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THE USE OF ACOUSTIC EMISSION IN THE CHARACTERIZATION OF STEEL PIPELINE DAMAGE

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Abstract *The behavior of Ultra Low Carbon Bainitic (ULCB) and High Strength Low Alloy (HSLA) steels has been analyzed when test specimens are loaded in controlled laboratory conditions. The loading procedure has been carried out with the use of standard tensile test equipment, and also monitored with the use of Acoustic Emission (AE) techniques. Even though AE has proved to be sensitive, concerning the damage mechanisms during early stages of load application, some unexpected anomalies in the obtained signals indicate the need for further testing. Metalography has been used to characterize the structure of the material and to identify changes which have occurred in the region of failure. As HSLA steels are typically used in pipeline applications and ULCB are currently being developed as an alternative to increase the yield limit, it is hoped that the present study should help to understand the failure mechanisms associated with this important application.*

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Keywords: *Acoustic Emission (AE), Damage, ULCB steels, API steels.*

1. Introduction

High Strength Low Alloy (HSLA) steels exhibit high mechanical strength, good weldability and low hardenability complying with most strict service requirements. The traditional production of these steels for the pipeline industry with the use of controlled rolling will provide a ferritic-perlitic microstructure with the yield limit reaching the 483 MPa (70ksi) (Vasconcelos 2000). Even though these steels possess very interesting properties, welded joints are not so good. In order to overcome this problem a new class of steels, the so called Ultra Low Carbon Bainitic (ULCB) steels, is presently being developed. The microstructure of ULCB steels can be reached by means of accelerated cooling used in conjunction with an optimized thermo-mechanical process, and with proper control of the chemical composition.

The previously mentioned considerations can be conveniently analyzed with the help of acoustic emission techniques as shall be presently seen in the following text.

2. History

2.1. Bainite morphology

The bainite morphology could be described as a ferrite and carbide particles (cementite) association, where carbide appearance is due to the transformation temperature (Batista and Souza, 2002).

A nomenclature for bainite in ULCB steels, cited by Edmonds and Cochrane (1990), is:

(a) Type I: is formed between 873-773K (600-500^{o}C), consisting of carbide-free bainitic laths and interlath martensite;

(b) Type II: is formed between 673-773K (450-500 ^{o}C) and has the upper bainite form with continuous cementite layers between the lath;

(c) Type III: is formed around the martensite transformation temperature M_s and has a cementite morphology and orientation similar to that of high-carbon lower bainite despite of almost identical upper bainite crystallographic characteristics.

A ULCB typical transformation structure is globular bainite that consists in a classical forms mixture of bainite with little martensite island with retained austenite, A-M. This microstructure is technologically important as a base of creep resistant steels.

2.2. Microstructure and Properties Relationship

The classic studies of structure-properties that relates yield stress σ with the bainite colonies average size, D, as in Hall-Petch equation, where $\sigma \propto D^{-1/2}$ (Dieter, 1986), did not foresee the important influence of mean lath width and dislocation density for the ULCB steels.

Garcia et al (1990) observed that the two larger contributions for the ULCB strength increase were due to dislocations and solid solution contribution.

An approach that deals with slip bands consider active slip systems in the bainite that can be parallel to the lath axis or oriented with some inclination to this axis.

An alternative to the classic model, proposed by Brozzo (apud Edmonds and Cochrane, 1990), relates σ with the slip band length, geometric parameter M, function of D and of the lath mean size, were $\sigma = M^{-1}$.

It is clear the dependence of the mechanical resistance to characteristic sub grain mechanisms for bainitic steels. To steels that present globular bainite, the increment in the ultimate tensile strength, compared with perlitic/ferritic steels, can appear from internal tensions in ferrite matrix resulting from the volume change due to A-M formation (Edmonds and Cochrane, 1990).

