Acoustic Emission multiplets during fatigue of aluminum.

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Abstract A series of uniaxial low cycle fatigue tests on pure Aluminum is investigated via the analysis of acoustic emission (AE). The different stages of macroscopic fatigue behavior are clearly differentiated in terms of AE. We define five different stages: initial hardening, initial softening, secondary hardening during shakedown stage, onset of secondary softening and failure. When most of the acoustic activity recorded in the two/three first stages is related to dislocation dynamics, the acoustic activity in the last stages is mostly due to the fracture phenomenon. Now, a detailed analysis of the discrete AE allowed to highlight the appearance, in the last third of the test, of acoustic signals occurring almost every cycle at a same given stress and having a quasi identical acoustic signature. We hypothesize that such multiplets, shown for the first time in acoustic emission, are the signature of the propagation, cycle after cycle, of a fatigue crack whose trace may be seen post-mortem with the fatigue striations on a fracture surface. This way, these signals could be considered as fracture precursors about several hundred cycles before the final failure of the material.

Keywords Acoustic Emission, Fatigue, Fracturing process, AE multiplet, Cracks

1. Introduction

Fatigue is perhaps the most dangerous and simultaneously less well understood mechanism of mechanical failure encountered in a variety of modern structures ranging from nuclear reactors to micro-electronic connections in cell-phones. Failure in cyclic loading appears unexpectedly when the structure is operating in a safe and apparently steady state regime. Despite a long history of theoretical and experimental studies, modern technology still lacks reliable tools capable of predicting the catastrophic failure in cyclic loading. The situation is particularly troublesome with early precursors of fatigue and thus it would be important to find new ways to follow fundamental changes in the development of fatigue at a microstructural scale in order to identify early precursors to fracture.

An appropriate tool to analyze dynamic instabilities involving such topological defects as dislocations, twin/martensitic boundaries and micro-cracks is certainly the monitoring of the Acoustic Emission (AE). To simplify the analysis of the signal, it seems appropriate to reduce the different possible sources of AE events. Therefore, for an easier understanding, we have chosen to work on pure Aluminum for which the expected AE sources are associated with dislocation dynamics and microcraking only.

AE monitoring has been developed as an effective non-destructive technique for the detection, location and monitoring of fatigue cracks. Several studies showed a correlation between AE count rates and crack propagation rates [1-3] or a relationship for acoustic emissions and the applied range of stress intensity [4]. We focus here on discrete AE (signals above a threshold) to study the dynamics of dislocations and cracks during low cyclic fatigue tests and we explore AE waveforms to extract promising information about the signature of crack propagation. In particular, we reveal the existence of multiplets, i.e. almost identical waveforms reoccurring at each fatigue cycle during the final part of the fatigue life, and which likely signatures of fatigue crack growth.

2. Experimental details

2.1. Material and experiments

We chose to study 99.95% pure aluminum in order to restrict the potential sources of AE to collective dislocation motions and microfracturing process. Indeed, impurities and phase transformations [5] in a material are possible AE sources but do not exist for pure aluminum. The base material was not pretreated, its polycrystalline structure consisting of large elongated grains, ~10 mm for the major axis and ~3 mm for the minor axis. This large grain size implies a lower impact of grain boundaries on the acoustic activity generated in the material [6].
Uniaxial tension-compression ($\varepsilon_{min}/\varepsilon_{max}$=-1) low cycle fatigue tests are performed at room temperature using an hydraulic machine designed and realized at MATEIS Lab [7, 8]. The cyclic total strain was imposed with an amplitude $\Delta\varepsilon$ varying from 0.5% to 1.8% and a loading frequency from 0.1 to 1 Hz. The specimens are cylindrical with 18mm gauge length and 9mm diameter. Stress and strain are recorded up to the macroscopic fracture.

2.1. Acoustic Emission

Acoustic emission is continuously monitored during the tests using a PCI2 Mistras data acquisition system of European Physical Acoustic (EPA) with a 8MHz sample rate and a 60 dB pre-amplification, the bandwidth being 50 kHz–1.2MHz. Our measurements are achieved with two resonant Nano30 EPA piezoelectric sensors (peak of resonance at 140 kHz) coupled to the material with silicon grease. The sensors are placed on the heads of the specimens. Three kind of measurements are performed: (i) the continuous AE measuring the mean acoustic power, sampled at 10Hz all along the test, (ii) the discrete AE which is an automatic detection of transient elastic waves distinguished from the background noise, above a given threshold (34dB) and (iii) a complete recording of the acoustic signal, sampled at 5 MHz: "datastreaming" for a few selected loading cycles.
In this paper, we focus on the discrete AE only. We distinguish AE hits from events: hits are AE signals detected by a single sensor whereas events are signals whose intensity is big enough to reach both sensors and that can be located along the specimen length. In general the form of the primitive wave changes during propagation through the medium, and the amplified signal from a resonant piezoelectric sensor bears little resemblance to the original pulse. Nevertheless, this coloration does not erase the differences or similarities in the sources and we assume that if the signals are similar at the source then the signals received by the sensors are similar.

