Damage mechanism evaluation in pipeline steels using acoustic emission analysis

Sergio BUDANO\textsuperscript{1}, Giuseppe GIUNTA\textsuperscript{2}, Antonio LUCCI\textsuperscript{1}

\textsuperscript{1} Centro Sviluppo Materiali (CSM), Rome (Italy)
Phone +39 06 5055 760, s.budano@c-s-m.it; Phone +39 06 5055 298, a.lucci@c-s-m.it
\textsuperscript{2} eni SpA, gas&power division, San Donato Milanese (Italy)
Phone + 39 02 52031209, giuseppe.giunta@eni.com

Abstract
Acoustic Emission (AE) is one of the most advanced non-destructive techniques widely used for successfully monitoring of pressure vessels, chemical plants and bridges. The AE technique allows the initiation and propagation monitoring of defects, which are submitted to static or variable stresses and aggressive environment exposure. In this way AE allows to control the damage being developed in service life of mechanical components. Pipeline steels representative of conventional and modern gas pipelines have been therefore selected, which are steels grades API 5L X65, X80 and X100 respectively. For these materials many fracture mechanical test specimens have been provided for investigating both crack initiation and growth. The aim of the hereby presented activity is to investigate the suitability of conventional/classic Acoustic Emission parameters and frequency-domain features to discriminate among different failure mechanisms (brittle and ductile) and to identify crack growth. Two different AE systems have been used and are hereby identified as AE-Vigilant and AMSY-5. AE data have been analyzed showing that beside the Acoustic Emission Energy, Frequency parameters could be useful in discriminating the failure mechanisms.

Keywords: Pipeline steels, Fracture Mechanics, Structural Reliability, Acoustic Emission, Frequency Analysis, Wavelet Transform.

1. Introduction

Acoustic Emission has been identified as one of the most advanced techniques to increase the structural reliability of high pressure gas pipelines. Following this perspective, a research project was planned by eni gas&power division in order to define a real-time monitoring technique based on AE, proficient for Pipeline Health Integrity Monitoring (PHIM) [1]. Centro Sviluppo Materiali (CSM) also participated in this project, taking advantage of its experience in metallurgy and behavior of pipe steels, fracture mechanics, non-destructive control and structural assessment, as well as in the acoustic emission technique [2].

A study about the state of the art of AE monitoring procedures has been performed. In this respect standards like ASTM E1316, ISO 12716, ASTM E 650, E750, E1139, E569, E976, give the guidelines to detail the terminology, the sensors, the instrument, the procedure for monitoring the structures as well as the criteria for data interpretation. Such standards, however, give only general indications. For example, ASTM E1139 considers the exponential increasing curve of AE events as the key for indicating a severe damage rate. No suggestion to correlate the AE activity to the defect mechanism is mentioned. In recent years significant work has been undertaken in order to analyze the transient data collected by the sensors during the AE monitoring.

These studies could improve the knowledge about this tool for revealing the ‘nature of the defect’, or the damage mechanism due to ductile, brittle, or stress corrosion processes. Information concerning the relationship between AE and defect is a prerequisite to improve the reliability of the assessment procedure, to be applied in real-time monitoring of structures that are submitted to loads and/or corrosive conditions.

Ways to allow AE source discrimination could be obtained using the frequency analysis of waveform, and in particular by using Fast Fourier Transform (FFT), Wavelet Transform (WT), Continuous Wavelet Transform (CWT) and Choi-Williams Transform (ChWT) [3].

The use of “frequency analysis” approach is becoming a new frontier for acoustic source classification due to the availability of advanced tools that make this approach very quick and effective [4]. Recent literature has employed frequency analysis to interpret AE results e.g. acoustic emission events to recognize defect location against other signals [5], to identify and to classify the AE noise [6], to identify the damage mechanisms in galvanized coatings [7], or to identify the differences between AE waveform sources from elastic deformation zone, plastic deformation or collapse zone of small diameter subsea pipelines [8].

