Study of the mechanics fracture in API 5L X70 and X70 steel pipes.

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Abstract

The development of petroleum exploitation in deep water (deeper than 1000 meters), demands the utilization of high strength steel pipes used to allow the flow of oil production.

The undersea 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.

These defects can be caused by various situations such as: Impact of components that falls from the offshore platform, excessive bending at the installation processes, superficial cracks caused during the transportation of the lines, among others.

Aiming to enhance the reliability of the installation and operation of complex offshore 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 X65 and X70 steels pipes.

The criterion of fracture mechanics used in the analysis was the CTOD (Crack Tip Opening Displacement) at low temperature.

Keywords: Fracture Toughness, CTOD, X65 and X70 steels pipes.

Introduction

Recent discoveries of petroleum and gas reserves in environments with severe operational conditions, such as artic regions and deep waters (deeper than 1000 meters), have pushed the utilization of steel procurement specification even stricter than they used to be. The main modifications concerns the mechanical resistance, toughness at low temperatures (less than 0^oC), weldability and resistance to embrittlement related to hydrogen[1].

In such context, the application of API 5L grade pipes such as X65 and X70, which consist in **High Steel Low Alloy (HSLA),** is presented as a potential solution to enhance the reliability in the operation of these pipes in hostile environments and consequently the attendance of all most strict details posted in the steel procurement specifications.

HSLA steels, where the carbon content is around 0.06% in weight, have been having na outstanding performance relate to regular C-Mn steels, due to their better combination of mechanical resistance and toughness. This combination is given through the addition of microalloying elements as Mo, Ti, V, Ni and Nb; and also due to thermo-mechanical heat treatments [1,2].

Microalloyed steels, as the HSLA, are characterized by their presentation of significant microstructural variations which results from different chemical composition and from different cooling rates after the thermo-mechanical heat treatments. The final desired properties are to have better resistance and toughness [1].

These steels can be rolled by the **Thermomechanical Controlled Rolling (TMCR)** process or by **Thermomechanical Controlled Process (TMCP)**. The TMCR consists in rolling slabs into plates in three main steps. First, rolling in temperatures of austenite recristallization (around 1250^oC); second, rolling in austenite non-recristallization temperatures (around 1050^oC); and third, finishing rolling in austenite – ferrite Ar_3 temperature (or even at lower temperatures depending on the carbon content and on the mechanical resistance aimed) and finally air cooled. The TMCP consists in the TMCR process followed by na water accelerated cooling after the third step of the controlled rolling [3,4]. However, there is a fundamental difference between both TMCR and TMCP processes, the final rolling pass temperature. In the TMCR process this temperature is lower because, as this process does not have accelerated cooling, the mechanical properties should be guaranteed during the final rolling pass. Reducing the temperature in this third step of the process TMCR gives the material microtextures in the steel microstructure. These textures have different orientations through steel plates thicknesses, which causes the development of residual stresses in the as rolled material and which allows the appearance of separations, figure 4 in the surface of Charpy and CTOD body specimens, with notches perpendicular to the plate surface, and fracture plan perpendicular to the rolling direction.

It is well known through the technical references that the separations suffer the influence not only from the rolling temperature, but also from the chemical composition, strain rate and quantity of non-metallic inclusions. The non-metallic inclusions, for example, behave as preferable nucleation sites for the separations, with the propagation occurring in grain boundaries in preferable crystallographic plans and in areas with segregation [5,6].

The CTOD parameter, in conjunction to the crack surface analysis, represents a precise technical to evaluation of the influence of microstructural variables in the mechanical behavior of metallic materials. Another factor enhancing the importance of CTOD is that, nowadays, this parameter is one of the most important for materials selection which will be submitted to severe environment working conditions. This can be seen in standards used in projects of offshore linepipes such as DNV OS F101 and N-1678 [7,8].

OBJECTIVE

The objective of this paper is to study the morphology of the separations and to determine the metallurgical factor more important for its occurrence in X65 and X70 steels, as well as to evidence the toughness resistance of these materials.

MATERIALS AND METHODS

The materials used in this research were extracted from base metal of API X65 and X70 pipes produced in a Brazilian steel Mill. The steels were microalloyed with Nb, Ti, V and Mo. The materials were send to us in plates with the following dimensions: 1.521 mm x 21,2 mm x 12.450 mm for the X65 and 1.978 mm x 26,3 mm x 12.450 mm for the X70.

