ACOUSTIC EMISSION MONITORING UNDER FATIGUE CONDITIONS OF ALUMINIUM MATRIX COMPOSITES REINFORCED BY CONTINUOUS ALUMINA FIBRES.

Marie Jacquesson[1], Pascal Paulmier[2], Nathalie Godin[3] , Roger Fougères[3]

[1] *ONERA/DMSC, BP 72, 92322 Châtillon Cedex, France.*
[2] *ONERA/DMSE, BP 72, 92322 Châtillon Cedex, France.*
[3] *INSA de Lyon, GEMPPM, UMR CNRS 5510,*
20, av. A. Einstein, 69621 Villeurbanne Cedex, France.

SUMMARY : A quasi-UD aluminium/alumina composite is subjected to tensile and fatigue loadings and Acoustic Emission monitoring. The aim of this study is to investigate the potential of the Acoustic Emission technique for locating and detecting damage initiation and propagation and, in relation with metallographic information, for evidencing the different damage mechanisms in this kind of composite. Acoustic Emission allows to detect a 3-stage evolution of damage during the fatigue life and to correlate these three stages to three main damage mechanisms that lead to the failure of the composite.

KEYWORDS : aluminium, alumina fibres, fatigue, Acoustic Emission, damage mechanisms.

INTRODUCTION

High purity 1199 aluminium matrix composites reinforced by Nextel 610 (N610) continuous alumina fibres are of a great industrial interest due to their high specific stiffness and specific strength, either in longitudinal or transverse directions, compared to other conventional engineering materials. However, a better understanding of the damage mechanisms is needed to optimize their potential properties and to define more precisely their application field.
In the present study, the composites are elaborated by the P-CAST process (gas pressure infiltration casting system) developed by Aérospatiale. Owing to the in-service loading conditions these composites should undergo, monotonic and fatigue tests combined with Acoustic Emission (AE) were performed at room temperature. AE is the term used to describe the spontaneous release of transient elastic waves within solids, caused by sudden localized changes in stress. Some possible sources of AE activity in the N610/1199 composite are fibre breaking and plastic deformation of the matrix. It is expected that different failure modes will result in different AE behaviours due to the differences in the energy released during the fibre failure compared to matrix deformation.

The purpose of this study is firstly to understand damage mechanisms occurring during the composite fatigue life through classical sample examinations and secondly to assess the sensitivity of the AE technique on this kind of materials. This study aims at showing the complementary aspect of AE to classical studies of performances in fatigue of a MMC.

MATERIALS AND EXPERIMENTAL DETAILS

Materials

A quasi-unidirectional preform realized by stacking 12 taffetas plies including 90% of Nextel 610 fibres in 0° orientation (longitudinal direction) and 10% of fibres in 90° orientation (transverse direction) is infiltrated by high purity aluminium 1199 (>99,99%) by the P-CAST route [1,2]. The Nextel 610 fibre (N610) is a 12 µm diameter polycrystalline filament of α-alumina ; its geometrical and mechanical characteristics, as well as the matrix properties, are listed in Table 1. The P-CAST process allows good aluminium infiltration but the matrix volume fraction in the bundles varies from 30% near the mid-plane of the plate to 50% in the outer parts. A high fibre volume fraction allows a good process reproducibility but leads to an undulation of the longitudinal bundles around the transverse one's. The process pressure is high enough to force the aluminium to wet the alumina so that the fibre-matrix interfacial bonding is strong.

Properties	**Nextel 610 fibre**	**1199 matrix**
Density (g/cm^3)	3.9-3.95 [3]	2.7
CTE (10^{-6} K^{-1})	7	23.6
E (GPa)	380-400 [3]	70
σ_F (MPa)	2800-3500 [3]	29
$R_{0,2}$ (MPa)	-	12
Weibull modulus	9-12 [3]	-

Table 1 : Matrix and fibre properties in the N610/1199 composite.

Experimental procedures

Static and fatigue tests are carried out on a servo-hydraulic Instron testing machine respectively under stroke controlled mode at a rate of 0.1 mm/min and at different stress amplitudes. Each static sample, smooth rectangular specimen 150x12x3mm in size, is equipped with extensometric gauges fixed on both faces. Tensile-tensile fatigue tests are performed on composite plates (250x8x3mm) until failure. The applied load is sinusoidal with a 0.1 minimum-to-maximum load ratio. The frequency is 10Hz.

