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Electromagnetic emission memory phenomena related to LiF ionic crystal deformation

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During the uniaxial compression of LiF ionic monocrystals, acoustic and electromagnetic emissions (EME) are detected. We observed that when the compression is performed in successive loading, unloading cycles and these emissions are being monitored, no new emissions will occur unless the maximum stress of the previous cycle is exceeded, meaning that the material presents memory characteristics. This is observed not only for the acoustic emission (AE), which is the well known Kaiser effect, but for the EME as well. In other words, the material appears to memorize and reveal the previously maximum stress it suffered while being deformed. The importance of an electromagnetic memory feature of a material can be related to various applications in material science, especially when the detection of AE is not feasible or gives false alert. Such cases may very well be earthquakes' predictive indications, monitoring of mines' stability, imminent landslides, etc. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2906346]

I. INTRODUCTION

Acoustic emission (AE) is a well known phenomenon of sound generation in materials under stress due to the strain energy release that follows the catastrophic events in the stressed material,[1–4] while a special feature of AE has been known as Kaiser effect since 1950.[5] In particular, Kaiser had reported in his Ph.D. thesis that if crystals of metals were stressed while the associated AE was monitored and the stress was then released, then no new emissions would occur unless the previous maximum stress was exceeded. This is an AE memory effect that appears in cyclic loading experiments provided that the peak stress value is progressively increased, i.e., from cycle to cycle.

Up until now, AE is known to be caused by dynamical processes associated to nucleation, motion, and emergence of dislocations, (namely, groups, sip bands, and cracks) on the surface of the material under stress.[6] Likewise, electrification phenomena and electromagnetic emissions (EMEs) due to deformation of crystals have also been known since the work of Gyulai and Hartly in 1928 (Ref. 7) and work of Stepanow in 1933 (Ref. 8). Since then, many works on stress-induced electrical polarization in ionic crystals under loading, electrification after splitting, crack propagation time-dependent polarization, stress-induced electric currents, and indentation experiments have been published.[9–14] Moreover, laboratory experiments of deformation of rocks or/and crystalline materials carried out by several scientific groups, have proved that both EME and AE exist from the beginning of the compressed samples' deformation until their failure. Both types of emissions are detected in various frequencies from dc up to megahertz and are closely related to processes occurring in the sample. Therefore, AE and EME are phenomena that must be considered particularly important in order to further investigate and explain the mechanisms responsible for the fracture of materials, an issue yet not fully understood and answered.[15–18] In this respect, an interesting application is the detection of the electromagnetic disturbances during tectonic processes associated with earthquakes' occurrence and thus connecting the earth's crust deformation with the above electromagnetic phenomena, i.e., as a means of a diagnostic method for earthquake prediction.[19–27]

Following the above, laboratory experiments on cyclic deformation of crystal samples are essential in order to examine whether memory effects exist not only for the AE but also for EME. Such a finding can then be a useful tool for possible prediction of an imminent earthquake.

In this work, we present laboratory results for cyclic compression of LiF monocrystals. Recently, we have reported preliminary results but it is essential to further extend the discussion for the natural mechanisms that explain the observed phenomena.[28] The use of ionic crystals instead of rock samples is important, firstly, because no previous experimentation has been allocated to ionic crystals for testing the existence of EME memory characteristics and, secondly, because of their noncomplexity with respect to rocks. This may eventually offer a clearer approach in addressing the question of emission mechanisms than otherwise. The rest of the paper is organized as follows. In Sec. II, the incorporated experimental setup is analytically described, while the obtained results are presented in Sec. III. The plausible mechanisms for EME generation and the revealed memory effect are discussed in Sec. IV, while concluding remarks are given in Sec. V.

