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Mechanical characterization of glass/vinylester ±55° filament wound pipes by acoustic emission under axial monotonic loading

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A B S T R A C T

In this article a mechanical characterization of filament wound pipes is investigated. The tested pipes are composed of E glass/vinylester with ±55° angle wedding. The mechanical behavior under axial monotonic loading is studied using acoustic emission. The test was carried out according to the instructions of standard ASTM-D 2105-01 test. The experiment determines the damage mode using two methods: acoustic emission and tensile test. The results of acoustic emission associated to those obtained from tensile test, are very promising and show the relevance of the developed nondestructive test to the prediction of the mechanical behavior of filament wound pipes.

1. Introduction

Acoustic emission (AE) is a nondestructive test which can be used to analyze the damage mode of filament wound pipes (FWP). Previous research tended to privilege mechanical tests to determine the mechanical behavior of FWP. Bai et al. [1] have investigated the mechanical behavior of ±55° filament wound glass-fiber/epoxy-resin tubes under pure tensile loading and stated that the mechanical behavior can be divided into three zones: transverse cracking, diffusion of the damage in the matrix, and final failure of the tubes. Gemi et al. [2] studied the impact of the angle of reinforcement on the mechanical behavior of specimens under pure internal pressure. Tarakcioglu et al. [3] stated that at high loads, fiber failure is so important that it controls the final damage while at low loads, the failure is controlled by matrix damage. Martens and Ellyin [4] have studied the damage behavior of multidirectional reinforced glass/epoxy pipes under biaxial monotonic loading and have shown that the important mechanical properties of a composite pipe are strength, stiffness and durability. Mertiny et al. [5] experimentally studied the effect of the winding angle upon the strength of filament wound composite members and concluded that multiangle winding has a significant effect on the strength of tubular composite structure.

More recent studies investigate the damage mode using AE of a unidirectional glass/polyester composite. Huguet et al. [6] study the use of acoustic emission to identify damage modes in glass fiber reinforced polyester, Godin et al. [7] explore the clustering of acoustic emission signals collected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers. Notwithstanding their scientific acumen, these studies do not seem to have sufficiently focused on the use of the acoustic emission activity during tensile test on FWP. This paper is an attempt to apply some implications of the very promising findings of these studies in FWP. Proceeding experimentally, we investigate the damage mode of FWP E glass/vinylester with a ±55° winding angle under axial loading by the AE. We observed final

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Table 1
Mechanical proprieties of the fiber and the resin.

Component	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile elongation (%)	Density 25 °C (g/ml)	Linear density (Tex)
Vinylester resin	86	3.2	5.0–6.0	1.046	–
E glass fiber	1970	78.794	–	–	2400

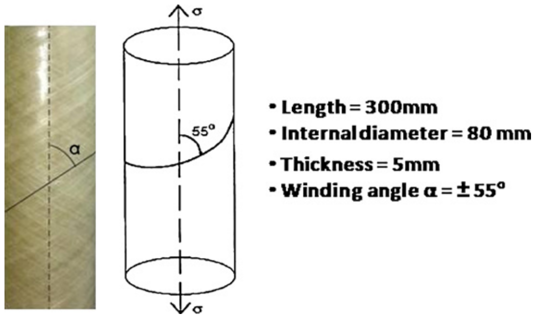

Fig. 1. Dimensions and characteristics of the specimen.

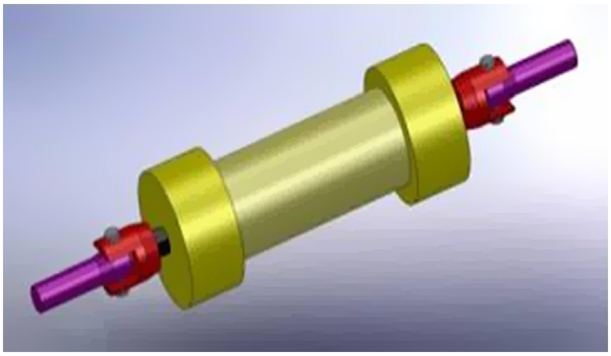

Fig. 2. Clamping of the pipe specimen.

failure levels and we represented the results that we obtained from our experiments by means of stress/strain curves, AE curves and microscopic observation.

