Critical character of plasticity from AE experiments in hcp and fcc metals

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Abstract

Metallic single crystals of hcp (Zn and Cd) and fcc (Cu) lattice structure with various crystallographic orientation were deformed in tension at room temperature. For the study of the intermittent, scale-invariant character of collective dislocation dynamics (crackling plasticity), initially discovered in ice samples, the acoustic emission technique was used. The AE event energy distributions always follow the power law given by $P(E) \sim E^{-\tau_E}$. The exponent τ_E was calculated for all single crystals and its value is discussed with respect to a character of plastic deformation (single or multi-slip, hardening, twinning).

K e y w o r d s: acoustic emission, plastic deformation, dislocation dynamics, self-organization and patterning

1. Introduction

During the last few years, acoustic emission (AE) experiments on creeping ice single crystals challenged the classical paradigm, which describes dislocation-driven plastic deformation as a flow process homogeneous in both space and time. It was observed that the collective dislocation dynamics self-organizes into a scale-free pattern of dislocation avalanches characterized by intermittency, power law distributions of avalanche sizes [1], aftershock triggering [2] as well as fractal patterns [3]. This crackling noise [4] suggests reconsidering dislocation-driven plasticity within a close-to-criticality non-equilibrium framework. These observations are supported by discrete dislocation dynamics [1], continuum [5] and phase-field [6] numerical models, which indicate that the observed picture might be of generic nature in plastic deformation of crystalline materials. Recently, an analysis of deformation curves of Ni micron-size samples gave an independent support to this intermittent, scale-free picture of plasticity [7].

The objective of the present paper is to give a new experimental insight regarding the possible generic nature of crackling plasticity. The original AE work referred only to ice [8]. Here we report AE experiments on plastically deforming hcp (Zn and Cd) and fcc (Cu) metallic single crystals. These various materials can deform under very different conditions, depending on their crystallographic orientation and the stage of deformation: single or multi-slip activity, low or high strain hardening rate, presence or absence of twinning.

2. Experiments

Uniaxial tensile tests were performed on Zn-0.08wt.%Al, Cd and Cu single crystals. Single crystals were grown under an argon atmosphere from raw metals by the horizontal Bridgman technique, using a graphite mould and oriented seed crystals. The single crystal orientations were determined by the back-reflection X-ray Laue technique and the main characteristics of Zn-0.08wt.%Al, Cd and Cu samples are assumed in Tables 1, 2. In Table 1, the λ_a is the initial angle between the c-axis and the tensile axis and φ is the initial

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Table 1. The main characteristics of Zn-0.08wt.%Al and Cd single crystals

Sample	Material	Diameter (mm)	Length (mm)	λ_a (°)	φ (°)	Schmid factor
a_1	Cd	3.72	17	72	22	0.29
a_2	Cd	3.95	22	64	35	0.36
a_3	Cd	3.58	25	48	44	0.48
a_4	Cd	3.60	30	43	51	0.46
a_5	Cd	3.98	25	67	33	0.33
a_6	Cd	3.75	30	70	24	0.31
a_7	Cd	3.72	30	14	82	0.14
b_1	Zn-0.08wt.%Al	5.39	25	57	33	0.46
b_2	Zn-0.08wt.%Al	5.47	25	70	22	0.33

Table 2. The main characteristics of Cu single crystals

Sample	Material	Diameter (mm)	Length (mm)	Orientation
c_1	Cu	4.02	57	multiple slip
c_2	Cu	3.53	65	multiple slip
c_3	Cu	3.87	22	multiple slip
c_4	Cu	3.91	18	multiple slip
c_5	Cu	3.50	14	multiple slip
c_6	Cu	3.10	26	multiple slip

angle between the slip direction and the tensile axis.

