The Iraqi Journal For Mechanical And Material Engineering, Vol.18, No.4, Dec, 2018

DURABILITY OF THE OIL PIPELINE SYSTEMS UNDER ENVIRONMENTAL EFFECTS

S.M. Beden[1], Ali Adel Battawi[1] and A.J. Shahrum[2]
[1]Email: engsabah1959@toc.edu.iq
[1] Technical Engineering College Baghdad, Middle Technical University, Iraq
[2]Engineering Faculty, the National University Malaysia

ABSTRACT

Recent discoveries of petroleum and gas reserves in environments with severe operational conditions metallic materials, carbon and low alloy steels, have pushed and prompted the need to find alternatives. The presence of gaseous hydrogen may cause the suffering of hydrogen damage and embrittlement. The effect of hydrogen and temperature on fatigue life properties, have pushed the utilization of steel procurement specification even stricter than they used to be. The main modifications concern the mechanical resistance, toughness at low temperatures weld ability and resistance to embrittlement related to hydrogen.

Aiming to enhance the reliability and operation of pipelines system, a study based on the elastoplastic fracture was carried out to determine high level prediction for the fatigue life, as well as to evidence the toughness resistance of the used materials. The materials tested here are API 5L X70 and X100 micro alloyed steels. Hydrogen had affecting the material properties, which are reducing the toughness and an influence spotted in Charpy tests.

KEYWORDS: **Charpy impact, Durability, Fracture Toughness, Pipeline steel, Temperature.**

قابلية التحمل لمنظومات خطوط انابيب النفط تحت تأثير الظروف البيئية

صباح معن بدن ، علي عادل بتاوي ، أحمد جمال شاهروم

الخلاصة

ان الاكتشافات المستمرة بخصوص احتياطيات النفط والغاز في البيئات المختلفة مع ظروف التشغيل الشديدة على خطوط الانابيب المصنعة من المواد المعدنية (الصلب الكاربوني و سبائكه المنخفضة)، دفعت الحاجة الى ايجاد البدائل لهذه المعادن. من بين الظروف البيئية المؤثرة وجود الهيدروجين بشكله الغازي الذي يؤدي الى معاناة التلف والتقصف. ان تأثير الهيدروجين ودرجة الحرارة على خصائص الكلال، دفعت استخدام الصلب بمواصفات أكثر صرامة مما كانت عليه. وقد شملت التعديلات الرئيسية في الخصائص المقاومة الميكانيكية، والمتانة وقدرة الحام في درجات الحرارة المنخفضة ومقاومة التقصف المتعلقة بالهيدروجين.

بهدف تعزيز موثوقية وتشغيل نظام خطوط الأنابيب، لقد أجريت دراسة على أساس الكسر المرن او اللدن لتحديد التنبؤ لعمر الكلال على مستوى عال ، فضلا عن المؤشرات على مقاومة الصلابة للمواد المستخدمة. المواد التي تم اختبارها هنا هي API 5L X70 و X100 من سبائك الصلب الدقيقة. كان للهيدروجين تأثير على خصائص المواد، والذي تسبب في تقليل المتانة وكذلك ظاهرة الانتشار التي تم رصدها في اختبارات تشاربي.

Received: 2018 - 1 - 9
Accepted: 2018 - 4 - 18

INTRODUCTION

Pipelines is the most convenient and effective ways of transporting energy (natural oil and gas) resources over long distance. Among mechanical characteristic, the fracture toughness is very important for pipeline steels in design and safe assessment of long distance 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 [Zheng et. al. 2005, Mulder et. al. 2007].

Natural gas pipeline in Chine will be built in 2020 around 50000 Km [Yongjie et. al. 2011]. The construction of pipeline is going in a direction of use as large diameter, wall thickness and also high-voltage transmission direction.

Ductility is a measure of deformation plastically before fracture, but only the ductility for any material does not make it tough. The combination of strength and ductility was a good key to toughness. A material with properties of good strength and softeners will give toughness higher than a one with low level of strength and high level of ductility.

Carbon steel and low alloy steel are in general used in oil and gas factories when the effect of corrosion due to the availability of CO_2 and H_2S which is to be passable to reach the life design. However, at the condition of sour, the effect of SSC (Sulphide Stress Cracking) with the H_2S on applied materials needs to be scrupulous [Capelle et. al. 2008]. Moreover, at low level of temperatures, (as below T= - 40 °C), are present, as in most available oil and gas fields, a synergistic bad effect on the mechanical behaviour of the used materials is a combination of the result from the sour conditions and of low level temperatures.