2.3. The Acoustic Emission Technique

AE is the technical term for the noise emitted by material and structures when they are subjected to stress. Types of stresses can be mechanical, thermal or phase transformation. This emission is caused by the rapid release of energy within a material due to events such as crack formation and the subsequent extension occurring under an applied stress, generating transient elastic waves which can be detected by suitable transducers. Hence, acoustic emission may be described as the “sound” emanating from regions of localized deformation within a material.

AE is a passive listening technique which is extremely sensitive and can detect defects such as a few atoms movements. AE can thus provide the early information on defect/deformation in any material or structure. The process of generation and detection is illustrated in Figure 1 (Maia, Medeiros, Bracarense, 2003).

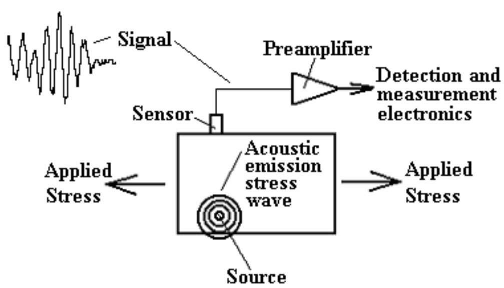


Figure 1. Basic principle of the acoustic emission method

Plastic deformation is the primary source of acoustic emission in loaded metallic materials. The initiation of plasticity, particularly at or near the yield stress, contributes to the highest level of acoustic emission activity observed on a stress-strain (load-elongation) curve. Plasticity also contributes to the highest levels of activity for count rate or root means square (rms) parameters of amplitude versus strain.

Most acoustic emission occurs around the yield stress of a material. However, it has been reported that in some instances high levels of acoustic emission activity take place before the yield stress. This is attributed to local plastic yielding and demonstrates that acoustic emission provides a good technique for detection of the onset of microyielding in certain materials.

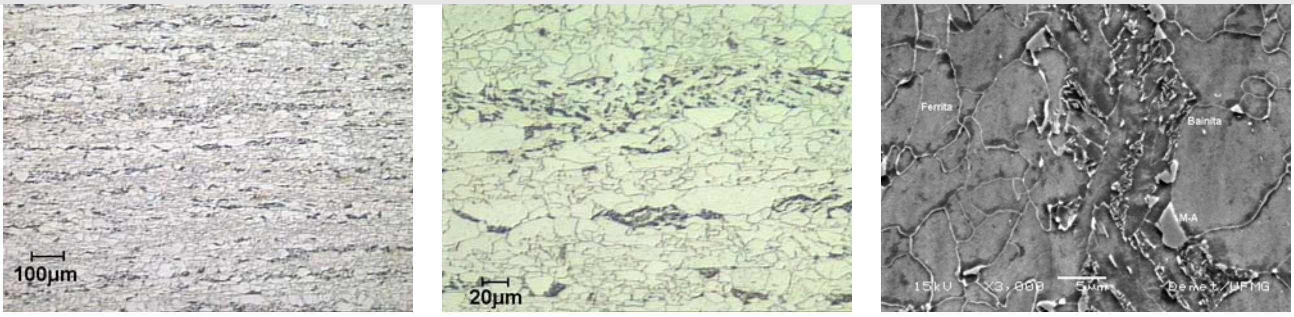
3. Materials and Methods

3.1. Materials

For the development of the study, samples of a ferritic-bainitic (bainitic called “X" in graphics) steel pipe with wall thickness of 16,0mm were removed. This material is from a project related with a national production and application of the API 5L X80 steels (Kojima, Sampaio and Bott, 2002). The original microstructure presents lamination texture with “pancked” ferrit grains, with approximately 9μm width and 19μm length, enlarged bainit bands with A-M constituent and cementite absence Fig. 2c.

