Reliability of the Installation and Operation of Pipeline Systems

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Abstract **Pipelines are one of the most convenient and effective ways of transporting petrol over a long distance. The environment applies, beyond extremely high external pressures, low temperatures and intensive corrosive process, the occurrence of defects on the pipe body, which compromises the structural integrity of pipelines leading to catastrophic failures. The main modifications concern the mechanical resistance, toughness at low temperatures weld ability and resistance to embrittlement related to hydrogen. Among mechanical characteristics, the fracture toughness is very important for pipeline steels in design and safe assessment. Aiming to enhance the reliability and operation of complex pipelines system, a study based on the mechanics of the elastoplastic fracture in order to determine better prediction of the fatigue life. The materials tested here are API 5L X42 and X52 micro alloyed steels, as well as to evidence the toughness resistance of these materials. Results indicated that both X42 and X52 steel behave in a similar way and in all cases a slight increase of the transition temperature was found. The characteristic toughness value shows an evident loss in mechanical performances if compared to the uncharged one.**

Keywords: Charpy impact, Fracture Toughness, Pipeline steel, Reliability, Temperature.

I. Introduction

Pipelines are one of the most convenient and effective ways of transporting natural energy resources over long distance. Among mechanical characteristic, the fracture toughness is very important for pipeline steels in design and safe assessment of long distance gas transmission pipelines. It is well known that the fracture behaviour of pipeline steel depend strongly on temperature, strain rate, specimen thickness and the stress state.[1]

Chine's natural gas pipeline will be built 50000 Km in 2020 [2]. Pipeline construction is moving in large diameter, large wall thickness, high-voltage transmission direction, which requires pipeline steel with high strength and high toughness.

Carbon steel and low alloy steel are commonly used in Oil and Gas industry when general corrosion due to the presence of CO_2 and H_2S is considered acceptable to stand the design life. However, when sour condition applies, the occurrence of Sulphide Stress Cracking (SSC) in the presence of H_2S on susceptible materials must be investigated [3]. Furthermore, when very low temperatures, as below T= - 40 °C, are also present, as in most recent oil and gas fields, a synergistic negative effect may result from the combination of sour conditions and low temperatures on the mechanical behaviour of the used materials.

Ductility is a measure of how much something deforms plastically before fracture, but just because a material is ductile does not make it tough. The key to toughness is a good combination of strength and ductility. A material with high strength and high ductility will have more toughness than a material with low strength and high ductility. Therefore, one way to measure toughness is by calculating the area under the stress strain curve from a tensile test.

Hydrogen charging of steels results in a complex interaction between solute hydrogen atoms and all the micro-structural components in the material. Such a complex correlation causes scatter in the experimental results and sometimes contradictory evidences. Nevertheless, decrease of impact strength, ductility (i.e. reduction in area in tensile tests) and fracture toughness of pipeline and pressure vessel steels has been reported in the literature [4]-[5]-[6]. The presence of hydrogen has a strong effect also on the fatigue behaviour of carbon and low alloy steels and there are several studies on this topic carried out using fracture mechanic approach [7]-[8].

The Charpy impact test has been used for the characterization of the failure behaviour of metals and alloys for the past one hundred years. Charpy impact testing is largely employed for determining the Ductile-to-Brittle Transition Temperature (DBTT) [9]-[10]. Fracture in the DBTT range is a complex phenomenon since two fracture mechanisms are in competition. Several models of the damage process have been proposed: the most used is so called the Gurson-Tvergaad-Needleman model (GTN model) [11]. The finite element method was used in order to compute the energy balance and the stress strain distribution in the Charpy V-notch specimen.

The V-notch Charpy impact test, which has been widely used as a pre-qualification test of material toughness [1], is also used for estimating "fracture mechanics based toughness of materials". However, there have not been any theoretical estimation methods to correlate Charpy test result [12].

Aiming to enhance the reliability of the installation and operation of complex pipeline systems, a study based on the mechanics of the elastoplastic fractures was done in order to allow a better prediction of the fracture toughness in API 5L X42 and X52 steel pipes. To reproduce the combined effect of hydrogen in the metals and different temperatures, the instrument Charpy impact tests are performed using V-notch specimens uncharged and charged with hydrogen.

II. METHODOLOGY

Experimental activities involved seamless pipes in quenched and tempered conditions. Micro-alloyed steel, API 5L X42 and

X52 (D=323 mm, t=46 mm). X42 and X52 [13,14] grade pipe is a pipe from conventional billet casting-piercing-hot rolling quench and tempering operations. Both materials are for sour service use, so that they underwent through all the required qualifications. In Table 1 the chemical compositions of the selected materials API 5L X42 and X52 steel microstructure is equiaxed and acicular ferrite with finely dispersed carbides.

