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Strain intermittency in shape memory alloys

N. Barrera[1,2], X. Balandraud[1], M. Grédiac[1], P. Biscari[2], G. Zanzotto[3]

Outline

1. Background
2. Experimental setup
3. Comparison with earlier tests
4. Results
5. Conclusions

1. Background
2. Experimental setup
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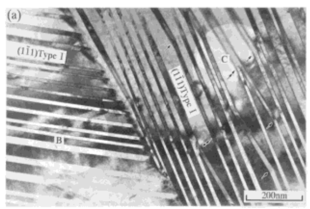
4. Results
5. Conclusions

1. Background

• SMA crystals exhibit microstructures at many scales during reversible martensitic phase transformation

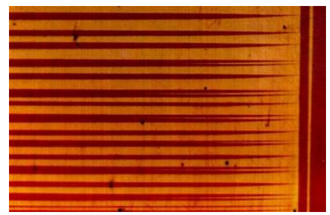
Morphologies largely constrained by crystallographic compatibility between phases and variants

1 μm



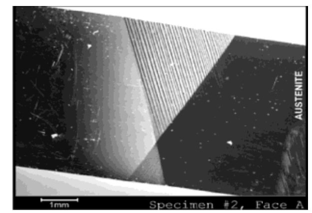
[Nishida et al., Acta Mat 97]

1 mm



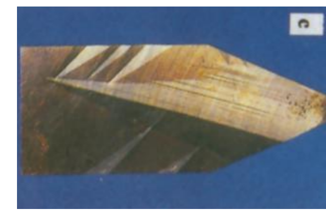
[Chu & James, Phase Trans 09]

1 mm



[Seiner et al., Phase Trans 09]

1 cm



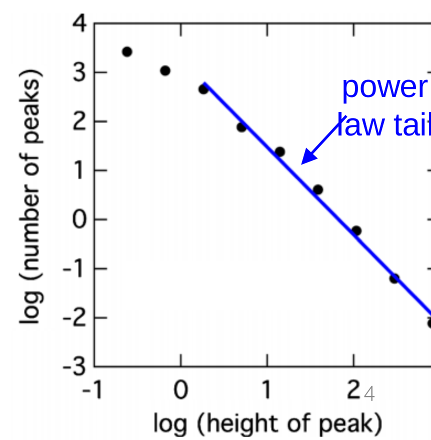
[Tan et al., Cont Mech Thermodyn 90]

• How do the microstructures evolve with the loading?

the phase transformation is in general not a continuous process – space and time intermittency can be observed under both thermal and mechanical driving

- Jerky dynamics through avalanches, shown for instance by acoustic emission studies
  - in typical cases, avalanches follow statistical distributions with heavy tails, often power laws → absence of characteristic scale

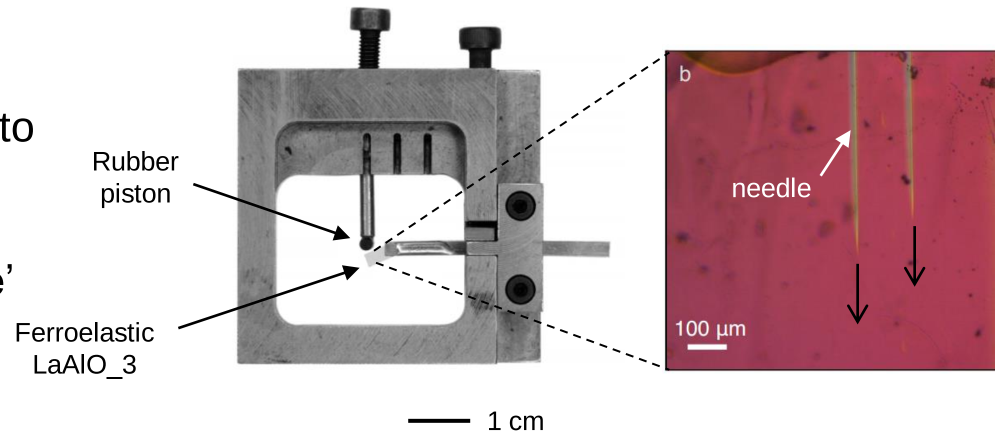
[Carrillo et al., Phys Rev Lett 98, Vives et al. Phys Rev B 09, Planes et al., J All Comp 11, Harrison & Salje 2014]



• Some recent work on evolution of spatial features of phase transformation:

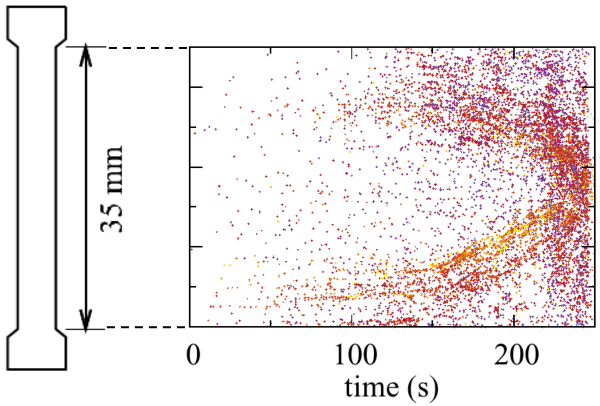
optical microscopy + AE + specific device to get small stress rate
→ Local analysis of intermittency in a needle progression → 'noise of the needle'

[Harrison & Salje, Appl Phys Lett 10]



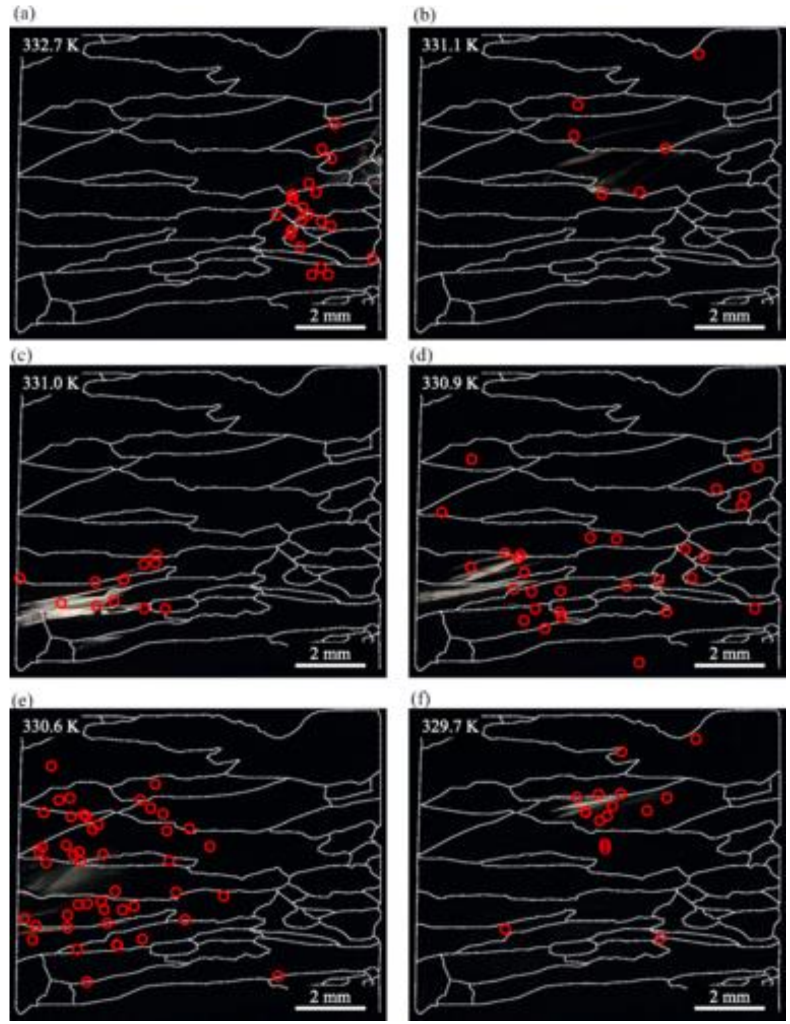
AE analysis with 2 transducers to localize transformation events
→ imaging of (1-d) dynamics of temperature-driven martensitic transformation over SMA CuZnAl sample

[Vives et al, Phys Rev B 11]

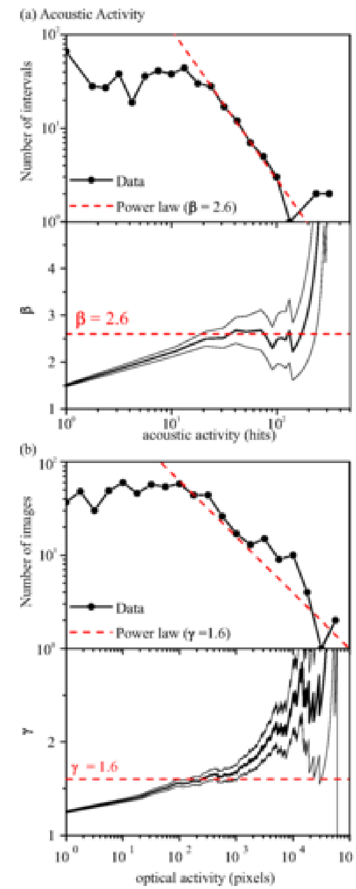


monitoring AE with 4 transducers + optical analysis
→ Localization of AE sources during martensitic transformation across sample + relation to microstructural changes

[R. Niemann, et al. PRB 2014]



[Niemann et al, Phys Rev B 14]



→ lack of systematic sample-wide strain data about intermittent progress of phase transformation

Aims of present study:

- strain field measurement made using the grid method, suitable for investigation of strain bursts

- loading device:

- capable of imposing a constant and small stress rate to the specimen (obtain monotonic loading)

- with minimal imposition of BC: crystal capable to freely adjust orientation in relation to loading to get the 'least complex' microstructures, developed in the absence of effects such as friction, plastification

→ try to investigate transformation strain intermittency occurring in the crystal in its most elementary and basic form

1. Background
2. Experimental setup
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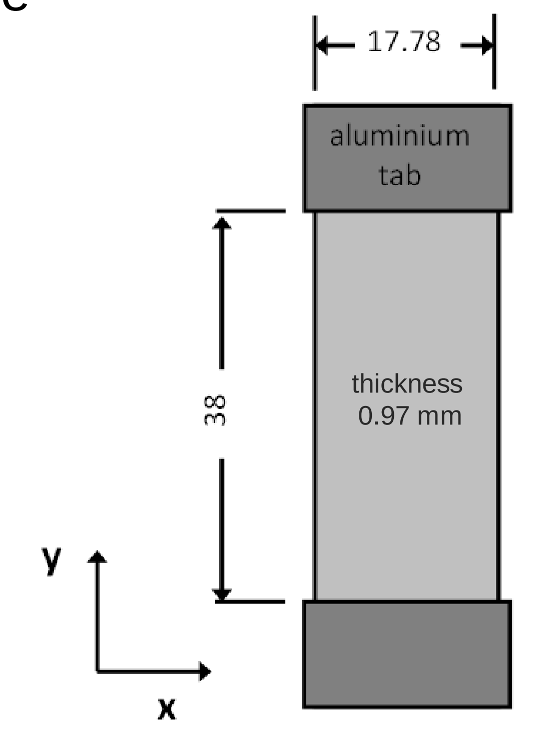
2. Experimental setup

- Specimen

  - Cu $Al_{11.4}$ $Be_{0.5}$ (wt.%)
  - single crystal
  - martensite start *Ms* = 2°C → austenitic at ambient temperature
  - superelastic behavior at ambient temperature