Regarding the development of projects focused to improve the safety of large diameter pipelines for gas/oil transport at high pressure, Petrobras has reported the AE activities carried out in recent years [9, 10].
The main results described after more than 20 years of activity in steels and pipeline AE monitoring, refers to the use of logistic models to evaluate the probabilities using standard AE parameters to correlate the fracture phenomenon.

Fracture mechanics tests, monitored using an AE sensor, have provided interesting results to relate the acoustic emission energy rate to the fracture mechanism operating during the tests: ductile and brittle fracture [1, 12].

Following these encouraging results, a further experimental lab activity was undertaken in order to investigate more deeply the waveform sound burst. The employment of Frequency Parameters allowed the identification with better confidence, of the process of fracture discovered through the acoustic emission source monitoring.

2. Experimental activities

2.1 Materials

An experimental activity has been set up aimed at reproducing the fracture mechanisms associated with ductile and brittle failure modes, for correlating the Acoustic Emission standard and advanced waveform parameters.

In the current investigation, 3 micro-alloyed steels were selected: API 5L grades X65, X80 and L690M or X100M, according to ISO3183. Micro-alloyed steel plates were obtained by means of a suitable combination of chemical composition and thermo-mechanical treatment in order to obtain the strength, toughness and weld ability requirements. The LSAW OD=48” pipes were manufactured through UOE process starting from a hot rolled plate characterized by a microstructure consisting mainly of ferrite and pearlite.

The manufacturing process promotes the segregation of elements at mid thickness originating a non homogeneous layer. As a consequence the interface between the layer and the matrix is brittle and leads failure with a relatively low energy when the component is subjected to very high stresses. Lower temperature tests shows an increase of this phenomenon. The X65 steel grade, being the most dated among the grades investigated, is more liable to this phenomenon. In any case, the global fracture behavior of the steel grades X65, X80 and X100, is mostly ductile at Room Temperature.

2.2 Acoustic Emission Systems

The following two systems have been used for the work hereby presented:

- Vigilant - AE (Balrue AE Monitor, UltraElectronics), Figure 1.
- AMSY-5 (Vallen), Figure 2.

The two systems are different in terms of data recording and collecting, and applicability. Vigilant unit records standard AE parameters and is suitable for long-term monitoring. AMSY-5 system has the capability of collecting Acoustic Emission Waveform. A detailed description of the two systems is reported below.

**Vigilant-AE**

Vigilant-AE is designed for stand-alone and long time monitoring. This system has been used during the experimental activity reported in [1, 12]. It features 24 AE BNC connector input channels located in the rear panel. In the front panel 10 BNC connector no-AE channels allow collection of DC input signals in the range ±10V. Each AE data channel is connected to the external preamplifiers, (40dB fixed gain and band-pass filter) and to the AE piezoelectric sensor. A real time electronic core allows collection of AE waveforms, their analysis, and to evaluate most of the AE standard parameters.

The digitalized data are stored in the internal magnetic support (standard HDD), in ASCII file format. A standard Ethernet connection is available in the front panel useful to connect an external PC for initial set-up and for data file downloading and post-processing. Data files are related to LEB (Leading Edge Burst) and PD (Peak Detected) bursts. LEB files contain the data parameters elaborated from the burst considered useful for source location according to threshold amplitude level, max delta T, rise time, waiting time, etc. as defined in the set-up parameters. PD files contain the rejected burst, available for further data elaboration.
These files could be useful in the case of continuous acoustic emission activity such as pressure leak failure, i.e. rejected AE bursts could be lower than the threshold amplitude level.

**AMSY-5**

This apparatus is a 12 channels configuration and has been used during the activity hereby presented [13]. SEB tests have been instrumented by VS75-SIC and VS 150-RIC AE sensors at RT and T=-20°C respectively.

Some AE channels are available to collect DC signals from other transducers related to physical parameters like pressure, load, etc. The performance allows digitalizing the AE transient collected during the monitoring. Advanced software, developed by Vallen, is available for data processing in term of AE standard parameters, source localization, frequency analysis etc. This last feature has been the key for selecting the AMSY-5 system.