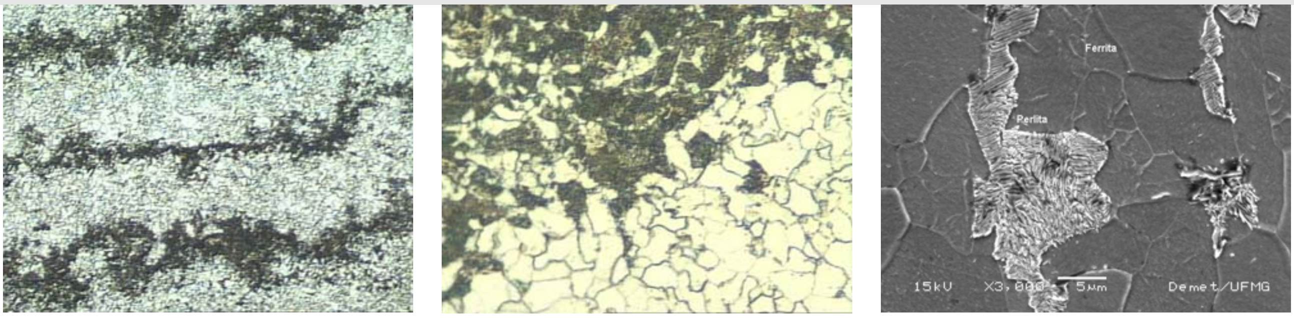
The ferritic-perlitic (perlitic called “U” in graphics) steel sample is part of an API 5L B degree plates lot with 16,0mm thickness used in API 5L X70 pipes production. Although the steel class definition for API standard (API, 2000) was done only after the pipe forming procedures, the plate was used to represent perlitic material behavior under the conditions in study. The material microstructure presents typical laminated texture, with “pancked” ferrite grains with approximately 15μm width and 29μm length. The perlite presents fine lamellas, Fig. 2f.

Bainitic steel



a) 100x b) 500x c) Bainite and A-M detail - 3000x

Perlitic steel



d) 100x e) 500x f) Perlite detail - 1000x

Figure 2. Original steels microstructures.

The chemical composition of the steels in study is presented in Table 1.

Table 1. Steel Chemical Composition (in % of weight)

Material \ Element	C	Si	Mn	P	S	Cr	Ni
Perlitic	0,121	0,260	0,920	0,014	0,008	0,000	0,007
Bainitic	0,050	0,260	1,720	0,019	0,008	0,210	0,040
Material \ Element	**Al**	**Cu**	**Nb**	**Ti**	**Mo**	**V**	**B**
Perlitic	0,002	0,008	0,006	0,005	0,000	0,004	0,000
Bainitic	0,051	0,013	0,058	0,011	0,150	0,005	0,000

4. Methods

For the test a cylindrical sample of the material was manufactured following the steels rolling direction, according to ASTM E 8M (ASTM, 2003) standard Figure 3. The tests were performed in an Instron Floor-Model TTDML 100kN machine with strain rate of 8.3×10^{-6}m/s (0.05cm/min) and the data collected in a graphic register. The cp X80-1-TR test was done with strain rate of 16.7×10^{-6}m/s (0.1cm/min) and the cp X80-3-TR was submitted a load/unload cycle before yield stress.

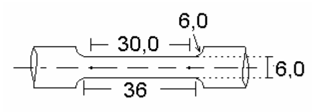


Figure 3. Tensile test sample

The fractured samples were photographed and the fracture surfaces observed in a scan electronic microscope SEM.

5. Results and Discussions

The stresses x strain curves obtained in tensile tests are presented in Fig. 4 and the corresponding data in Table 2.