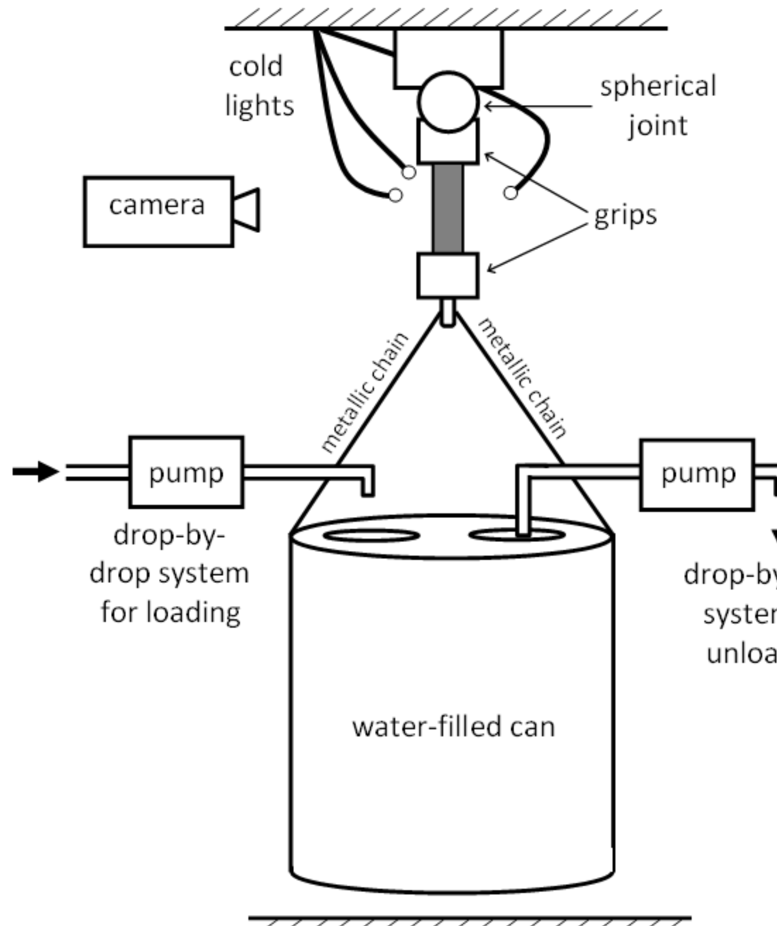
  - austenite: cubic (DO3 structure)
    martensite: monoclinic (M18R structure)

martensite compatible with austenite
(no need of martensite twinning for phase coexistence)
[James & Hane, Acta Mat 00]



- Loading apparatus

mechanical device based on gravity – water-filled tank hung to specimen and system of electronic pumps controls a constant very low water flow



Earlier dead loading tests on SMA (acoustic emission): [Carrillo et al., Phys Rev B 97] [Bonnot et al., Phys Rev B 07] [Vives et al., Phys Rev B 09]

Advantages

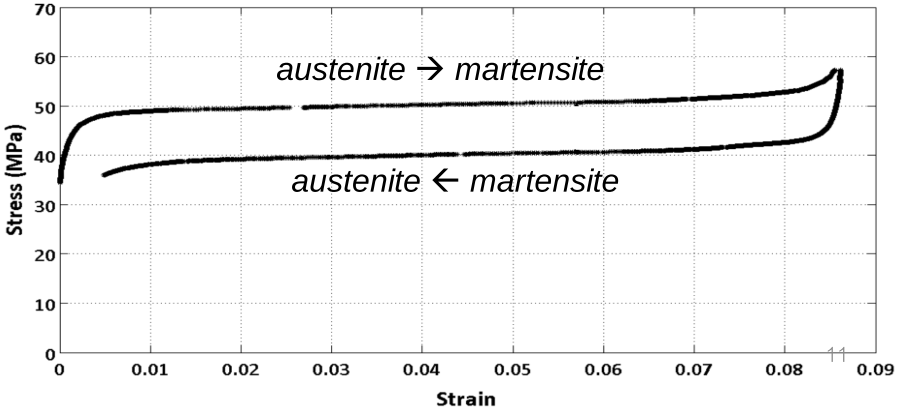
- loading conditions not achievable with conventional testing machines (no feedback loop)
- very small load increments
- perfectly monotonic stress-controlled loading
- ball joints, minimal boundary conditions

Rates in present test

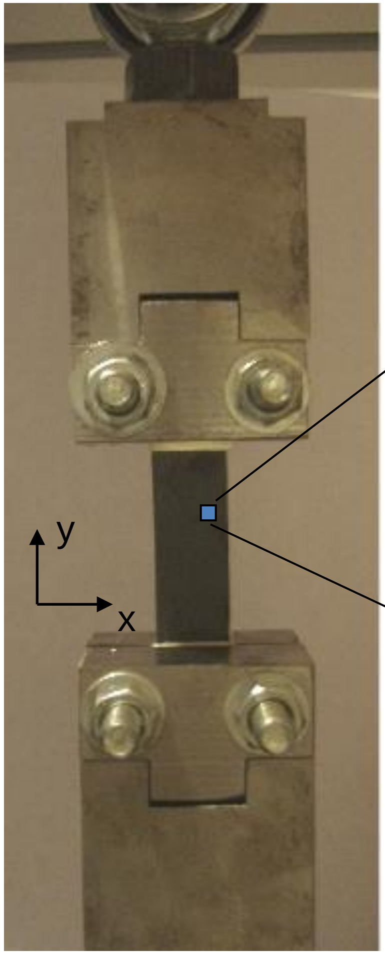
- Step 1: preload (up to 60 liters) → elastic regime, no phase transition
- Step 2: loading rate of 1.055 MPa/h (≈ 17 N/h ≈ 5 mN/s) up to 57.29 MPa (lasted about 22 h)
- Step 3: unloading rate of -0.915 MPa/h (≈ -16 N/h ≈ -4.4 mN/s) down to 35.95 MPa (lasted about 23 h)

test duration: ≈ 45 h

Specific attention to maintain constant ambient temperature over test duration

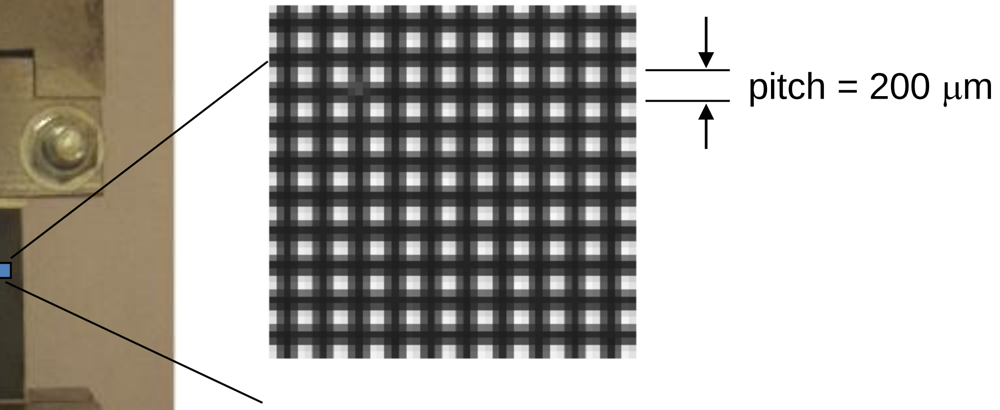


• Measuring strain with the grid method



- Square grid transferred onto specimen, encoded with 5 pixels/period

- Sensicam QE camera featuring 12-bit/1040×1376 pixel sensor and 105 mm Sigma lens



→ Method gives ≈ 600,000 strain gauges bonded onto sample

[Piro et al, **Exp Tech** 2004, Badulescu, et al, **Exp Mech**, 2009, Badulescu et al, **Meas Sci and Tech**, 2009]

- images of the grid captured during entire loading process give the three in-plane strain components and the local rotation about the z-axis, one value per pixel

- one grid image every 8 s, ≈2.2 kPa or ≈0.038 N increase between consecutive images; also ≈10-min break every 100 min for data recording and filling reservoirs

→ in total ≈ 20,000 images obtained along loading/unloading path

1. Context
2. Experimental set up
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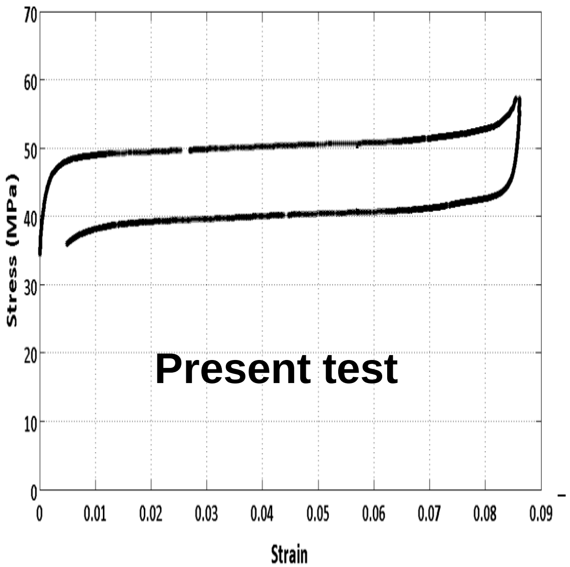
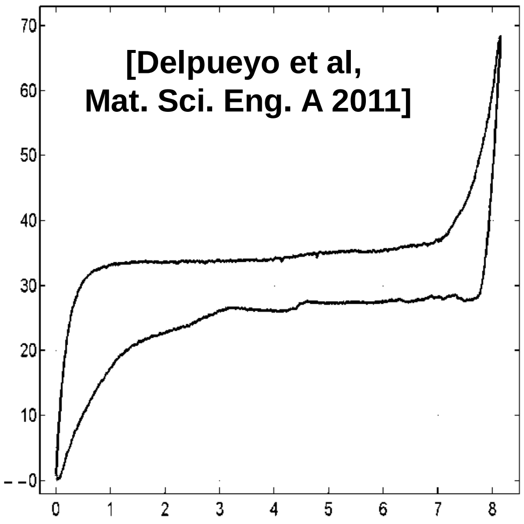
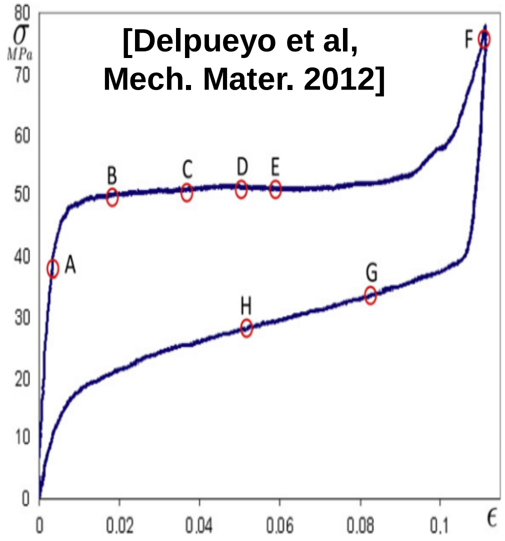
3. Comparison with earlier tests

- stress-strain curve under different loading conditions (**same specimen**)







- present loading system
- ambient ≈ 27 °C
- plateau duration ≈ 6 hours
- stress-controlled

- MTS hydraulic testing machine
- ambient ≈ 22 °C
- plateau duration ≈ 30 min
- strain-controlled

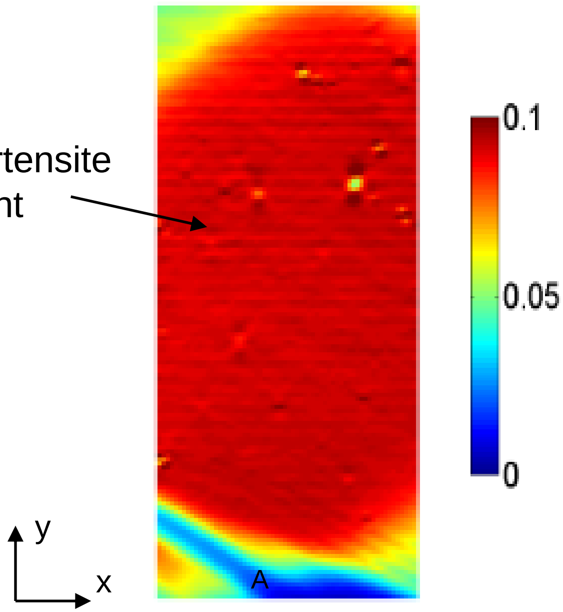
- MTS hydraulic testing machine
- ambient ≈ 22 °C
- plateau duration ≈ 1 min
- strain-controlled during loading stress-controlled during unloading