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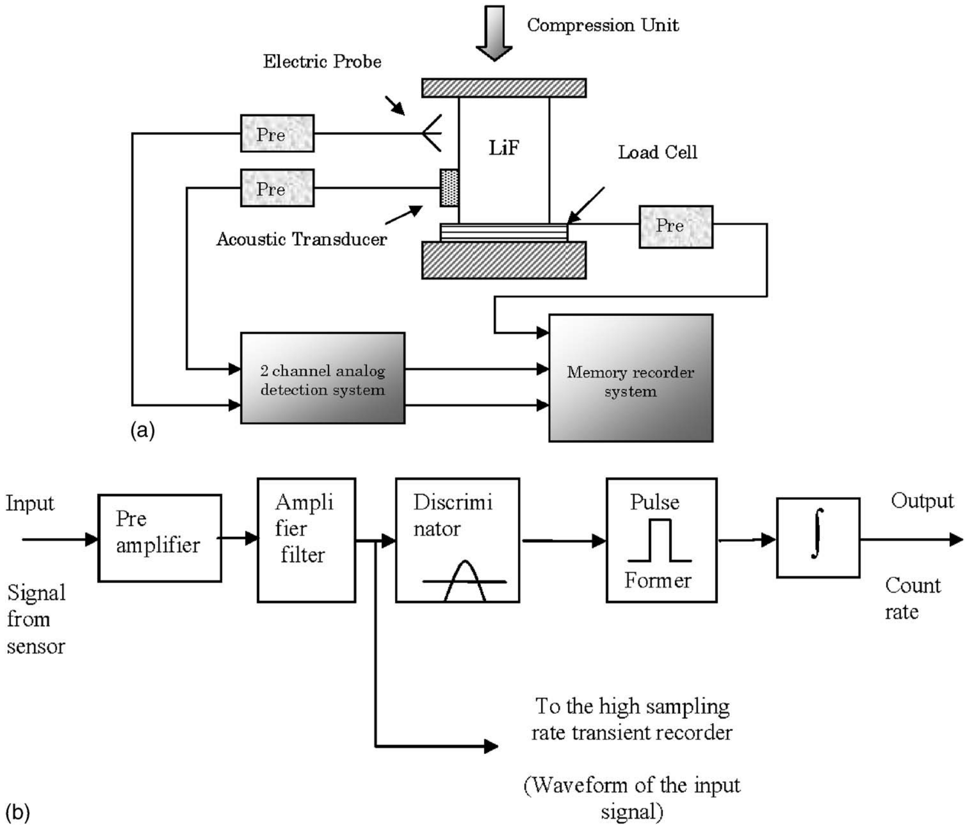

FIG. 1. (a) Layout of the laboratory experimental setup. (b) Block diagram of the analog detection system (one channel).

II. DESCRIPTION OF THE EXPERIMENTAL SETUP

The required experimental setup for the compression of the samples and the simultaneous recording of AE and EME is described in this section. The complete instrumentation has been developed in our laboratory, in order to particularly investigate the existence of memory characteristics in the EM emission that occurs during successive cycles of mechanical loading-unloading of LiF samples.[28]

The block diagram of the incorporated instrumentation is shown in Fig. 1(a). It includes a manually operated loading machine for the uniaxial compression of the crystal sample and an electronic part, consisting of a two-channel analog detection system and a digital recorder for visualization and plotting purposes. The maximum sampling rate of the digital recorder is 1 Msample/s. Two low-signal preamplifiers (with voltage gain: 20 db, frequency bandwidth: 1 KHz–1 MHz, $R_{\text{input}}=1\ \text{M}\Omega$) are used to interface the signals from the EM and acoustic signal sensors to the analog detection system.

In order to sense the electric field disturbances, we use the tip of the central part of a coaxial cable which is placed at approximately 1 cm from the sample. The AE signal sensor is a mechanoelectric (piezoelectric) transducer which is sensitive in the frequency range from some decades of hertz up to 1 MHz, with maximum response at 60 KHz. A load cell is also used for simultaneous measuring of the applied mechanical load and its output is fed to the digital recorder through an appropriate preamplifier. The analog detection system consists of two identical channels, one for the acoustic and one for the EM emission. As shown in Fig. 1(b), each channel includes an amplification and filtering unit (1 KHz–1 MHz), a discriminator, a pulse former unit, and an output integrator.

The complete system serves as a counter of acoustic and electromagnetic events, in such a manner that every time its input accepts a signal with amplitude higher than a predetermined level of the discriminator, the pulse former sends an appropriate pulse to the output integrator. The aforementioned discriminator level is adjusted as follows. Before initiating the compression process, we set the discriminator's level so that the system can record (count) noise. By increasing the discriminator's level a little higher than the noise level, the system will be ready to count any signal event above the noise level. Then, we start compressing the sample. The sensors capture the acoustic and electromagnetic signals and the output of each sensor is fed into one of the two channels of the analog system of Fig. 1(b). Hence, whenever the amplitude of an input signal (from either of the two signal sensors) exceeds the corresponding discriminator's predetermined level, the pulse former will send a pulse to the integrator, which will produce the count rate of the considered input signal. Moreover, it must be noted that, as shown in Fig. 1(b), our experimental setup has the ability to simultaneously record and with high sampling rate (1 Msample/s) the individual AE and EME wave forms that correspond to the opening of the same microcrack. This is accomplished by incorporating internal triggering in the transient recorder in order to capture such pairs of the whole time series. Finally, in order to ensure EM noise immunity, the experiment is carried out in a shielded room (Faraday cage). For the experimental setup, see also (Refs. 28 and 31).

