Detection and characterization of fatigue crack growth by acoustic emission and digital image correlation

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Résumé :

Des signaux d'émission acoustique (EA) spécifiques à l'avancée incrémentale de fissure de fatigue peuvent etre détectés, cycles après cycles lors d'essais de propagation de fissure dans les métaux : ce sont des multiplets acoustiques. Afin d'en savoir plus sur les mécanismes physiques à leur source, une analyse de corrélation d'images numériques (DIC) couplée à l'EA est menée dans cette étude. Il est montré que ce type d'analyse est efficace pour distinguer les multiplets issus de 2 catégories de sources : la propagation de fissure par rupture ou plasticité en pointe de fissure et le frottement des lèvres contre elles-meme.

Abstract :

Acoustic emission (AE) signals specific to the incremental advance of fatigue cracks can be detected, cycle after cycle, during crack propagation tests in metals : they are acoustic multiplets. In order to learn more about the physical mechanisms source, a digital image correlation (DIC) analysis coupled to the AE is conducted in this study. It is shown that this type of analysis is effective to distinguish the multiplets generating from 2 categories of sources : crack propagation by cleavage or plasticity at the crack tip and the friction of the lips against themselves.

Key words :
Fatigue crack growth, acoustic emission, digital image correlation, acoustic multiplets

1 Introduction

Context Despite many efforts over the last hundred years to understand its causes and detect its possible precursors, fatigue of materials remains one of the major causes of failure of industrial parts [1]. The problem is "How to alert in real time when a crack is likely to lead to the ruin of the part ?". Acoustic emission (AE) is a key method of non-destructive testing, as it enables the recording of transient elastic waves occurring during damage of materials and structures. Numerous works carried out with this method have shown that there is a correlation between the global acoustic activity and damage, including during fatigue [2]. However, this correlation only becomes significant near the final failure and thus far too late [3]. Indeed, the monitoring of slow crack growth from a global measurement is difficult and very sensitive to the signal to noise ratio (SNR). Moreover, the non-specific nature of these AE measurements makes the identification of sources difficult [4].

State of the art A new approach, recently proposed [4, 5], allows the detection of acoustic emissions specific of fatigue crack growth, called "acoustic multiplets" in reference to the analogous phenomenon in seismology [6]. These so-called acoustic multiplets are characterized by highly correlated waveforms (figure 1 a), signature of a unique source. They are repeatedly triggered over many successive loading cycles at almost the same stress level (figure 1 c, d and e) and originate from a single location (figure 1 a). They are considered to mark the slow, incremental propagation of a crack at each cycle (see striations on figure 1 b), or the rubbing along its faces (fretting). Being specific to incremental fatigue cracking, they can therefore potentially be used as early warnings of global failure of industrial parts [5].