During both types of tests, AE was monitored using a MISTRAS 2001 computerized system (EPA). The operating parameters are : two AE transducers (µ80 resonant transducers from PAC) placed at each end of the specimen gauge length, system threshold level : 32dB, fixed gain : 40dB, dead time : 1ms. The two sensors are used to locate the sources of AE and to ensure that only signals generated inside the gauge length are considered. Before mechanical tests, pencil break on the surface of the specimen allows to evaluate the wave propagation velocity and to check that attenuation is negligible. Fatigue test equipped with AE are performed at a frequency of 1Hz in order to minimize interferences. It is admitted that damage mechanisms existing in this kind of material cyclically loaded at 1Hz are identical to those operating at 10Hz.

In order to study the different damage mechanisms, examinations of fracture surfaces and polished sections extracted from post-mortem specimens are realized for each test.

RESULTS

Longitudinal and transverse tensile tests

Mechanical tests

Mechanical results are given in table 2. The longitudinal tensile stress-strain curve (fig.1) presents two linear parts corresponding to an initial Young's modulus of 240 GPa and, for the upper part of the curve (starting at 0.1%) to a modulus of 200 GPa. The fracture surface is globally flat, with a succession of more or less wide plateaus bounded by thin ligaments of non-reinforced matrix or by transverse bundles (in the 90° direction). The flatness of the plateaus is due to a rapid crack propagation through a bundle. No significant pull-out is noticed which demonstrates a strong interface behaviour. Matrix stretches through ductile ridges around the longitudinal fibres. Transverse tensile tests reveal a higher Young's modulus than for a pure UD [3]. The fracture surface of the transverse tensile samples is globally flat and, because of shear stresses, is oriented at 45° from the loading direction. All longitudinal fibres are covered with a thin layer of matrix producing numerous ductile cavities. Some fibres are in pull-out in transverse bundles. This quasi-UD fibre-matrix system combines good longitudinal properties with better transverse characteristics than UD composites, owing to the contribution of the transverse bundles.

		N610/1199
Longitudinal tensile properties	σ_F (MPa)	1090 ± 20
	E_L/E'_L (GPa)	240 ± 14 /200 ± 7
	ε_F (%)	0.54 ± 0.02
	ν	0.26 ± 0.03
Transverse tensile properties	σ_F (MPa)	210 ± 3 (ε=0.3% to failure)
	E_T (GPa)	152 ± 32
	ε_F (%)	0.36 ± 0.02

Table 2 : Monotonic characterization of the N610/1199 composite.

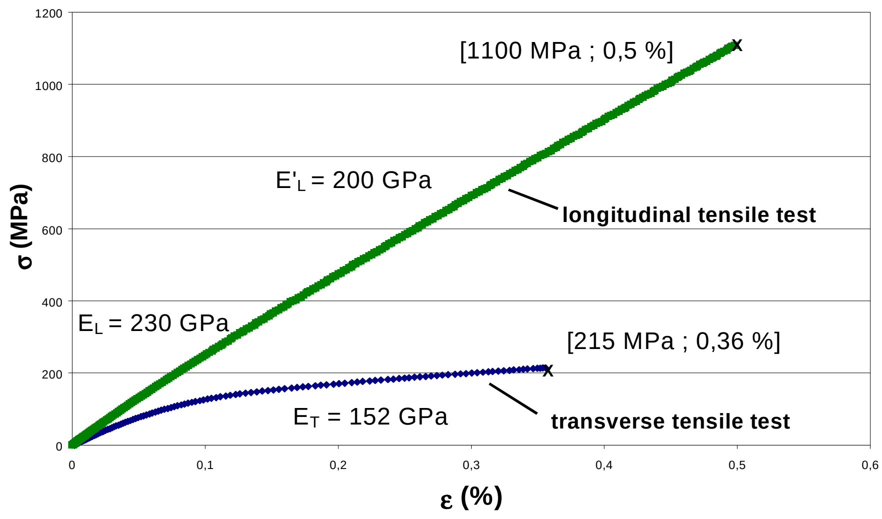

Fig.1 : Longitudinal and transverse tensile response of N610/1199 composite.

Acoustic emission

The acoustical activity starts at a stress threshold. For instance, no event is recorded before 917 MPa i.e. 83% of the failure stress (fig.2). On and after this threshold, energy of events roughly increases. The amplitude distribution is centered on 65 dB (fig.3). Amplitudes of the first events are close to 65 dB then amplitudes of the following hits scatter with the increasing stress amplitude spreading out on a wide range from 42 to 96 dB. At the end of the tensile test very energetic events are detected. The localization of AE sources allows to determine the position of the emitting sources between the middle of the sample and transducer n°2, a region which will become the fracture zone.