2. Production of the specimen

The FWP is produced by the CTRA Tunisia Co. E glass direct roving and vinylester resin were used for this production. The winding angle of ±55° was manufactured by using a CNC winding machine. The mechanical properties of the matrix and reinforcement materials are given in Table 1 and dimensions of the specimen are reproduced in Fig. 1.

A burn-off test according to the standard test T57-518 [8] is performed to determine the fiber rate (%) for each tube. The average value is 60 ± 2%.

3. Test procedure

In this work, three types of tests were performed. In the first step, a tensile test is made in order to identify the mechanical characteristics of the FWP. The clamping of the specimens to a special device manufactured according to the ASTM-D 2105-01 [9] standard test is shown in Fig. 2. This device is mounted on a tensile machine SHIMADZU UH-F30A as shown in Fig. 3(a). The tensile machine mode applied is an imposed displacement with a 10 mm/min displacement rate.

The second step is the tensile test coupled with the AE. This nondestructive testing is performed to identify the damage mode of the FWP under tensile test in real time. According to the ASTM E1067 [10], the AE instrumentation consists of sensors, signal processors, and recording equipment. Therefore, an acoustic emission acquisition system produced by the Physical Acoustic Corporation is used. The acquisition system, named PCI-2, consists of two channels of Acoustic Emission connected with two sensors denoted by C1 and C2 which correspond respectively to the first and the second sensor. In addition to two AE channels, the system also has two parametric channels for other transducers, such as strain gage, pressure and temperature load [11]. An AEwin software is then used to plot the acoustic response of the damage of the FWP. The clamping of the two sensors (C1 and C2) and the PCI-2 system is shown respectively in Figs. 3(a) and 3(b). A constant crosshead speed of 10 mm/min is maintained during the tensile test coupled to the AE acquisition.

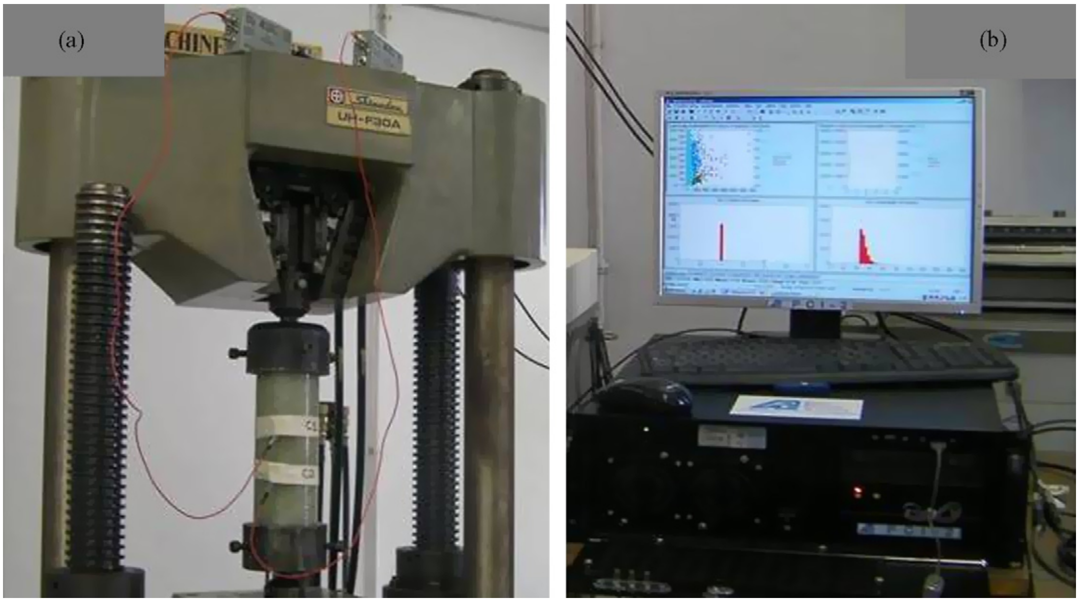

Fig. 3. (a) Assembly of the device system on the testing machine and clamping of AE sensors in filament tube; (b) PCI-2 system.

