Concurrent tracking of strain and noise bursts at ferroelastic phase fronts

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Many technological applications are based on functional materials that exhibit reversible first-order ferroelastic transitions, including elastocaloric refrigeration, energy harvesting, and sensing and actuation. During these phase changes inhomogeneous microstructures are formed which fit together different crystalline phases, and evolve abruptly through strain bursts related to domain nucleation and the propagation of phase fronts, accompanied by acoustic emission. Mechanical performance is strongly affected by such microstructure formation and evolution, yet visualisation of these processes remains challenging. Here we report a detailed study of the bursty dynamics during a reversible stress-induced martensitic transformation in a CuZnAl shape-memory alloy. We combine full-field strain-burst detection, performed by means of an optical grid method, with the acoustic tracking of martensitic strain avalanches using two transducers, which allows for the location of the acoustic-emission events to be determined and the measurement of their energies. The matching of these two techniques reveals interface formation, advancement, jamming and arrest at pinning points within the transforming crystal.

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Martensitic transformations are first-order diffusionless phase transitions observed in a variety of crystalline materials, including metals, ceramics and proteins \textsuperscript{1–3}. They occur via cooperative atomic motions producing rapid changes of lattice structure, and typically form inhomogeneous microstructures involving different coexisting crystalline phases and variants. Many technological applications, such as environmentally-friendly elastocaloric refrigeration \textsuperscript{4–6}, energy harvesting \textsuperscript{7,8}, smart sensing and actuating \textsuperscript{1–3}, are based on functional ferroelastic materials, like shape-memory alloys, exhibiting highly reversible martensites \textsuperscript{7,9–11}. The intermittent progress of the structural transformations is inherent to the first-order character of these solid-state phase transitions \textsuperscript{12}. The microstructure responds to changes in environmental conditions through strain avalanching \textsuperscript{12,13}, with associated bursts of acoustic emission (AE) \textsuperscript{13–20}, related to the nucleation of phase domains and to phase-front advancements \textsuperscript{12–14}. The functional properties and stability of the material are strongly affected \textsuperscript{6,7,10,11} by these events marking microstructural evolution and reorganization, and their visualisation and thorough understanding is currently a challenge \textsuperscript{12,13,17,21–24}.

To shed light on the details of these phenomena, we have studied the strain-avalanching in the stress-induced martensitic transformation in a CuZnAl shape-memory alloy \textsuperscript{12,14}. For this purpose we combined two different techniques: on the one hand, AE detection using two transducers \textsuperscript{21}, which has unbeatable time resolution \textsuperscript{16} and allows for avalanche localisation and energy measurement; and, on the other hand, strain measurement via the grid method, allowing for full-field strain imaging \textsuperscript{25–29}. These approaches, used separately so far, have much contributed to our understanding of structural transformations in crystalline solids. They are used concurrently here for the first time.

**Results**

**Elongation test.** We have used a Cu\textsubscript{68.13}Zn\textsubscript{15.74}Al\textsubscript{16.13} (at.%) single-crystal grown by the Bridgman method. The specimen is a thin elongated parallelepiped with cylindrical heads for gripping. The vertical y-axis is oriented along the sample length, and close to the [001] crystallographic direction in the bcc austenitic lattice (see refs. \textsuperscript{14,21} and Fig. 1a, b for dimensions and details). The elongated shape of this specimen is particularly suitable for our study, which concentrates on lengthwise phase-front propagation treated in a one-dimensional (1D) setting along the y direction (see below). In the absence of applied external force, this alloy exhibits a reversible symmetry-breaking martensitic transformation at $M_s = 234$ K from a cubic L\textsubscript{2} high-temperature parent phase (austenite) to a lower-temperature monoclinic 18R product phase (martensite). The transition can also be induced at room temperature by applying a uniaxial loading. Prior to the present test, an appropriate heat treatment was performed so that the alloy was in an ordered state, free from internal stresses, and with a minimum vacancy concentration. The specimen was then submitted to a series of more than 20 loading-unloading cycles to reach a stationary transition path between the parent and product phases.

Figure 1a, b also show the bidimensional grid (with pitch 0.2 mm) transferred onto the specimen\textsuperscript{25} to follow the strain evolution through the GM (see Methods). The parallel 1D study of AE along the y direction (see Methods) involved the recording of acoustic activity by means of two transducers suitably placed on the grips of the loading apparatus, as in Fig. 1c. The latter is an in-house designed gravity-based device\textsuperscript{12} producing a strictly monotonic uniaxial load, which can be applied at a very low rate. During the elongation test, with time $t$ running in seconds, we monitored the stress-induced martensitic transformation under the following conditions: (a) preloading of 81.92 MPa; (b) constant loading rate 109.7 Pa/s, up to 88.97 MPa, with a total duration of about 64,200 s (i.e. ~8 h; room temperature: 25.7 ± 0.5 °C). After the application of the preload the force was increased very slowly so as to approach the transformation plateau in almost adiabatic conditions, and to obtain the phase transition with a minimum of precursors or spurious disturbances, and a minimal dependence on the loading history. The observed plateau (duration ~27 min) indeed resulted to be nearly horizontal, shown in black on the macroscopic stress-strain curve of Fig. 2a, with the elastic load-up portions shown in red. To ensure specimen integrity, the loading was stopped shortly after the elastic response resumed at the end of the plateau, although
The residual austenite might have further transformed at higher loads. The monitoring of AE during the test, done concurrently to strain detection, recorded ~110,000 (~60,000) AE hits at the upper [lower] transducer, with the corresponding amplitudes and energies (see Methods).

**Strain field evolution.** By suitably processing\(^\text{25-28}\) the captured images of the deforming grid, we obtained a sequence of (x, y)-maps during the entire elongation test, giving the spatial distribution on the sample’s face of the linear in-plane strain components \(\varepsilon_{xx}\), \(\varepsilon_{yy}\), \(\varepsilon_{xy}\) and of the local rotation angle \(\omega\), corresponding to the average-strain value \(\varepsilon_{yy} = 0.052\). See also Supplementary Movie 1.

Analysis of global strain- and AE-intermittency. We first assess the global stress-strain behaviour of the specimen during the elongation test. We consider the average of the \(\varepsilon_{yy}\) strain \([\sigma_{yy}\) stress] over the entire sample, denoted by \(\bar{\varepsilon}_{yy}\) [\(\bar{\sigma}_{yy}\)]. These quantities undergo a quite continuous evolution at the time scale of the plateau duration, as shown by the black curves in Figs. 2a and 3a. The corresponding strain rate \(\dot{\varepsilon}_{yy}\) was then computed by taking the differences in consecutive strain maps separated by a time interval of 3.8 s. The resulting values of \(\dot{\varepsilon}_{yy}\) exhibit the spiky time evolution shown in red in Fig. 3a. This clearly highlights the jerky progress of the martensitic transformation despite the very small and constant loading rate and the apparent continuity of \(\bar{\varepsilon}_{yy}\). The time evolution of the number of AE hits, recorded within the same 3.8-s bins, is also plotted in blue in Fig. 3a. The high correlation of this intermittent AE signal with the strain-rate spiking can be noticed, giving a scatter plot tightly clustered near the graph bisector in Fig. 3b. The off-diagonal crosses near the bottom of Fig. 3b correspond to the decoupling of the AE and the strain-rate signals at the end of the transformation plateau (shaded area of Fig. 3a). This is due to the lower phase front moving progressively out of the grid zone near the end of the loading test, so that AE recording continued while strain events could no longer be detected (see the lower orange triangle exiting through the bottom end of the strain maps in the last snapshots of Fig. 2a, and the end of Supplementary Movie 1).

Analysis of local strain- and AE-events. The intermittent evolution of the global quantities in Fig. 3 results from the local intermittency in the underlying structural transformation within the specimen. We studied this first through the localisation of the acoustic emission in the sample. From the total ~70,000 AE hits recorded during the test, it was possible to determine the y-location of ~38,000 AE events (see Methods). Their (t, y)-chart with energies is given in Fig. 4a, with Fig. 4b displaying the corresponding AE number density. We studied at the same time the associated local space-time strain intermittency by first considering the differences between consecutive 2D \(\varepsilon_{yy}\)-strain maps, with the same 3.8-s time step as in Fig. 3a (see also Supplementary Movie 1). Through x-averaging, these maps give the y-profiles of the 1D strain rate \(\dot{\varepsilon}_{yy}\) vs. time t, where \(\varepsilon_{yy}\) is the transformation mainly proceeded here through the creation and propagation of two triangular fronts (in yellow-orange on the strain maps) lying between pure austenite (in red) and pure martensite (in green). Martensite nucleated at a point with higher stress fluctuations within the bulk or on the surface of the sample. The triangular shape of the observed fronts is explained by the formation of martensitic twinned micro-layers, whose average strains are kinematically compatible with austenite and pure martensite across suitable non-parallel transversal planes in the sample, see for instance the X-microstructures analyzed in Ref. \(^\text{30}\). Supplementary Movie 1 also shows the temporal evolution of the associated strain-rate \(\dot{\varepsilon}_{yy}\) maps on the sample (see Methods), which clearly highlight the bursty propagation of the triangle-shaped fronts. Strain-rate values are here limited to 2.5 x \(10^{-3}\) s\(^{-1}\) for better visualisation of the transformation intermittency investigated in detail below. While the advancing phase front carried most of the strain avalanching during the elongation, small transformation-strain bursts occurred nonetheless throughout the specimen, with small precursor events taking place also before entering the transformation plateau\(^\text{31}\), producing the slight non-linearity in the red elastic part of the stress-strain curve in Fig. 2a.

**Fig. 2** Stress-strain curve and evolution of the strain field. a The elastic part of the stress-strain curve is indicated in red and the transformation plateau in black. Snapshots of the map for the strain component \(\varepsilon_{yy}\) are shown at various loading stages, marked by blue dots on the plateau. b Maps of all the in-plane strain components \(\varepsilon_{xx}\), \(\varepsilon_{yy}\), \(\varepsilon_{xy}\), and of the local rotation angle \(\omega\), corresponding to the average-strain value \(\varepsilon_{yy} = 0.052\). See also Supplementary Movie 1.
At any given $t$, a 1D strain event is thus defined by each separate $y$-interval on which $\bar{\varepsilon}_{yy}$ reaches above the threshold. This assures that localised strain-rate surges emerging from the noise floor while monitoring the phase-change reliably reflect the occurrence of a transformation burst. In this way, ~1100 strain avalanches were identified on the plateau, see Fig. 4d. Besides its interval size, each 1D strain event is also characterised by its epicenter, i.e. the value of $y$ on which $\bar{\varepsilon}_{yy}$ is maximal, as well as its magnitude, defined by the sum of the squared values of $\bar{\varepsilon}_{yy}$ over the interval. The results shown in the four panels of Fig. 4 clearly highlight various different aspects of the strong spatial and temporal heterogeneity in the phase-transformation activity under the slow, steady forcing. This is also underscored by the heavy-tailed distributions in Fig. 5, pointing to the emergence of scale-free behaviour in the material during the transition process, as reported earlier separately for strain$^{12,13}$ and AE avalanching. In Fig. 5 the dashed blue line indicates a power-law distribution with exponent $\sim$1.8, which is in the range of the AE exponents previously found in these SMAs$^{14-16}$.

The 3.8-s time step considered above for the strain maps is orders of magnitude larger than the typical time scales of AE avalanches$^{16}$. Each strain event evidenced in Fig. 4d thus originates from the merging of a large and variable number of microscale transition bursts. Such wide separation of scales is partially obviated by considering the density of localised AE events in suitable time bins, as done in Fig. 4b. To the latter we can thus superpose the strain-burst data of Fig. 4d. The result can be seen in Fig. 6a, where we notice the remarkably good agreement between the two measurement techniques utilised to track the transformation intermittency in space and time. The inset to Fig. 6a shows the good correlation between the AE and strain data even at the present scale of local transition events, and not solely at the scale of the overall sample as in Fig. 3b. Some specific features of this concordance are seen in the close-up Fig. 6b. Here the different experimental techniques concurrently detect successive changes in the phase transformation intensity levels as they occur in the sample. We notice a low activity interval at $t = 63,050-63,100$ s, followed by strong activity from about $t = 63,100$ s to an almost complete pause near $t = 63,200$ s, possibly due to a strong pinning site. There ensues a rapid sequence of large transformation bursts at $t = 63,210-63,230$ s. Such details greatly enhance and very usefully complement the spatially opaque description of the global sample behaviour obtained via the averaged quantities in Fig. 3a.

**Discussion**

We have performed a detailed investigation of the stress-induced reversible martensitic transformation in a CuZnAl shape-memory alloy, considering a simplest case wherein the phase change largely occurs through the development and advancement of two diverging austenite-martensite triangle-shaped strain fronts. We have studied the intermittent progress of these complex interfaces by combining the full-field strain-burst detection via the optical grid method, concurrently with acoustic detection allowing for parallel high-activity bands in the $(t, y)$-plane. This is especially evident for the lower phase front in the white-dashed inset of Fig. 4c. We notice that small transformation events, detected by both strain and acoustic emission, are present also away from the phase fronts, especially in the martensitic region of the sample.

In the present 1D framework, the distinct transformation-strain avalanches on the sample are then tracked by considering, on each $y$-profile of $\bar{\varepsilon}_{yy}$ in 4c, the set of $y$-coordinates whereon the value of the strain rate $\bar{\varepsilon}_{yy}$ exceeds the noise threshold $3 \times 10^{-4}$ s$^{-1}$ (see Methods). At any given $t$, a 1D strain event is thus defined by each separate $y$-interval on which $\bar{\varepsilon}_{yy}$ reaches above the threshold. This assures that localised strain-rate surges emerging from the noise floor while monitoring the phase-change reliably reflect the occurrence of a transformation burst. In this way, ~1100 strain avalanches were identified on the plateau, see Fig. 4d. Besides its interval size, each 1D strain event is also characterised by its epicenter, i.e. the value of $y$ on which $\bar{\varepsilon}_{yy}$ is maximal, as well as its magnitude, defined by the sum of the squared values of $\bar{\varepsilon}_{yy}$ over the interval. The results shown in the four panels of Fig. 4 clearly highlight various different aspects of the strong spatial and temporal heterogeneity in the phase-transformation activity under the slow, steady forcing. This is also underscored by the heavy-tailed distributions in Fig. 5, pointing to the emergence of scale-free behaviour in the material during the transition process, as reported earlier separately for strain$^{12,13}$ and AE avalanching. In Fig. 5 the dashed blue line indicates a power-law distribution with exponent $\sim$1.8, which is in the range of the AE exponents previously found in these SMAs$^{14-16}$.

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the 1D localisation of AE avalanches and the measurement of their energies. The matching of these two microseismological techniques revealed the great correlation of the independently collected data for strain and acoustic events in space and time, a property which could so far only be hitherto true, due to the expected common transformational origin of these phenomena. Our results highlight with unprecedented detail interface formation, advancement, jamming, and arrest at pinning points, within the crystal undergoing the phase transformation.

The experimental approach explored here for solid-state phase transitions can be readily adapted to more general and diverse shapes of the transforming sample, and under more complex loading conditions, as might be suggested by particular applications of reversible martensitic materials. Furthermore, it can be applied to the study of analogous bursty phenomena in the plasticity32 and fracture33 of crystalline solids, as well as metallic glasses34 and porous media35, where the investigation and modeling of materials’ behavior can greatly benefit from the detailed visualization and analysis made possible by the presently described techniques.