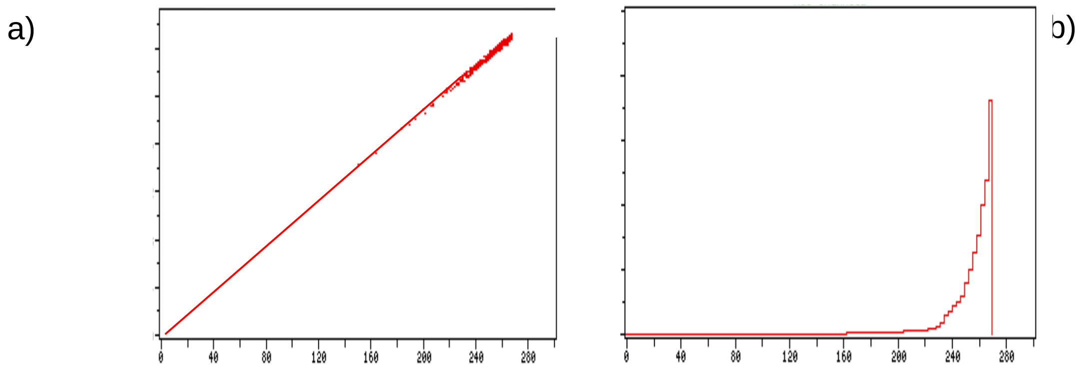

Fig .2 : AE response during a tensile test on the N610/1199 composite a)load (kN) vs time (s), b) energy (a.u.) vs time(s).

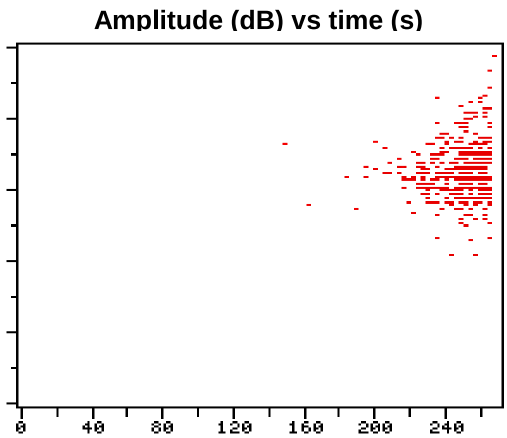

Fig.3 : Events amplitude vs time during a tensile test on the N610/1199 composite.

Fatigue

Mechanical tests

Fatigue tests are conducted until failure in order to determine the S-N curve (fig.4). The fatigue limit is about 700 MPa i.e. 65 % of the tensile strength. The curve looks rather flat but with a sigmoidal aspect typical of the monolithic aluminium S-N curve. After microstructural examinations, two clearly defined areas can be detected on the composite fracture surface (fig.5a) :

- a very uneven area (area 1, fig. 5b) with numerous debonded fibres in pull-out always covered with matrix residues and some spots of multicracked matrix in non-reinforced matrix zones, either intra or inter-bundles zones.

- an area of sudden failure (area 2, fig. 5c) similar to the monotonic tensile fracture surface i.e. flat with ridges of ductile matrix around fibres in a bundle.

Examinations of polished sections extracted from a sample, which test was interrupted before failure, reveal cracks initiated in longitudinal-transverse bundles contact areas. These cracks propagate during the test in non-reinforced matrix regions and then branch off in the neighbouring bundle.