Table 2
The mechanical properties of glass/vinylester ±55° filament wound pipe.

Tubes	Young modulus (GPa)	Fracture strength (MPa)	Fracture strain (%)
T1	11.88	52.78	4.8
T2	11.73	54.11	2.7
T3	11.59	54.28	3.76
T4	11.37	60.77	2.83
Average values	11.64	55.49	3.52
Gap type	±0.22	±3.59	±0.97

The third step is the microscopic observation which is made in order to identify the different damage modes. This observation was carried out using the SIGMA Advanced Analytical Scanning Electron Microscope SEM from Carl Zeiss within the Roberval laboratory of the UTC in Compiegne in France.

4. Results

4.1. Tensile test

First, the behavior of the E glass/vinylester ±55° FWP under axial monotonic loading is studied. A series of tests of four pipes (T1, T2, T3 and T4) are realized to determine the average values of mechanical properties. Table 2 shows the results of this test.

In order to study the mechanical behavior of the glass/vinylester ±55° FWP, a stress/strain curve was plotted in Fig. 4. It is noticed that this curve is divided into three zones: The first, linear zone, corresponds to the elastic behavior of the composite material; this linear and reversible behavior is often associated with a material which is not damaged. Thereafter, a progressive transverse cracking in the matrix starts. This phenomenon is observed in the outer skin of resin. A second zone (noted by Zone 2), starts from the limit of the first zone: the curve becomes nonlinear and the slope decreases gradually. We observe a pronounced peak at an axial stress of about 60.77 MPa and an axial strain of about 2.83%. This zone is associated to the matrix failure. The last, third zone (noted by Zone 3), is associated with a continuous accumulation of the individual fiber failure which involves the failure of the fiber bands on the surface of the FWP and leads to the total damage of the FWP. Fig. 5 shows a damaged tube after an axial monotonic loading.

These results are in line with the state-of-the-art findings of the researches mentioned in the introduction. However, there are indices obtained in the experimental process pointing to the possibility of there being a fourth zone. The existence of the latter can be shown only after conducting the necessary AE analysis.

4.2. Acoustic emission (AE)

In this part, the acoustic activity and waveform of E glass/vinylester ±55° FWP under axial monotonic loading is studied. First, a statistic analysis is performed to identify the sensor (C1 or C2) which presents the best acquisition of signals and

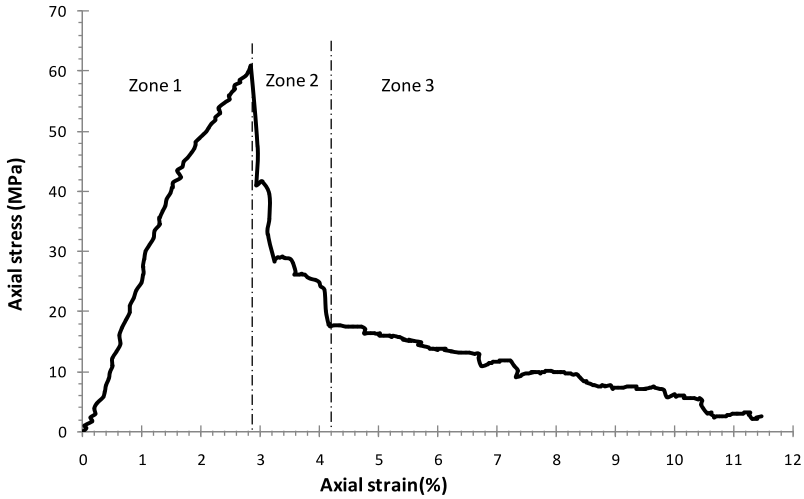

Fig. 4. Stress/strain curves of four glass/vinylester ±55° filament wound pipes.

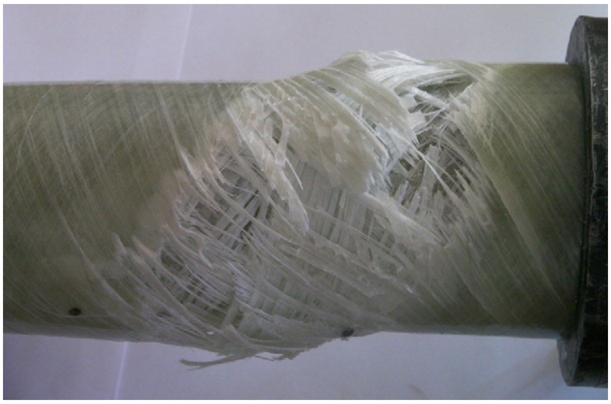

Fig. 5. Damaged tube after axial monotonic loading.

