FRACTURE BEHAVIOUR AND DEFECT EVALUATION OF LARGE DIAMETER, HSLA STEELS, VERY HIGH PRESSURE LINEPIPES

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ABSTRACT

Actually, the increase in natural gas needs in the European market, foreseen for the beginning of the next century, compels to develop new solutions for the exploitation of gas fields in remote areas. For natural gas transportation over long distances the hypothesis of a large diameter high-pressure pipeline, up to 150 bar (doubling of the actual one) has been found economically attractive, resulting in significant reduction of the transportation cost of the hydrocarbon. In this contest the interest amongst gas companies in the possible applications of high-grade steels (up to API X100) is growing. A research program, partially financed by E.C.S.C. (European Community for Coal and Steel), by a joint co-operation among Centro Sviluppo Materiali (CSM), S.N.A.M. and Europipe in order to investigate the fracture behaviour of large diameter, API X100 grade pipes at very high pressure (up to 150 bar) has been carried out.

This paper presents: the current status of technology of API X100 steel with respect to the combination of chemical composition, rolling variables and mechanical properties the results obtained from West Jefferson tests, in order to confirm the ductile-brittle transition behaviour stated from laboratory tests (DWTT), the results obtained concerning the control of long shear propagating fracture and in particular the results of a full scale crack propagation test on line operating at very high hoop stress (470 MPa). Besides, in order to investigate the defect tolerance behaviour of the pipe with respect to axial surface defect, burst tests with water as pressurising medium have been carried out and the relative results are presented and discussed.

INTRODUCTION

The growth in natural gas needs on the European market, foreseen for the immediate future, leads to the necessity of developing new transportation solutions in order to exploit gas fields placed in remote areas, 5000-6000 km far from market regions.

In order to verify the possible application of high pressure, long distance natural gas transportation, in 1995 E.N.I. sponsored a research program developed by a joint co-operation with the aim of assessing the fracture behaviour of large diameter, heavy wall thickness, high steel grade (API 5L X70 and X80) pipes for operating pressure over 15 MPa/1/.2/. Also on the basis of the obtained results, showing, for this supply scenario, substantial cost savings (30-35%) it has been decided to carry on this type of activity,
passing to the assessment of fracture behaviour of higher steel grade.

The API X100 steel pipes are nowadays industrially producible, even if not yet used /3/; so the aim of the research, carried out by a joint co-operation among CSM, SNAM and Europipe (partially financed by E.C.S.C. /4/), was not the determination of the pipes toughness requirements for a specific project, but the definition of the fracture behaviour and the validation of existing predictive methods in order to avoid fracture phenomena in large diameter up to 56", API X100 SAW linepipes operated at pressure up to 150 bar.

In order to do this, the fitness of DWT Test /5/ in defining ductile to brittle transition temperature has been detected by means of comparing their results with those obtained with full scale West Jefferson tests. The validity of the current approach /6/ /7/to ductile fracture propagation control, by means of predictive CharpyV formulae, has been investigated with a full scale burst test at very high hoop stress (470 MPa). Understanding the behaviour of defects and their consequences on the serviceability of high-pressure pipelines is another key point to be solved in order to assure complete safety in their application. Respect to this point, it is particularly important to validate the relation between flaw size and failure stress, developed by Battelle Memorial Institute on the base of experimental results obtained on lower grade pipes /6/. This aspect has been investigated by means of burst tests, with water as pressurising medium, carried out on test pipes with suitable machining notch. This paper presents the results obtained in this specific joint test project.

MATERIALS

The material used is a special High Strength Low Alloy steel obtained by means of a suitable combination of chemical composition and thermomechanical treatment parameters in order to have a balance between strength, toughness and weldability. The plates were made by Dillinger Hutte, using controlled rolling and on line accelerated cooling, afterwards Europipe formed the plates to pipes in their Mulheim UOE pipe mill.