Pipe formation technique used was the U-O-E process with longitudinal SAW (Submerged Arc Weld), as can be seen in figure 1. The API X65 pipes were produced with an external diameter off 508 mm. The X70 pipes were produced with an external diameter of 660,40 mm.

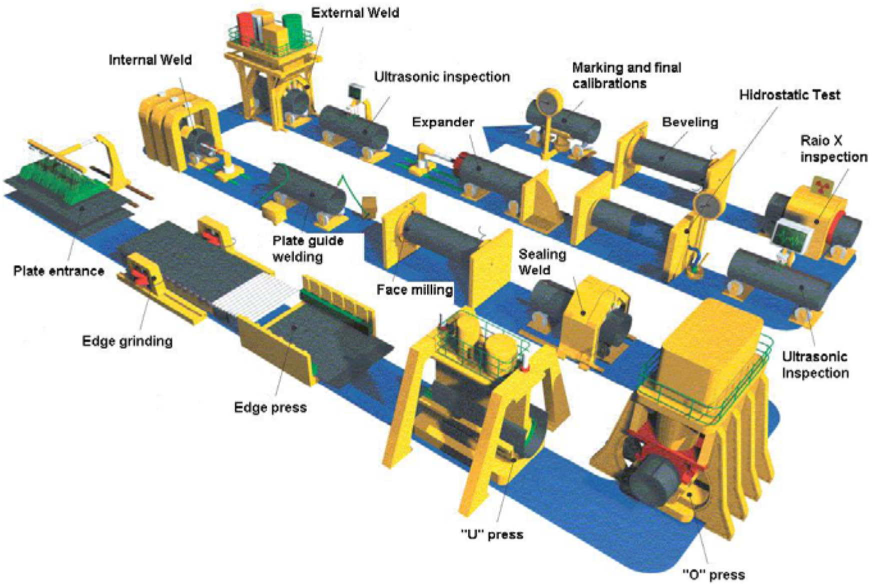


Figure 1: UOE/SAW pipe process

The chemical analyses were performed according to ASTM A751 using the gasometrical analysis and plasma spectrometry [9].

The tensile tests were performed in the longitudinal and transversal directions in relation to the rolling direction, which is parallel to the weld line. Figure 2 shows the positions and directions from which the specimens were taken. The tests were done according to the ASTM A370 standard with rectangular section specimens, with 450 mm length, 50 mm width and 38,1 mm width of the reduced section. The thicknesses of the specimens were the same of the pipes, i.e., 21.2 mm for the X65 and 26.4 mm for the X70 [10,11].

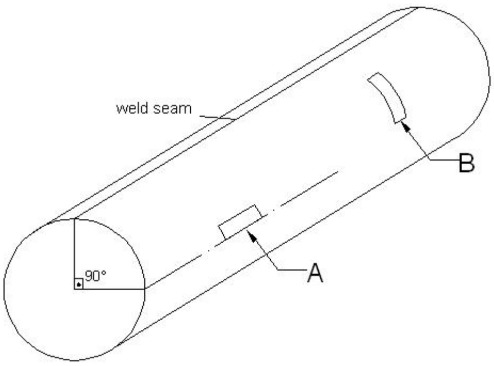


Figure 2: Tensile specimen taken position

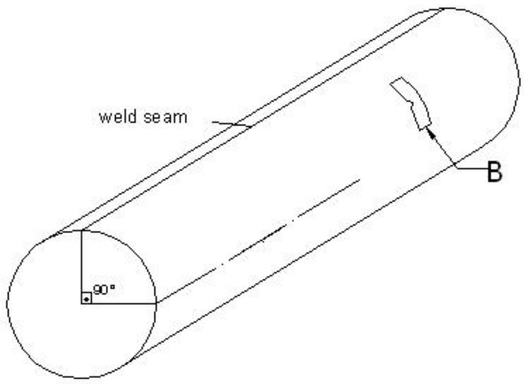


Figure 3: Charpy impact and CTOD specimen taken

Note:

A – Longitudinal tensile specimen

B – Transversal Tensile specimen (figure 2), Charpy impact and CTOD specimens (figure 3).