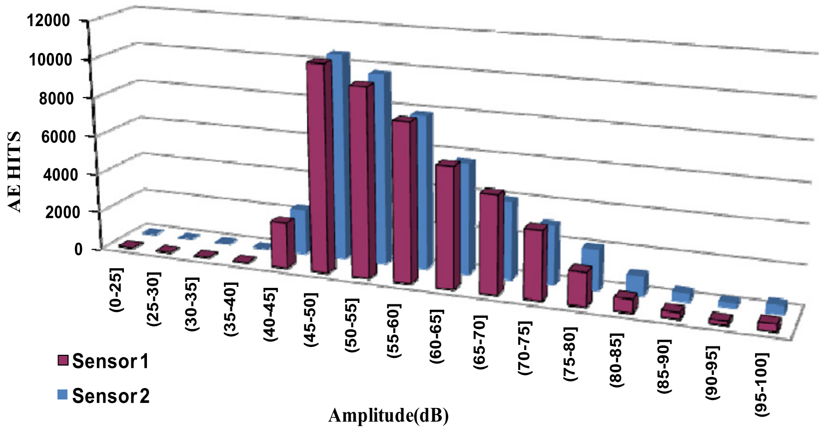

Fig. 6. Amplitude distribution range of glass/vinylester resin ±55° FWP under axial monotonic loading.

Table 3
Numbers of AE hits for each sensor.

AE hits	
C1	86 378
C2	35 599

Table 4
Distribution of amplitude range.

Amplitude (dB)	(45–50]	(50–55]	(55–60]	(60–65]	(65–70]	(70–75]	(75–80]
Hits	27 213	26 380	21 317	13 849	8513	4641	2605

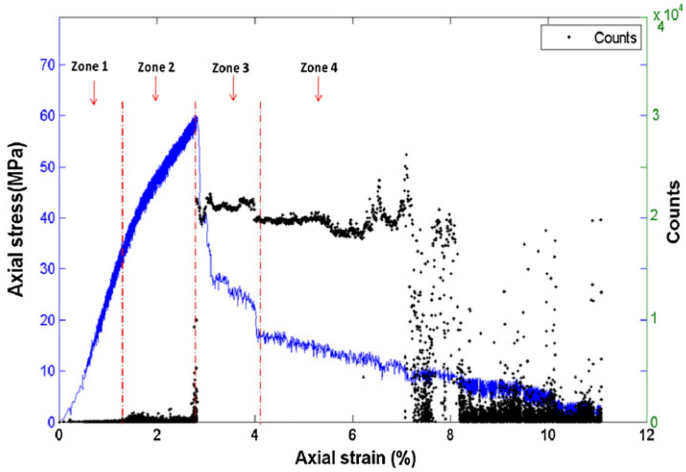

Fig. 7. AE activity based on strain vs. counts/stress curve of glass/vinylester resin ±55° FWP relative to sensor C1.

Table 5
Correlation between the acoustic emission parameters based on mechanical parameters.

Mechanical parameters	Fracture stress (MPa)	60.77
	Fracture strain (%)	2.83
AE parameters	Counts	439
	Amplitude (dB)	79

at the same time to identify the amplitude distribution range. Fig. 6 shows that the first sensor C1 is more representative than the second sensor C2 in a number of AE hits which represent the process of detecting and measuring an AE signal on a channel [12]. Table 3 recapitulates the number of AE hits for each sensor. We notice that C1 presents more events that C2. Following these results, only sensor C1 will be used in the cumulative analyses. For the distribution of amplitude range, we observe that most AE hits are in the range between 45 dB and 75 dB for the two sensors as shown in Table 4. This distribution of amplitude range is associated with matrix cracking and interfacial debonding [6,13].