III. EXPERIMENTAL RESULTS

Specimens of LiF monocrystals of size $0.5\times0.5\times1\ \text{cm}^3$ have been cut along the [100], [010], and [001]

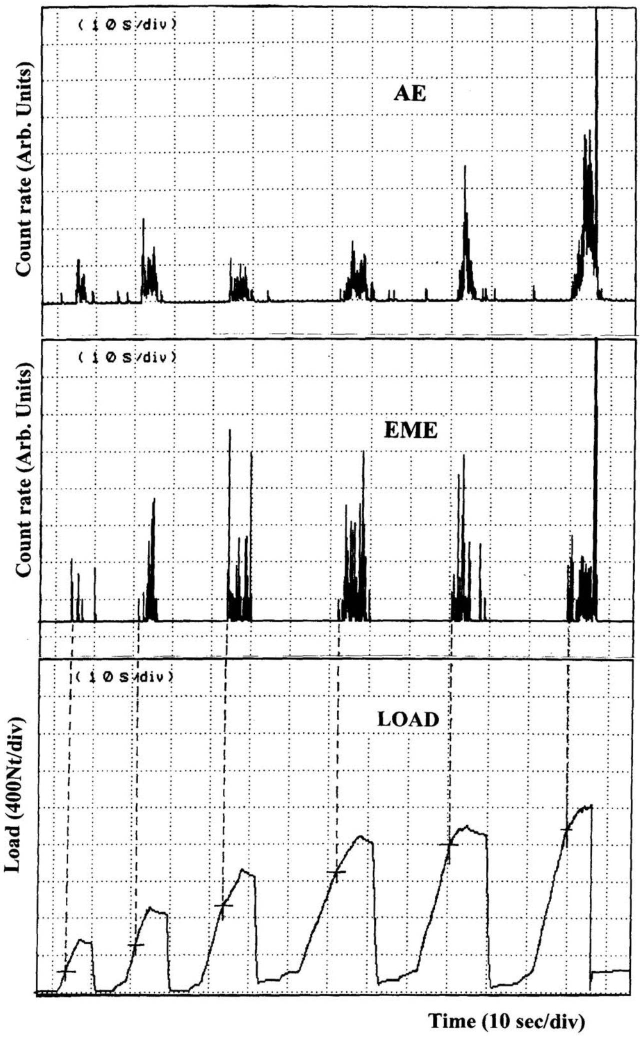

FIG. 2. (a) Upper: the AE events rate, (b) middle: the EME rate, and (c) Lower: cyclic mechanical load (the last cycle leads to the complete failure of the sample).

directions, while no special treatment of the crystal surface has been made or needed. Each sample has been uniaxially subjected to cyclic loading, with the peak stress increasing from cycle to cycle, (otherwise no new signals would have been observed). The AE, the EME, and the applied load are then being monitored throughout the experiment.

Figure 2 depicts an indicative recording of (a) the AE events rate, (b) the EME events rate, and (c) the mechanically applied load. The manipulation of the loading machine is manually performed while the loading rate is deduced from the lower part of Fig. 2. More specifically, the stress is applied in cycles (loading-unloading), with each cycle preceding the next by some seconds. During each cycle, both acoustic and electromagnetic signals are emitted and recorded. It is obvious that for the AE to reappear in each loading cycle, the previous maximum stress must be exceeded. This is a well known and extensively studied memory phenomenon for the AE, the so called Kaiser effect. However, careful consideration of Fig. 2 reveals that the same holds for the EME as well. This means that similar to the Kaiser effect, a memory effect holds also for the EME from a cyclically deformed sample of a dielectric crystalline material such as LiF.

Hence, if we follow any two successive cycles of mechanical loading-unloading of the total shown in Fig. 2, we can see that during the first cycle, there are numerous EME events, which start when the increasing stress value exceeds a stress threshold. During the next cycle, EME events only start when the reincreasing stress value exceeds the previously reached maximum value. The same holds for every pair of cycles. Hence, considering the maximum stress value reached during the loading portion of a first cycle as threshold for the second cycle, it is evident that during the second cycle, no EME event will occur until the stress exceeds its previously reached maximum value, as identified by the end of the corresponding emission events.