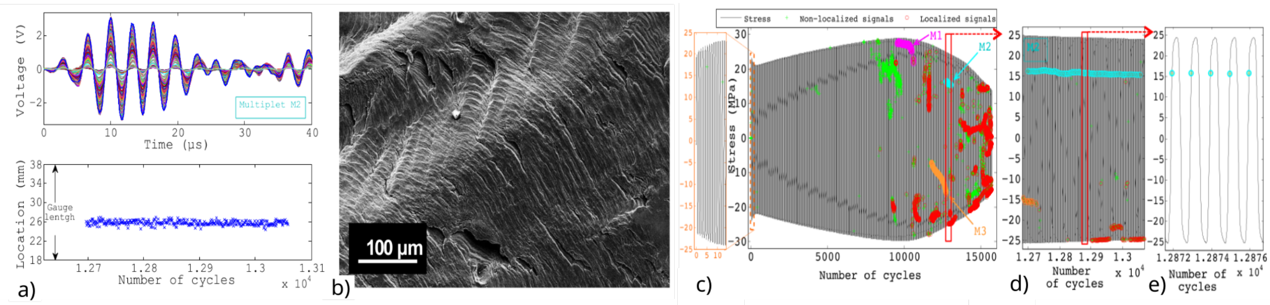

Figure 1 – *Acoustic multiplets as a signature of fatigue crack growth (from [4]) - a) Waveforms of acoustic signal belonging to a multiplet during fatigue of Aluminum at 0.1 Hz, and locations of the corresponding AE signals on the specimen ; b) Striations on a post-mortem SEM image of the crack face of the sample ; c) Acoustic activity during a fatigue test on aluminum : stress vs number of cycles. Magenta, cyan and orange clusters correspond to typical examples of multiplets ; d) Enlargement on a specific multiplet and e) on some loading cycles.*

However, in this former study [4, 5], a direct monitoring of fatigue crack propagation was not performed. The attribution of the AE multiplets to specific source mechanisms was therefore partly speculative. In the present study, through a combined digital image correlation (DIC) and AE multiplets analysis, we attempt to specify the physical sources (plasticity, cleavage or fretting) of the multiplets during fatigue crack growth. Different loading conditions are studied on two materials with three different sensors.

2 Materials and methods

Experiments where carried out on a 42CD4 steel chosen for its high tensile strength and a 5083 aluminium alloy chosen for its ductile behaviour. 42CD4 steel (AISI 4140) is quenched and tempered and shows a martensitic microstructure with a former austenitic grain size of 4 µm. 5083 aluminium has an estimated grain size of 20 µm. The DENT (double edge notched tension) geometry is chosen (figure 2) : with the two symmetrical pre-cracks, in principle, two cracks nucleate and propagate until their coalescence leads to global failure. Experimentally, however, due to material heterogeneity and a non-perfectly symmetric loading, one crack growths generally faster : for simplicity, we only focus on this particular one. Uniaxial tension-tension strain-controlled fatigue tests were performed ($R_\epsilon = \frac{\epsilon_{min}}{\epsilon_{max}} = 0.1; \Delta\epsilon = \epsilon_{max} - \epsilon_{min} = cst$) for the 42CD4 specimens, and stress-controlled tests ($R_\sigma = \frac{\sigma_{min}}{\sigma_{max}} = 0.1; \Delta\sigma = \sigma_{max} - \sigma_{min} = cst$) for the 5083 aluminum alloy. For clarity, we refer to the two tests according to the material of the specimens : 42CD4 or 5083.

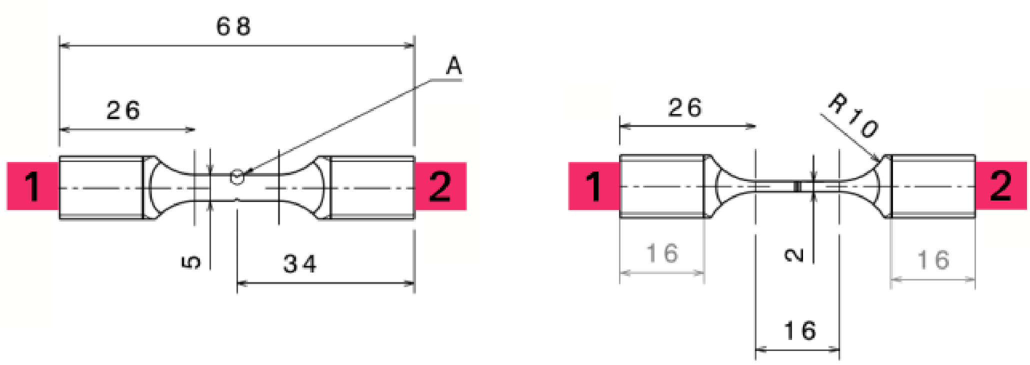

FIGURE 2 – DENT geometry and location of sensors 1 and 2

DIC settings A speckle, necessary for the proper functioning of the DIC method, is made on the surface of the samples before loading. The OPTRONIS camera, model CP70-12-M-188 with a telecentric lens with a x2 magnification, continuously takes 20 images per fatigue cycle of the region of interest (ROI) centered around the crack tip. One pixel of the sensor represents 2.75 µm on the specimen.