![Figure 1. AE apparatus VIGILANT (UltraElectronics).](image1)

![Figure 2. AE apparatus AMSY-5 (Vallen).](image2)

### 2.3 Setup and Test description

The experimental activity was carried out in two steps; in the first step Vigilant unit was employed to record and collect AE data, while in the second AMSY-5 system was used to collect both the AE standard parameter and the complete AE waveform.

An *Instron* servo-mechanical testing machine, with the maximum load equal to P_{max}=100kN, has been used (Figure 3). The servo-mechanism provides a movement of the actuator with very low level of background noise, compared to the servo-hydraulic testing machine where the noise generated by the dither signal inside the servo-valve is so high as to inhibit the use of the AE technique. Signal data such as load, stroke, and clip gage displacement have been collected during the tests directly by the *Instron* controller. The tests have been performed with cross-head speed equal to V=0.01mm/sec.

Bending tests using Single Edge Bend (SE(B)) specimens, fatigue pre-cracked, extracted and machined from the above mentioned OD 48” pipes have been performed. Some tests have been carried out up to failure, while some others have been interrupted at the occurrence of a AE Hit characterized by a significant amplitude (i.e. A>75dB). Bending tests have been carried out according to the toughness test ASTM E1820.

To investigate different fracture mechanisms, the mechanical test has been performed at Room Temperature (RT) and at Low Temperature (LT) T=-20°C. Low temperature tests were carried out by filling nitrogen liquid inside an insulated box arranged to contain the SEB specimens. The test temperature measured near the notch has been controlled by a type K thermocouple. Each SEB specimen has been instrumented by one AE sensor. A clip gage has been installed at the mouth of the notch to measure the crack opening, a measure necessary to evaluate fracture mechanics parameters, Figure 4.

During the fracture mechanics test, when the triaxial stress is high, the brittle fracture related to the failure of the interface layer-matrix appears characterized by a pop-in. Based on this considerations some bending tests have been carried out up to collapse, while other tests have been stopped after and before the first Acoustic Emission burst with amplitude over 75dB. The current work present the results obtained in the experimental tests summarized in Table 1.

Metallographic investigations of the SEB specimens have been also carried out on the surfaces at the half thickness and etching the steel surface by using a Nital 2% solution.
3. Results

3.1 Room Temperature Tests

The test at room temperature has been carried out on X65 material following this sequence:
- stop at failure
- stop after 1st hit A>75dB
- stop after 1st hit A>75dB
- stop before 1st hit.

An example of the results obtained from the tests at room temperature (X65 1-6, Table 1) carried out up to failure/collapse can be observed in Figure 5. During the loading phase, the AE sensor detects the hits acquired by the AMSY-5 system. When maximum load is reached the bending test is stopped, and the specimen is removed from the machine and heated (blue oxidation) to put in evidence the ductile stable crack propagation located at the crack tip. Afterwards, the specimen is cooled in liquid nitrogen and is quickly opened applying a bending stress. This fracture is very brittle and the surface morphology showed a good brightness and contrast. This procedure is relevant to comprehend the relationship between the AE data and the damage that has occurred in the specimen. Moreover, AE data are correlated to the loading behavior and to the fracture morphology.

Nevertheless some SEB tests have been stopped just after the emission of the first hit with amplitude A>70 dB. Then, these specimens have been machined, removing the material until the middle thickness close to the crack, where the stress triaxiality is higher. In this section the probability to discover the early stage of the damage is higher. A typical fracture surface of X65 specimen is reported in Figure 5.

This image shows the presence of a metallic separation in the central area; the path of this defect is perpendicular to the main surface crack. The graphic of Figure 5, representative of the “Load-AE events vs
Test Time", highlights at least three pop-in events. These events can be related to the brittle fracture and the formation of the separation. The instant time of the fracture is often announced by an audible noise.