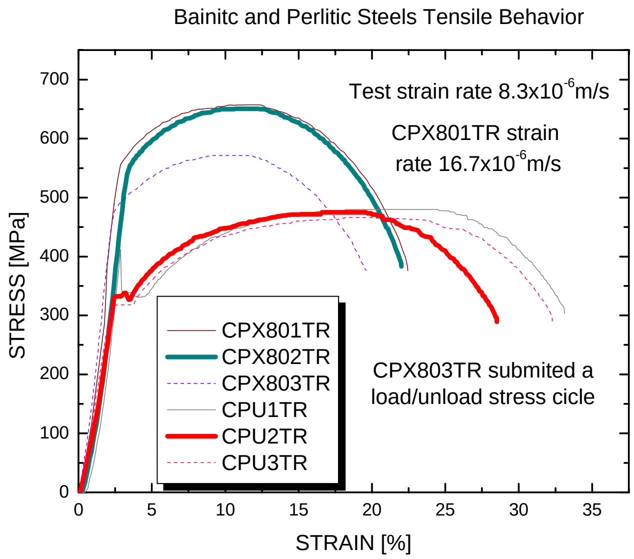


Figure 4. Stress x Strain curves

Table 2. Mechanical properties from the steels in study

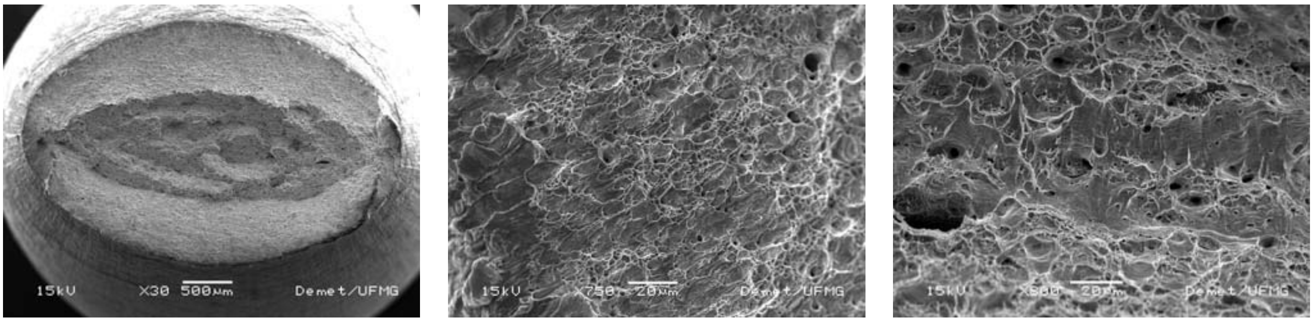
Steel	L_0 *[mm]*	σ_y *[MPa]*	*UTS [MPa]*	σ_r *[MPa]*	*ΔL%*	**RA%*
Bainitic	30.0	567	653.5	386.5	21.5	67
Perlitic	30.0	356	474	296.3	31	64

*($RA = \dfrac{(S_f - S_0)}{S_0} 100 \text{ where } S_f = \pi \dfrac{(D_1 . D_2)}{4}$)

Figure 5a presents a typical fracture of a bainitic steel sample with ductile behavior. As can be observed, the fracture appears to occur by dimples mechanism, also verified by Lima, Bott and Gomes (2003) for these steels.

The tested samples present elliptic fractures with mean percentile difference of diameters around 49%. The fact of the straight section were not circular, points out the anisotropic character of the deformation in that case and can indicate that the deformation of the material happens from different behavior between the ferrite bands and the bainite and A-M one, as told by Chae et al (2000).

Chae et al (2000) described a similar behavior in HY100 steels, where the ferrite bands present equiaxiated dimples, as in Fig. 5b, and the bainite bands present elongated dimples, mainly in the intersection of the bands, where also happens many microvoids, similar behavior with the presented in Fig. 5c.



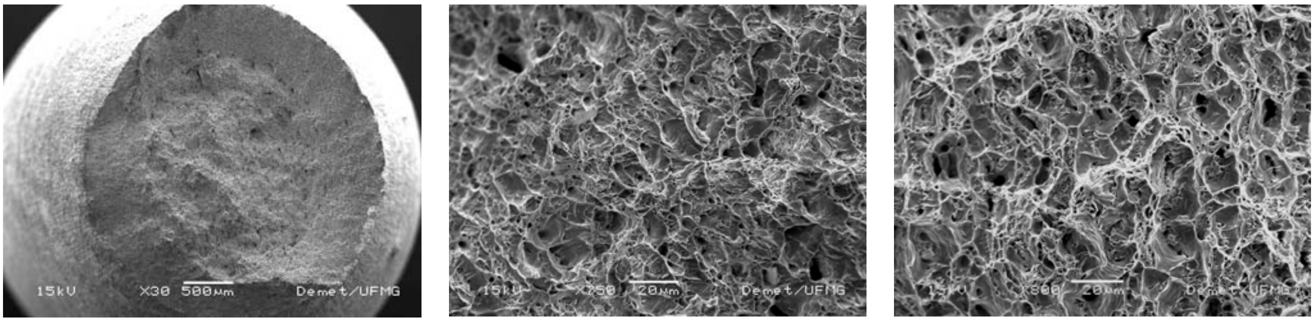
a) Fracture face from a tensile sample – 20x