The images are post-processed by digital image correlation (DIC). A global method, based on a finite-element mesh, taking 5 px elements in a 1000x350 px ROI, is used to determine the displacement fields of each deformed image relative to the reference image. Then, to obtain the crack tip position and the stress intensity factor, the displacement fields are projected onto the Williams series [7, 8]. The super-singular terms are used to determine the position of the crack tip and the singular terms give the values of the stress intensity factor K_I of crack propagation.

Two analysis based on this method are made here : a global analysis that covers the entire test and a localized one on few cycles around a multiplet.

— Global : for both tests, the displacement field around the crack is calculated for each cycle between the images recorded at the maximum and minimum of the loading. The extraction of the

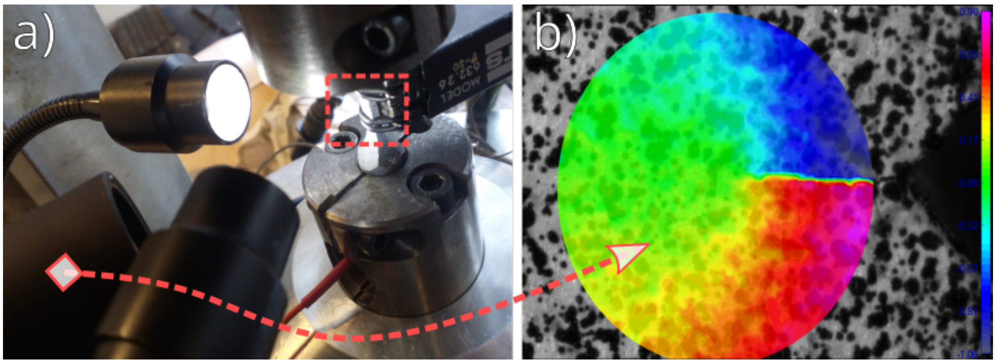

FIGURE 3 – *a) Photo of the fatigue test setup with camera and lighting ;*
b) Example of a displacement field around a crack calculated by DIC

crack tip position and stress intensity factor from the maximum displacement fields is then performed as described previously. This allows to obtain the crack tip position a and stress intensity factor K_I as a function of time from the beginning to the end of the test. $\frac{da}{dN}$ versus ΔK curve is also plotted in log-log scale.

— Localized : for each multiplets studied, the displacement field around the crack is calculated between the image at the minimum load (1st image) and all the 19 other images of the same cycle. The extraction is then done to deduce an evaluation of the crack tip position and the stress intensity factor over few cycles.

AE system and multiplets detection AE signals were recorded with a Physical Acoustics PCI-2 AE System. Two piezoelectric sensors where coupled on the specimen heads (figure 2) :
— 42CD4 : 2 resonant *nano30* sensors (*[150-750] kHz*)
— 5083 : 1 resonant μ *80* sensor (*[200-900] kHz*) (channel 1) and 1 wideband μ *200* sensor (*[500-4500] kHz*) (channel 2)

The sensors are connected to the data acquisition system via a preamplifier with a 40 dB gain and a 20-1200kHz bandwidth. All along the test, waveforms are recorded when the signal exceeds a fixed threshold which depends on the sensitivity of the sensor (micro200 is less sensitive). These waveforms are sampled at 5MHz during a few hundred µs. Once the tests are completed, a previously developed algorithm [5] clusters in multiplets the waveforms recorded at the same loading level, separated from each other by at most 5 cycles and whose 2-by-2 cross-correlation level exceeds 95%.

3 Results and discussions

Multiplets detection Multiplets of variable sizes (number of waveforms belonging to the multiplet) are detected in every test for all sensors except the wideband sensor (*µ200*) due to its low sensitivity. Examples of detected multiplets are shown for 5083 Aluminum and 42CD4 steel in figure 5 and figure 4. It should be mentioned that for the fatigue test on 42CD4 presented here (at imposed tension-tension strain), between 8,000s and 12,000s the loading changed due to hydraulic saturation (still in strain-controlled mode but at a lower amplitude).