The charging of steels with hydrogen leads to high level of interaction between the hydrogen solute of atoms and the components of the micro-structural for the material [Melaina et. al. 2013, Nykyforchyn et. al. 2016]. For these complexion of such correlation, leads to a high differences in the results of experimental and sometimes not in the same order [Joe et. al. 2016]. Nevertheless, minimize of strength at impact leads to softness and failure toughness of pipelines as well as pressure vessel steels which were reported in the previous literature [Nykyforchyn et. al. 2010]. A strong effect can be shown on the fatigue behaviour of low alloy steels at the presence of hydrogen and based on fracture mechanic approach, several studies on this topic was carried out [Murakami 2002, Fassina et. al. 2013, Jose 2017].

Many researchers used the Charpy impact test (for the past one hundred years) for the characterization of the behaviour during failure of alloys as well as metals test for the material toughness. The impact of Charpy testes is largely applied for measuring the Ductile-to-Brittle Transition Temperature (DBTT) [Fadi 2010, Anderson et. al. 2014]. The fracture in the DBTT level is a not regular phenomenon since the competition of the two mechanisms fracture. Several models of the damage process have been proposed: the most used is so called Gurson–Tvergaard–Needleman model [Petr et. al. 2005]. The finite element technique used in order to calculate the equating energy and the distribution of the stress strain in the specimen.

Only one output can be obtained from the impact (Charpy) machine (i.e. for the test specimen for the overall energy). In order to develop a new test method, comprehensive efforts have been made to obtain as much information for the failure as possible from the impact test. For that purpose, many researchers used different computational techniques and tests. Kobayashi applied an aided instrumented computer Charpy test, which was attached to a film (potentiometer) located on the rotating axis of the machine hammer edge, which consist of semiconductor strain gauges [Kobayashi et. al. 2001]. Lorriot in his work was reported that for direct measurement, he applied for the hammer displacement an optical sensor and laser beam [Lorriot 2002]. While Tronskar used a strain gauge (piezoelectric) transducers on the edge of the striker in order to measure the trace load [Tronskar et. al.2002]. The instrumented (test) data was reproduce from a full 3D model (Charpy), and finite element analysis bases has been applied [Andreas et. al. 2007].

The previous works show that, there are not done yet for any estimation using theoretical methods to correlate the Charpy test result [Yasuhito et.al. 2006]. Due to the complexity of the experimentation, the reasons that cause the embrittlement of materials are still debated in the scientific community. Hydrogen embrittlement detection seems to be one of the most difficult aspects of the problem [Vergani et al. 2014].

Aiming to evaluate the durability of the installation and operation of the pipeline systems, this study used the elastoplastic fractures mechanisms to allow a good prediction of the fracture toughness. The chosen pipe steels are X70 representative of the used steel in the actual gas network and X100 pipe steel representative of the high strength steel used in new pipelines with larger diameter and working at higher service pressure. Also to study the double effect of hydrogen and different temperatures on metals, the instrument (Charpy impact tests) are performed using (V-notch) specimens uncharged and charged with hydrogen. Results showed that both X70 and X100 steel behave in a similar way for all cases and a small increase was found for the range of temperature (transition).

EXPERIMENTAL WORK

Micro-alloyed steel, API 5L X70 and X100 [API Specification 2004] is a pipe from conventional billet casting hot rolling (quench) and operations of tempering. Both materials are for the sour use. For the selected materials, **Table 1** shows the chemical compositions [API 2004].

From the original pipe, a test plate (for the tensile samples) was taken by flame cutting. To remove the curvature, a shaping machine was used for this purpose. A set of tensile standard specimens used to conduct these types of experiments (tensile). The machine for testing capacity 600 kN loading capacity was used, which was carried out under a low displacement rate and room temperature. At each experiment, was monitored for the load data and axial elongation. It is important to determine the exact or nominal and all true properties (stress–strain) of the steel (X70 and X100 steel).

For such application of heavy wall pipeline for natural gas and oil pipelines, drilling pipe and submerged pipeline equipment for onshore and offshore drilling products to be conform or to exceed ASTM, API, ASME and ANSI standards. Results of mechanical properties of the above steel pipes are collected in **Table 2**.

Based on standard specimens, fracture mechanics tests in this work were carried out following the ASTM 1820 [ASTM standards 2009]. A very important parameter is the thickness of the specimen during the test. In order to have a plane strain behavior a large thickness is needed for the material; on the other hand depend on the surface/volume ratio and for easier and faster charging processes the small thickness needs for that. Both those requirements in designing the specimen should be taken into account. The specimens were machined on (side grooves), in the crack propagation direction, this leads to reduce the plane stress condition.

For the requirements of this work, the fracture toughness will be determined using standard Charpy V-notch (impact test) specimens. For the purpose of characterizing the mechanical behaviour of both steels with and without hydrogen, a number of experimental tests were executed.

The impact testing (Charpy) includes a standard specimen (notched) using a controlled weight (pendulum) swung from a height sated before. An anvil and struck on the opposite face to the notch is supported the specimen at its two ends. The measurement of the amount of energy absorbed in fracturing of the test-piece gives an indication of the toughness of the test material.