3. Results and discussion

3.1. Macroscopic cyclic response and discrete AE

Let us take the example of a 1 Hz cyclic fatigue test at imposed total strain $\Delta\varepsilon$=0.96% that failed after 3383 cycles. The macroscopic response (maximum stress reached at each cycle) is represented in Figure 1 together with the evolution of the discrete AE activity (cumulative number of hits (Figure 1a) and acoustic energy of hits (Figure 1b)). The different stages of fatigue are clearly differentiated in terms of AE. We define five different stages, each of them being associated to a color: (1, black) initial hardening during the first cycles, (2, red) initial softening at the beginning of a shakedown stage corresponding to a saturation of the stress, (3, green) secondary hardening during shakedown stage, (4, green) onset of secondary softening stage associated to increasing damage before (5, pink) the final failure of the material.

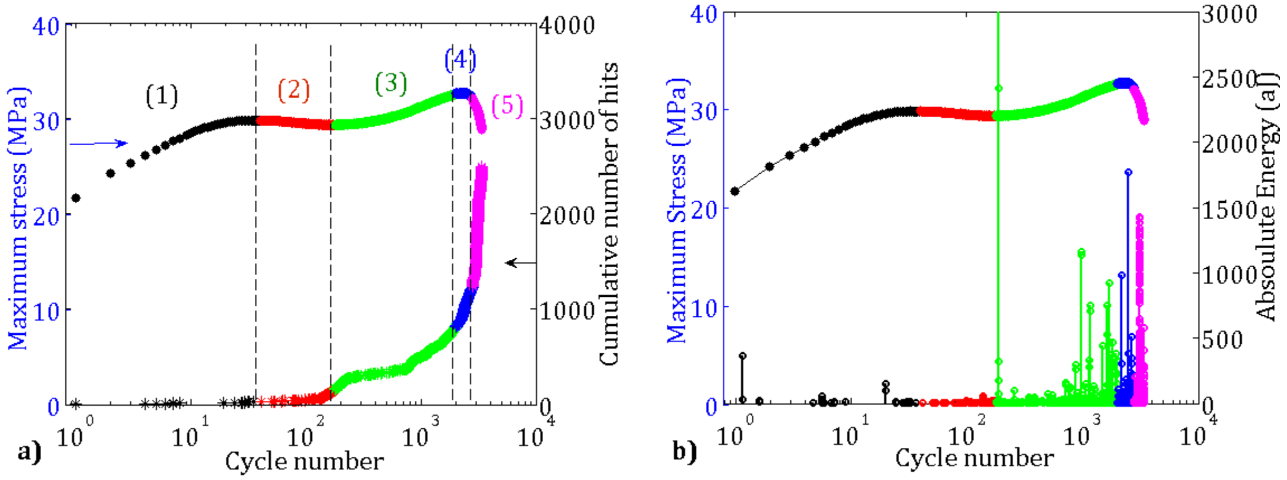

Figure 1 Evolution of the maximum stress during a fatigue test at Δε=0.95% on aluminum (99.95%) along the five different stages, together with a) the cumulative number of hits and b) the acoustic energy of the hits.

The acoustic activity is also represented in Figure 2 with the stress as a function of time along the cycles; Figure 2a shows the occurrence of hits and events and Figure 2b represents the evolution of the discrete AE (normalized number of hits) during selected loading stages of the fatigue test.

