Strain intermittency in shape memory alloys

N. Barrera\textsuperscript{1,2}, X. Balandraud\textsuperscript{1}, M. Grédiac\textsuperscript{1}, P. Biscari\textsuperscript{2}, G. Zanzotto\textsuperscript{3}
Outline

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

  [Nishida et al., Acta Mat 97] [Chu & James, Phase Trans 09] [Seiner et al., Phase Trans 09] [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

• 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

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

- **Specimen**

  - Cu Al$_{11.4}$ Be$_{0.5}$ (wt.%)
  - single crystal
  - martensite start $M_s = 2^\circ C \rightarrow$ 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

![Stress vs Strain Graph](image)

### Austenite → Martensite

### Austenite ← Martensite
• 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

- 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
3. Comparison with earlier tests
4. Results
5. Conclusions
3. Comparison with earlier tests

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

Present test:
- 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

gravity

Imposed elongation + horizontal displacement not allowed

heterogeneous stress field

[Delpueyo et al. 2012]

Martensite twin (two martensite variants)

imposed displacement
1. Context
2. Experimental set up
3. Comparison with earlier tests
4. Results
5. Conclusions
Tracking the $A \leftrightarrow M$ 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
4 Results

4.1 Hysteresis and strain maps

4.2 Strain clustering

4.3 Intermittency

4.4 Coordinated spatial activity, avalanching
- Transformation through \textit{nucleation} and \textit{front propagation}
- Evolution of martensitic band-like formations (angles compatible with theory)

- Simple microstructures
- Different strain distributions between loading and unloading
- martensitic volume fraction $\nu = \%$ sample surface where $\varepsilon_{yy}>0.05$ ($\approx50\%$ of max of $\varepsilon_{yy}$ during tests)

- hysteresis in the evolution of $\nu$ vs. $\sigma_{yy}$

- at these scales fairly smooth curves, although $\nu$ 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

**Present test**

- Single martensite variant

**[Delpueyo et al. 2012]**

- Martensite twin (two martensite variants)
• 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

4.2 Strain clustering

4.3 Intermittency

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 $\Delta \varepsilon_{ij} : 4 \times 10^{-4}$
- 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: $1 \times 10^{-6}$

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 $P(\Delta \varepsilon_{yy})$ exhibit heavy tails over about 2 decades
intermittency in $\Delta \varepsilon_{yy}$ 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 $\rightarrow$ truncated distributions span about one decade
4 Results

4.1 Hysteresis and strain maps

4.2 Strain clustering

4.3 Intermittency

4.4 Coordinated spatial activity, avalanching
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 $S$: total number of pixels in a given avalanche
  - magnitude $M$: integral of $|\Delta \varepsilon|$ over given avalanche

(no durations)
How many events? \( \approx 14,000 \) avalanches detected along cycle

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)
Statistics for the resulting avalanche dynamics:

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

- Different power-law exponents: forward $\approx 1.5$; reverse $\approx 2$. 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 $S$ and magnitude $M$ depend on threshold – but we observed that threshold value within reasonable bounds affects distributions $P(M)$ and $P(S)$ only slightly
1. Context
2. Experimental set up
3. Comparison with classic tests
4. Results
5. Conclusions
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)

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

‘GARBO TALKS!’
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: