Complex dislocation dynamics in ice: experiments

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We present a statistical analysis of the acoustic emissions induced by dislocation motion during the creep of ice single crystals. The recorded acoustic waves provide an indirect measure of the inelastic energy dissipated during dislocation motion. Compression and torsion creep experiments indicate that viscoplastic deformation, even in the steady-state (secondary creep), is a complex and inhomogeneous process characterized by avalanches in the motion of dislocations. The distribution of avalanche sizes, identified with the acoustic wave amplitude (or the acoustic wave energy), is found to follow a power law with a cutoff at large amplitudes which depends on the creep stage (primary, secondary, tertiary). These results suggest that viscoplastic deformation in ice and possibly in other materials could be described in the framework of non-equilibrium critical phenomena.

Keywords: dislocation, acoustic emission, avalanches, critical phenomena, ice

I. INTRODUCTION

Within a material-dependent range of temperature and stress \([1]\), the (visco)plastic deformation of crystalline materials involves the motion of a large number of dislocations. The importance of collective effects, through elastic interactions, on dislocation dynamics and the heterogeneous character of plasticity has been recognized for a long time (see e.g. \([2]\) ). Only relatively recently, 2D \([3,4]\) as well as 3D \([5]\) numerical simulations of collective dislocation interactions have revealed a spontaneous self-organization of dislocation patterns with walls and cells, in agreement with observations \([6]\) . However, collective dislocation dynamics has received much less attention, with the exception of the special case of Portevin-Le Chatelier (PLC) effect (see below). This may be due to the difficulty to monitor experimentally the variations of dislocation motion in time, energy and space domains. Here, we report an experimental analysis of acoustic emissions (AE) generated by dislocation motions which allow to reveal the intermittent and jerky character of collective dislocation dynamics. Experiments are performed on almost disorder free (except dislocations) ice single crystals. In a companion paper \([7]\), we present numerical simulations which reproduce the main statistical characteristics of the AE measurements. This work (experiments and model) show that complex and jerky plastic flow is not restricted to the PLC effect, and rather the rule than the exception.

II. ACOUSTIC EMISSION TO MONITOR DISLOCATION DYNAMICS

In solid materials, sudden local changes of inelastic strain generate AE waves \([8]\). The sources can be crack nucleation and propagation, twinning, or dislocation motion. In the present work, AE is used to monitor dislocation dynamics. In our experiments, given the amplitude threshold and the frequency range of our transducer, the detected AE are unlikely to be the result of a single moving dislocation but most probably are related to synchronized accelerations of dislocations, called plastic instabilities or dislocation avalanches \([9]\). From the theoretical analysis of Rouby et al. \([10]\) one can relate the maximum amplitude of the acoustic wave \(A\) resulting from a plastic instability, to the number of involved dislocations \(n\) and their velocity \(v\) \([9]\):

\[
A = k \frac{nLbv_0}{d}
\]

where \(k\) is a coefficient related to material properties and the piezoelectric constant of the transducer (dimension: \(\text{V/m}\)), \(b\) is the Burger’s vector, \(L\) is the length of the \(n\) moving dislocations, \(t_0\) is the travel time of the acoustic wave through the transducer (considered to be constant), and \(d\) is the source/transducer distance (supposed to be large compared to \(L\)). In this crude model, \(L\) and \(v\) are supposed to be identical for all the involved moving dislocations. The dislocation velocity \(v\) is considered to be zero before and after the event and constant during the event. The term \(1/d\) represents
the geometrical attenuation of the acoustic waves. From (1), Weiss and Grasso showed that the AE amplitude $A$ is a measure of the local strain associated with the dislocation avalanche. Therefore, the rate of global AE activity is an indirect measure of the global strain rate of the sample.

The AE energy radiated by the acoustic wave is proportional to $A^2$. According to Kiesewitter and Schiller, the energy dissipated by viscoplastic deformation during an event also scales with $A^2$. This results from an expression given by Eshelby for the energy dissipated at the source by a single screw dislocation of length $L$ moving at a velocity $v$:

$$E = KL^2b^2v^2$$

(2)

where $K$ is a coefficient depending on material constants, including the shear modulus and the velocity of acoustic transverse waves, and $b$ the Burger’s vector. A comparison of (1) and (2) with $n = 1$ shows that $E \sim A^2$. This scaling has been observed during our experiments. Therefore AE allows to study during deformation the dislocation dynamics in energy, time, and possibly space (if AE sources locations are determined with the help of multiple transducers) domains. In the present study, only two transducers were used, which did not allow 3D localization.

III. EXPERIMENTAL PROCEDURE

As a model material to study dislocation dynamics from acoustic emission, ice provides the following advantages: single crystals or polycrystals with various microstructures can be easily grown in the laboratory; transparency allows verification that AE activity is not related to microcracking; and an excellent coupling between the ice and the AE transducers can be obtained by fusion/freezing. Within the range of temperature and stress corresponding to our experimental conditions, diffusional flow is not a significant mechanism of deformation in ice, and viscoplastic deformation occurs by dislocation motion. Hexagonal ice Ih presents a very strong plastic anisotropy of the single crystal: viscoplastic deformation of single crystals occurs essentially by basal glide.

Uniaxial compression creep as well as torsion creep experiments were performed at -10 °C on artificial ice single crystals (150 mm X 75mm), each of them constituted by several steps of constant applied stress. These experiments were similar to experiments performed previously and which are detailed in [9] and [13]. For the present new set of experiments, a new AE recording device was used which allowed to record, for each event, different characteristics including the arrival time (at a precision of 0.1 μs), the amplitude, the acoustic energy or the average frequency. Owing to a greater sensitivity of the recording device, much better statistics on AE events were obtained compared to previous work [13,14]. The frequency bandwidth of the transducers was 10-100 kHz. During an experiment the event amplitude threshold was adjusted to 30 dB, or $3 \times 10^{-3}$ Volts, i.e. about 5 dB above the noise level. The dynamic range between the amplitude threshold ($310 - 3$ V) and the maximum recordable amplitude (10 V, or 100 dB) was 70 dB, i.e., 3.5 orders of magnitude. The corresponding dynamic range for energies was 7 to 8 orders of magnitude.

Several independent evidences for recorded AE to be related to dislocation motion, including an absence of microcracks or a proportionality between the global strain-rate and the global AE rate have been detailed elsewhere [13].

IV. STATISTICAL ANALYSIS OF AE AMPLITUDES AND ENERGIES

From equation (1), the acoustic activity $A(t)$ monitor the evolution of dislocation activity and viscoplastic dissipation. Figure 1 shows this evolution during the first loading step of a compressive creep test. It appears immediately that the instantaneous viscoplastic dissipation is intermittent and jerky, showing bursts of activity that can be considered as avalanches of dislocations moving collectively in the material. Although the cumulated acoustic activity, i.e. an estimate of the strain, appears relatively smooth at the time scale of several thousands of seconds (Figure 1), At smaller time scales, or in terms of dissipated energy $E(t)$, this avalanche behavior is more obvious (Figure 2): dislocation dynamics during viscoplastic deformation is heterogeneous in time and energy domains. This recalls the jerky flow associated to Portevin-Le Chatelier effect occurring in different alloys (see e.g. [16,17]). However, whereas PLC effect is attributed to the dynamic interaction of two defect populations, namely mobile dislocations and solute atoms [17], the avalanche behavior reported here results only from collective dislocation interactions (solid solutions in the artificial single crystals are below 10-10 mole frac. cite13 ). For this reason, we believe that this kind of behavior should not be restricted to ice, as confirmed by a numerical modelling of this effect in a companion paper [6].

This avalanche behavior is recovered whatever the type of loading (compression or torsion), the applied stress, or the creep stage (primary, secondary, tertiary). However, interestingly and unexpectedly, the classical distinction between these creep stages corresponds also to different dislocation dynamics: primary and tertiary creep are associated to a pronounced jerky character and some very large events, whereas secondary creep appears smoother, at least
at a large time scale. This difference, visible on figure 1, is clearer on the amplitude distributions. Secondary creep is characterized by power law statistics with an exponential cutoff at large amplitudes (or energies) (Figure 3):

\[ N(A) \sim A^{-\tau}e^{-A/A_c} \]  

or the discrete distribution calculated with linear bins, or

\[ N(A') > A \sim A^{-\tau+1}e^{-A/A_c} \]

for the cumulative distribution. Because of the scaling \( E \sim A^2 \), similar relations are obtained for energy distributions with an exponent \((\tau + 1)/2\). For secondary creep under compression, the exponent \( \tau \) of the discrete distributions, estimated from a linear fit on a log-log plot below the amplitude cutoff \( A_c \), is found to be stable through creep deformation, independent of the applied stress and equal to 2.0 ± 0.05. Similarly, \( A_c \) is found to be constant during a given loading step (Figure 3) and does not seem to vary significantly with the applied stress around \( A_c \sim 0.4 - 0.5V \). This means that power law scaling is clearly observed over 1.5 orders of magnitude, i.e. 3 to 4 orders for energies. The stability of this scaling justifies, on the dynamical point of view, the term steady-state sometimes used to identify secondary creep.

On the other hand, statistics of dislocation avalanches change with the stage of creep. Primary as well as tertiary creep are characterized by a power law scaling without detectable upper cutoff over the experimental scale range (\( A \sim 10^7 \)). In other words, \( A_c \), if any, is rejected towards much larger scales compared to secondary creep. This transition from secondary to tertiary creep is visible on figure 4. Slightly larger \( \tau \) exponents, around 2.15 ± 0.05 seem also to be associated with primary and tertiary creep. The variation of AC with the creep stage suggests that this upper cutoff is not a finite-size effect. Under torsion creep, power law scaling was also observed without detectable upper cutoff, but with a smaller exponent, \( \tau = 1.7 \). This difference of \( \tau \) on the loading mode is not explained so far.