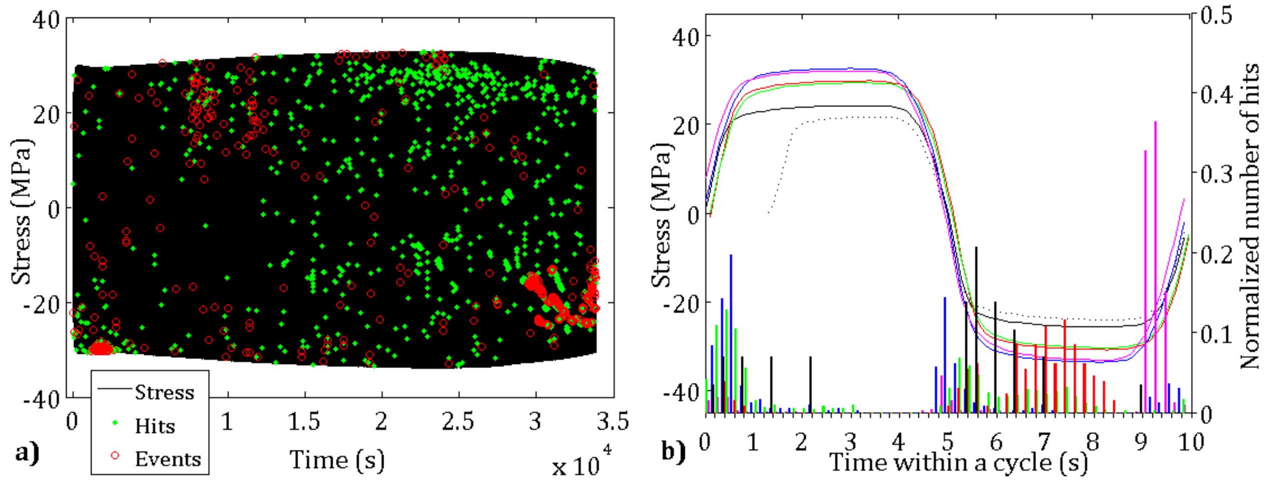

Figure 2 a) Acoustic activity during a fatigue test at Δε=0.95% on aluminum at 1Hz b) Normalized number of hits for each fatigue stage: time of occurrence within a cycle (10s) in correspondence to the stress. Black, red, green, blue, pink colors correspond to the five different stages respectively.

During the first stage, formation of dislocation structures such as cells and walls result in a strong strain hardening of the loaded material [9, 10]. AE hits, recorded during the elastic-plastic transition (Figure 2b), may be due to collective dislocation avalanches. The initial softening exhibits a lower and less energetic discrete AE activity that may be due to the formed microstructures which restrains the spreading of dislocation avalanches. Stronger hits are recorded at the secondary hardening during shakedown stage associated with sudden dislocation cell rearrangements. This stage is characterized by AE hits of various sizes in both tension and compression (Figure 2b). The hits recorded in the last part of this third stage could already be the onset of microcracking and damage. The secondary softening is associated with a strong increase of discrete AE activity that could be a signature of the cell structure destabilization. During the last stage, the acoustic activity rises even more as the result of microcracking leading to the collapse of the macroscopic properties of the material. This activity, mainly due to the fracture phenomenon, is strongly asymmetrical (tension vs compression): most of the hits occur when the material is loaded only, at the onset of stretching but still under compression (Figure 2b). These AE signals could then be an indicator of the friction between the surfaces of the cracks and their growth.

3.2. AE multiplets

On the last third of the studied cyclic fatigue tests carried out on pure aluminum, we have observed the appearance of acoustic signals occurring almost every cycle at a given stress level during a certain number of cycles. Figure 3 shows these lines of hits or events arising at a quasi-identical level of stress (plotted as a function of time) in the end of a fatigue test at Δε=0.95%. We notice several lines at negative stresses but Figure 3b evidences that the AE signals appear at positive stress rate.