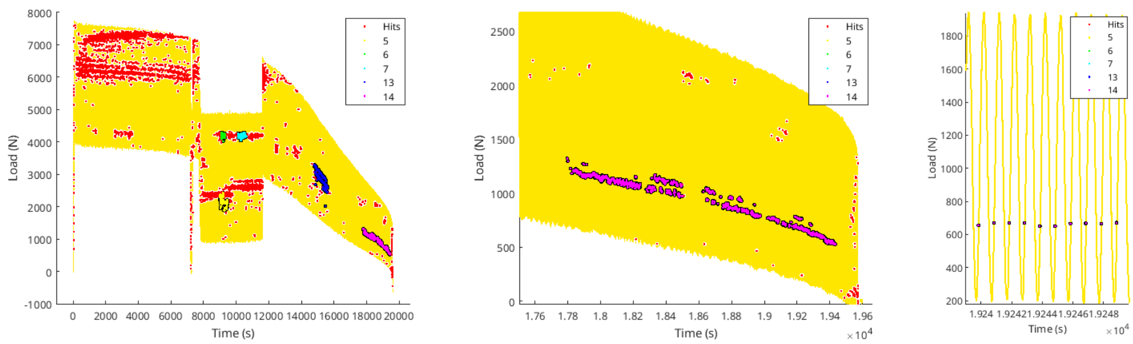

FIGURE 4 – Acoustic activity during a uniaxial tension-tension strain-controlled fatigue test on 42CD4 at 1 Hz : load vs time. Red dots correspond to all signals recorded above the detection threshold by sensor 1. Other colors correspond to different identified multiplets. From left to right : the entire test, and two successive zooms on multiplet M14.

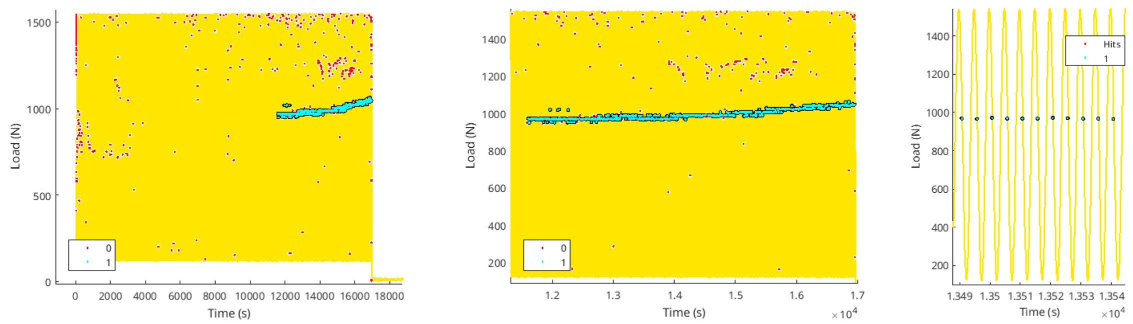

FIGURE 5 – Acoustic activity during a uniaxial tension-tension stress-controlled fatigue test on 5083 aluminum at 0.5 Hz : load vs time. Red dots correspond to all signals recorded above the detection threshold by sensor 1, and blue dots correspond to the signals belonging to the multiplet M1. From left to right : the entire test, and two successive zooms on multiplet M1.