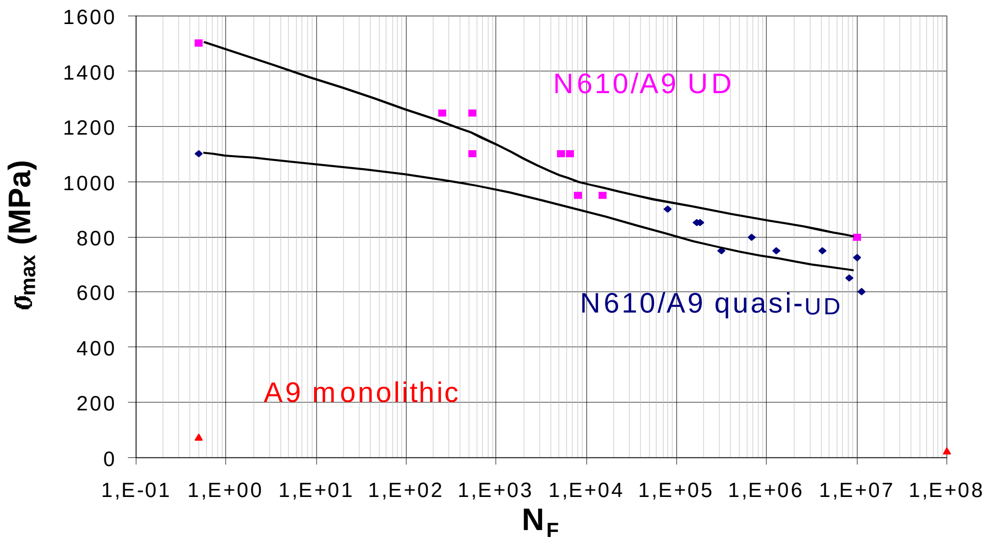

Fig.4 : S-N curve of the N610/1199 composite

Acoustic Emission

The AE activity monitored during a fatigue test (σ_{max} = 800MPa, R = 0.1, f = 1Hz, N_F = 39000 cycles) exhibits three stages (fig.6) : A = 0-4000 cycles, B = 4000-30000 cycles, and C above 30000 cycles. The amplitude distribution histogram of all events accumulated during the fatigue test, reveals three ranges of amplitude (fig.7a and b) : range 1 = [32-50dB] ; range 2 = [50-80dB] ; range 3 = [80-100dB]. Moreover, range 1 events exhibit long rise time and low energy, range 2 events reveal lower rise time and higher energy, range 3 events present the same order of rise time and a much higher energy (at least ten times higher than range 2). So, energy seems to be another discriminating parameter. Then, during analysis, the total number of generated events is separated into events accumulated within the three amplitude ranges (fig.8a, b, c). It appears that a correlation exists between amplitude ranges and AE stages. Thus, range 2 begins at a relatively low number of cycles (period A) and extends to the entire lifetime. Range 1 events appear continuously during period B until fracture and seem to be subsequent to range 2 events. Range 3 is related to events appearing during the last period (period C) leading to failure ; their number is quite limited.

On figure 9, positions of AE sources during the fatigue life are represented. The sudden rise in energy after 30 000 cycles is clearly noticed and three highly energetic hits appear at the end of the test (already remarked on fig.7 by discontinuities in the cumulative representation, at cycles 33 000 and 37 000). The source of these is located between transducer n°1 and the middle of the sample, in a region where the specimen failure will finally occur.

