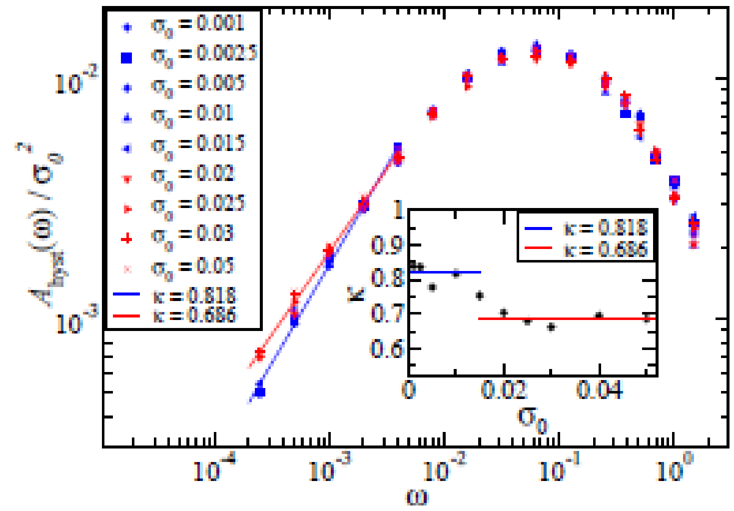
The paradigm of DH

The loop area: maximum.

Low and high-frequency tails?

Dominating processes, location of the peak.

(Ising magnets)



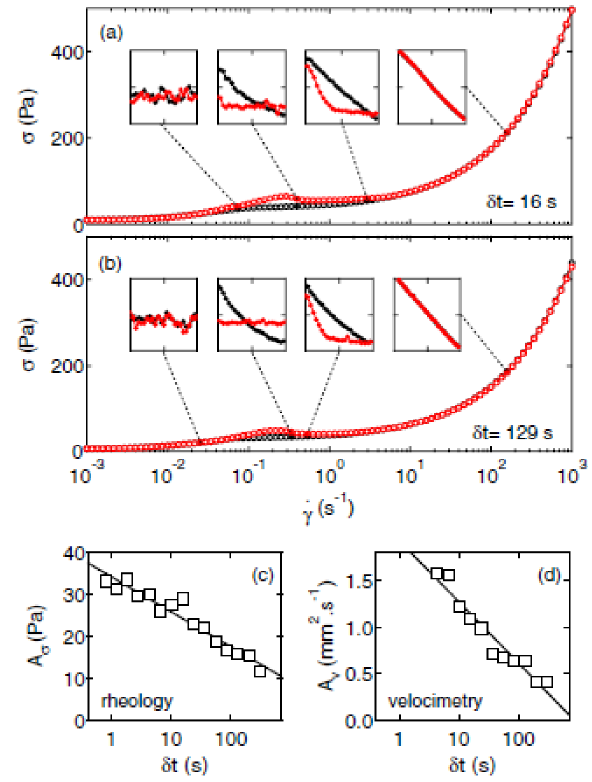
Example: a disordered system (Laurson, Alava, PRL 2012)

Faster relaxation:

Carbopol: ideal Yield Stress Fluid (HB-fluid),

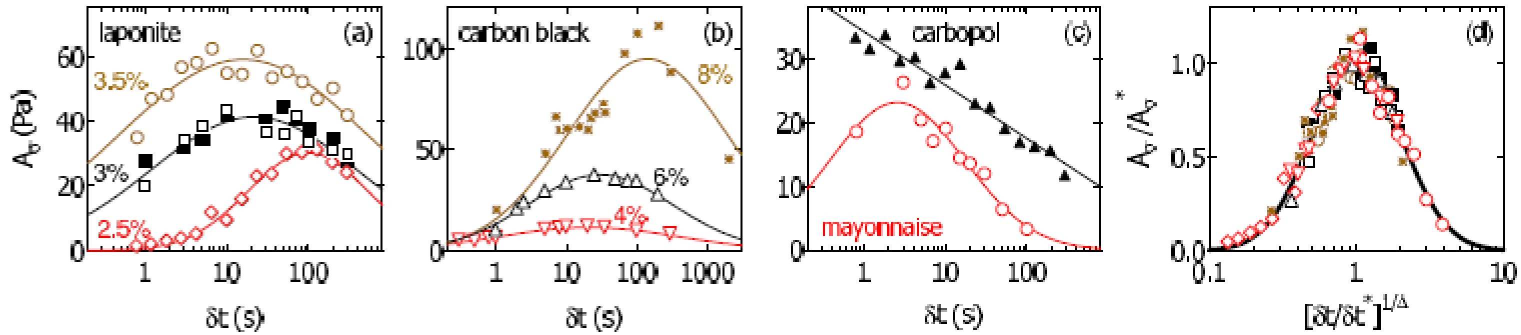
Transient Shear Bands.

No peak, but decaying hysteresis. TSBs.



Universality?

Summary of experimental fact: a single hysteresis loop area curve.



Minimal model....

Origin of hysteresis:

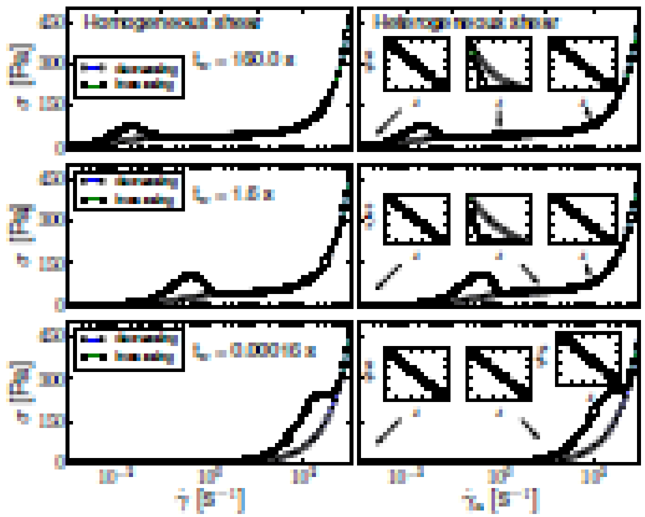
Response of the internal structure.