- X42 Pipe is seam welded in submerged arc welding (SAW) for such pipe does not have to be cold worked or extensively machined for a flat shape; pipe for oil wells.
- The main characteristic of the X52 Pipe is controlled rolling process with a very low reheating temperature and rolling in the austenite ferrite of the pipe. The pipe microstructure comprises a mixture elongated martensite deformed and non-deformed ferrite providing a dual-phase structure; this is a micro-alloy pipe for petroleum pipelines.

Table 1: Chemical composition of the materials

Material / Components	X42	X52
C	0.07	0.09
Mn	1.63	1.72
Cr	0.0023	0.0022
S	0.001	0.001
P	0.015	0.016
Mo	0.006	0.006
Nb+Ti+V	0.12	0.12
Fe	Bal.	Bal.

The microstructure is rather homogeneous. Inclusion shape is round. Mechanical properties have been evaluated at room temperature**.** Heavy wall pipeline for natural gas and oil pipelines, drilling pipe and submerged pipeline equipment for onshore and offshore drilling and production Pipe and tubing products conform to or exceed ASTM, API, ASME and ANSI standards for heavy-duty drilling and production. Whether you need pipe and tubing for offshore drilling, or for gas or oil lines, or for use in submerged or even cold temperature (arctic environments). Results of mechanical properties of the above steel pipes are collected in Table 2.

Table 2: Mechanical properties of the materials

Material	X42	X52
Yield strength (MPa)	337.6	418
Tensile strength (MPa)	363	449.5
Yield to Tensile Ratio	0.93	0.93
Elongation (%)	44	44.5

The fracture toughness of the pipe shall be determined using Charpy V-notch impact test specimens. A large number of experimental tests were carried out to characterize the mechanical behaviour of the uncharged and hydrogen charged steels, obtained by impact test using standard V notched Charpy compact tension (CT) specimens.

The electrochemical method proposed for hydrogen charging has the primary purpose to obtain controlled and reproducible charging conditions in an environment that can be prepared, handled and disposed in a simple and safe way. Hydrogen content charged into thick steel specimens should be comparable to that found in pipeline steels after a long service time. The basis for the setup of the hydrogen charging method was the work of Newman and Shreir [15]. The procedure finally setup in laboratories for electrochemical hydrogen charging has been:

- Solution: 0.4 mol of acetic acid (ethanol acid) and 0.2 mol of sodium acetate (sodium ethanonic), buffered at pH 4.3 and with 600 parts per million (Ppm) of sulfide from hydrated sodium sulfide;
- complete de-oxygenation with pure nitrogen;
- room temperature, T = 25 ± 3 °C;
- current density equal to 0.5 mA/cm^2 for 20 hours.

In order to avoid hydrogen release due to diffusion during the time interval from charging to mechanical testing the charged specimens were immerged into liquid nitrogen at T=-196 °C. An approximate estimation of the diffusible hydrogen content of the charged specimens has been made by using the hot glycerol method. This method is very simple and quick, then it is suitable for a routine control but underestimate the actual hydrogen content. The details of the experiments are reported in the paper [16]. Charpy tests were carried out on as received materials and after hydrogenation, according to ISO 148 [17]. The specimens were cooled down, by an ethanol-liquid nitrogen bath kept at the test temperature.

Two methods were followed to define the DBTT or by the Fracture Appearance Transition Temperature (FATT) and by determining the temperature in correspondence of the energy equal to 27J. The FATT is typically defined as the temperature at which the fracture surface contains the 50% of brittle area.

Fracture mechanics tests were carried out on standard CT specimens, (Fig. 1) following the ASTM 1820 [12]-[18]-[19]-[20]. Thickness of the specimen is a very important parameter for the test. Large thickness is needed to have a plane strain behavior of the material; on the other hand small thickness allows easier and faster charging processes that depend on the surface/volume ratio. In designing the specimen both those requirements were taken into account and thickness was set equal to B=20mm. Side grooves were machined on the specimens, along the crack propagation direction, in order to reduce the plane stress condition.

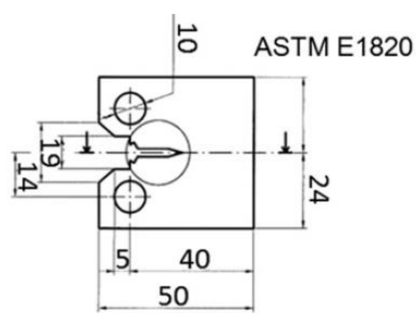

Fig.1: Specimen geometry (Note: all dimensions)

Charpy impact testing involves striking a standard notched specimen with a controlled weight pendulum swung from a set height. The specimen is supported at its two ends on an anvil and struck on the opposite face to the notch by the pendulum.