The multiplets can be classified into two categories : those recorded during the loading phase of the fatigue cycle, and those recorded during the unloading phase. This distinction is a first indication to associate each multiplet to a potential source mechanism. In what follows, we present in more details two examples :

- 42CD4 : multiplet M14, recorded during loading
- 5083 : multiplet M1, recorded during unloading

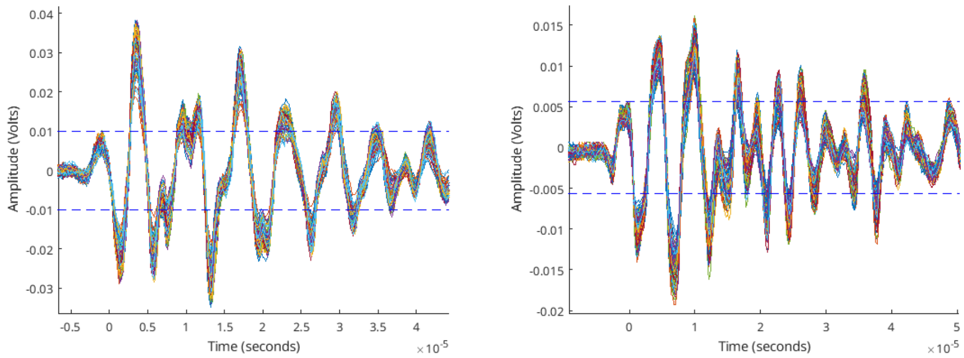

FIGURE 6 – Waveforms of all signals belonging to a multiplet. Dashed blue lines correspond to the detection threshold.
Left : M14 - uniaxial tension-tension strain-controlled fatigue test on 42CD4 at 1 Hz
Right : M1 - uniaxial tension-tension stress-controlled fatigue test on 5083 aluminum at 0.5 Hz

Global crack growth and AE activity

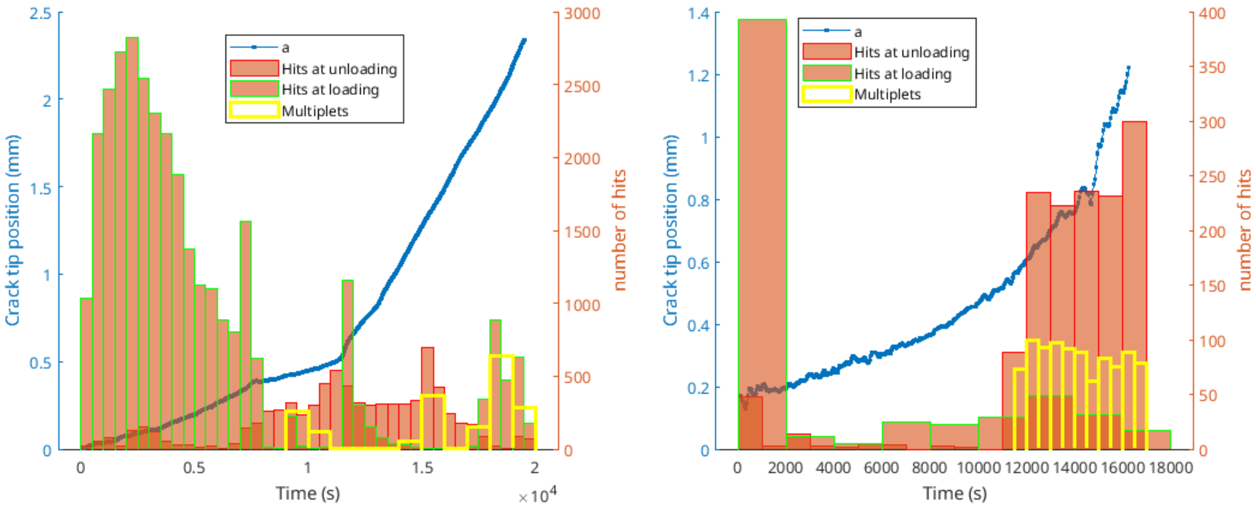

FIGURE 7 – Crack length versus time and number of AE signals recorded during loading, unloading, and number of signals belonging to an identified multiplet.
Left : uniaxial tension-tension strain-controlled fatigue test on 42CD4 steel at 1 Hz
Right : uniaxial tension-tension stress-controlled fatigue test on 5083 aluminum at 0.5 Hz