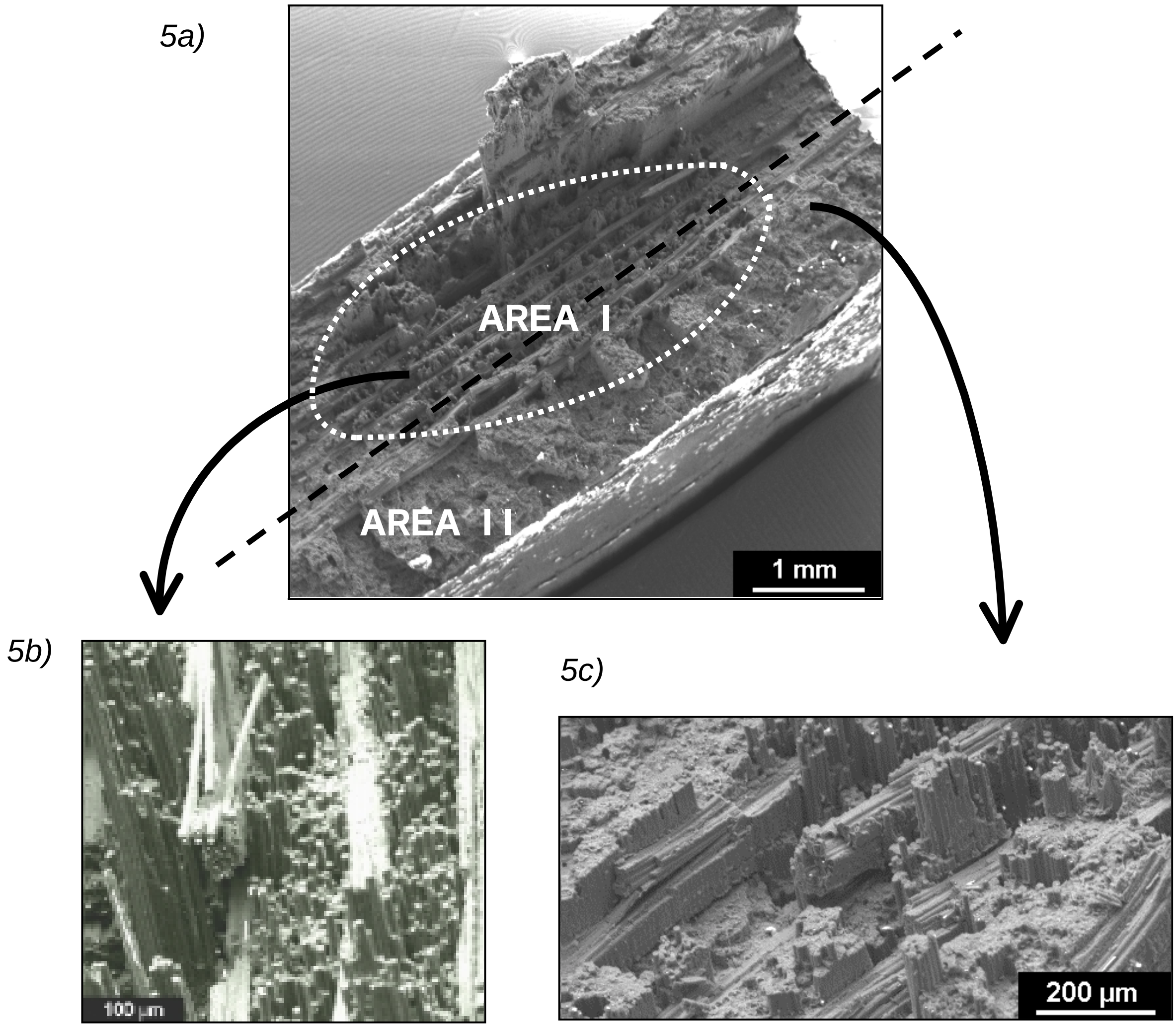

Fig.5 : Fracture surface showing two zones of the N610/1199 cyclically loaded composite.

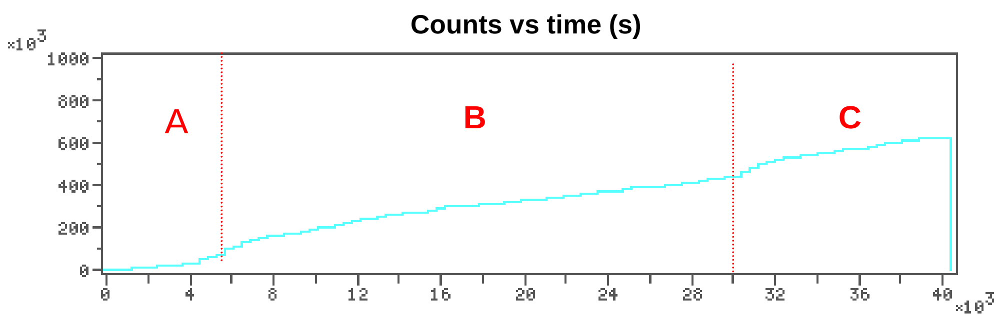

Fig.6 : Event counts vs test time : 3-stage evolution

DISCUSSION

Longitudinal tensile test

Mechanical performances

The behaviour of composites in a longitudinal tensile test is related to the purely elastic behaviour of fibres. Besides, the composite failure strain (0,5%) is close to the fibre failure strain. The tensile strength (1100 MPa) is lower than Deve *et al.* results on UD [3,4] : transverse bundles, around which longitudinal bundles undulate, can play an important role since they create contact zones where high stress concentration takes place. The Young's modulus (240 GPa) is equal to UD Young's modulus and follows the rule of mixtures of a UD assuming that the fibre volume fraction is equal to the longitudinal part of the fibre volume fraction of the quasi-UD. The lower part of the curve is attributed to the elastic behaviour of the two components, fibre and matrix. The upper part of the curve exhibits a lower stiffness (200 GPa) which corresponds to the perfect plastic yielding of the matrix combined to the elastic behaviour of the fibres. The transverse tensile stress-strain curve shows the plastic contribution of the 1199 matrix (first part of the curve). In the second part, interface debonding and transverse bundles contribution finally lead to a restricted failure strain. The combination of strong interface and ductile matrix ensures good mechanical performances in longitudinal and transverse directions. Composites with a strong interface usually damage by propagation of a macroscopic crack (Local Load Sharing - LLS - as defined in [3]), on the contrary, the combination alumina/aluminium preserves a good interfacial resistance whereas the matrix ductility allows a more progressive damage through Global Load Sharing (GLS). The fracture surface thus presents an aspect of terraces produced by the branching of one (or several) macroscopic crack(s) in ductile matrix filaments. This branching phenomenon, enhanced by the great matrix ductility, slows down the damage propagation.