V. TIME PATTERNING

To study the time patterning of dislocation dynamics, we calculated the correlation integral \( C(t) \):

\[ C(t) = \frac{2}{N(N-1)}n(\Delta t < t) \]  

where \( N \) is the total number of events and \( n(\Delta t < t) \) is the number of pairs of events (not necessarily successive events) separated by less than a time \( t \). \( C(t) \) is therefore simply the probability for two acoustic events to be separated in time by less than \( t \). Note that this analysis does not take into account the amplitude of the events. For a random Poisson process with uncorrelated (identical) events, \( C(t) \sim t \). A typical profile of \( C(t) \) is given on figure 5. Whereas a scaling \( C(t) \sim t \) is observed above a threshold \( t_c \), the events are clustered below \( t_c \) (the probability \( C(t) \) is larger than expected for uncorrelated events). This behavior was observed whatever the type of loading (compression/torsion), the applied stress or the creep stage, but \( t_c \) was found to follow the evolution of \(<\Delta t>\), the average time interval between two successive events. These observations, along with detailed examinations of the data files, can be explained as follows: dislocation avalanches consist of a mainshock correlated in time with a sequence of few aftershocks. Note that these shocks are distinct dynamical events characterized by distinct acoustic waves. At larger time scales, viscoplastic deformation consists of avalanches which are themselves uncorrelated in time. When the AE activity is very high, the frequency of avalanches is so high such that the aftershock sequences are not revealed by the correlation integral analysis.

VI. DISCUSSION AND CONCLUSION

From a statistical analysis of acoustic emissions generated by dislocation motion, we have shown that: (i) viscoplastic deformation during the creep of ice occurs by a succession of dislocation avalanches. This avalanche behavior, in very pure ice single crystals, results only from dislocation-dislocation elastic interactions. (ii) dislocation avalanches consist of a mainshock correlated in time with a sequence of few aftershocks. These avalanches are themselves uncorrelated in time. (iii) the distributions of AE amplitudes (the “size” of the avalanche) or AE energies follow a power law scaling with an exponential upper cutoff which depends on the creep stage. For a specific creep stage, the statistical properties are stable and do not vary with time or the applied stress. Such power law scaling of dislocation avalanches suggests that viscoplastic deformation in ice and possibly in other materials could be described in the framework of non-equilibrium critical phenomena [5]. In particular, driven-dissipative systems have the tendency to develop singular response functions and avalanche like behavior depending on the driving mechanism. This critical behavior is, in fact, resulting from the collective behavior of the many microscopic degrees of freedom of the system responding to the external perturbation. It is then of a major interest to develop theoretical models that can relate the observed experimental behavior with the microscopic dynamics of dislocations...
and its interactions with the external driving fields. In the companion paper [7] we provide an attempt in this direction by developing a numerical model that successfully reproduces the avalanche behavior of dislocation motion. (iv) whatever the very nature of the involved critical phenomena, Weiss et al. have shown that power law distributions of dislocation avalanches imply that large plastic instabilities account for most of the viscoplastic deformation, rather than independent movements of individual dislocations.

The results presented in a companion paper [7] represent a further evidence to argue that this avalanche behavior could not be specific to ice, rather a common feature of collective dislocation dynamics.

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FIG. 1. Instantaneous as well as cumulated acoustic activity (amplitude) during the first loading step of a compression creep test (applied stress=0.58 MPa). Transition from primary to secondary creep.
FIG. 2. Detail of figure 1 within a time window: Cumulated amplitude (solid line) as well as cumulated energy (dashed line).

FIG. 3. Cumulative amplitude distributions $N(A' > A)$, normalized by the total number of events in the time window, $N$, during secondary creep under compression (fourth step of loading; applied stress=1.29 MPa). The three sets of data correspond to three non-overlapping time windows of duration about 110-120s. The dashed line corresponds to $\tau = 2$ ($\tau - 1 = 1$ for the cumulative distribution).

FIG. 4. Cumulative amplitude distributions $N(A' > A)$, normalized by the total number of events in the time window, $N$, during the sixth step of loading of a compression creep test (applied stress=1.64 MPa): Transition from secondary to tertiary creep. The three sets of data correspond to three non-overlapping time windows of duration 258s. This duration corresponds to about 5000 events for two windows (and ) and about 71000 events for the last one (F, tertiary creep).

FIG. 5. Correlation integral $C(t)$ calculated on two non-overlapping time windows (2500 events each) during the second loading step of a compression creep test (applied stress=0.71 MPa). The dashed line corresponds to $C(t) \sim t$. The sharp decrease of $C(t)$ below $510^{-3}s$ results from the duration of the longest events: the experimental device is unable to detect a new event as long as the former event is not finished. This limits artificially $C(t)$. 