In order to achieve minimum values on pipe, the following mechanical properties values, table 1, have to be reached on API X100 plate:

<table>
<thead>
<tr>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>YS/UTS [%]</th>
<th>Elong. A5 [%]</th>
<th>Shelf Charpy V Energy (J)</th>
<th>DWTI 85% Shear Area (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;690</td>
<td>&gt;770</td>
<td>≤0.9</td>
<td>≥18</td>
<td>≥150</td>
<td>≤-20</td>
</tr>
</tbody>
</table>

Table 1: Requirements of API X100 plates.

In particular the Charpy V toughness levels were design in the range 150 - 300 J on the base of specific full scale test requirements.

In table 2 is reported the actual chemical composition of a standard pipe together the minimum and maximum target values.

<table>
<thead>
<tr>
<th></th>
<th>Actual [%]</th>
<th>Minimum [%]</th>
<th>Maximum [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.066</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>Si</td>
<td>0.302</td>
<td>0.20</td>
<td>0.35</td>
</tr>
<tr>
<td>Mn</td>
<td>1.93</td>
<td>1.90</td>
<td>2.00</td>
</tr>
<tr>
<td>S</td>
<td>0.0024</td>
<td>/</td>
<td>0.003</td>
</tr>
<tr>
<td>Cu</td>
<td>0.215</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>Al</td>
<td>0.041</td>
<td>0.020</td>
<td>0.05</td>
</tr>
<tr>
<td>Cr</td>
<td>0.031</td>
<td>/</td>
<td>0.10</td>
</tr>
<tr>
<td>Ni</td>
<td>0.333</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Mo</td>
<td>0.168</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>Nb</td>
<td>0.043</td>
<td>0.040</td>
<td>0.050</td>
</tr>
<tr>
<td>Ti</td>
<td>0.018</td>
<td>0.015</td>
<td>0.020</td>
</tr>
<tr>
<td>B</td>
<td>0.0001</td>
<td>/</td>
<td>0.0003</td>
</tr>
<tr>
<td>PCM</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CElIIW</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Typical chemical composition of API X100 steel.

The range of design parameters for controlled rolling and on line accelerated cooling process are reported on the table 3.

<table>
<thead>
<tr>
<th>Reheating Temperature (°C)</th>
<th>Finish rolling Temperature (°C)</th>
<th>Cooling stop Temperature (°C)</th>
<th>Cooling rate (°C/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1140 ÷ 1200</td>
<td>670 ÷ 710</td>
<td>200 ÷ 400</td>
<td>20 ÷ 50</td>
</tr>
</tbody>
</table>

Table 3: Plate manufacturing parameters.
The relative wide range of rolling parameters was necessary to achieve the different toughness levels and finally all pipes produced from these plates reached the expected mechanical properties.

**DUCTILE TO BRITTLE TRANSITION TEMPERATURE**

The fitness of 85% shear area Battelle criterion, based on the DWT Test, to define the ductile to brittle transition temperature for API X100 has been investigated by comparing laboratory DWT Test and full scale West Jefferson tests.

In order to determine the ductile to brittle transition curve the DWT Tests on full thickness specimens have been carried out and two full scale West Jefferson tests have been performed at temperature below zero. The tests have been conducted using water as a pressurising medium, with a limited percentage of air (5 to 10%) to assure enough energy to propagate the fracture, at a pressure (about 133 bar) corresponding to 72% of the specified minimum yield strength. The temperatures at which the West Jefferson tests were carried out had been selected in order to reproduce upper and central part of the DWTT transition curve. The instrumentation used to measure the test temperature was formed by a series of thermocouples placed inside and outside the pipe.

In figure 1 can be observed the transition curves obtained by DWT tests and Charpy V tests in comparison with the West Jefferson tests results. It can be noted the Battelle criterion is completely fulfilled and the DWT tests allow determining the pipe transition temperature in a conservative way even if the full-scale results are a little spread. This fact can depend also from the scatter due to both temperature measurements and difficulty to detect the brittle percentage because this steel usually shows a lot of separations. In figure 2 the typical fracture surface of both DWTT specimen and West Jefferson test carried out at -20 °C are shown.

