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Avalanche dynamics in crumpled aluminum thin foils

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Uniaxial compression of crumpled aluminum thin foils with different relative densities was studied using an acoustic emission (AE) technique. The AE signal analysis reveals a power law linking the probable density and amplitudes of acoustic events, proving an avalanche dynamics of plastic deformation. The exponent found for the distributions of squared amplitudes that reflect the dissipated mechanical energy places the observed behavior among those found previously for bulk samples of various pure materials.

Keywords: Crumpled materials; Cellular materials; Plastic deformation; Acoustic; Self-organization

Interest in cellular materials for structural applications is focused mainly on foams (for complete reviews see Refs. [1,2]), and more recently on entangled materials [3–7] and truss structures [8–10]. On the other hand, randomly crumpled materials, such as polymerized membranes, biological cells, thin paper and metallic sheets, have attracted strong attention in the last decade, because of their fascinating topological features and the scaling laws linking the elastic and plastic properties to the relative density [11–15]. More recently a complete mechanical characterization has been performed on aluminum thin foils [16]. This work highlighted that crumpled materials can present mechanical behavior that is a hybrid between those of foams and entangled fibrous materials. They exhibit a clear plasticity and a low loading/unloading hysteresis, similar to foams, but no plateau beyond the yield stress. Instead, strain hardening occurs immediately after reaching the yield stress. As this aspect is scientifically intriguing, and because crumpled materials can potential be used for structural applications due to the good combination of their mechanical properties, density and ease of processing, they have become the object of great interest for physicists and material scientists.

In order to obtain better insight into the deformation mechanisms of crumpled materials, an acoustic emission (AE) technique was applied in the present work, with the objective of clarifying how the mechanical energy is dissipated during their plastic deformation. The AE provides a high-resolution technique that gives access to the dispersion of energy on a scale beyond the reach of standard mechanical tests [17]. In particular, its application has revealed the inherently intermittent nature of plastic deformation of solids even when smooth deformation curves are observed [18]. The intermittency is caused by collective processes of plastic deformation which give rise to scale-invariant statistical behavior. It has also been observed on the macroscopic scale, i.e. when the deformation curves themselves manifest intermittency in the form of stress serrations [19]. However, in this case, the scaling laws are not universal but may depend on the experimental conditions, and require various approaches to their statistical analysis [19–23]. The corresponding discrete AE was found to display power-law distributions of acoustic event amplitudes under all experimental conditions and for all materials investigated so far [18,23–25]. Such statistics are usually ascribed to the phenomenon of self-organized criticality, which was suggested to explain the universal avalanche-like behavior in extended dynamical systems [26]. Evidence of this phenomenon was recently detected during the compression of aluminum foams [27]. Thus, one of the objectives of the present work is to verify whether the processes of plastic deformation in crumpled materials obey similar scaling laws.

Samples for compression were prepared from 18 μm thick aluminum foils. Each foil was randomly crumpled

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and inserted into a cylindrical die in order to obtain cylindrical samples with 16 mm radius and 30 mm height. Following this processing route and using different initial amounts of aluminum, i.e. different lengths of rectangular shaped foils, $L = 370$–520 mm (for a unique width of 290 mm), it was possible to produce crumpled specimens with varied initial density, $\rho_0 = 0.21$–0.29 g cm^{-3} (compared with $\rho_{Al} = 2.7$ g cm^{-3}).

Uniaxial compression tests were carried out at a constant nominal strain rate of $\dot{\varepsilon} = 4 \times 10^{-4} s^{-1}$. The AE was recorded using a setup described in Ref. [28], with a piezoelectric transducer operating in the frequency band 200–900 kHz. In contrast to solid materials, fixation of the AE sensor to the porous rounded surface of a crumpled sample cannot provide a good acoustic contact. Rather, good results were obtained when it was clamped to the greased surface of a flat edge milled on the upper punch, as illustrated in Figure 1.

The procedure of real-time capture of individual AE events is described elsewhere [23], so is outlined only briefly below. Several preset parameters are applied. An event ("hit") starts when the signal exceeds the voltage threshold foreseen to cut off the noise (26 dB in the present work). The device constantly keeps a large enough portion of the signal in the buffer memory. This makes it possible to determine the end of the event after the signal has dropped and remained below the noise level for a period equal to a hit definition time (HDT). The device then stands in the idle regime for a hit lockout time (HLT), in order to filter out sound reflections. The values of these time parameters, HDT = 300 µs and HLT = 40 µs, were chosen as suggested in Ref. [29] in order to avoid the possible effect of hits superposition on their individualization and, therefore, the resulting statistical distributions.