→ rather small and quite smooth hysteresis loop

• The strain fields under different loading conditions

Present test

Single martensite variant

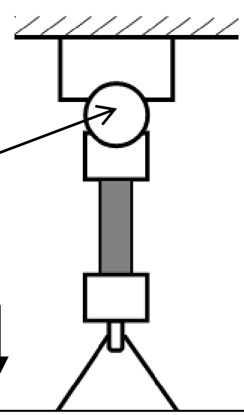


Ball joint + constant force direction

uniaxial loading

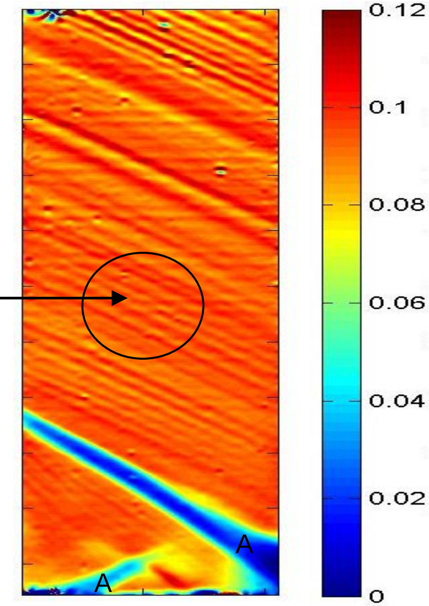
ball joint

gravity



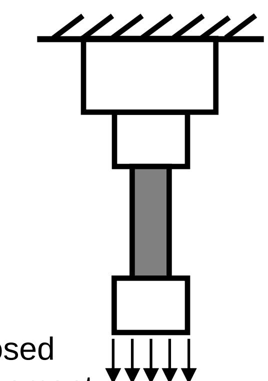
[Delpueyo et al. 2012]

Martensite twin (two martensite variants)



Imposed elongation + horizontal displacement not allowed

heterogeneous stress field



imposed displacement

1. Context
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Tracking the A↔M transformation and its intermittency under the loading

4 Results

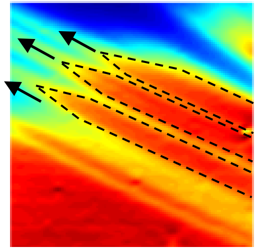
4.1 Hysteresis and strain maps

4.2 Strain clustering

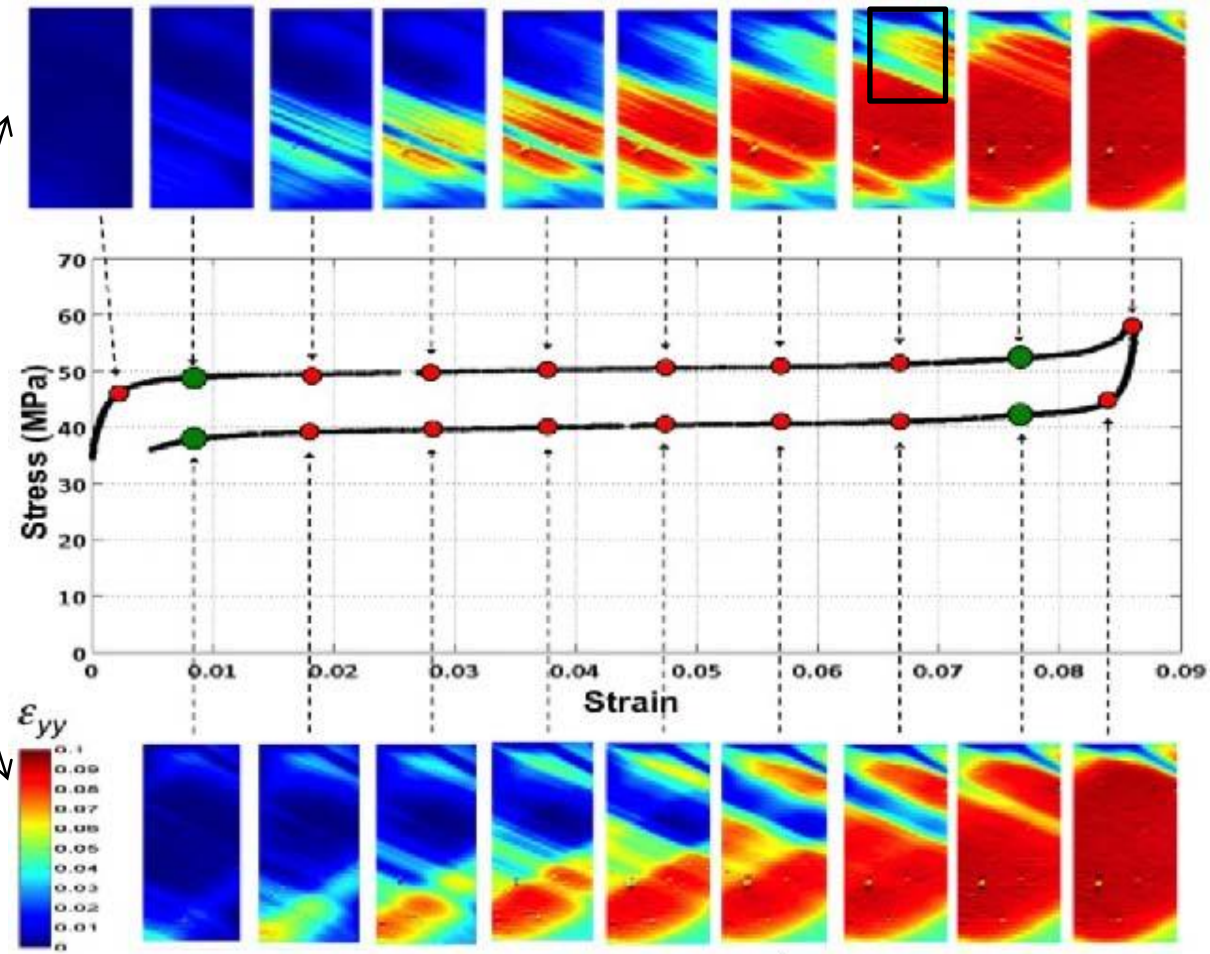
4.3 Intermittency

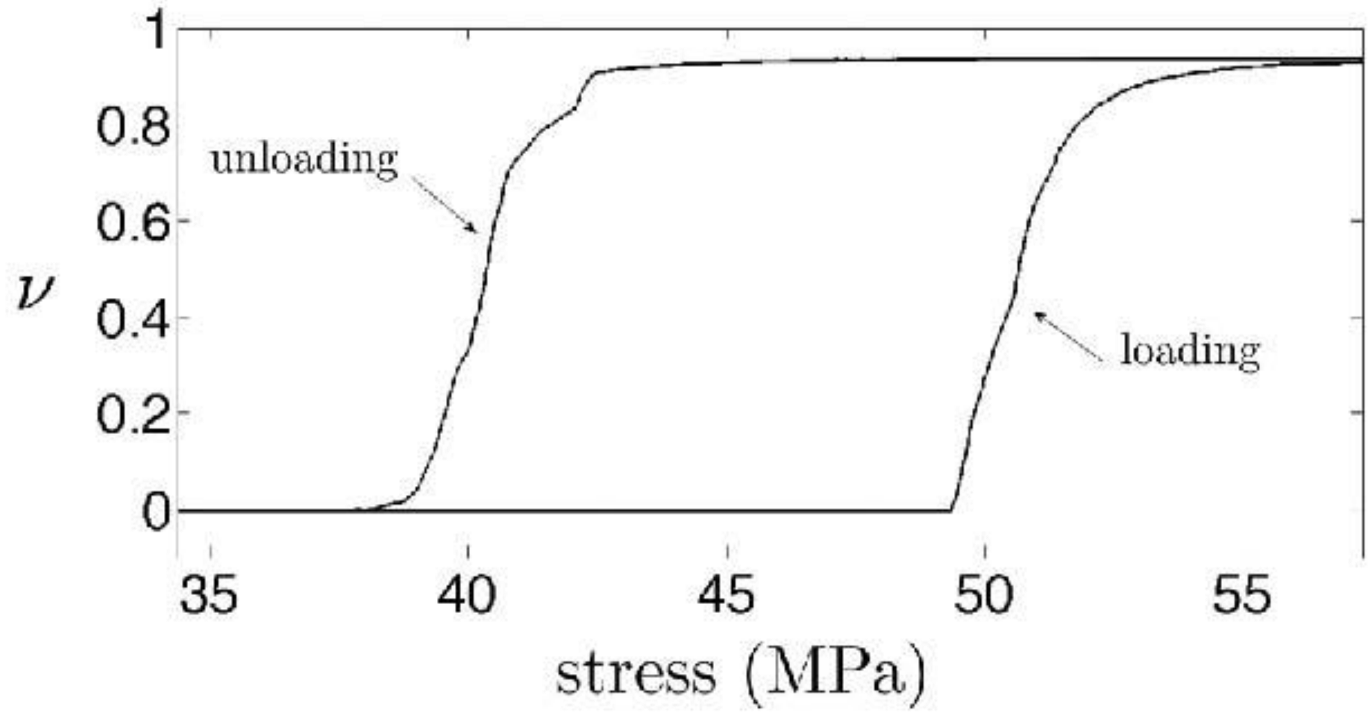
4.4 Coordinated spatial activity, avalanching

- Transformation through nucleation and front propagation
- Evolution of martensitic band-like formations (angles compatible with theory)



- Simple microstructures
- Different strain distributions between loading and unloading