In this study the Charpy apparatus used was a typical kind of 300 Joules machine pursued the ASTM E23 [ASTM E23-96]. At the highest working capacity (300 J), the nominal pendulum impact velocity was 5.5 m/s. For such instrumentation a load-cell (strain gauge) attached in order to a modified striker (Charpy) close to the impact point. **Figure (1)** shows a sketch of the Charpy testing arrangement. Conventionally, the results are averaged for all the tested specimens at any desired temperature.

The proposed method of electrochemical hydrogen loading is the main purpose in order to obtain good and acceptable conditions (charging) in preparation of environment. The basis setup for the hydrogen charging method was a work done by Newman and Shreir [Newman and Shreir 1977] and the setup of the procedure of electrochemical charging (with hydrogen) in laboratories has been:

- Solution: 0.4 mol of acetic acid (CH3COOH + 0.2 mol), which buffered at pH 4.3 and 600 ppm of the sulfide;
- De-oxygenation (complete) with pure N_2;
- The density (current) equal to 0.5 mA/cm^2 for each (20) hours.

Due to diffusion and to avoid hydrogen release during the time interval before mechanical testing the charged specimens were to be immerged into liquid nitrogen at temperature of T=-196 °C. The experimental details are reported in the previous paper [Bolzoni et. al. 2010]. According to ISO 148 the tests (Charpy) were carried out on materials (as received) and after hydrogenation [ISO standards 2009]. In order to keep the temperature (test) stable, an ethanol-liquid nitrogen bath to cool the specimens down.

At different controlled temperatures, a preformation of the tests has been carried out based on liquid nitrogen fed using an environmental chamber. To check the specimen temperature in the bulk, (this is done before and during tests), for this purpose, a small hole was machined in the specimens (without interfering with the test) and a thermocouple (T-type) was welded in.

Following two methods to define the DBTT or by the Fracture Appearance Transition Temperature (FATT). At any temperature, the fracture (surface) contains the 50% of brittle area; this temperature is called the FATT.

RESULTS AND DISCUSSIONS

For the cases of low-grade (pipeline) steels is normally concentrate on the overall fracture absorbed energy in design against ductile fracture [Kabayashi et. al. 2001]. The measurements of fracture energy are on standard Charpy (V-notched) specimens. This result is related then through semi-empirical formulae to the ductility of the pipe tearing resistance. These equations give a relation of the pipe (geometry) and conditions of the loads to the **Charpy fracture** energy. Such formulas are coming from the results of calibration figures using laboratory data (impact specimens) and the information of failure. The formulae which were calibrated are used for prediction of the arrest toughness of pipelines. Obviously, the required energy (Charpy) must be passed the actual energy (Charpy) of the pipeline to be safe and with good performance. The well-known Battelle Two Curve Model (TCM) is an example of such failure models which has the relation of the geometry for the pipe and conditions of the loads on fracture Charpy energy [Rothwell 2000]:

$$(C.V)_{2/3}= 2.382 \times 10^{-5} \sigma_h^2 (Rt)^{1/3} \quad (1)$$

where $(C.V)_{2/3}$ is the Charpy energy measured on 2/3 thickness specimens for the fracture arrest (in Joules), while the hoop stress is σ_h (MPa), and the pipe radius with wall thickness were represent by R and t (mm), respectively. The construction of the model was based on

Charpy energy as indicate fracture resistance for the material [Rothwell 2000]. For estimation of impact energy from the load (from the recorded) test data were numerically calculated.

How strong or how ductile a metal is, it is not sufficient to learn only that it in strength (as a tensile). The information also is of prime importance as to how it behaves under impact for a sudden case. This type of quality is well established for a property as toughness, which is calculated by impact tests.

Figure(2) (a and b) show the comparison between the detour load with load line displacement for specimens (i.e. different steels of X70 and X100): with and without hydrogenated specimens, the uncharged one shows a very long plateau with very small increment load and an considerably limited crack stretching. The hydrogenated specimen's curves show a minimum load and a very much restricted, and also show the brittleness of such materials. The presence of hydrogen will accelerate the crack growth; it will itself not change the appearance of the newly formed microstructure.

The metal can be classified as being either brittle or ductile based on tests (Charpy). With decreasing temperature, it is may be special useful for steels (ferritic) which can give a shape of a transition of ductile to brittle. The absorption of the amount of energy at impact tested is a measure of the ductility or brittleness of the metal.

From such types of experiments (Charpy), we may be taking into account a correction factor for the toughness of the steels pipeline; the proportion of the values of the absorbed energy to fracture and to propagation of the energy. This factor has good values with a contribution of initiation for the fracture energy. For less tough and old pipeline steels, this value of such ratio was almost equating to unity in which initiation of fracture energy (or nonfracture concerning energy) was very small. In a line surface of the fracture (test samples), the absorbed energy used in the propagation of fracture through the ligaments for specimen resulted. The preliminary results for the tested steel were shown in **Figure(3)**.