b) Fracture appearance from the sample border - 750x

c) Fracture appearance from the sample center - 800x

Figure 5. Typical fracture of a bainitic steel sample

Figure 6 presents the ductile fracture characteristics of the perlitic steel with the presence of dimples. The samples did not present fracture surfaces in elliptic shape, with a mean percentile difference around 3.5% between diameters. The smallest difference between the samples diameters suggests that the perlitic steel had isotropic deformation behavior, like described by Lima Bott and Gomes (2003) for another perlitic steel.



a) Fracture face from a tensile sample – 20x

b) Fracture appearance from the sample border - 750x

c) Fracture appearance from the sample center - 800x

Figure 6. Typical fracture of a perlitic steel sample

Figure 7 and Figure 8 present the material acoustic activity (counts and average frequency) during tensile test. It is observed that even before the defined yield for the engineering standards (σ = 0.2%) the material presents intense acoustic activity.

By dislocations point of view this is a "very macroscopic" value for yield beginning. Dieter (1986) has mentions that for special tests with strain levels of 10^6 order in single crystals, the real elastic limit is smaller than the established in the standards. This approach indicates that before the macroscopic yield, foreseen by engineering standards, movement dislocations and located plasticity already happens. This fact was told by Moorthy, Jayakumar and Raj (1995), where great picks of acoustic activity before the macroscopic yield were interpreted like inelastic and plastic microstrain occurrence, attributed to the dislocations generation by sources interior to the grains.

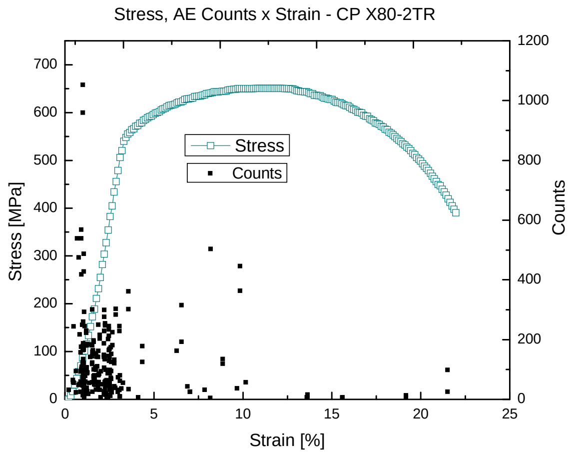
The presence of several counts picks close to the area of the macroscopic yield was related to dislocations sources in grains boundary activated by pile ups (Moorthy, Jayakumar and Raj, 1995).

The same authors mention that the counts fall of AE signs with stress increases can be related to the change in gauge frequency of the signs that commits the efficiency of the observation. Bohlen et al (2004) say that the fall in the acoustic activity after the yield is due to the increase in dislocations density and fall in the free medium course.