Samples were deformed in a universal testing machine INSTRON® 1195 at room temperature (RT) and at constant crosshead speed. The initial strain-rate varied from 1.11×10^{-3} s^{-1} to 1.96×10^{-3} s^{-1} for Zn, Cd and from 2.92×10^{-4} s^{-1} to 3.8×10^{-2} s^{-1} for Cu in dependence on the gauge length (Tables 1, 2). Miniaturized piezoelectric transducer MST8S (diameter 3 mm, almost point AE detection, a flat response in a frequency band from 100 to 600 kHz, sensitivity 55 dB ref. 1 V_{ef}) was fastened to the surface of each specimen. The AE acquisition system (Euro Physical Acoustics, Mistras 2001) allocates different parameters to each detected event, such as the arrival time t_0, the maximum amplitude A_0, or the AE signal energy E. The event detection threshold was fixed to 3×10^{-3} V (30 dB) and the full scale of the A/D converter was ± 10 V (100 dB). More details on the set-up can be found in [8, 9].

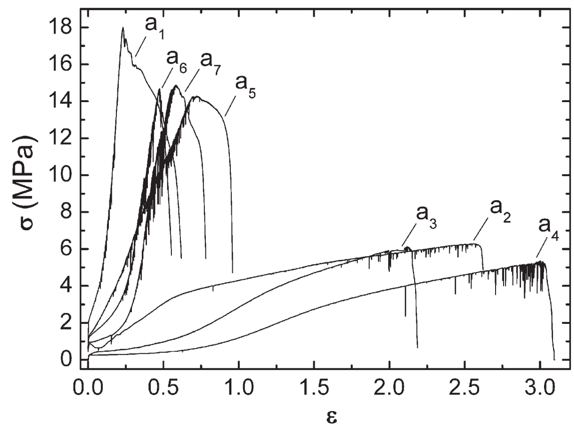

Fig. 1. The stress-strain curves for single crystals of Cd with different values of the Schmid factor.

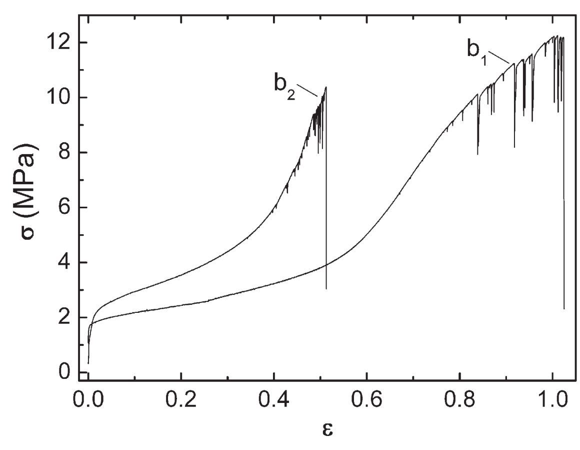

Fig. 2. The stress-strain curves for single crystals of Zn-0.08wt.%Al with different values of the Schmid factor.

3. Results and discussion

The stress-strain curves for single crystals of Cd and Zn-0.08wt.%Al are shown in Figs. 1 and 2, respectively. For hexagonal metals (hcp), specimens with orientation favourable for basal glide exhibited a typical easy basal glide stage I, characterized by a low stress plateau, followed by a stage II with a sharp increase of the stress, characteristic of strain hardening, due to the activation of nonbasal slip systems. Then, a stage III was observed with serrations indicating twinning.

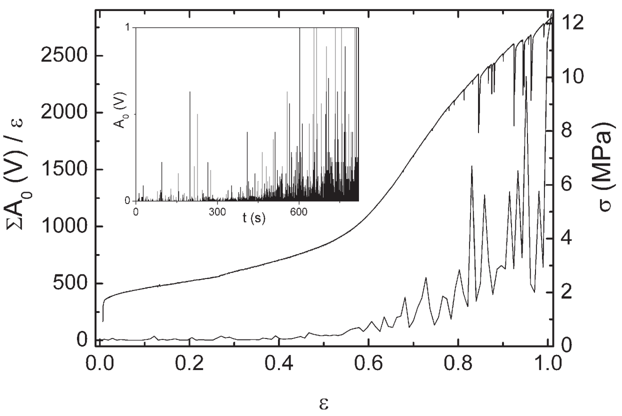

Fig. 3. The stress-strain curve and the evolution of the AE activity during deformation of the sample b_1. The curve represents the amplitudes of the AE events (A_0) cumulated over a time window of 7 s and normalized by the corresponding strain. The inset shows the recorded AE signal.