IV. DISCUSSION

A plausible mechanism for the generation of EME can be elaborated as follows: Within a crystal sample, there exist dislocations. These dislocations are immobile at first. In order to move, a stress threshold is necessary to be reached. As soon as an external stress attains a stress value σ_0, the dislocations start gliding and multiply, according to the Frank–Read mechanism.[29,30] The gliding edge dislocations sweep up the vacancies of a preferable sign. Consequently, a certain nonequilibrium charge density is accumulated at the head of the dislocation, resulting in electric polarization. As the external applied load increases, the dislocations of intersecting glide planes meet and form pileups. The dislocations then cease moving. A large stress concentration is generated there and hardening of the material is locally produced. A locked dislocation pileup, upon further stress increase, bursts through the stoppers forming a microcrack and quickly abandons its bounded charge. The relaxation of this charge produces an intrinsic polarization current generating an electric pulse.[31] The integral of such pulses, during a certain time window, is recorded and depicted, as shown in Fig. 2. Hence, it becomes clear that electrical phenomena are absolutely connected to mechanical phenomena in the crystal due to its compression.

Following the above elaboration, a plausible mechanism for the generation of AE can now be suggested. The aforementioned material hardening results in formation of cracks, the opening of which releases elastic energy in the form of AE waves. An experimental result that supports our argument that the acoustic emission is due to the microcrack opening is depicted in Fig. 3. In particular, Fig. 3 is a digital recording with a very high sampling rate of individual electromagnetic and acoustic wave forms that correspond to the same microcracking event. Moreover, the simultaneous emission of a pair of individual EM and AC is the confirmation of a microfracturing event.

This can also be clearly seen in Fig. 2, where even for the first (virgin) stress cycle, a stress threshold is observed for initiating both the AE and EME. Then, during the next stress cycle, dislocations will be unpinned and start gliding again only when the stress is to exceed the maximum stress of the previous cycle. Consequently, new pileups are formed and the aforementioned procedure is repeated. However, we must take into account that the deformation attained up to the

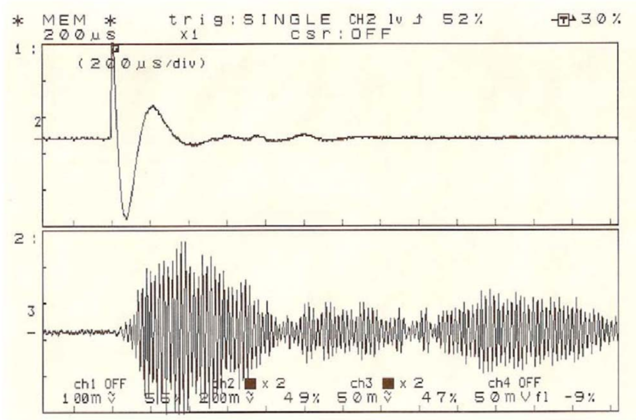

FIG. 3. (Color online) Wave forms of individual electric pulse (upper) and acoustic wave train (lower) corresponding to the same microfracture event (microcrack opening).

maximum stress of the previous stress cycle creates irreversible damages, which remain in the crystal lattice and prevent further movement of dislocations, unless the previously reached maximum stress value is again exceeded. These crystal damages represent a "fingerprint" of the material's loading history and convey information about the maximum stresses attained during previous loadings. Therefore, the sample under investigation "memorizes" the previous maximum stress level to which it was subjected, by memorizing the inner damages that were created due to its deformation process.

V. CONCLUSION

In this work, we presented experimental results obtained during the cyclic compression of LiF monocrystals revealing that besides the well known Kaiser effect for the AE from materials subjected to cyclic loading, a similar memory effect also holds for the detected EME. The observed phenomenon can be particularly useful in cases for which monitoring and follow up of AE is not easy, e.g., for tectonic processes in earth's crust before imminent earthquakes, drilling purposes, mines, etc. Clearly, the recorded ability of the materials to memorize information about the previous maximum stress they have been subjected to, during deformation, is a quite significant issue as it might have importance in the evaluation of the stress history of the material. This can be an essential requirement in mechanics, engineering, geotectonics, etc. Finally, our experimentation with LiF ionic crystal is based on the fact that these materials are not as complex as rocks, and thus it would ease the clarification of the underlying procedures leading to the samples' failure as well as it would provide a new tool for the suggestion of plausible mechanisms for the deformation of the materials.

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