the beginning of the tests on 42DC4 and 5083, during the crack initiation, the AE activity is significant and concentrated during the loading phase of the fatigue cycles (stage I and beginning of stage II of fatigue crack growth on figure 8), but not associated with identified multiplets (figure 7). Then, when the cracks becomes sufficiently long, AE activity at unloading highly increases, suggesting that the crack faces are rubbing against each other. The activity at loading decreases significantly when the crack becomes larger and enters the Paris regime (figure 8). Thanks to the crack growth curve $\frac{da}{dN}$ versus ΔK on figure 8, we proved that the crack reaches the 3 regimes of propagation by recognizing the linear shape of the Paris' law $\frac{da}{dN} = C\Delta K^m$, where C and m are material constants [10]. We verify in consequence that multiplets, recorded either during the loading or unloading phases, are emitted only in stage II as predicted. This is consistent with the initial hypotheses made on the potential sources of AE multiplets [5].

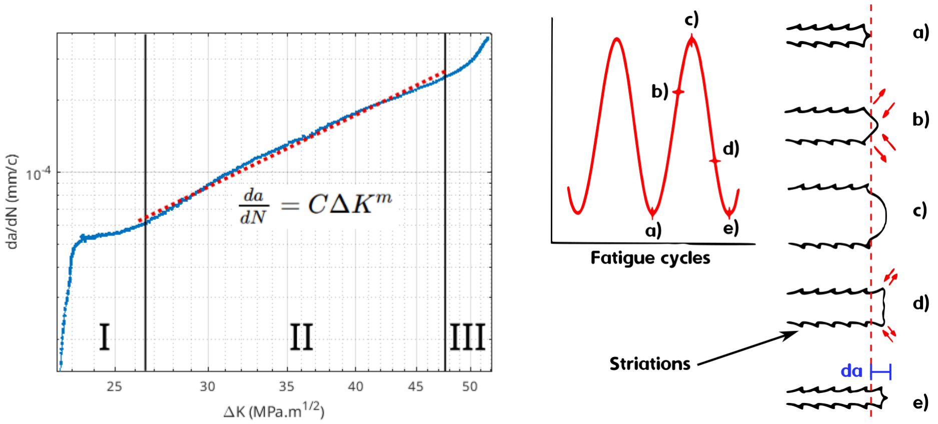

FIGURE 8 – **Left :** the 3 classical regimes of fatigue crack growth $\frac{da}{dN}$ versus ΔK from 5083 test : **I** threshold regime - **II** Paris regime - **III** fracture regime.
Right : Mechanism of crack propagation by plasticity in Paris regime ; formation of striations

