Debrecen, august 29th, 2022
Avalanche 2022

UNIVERSITAT DE BARCELONA

Avalanche dynamics in materials for elastocaloric cooling

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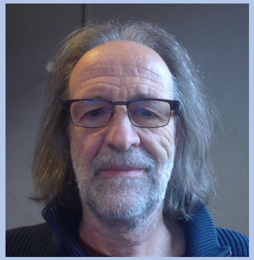
Research team: Materials and Phase Transitions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Outline

- 1-Introduction
  - Structural phase transitions in solids (martensitic)
  - Caloric effects
  - Avalanche dynamics
  - Experimental: Acoustic Emission (AE) & infrared (IR)

- 2-Recent results: AE location & dynamics of heat sources and sinks
  - 2-1 Elastocaloric experiments
  - 2-2 Flexocaloric experiments

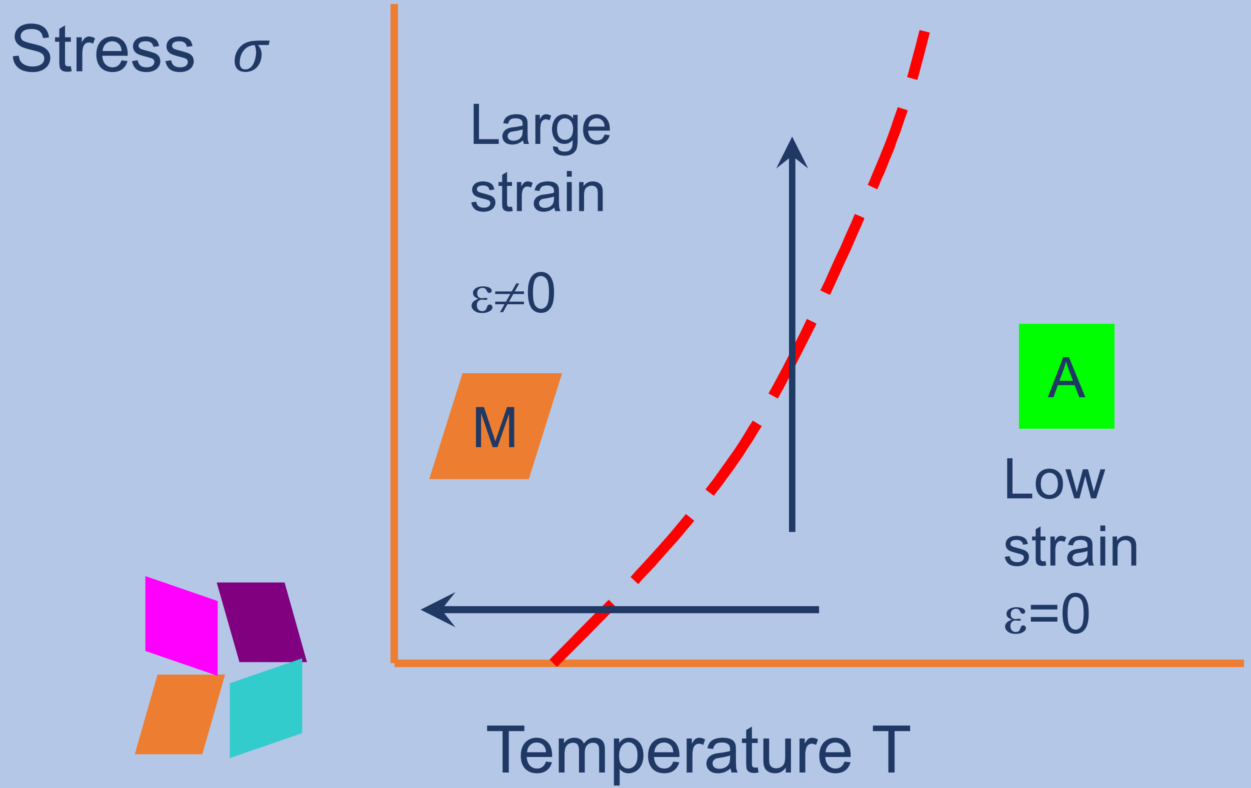
- 3-Conclusion

Outline

1-Introduction

Structural phase transitions in solids (martensitic)

First order martensitic transitions in solids



Stress σ

Large
strain

$\varepsilon \neq 0$

M

A

Low
strain
$\varepsilon = 0$

Temperature T

Examples:

Fe, Steel,

FePd, NiTi,…

Cu-based

CuZnAl

CuAlNi

…..

Low symmetry phase exhibits symmetry related equivalent variants

Martensitic microstructure

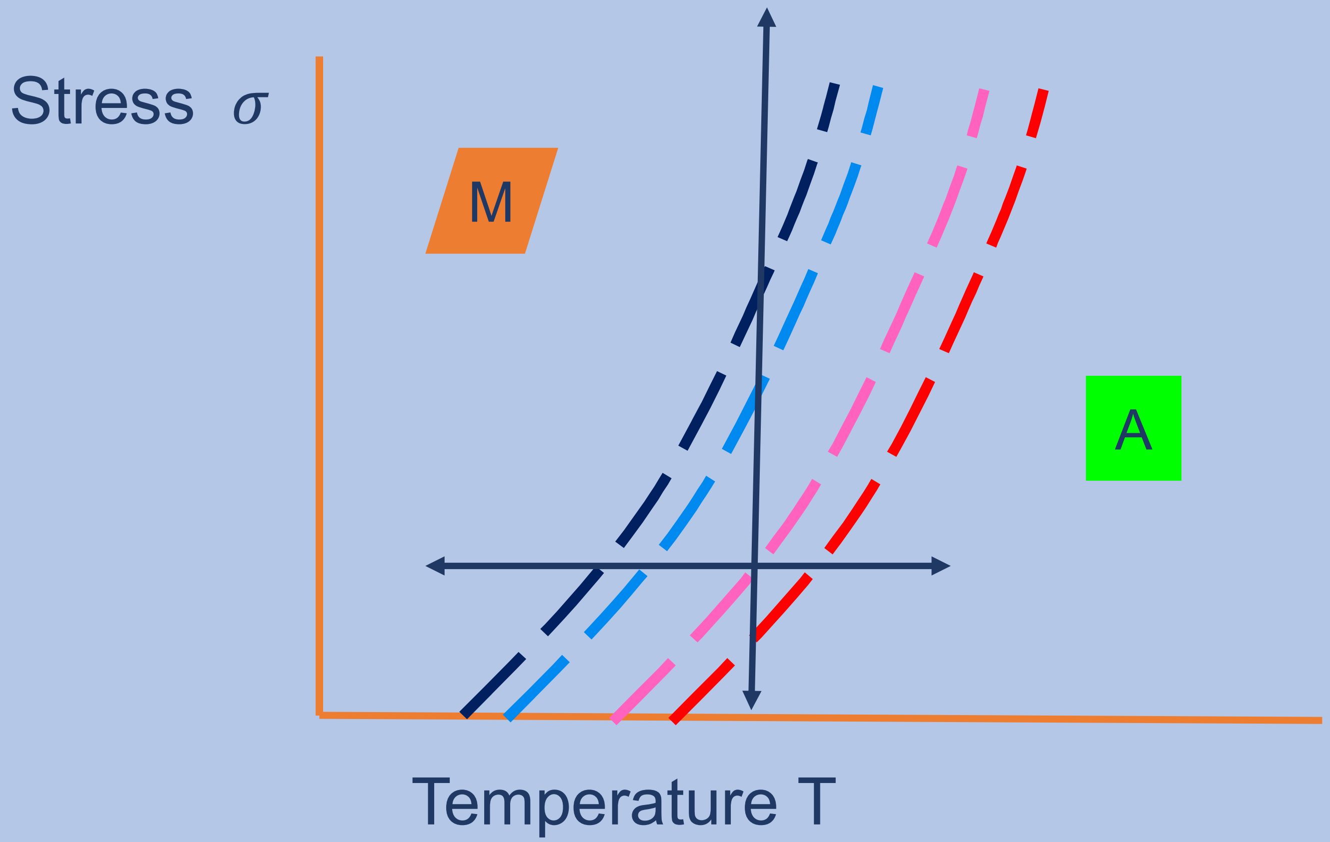
Cu-Zn-Al single crystal, below the martensitic transition temperature

Optical image polarized light

(3 mm x 2 mm)

12 equivalent martensitic variants

Metastability and non-equilibrium effects



Due to disorder and thermoelastic effects:

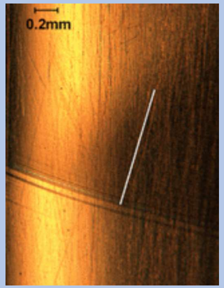
- Hysteresis
- Extended transition

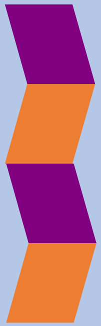
Martensitic microstructure induced by external uniaxial stress

CuZnAl single crystal, above the martensitic transition temperature, with applied uniaxial stress in (100) direction

optical image polarized light

Two equivalent martensitic variants (twins)



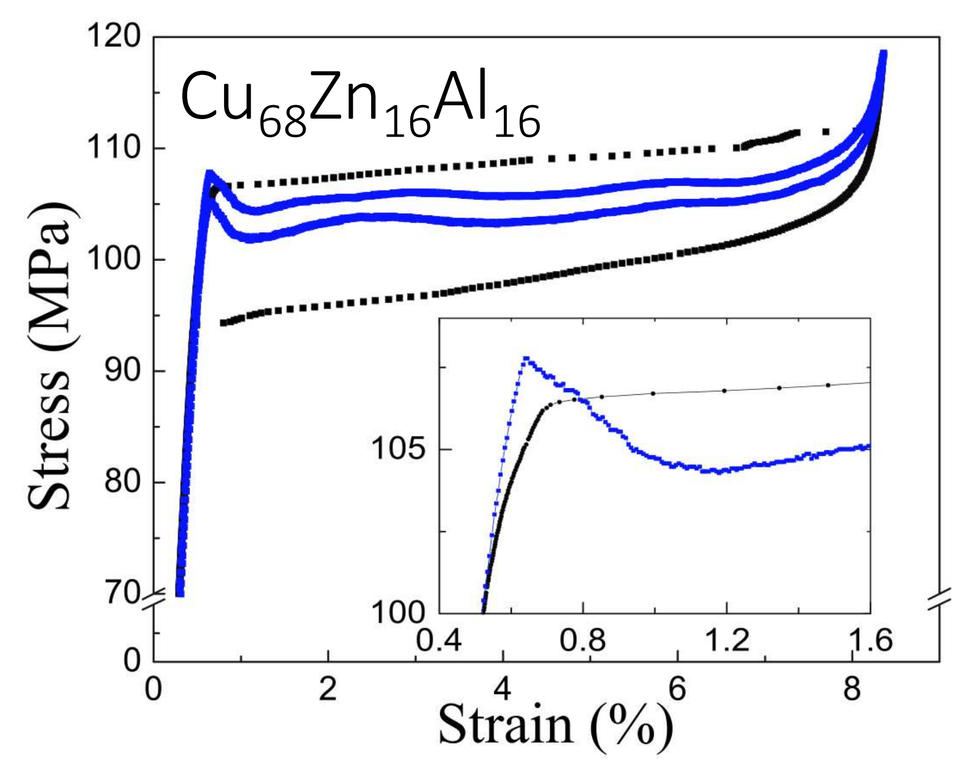


Stress-strain

The martensitic transition is the key ingredient beyond interesting properties for applications:

superelasticity,
high damping
shape memory properties

Non-equilibrium effects show-up at macroscopic scales due to different driving conditions



E.Bonnot, R.Romero, et al.,
Hysteresis in a system driven by either generalized force or displacement variables: Martensitic phase transition in single-crystalline Cu-Zn-Al
Phys. Rev. B 76, 064105 (2007)

Outline

1-Introduction

- Structural phase transitions in solids
- Caloric effects

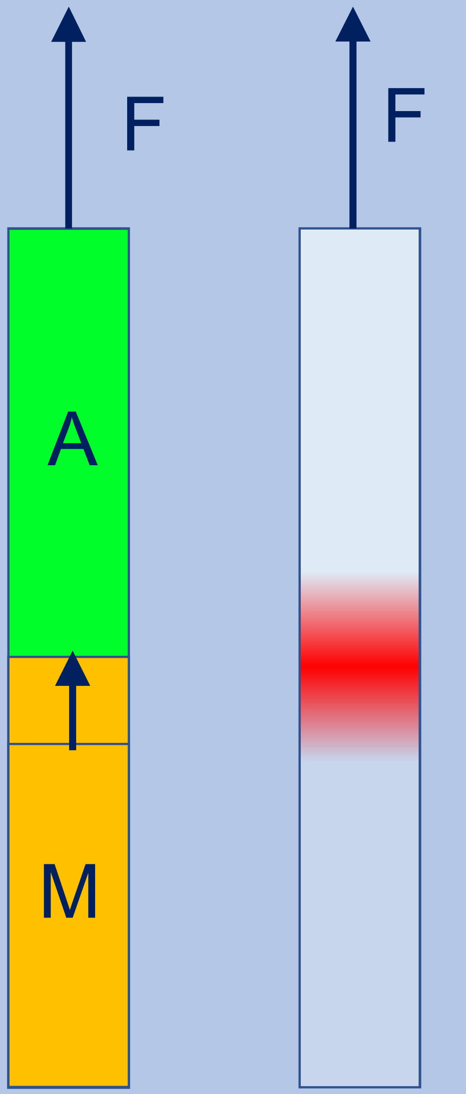
Latent heat

Martensitic transitions proceed by nucleation and advancing fronts.