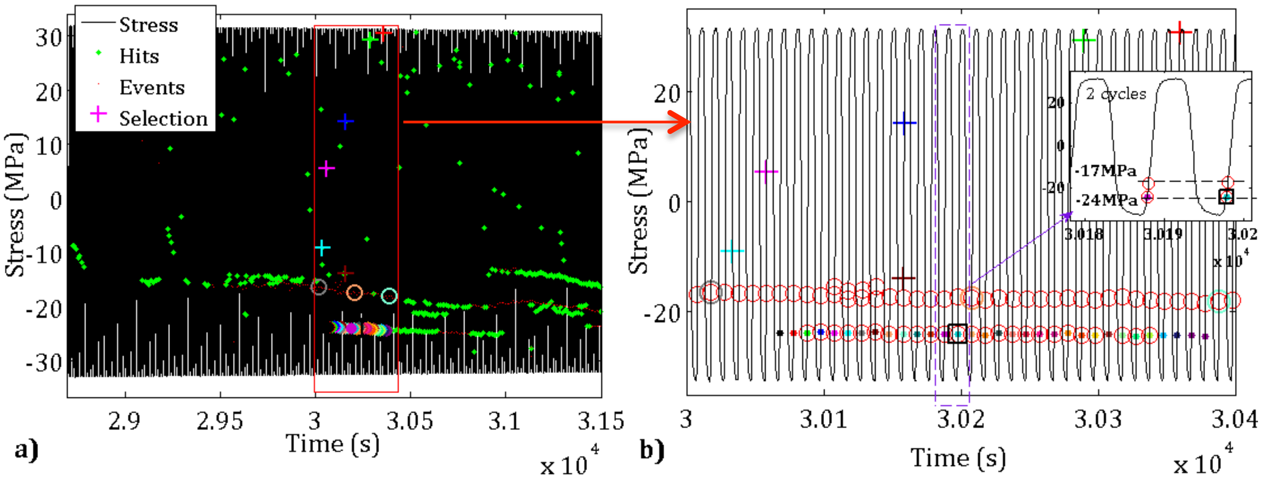

Figure 3 a) Hits or events occurring at specific values of stress, cycle after cycle, in the last stage of a fatigue test at Δε=0.95%. b) Zoom corresponding to the red rectangle. Colored dots correspond to AE signals occurring almost every cycle at a same given stress (~ -24 MPa). Red circles are events. Crosses correspond to random hits occurring at random stress. Inset: 2 cycles.

In order to compare their waveforms, we select several AE signals (colored dots of Figure 3) arising at about -24MPa (when the material is loaded again), cycle after cycle, in a 310s time window (30068s-30378s, 32 waveforms in 32 cycles). We notice in Figure 4a that their waveforms are almost identical. We therefore name these acoustic signals occurring at a same stress level "AE mutliplets". Multiplets have been studied in seismology [11-13]: multiplet is a group of microseismic events with very similar waveforms and is likely the expression of stress release on the same structure. Here they are AE multiplets and we notice in the cyclic fatigue tests we have studied on pure Aluminum that they appear several hundred cycles before the final failure.

In addition, Figure 4a shows a slight tendency for the values of the waveform maximum amplitude to increase with the stress at which they occurred -the amplitude increases roughly of 0.06V (or about 3dB) per Mpa-.

In Figure 4b we compare waveforms taken randomly in the same time window: the colored crosses, the grey orange green circles and the black square of Figure 3. We notice this time that they do not match, thus confirming the special nature of the aforementioned multiplets.

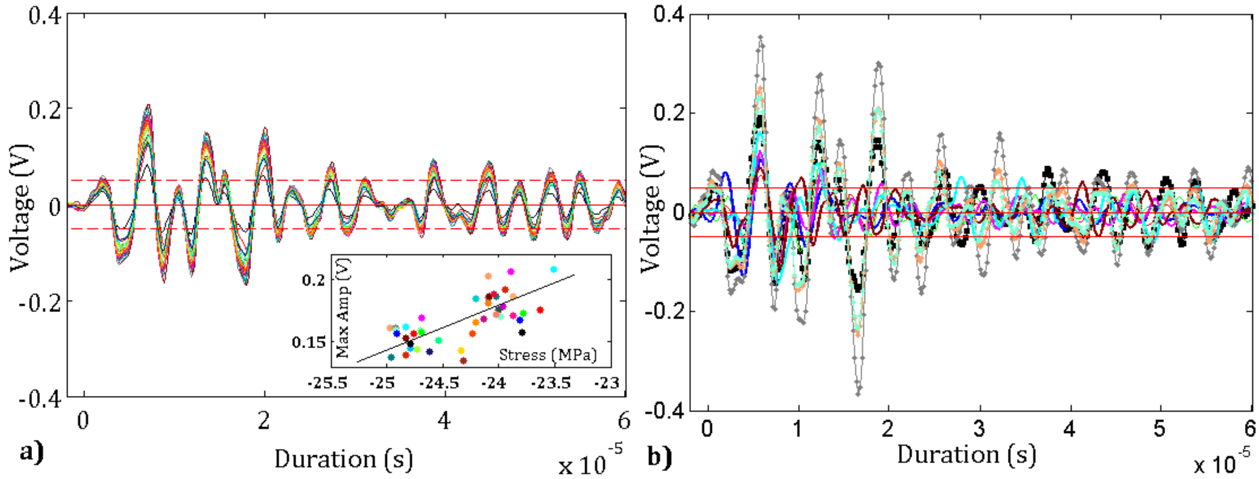

Figure 4 a) Waveforms corresponding to the colored dots of figure 3 (AE signals occurring every cycle at ~ -24 MPa during more than 30 cycles). Inset: maximum of amplitude as a function of the stress where the AE signal occured. b) Ten waveforms corresponding to the selection of AE signals of figure 3 (colored crosses at random stresses, grey orange green circles at ~ -17 MPa and the black square at ~ -24 MPa). Colors of waveforms correspond to colors of markers.