AE and DIC combined analysis on multiplets

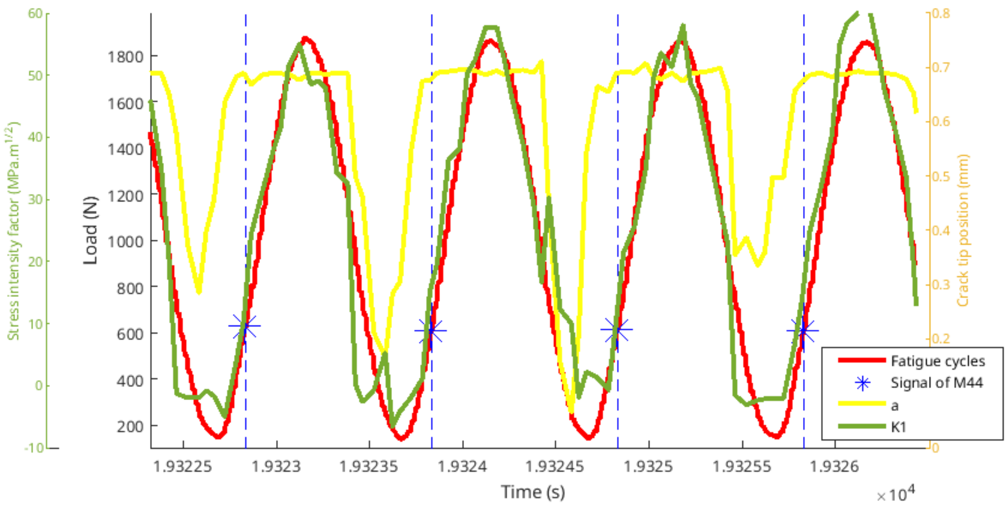

FIGURE 9 – Evolution of the crack tip position a, the stress intensity factor K_I and the applied load during a uniaxial tension-tension strain-controlled fatigue test on 42CD4 steel at 1 Hz. The occurrence of AE signals belonging to multiplet M14 are shown as blue stars.

Figures 9 and 10 represent the evolution of the crack tip position a together with the stress intensity factor K_I for few loading cycles during which AE signals belonging to a multiplet were recorded. The occurrence of these AE signals within the cycle are indicated by blue dots or stars. These two figures illustrate that the crack tip position a presents a plateau at each cycle while sharp wells appear when load is near its minimum. This means that the tip of the crack, as detected by the camera, is going back cyclically under a certain load : around $900 MPa$ for M14 on 42CD4 specimen and $500 MPa$ for M1

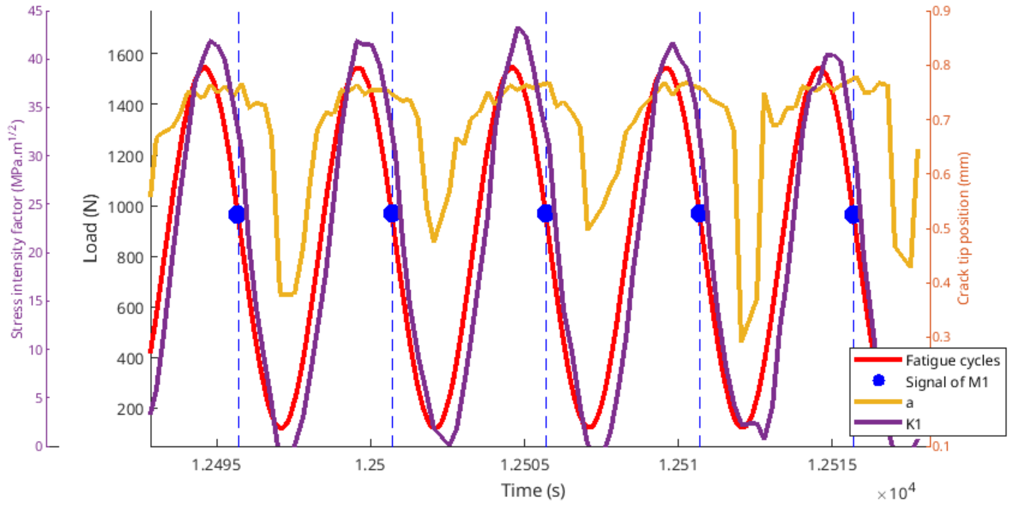

FIGURE 10 – Evolution of the crack tip position a, the stress intensity factor K_I and the applied load during a uniaxial tension-tension stress-controlled fatigue test on 5083 Aluminum at 0.5 Hz. The occurrence of AE signals belonging to multiplet M1 are shown as blue dots.

on 5083 specimen. Physically, during unloading phases, the crack tip stays at its position but the crack is closing its faces via a mechanism called plasticity-induced crack closure [11], generating a backward motion detected by the DIC analysis. This interpretation seems to be validated by the stress intensity factor curves which reach a floor level $K_I \simeq 0$ MPa$\sqrt{m}$ when the crack tip position moves back. It means that on the plateau, the crack is fully opened. The beginning and the end of crack closure can then be determined, at each cycle, thanks to the sharp wells on the crack tip detection curve.