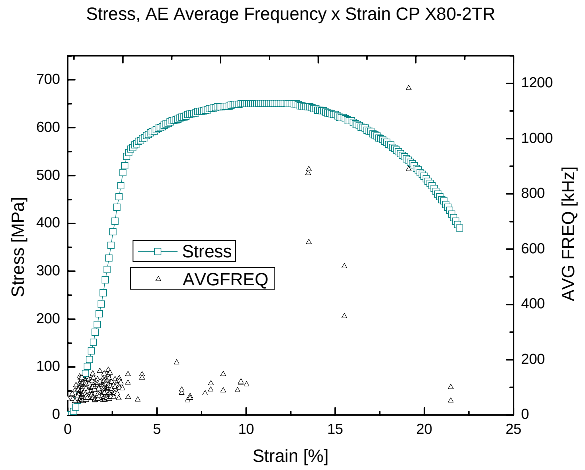
In a point of the material, great number of accumulated dislocations breaks the barrier that stops them and move in avalanche with smaller tension rates and larger strain rates. The great number of dislocations in movement runs over the subgrain structures and grains boundary opening micro cracks that moves and are stopped in subgrain and/or grain boundaries and/or dislocations cells, the movement is in steps.

The strain in this stage is plastic and uniform in all the samples extension. Some dislocations get to win the obstacles into the grain and they dash in the grains boundary. The strain levels grow continually and the tension levels grow in smaller rates.

In mixed structures, as the studied here (ferrite-perlite and ferrite-bainite-A-M), the description is applied to each structure (band) because each one of them has different strain behavior. The ferrite, soft and ductile, should deform continually with defined yield point in lower loads than the neighbors (DeArdo, 1992) (Cota, Barbosa and Santos, 2000).

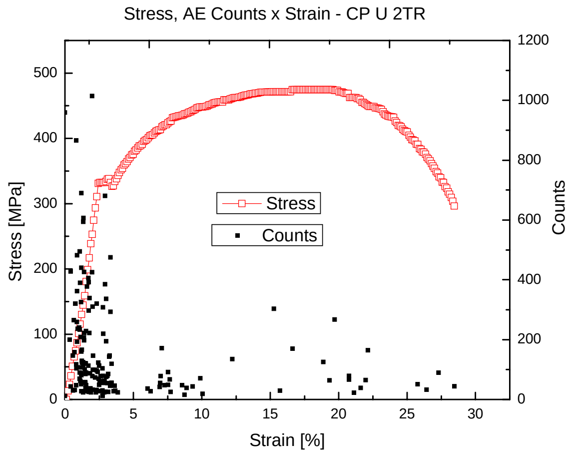


a) Stress, AE Counts x Strain to bainitic steel

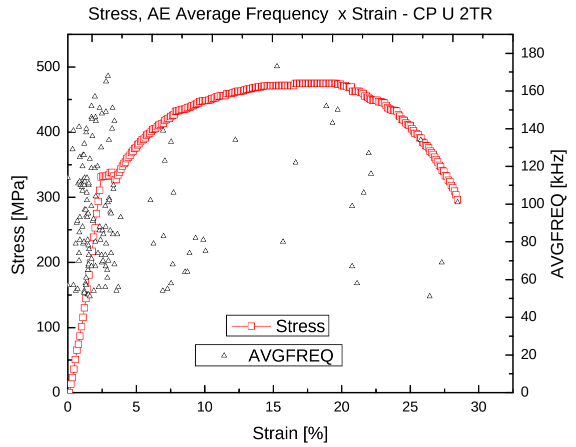


b) Stress, AE Average Frequency x Strain to bainitic steel

Figure 7. Variation of Stress, Counts and Average Frequency *x* Strain to bainitic steel.



a) Stress, AE Counts x Strain to perlitic steel



b) Stress, AE Average Frequency x Strain to perlitic steel

Figure 8. Variation of Stress, Counts and Average Frequency *x* Strain to perlitic steel

The bainite, as a kind of ferrite is ductile, but has many obstacles to the strain development (A-M islands in a matrix with high dislocation density). It resists to the deformation up to great loads while the neighbor ferrite deforms (yields) and reduces the band width compared to the original. This fact leads to sample narrowing in a diameter direction more than in the other (anisotropic deformation that gives the final elliptic form) (DeArdo, 1992) (Cota, Barbosa and Santos, 2000).