Acoustic Emission

AE denotes the suddenness of damage initiation and its propagation until failure of the composite. No acoustical activity is recorded before the stress threshold (83% of failure stress) hence collective dislocation motion, occurring from the beginning of the test, creates no detectable AE. Beyond the stress threshold, AE is recorded with an amplitude of about 65 dB in mean value and with increasing energy (fig.2). During this part of the test, the main damage mechanism involved in tension is fibre failure. So AE events could be attributed to fibre failure. Nevertheless, fibre failure also induces matrix plastic deformation in the small regions surrounding the broken fibre : plastic deformation of the matrix may generate a weaker additional AE activity. Near fracture, a fibre break can quickly lead to the failure of some of its nearest neighbours. This phenomenon is emphasized by the strong interfacial bonding. Then event number and event energy increase. Finally, entire bundles fail : this damage mechanism corresponds to events with very high energy and long duration. The superposition of these different fibre failure modes (individual, by bunches, by bundles) explains the observed progressive widening of amplitude range during the test (fig.3). This basic test supplies AE characteristics of fibre failure.

Fatigue

Mechanical performances and damage mechanisms

Even if monotonic mechanical performances of quasi-UD are lower than those of UD, the quasi-UD fatigue limit is equivalent to that of a UD. As far as transverse bundles are directly involved in the quasi-UD tensile damage formation, the composite seems to accommodate this kind of macroscopic defect during fatigue. Besides, other mechanisms play a role in fatigue. Examination of fracture surfaces and polished sections allow to determine the different damage mechanisms leading to failure. The dark area with fibres in pull-out is the zone really damaged by fatigue (fig.5b) whereas the peripheral flat area denotes the sudden final fracture of the composite (fig.5c). More precisely, during the early cycles, damage starts with individual fibre failure (on intrinsic or elaboration defects), in chain failure in high fibre volume fraction zones and failure in longitudinal-transverse bundles contact zones. In regions where fibres are broken, matrix strains and crumbles gradually. Therefore, these regions undergo a very progressive damage in fatigue. Elsewhere load transfer is assumed by the matrix to the neighbouring fibres by plastic straining and the composite undergoes no damage. At a given time, the fatigue damage zone is too wide for the composite to withstand the imposed load. Damage accelerates : longitudinal fibre bunches break, stress concentrations at the crack tip become too high to be dissipated in the neighbouring matrix. The crack then propagates through a very brutal quasi-static mode. Cracks are sometimes slightly deflected by non reinforced matrix ligaments, creating a terrace fracture surface. At last, the sample breaks by the failure of the last longitudinal fibre bunches and finally by failure of the transverse bundles.

Acoustic Emission

Owing to AE results obtained during a fatigue test, amplitude and energy seems to be discriminating parameters. This allows to distinguish a category of events from another and hence a set of mechanisms from another. Thus the cumulative representation of event energy versus time for each of the amplitude ranges (fig.8a, b and c) helps to recall the chronology of appearance of different AE sources. The coupling of AE results with examination conclusions allows to propose a precise description of the damage evolution occurring in the cyclically loaded composite :

- during **period A** (0-4000 cycles), events are very energetic, with high amplitudes, and rather short rise times. First form of damage, they can be correlated to **fibre breaks** (individual, by bunches, at the level of transverse bundles). Indeed, event characteristics (especially the amplitude) are close to those recorded during a tensile test where the main damage mode is fibre fracture.
- during **period B**, the typical activity of period A goes on but a second mechanism occurs : **progressive damage of the matrix by multicracking**. AE event amplitude and energy are much lower, rise time is much longer. In short, the emission evolution is more monotonic and fits well with a less violent and more progressive damage mechanism that exists until failure of the composite. It is reasonable to assign to this kind of AE response a set of mechanisms including matrix progressive damage, friction at interfaces, dislocations motion…

- during **period C** (beyond 30 000 cycles), AE activity becomes more intense in energy, amplitude, events duration and rise time. Some events are highly energetic and have a particularly important amplitude. It represents the final phase of the composite life. Fibres break in chain, failures are rapid and spread to the whole bundle : first on longitudinal bundles, then to the transverse bundles in the latest cycles. It seems that **bundles breaks** could be associated with the most energetic signals (the three events on fig.9) of high amplitude and very long duration.