Figure 5a exhibits two other groups of AE events occurring at a given level of stress in the last stage of the test: colored crosses around -17 MPa and colored stars around -15 MPa. Figure 5b shows the location along the gauge length of the specimen and the waveforms of those AE events. We notice that the AE signals appearing at the same stress level are located at about the same site on the specimen and have a same type of waveform (Figure 5b).

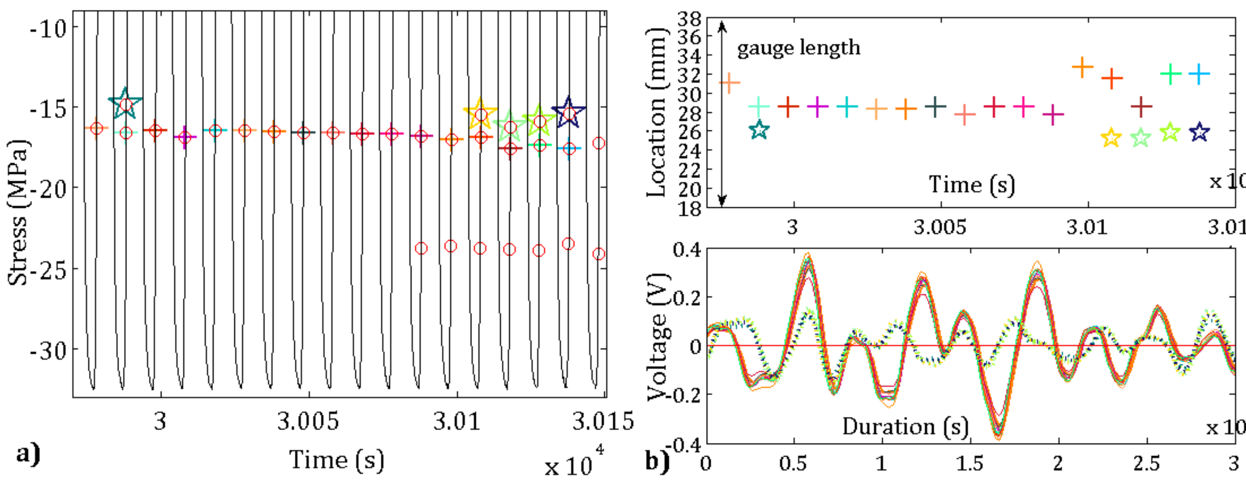

Figure 5 a) Groups of AE events occurring at a same level of stress in the last stage of a fatigue test on aluminum ($\Delta\varepsilon$=0.95%). b) Linear location of AE events along the gauge length of the specimen and corresponding waveforms, continuous lines for the crosses and dashed lines for stars.

Each line of AE signals would come from the same source, being activated again when approximately the same level of stress is reached. Therefore, we hypothesize that such multiplets, shown for the first time in acoustic emission, are the signature of the propagation, cycle after cycle, of a fatigue crack whose trace may be seen post-mortem with the fatigue striations on a fracture surface (Figure 6).

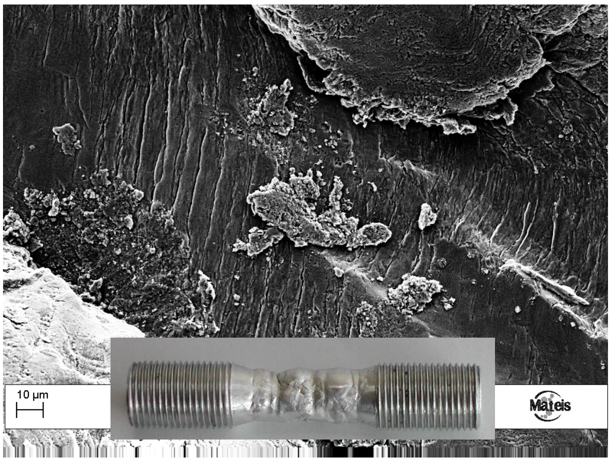

Figure 6 SEM observation of fatigue striations on a fracture surface of pure aluminum after 3024 cycles of a fatigue test at $\Delta\varepsilon$=0.95%. Inset: picture of a specimen just before final failure.

3. Conclusion

Although preliminary, these results give insights into the presence of multiplets in acoustic emission being the signature of the propagation, cycle after cycle, of a fatigue crack. These acoustic signals, with identical waveforms, could therefore be considered as fracture precursors as they appear several hundred cycles before the final failure of the material.

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