In order to advance, the fronts needs to exchange energy (latent heat)

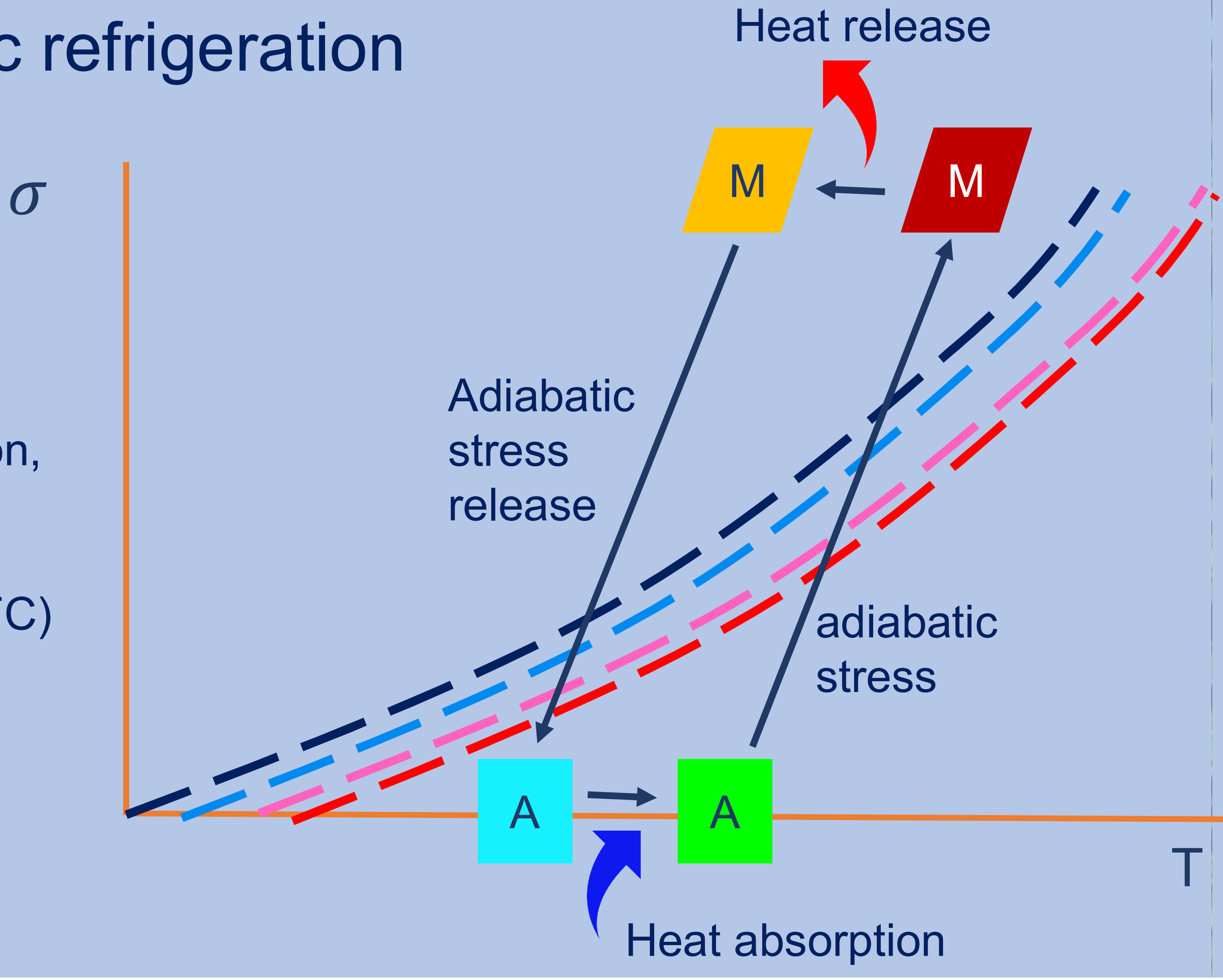
In adiabatic conditions (fast), this results in a change of the local temperature of the sample

Front velocity ↔ thermal conductivity



Elastocaloric refrigeration

Solid state environmentally friendly refrigeration, without the use of fluorinated gases (CFC, HCFC & HFC)



Heat release

Adiabatic stress release

adiabatic stress

Heat absorption

1-Introduction

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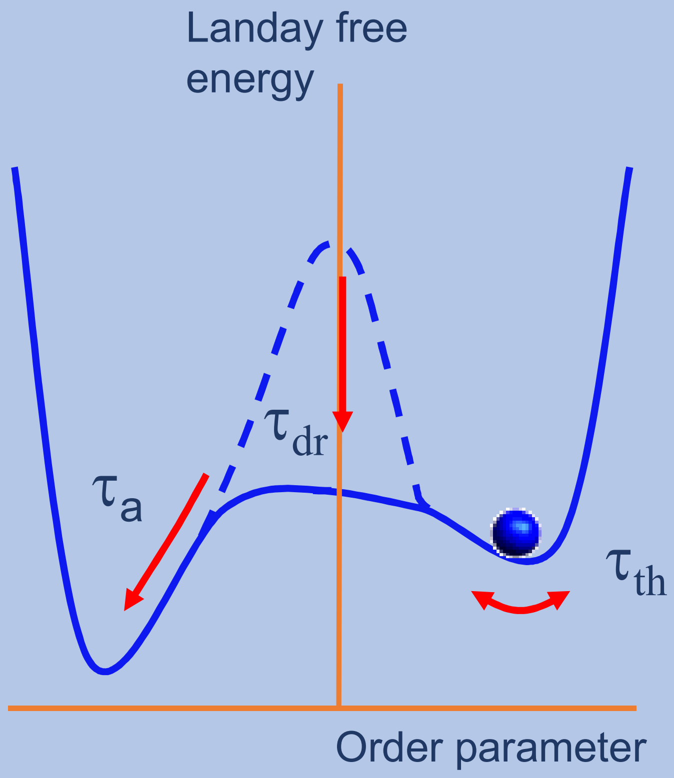
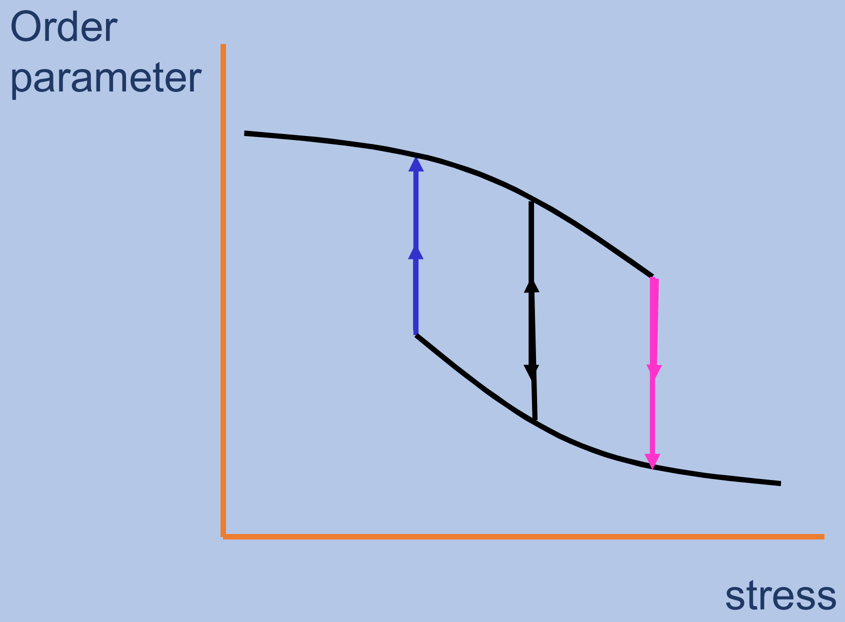
Athermal FOPT and rate independent hysteresis



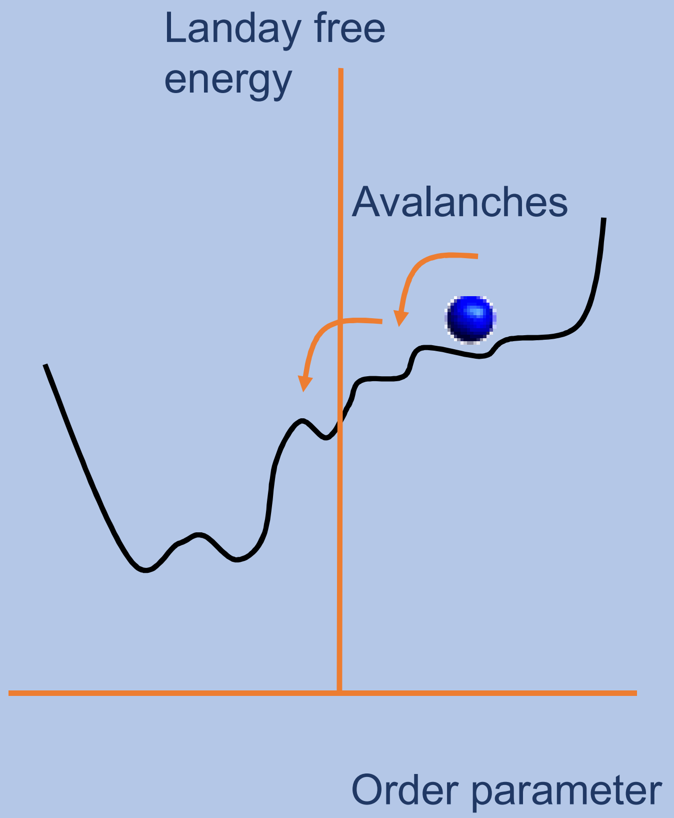
F.J. Pérez-Reche et al.,
Athermal Character of Structural Phase Transitions
Phys. Rev. Lett 87, 195701 (2001)

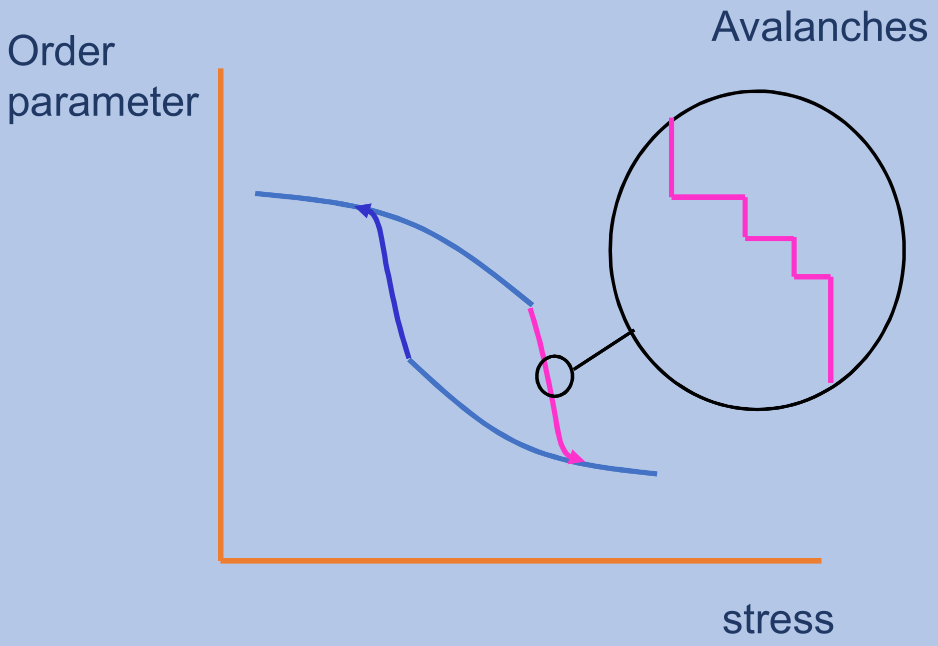


Competition between three time scales:

$$\tau_a \ll \tau_{dr} \ll \tau_{th}$$

Influence of disorder





The existence of disorder and the athermal behaviour of MT explains the existence of avalanche dynamics, hystheresis, and extended transitions