The perlite is more fragile with higher yield loads than the ferrite. The interface between them try to stay together, but the different deformation behavior promote discontinuity (dimples) that goes to separate the two bands (DeArdo, 1992) (Cota, Barbosa and Santos, 2000).

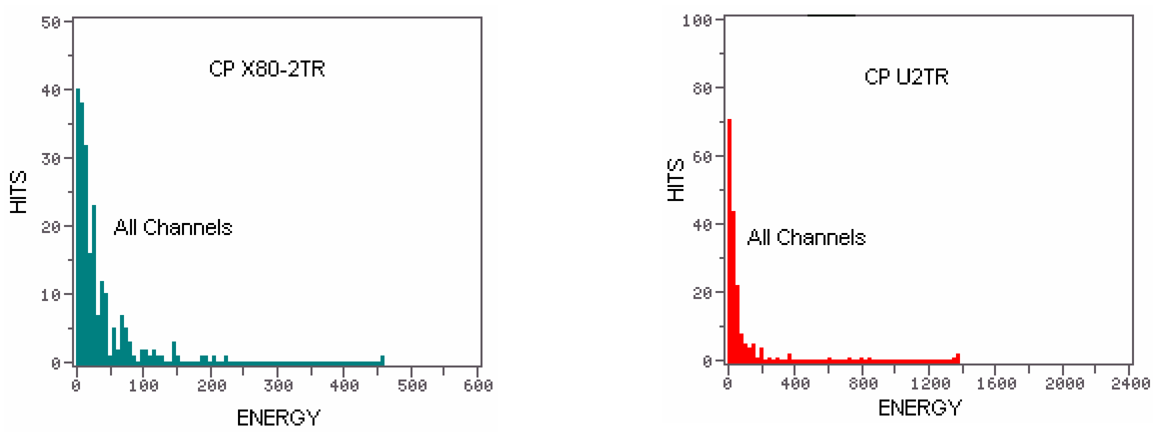
The perlitic steels are conventional steels, quite used in pressure vessels fabrication and pipelines under deformation gradients. This category of steels was studied with the objective of establishing accept/reject patterns as a function of the magnitude of the signs of AE observed during operation (Maia, Medeiros, Bracarense, 2003).

The BRASITEST criterion, for instance, establishes quantitative values for the analysis of the AE data based in the energy behavior during the test. Table 3 show the accept/reject criteria.

Table 3 - BRASITEST accept/reject Criterion (Maia, Medeiros, Bracarense, 2003)

Energy Value Gauge	**Signals Quantity (Hits)**	**AE Source Class**	**Recommendation**
0 to 1,000	Among 0 and 30	D	Irrelevant
0 to 1,000	More than 30	C	Register
1,000 to 2,000	More than 0	B	Inspection
2,000 to 10,000	Among 0 and 2	B	Inspection
2,000 to 10,000	More than 2	A	Inspection
over 10,000	More than 0	A	Interrupt test

Comparing the energy performance of the steels, Fig. 9 with BRASITEST criterion, the CP X80-2TR, bainitic steel sample, were not disqualified up to the rupture. The CP U2TR data, perlitic steel sample, enough to qualify the damage.



a) Bainitic steel

b) Perlitic steel

Figure 9. AE energy performance

6. Conclusion

- The microstructures differences between the two studied materials implies in a different mechanical behavior.
- The high ultimate tensile stress reached by the bainitic steel didn't harm its ductility verified by the anisotropic strain behavior and the fracture mechanisms.
- The AE signs indicated local plastic deformation mechanisms before the macroscopic yield for both materials.
- The AE technique was sensitive for the detection of the damage mechanisms in early stages of load application.
- The difference of profiles among the AE signs obtained for the two materials justifies a more detailed study to obtaining an accept/reject parameters for bainitic steels.
- The BRASITEST accept/reject criterion is not enough to evaluate the bainitic steel health before the flaw.
- The frequency behavior for both materials need better understood.