Fig. 7 presents the acoustic activity based on strain vs. counts/stress curve of glass/vinylester resin ±55° FWP relative to the first sensor C1. We notice that acoustic response is divided into four zones. In the first zone, acoustic activity is clearly missing. This zone, which is limited to the value of 1.2% of axial strain, is relative to the elastic zone where no damage is recorded. In the beginning of the second zone, we notice that a low acoustic activity starts at this zone and we record an increasing number of counts according to the rise of the stress level. At first this zone is relative to matrix cracking (in this zone, amplitude value is about the range of 45 and 55 dB) but when stress level increases, we observe a transverse cracking as a second mechanism of damage. The limit of axial strain is about 3.2%. At this limit, the third zone starts and we note that a significant number of counts is recorded. In this zone, the distribution of amplitude range is between 50 and 70 dB. This amplitude range is associated with matrix failure. Table 5 presents a correlation between acoustic emission parameters based on mechanical parameters at the fracture zone. Finally, the last zone starts at the value of 6.7% as axial deformation in association with a variable acoustic activity. This activity presents a variable number of counts which characterizes fiber failure.

The waveforms of the AE signature for the three zones (Zone 2, Zone 3 and Zone 4) are plotted in Fig. 8. Fig. 8(a) represents the AE waveform of the acoustic response of microscopic cracks to the interfaces fiber/matrix linked to Zone 2. This waveform is characterized by 51 dB and 6 μs as the values respectively of AE amplitude and rise time. This result is comparable to previous studies [6,7,13]. Fig. 8(b) represents the AE waveform of the propagation of cracks through the matrix of the specimen linked also to Zone 2. Among the characteristics stored from this waveform we record 74 dB as AE amplitude and 92 μs as rise time. We state that, the nature of this waveform is the same as the waveform (type A) found by Nechad H [13]. Fig. 8(c) represents the AE waveform of the acoustic response of matrix failure associated to Zone 3. Fig. 8(d) shows the waveform of the acoustic response of the fiber cracking linked to Zone 4. The characteristics of these waveforms are summarized in Table 6. We can therefore conclude that mechanical behavior has a significant impact on the acoustic waveforms.