The dashed blue vertical lines indicate when the multiplet signals occur during the loading cycles. It is therefore possible to discriminate the signals related to rubbing (emitted during crack closure) from those originating from the crack tip plasticity or from cleavage (emitted during the plateau). For example, in figure 4, although the M14 signals (strain-imposed test on a 42CD4 specimen) are recorded below the mean load of each cycle, they occur just after the onset of the plateau, suggesting that these signals may be related to plasticity at crack tip (cf. (b) step in figure 8 on the right). In the case of the multiplet M1 (load-imposed test on a 5083 specimen), the signals were emitted during unloading and near the mean load level. As a result, one might initially assign this multiplet to the group of rubbing multiplets. However, according to figure5, these signals were emitted during a phase for which the crack was still fully-opened. Consequently, M1 can be attributed to crack tip plasticity in compression [9] (cf. (d) step in figure 8 on the right).

4 Conclusions and perspectives

In this article, we show that AE multiplets can be detected and used as a signature of fatigue crack growth for two different materials (a high strength steel as well as an aluminium alloy) and different loading modes (strain-imposed and load-imposed). The combination of DIC and AE methods allows to investigate the nature of the physical sources of AE multiplets, allowing to discriminate multiplets due to crack tip plasticity or cleavage from those due to crack faces rubbing. Some of the results shown here give unexpected results : depending on loading conditions, multiplets can be emitted at the crack tip even below the mean load of the fatigue cycle or during the unloading phase.

The results presented in this paper are preliminary. A more systematic analysis of the different multiplets recorded in different tests will allow to define general patterns for the considered physical AE sources. In addition, a more detailed analysis of the multiplets waveforms (evolution of energy, spectral density, or decorrelation of the coda [5]) will be linked to the evolution of the crack growth rate or of the stress intensity factor.

Références

[1] Suresh S.,Fatigue of materials, Cambridge University Press (1998)

[2] Harris, D.O. and Dunegan, H.L., Continuous monitoring of fatigue-crack growth by acoustic emission techniques, Experimental Mechanics, 14(2), 71-81 (1974)

[3] Berkovits, A. and Fang, D.N., Study of fatigue-crack characteristics by acoustic emission, Engineering Fracture Mechanics, 51(3), 401-416 (1995)

[4] Deschanel, S. and Weiss, J., Contrôle de la fatigue des matérieux par émission acoustique, Techniques de l'Ingénieur, 12, IN 226, 1-15 (2018)

[5] S. Deschanel, W. Ben Rhouma, and J. Weiss, Acoustic emission multiplets as early warnings of fatigue failure in metallic materials, Sci Rep, 7(1), 13680 (2017)

[6] Lengliné O.,and D. Marsan, Inferring the Coseismic and Postseismic Stress Changes caused by the 2004, M=6 Parkfield Earthquake from Variations of Recurrence Times of Microearthquakes, J. Geophys. Res., 114, B10303 (2009)

[7] S. McNeill, W. Peters, M. Sutton, Estimation of stress intensity factor by digital image correlation, Engineering Fracture Mechanics 28 (1) (1987)

[8] R. Hamam,F. Hild, and S. Roux, Stress intensity factor gauging by digital image correlation : Application in cyclic fatigue. Strain, 43(3) (2007)

[9] C. Laird, The influence of metallurgical structure on the mechanisms of fatigue crack propagation, In Fatigue crack propagation, STP 415, pp. 131-68. Philadelphia, ASTM (1967)

[10] P.C. Paris, M.P. Gomez, W.P. Anderson, A rational analytic theory of fatigue. The trend in engineering 13 (1961)

[11] K. Tanaka,Y. Akiniwa, Modeling of fatigue crack growth : mechanistic models. In Comprehensive structural integrity. Volume 4. 1. Edited by Milne I. Elsevier Ltd., Oxford, UK, (2003)

[12] R. Pippan, A. Hohenwarter, Fatigue crack closure : a review of the physical phenomena : Fatigue Crack Closure. Fatigue Fract Engng Mater Struct 40, (2017)