The characterization of this inhomogeneous and intermittent dynamics can be done with different experimental techniques

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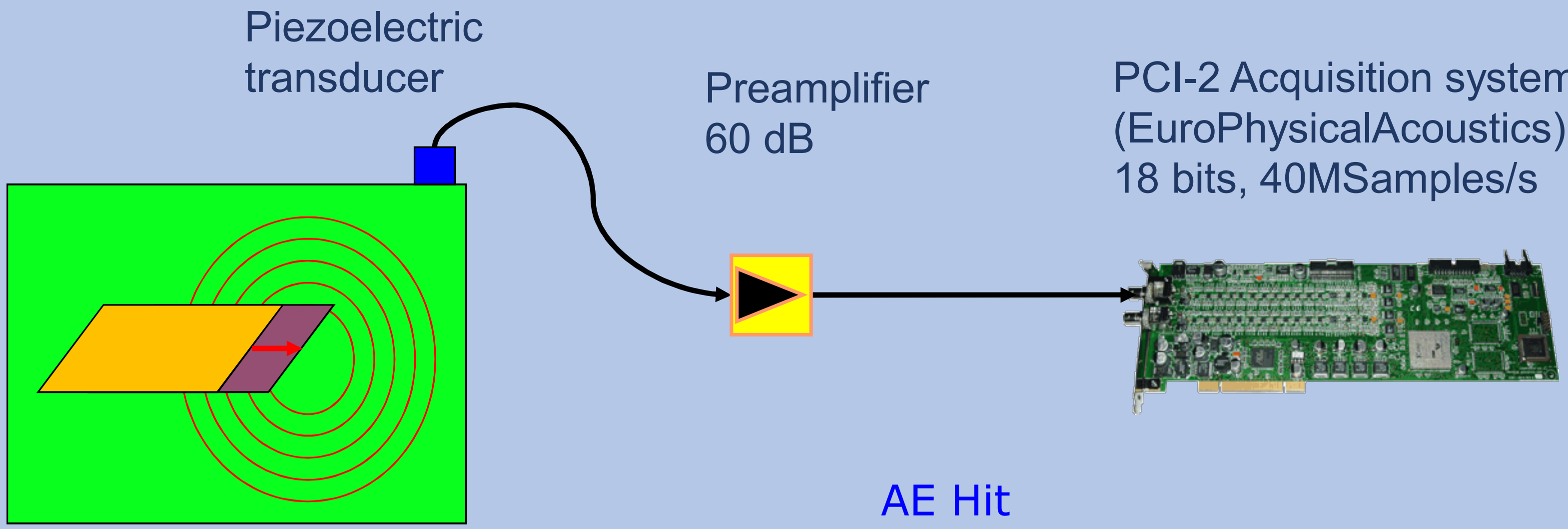
Acoustic emission detection

C.B.Scruby. *An introduction to Acoustic Emission*

J.Phys.E: Sci.Instrum. 20, 946 (1987)

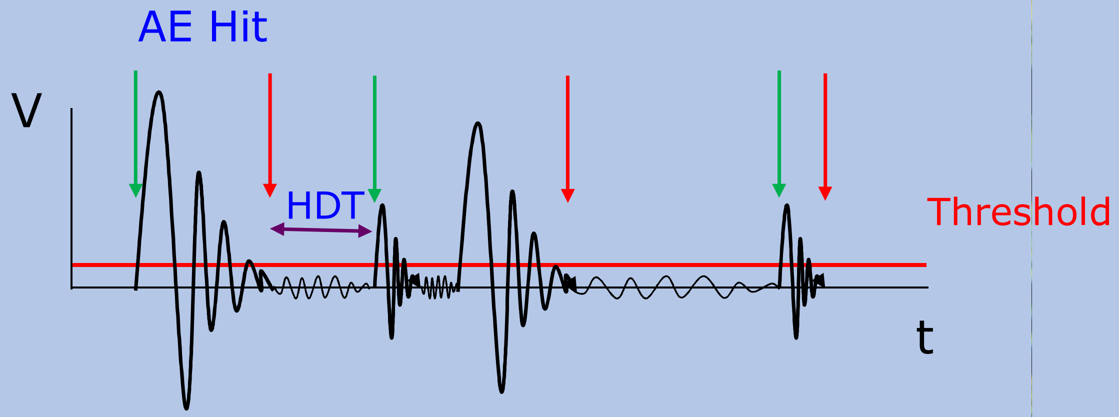


Piezoelectric
transducer

Preamplifier
60 dB

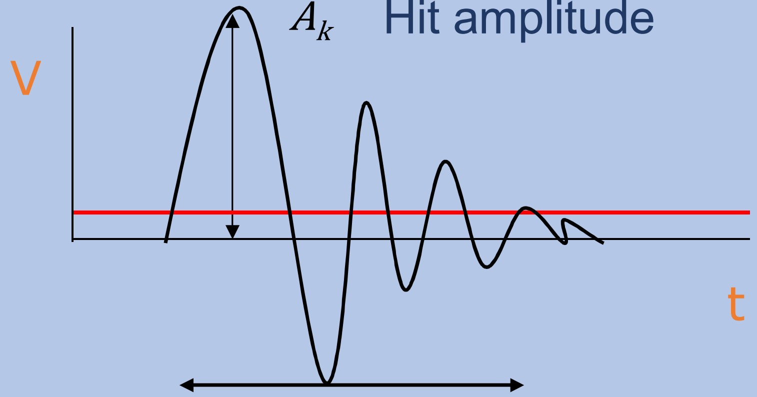
PCI-2 Acquisition system
(EuroPhysicalAcoustics)
18 bits, 40MSamples/s

$$V(t) = Ce^{-d/\lambda} \int_{-\infty}^{t} R(t-z) \left| \frac{dx}{dt} \right| dz$$



Acoustic emission: hit properties

For each hit k, besides the occurrence time t_k we determine several properties, in order to characterize it:



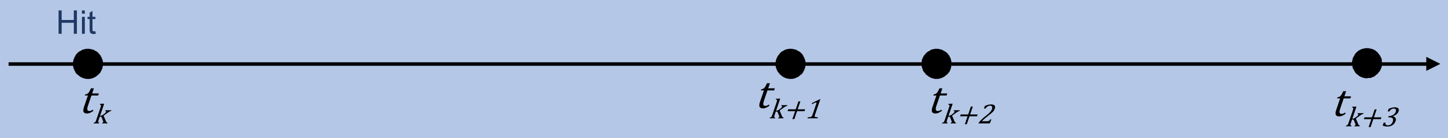
A_k Hit amplitude

Hit energy:

$$E_k \propto \int [V(t)]^2 dt$$

Hit duration: $\Delta_k = t_f - t_s$

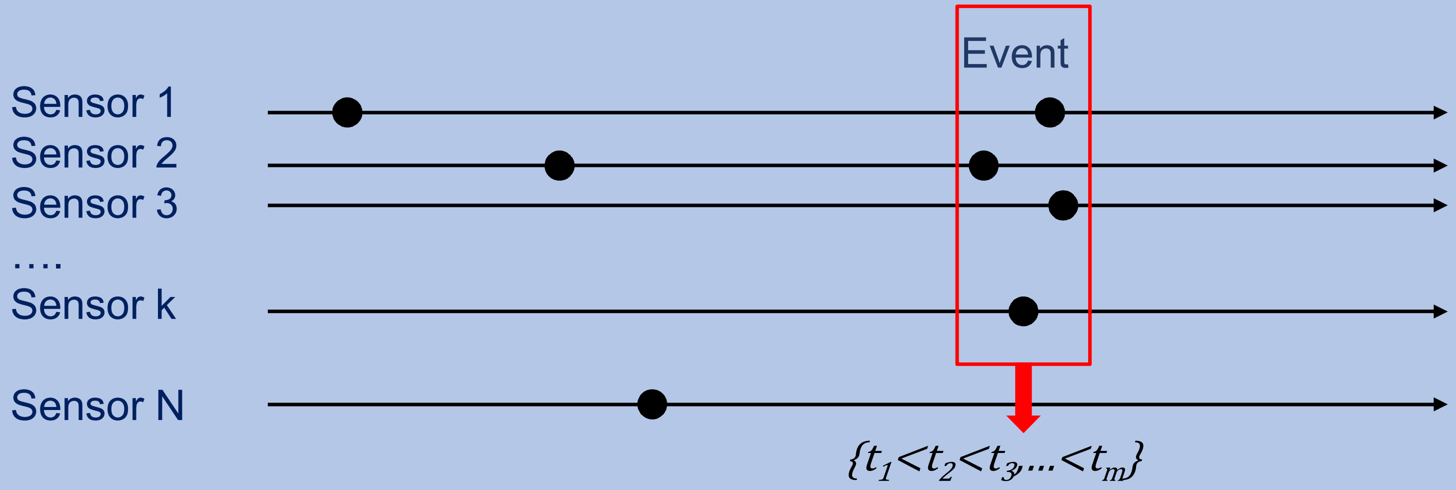
Hit catalogue:



The complex AE signal is reduced to a sequence of time instants and associated properties

$$\{(t_k; A_k, E_k, \Delta_k, \ldots)\ k=1,\ldots,N\}$$

Acoustic emission location



Set of non m non linear equations with 4 unknowns (3D location)

$$t_k - t_0 = \sqrt{(x_k - x_0)^2 + (y_k - y_0)^2 + \cdots}/c$$

Simplest case: 2D location with 2 trasducers

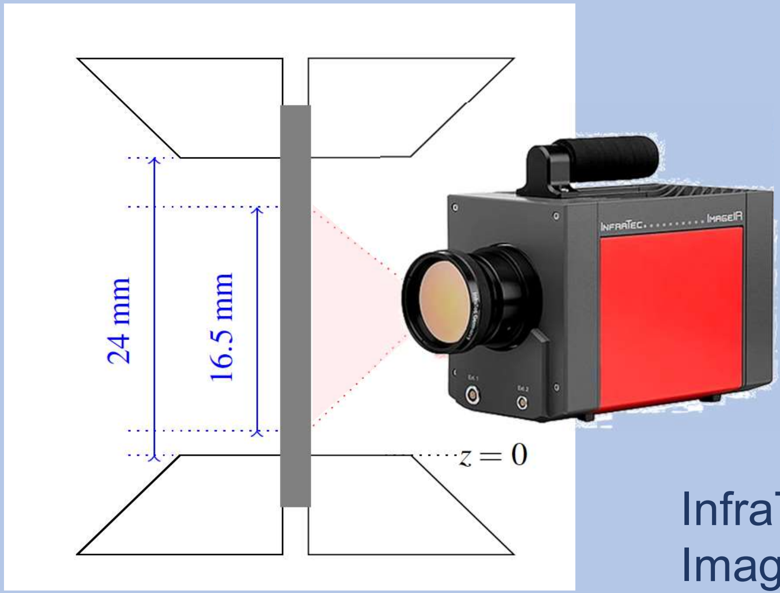
$$X = \frac{1}{2} L \left(1 - \frac{t_2 - t_1}{t_{max}}\right)$$

$$E_0 \propto \sqrt{E_1 E_2}$$

IR measurements

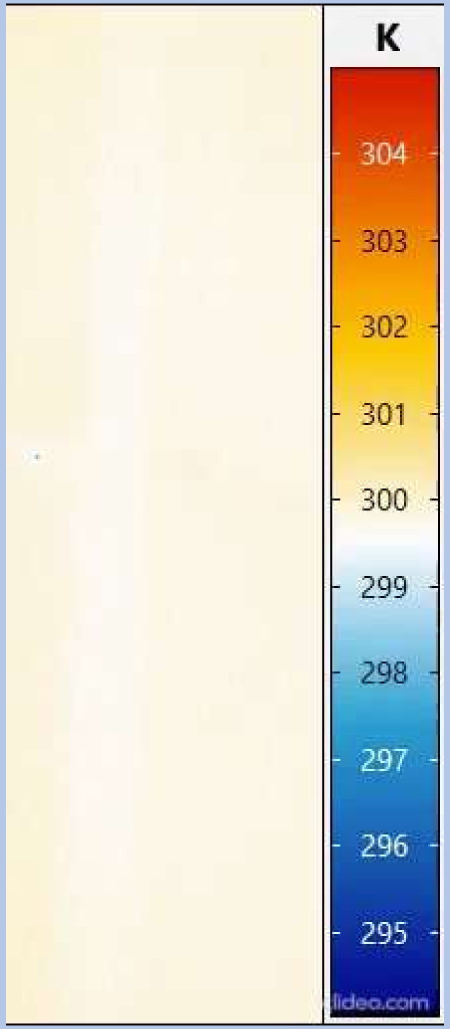
Recording 2D thermal maps of the sample surface as a function of time