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8. References

API, 2000, "API Specification 5L Specification for Line Pipe", Forty-Second Ed., API, Washington, USA,

ASTM, 2003, "ASTM E8M", ASTM Annual Book of Standards, New York, USA, Vol. 03.01,

Batista, G. Z., Souza, I. S., Rios, P. R, 2002, "Effect of MA Constituent on Mechanical Properties of a Nb-Cr/Nb-Cr-Mo API X-80 Steel", International Conference on Thermomechanical Processing: Mechanics, Microstructure & Control, Sheffield-England

Bohlen, J. Chmelik, F., Dobron, P., Kaiser, F., Letzig, D., Lukác, P., Kainer, K. U., 2004, "Orientation effects on acoustic emission during tensile deformation of rolled magnesium alloy AZ31", Journal of Alloys and Compounds / Elsevier, v. 378, pp. 207-213

Chae, D., Koss, D. A., Wilsom, A. L., Howell, P. R., 2000, "The Effect of Microstructural Banding on Failure Iniciation of HY-100 Steel", Metallurgical and Materials Transactions A, Vol. 31A, pp. 995-1005,

Cota, A. B., Barbosa, R., Santos, D. B., 2000, "Simulation of the controlled rolling and accelerated cooling of a bainitic steel using torsion testing", Journal of Material Processing Technology, Vol. 100, pp. 156-162

DeArdo, A. J., 1992, "New Developments in the Alloy Design of Microalloyed and other Modern HSLA Steels", HSLA Steels: Processing, Properties and Applications, pp. 21-31

Dieter, G. E., 1986, "Mechanical Metallurgy", Ed. McGraw Hill, New York, USA

Edmonds, D. V., Cochrane, R. C., 1990, "Structure-Property Relationships in Bainitic Steels", Metalurgical Transactions A, Vol. 21A, pp. 1527-1540

Garcia C. I., Lis, A. K., Pytel, S. M., Deardo, A. J., 1990, "Ultra-Low Carbon Bainitic Plate Steels: Processing, Microstructure and Properties", Transactions of the ISS, pp. 97-106

Kojima, S. S., Sampaio, M. A. C. A., Bott, I. S., 2002, "The development of API 5L-X80 steel for pipe production by the TMCR process", T & B Petroleum Technology, Vol. 15, p p. 68-70

Lima, K. R. S., Bott, I. V., Gomes, J. A. C. P., 2003, "Comportamento de Aços da Classe API em Corrosão sob Tensão", 58º Congresso Anual da ABM, Rio de Janeiro-RJ

Maia, N. S., Medeiros, E. B., Bracarense, A. Q., 2003, "Utilização da Emissão Acústica em Manutenção", Anais VI Congresso Ibero-Americano de Engenharia Mecânica – CIBEM6, pp. 473-484

Manohar, P. A., Chandra, T., 1998, "Continuous Cooling Transformation Behavior of High Strength Microalloyed Steels for Pipe Line Applications", ISIJ International, Vol. 38, pp. 766-774

Moorthy, V., Jayakumar, T., Raj, B., 1995, "Acoustic emission technique for detecting micro- and macroyielding in solution-annealed AISI Type 316 austenitic stainless steel", Int. J. Ves. & Piping / Elsevier, Vol. 64, pp. 161-168

Nikulin, S. A., Shtremel, M. A., Khanzhin, V. G., Kurianova, E. Y., Markelov, A. P., 1999, "Analysis of Fracture Scale and Material Quality Monitoring with the Help of Acoustic Emission Measurements", Acoustic Emission Test. ASTM STP 1353, pp. 125-139

Vasconcelos, C. S., Perspectivas e Regulamentação de Tubos API, www.petrobras.com.br/portugues/tecnolog/centropq/tecen31h.htm

Zhao, M-C, Yang, K., Shan, Y., 2002, "The Effects of Thermo-Mechanical Control Process on Microstructures and Mechanical Properties of a Commercial Pipeline Steel", Materials Science and Engineering A, Vol. 335, pp. 14-20

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