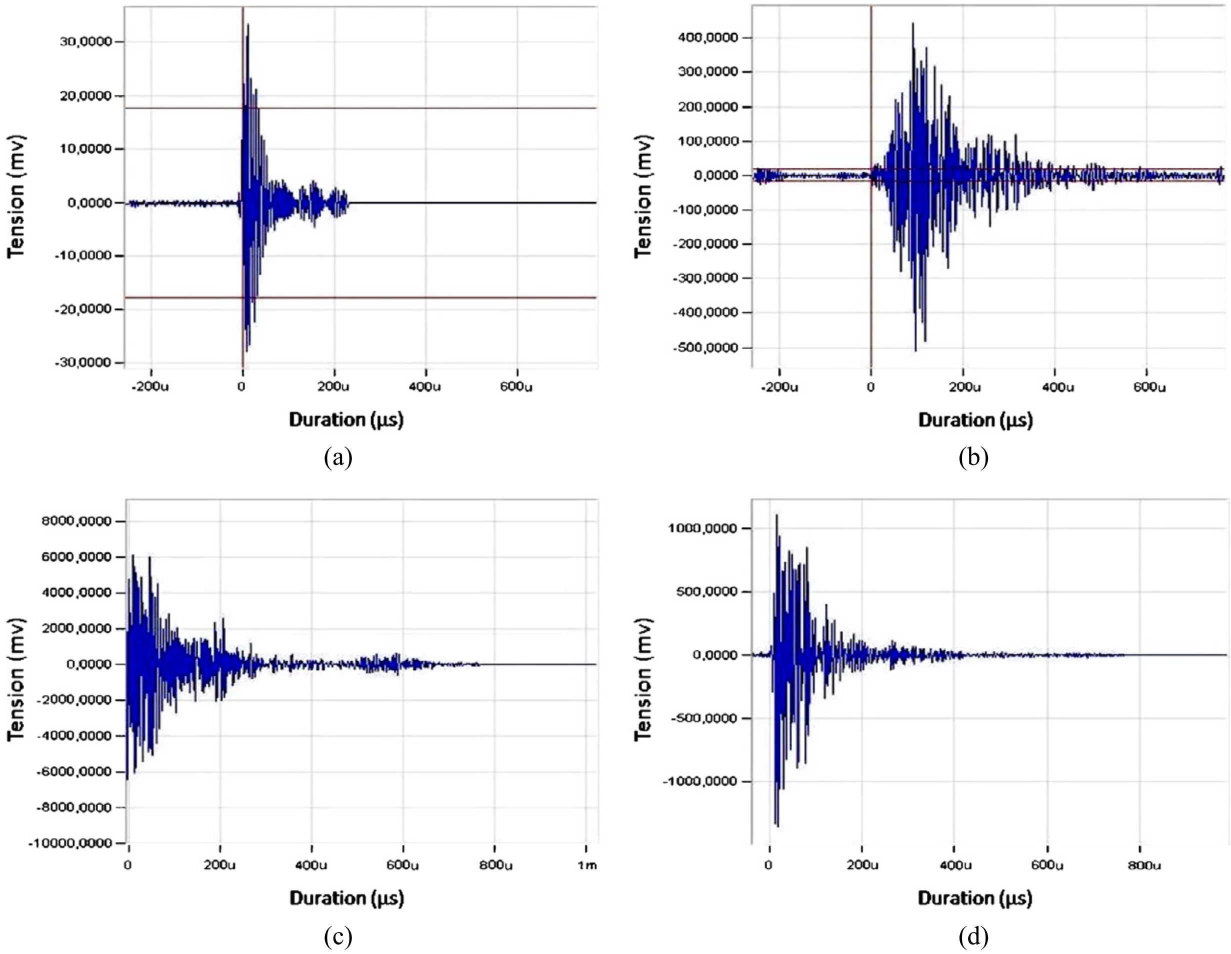

Fig. 8. Waveforms of: (a) microscopic cracks to the interfaces fiber/matrix; (b) propagation of cracks through the matrix; (c) matrix failure; (d) fiber cracking.

Table 6
Characteristics of some waveforms.

Waveform	Amplitude (dB)	Rise time (µs)	Duration (µs)	Energy (J)	Counts
Fig. 9(a)	51	6	31	7	6
Fig. 9(b)	74	92	2993	858	205
Fig. 9(c)	99	31 224	100 000	65 535	16 548
Fig. 9(d)	83	11 287	17 077	8666	1833

4.3. Microscopic observation

For this micro-structural characterization, two portions of the damaged tube were used. The outside part (Fig. 9(a)) and the inside part (Fig. 9(b)) were cut from a damaged tube after pure tensile test failure (Fig. 5) by a circular saw PRACTYL. These portions measure about 20 mm × 10 mm in size.

Figs. 10(a) and (b) shown the propagation of the cracks in the matrix. This damage mode is related to the second zone of the stress/strain curve relative to the behavior of the filament wound pipe under pure tensile test. These matrix cracks create a phenomenon named Phenomenon of languets (Strips) as shown by the enlarging 937× (Fig. 10(b)). When the level of stress increases, an initiation of microscopic cracks to the fiber/matrix interfaces appears as shown by Fig. 11. An observation of the inside part of the tube shows that there is a propagation of cracks from the inside to the outside of the pipe. This propagation is shown in Fig. 12. The failure of fiber and the fiber/matrix debonding which are relative to Zone 4 of the tensile test can be clearly noticed (Fig. 13).

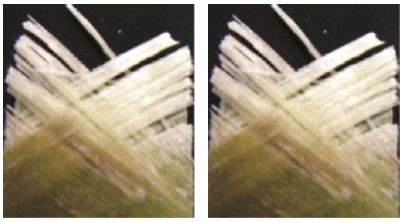

Fig. 9. Tow parts of a damaged tube: (a) outside part, (b) inside part.