Caution: focus, increase emissivity, avoid reflectivity,…



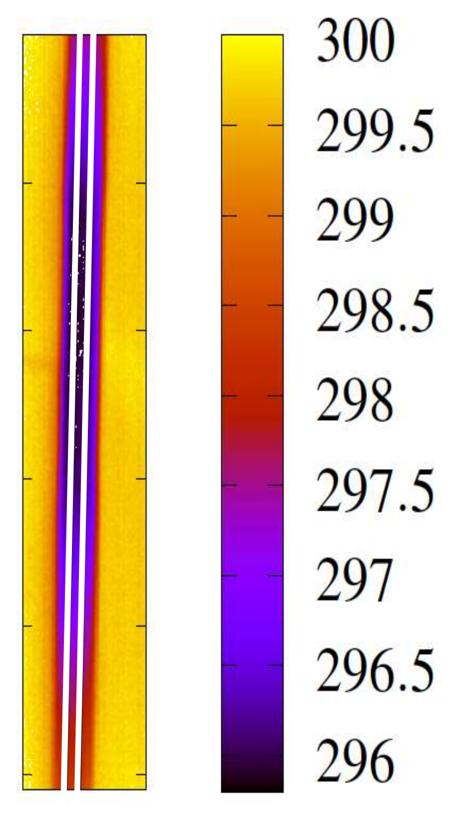
InfraTec camera
ImageIR 8800

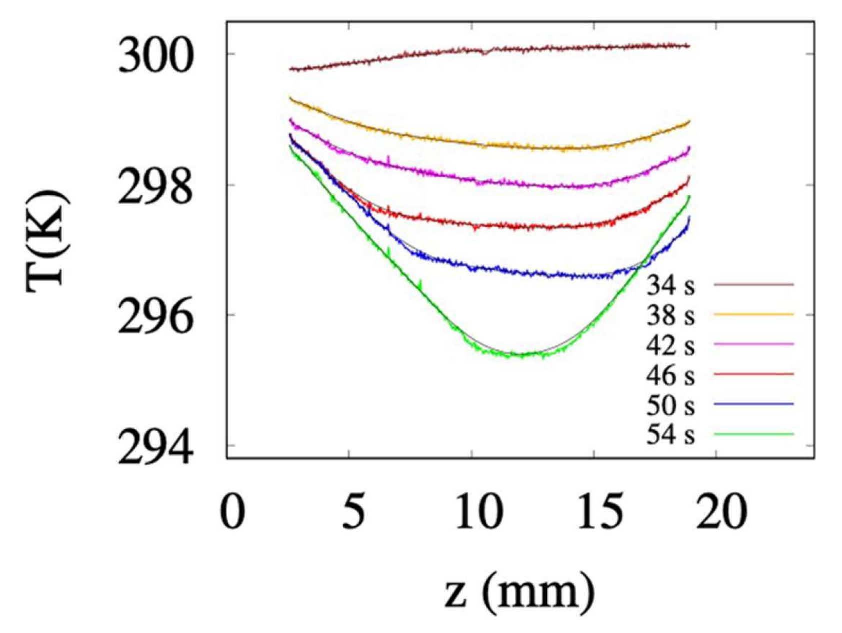
Δt=0.01 s/frame,
Δz=0.0322 mm/pixel
ΔT=0.01K



IR measurements : averaging 1D profiles

Numerical processing of 2D maps to obtain 1D temperature profiles





IR location of heat sources and sinks

Neglecting losses to air, we can consider a simple 1D Fourier equation describing the evoltuion of the temperature profiles

$$C\rho \frac{\partial T(x,t)}{\partial t} = \kappa \frac{\partial^2 T(x,t)}{\partial x^2} + \sigma\,(x,t)$$

Discretizing time $t = k\Delta t$ and space $x = i\Delta x$: $T(i,k)$

$$\Sigma(i,k) \equiv \frac{\sigma(i,k)}{C\,\rho} = \frac{1}{\Delta t}\frac{\partial T(i,k)}{\partial k} - \frac{\kappa}{C\rho\Delta x^2}\frac{\partial^2 T(i,k)}{\partial i^2}$$

Noise reduction: gaussian filter + 5 point stencil formula for the numerical derivatives

$$\bar{T}(i,k) = \sum_{n=-4\sigma}^{4\sigma} T(i,k+n)\,G_n(r,\sigma)$$

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    2-1 Elastocaloric experiments

Locating heat sources and sinks in tensile experiments with elastocaloric materials

L.Ianniciello et al., Appl. Phys. Lett. **116**, 183901 (2020)
G.Capellera, et al., Appl.Phys. Lett **119**, 151905 (2021)

Sample: $Cu_{70.6}Al_{25.7}Ni_{3.7}$ (at%)

single crystal wire <100> direction

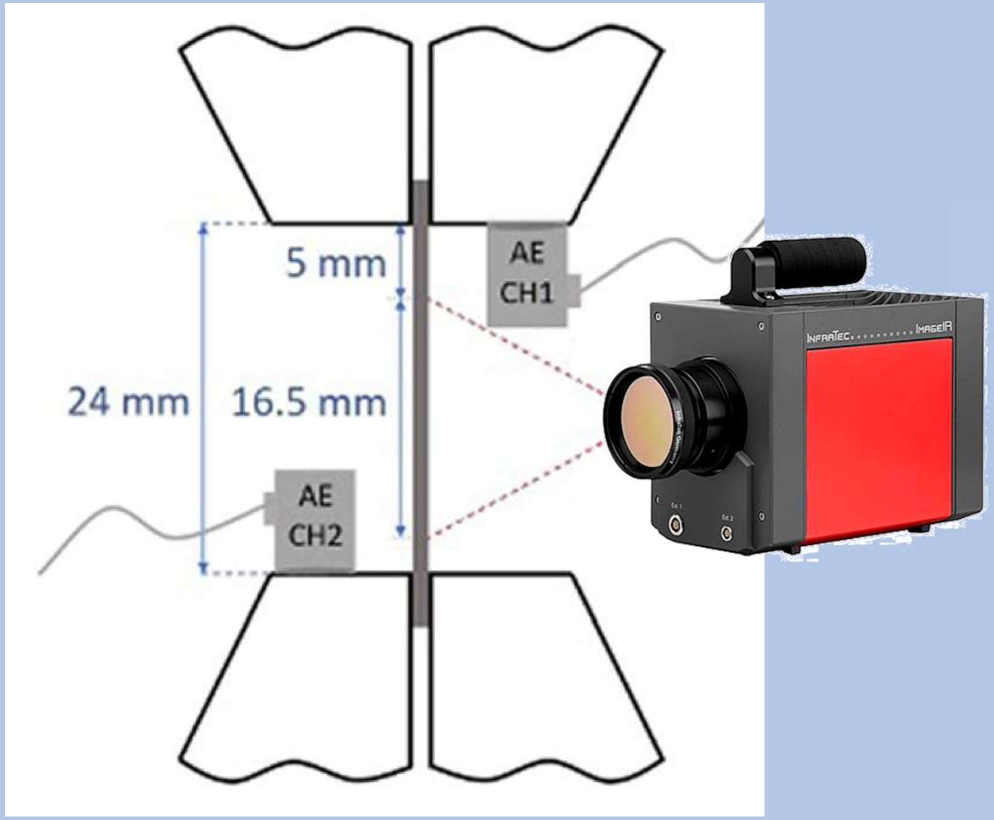
30mm x ϕ1mm

Cubic →18R martensite

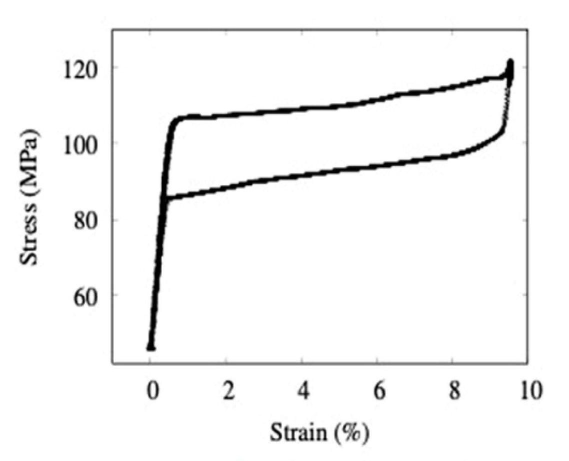
Zwick/Roell Z005 materials testing machine with displacement control 0.1 mm/s

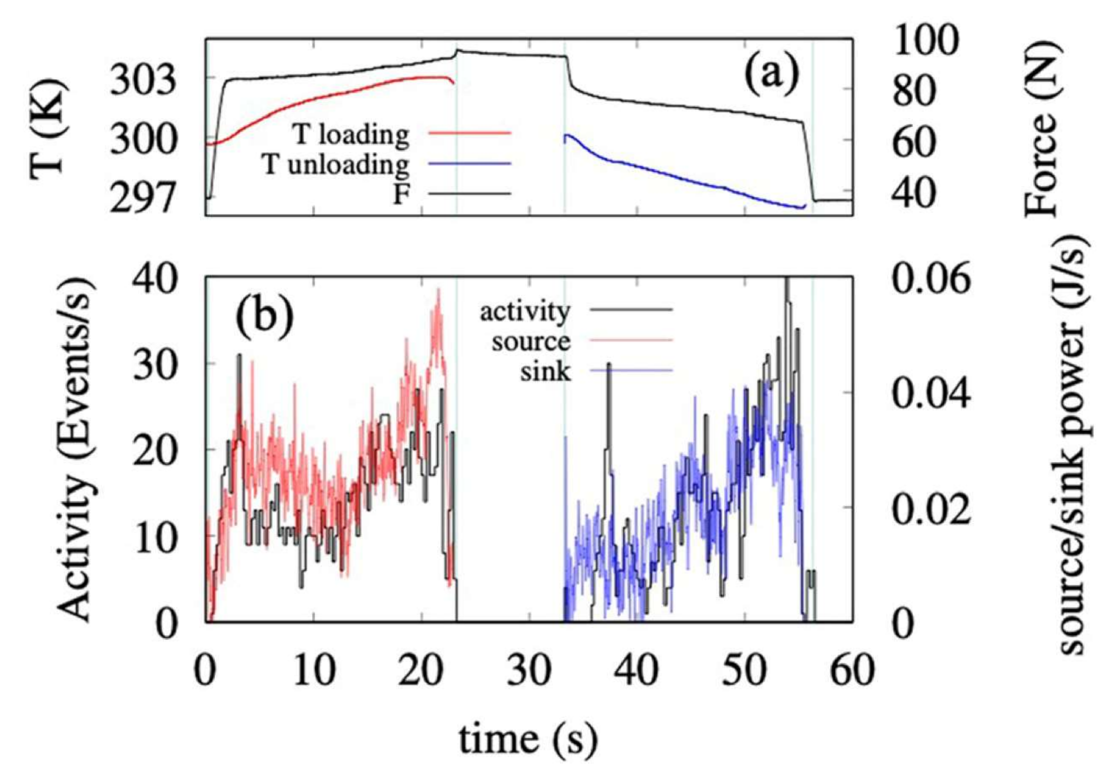
IR Infratec 8800 camera

Two AE sensors connected to PCI2 card (Mistras).