From the results of this research, the suggestion was that the correction factors of at least 1.2 to 1.6. The extrapolating of the relations (semi-empirical) for metal specimens X70 and X100 may be required to calibrate on small tough materials (pipeline) to measure the toughness (Charpy) for crack stay in pipeline. A good agreement can be seen with the suggested correction factors (1.2) with a lower bound of a correction factor of 1.2 –1.6.

The second part of this work for measuring the energy was the experimental part based on charpy impact tests. **Figure(4 to7)** give the energy of the Charpy impact energy values and the percentage of brittle area as a temperature function for X70 and X100 steel respectively. The values for impact energy of with and without hydrogen of X70 specimens are presented in **Figure(4)**. The same results are completed from the diagram for the percentage of brittle area shown in **Figure(5)**. The area of brittleness is around values of 5 to 10%, for the values of test temperature.

In fact, the presence of hydrogen atoms in a solid metal dissolved in the metal grid and accumulated in disturbed lattice regions results in the reduction of its ductility by decreasing the energy of cohesion and consequently in the increase of its probability of brittle fracture. Furthermore, the concentration of hydrogen at grain boundaries, possibly in molecular form, and the potential of formation of hydrates after the reaction of hydrogen with the metal, are additional mechanisms that may lead to embrittlement.

For the second material (X100), **Figure(6)** shows that the values of the energy reduce depending on temperature. The transition zone of impact energy for the charged specimens is higher and the values of energy are very scattered. The values of DBTT of charged steel (X70 specimens) will be increase of about 30°C depend on that of the nonhydrogenated specimens, when it is reflect the value in depending on the energy (impact) with 27J, as mentioned in ISO 148. When taking into account, the values of FATT, the increase is in the range of 20°C. The shelf (upper) energy is small decreased from the range of 270 to 230 J; these results clearly can be shown in **Figure(7).** These results have the same behaviour with the results performed and published previously [Fassina et. al. 2010].

It is understood that hydrogen can cause embrittlement when present in a metal or alloy in its atomic form and not as a molecule. Dissolved hydrogen atoms in metals tend to concentrate in defects of the crystal structure (dislocations, grain boundaries …), imposing a barrier to the movement of dislocations, and effectively impeding the plastic flow of the material. As a result, the ductility of the metal decreases and the material becomes brittle.

The under graphic in **Figure(8)** illustrates the transition curves obtained for pipes X70 and X100. The X70 charged steel specimens show small differences in such behavior, if we compare to the nonhydrogeneted material. The transition was with high localization. When the value of DBTT increase around of 10°C, this lead to a values which will estimate a values after hydrogenation, using the FATT and 27J criterion. The upper shelf energy is slightly decreased from 240 to 220J. An important portion is the high scattered in the results for both (energy and brittle area) values of charged samples when we compare with one of uncharged material.

Results showed that both X70 and X100 steel manage in a same way and for all cases a small increment of the transition temperature. The above results have the same trend with that results performed and published before [Fassina et. al. 2012].

Figure(9-a and b) show the energy values (J) separated into components (i.e. elastic J_{el} and plastic J_{pl}) for X70 and X100: the availability of hydrogen prohibits the material plasticization. It is important that the elastic component in general was constant; in other word, the availability of hydrogen originally minimize the plastic one. Moreover, the availability of hydrogen gives good values of the material fracture mode: the plastic zone is lesser which leads to increases the crack propagation.

In presence of hydrogen energy (J) value is reduced to 20-25 % of its value in absence of hydrogen. If J value of hydrogen charged specimens is split in its elastic and plastic components, it is possible to notice that this second one is much bigger than the elastic, which is almost negligible: this evidences the non-ductile behavior of the steel. The hydrogen distribution in a metal under stress is highly non-uniform which can lead to locally increased hydrogen-enhanced plasticity causing local microscopic deformation and eventually a failure.

CONCLUSIONS

In this work, the mechanical behavior of the two charged and noncharged steels was studied. The two steels, a microalloyed steel API 5L X70 and X100, are used in a wide manner in pipelines (oil and gas). An acceptable procedure was used for testing of hydrogen (charged specimens) in the aim of obtaining the mechanical properties without loss of hydrogen.

The conclusions may be summarized as follows:

- The description in this research work showed that the fracture toughness prophesy by empirical equations needs to be multiplied by factors of 1.2 to 1.6. The high initiation energy for tougher pipeline steels tuned on less-tough materials with less crack initiation energy. An increment in crack toughness, which is more regarded with the actual Charpy toughness, which were measured in the laboratory based on using result of those correction factors.
- The impact specimen fracture by a ductile mechanism was carried out at temperature above transition, which absorb relatively high values of energy. While at lower temperature, the fracture in that manner (brittle) which absorb small energy. Generally the fracture will be a mixture of areas (both ductile and brittle) fracture within that transition range. The temperature range of the transition were varies according to the material which have been tested.