The Charpy tests were also performed according to the ASTM A370 standard. Tests were done with the notch plan directed transversally to the rolling direction as illustrate in figure 3. Specimens had dimensions of 55 mm x 7,5 mm, length x width, with notch centralized in relation to the length. Test temperatures were in the range –70^{o}C to 25^{o}C.

The toughness criterion used was the CTOD (Crack Tip Opening Displacement), were the test temperature was -10^{o}C and the specimens were made as type SE(B), three point bend. These tests followed the methodology described in BS 7448 standard part 1, with maximum load. The dimensions of the specimens were: 200 mm x 40 mm x 20 mm (length x width x thickness) and taken at transversal pipes direction, figure 3 [12].

CTOD tests were done in a servo-hydraulic machine MTS 810 with 100 kN capacity. A clip-gage was placed in the top of the notch and monitored its opening as a function of the applied load, allowing to plot a graphic called CMOD (Crack Mouth Opening Displacement) versus applied load. The specimens were immersed in a water/alcohol bath, cooled with solid CO2, were the temperature was controlled with thermocouples, one of them linked to the data acquiring system, and the other to a digital thermometer. Specimens' temperatures were stabilized during 20 minutes at –10^{o}C temperature before they were submitted to the loading process. Figure 4 shows the device used in the CTOD tests.

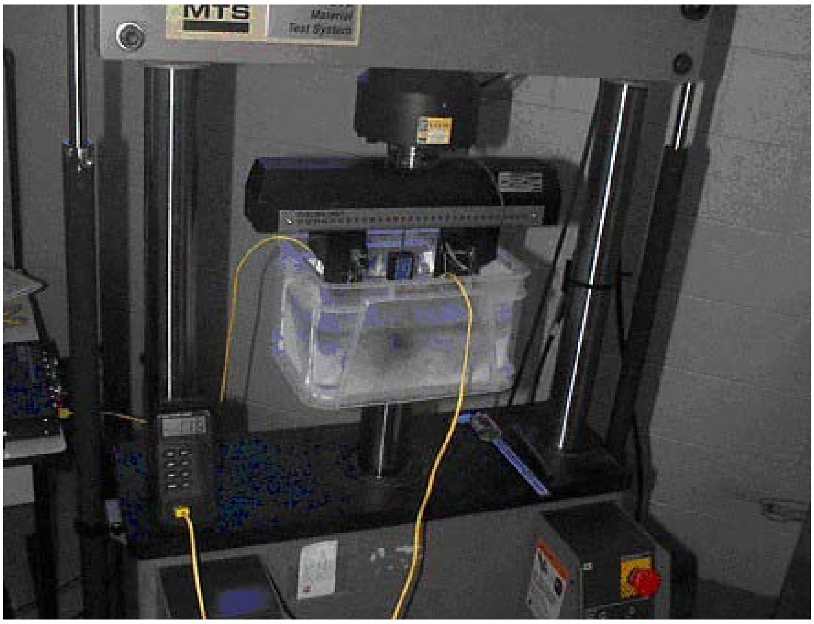


Figure 4: CTOD experimental apparatus

Results and Discussion

Chemical analysis

Carbon, sulfur and nitrogen contents were measured by gasometrical analysis, while the other elements weight percentage were measured by plasma spectrometry. Tables 1 and 2 show the chemical element contents in the base metal of pipes API X65 and X70, respectively.

C	Mn	Ca	S	P	Mo	Nb+Ti+V	Al/N	CE	Pcm
0.07	1.63	0.0023	0.001	0.015	0.006	0.12	5.9	0.37	0.17

Table 1: Average values in weight % of main elements and chemical parameters of pipes X65.

C	Mn	Ca	S	P	Mo	Nb+Ti+V	Al/N	CE	Pcm
0,09	1,72	0,0022	0,001	0,016	0,006	0,12	5,1	0,40	0,19

Table 2: Average values in weight % of main elements and chemical parameters of pipes X70.

Transverse and longitudinal tensile test

Tables 3 and 4 present obtained values of yield strength (YS), tensile strength (TS), elongation and YS/TS ratio for pipes X65 and X70, respectively.