Stress-strain, average temperature and AE activity



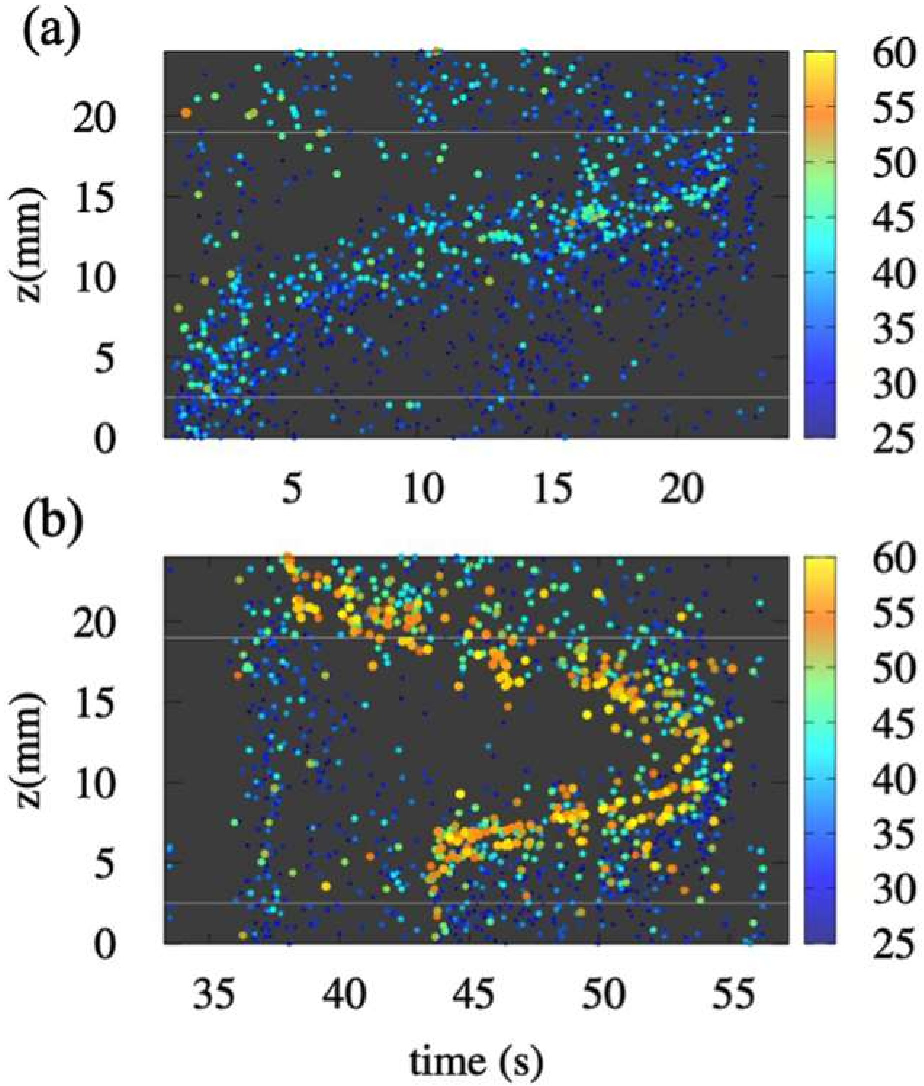


AE location

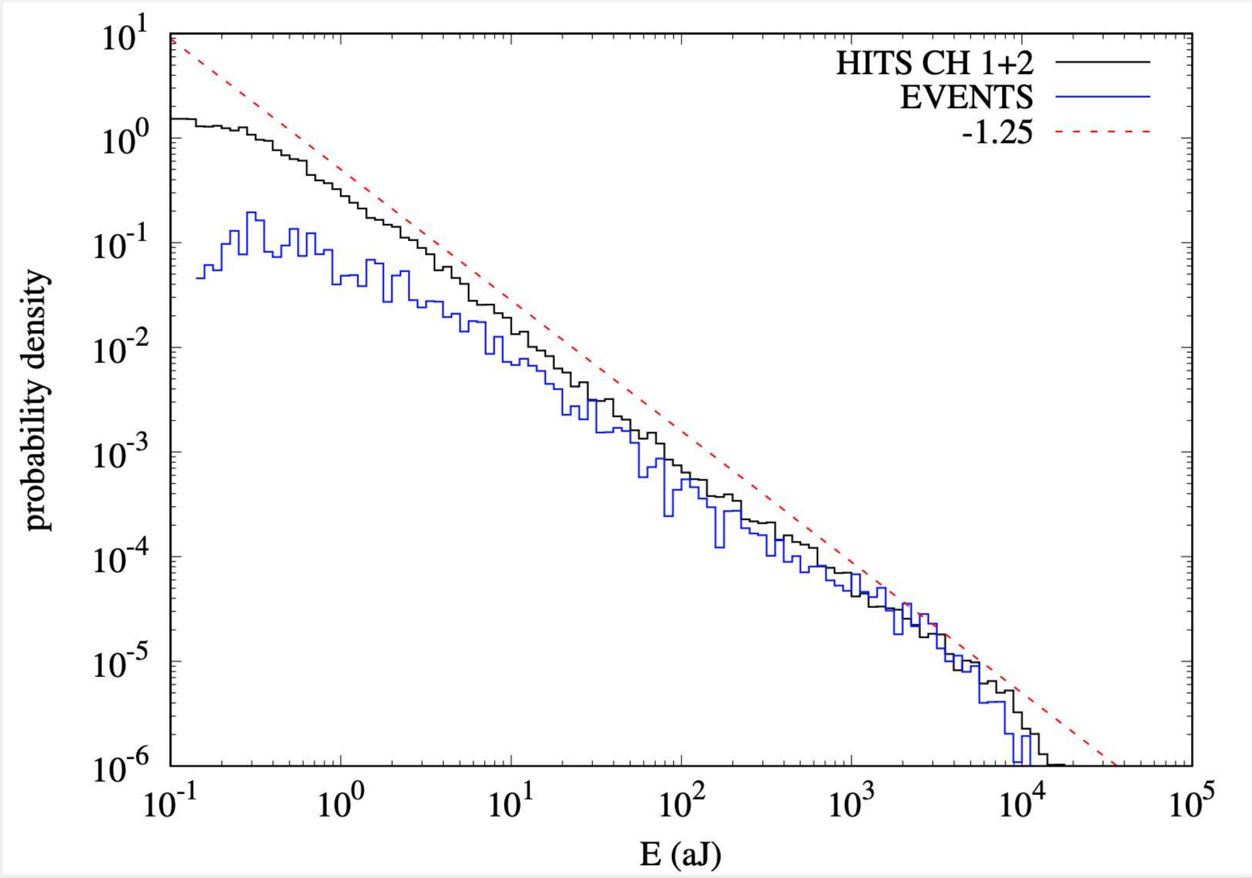
Loading

Unloading

Colour corresponds to the amplitude of the AE events (dB)



AE energy distribution unloading



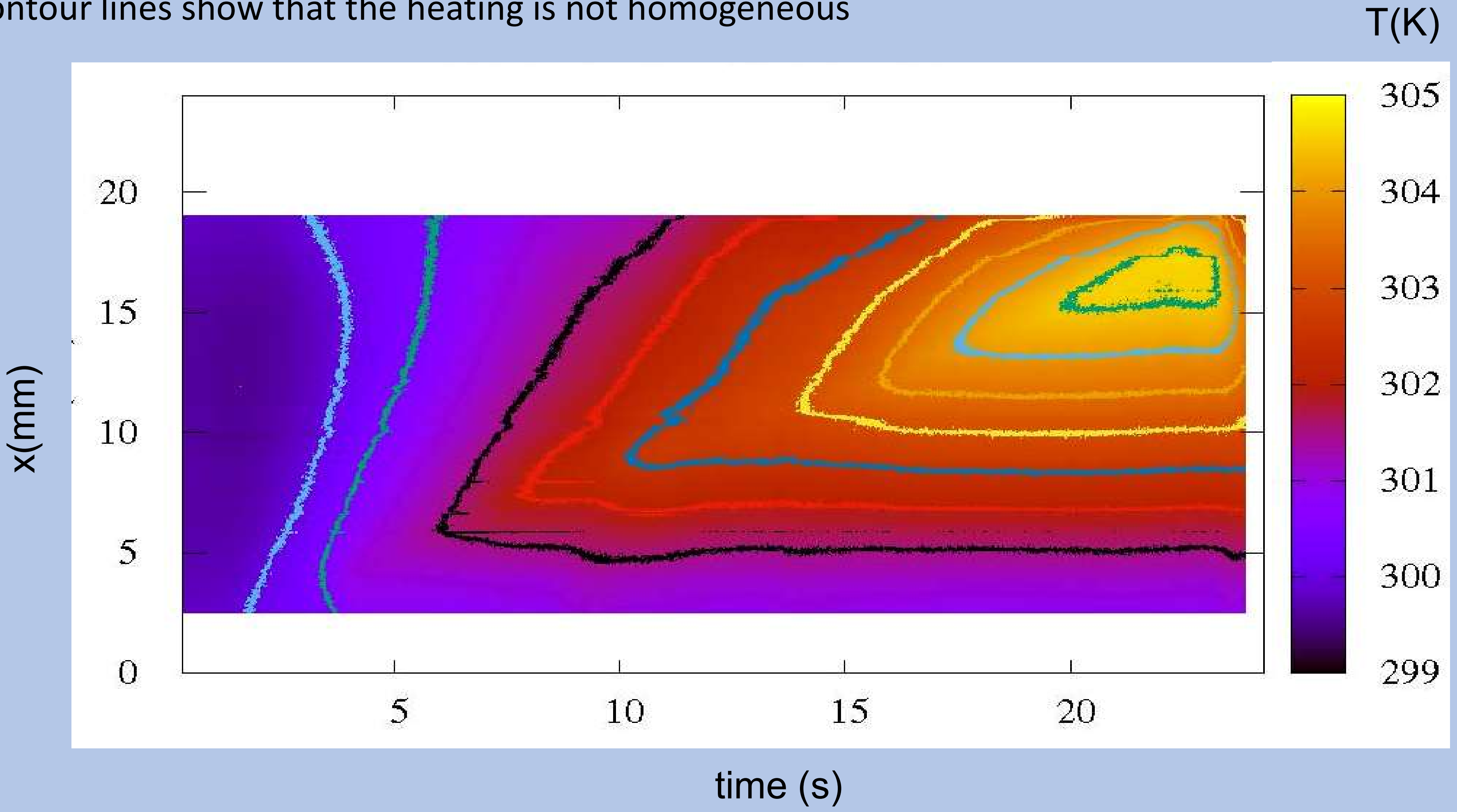
In previous experiments in Cu-Zn-Al we found -1.91 but in that case the transition was not single variant.

E.Vives, D.Soto-Parra et al., Phys. Rev. B. **80**, 180101R (2009)

Evolution of 1D thermal profiles with time during loading (extension)