The acoustic emission technique is able to predict this damage with many events revealed before the brittle fracture. At the failure time some AE hits have been detected up to the amplitude $A \approx 95\text{dB}$ but these transient events in saturation cannot be analyzed. Many AE hits revealed with amplitude $A > 70\text{dB}$ could be attributed to the crack propagation phenomenon.

Figure 5 – Specimen X65-1-6. Surface crack (left) and acoustic emission activity recorded (right).

Tests have been carried out at room temperature (RT) and stopped at the first AE hit with significant amplitude $A > 70\text{dB}$. The hit amplitude greater than 70 dB could be related to the crack formation. Figure 6 shows the plot “Load-AE Amplitude vs Test Time” of the test id: X65-1.1, stopped just after the hit amplitude $A > 90\text{ dB}$. Similarly, Figure 7 shows the test id: X65-1-3.

Further test, id: X 65-1-5 was used as a check i.e. no crack growth. Before the emission of AE hit with amplitude $A > 70\text{dB}$ the test has been scheduled and stopped, see Figure 8. In this case all AE hits have been lower than $A < 60\text{dB}$. The comparison of these three trials must be considered with the load levels at the stop are comparable: $P \approx 16\text{kN}$. Metallographic micrographs in Figure 9 show the macro aspect of the crack tip of the mentioned SEB specimens.
Figure 8 - Specimen id: X65-1-5. Load-AE amplitude vs time. Test stopped before the presence of hit with amplitude A<70dB. T°=RT.

Figure 9 – Macro feature of crack tip of SEB specimens, id: X65-1-1, X65-1-3 and X65-1-5. In evidence: V notch and the fatigue crack path.

Samples have been observed by light microscopy at x200 and x500 magnification at the crack tips. The results highlighted what follows:

Test id: X65-1-1, Figure 10. Stable ductile propagation is present after the fatigue notch tip, with length $\Delta a \approx 100 \mu m$. The crack growth has a zig-zag path, typical of the coalescence of different cracks generated from the fracture of brittle constituents, such as the pearlite phase.

Test id: X65-1-3, Figure 11. The crack propagation results smaller and about: $\Delta a \approx 20 \mu m$. Near the crack tip the optical micrograph shows a void created by the fracture of the pearlite. It is localized in the highly stressed volume. During the loading test the fracture grows step by step. The fracture mechanism is referred to the coalescence between the main crack and the voids generated by the fracture of the pearlite phase.

Test id: X65-1-5, Figure 12. The observations done at higher magnification (x500) show no new cracks at the crack tip, only strain markings are apparent.

3.2 Low Temperature Tests

The low temperature tests has been carried out at T= - 20°C using X65 and X100 material and following this sequence:

- stop at failure
- stop after 1st hit A>75dB
- stop after 1st hit A>75dB.
A proper AE sensor (V150-RIC-40dB by Vallen) suitable for low temperature (up to T0-60°C) was used. Eight tests have been carried out. Four up to failure and four closing the tests just after the first AE hit with amplitude A>70dB. Typical aspects of the surface crack of X100 steel grade after the tests are shown in Figure 13. The load curve doesn’t show any pop-in event. The fracture surface is free from separation. The test temperature equal to T=−20°C is not low enough to promote brittle fracture, even localized. Fracture behavior of X100 steel is in the ductile regime as well as the X65 steel.

The results obtained from the tests carried out up to failure are resumed in the case shown in Figure 13. During the loading the main cracks grow and the AE sensors detect many hits. Significant AE activity has been recorded before the maximum load. AE reveals many hits that could be associated with the ductile stable crack propagation, Figure 13 (shown by black arrow). The highest amplitude hit (A≈90dB) has been detected close to the maximum load, Figure 13 (shown by green arrow).