Transverse specimen				Longitudinal specimen			
YS (MPa)	UTS (MPa)	El (%)	(YS/UTS)	YS (MPa)	UTS (MPa)	El (%)	(YS/UTS)
522.5	608.5	44.4	0.86	541.0	608.5	43.5	0.89

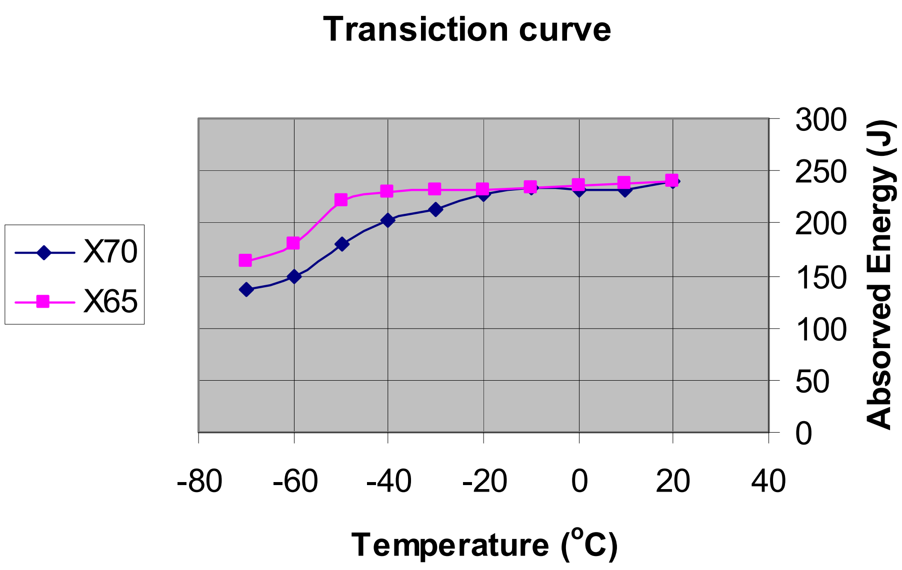
Table 3: Average obtained values in tensile tests for grade X65.

Transverse specimen				Longitudinal specimen			
YS (MPa)	UTS (MPa)	El (%)	(YS/UTS)	YS (MPa)	UTS (MPa)	El (%)	(YS/UTS)
528.5	650.5	44.5	0.81	538.0	614	46.5	0.88

Table 4: Average obtained values in tensile tests for grade X70.

Charpy impact test

The under graphic illustrates the transition curves obtained for pipes X65 and X70. The average absorved energy are multiplied for subsize factor that is 0,75 [11].



Graphic 1: Average Transition Curves obtained in Charpy tests.

Fracture Toughness test

Tables below show the CTOD values for the steels of the studied pipes. For CTOD calculation, the criterion that was used was the intensity of load drop in the instability points, pop-in, established by BS 7448 standard part 1. According to this criterion, if the load drop ($d_n\%F_1$) in the load x dislocation curve is bigger than 5% in the pop-in, the drop in considered significant and the CTOD should be calculated using the stress value at the graphic discontinuity beginning, region of instability.

CTOD values presented in tables 6 and 7 were calculated taking the maximum load values from the graphic load x dislocation, as in none of the tests, for both grades, the pop-in presented were significant, i.e., the load drop at the instability points was always lower than 5%.

Specimen	W [mm]	a_o [mm]	B [mm]	$CTOD_m$
SE(B) A	40.02	21.15	20.02	0.945
SE(B) B	40.01	21.40	20.01	0.836
SE(B) C	40.02	21.99	20.01	0.968
SE(B) D	40.02	21.00	20.03	0.736

Table 5: CTOD values obtained for grade X65.

Specimen	W [mm]	a_o [mm]	B [mm]	$CTOD_m$
SE(B) 01	40.05	21.75	19.99	0.519
SE(B) 02	40.05	22.07	20.00	0.551
SE(B) 03	40.07	21.71	20.00	0.540
SE(B) 04	40.06	21.04	20.05	0.617

Table 6: CTOD values obtained for grade X70.