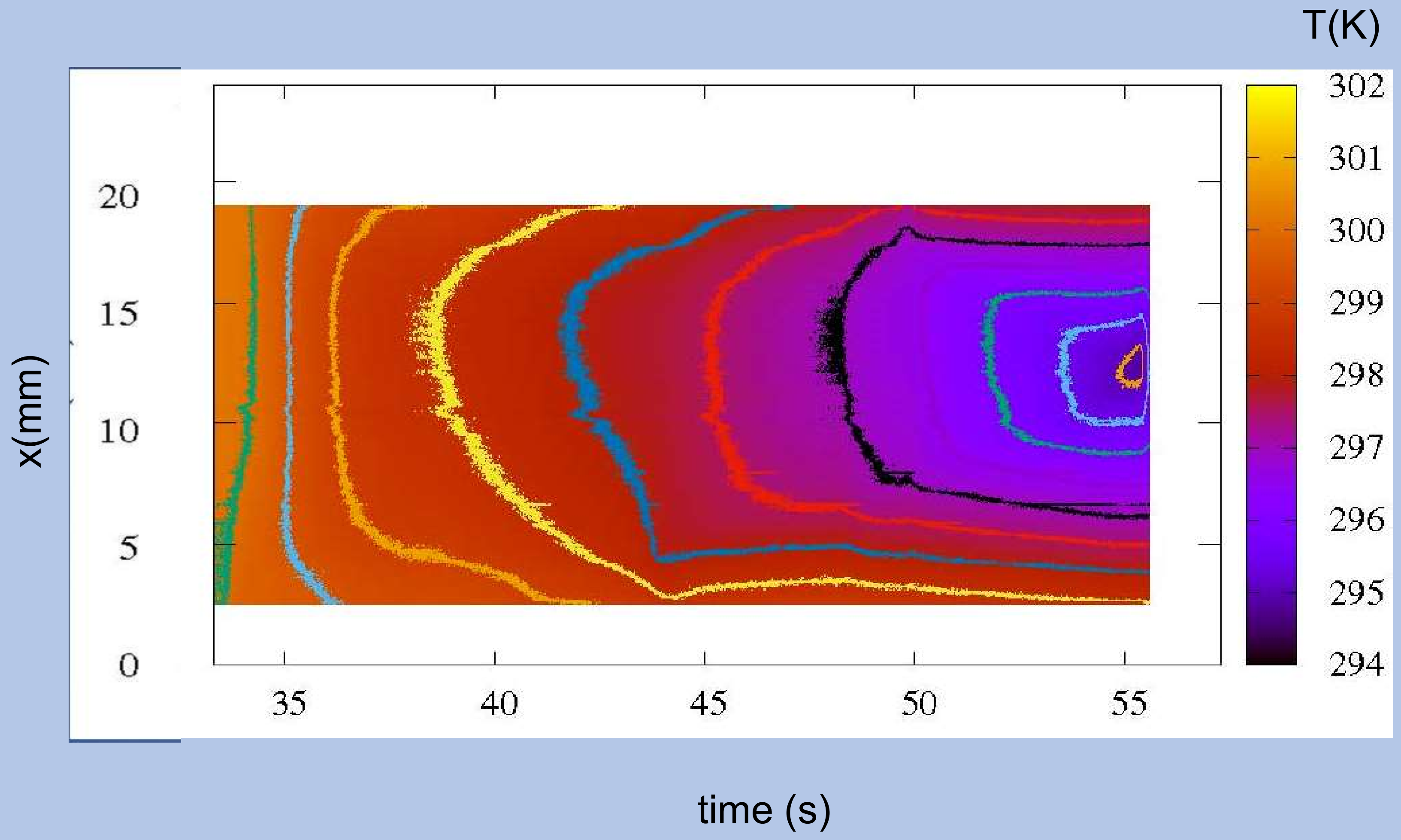
Exothermic transition: overheating +5K

Contour lines show that the heating is not homogeneous



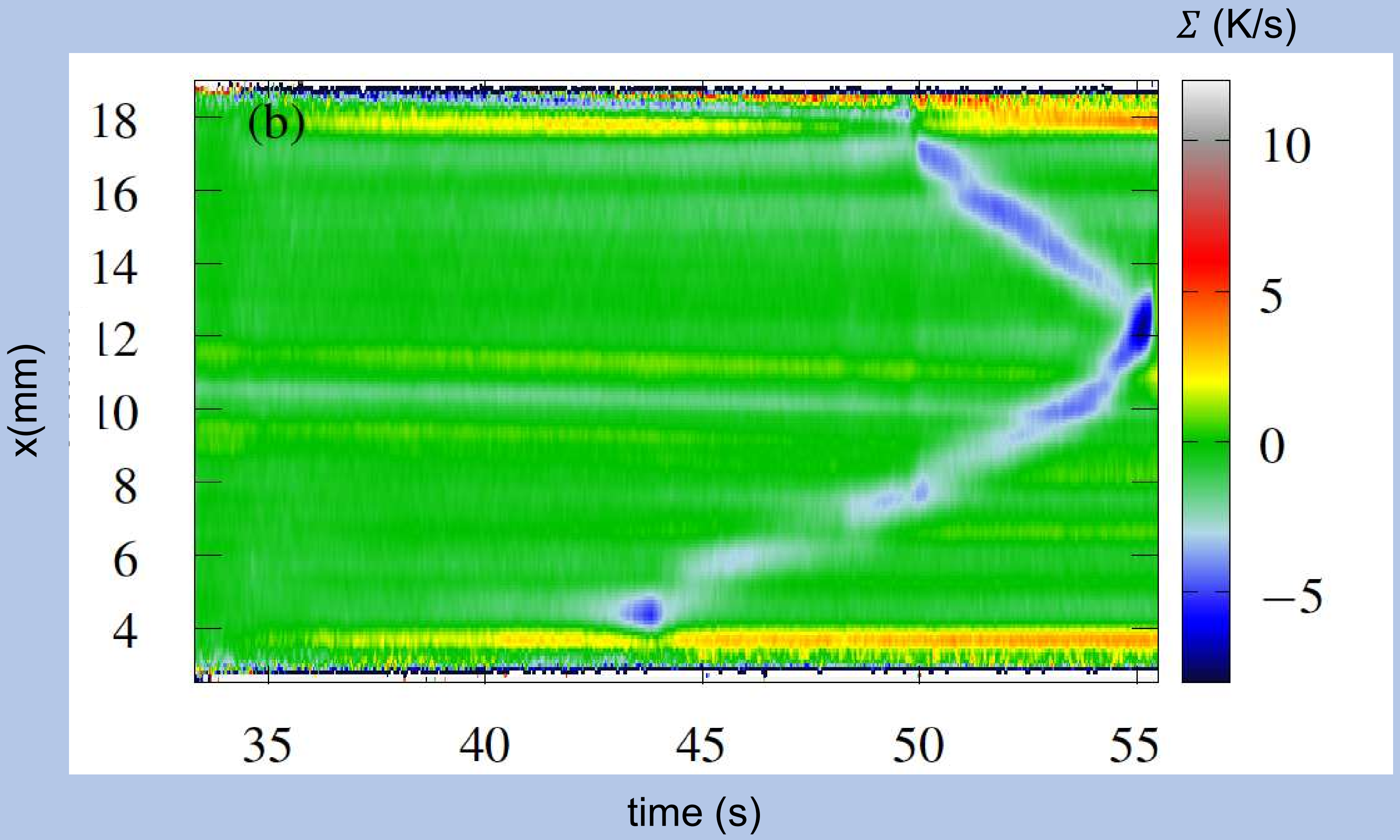
Evolution of 1D thermal profiles with time during unloading (shrinking)

Endothermic transition: undercooling -5K



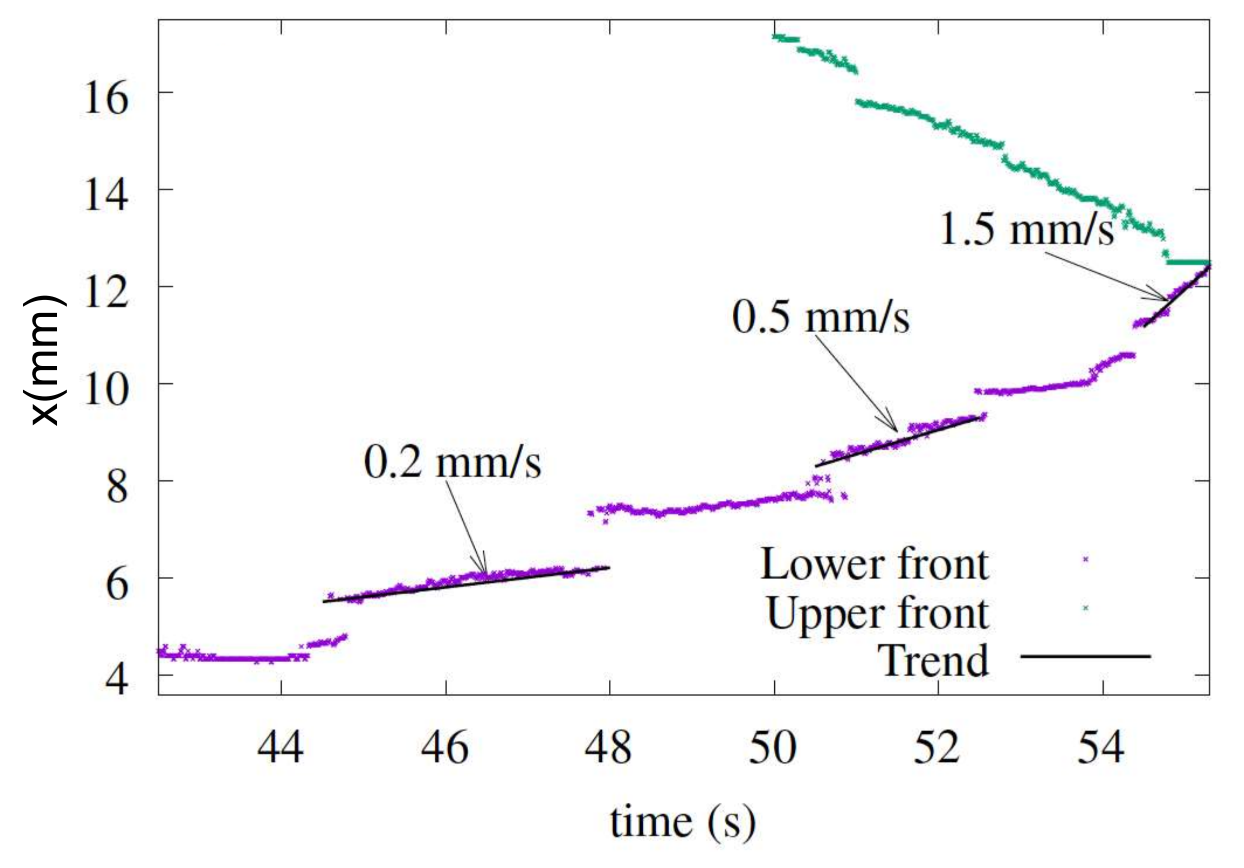
Calculation of heat sinks during unloading

Heat absorption occurs on the position of the moving austenite-martensite fronts



Dynamics of the heat sinks (I)

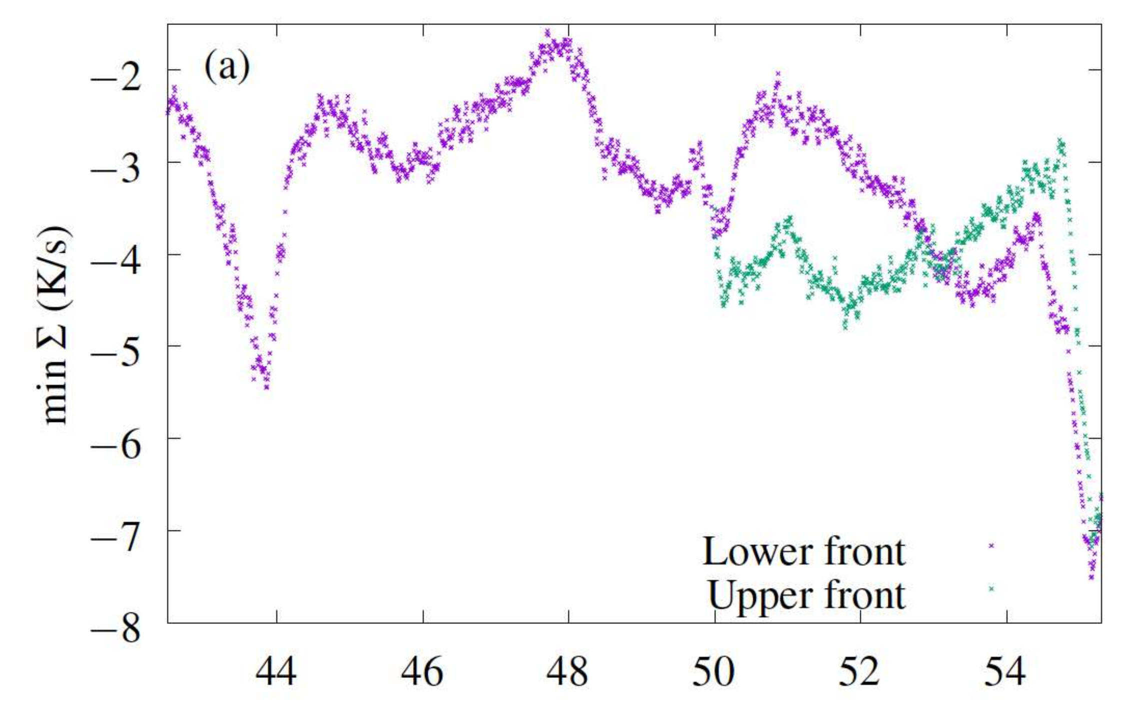
Position of the minimum (most negative) heat sink as a function of time



Dynamics of the heat sinks (II)

Value of the maximum cooling power (most negative Σ) as a function of time

Cooling is intermittent and there are some evidences of correlations between the two fronts
Maximum heat extraction when fronts collide



time (s)

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Flexocaloric experiment

Unpublished (2022)

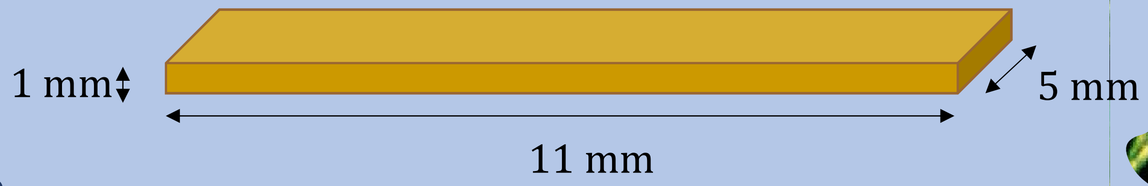
Sample: $Cu_{67.7}Al_{26.7}Ni_{5.6}$ (at%)

single crystal beam: long axis <100> direction

Cubic →18R martensite

Top surface covered with matte paint

White dots painted in the back edge of the sample



Room temperature

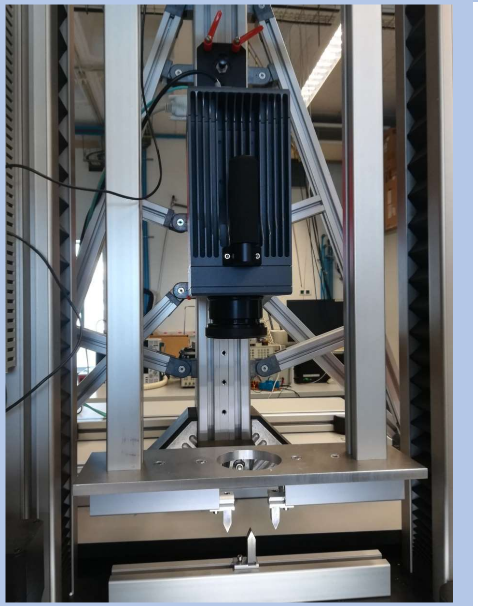
Zwick/Roell Z005 materials testing machine with an inverted three-point bending frame