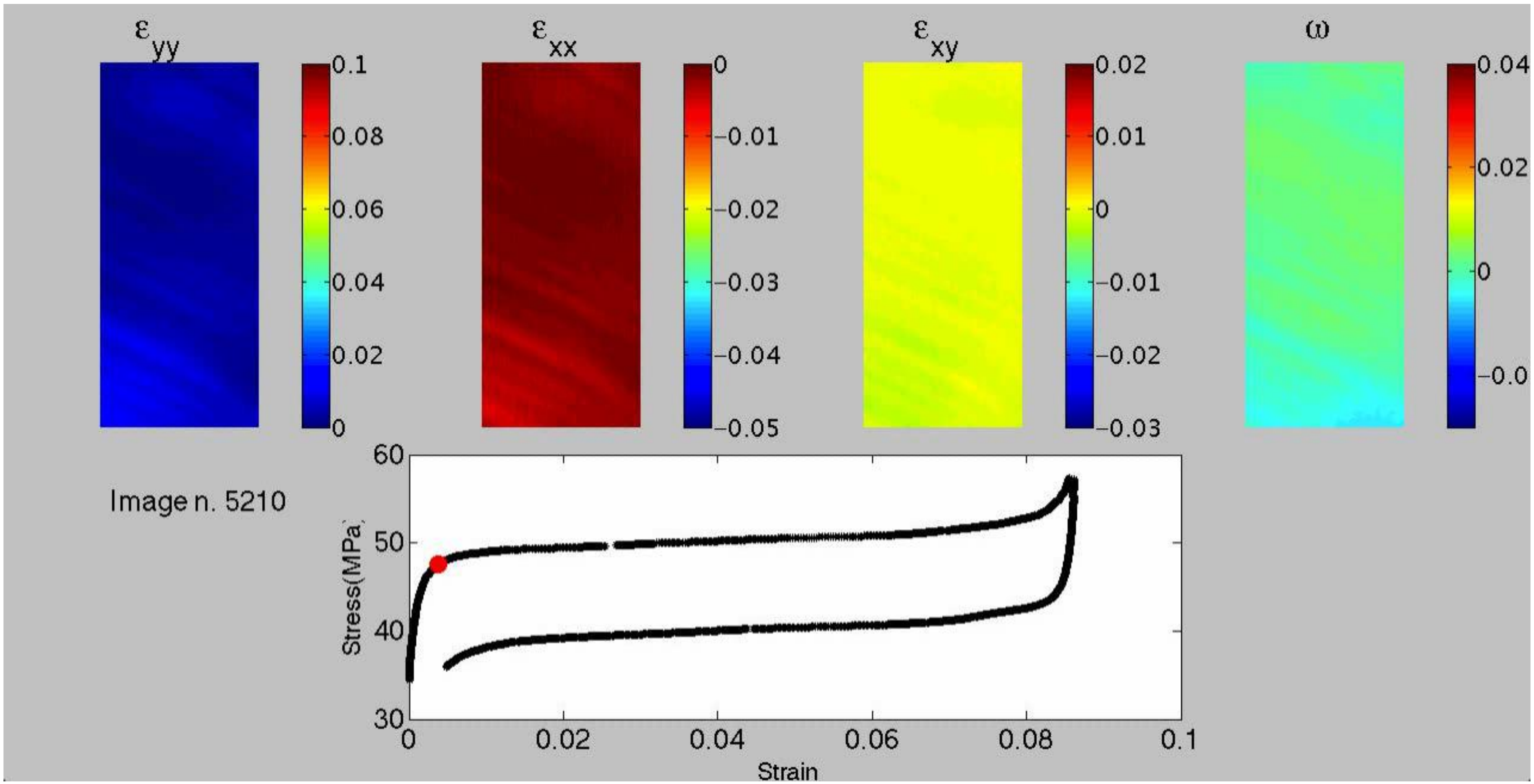


- martensitic volume fraction ν = % sample surface where ε_{yy}>0.05 (≈50% of max of ε_{yy} during tests)

- hysteresis in the evolution of ν *vs.* $\bar{\sigma}_{yy}$

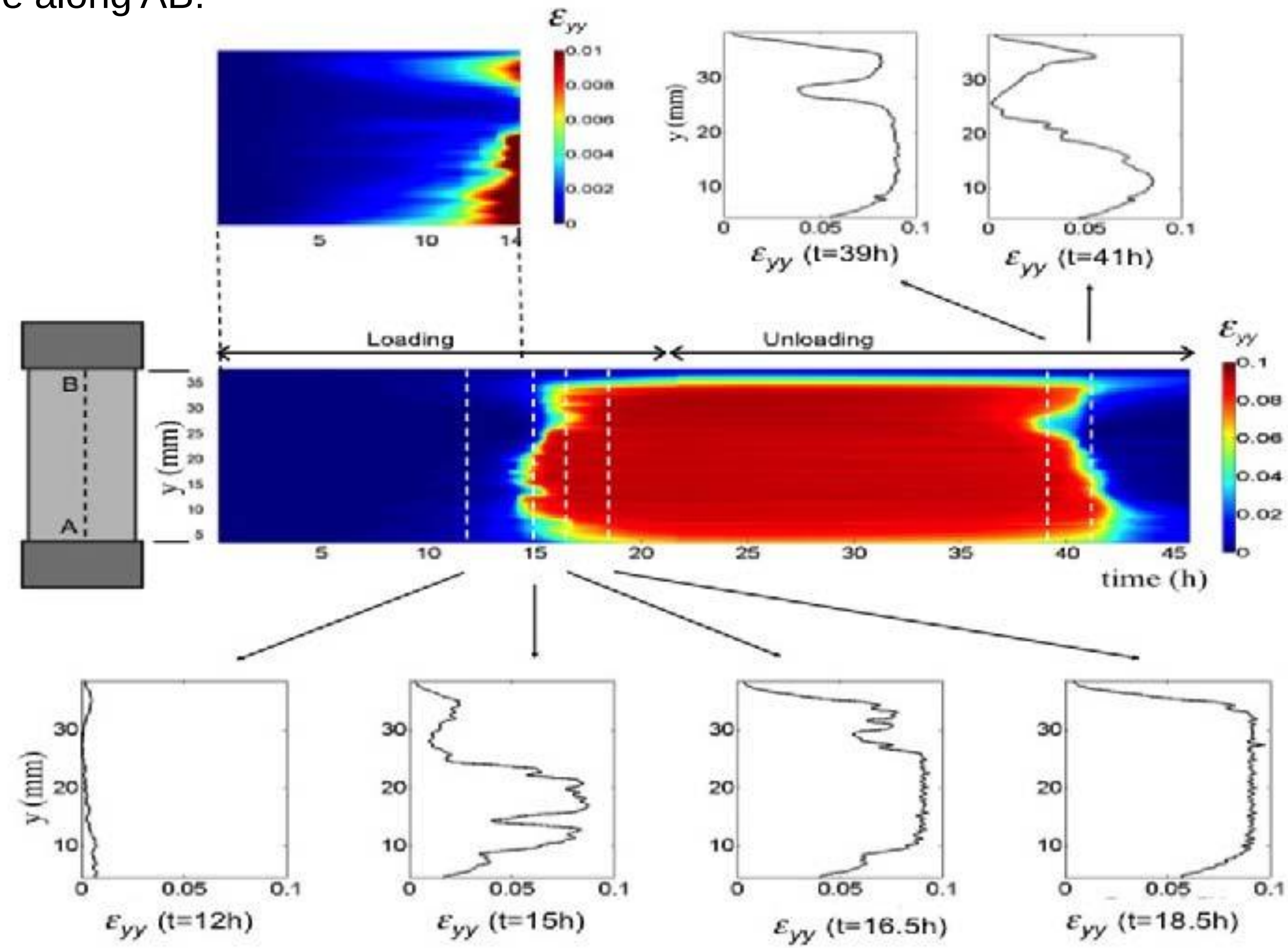
- at these scales fairly smooth curves, although ν more irregular than mean strain

- Strain field during test – forward transformation



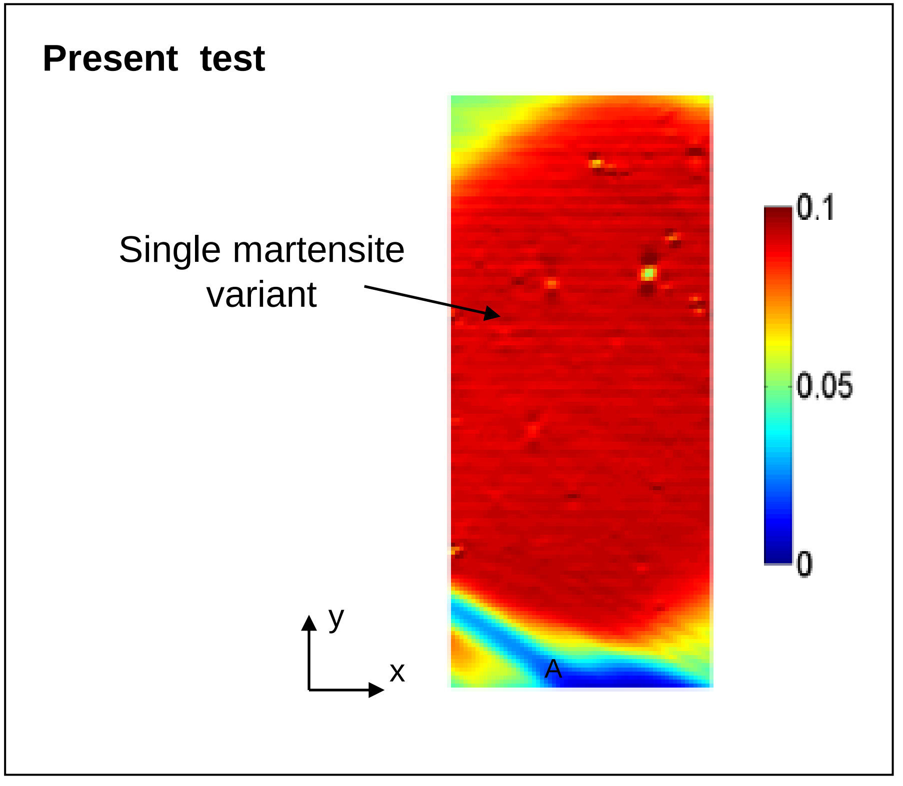
- strain profile vs. time

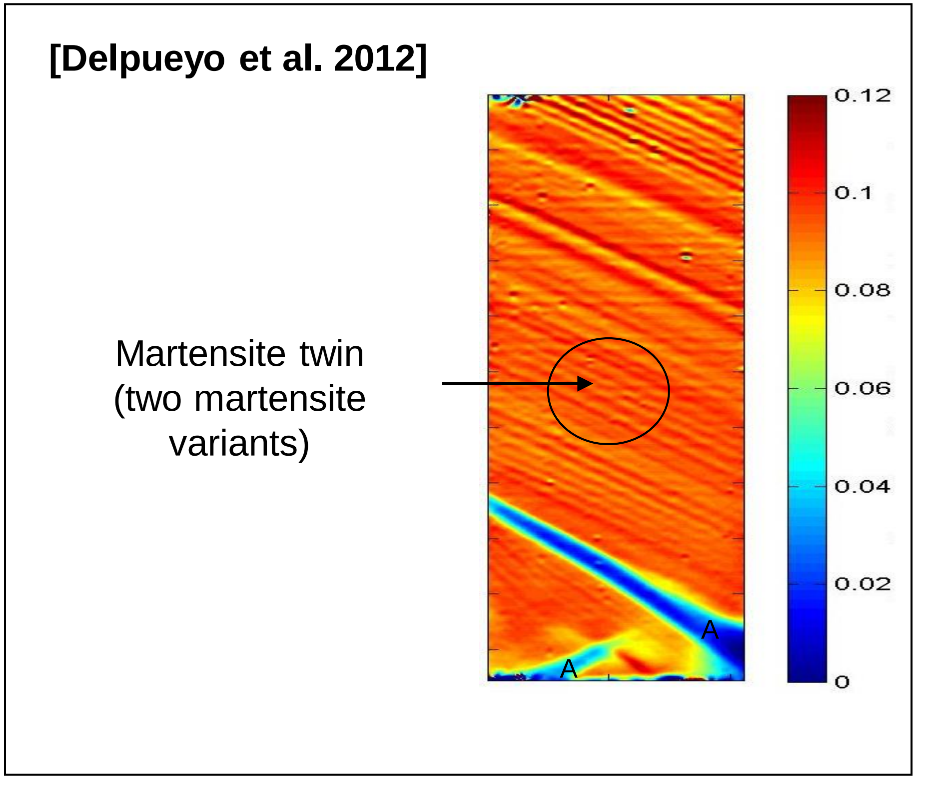
Strain profile along AB:



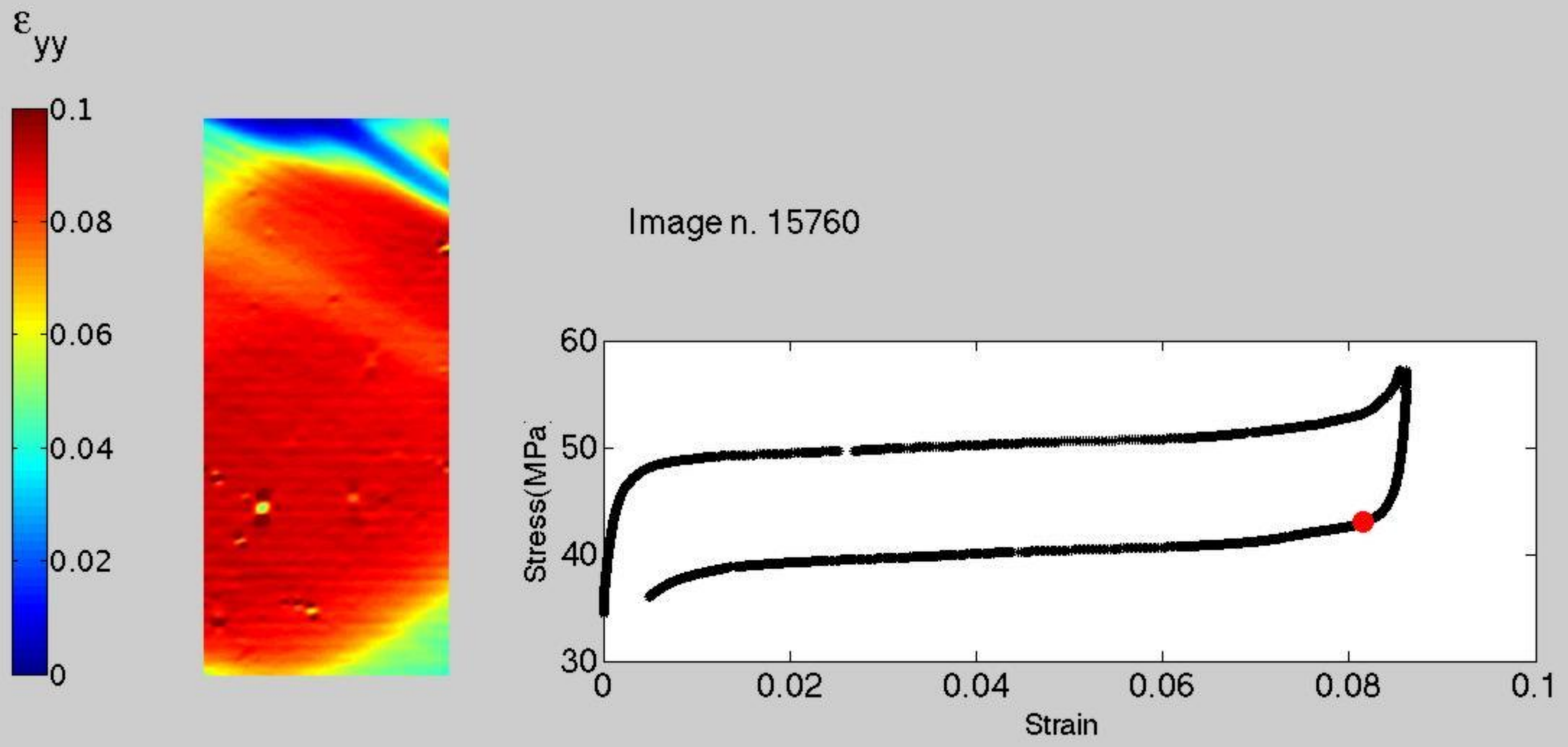
- asymmetric response between loading and unloading phases

- Recall difference with previous test





- Strain field during test – reverse transformation



4 Results

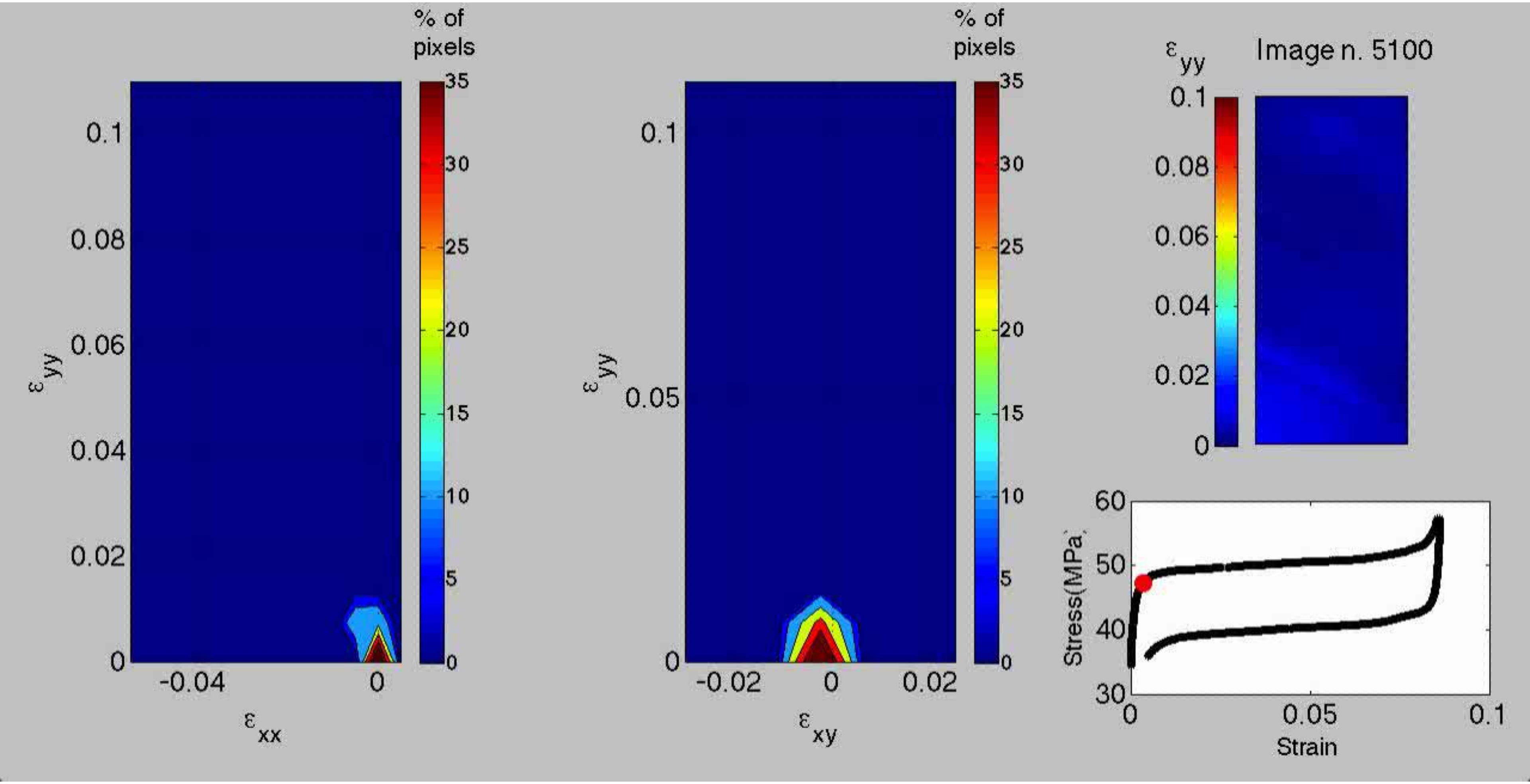
4.1 Hysteresis and strain maps

4.2 Strain clustering

4.3 Intermittency

4.4 Coordinated spatial activity, avalanching

- Strain clustering - forward transformation



- On loading material moves from “austenite well” to “martensite well” in strain space

4 Results

4.1 Hysteresis and strain maps

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4.4 Coordinated spatial activity, avalanching

- Small strain increments → real signal or noise?
  (some technical info)

- strain increments between two images have rather wide range
- smaller increments are real or are noise? (noise mainly from camera sensor)

→ must impose suitable lower thresholds on strain measurements

Based on camera and grid features, recent theory leads to:

- threshold on local strain increments $\Delta\varepsilon_{ij}$: 4×10^{-4}

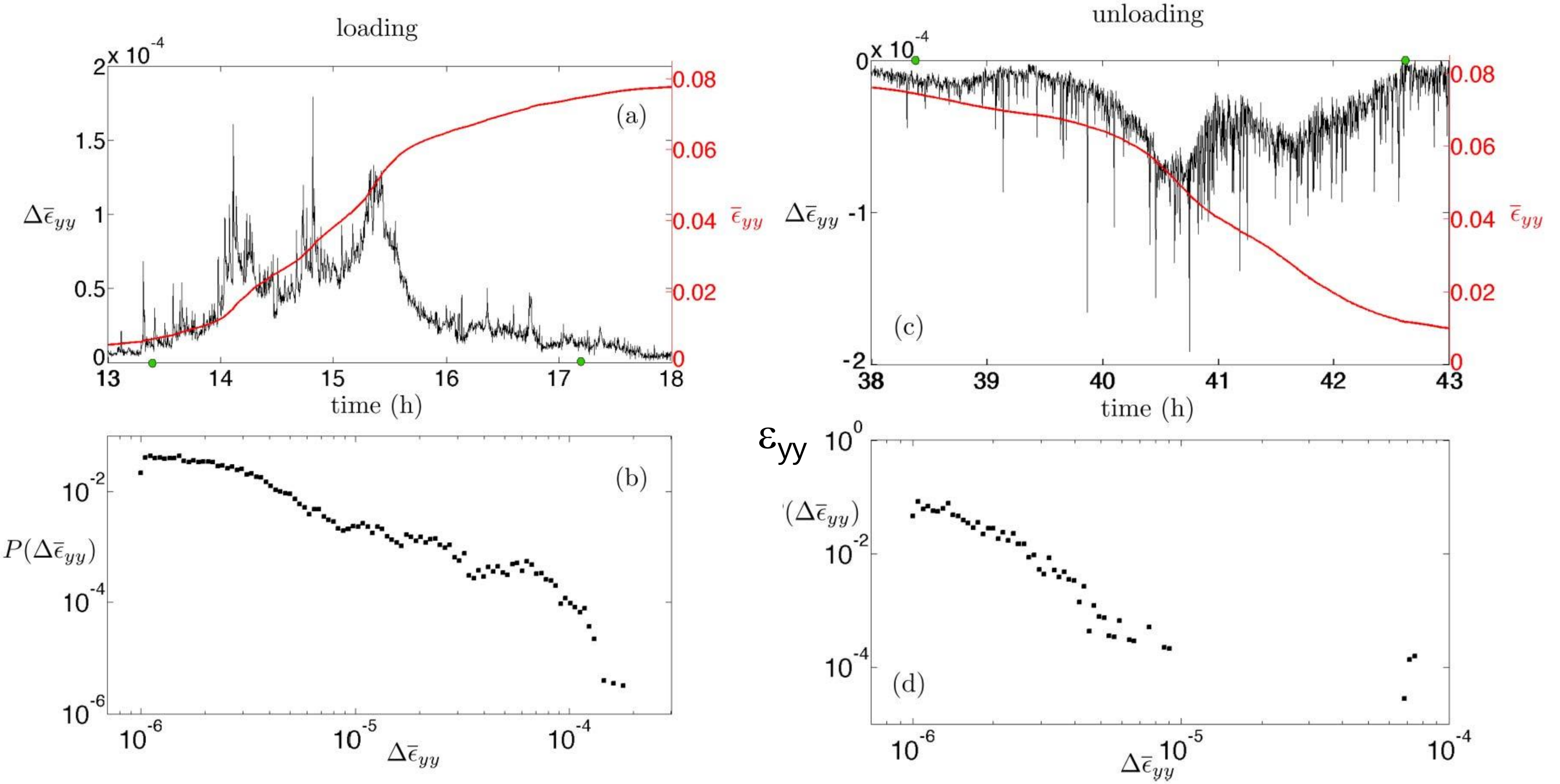
- we consider same threshold on $|\Delta\varepsilon| = (\Delta\varepsilon_{yy} + \Delta\varepsilon_{xx} + 2\Delta\varepsilon_{xy})^{1/2}$

- threshold for the mean strain components: 1×10^{-6}

Analysis derived from [Grédiac et al. **Strain** 2014, Sur et al., **IEEE Sign Proc Lett** 2014, Sur et al. **Opt Las Eng** 2015]

So far, fairly smooth global behavior, but a closer look **reveals bursty evolution** under the smooth loading (expected, from AE results)