- At low temperatures, the brittleness of the material is high while the impact toughness is small value. At high value of temperatures the material is on the inversion. The boundary between brittle and ductile behavior is the transition temperature and this temperature is often an extremely important consideration in the selection of a material.
- A change in mechanical properties for the charged (material) which has been listed. The lattice decohesion effect is presumed to cause embrittlement by a decrease in the atomic bonding strength in the presence of hydrogen. A fracture occurs when the stress exceeds the cohesive stress.
- One important point is the impact of hydrogen on the time of crack initiation, hydrogen promote crack propagation. So it is very important to find procedure to detect crack on pipe, to be anticipate pipe burst.

Further research on high grade steel pipeline has been planned in this program because this is an area need to be investigated.

Table 1: Chemical composition of the materials

Material	C	Mn	Si	Cr	Ni	Mo	S	Cu	Ti	Nb	Al
X70	0.125	1.68	0.27	0.051	0.04	0.021	0.005	0.045	0.003	0.033	0.038
X100	0.059	1.97	0.315	0.024	0.23	0.315	0.002	0.022	0.022	0.046	0.037

Table 2: Mechanical properties of the materials

Material	The Young Modulus (MPa)	The Yield strength (MPa)	The Ultimate Strength MPa)	Elongation (%)
X70	215	590	712	18.3
X100	210	866	880	6.75