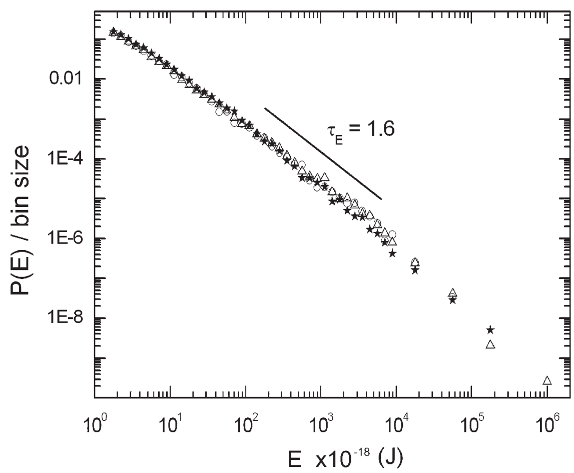

Fig. 4. Distribution of AE energies recorded during the plastic deformation of hcp metallic single crystals. Triangles: Cd (sample a_5), strong forest hardening + twinning. Circles: Cd (sample a_3), stage I, easy basal glide. Stars: Zn-0.08wt.%Al (sample b_2).

Twinning is an important deformation mechanism in hcp metals, as the number of glide systems is limited [10]. Moreover, twinning is an excellent source of acoustic emission [11–13]. Zn (1.86) and Cd (1.89) have the ratio c/a (c, a – lattice parameters) higher than ideal value ($\sqrt{8/3}$) and therefore only the twinning system $\{10\bar{1}2\}$ $[10\bar{1}1]$ may be activated. In hcp specimens oriented for glide unfavourably (low value of the Schmid factor), stage I was suppressed and twinning enhanced. Thus, the hcp metals can produce the AE signals from two sources: dislocation glide avalanches and twinning. Slip avalanches and twinning events can be discriminated from their AE waveforms [9].

The deformation of the Cu single crystals (oriented to multiple slip) was characterized by the absence of stage I and large hardening rates, and the AE events were of the slip avalanche type (no twinning).

All stages of plastic deformation of hcp specimens were characterized by a strong, intermittent AE activity (Fig. 3). The AE signals recorded during stage I (easy basal glide) where twinning is absent, indicate the occurrence of dislocation glide avalanches, as it was observed previously in ice [8]. The relative proportion of twinning events *vs.* slip avalanches increased from stage I to stage III, as expected. Whatever the material or the stage of deformation, a power law distribution of AE energies was observed, $P(E) \sim E^{-\tau_E}$, with the exponent $\tau_E = 1.6 \pm 0.1$ independent of the material or of the stage of deformation (Fig. 4). This reveals that the generic character of crackling plasticity is not restricted to single-slip systems (such as ice), but is also observed in the presence of forest hardening or twinning. Twinning and slip avalanches can be discriminated from the AE waveforms and both populations are characterized by the same power law distribution [9]. Plastic instabilities are clustered in time, as manifested by the presence of aftershocks. Moreover, it was shown that twinning events can trigger slip avalanches, or the reverse, suggesting that both types of instabilities participate to the same global critical-like dynamics.