Shear-bands?

Viscoelastic (Maxwell) relaxation?

Repeat the TSB program....

Puisto et al, Soft Matter subm.

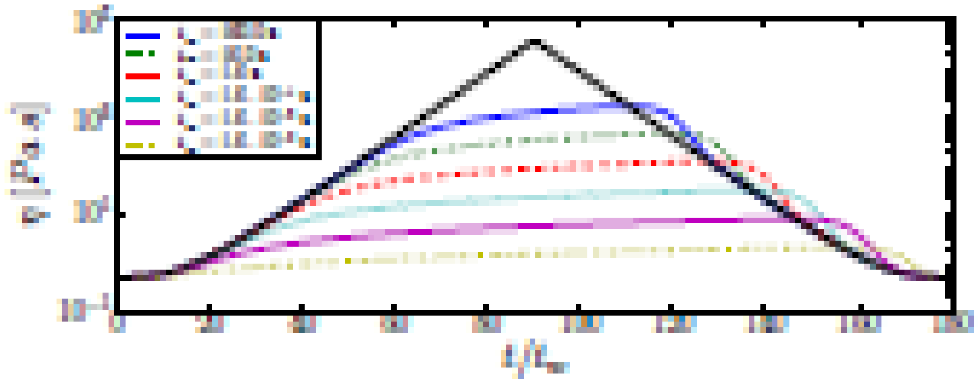


$$\frac{d\phi}{dt} = \frac{A_b}{(\eta/\eta_o)^m} + (A_s - B_s\phi)\left(\frac{\dot{\gamma}}{\dot{\gamma}_0}\right)^k,$$

$$\sigma = \dot{\gamma}\eta + \frac{\eta}{G_0}\dot{\sigma}$$

Look at the viscosity…

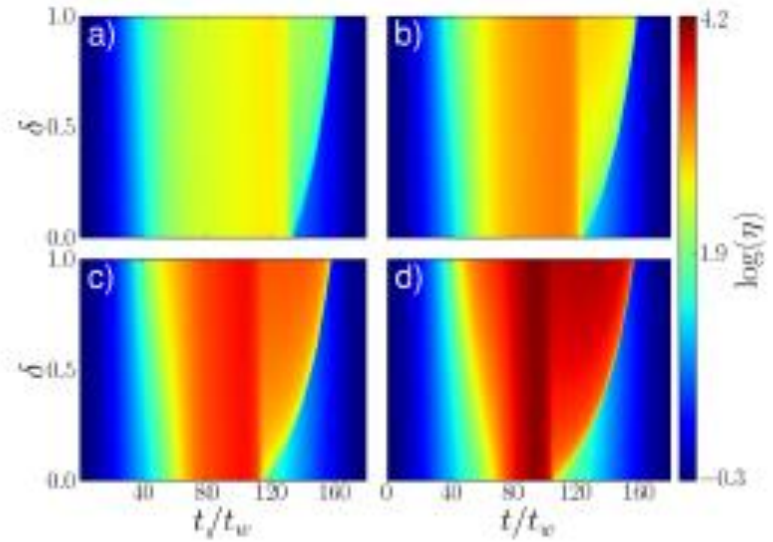
The hysteretic response originates (mostly) from the internal response: the viscosity shows inertia as a consequence.



Role of TSB: gap velocity

Comparison of "MF" and spatially explicit (Couette) case: yes, the TSB(s) depend on waiting times.

Effect however…



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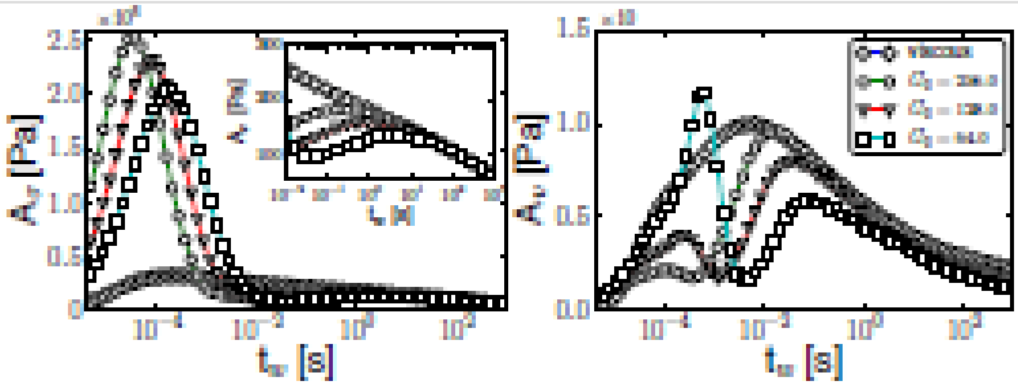
Role of viscoelasticity

A second peak develops in the hysteresis plot.

Natural, as another ratio of timescales is added, check in expts!



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Complex particle suspensions

- Time-dependent shear-bands.
- Here: models for particles in fluids. SGM, ”flowing solids”, STZ in particular.
- Models of various sophistication (”rheometer”, PBE, ”lambda”, ….).
- How to understand/define/quantify:
  Memory = complexity?
- Hysteresis: a spectrum of relaxation times.