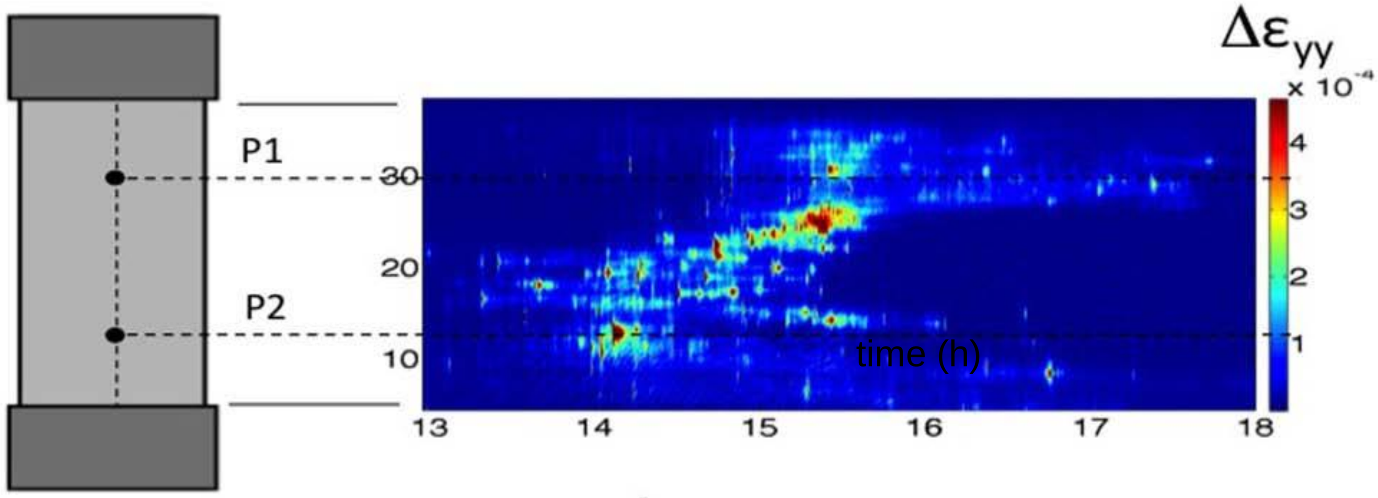
→ behavior of mean strain increments along plateaus:



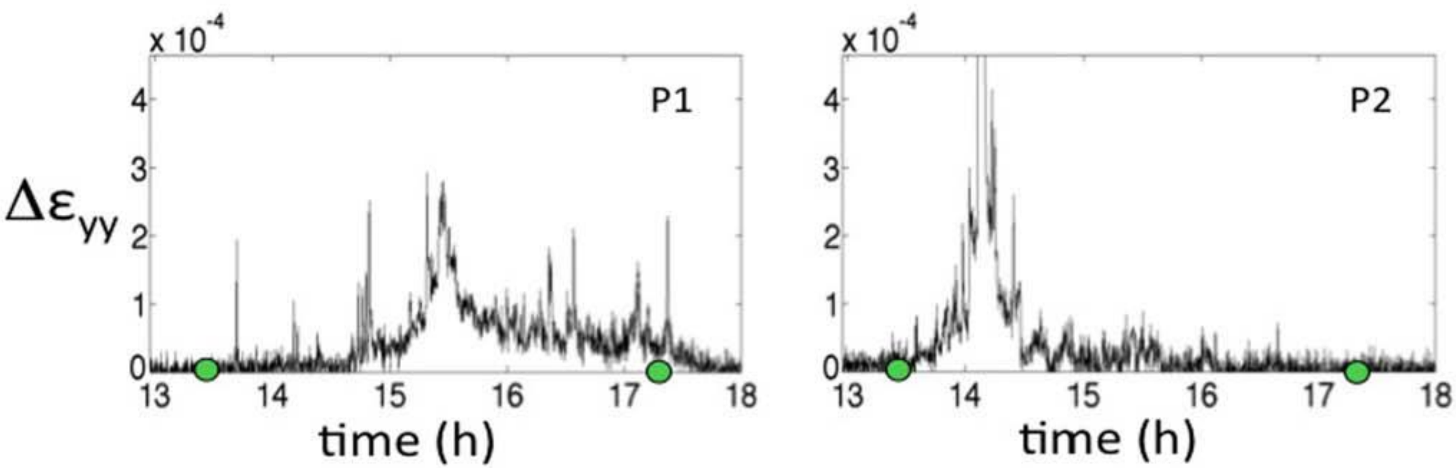
- bursty evolution is clearly observed (also non-stationarity)
- probability densities $P(\Delta\bar{\varepsilon}_{yy})$ exhibit heavy tails over about 2 decades

• intermittency in $\Delta\bar{\varepsilon}_{yy}$ originates from intermittency from local $\Delta\varepsilon_{yy}$ activity: check behavior of local strain increments on the sample

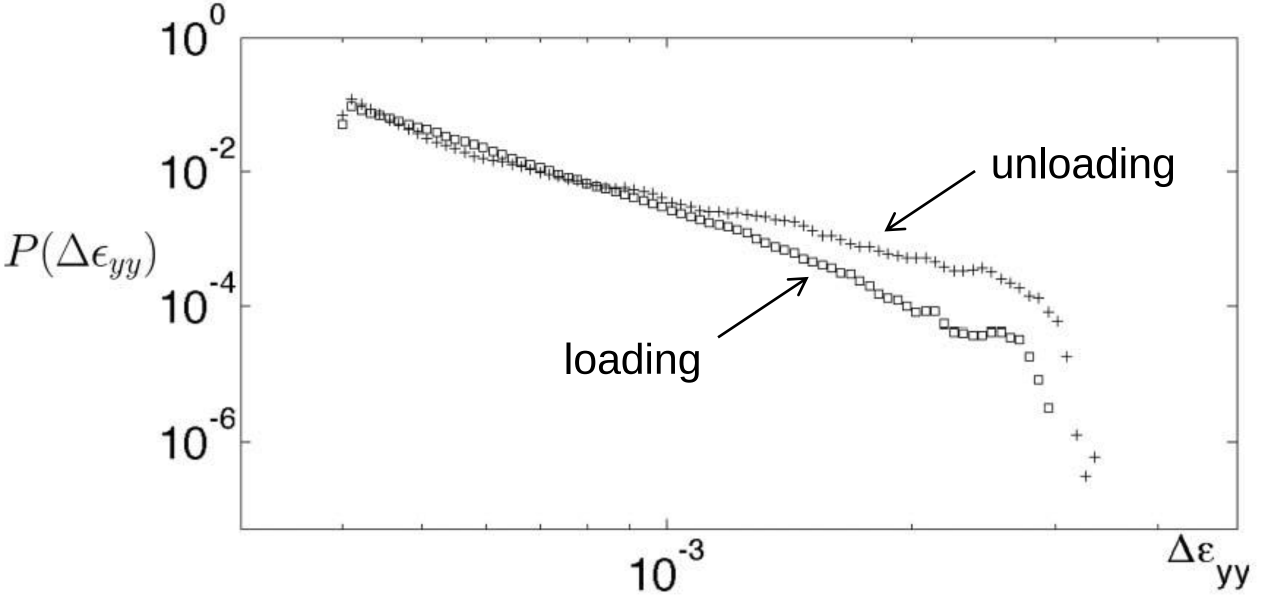
- Localization of strain activity in space and time (loading):



- Strain increments detected at two given pixels (loading):



- $P(\Delta\varepsilon_{yy})$ for all pixels during forward and reverse transformation



(Thresholded-below) pixel-level values of $\Delta\varepsilon_{yy}$ throughout sample bounded above by transformation strain → truncated distributions span about one decade

4 Results

4.1 Hysteresis and strain maps

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So far, info on local strain activity.

Must also investigate the spatial organization of phase transformation

→ Strain avalanches

- definition: suitable regions in $\Delta\varepsilon_{ij}$ or in $|\Delta\varepsilon| = (\Delta\varepsilon_{yy} + \Delta\varepsilon_{xx} + 2\Delta\varepsilon_{xy})^{1/2}$ maps define spatial events/avalanches –- given by connected subsets of sample whereon pixel activity in $\Delta\varepsilon_{ij}$ or $|\Delta\varepsilon|$ exceeds a given threshold

- Spatial events characterized by two quantities:

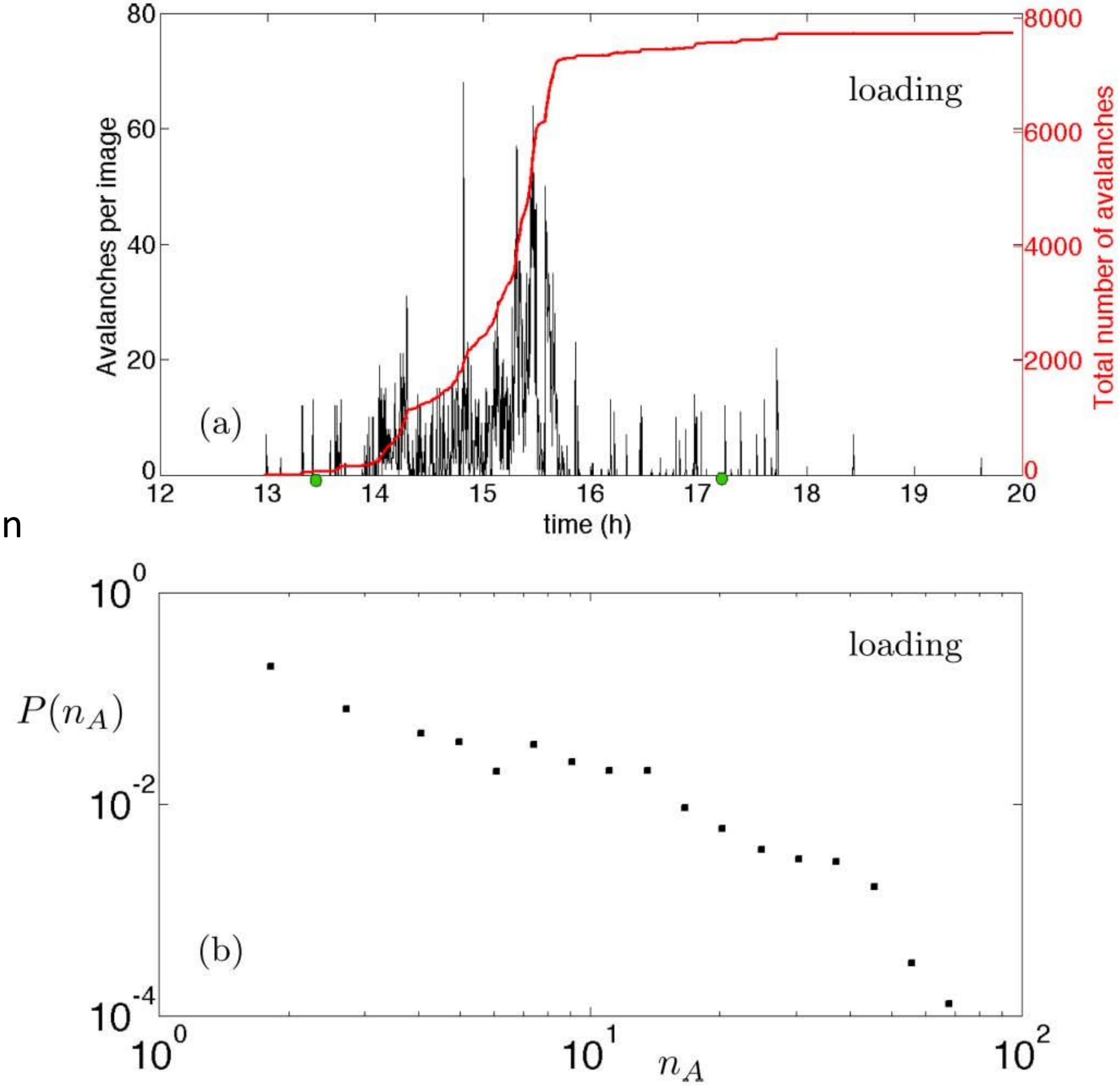
- size $\mathcal{S}$: total number of pixels in a given avalanche

- magnitude $\mathcal{M}$: integral of $|\Delta\varepsilon|$ over given avalanche

(no durations)