The amount of energy absorbed in fracturing the test-piece is measured and this gives an indication of the notch toughness of the test material. The pendulum swings through the test, the height of the swing being a measure of the amount of energy absorbed in fracturing the specimen. Conventionally, three specimens are tested at any one temperature and the results averaged.

Impact energy is a measure of the work done to fracture a test specimen. Calculation of absorbed energy on Charpy impact test based the following equation:

$$\text{Energy} = WgR\,(\cos\beta - \cos\alpha) - L$$

Where

W: mass of hammer;

g : gravitational acceleration;

R: length of the arm ;

α: angle of fall;

β : angle at the end of the swing;

L: energy Loss.

The tests have been performed at different controlled temperatures by using an environmental chamber fed with liquid nitrogen. To check the specimen temperature in the bulk, before and during tests, a small hole was machined in the specimens and a T-type thermocouple was welded in, without interfering with the test.

The details of the experiments are reported in the previous paper [19]. All the specimens, after the hydrogen charge, were maintained in liquid nitrogen, while some specimens were kept in air at room temperature for 24h to allow some diffusible hydrogen to escape from the specimen and verify if there is a permanent effect of hydrogen charge.

III. Results and Discussions

Charpy tests show whether a metal can be classified as being either brittle or ductile. This is particularly useful for ferritic steels that show a ductile to brittle transition with decreasing temperature. A brittle metal will absorb a small amount of energy when impact tested; a tough ductile metal absorbs a large amount of energy.

It is not enough to know only how strong a metal is in tensile strength, or how ductile it is; information as to how it reacts under sudden impact also is of prime importance. This quality is known as toughness. This is determined by impact test. Information about impact test is given in this article.

Figs. 2 to 5 show the Charpy impact energy values and the percentage of brittle area as a function of temperature for X42 and X52 steel respectively. The impact energy values of uncharged X42 specimens are almost constant to a temperature equal to T=-100°C (Fig. 2). The same results are achievedfrom the percentage of brittle area diagram (Figure 3), the brittle area is between 5-10%, when test temperature is equal to T=-100°C. For the second material (X52), Figure 4 shows that, the energy values drop suddenly in correspondence of T=-110°C. The transition zone of impact energy of hydrogenated specimens is larger and the energy values are more scattered. The BDTT of hydrogenated X42 specimens increases of about 30°C with respect of the non hydrogenated specimens, if it is considered the value in correspondence of impact energy 27J, as in ISO 148. By considering, on the contrary, the FATT value, the increase is in the range of 20°C. Upper shelf energy is slightly decreased from 270 to 230 J, these results clearly can be shown in Fig. 5.

The under graphic in Fig. 6 illustrates the transition curves obtained for pipes X42 and X52.

X52 steel hydrogenated specimens show a slightly different behaviour, if compared to the uncharged material one. The transition was a bit more localized. An increase of BDTT of about 10°C can be appreciated after hydrogenation, using both the FATT and the 27J criterion. The upper shelf energy is slightly decreased from 240 to 220J. An important aspect is the more scattered results for both energy and brittle area values of hydrogenated samples compared to those of uncharged material.

Results indicated that both X42 and X52 steel behave in a similar way and in all cases a slight increase of the transition temperature was found. The above results have the same trend with that results performed and published by Fassina et al.[20].