The general behavior of the compression curves was found to be similar to that observed previously [16]. First, samples with the same initial density displayed good reproducibility, which allowed us to verify that a higher stress is needed to deform a more compact sample. Second, as illustrated by the example in Figure 2(a), the deformation curve clearly reveals a nonzero work hardening rate after the apparent elastoplastic transition, which bears evidence to plastic deformation being associated with the bending of the ridges and walls composing the crumpled structures. Finally, the work hardening accelerates after some strain, indicating the increasing contribution of the compression mode when the ridges come into contact.

The logarithmic amplitudes $A_{\log}$ and durations D traced, respectively, in Figure 2(c) and (d) visualize the accompanying series of AE events. It can be recognized that, in spite

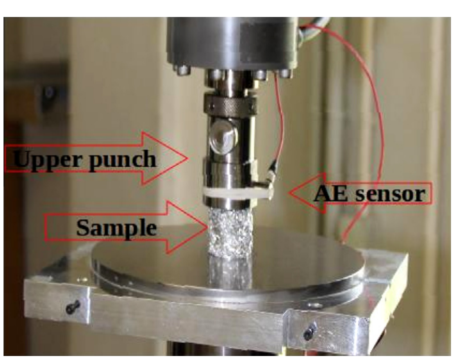

Figure 1. Experimental setup.

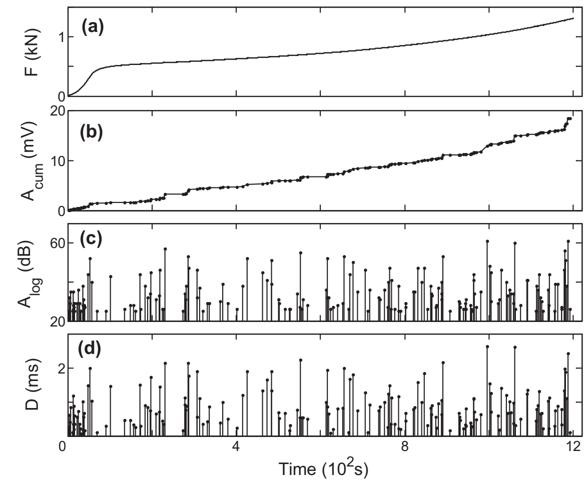

Figure 2. Example of comparison of (a) the evolution of the force F(t) during compression of a specimen with $\rho_0 = 0.28$ g cm^{-3} and (b–d) characteristics of the accompanying AE: (b) cumulated amplitude A_{cum}, (c) logarithmic amplitude $A_{\log}$ and (d) duration D of individual hits.

of the obviously high damping capacity of crumpled structures, it is possible to record series of discrete AE events. As in the case of solids [17,18,23–25], the AE is recorded from the very beginning of deformation. This is generally explained by a virtually zero yield stress for the onset of microplasticity during the seemingly elastic deformation. Such argument is likely to be valid for the crumpled materials. Indeed, other potential sources of AE could be friction between different fragments or cracking at the corners of the crumpled foil. However, friction was shown to play a negligible role in the deformation of similar samples [16]. Furthermore, the estimate of the upper strain limit at the corners can be obtained by suggesting that the foil is folded over itself. Even such an unrealistic suggestion renders a maximum strain of about 0.6 for the thickness of the foil used in the present work. This value is too low to cause cracking in pure aluminum. Besides, the microtomography data reported in Ref. [16] prove that the corners are quite smooth in the crumpled structures.

It is known that the microplasticity stage in solid samples is often characterized by higher-amplitude hits than those observed during later deformation stages, due to the longer flight distance and free length of dislocations moving through the initially sparse population of obstacles. Such intense AE was not observed for crumpled samples in the present work. This difference is most likely due to predeformation introduced during the preparation of the initial samples. It should also be taken into account that the flight distance of the dislocations is limited because of the micrometer thickness of the initial foil.

The intermittent character of AE also manifests itself as steps on the curve of the evolution of the cumulated event amplitudes, represented in Figure 2(b). At the same time, this dependence shows a remarkable similarity with the compression curve. It can be concluded that $A_{cum}(t)$ may reflect both the overall accumulation of crystal defects, controlling the average work hardening rate, and the intermittent nature of deformation processes.

It should be noted, however, that the example of Figure 2 is specific in the sense that such a strong similarity was not found for all specimens. In particular, drastic steps or