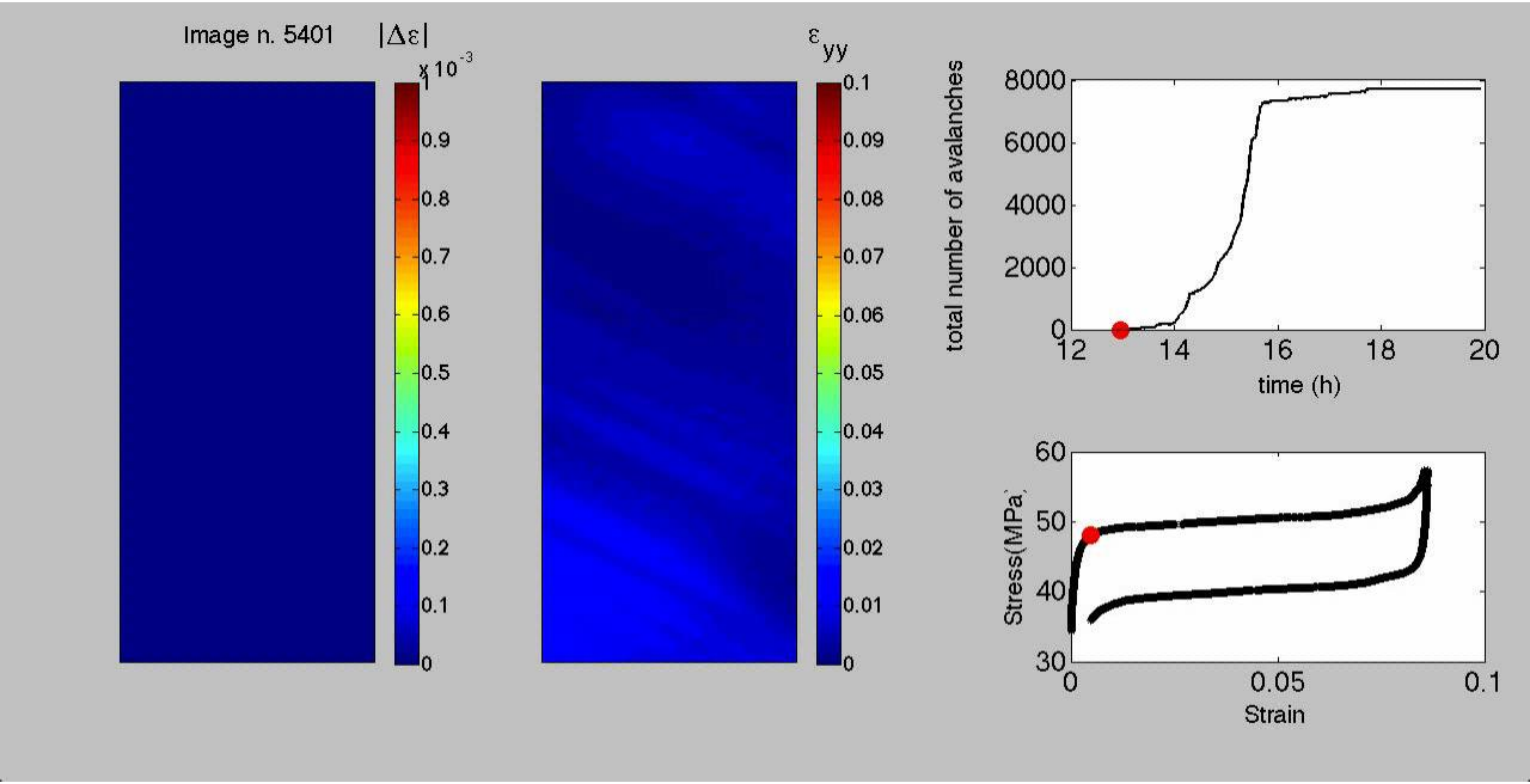
How many events? ≈ 14,000 avalanches detected along cycle

forward transformation

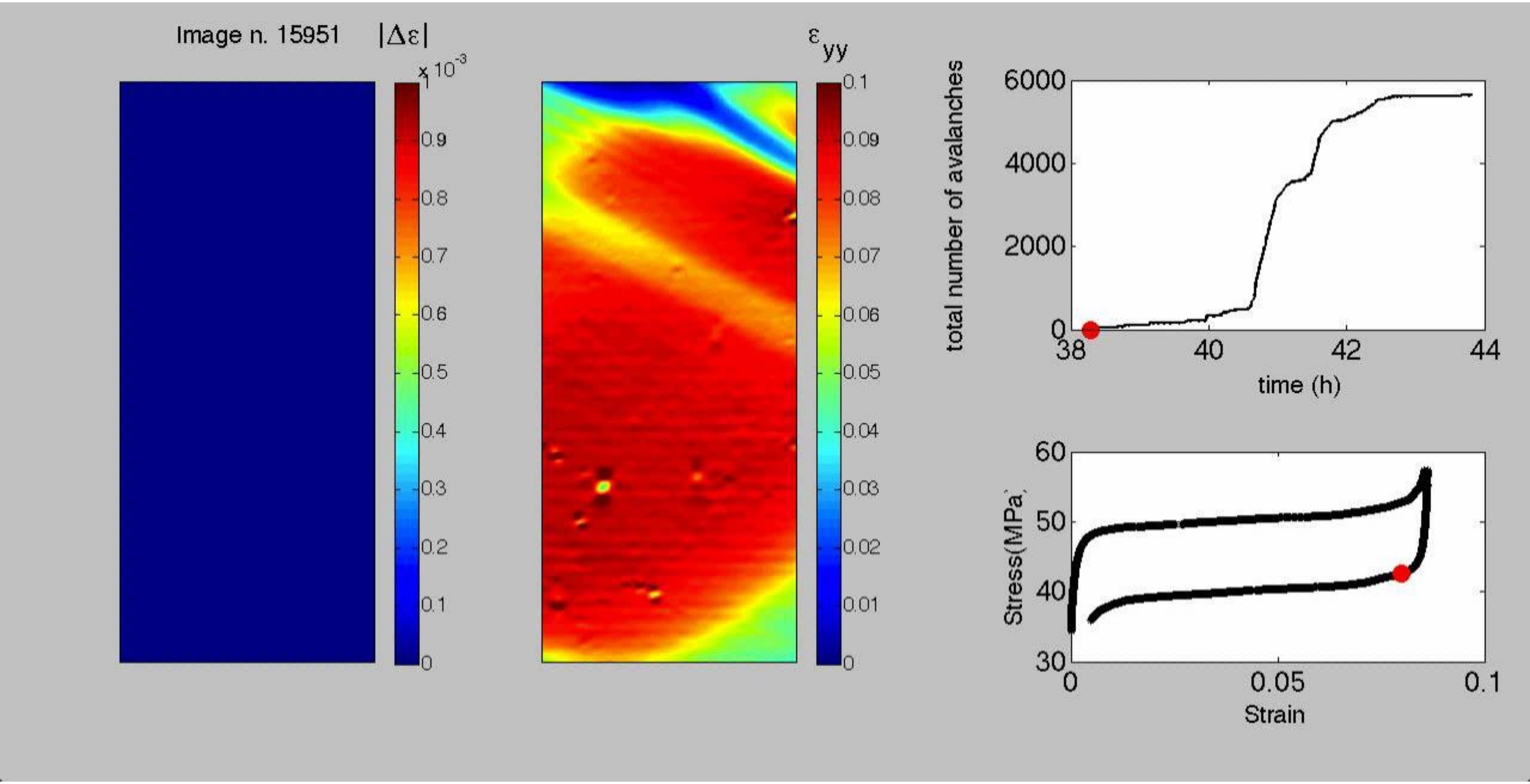


Notice again non-stationarity of transformation progress

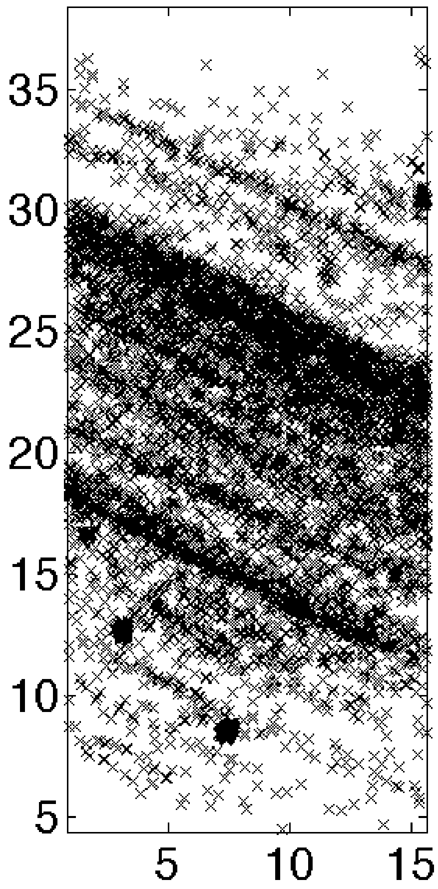
- Avalanches during forward plateau $(|\Delta\varepsilon| = (\Delta\varepsilon_{yy} + \Delta\varepsilon_{xx} + 2\Delta\varepsilon_{xy})^{1/2})$



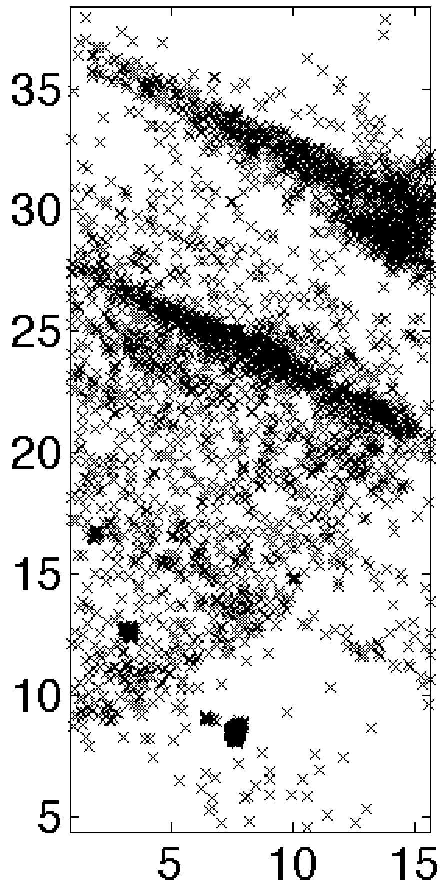
- Avalanches during reverse plateau $(|\Delta\varepsilon| = (\Delta\varepsilon_{yy} + \Delta\varepsilon_{xx} + 2\Delta\varepsilon_{xy})^{1/2})$