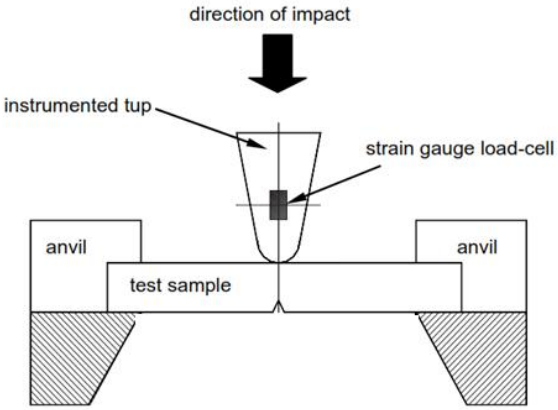

Fig. 1: Charpy testing arrangement

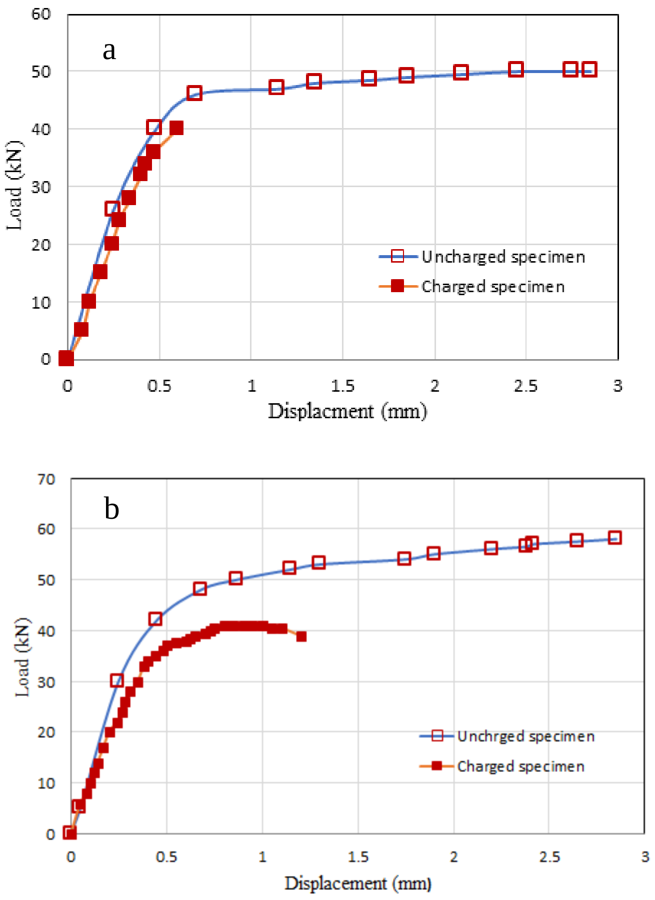

Figure 2: Load vs. Load line displacement (a) X70 and (b) X100

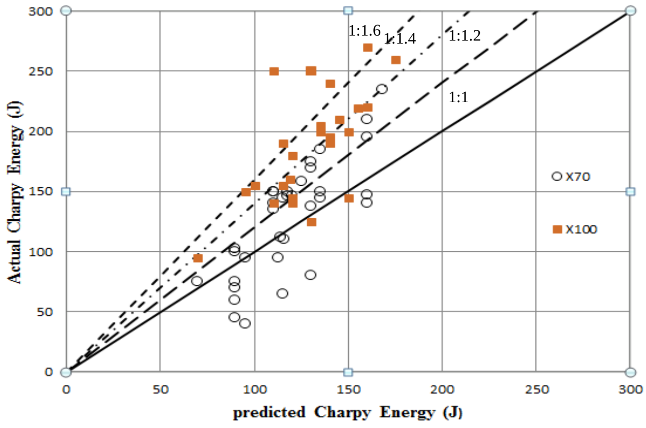

Fig. 3: Impact energy vs. temperature for X70 and X100 Steels

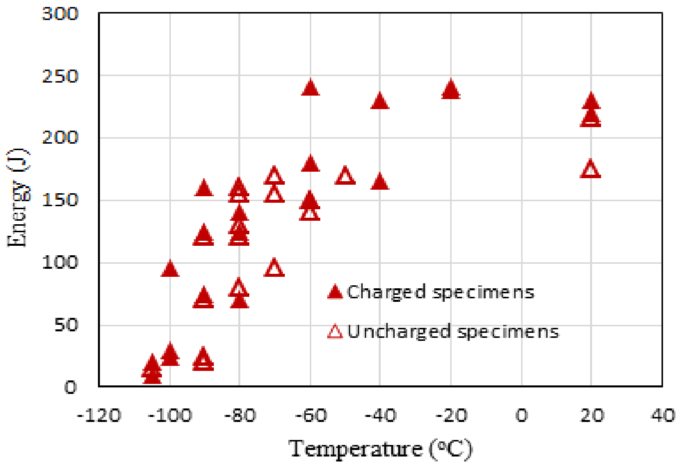

Fig. 4: Impact energy vs. temperature for X70 Steel

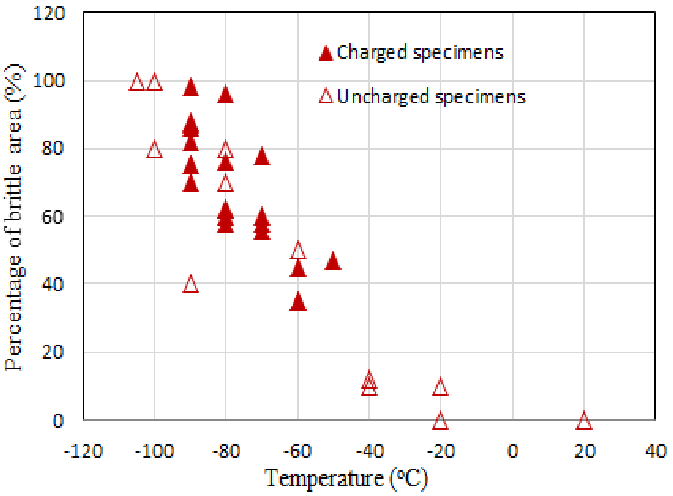

Figure 5: Brittle area vs. temperature for X70 (percentage values)