![Figure 13](image13.png)

More certainty has been provided by the metallographic investigation, carried out for the SEB tests stopped after the first AE hit with amplitude A>70dB, see Figure 14. The micro observation focused at the bottom of the fatigue pre-crack reveals the presence of an early stage of crack propagation with dimension equal to Δa=40μm, see Figure 14. Around the crack tip some voids are present too. The morphology of the discovered cracks is not related to the shape path crack ‘zig-zag’ as shown in Figure 10, where the crack coalesced step by step joining the voids. In fact, in this case, AE revealed only one AE hit, Figure 14.

The AE hits detected at the low load should be associated with the rupture of the oxides that were formed on the fracture surface of the fatigue pre-crack. In fact X100 SEB specimens were already pre-cracked at least from a year, when the experimental activity was closed and reported in [12]. Analyzing the behavior of AE activity collected during the test id X100-H, Figure 15, a high density of AE hits appears at the start of loading, confirming the assertion on the oxidation of the fracture surfaces.

From the test id X100-H interesting results have been obtained. In fact from the micrograph some voids are revealed near the crack tip.

The crack grows by coalescence from crack to void. The path drawn from the crack tip to the void is equal to Δa=30μm. So, if AE hits with amplitude A>70 dB can be related to the crack propagation, it is reasonable to associate the AE hits in the range amplitude of A=50÷60dB with the creation of the voids. Interesting results also come from the analysis of the SEB test id: X65-1-9. The specimens extracted from the pipe wall of steel X65 were machined and pre-cracked just before the static SEB test.

In fact no intense AE hits have been detected at the start, see Figure 16. The crack tip examined by micro-optical observation shows a very interesting aspect: the presence of a pearlite island, and crack propagation due both to the coalescence of the main crack and to the defects produced by the fracture of the brittle pearlite, see Figure 16. The graphic, recorded during the loading SEB test, reports many AE hits with the amplitude in the range A=50÷60 dB. Then, there are two
AE hits with amplitude A>65dB (orange circles) and one AE hit with A>70 dB (blue circle) that matched the end test criterion. In these tests it’s also correct to relate higher amplitude hits A>70dB to the crack propagation and the other AE hits lower to the microscopic damage of the pearlite phase.

Figure 14 – Id: X100E. Left (x200). Presence of a micro-crack of Δa=40μm at the fatigue crack tip and the relationship with the acoustic emission hit of amplitude A>70dB. Right. Graphic of Load-AE Hit amplitude vs Time. T=−20°C.

Figure 15 - Id: X100-H. Left (x200). Presence of a micro crack of total length Δa=80mm at the fatigue crack tip and the relationship with the acoustic emission hit of amplitude A>70dB. In evidence the voids and the coalescence between the void and the main crack. Right. Graphic of Load-AE Hit amplitude vs time. T=−20°C.

Figure 16 – Id: X65-1-9. Left (x500, x1000). Presence of micro cracks in pearlite areas localized at the bottom of the fatigue cracks and the relationship with the acoustic emission hit of amplitude A>70dB. Right. Graphic of Load-AE Hit amplitude vs time. T=−20°C.
3.3 AE waveform analysis

The classification of the signal waveform based on the analysis in frequency results in a powerful method to interpret the AE roots [3]. The data reported in Figure 17, referring to a test where AE has detected the crack initiation (id: X65-1-3, Figure 7 and Figure 11) highlight that the frequency-domain contents evaluated in term of Peak Frequency (FMXA) and Frequency Centroid (FCOG) do not provide useful indications to suggest a clear and unequivocal classification of AE source mechanisms. In the same diagram is noticeable that no relationship exist between AE hit amplitude and frequency parameters FMXA and FCOG.

Most of FMXA and FCOG data are located in the range of frequency $\Delta f = 80 \div 100$ kHz according to sensor characteristics. In fact at room temperature the Acoustic Emission of the SEB specimens has been monitored by VS75-SIC-50dB sensor. The band-pass filter was selected: range from 35 to 500 kHz. Probably the frequency bandwidth of the AE waveforms should be focused near $f = 75$ kHz, though the band of the sensor is in the range $\Delta f = 25 \div 125$ kHz at 15dB of response function [13]. Higher FCOG values $>160$ kHz are related to hits with amplitude $A = 54$dB and $A = 68$dB as highlighted in the Figure 17.