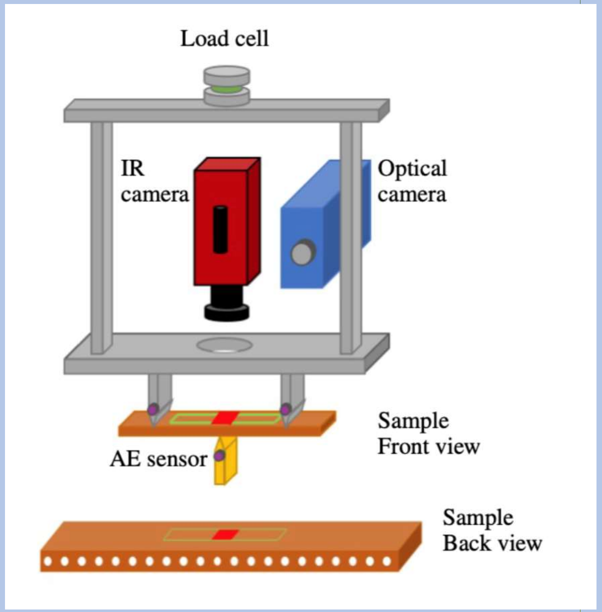
Polyestirene shield to avoid IR reflection

IR Infratec 800 camera in vertical position

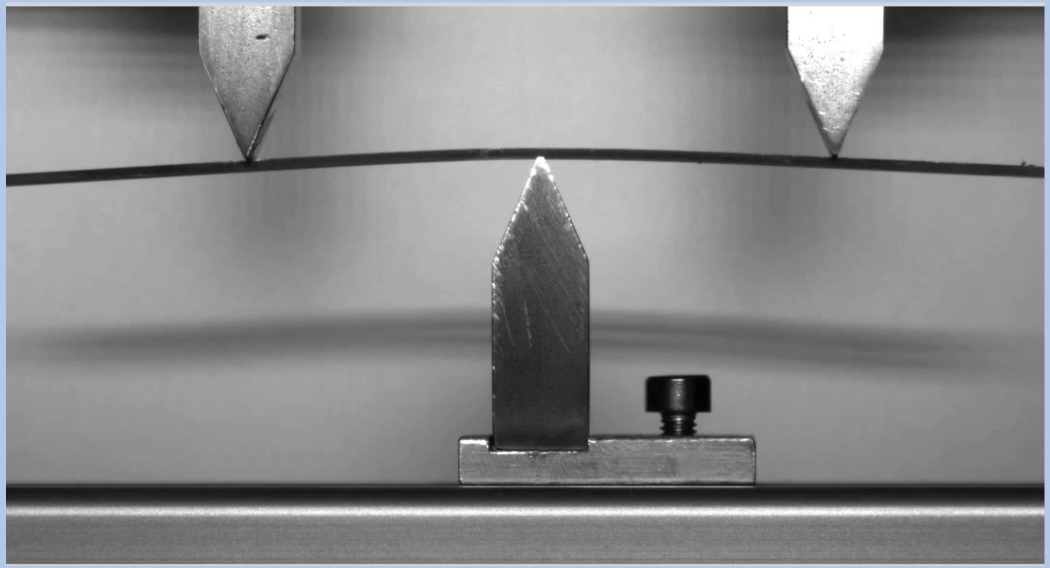
Optical CCD camera recording the sample shape

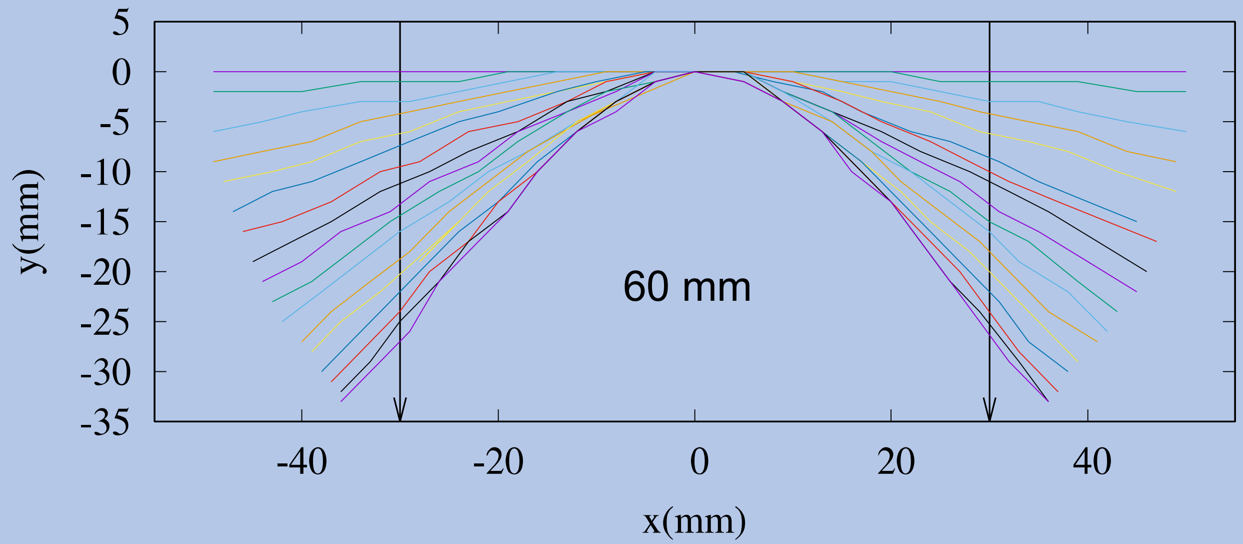
AE sensors on the bending pins





Video

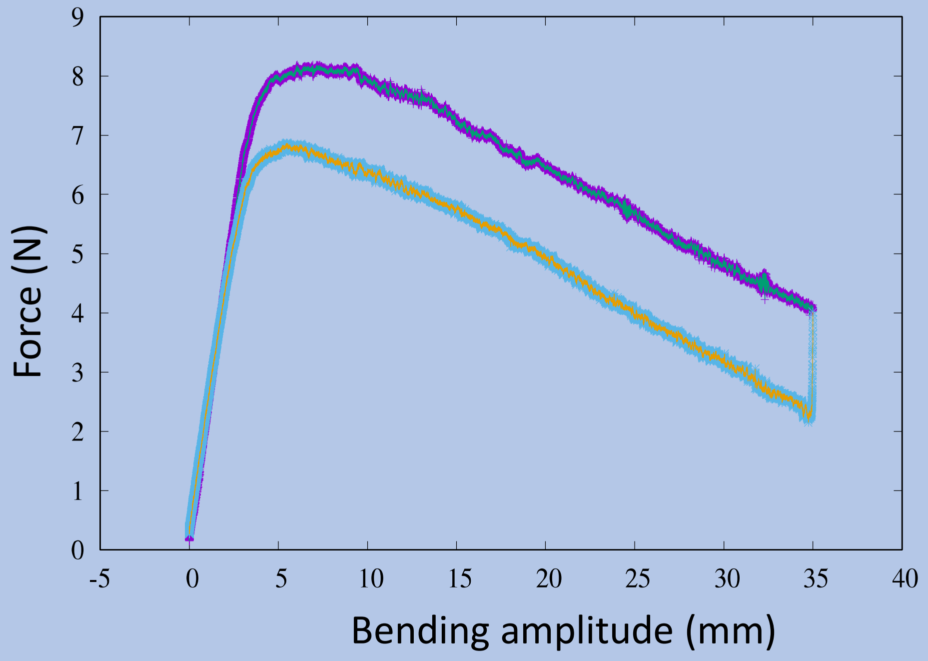




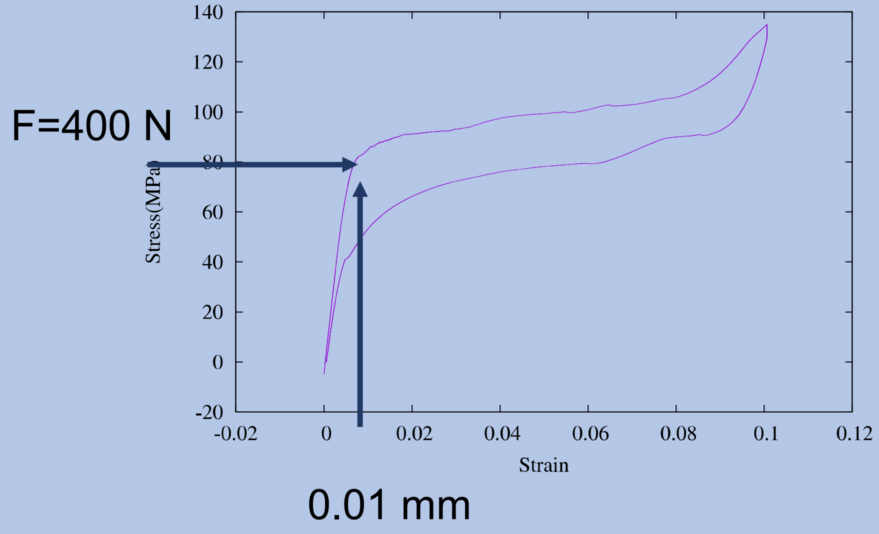
500 mm/min

Mechanical response:

Force versus bending amplitude during slow cycles at 1 mm/min



Standard stress-strain uniaxial experiment

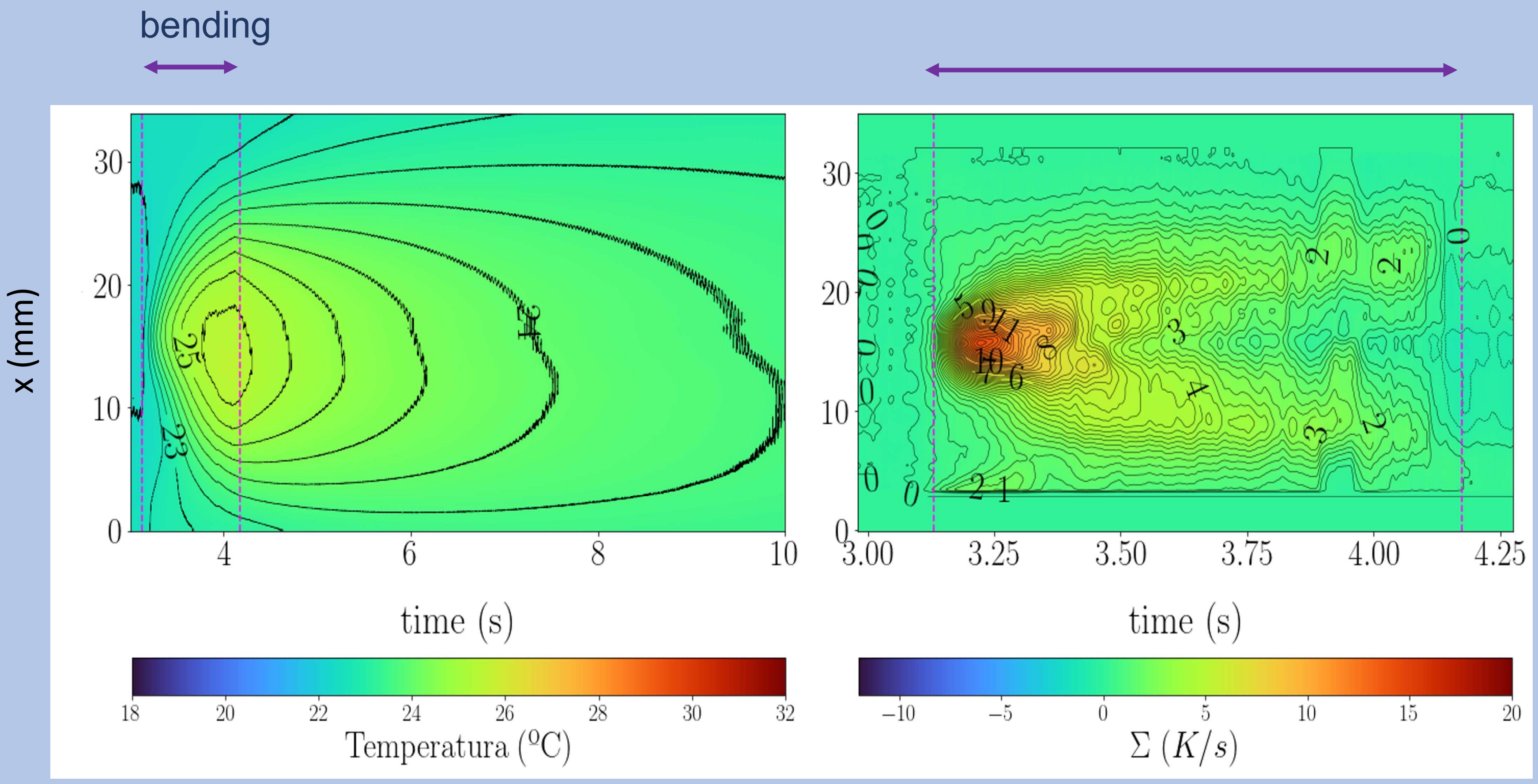

F=400 N

0.01 mm

Hysteresis is intrinsic, related to the front movement, not related to the friction between the pins and the sample