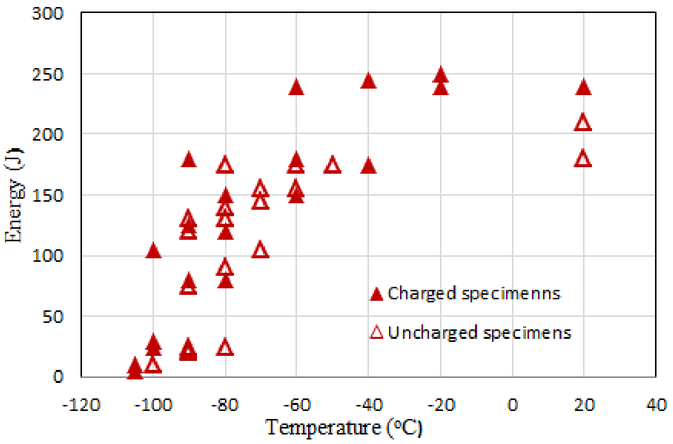

Fig. 6: Impact energy vs. temperature for X100 Steel

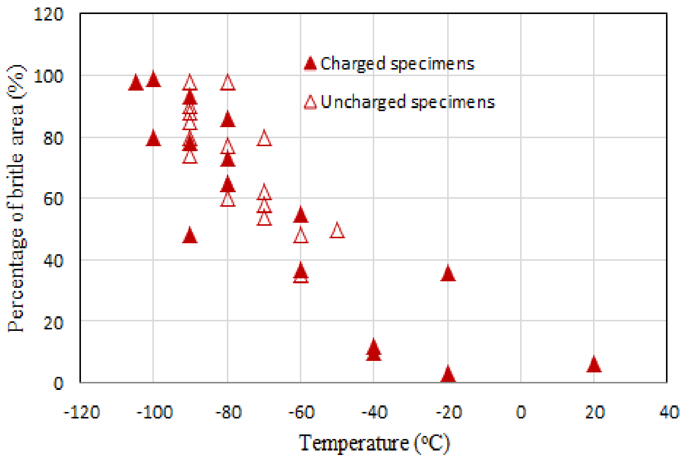

Fig. 7: Brittle area vs. temperature for X100 (percentage values

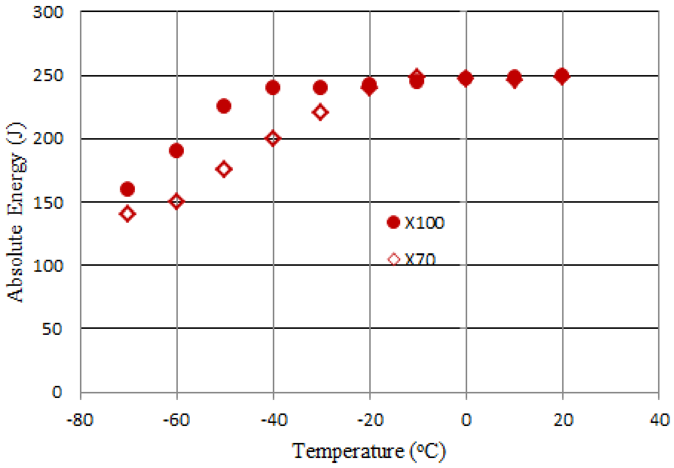

Fig. 8: Average transition curves obtained in charpy tests

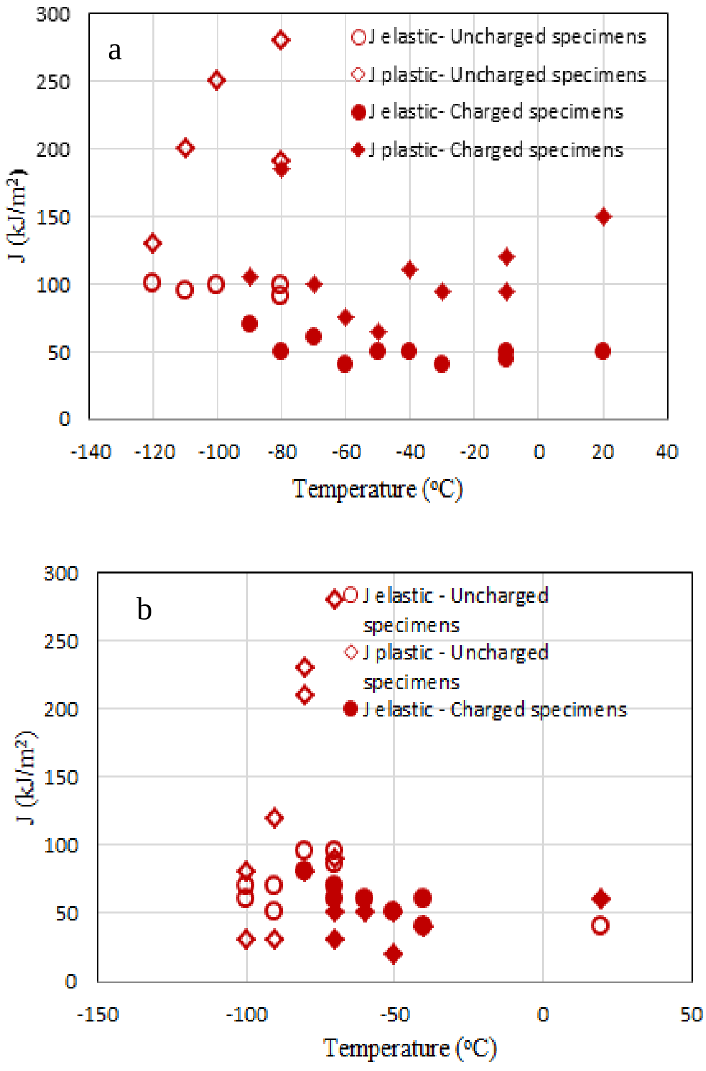

Fig.9: J_{el} and J_{pl} components vs. temperature for charged and uncharged specimen (a) X70 and (b) X100.

REFRENCES

Anderson Barbosa, Michal Oliveria, and Sergio Monterio. (2014) Charpy impact test of epoxy matrix composites reinforced with buriti fibers. Materials science Forum, Vol. 775-776 pp. 296-301.

Andreas E., Michael U., Meinhard K., Annette L. and Peter T. (2007). Indirect measuring of crack growth by means of a key-curve-method in pre-cracked Charpy specimens made of nodular cast iron. International Journal of Fracture, Volume 145, Issue 1, pp. 47–61.

API Specification 5L, Specification for Line Pipe. Washington: American Petroleum Institute; 2004.