Nevertheless, the pop-ins those were present in the CTOD tests for pipes X65 and X70 were caused by separations or delaminations in plans perpendiculars to the fatigue crack plan. Figure 5 illustrates the fatigue crack plan showing the separations.

a) X65 b) X70

Figure 5: Specimen crack surface after CTOD test.

The separations are parallel to the plates rolling surfaces. These separations have a brittle-ductile propagation mechanism, i.e., the crack initiates in a brittle way (cleavage) and after is arrested by a ductile region. Figures 6 and 7 illustrates the surface of delaminations for grade X65.

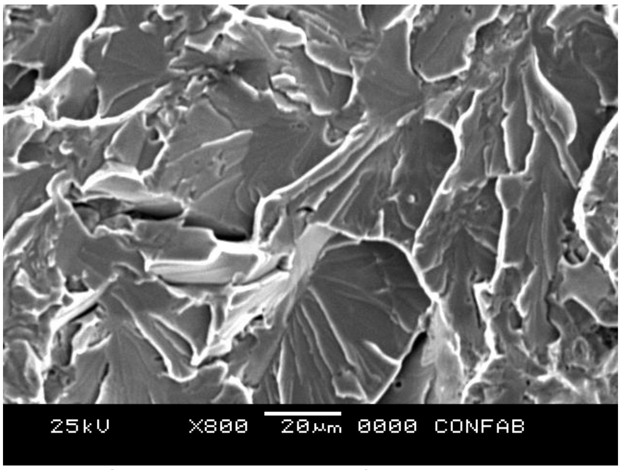


Figure 6: Separation plane. Brittle fracture by transgranular cleavage.

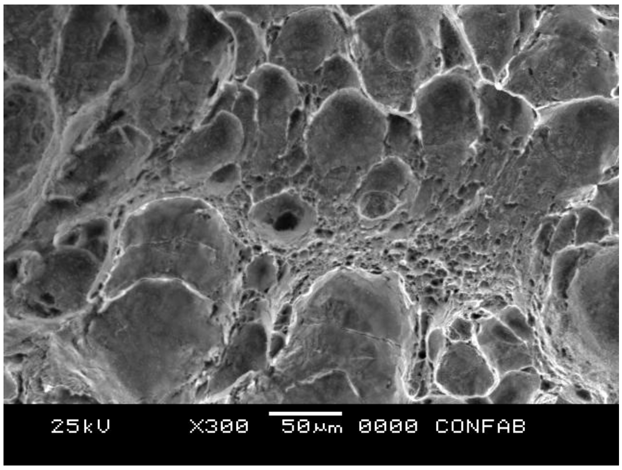


Figure 7: End of separation. Ductile Fracture (*Dimples*).

In case of X70 pipe, it was not possible to study the separation surface, as for this grade the defects present a very small opening which makes the specimen preparation process much more difficult. A finer metallographic preparation will be done (unfortunately not for this paper) with the objective of revealing and characterizing the separation surface of grades X70.

Conclusion

The pop-in related to the separation phenomenon is considerably less critical if compared to the instability due to the brittle propagation of the fatigue crack and posterior arrestment of such crack, as usually occurs in CTOD tests. This statement is based in the fact that delaminations occurs in a certain material to relieve the stresses oriented in the thickness direction of the specimen, σ_{zz}, in plans of preferential crystallographic orientation, textures. The texture's residual stresses related to the applied stresses, stress concentrators (notch + fatigue crack) and the low temperature; cause the delaminations during the CTOD tests.

Therefore, it is very conservative to analyze the load x dislocation graphic pop-ins, when they can be attributed to separations. This is because the analysis will be based on the unstable propagation of the fatigue crack;

The cleanliness level and the appearance of globulized inclusions in the base metal, have a secondary role in the separation occurrence, because the main factors related to the separations are the textures formed in the thermomechanical controlled rolling with finishing temperatures below Ar_3 and low cooling rates (air cooling). Nevertheless, as we decrease the S content and globalize the inclusions, we increase the toughness and consequently the probability of separations occurrence in the material;

Stresses σ_{zz} decrease during the separation propagation, which consolidates the theory that the delaminations are a phenomenon of stress relief due to its load state;

The delaminations in grades X65 occur by a ductile – brittle fracture mechanism, initiating in a brittle way by transgranular cleavage, and ending ductile;

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