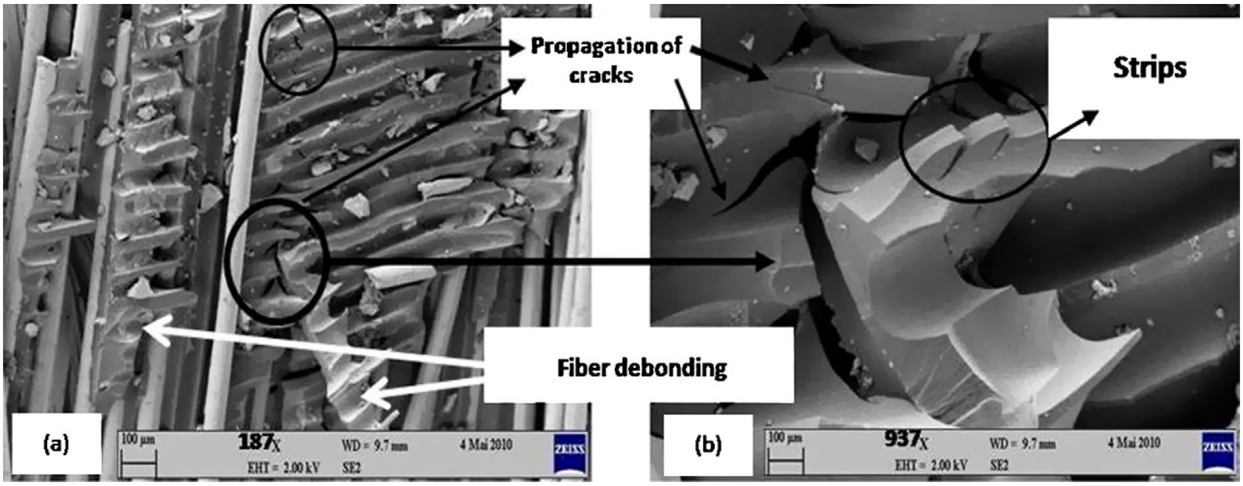

Fig. 10. Matrix cracking (enlarging: (a) 187×, (b) 937×).

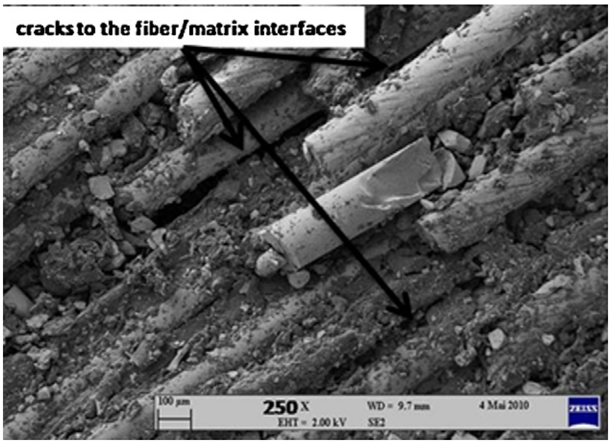

Fig. 11. Initiation of microscopic cracks to the interfaces fiber/matrix (enlarging 250×).

5. Conclusion

In this article, we studied the damage of filament wound glass/vinylester ±55° pipe under pure tensile test by acoustic emission and microscopic observation.

The tensile test divided the damage of the filament wound pipe into four steps: matrix cracking, microscopic cracks to the fiber/matrix interfaces, propagation of cracks in the matrix and fiber failure.

We observed that, for each step of damage, there is a special response of acoustic emission which corresponds to a specific waveform. We made recourse to SEM microscopic observation to identify the actual extent of the damage for each of the four steps. After thoroughly checking the microscopic observations, we conclude that these correlate to results found through acoustic emission.

We, therefore, contend that acoustic emission is a reliable method to control the behavior of the filament wound pipe.

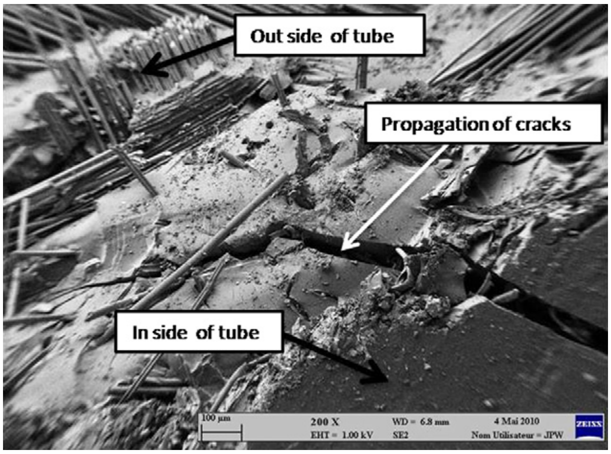

Fig. 12. Propagation of cracks from the inside to the outside of the pipe (enlarging 200×).