ASTM E23-96, Standard test methods for notched bar impact testing of metallic materials. American Society for Testing and Materials.

Bolzoni F, Fassina P, Fumagalli G, Lazzari L, Re G. (2010) Hydrogen charging of carbon and low alloy steel by electrochemical methods. Proceedings of European Corrosion Congress EUROCORR; Sep 13-17.

Capelle J., Gilgert I., Dmytrakh G., Pluvinage G. (2008) Sensitivity of pipelines with steel API X52 to hydrogen embrittlement. International Journal of Hydrogen Energy, Vol. 33, Issue 24, December 2008, Pages 7630-7641.

E 1820-09, Standard Test Method for Measurement of Fracture Toughness. Annual book of ASTM standards 2009. West Conshohocken, USA: American Society of Testing and Materials.

Fadi A. Ghaith. (2010) Nonlinear finite element modeling of Charpy test. Advanced Material Research, 83-86:182-189.

Fassina P., Bolzoni F., Fumagalli G., Lazzari L., Vergani L., Sciuccati A. (2012) Influence of hydrogen and low temperature on mechanical behaviour of two pipeline steels. Engineering Fracture Mechanics, 81:43–55.

Fassina P., Brunella M.F. , Lazzari L., Reb G., Vergani L., Sciuccati A. (2013) Effect of hydrogen and low temperature on fatigue crack growth of pipeline steels. Engineering Fracture Mechanics, 103:10–25.

Fassina P, Morana R, Alleva L, Mortali G, Vergani L, Sciuccati A. (2010) Materials behavior in extreme conditions: influence of large amounts of H_2S on steel toughness in low temperature environments. Proceedings of European Corrosion Congress EUROCORR; Sep 13-17; Moscow.

ISO standards 2009. 148-1, Metallic materials - Charpy pendulum - impact test. Geneva, Switzerland: International Organization for Standardization.

Joe A. and Brian P. (2016) Hydrogen Effects on Fatigue Crack Growth Rates in Pipeline Steel Welds. Paper No. PVP 2016, pp. V06BT06A035; 10 pages.

Kobayashi T, Kim H, Morita S. (2001) Progress and development in instrumented Charpy test. Mat.-wiss. Werkstofftech; 32:525–531.

Lorriot T. (2002) Specimen loading determined by displacement measurement in instrumented Charpy impact test. Engng. Fracture Mech. ;65:703–713.

Melaina, O. Antonia, and M. Penev. (2013) Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues M. W. National Renewable Energy Laboratory March 2013.

Mulder G., Hetland J. and Lenaers G. (2007) Towards a sustainable hydrogen economy: Hydrogen pathways and intrastructure. International Journal of Hydrogen Energy, 32 Issue 10-11, pp 1324-1331.

Murakami Y. Metal Fatigue: (2002) Effects of Small Defects and Nonmetallic Inclusions. Oxford: Elsevier.

Newman JF, Shreir LL. (1997) Role of Hydrides in Hydrogen Entry into Steel from Solutions Containing Promoters. Corrosion Science, 9:631-641.

Nykyforchyn H, Lunarska E, Tsyrulnyk OT, Nikiforov K, Genarro ME, Gabetta G. (2010) Environmentally assisted ‘‘in-bulk’’ steel degradation of long term service gas trunkline. Engineering Failure Analysis, 17:624–632.

Nykyforchyn M., Zvirko I., Tsyrulnyk T. (2016) Hydrogen assisted macrodelamination in gas lateral pipe. 21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Petr Hausild, Clotilde Berdin, Andreas Rossoll. (2005) Modelling of the Charpy impact test in the DBTT rang. Materials science Forum, 482:331-334.

Rothwell AB. (2000) Fracture propagation control for gas pipelines – past, present and future. Pipeline Technology, l.1:387–405.

Tronskar JP, Mannan MA, Lai MO. (2002) Measurement of fracture initiation toughness and crack resistance in instrumented Charpy impact testing. Engng Fracture Mechanics, 69:321–38.

Vergania Laura, Chiara Colombo, Giorgia Gobbi, Fabio Maria Bolzoni and Gabriele Fumagalli (2014) Hydrogen effect on fatigue behavior of a quenched&tempered steel. International Colloquium on Mechanical Fatigue of Metals 74:468 – 471.

Yasuhito Takashima, Mitsuru Ohata and Fumiyoshi Minami. (2006) Evaluation method for fracture mechanics based material toughness from Carpy impact test. Materials science Forum, 512:61-66.

Yongjie Ma, Xilu Liu,Guangliang Zang. (2011) Quenching temperature's impact on the microstructure and mechanical properties of X80 pipeline. Advanced material research, 308-310:762-766.

Zheng Yang, Chunyong Huo and Wanlin Guo. (2005) The Charpy notch impact test of X70 pipeline steel with delamination cracks. Key engineering materials, 297-300: 2391-2396.