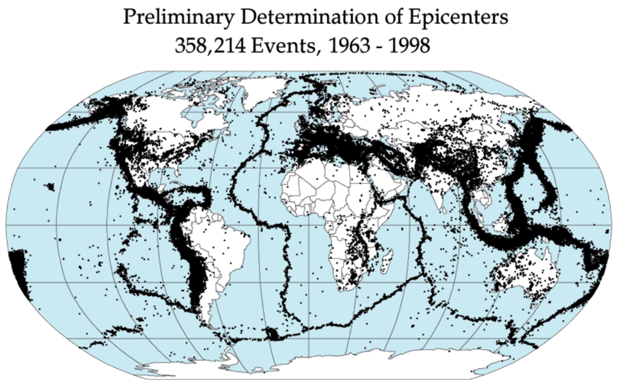
- Can also locate transformation ‘epicenters’ during test
(pixels where $|\Delta\varepsilon|$ is max for each event)



loading

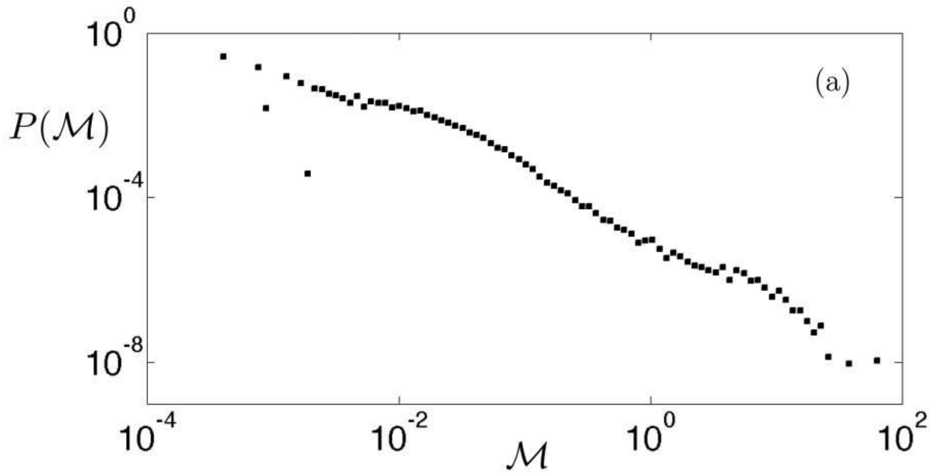


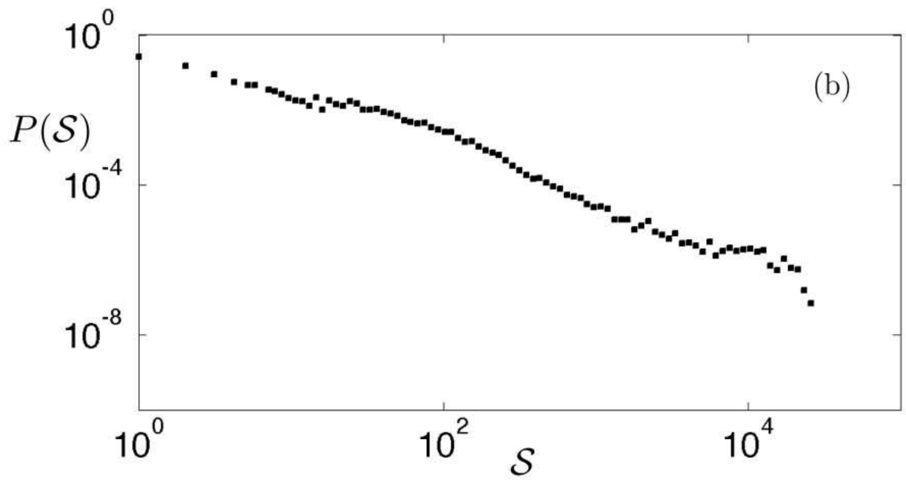
unloading

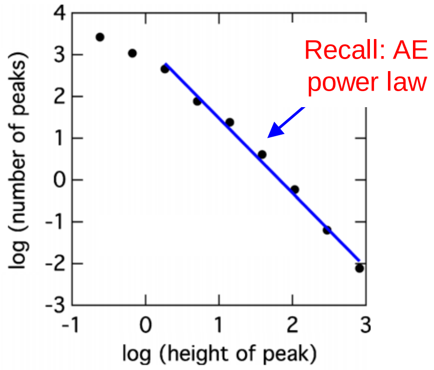


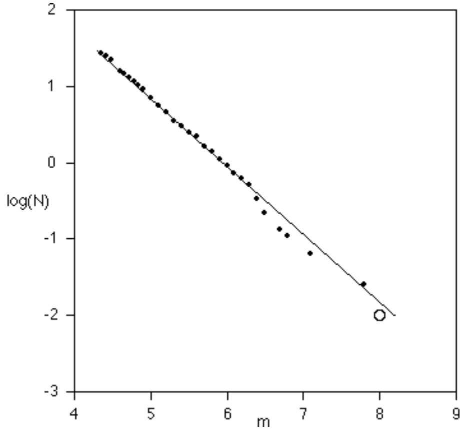
(Nasa)

Statistics for the resulting avalanche dynamics:







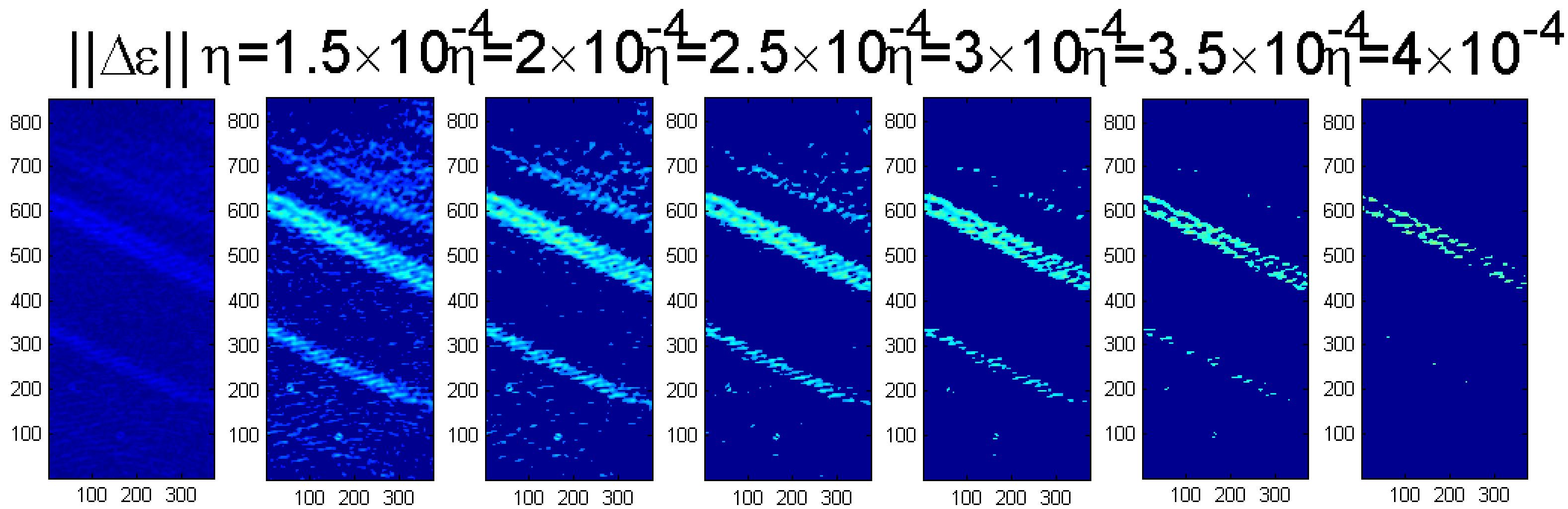


Gutenberg-Richter So. Cal.

- Fairly linear trend of distributions P($\mathcal{M}$) and P($\mathcal{S}$) – indicates emergence of power-law behavior of strain avalanching during the phase transformation (almost 6 decades in $\mathcal{M}$!)

- Different power-law exponents: forward ≈ 1.5; reverse ≈ 2. Consistent with AE results

[Rosinberg & Vives, 2012]



- question: the number of 'spots' increases as the threshold value is decreased
→ what is really an event?

- both avalanche size $\mathcal{S}$ and magnitude $\mathcal{M}$ depend on threshold – but we observed that threshold value within reasonable bounds affects distributions P($\mathcal{M}$) and P($\mathcal{S}$) only slightly

5. Conclusions

- Designed a mechanical device based on gravity to apply a monotonic and very slowly growing stress-controlled load with minimal boundary constraints on SMA sample

- Observation and characterization of elemental strain intermittency during martensitic transformation

- Avalanches exhibit a fairly clean power-law behavior as in AE (‘criticality’?)

Current work:

• coupling full-field measurements and AE analysis to study both acoustic and strain avalanches (together with Clermont and Barcelona groups)

'GARBO TALKS!'

• Modelling: materials with complex energy landscapes, Ericksen-inspired, GL(2, Z) invariance (with Paris and Aberdeen groups)

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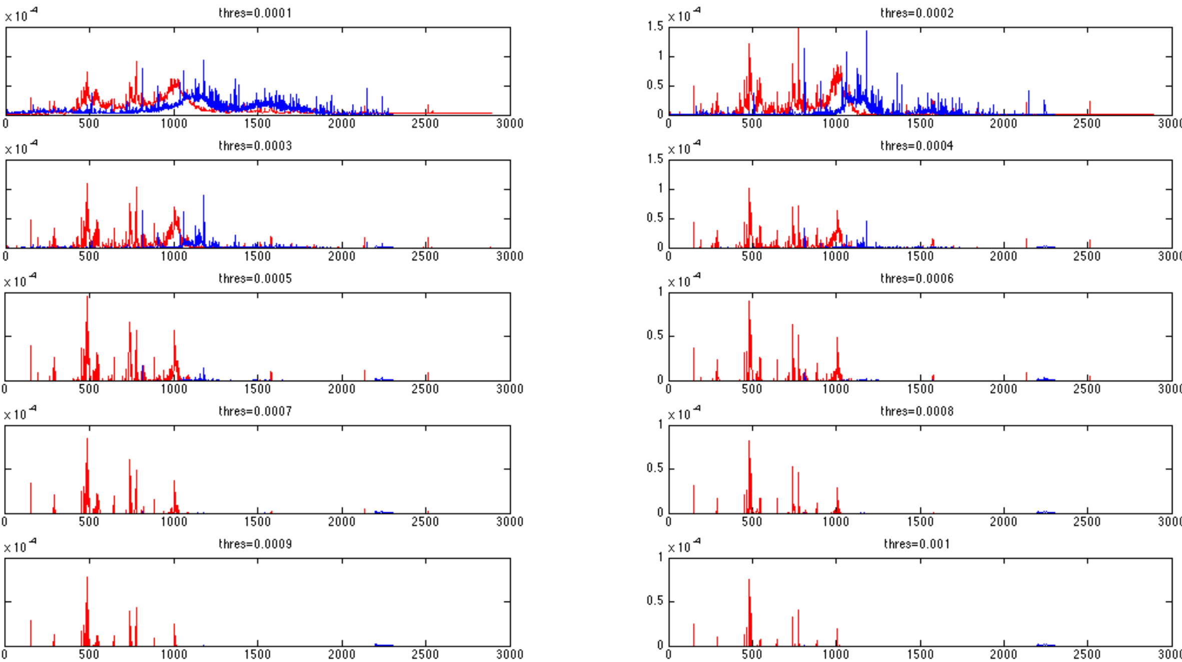
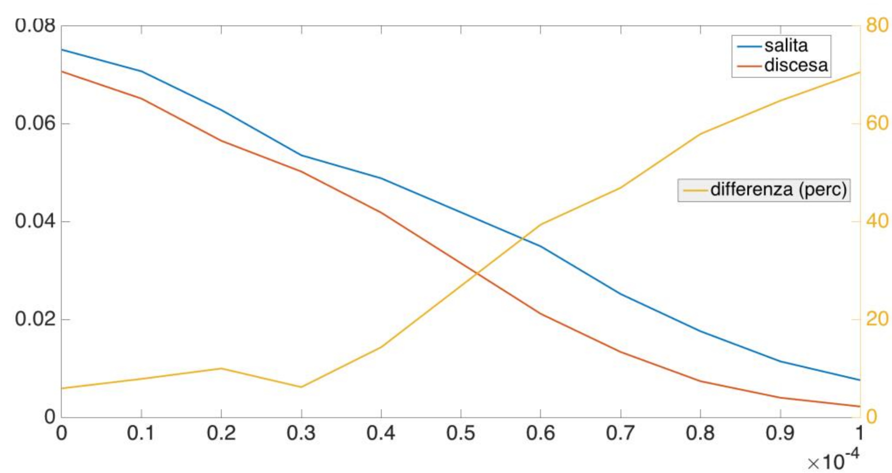
Also: study in more detail finer effects in the data (e.g. non-stationarity and forward vs. reverse asymmetry)



Asymmetry in forward vs reverse transformation



More information and videos:

X. Balandraud, N. Barrera, P. Biscari, M. Grédiac, G. Zanzotto,
Strain intermittency in shape memory alloys,
Physical Review B 91, 174111, 2015