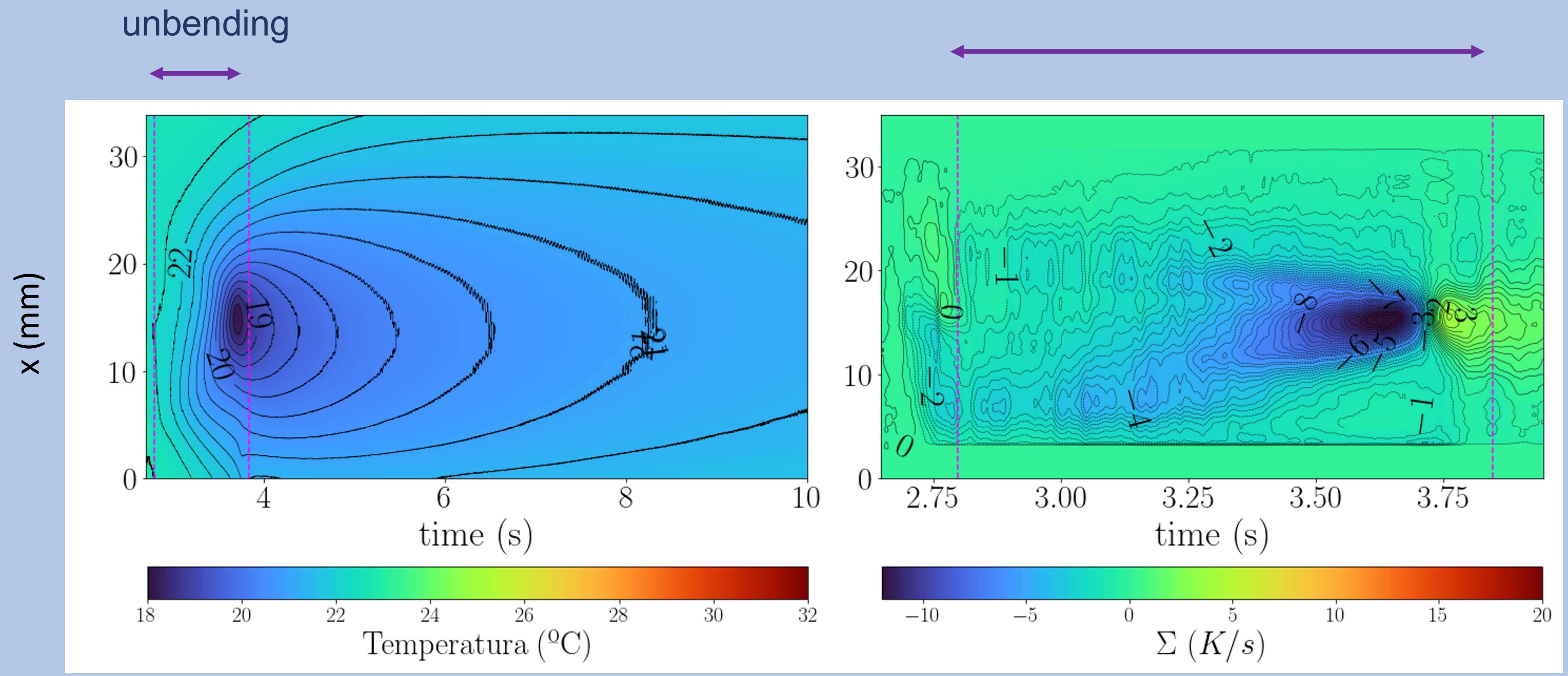
Thermal response: bending

Evolution of 1D temperature profiles and corresponding heat sources (2000 mm/min, bending amplitude 0 →35mm)



Thermal response: unbending

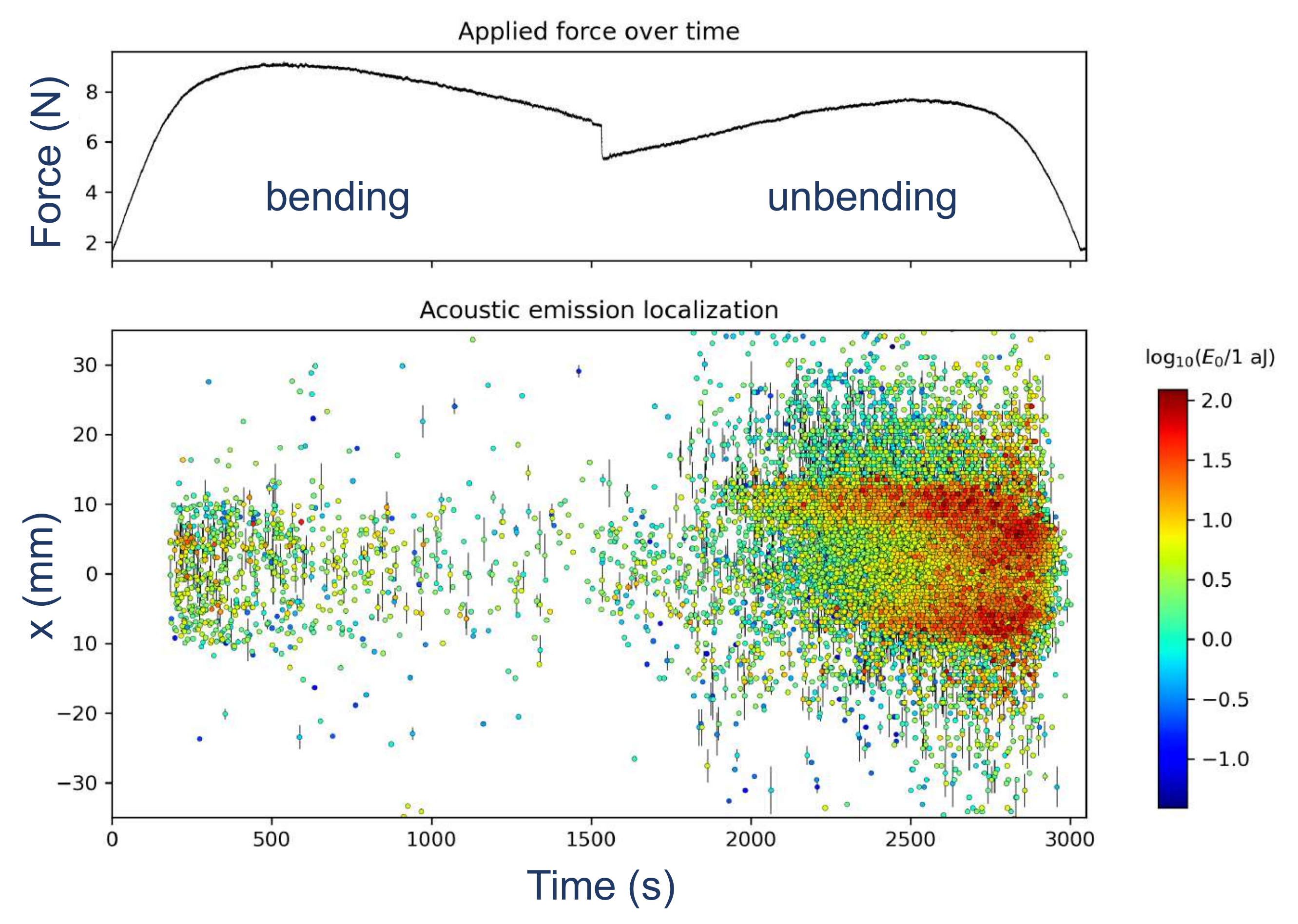
Evolution of 1D temperature profiles and corresponding heat sinks (2000 mm/min, bending amplitude of 35→0 mm)


unbending

Acoustic response: bending + unbending

Location of AE events along the sample

1 mm/min,
amplitude 25 mm.
th=25dB,

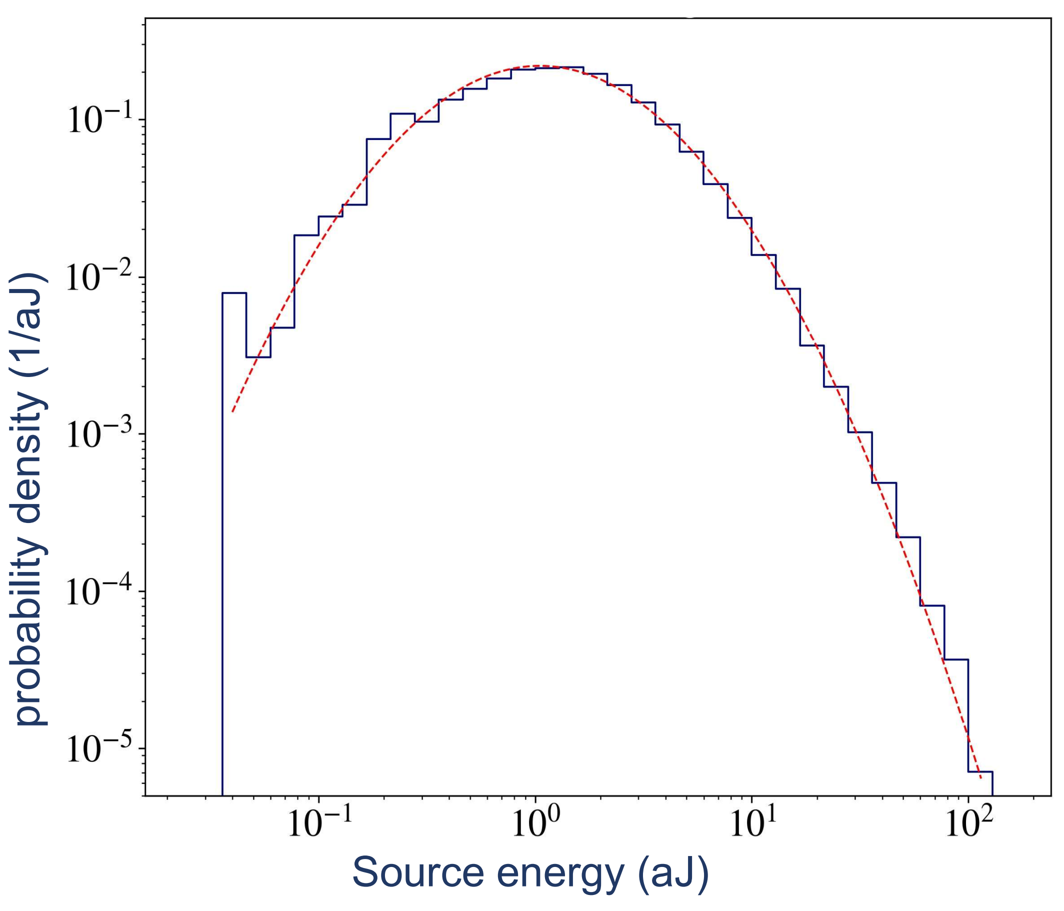


Acoustic response: avalanche energy distribution (unloading)

Fit: log-normal distribution

Not a critical (power-law) distribution

The microstructure is highly constrained due to strain gradient and sample height



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Take home messages

Elastocaloric materials based on first-order martensitic transition show good caloric properties, due to its large latent heat

Heat absorption and release in these materials is associated with martensite-austenite fronts movement that, at microscopic scales, follow avalanche dynamics

The heat sinks and sources are, consequently, heterogeneous in space, and move along the sample with intermittent activity

The fronts can be tracked by different experimental techniques:

-AE with location algorithms
-IR imaging with inversion of Fourier equation to detect heat sources and sinks