Methods

Strain and strain-rate mapping. The strain maps were obtained via the grid method26–29. A bidimensional grid with pitch 0.2 mm was first printed with a 50,800 dpi photoplotter on a polymeric sheet and then transferred onto the sample surface by using a white E504 Epotecnny adhesive.25 The grid was slightly rotated with respect to pixel lines to avoid aliasing and the associated parasitic fringes28. Grid images during the test were captured by a Sensicam QE camera featuring a 12-bit 1040 × 1376 pixel sensor and a 105 mm Tokina lens, with 10-ms shutter time and about 17 Hz acquisition frequency. Magnification was adjusted so that one grid pitch was encoded with about seven pixels, leading to a pixel size of 0.0274 mm on the sample. A direct-current LED system was used for lighting to avoid flickering. Grid images were processed by using the Localised Spectrum Analysis27, with a Gaussian window characterized by a 7-pixel standard deviation. The movement of the physical points between reference and current grids was compensated27, leading to the disappearance of the small local grid defects when subtracting the current and
reference distributions of the phases’ modulation of the regular grid pattern caused by deformation. With the present data, the spatial resolution for strain measurements is conservatively estimated to be ~42 pixels, i.e. ~1.15 mm on the sample. The strain increments were first computed between two consecutive strain maps set apart by 64 grid images (i.e. ~3.8 s), and then divided by the corresponding 3.8 s time separation, to obtain strain rates in s⁻¹. This choice of time step gives a convenient trade-off between the measurement and temporal resolutions for strain-rate bursts, and for AE processing, and produces ~420 strain-increment maps on the transformation plateau, conventionally defined in both channels in the following way: a hit starts at time \( t_{\text{ini}} \) when the absolute value of the preamplified signal \( |V(t)| \) from any channel crosses a noise threshold (21 dB, equivalent to 11.22 mV), and ends at \( t_{\text{final}} \) when \( |V(t)| \) remains below the threshold until \( t_{\text{final}} + 100 \mu s \). The amplitude of the hit is defined from the maximum value \( |V_{\text{max}}| \) of the preamplified signal in the first 100µs, converted to dB according to \( A(\text{dB}) = 20 \log(V_{\text{max}}/\mu \text{V}) \). Then an \( A = 60 \text{ dB} \) signal corresponds to a 1V peak in the preamplified signal and 1mV peak in the signal from the transducer. The energy of the hit is given by

\[
E = \frac{1}{2} \int_{t_{\text{ini}}}^{t_{\text{final}}} (V(t))^2 dt.
\]

With event location given by

\[y = 0.51 \left(1 - \frac{L}{20}\right), \quad \text{for} \quad L = 35 \text{ mm} \]

the central part of the sample, and \( \Delta t \) the delay between the two hits. In this way 37,540 acoustic events were located along the \( y \)-axis of the specimen in Fig 1a, of which 28,266 belong to the 25-mm interval in the averaging zone of Fig. 1b. The source energy of a located event is estimated by

\[E = \sqrt{E_1 E_2},\]

where \( E_1 \) and \( E_2 \) are the energies measured in channel 1 and 2, respectively. This formula approximately corrects for the effects of attenuation in the sample, assuming a constant

**AE detection and location.** AE from the sample was detected by means of two micro-80 piezoelectric transducers from Europhysical Acoustics, working with a relatively flat response in the range 0.2–1 MHz. They were acoustically coupled to the upper and lower grips on the opposite face with respect to the camera. Electric

**Fig. 6 Concurrent tracking of strain and AE avalanches in the sample during the phase transformation.** a Superimposition of the strain avalanches in Fig. 4d onto the AE density map in Fig. 4b. Inset: correlation of strain-event magnitudes with pooled AE-event energies (normalised), when AE locations and strain avalanches are paired along the \( y \)-direction for each value of \( t \). Pearson [Spearman] correlation is ~0.42 [-0.79]. b Temporal zoom highlighting details of the bursty phase transformation progress in the sample during the elongation test.
exponential damping factor. Similarly, given its logarithmic character, the source amplitude is defined as $\beta = (\alpha + \lambda)/2$.

**Data availability**
The data that support the findings of this study are available from the corresponding authors on reasonable request.

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**Author contributions**
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**Competing interests**
The authors declare no competing interests.

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