Furthermore, this correlation allows to establish AE characteristics for the different damage mechanisms in the N610/1199 composite during this kind of test :

- **range 1** (low amplitude events) : **matrix damage**.
- **range 2** (middle high amplitude events) : **fibres breaks**.
- **range 3** (high amplitude events) : **bundles breaks**.

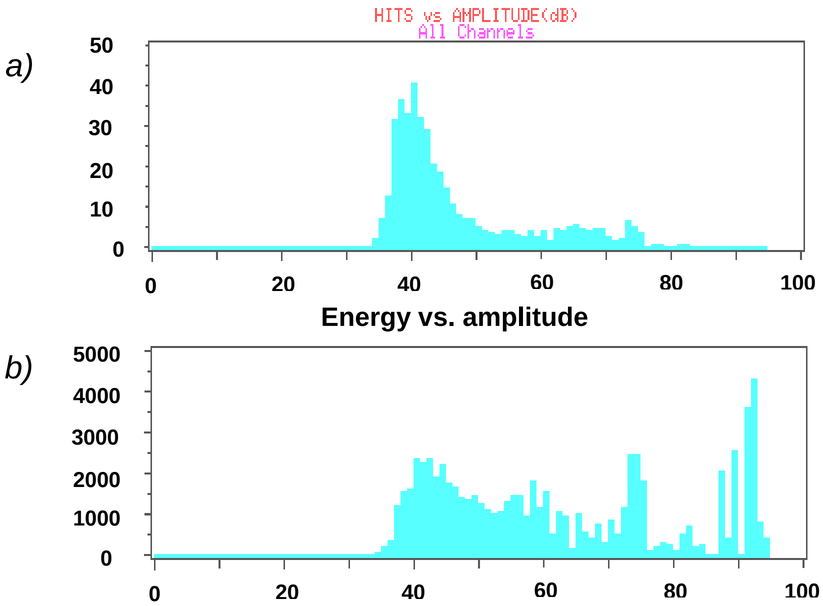

Fig.7 : a) amplitude distribution - b) energy distribution during a fatigue test on the N610/1199 composite