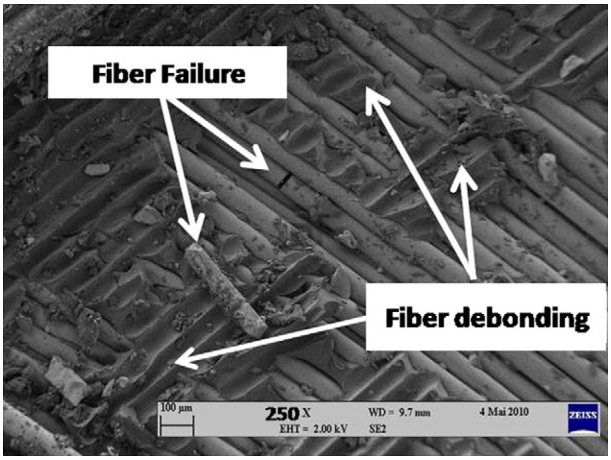

Fig. 13. Failure of fibers and fiber debonding from the matrix.

References

[1] J. Bai, P. Seeleuthner, P. Bompard, Mechanical behaviour of ±55° filament-wound glass-fibre/epoxy-resin tubes: I: Microstructural analyses, mechanical behavior and damage mechanisms of composite tubes under pure tensile loading, pure internal pressure, and combined loading, Composites Science and Technology 51 (1997) 141–153.
[2] L. Gemi, N. Tarakçioglu, A. Akdemir, S.Ö. Sahin, Progressive fatigue failure behavior of glass/epoxy (±75°) filament wound pipes under pure internal pressure, Materials and Design 30 (2009) 4293–4298.
[3] N. Tarakcioglu, Fatigue failure behavior of glass/epoxy ±55 filament wound pipes under internal pressure, Composites Science and Technology 65 (2005) 703–708.
[4] M. Martens, F. Ellyin, Biaxial monotonic behavior of a multidirectional glass fiber epoxy pipe, Composites, Part A 31 (2000) 1001–1014.
[5] P. Mertiny, F. Ellyin, A. Hothan, An experimental investigation on the effect of multi angle filament winding on the strength of tubular composite structures, Composites Science and Technology 64 (1) (2004) 1.
[6] S. Huguet, N. Godin, R. Gaertner, L. Salmon, D. Villard, Use of acoustic emission to identify damage modes in glass fibre reinforced polyester, Composites Science and Technology 62 (2002) 1433–1444.
[7] N. Godin, S. Huguet, R. Gaertner, L. Salmon, Clustering of acoustic emission signals collected during tensile tests on unidirectional glass/polyester composite using supervised and unsupervised classifiers, NDT&E International 37 (2004) 253–264.
[8] NF T57-518, Plastique renforcé au verre textile, Préimprégnés, Teneur en verre et en charge, Méthode par calcination Normalisation française, Octobre, 1987.
[9] D-2105-01, Standard test method for longitudinal tensile properties of “fiberglass” (glass-fiber-reinforced thermosetting-resin) pipe and tube, American Society for Testing Materials (ASTM) designation: D2105-01.
[10] E 1067-96, Standard practice for acoustic emission examination of fiberglass reinforced plastic resin (FRP) tanks/vessels, American Society for Testing Materials (ASTM) designation: E 1067-96.
[11] PCI-2 based AE system user’s manual, rev 3 part #: 6301 – 1000, Physical Acoustics Corporation, Princeton Junction, NJ, April 2007.
[12] E-1316-11, Standard terminology for nondestructive examinations, American Society for Testing Materials (ASTM) designation: E-1316-11.
[13] H. Nechad, Evaluation de l’endommagement et de la rupture de matériaux hétérogènes par ultrasons et émission acoustique : Estimation de la durée de vie restant, thèse à L’Institut National des Sciences Appliquées de Lyon, 2004.