The AE hit with the highest amplitude $A = 77$ dB, indicated by the blue arrows in Figure 17, has been ascribed to the crack damage, as shown in Figure 11. The trend coming from a single waveform analysis is not so much clear.

![Figure 17 - Id: X65-1-3- Peak frequency (FMXA) and Frequency Centroid (FCOG) of the AE waveform hits detected during SEB test at R.T.](image)

At low temperature tests $T = -20$ °C, the VS150-RIC-40 sensor has been selected. However the maximum sensitivity of this sensor is at $f = 150$ kHz, in a larger band from 90 to 500 kHz the scatter of the performances is in the range of 15 dB response function [13]. The same frequency analysis has been done considering the AE transient collected during the SEB test id X100-H where a good relationship was found with the damage, see Figure 15. At such low temperatures $T = -20$°C, the trend of peak frequency FMXA and Frequency Centroid FCOG parameters seems to be different. At lower AE hit amplitude the FMXA is lower than the FCOG. Increasing the AE hit amplitude, i.e increasing the damage, means the frequencies have a tendency to overlap as it appears at the final point with $A = 75$ dB, see Figure 18.

The frequency analysis of all the AE transients collected in the SEB test id: X100-G carried out and stopped over than the maximum load, shows that the FCOG parameter (close to the maximum load near the collapse) is increasing (see Figure 19).

Further and deeper frequency analysis, in terms of wavelet transform (WT), has been predominantly considered at EWGAE 2010 in Vienna. However, no evidence of a relationship between the wavelet parameters and the damage was clearly shown [14, 15]. WT’s of many SEB tests have been found with redundant patterns of AE hits collected from low load up to the load near the collapse of the specimen. Such AE hits were not correlated with the same acoustic source mechanism.
The wavelet transforms of the transients collected during the SEB test id: X65-1-6 (see Figure 5) shows redundant patterns in Figure 20 and Figure 21. The colour pattern and the intensity represent the different transient amplitudes: A=66 dB and A=71 dB.

Figure 18 - Id:100-H. Peak frequency (FMXA Blue dots, Frequency Centroid (FCOG) Red dots) vs AE hit amplitude of the AE waveform hits detected during SEB test. T=-20°C.

Figure 19 - Id:100-G. Peak frequency (FMXA and Frequency Centroid (FCOG)) vs Load of the AE waveform hits detected during SEB test. T=-20°C.

Figure 20 - SEB id: X65-1. Wavelet transform of AE hit with amplitude A=66dB.

Figure 21- SEB id: X65-1. Wavelet transform of AE hit with amplitude A=71dB.

4. Conclusions

The aim of the present paper was to investigate the suitability of conventional/classic Acoustic Emission parameters and frequency-domain features to discriminate between different failure mechanisms (brittle and ductile) and to identify crack growth. The AE Hits have been recorded, analyzed and elaborated in the frequency domain.

The AE hits analysis, acquired in the monitoring of SEB specimens submitted to bending stress in the laboratory, led to the following conclusions:
• AE hits amplitude standard parameter is useful to identify the acoustic source mechanism in SEB specimens. The threshold of $A \approx 70$ dB refers to the point above which fracture was brittle. Below the threshold fracture occurred by a ductile mechanism.
• Frequency analysis of the AE transients elaborated in terms of FMXA and FCOG does not allow to discriminate between the acoustic source mechanisms, considering a single AE hit.
• The trend of the FCOG, investigated during a whole SEB test up to the collapse of the specimens, seems to be useful to predict the failure. The FCOG reveals the incipient failure by increasing of the frequency pattern.
• The WT analysis shows a frequency pattern of the transient for each specimen. The small dimension of the specimens (thickness=15mm) and the consequent short time wave reflection on the surfaces, could hide interesting frequency information. Further studies on this issue could be performed considering large or full scale samples.

5. References

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