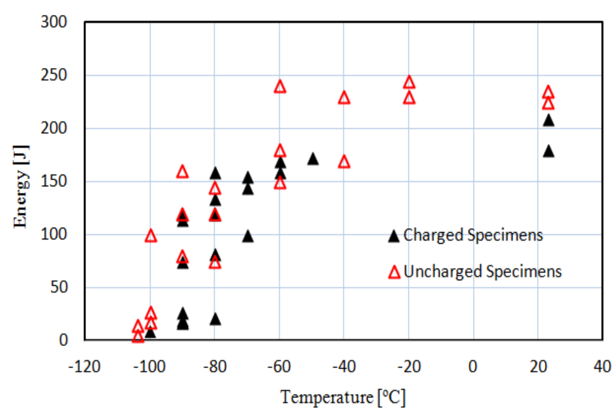

Fig. 2: Impact energy vs. temperature for X42 Steel

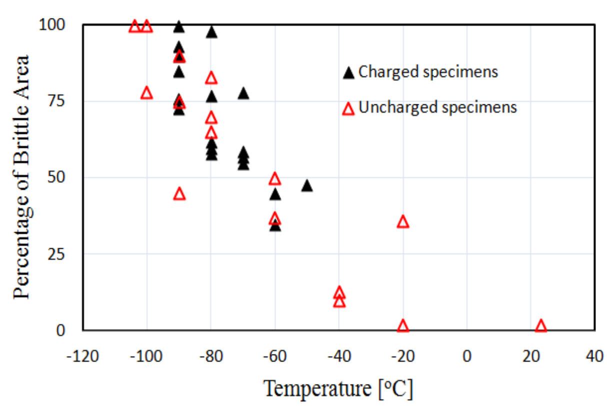

Fig. 3: Percentage of brittle area vs. temperature for X42

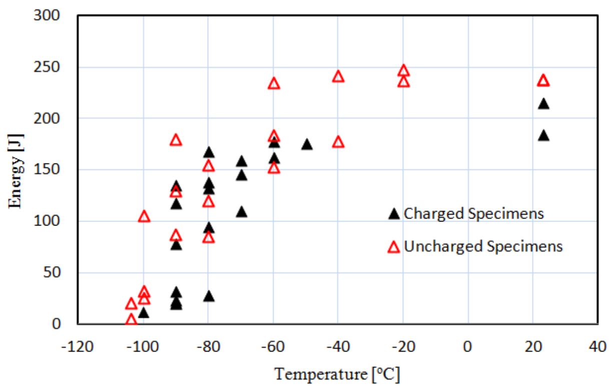

Fig. 4: Impact energy vs. temperature for X52 Steel

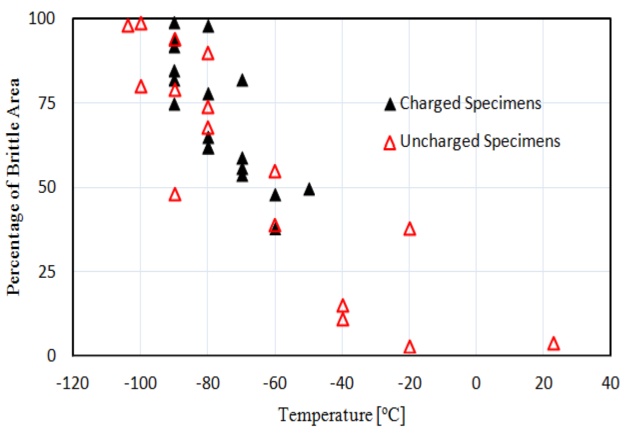

Fig. 5: Percentage of brittle area vs. temperature for X52

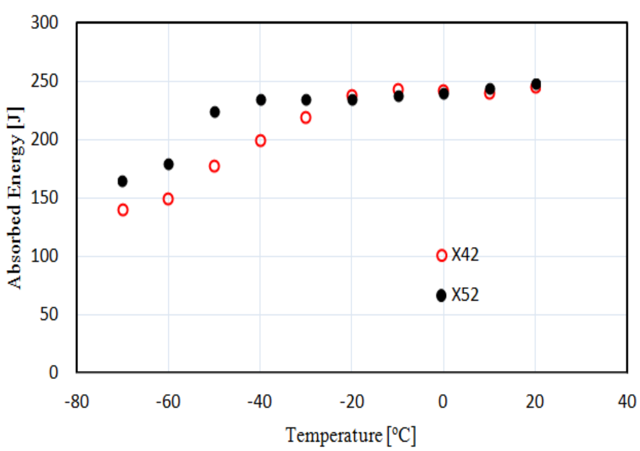

Fig. 6: Average transition curves obtained in charpy tests

IV. CONCLUSION

In this paper, the mechanical behavior of two hydrogenated steels was investigated. Both steels, a microalloyed steel API 5L X42 and X52, are widely used in oil and gas pipelines. The conclusions can be summarized as follows:

- An electrochemical hydrogen charging technique was developed; hydrogen content in the specimens was measured between 0.6 - 2 Ppm; hydrogen diffusion outside the specimen was prevented by means of putting specimens in liquid nitrogen.
- A suitable procedure was applied for testing of hydrogen charged specimens in order to obtain mechanical properties without loss of hydrogen.
- At temperature above transition, impact specimen fracture by a ductile mechanism, absorbing relatively large amounts of energy. At lower temperature, they fracture in a brittle manner absorbing less energy. Within the transition range, the fracture will generally be a mixture of areas of ductile fracture and brittle fracture. The temperature range of the transition from one type of behavior to the other varies according to the material being tested.
- It can be seen that at low temperatures the material is more brittle and impact toughness is low. At high temperatures the material is more ductile and impact toughness is higher. The transition temperature is the boundary between brittle and ductile behavior and this temperature is often an extremely important consideration in the selection of a material.
- A drastic change in mechanical properties of the hydrogenated material has been shown; the effect, as expected, was remarkable in those tests that require a longer time to be performed.
- The characteristic toughness value, shows an evident loss in mechanical performances if compared to the uncharged one. In particular the material loses the ability to plasticize under high loads and stresses and its behaviour shifts to those of medium tough steels.

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