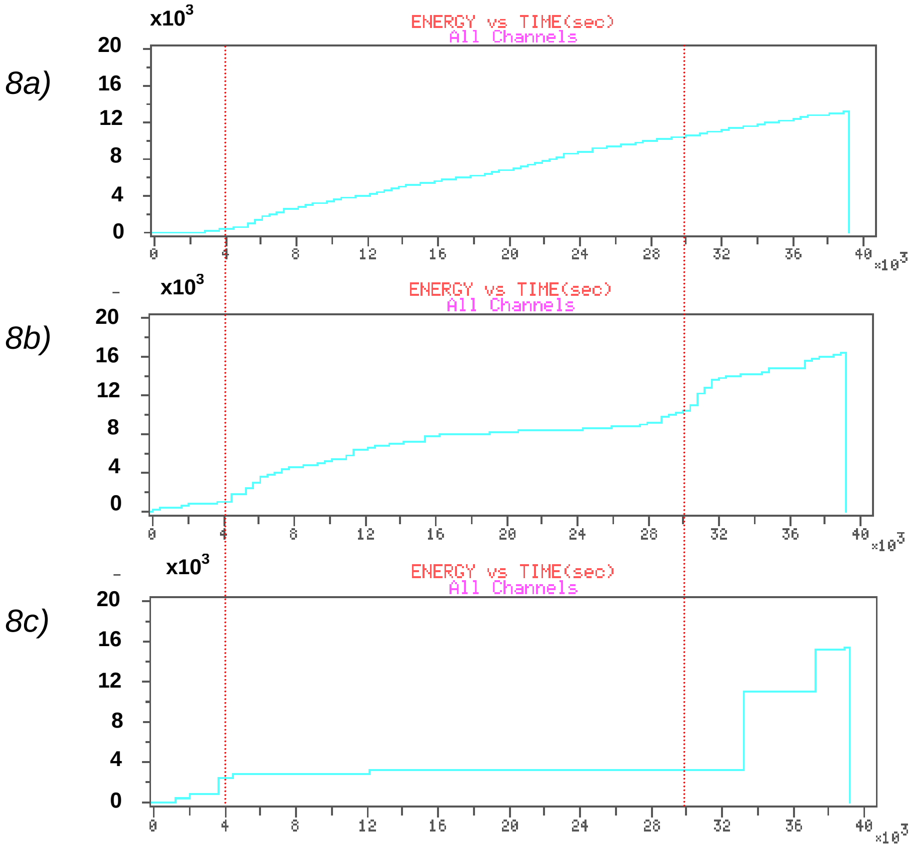

Fig.8 :Time evolution of event counts and event energy according to 3 amplitude ranges : a) [32-50dB] b) [50-80dB] c) [80-100dB]

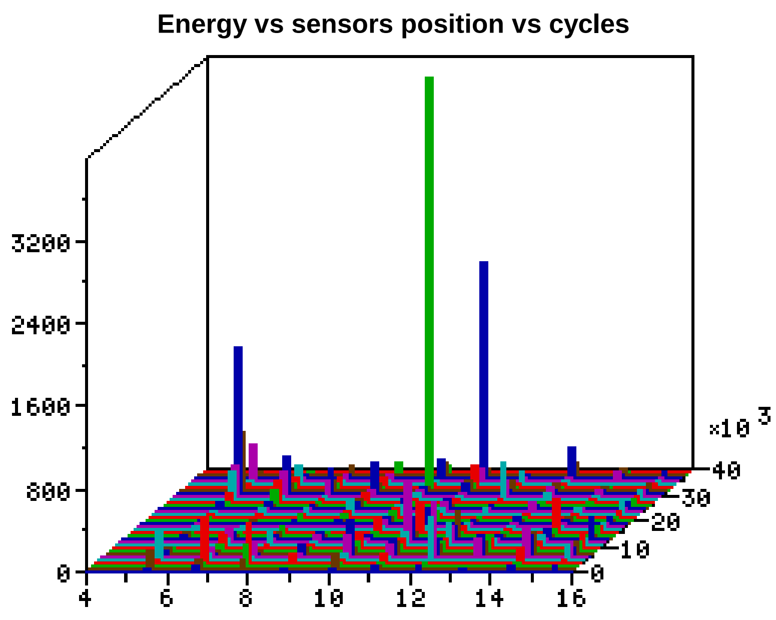

Fig.9 : Localization of AE sources on the N610/1199 cyclically loaded composite (X = sensor position (sensor n°1 is at 5, sensor n°2 is at 16) ; Y = cycles ; Z = energy)

CONCLUSION

The fatigue behaviour of a quasi-UD Al_2O_3/Al MMC has been first studied using a classical approach : once the fundamental mechanical performances in longitudinal and transverse directions are obtained, fatigue tests conducted to failure allowed to determine the fatigue limit. Systematic examination revealed different mechanisms occurring during the composite damage. The Acoustic Emission technique gives, in term of event amplitude, the damage chronology (displayed as 3 distinct regimes) and confirms the hypothesis stated through fracture surface examination (existence of 3 amplitude ranges, i.e. 3 categories of hits with their own acoustic characteristics, that is to say 3 categories of damage mechanisms). Furthermore, this method is of a great interest because it allows to follow damage stages during the life of a composite structure in real-time.

REFERENCES

1. Pora, J., Le Vacon, P., Carré, C, Santini, P., Schneider, C., Merle, P., “Gas pressure infiltration processing and mechanical properties of alumina and carbon fibers reinforced aluminum alloys”, *ICCM10*, vol.2, ed. by A. Poursartip, K. Street, 1995, pp. 19-26.
2. Rabinovitch, M., Raviart, J.L., Daux, J.C., Vidal-Sétif, M.H., Pora, J., Le Vacon, P., “Saut technologique , Matériaux composites à matrice métallique”, *Rapport d'avancement n°9*, juil. 1996.
3. Deve, H.E., Mc Cullough, C., **“**Continuous-fiber reinforced Al composites : a new generation”, *JOM*, vol.47, july 1995, pp. 33-37.
4. Mc Cullough, C., Deve, H.E., Channel, T.E., **“**Mechanical response of continuous fibre reinforced Al_2O_3-Al composites produced by pressure infiltration casting”, *Mat. Sci. Eng.*, vol.A189, 1994, pp. 147-154.