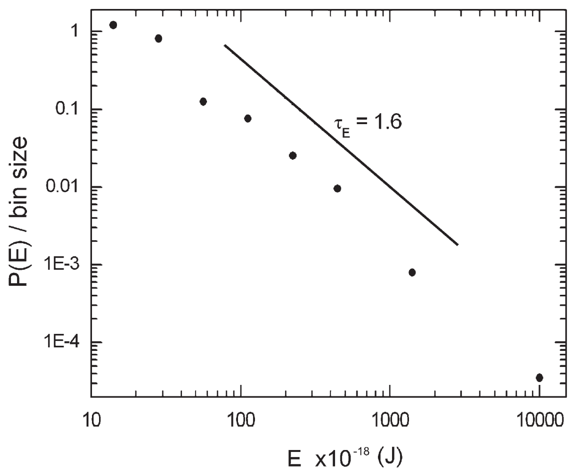

Fig. 5. Distribution of AE energies for Cu (obtained by regrouping the data recorded during the 6 tests on samples c_1–c_6). Owing to the limited number of recorded events, the bin sizes have been increased compared to Fig. 4.

The multi-slip character of plasticity is even more obvious for Cu, as different slip systems contribute more or less equally to global plastic deformation in this case. The deformation of pure Cu was also characterized by power law distribution of AE events with

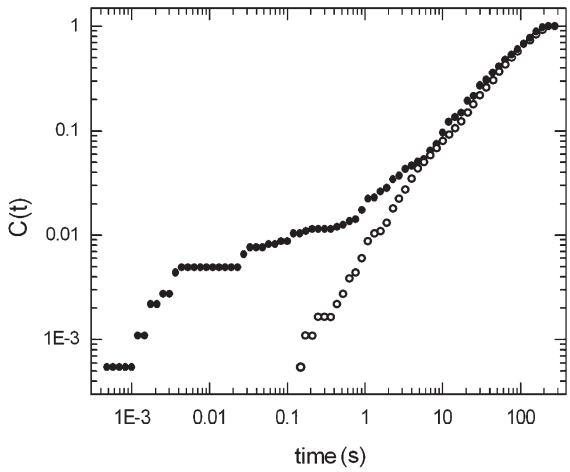

Fig. 6. Correlation integral analysis of the time clustering of AE events during plastic deformation of a Cu single crystal (sample c_2), where $C(t)$ is the probability for 2 events to be separated in time by less than t. Closed symbols: recorded AE events. Open symbols: the same analysis for a poissonian (i.e. uncorrelated) population with the same number of events.

the same exponent $\tau_E = 1.6$ (Fig. 5), thus confirming the universal character of the underlying critical dynamics. Time clustering and aftershock triggering was revealed in this case by a correlation integral analysis (Fig. 6).

However, in Cu, the number of AE events per unit strain was strongly reduced by comparison to hcp metals. This could be explained in two ways: (i) by breaking of scale-invariance towards small scales with a very large number of small, undetectable events contributing to most of the plastic deformation, or (ii) by the fact that the fraction of energy dissipated through AE for a dislocation avalanche of a given size (at the source) could be strongly limited in Cu, thus making "silent" the small amplitude events. Hypothesis (i) is unlikely, as one could more expect a breaking of scaling towards large scales (e.g. as a result of strain hardening), whereas hypothesis (ii) is more likely as the relative proportion of the dislocation avalanche energy dissipated into AE, heat, or the creation of lattice defects could strongly vary with the material considered.

5. Conclusions

The intermittent, scale-invariant character of collective dislocation dynamics (crackling plasticity) in single crystals of hcp (Zn-0.08wt.%Al, Cd) and fcc (Cu) metals was investigated by the acoustic emission technique. The deformation of all single crystals can be characterized by a power law distribution of AE events with the same exponent $\tau_E = 1.6$, even when multi-slip, forest hardening or twinning occur. The exponent τ_E is in perfect agreement with those previously found in ice single crystals.

The robustness of the associated statistical and scaling properties strongly argues for an underlying universal physics related to elastic interactions between dislocations and resulting collective dislocation dynamics.

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