The results show that for the APIX100 steel the validity of the Battelle criterion is confirmed and that the DWT Test is able to determine the pipe transition temperature in a conservative way. These results are in agreement with previous experimental experiences.[2].

**FRACTURE PROPAGATION EVALUATION BY FULL-SCALE BURST TEST**

In order to assess the existing predictive formulae for arresting ductile propagation fracture behaviour of API X100 large diameter pipeline, a full-scale test has been carried out at the CSM Perdasdefogu shooting Test Station in Sardinia.

Seven pipes have been used in this full-scale ductile fracture propagation test: one initiation pipe, six test pipes and two reservoirs to avoid the reflection of the pressure waves and their interaction with fracture propagation. The test line was about 70 m long and consisted of pipes having an increasing Charpy V toughness from the centre. In figure 3 test lay-out, Charpy V shelf energy at room temperature and predictive Battelle formulae fracture behaviour, in terms of arrest (A) and propagation (P) event of a running crack, are shown. In table 4 the mechanical properties, at room temperature, of API X100 pipes involved in the burst test are reported, in particular it must be remembered all specimens are taken transversally to pipe axis and Charpy V shelf energy on full size specimen.

<table>
<thead>
<tr>
<th>Test Line (West side)</th>
<th>Yield Strength YS [MPa]</th>
<th>Tensile Strength TS [MPa]</th>
<th>YS/TS</th>
<th>Charpy V Average [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>846020</td>
<td>707</td>
<td>766</td>
<td>0.92</td>
<td>271</td>
</tr>
<tr>
<td>84038</td>
<td>719</td>
<td>766</td>
<td>0.94</td>
<td>245</td>
</tr>
<tr>
<td>846129</td>
<td>780</td>
<td>832</td>
<td>0.94</td>
<td>200</td>
</tr>
<tr>
<td>846113 (Init. pipe)</td>
<td>773</td>
<td>858</td>
<td>0.90</td>
<td>151</td>
</tr>
<tr>
<td>846058</td>
<td>755</td>
<td>829</td>
<td>0.91</td>
<td>170</td>
</tr>
<tr>
<td>846157</td>
<td>663</td>
<td>762</td>
<td>0.87</td>
<td>263</td>
</tr>
<tr>
<td>846061 (East side)</td>
<td>722</td>
<td>778</td>
<td>0.93</td>
<td>284</td>
</tr>
</tbody>
</table>

Table 4: Mechanical properties of X100 pipes involved in the burst test

The main full-scale burst test conditions were:
- Nominal diameter: 56" (1422.4) [mm]
- Nominal thickness: 19.1 [mm]
- Ground backfill: Soil, 1.3 [m]
- Pressurising medium: Air
- Test pressure 12.6 [MPa]
- Test hoop stress 469 [MPa] (corresponding to 68% of SMYS)
- Test temperature +20 °C

Since it is necessary to know crack speed, gas decompression behaviour inside the test pipes, test temperature at the burst time, the instrumentation used at this purpose was composed by: Timing Wires, internal pressure transducers and thermocouples.

The fracture propagation test layout is shown in figure 3: after the initiation, placed in the middle of the test length by means of an explosive shaped charge, the fracture propagated on the upper pipe generatrix at a very high speed in both test line sides. However the crack (figure 4 can be observed the appearance of the line after the burst test) had a different propagation behaviour in the West and East direction:

- **West side**: The crack, after the initiation, propagated in the first pipe, but in correspondence of the girth weld with the adjacent pipe it split in two (see figure 3) running separately both in clockwise and in counter-clockwise direction for about 200 mm along the weld joint. The two separate cracks went back in the base metal of the previous pipe (i.e. in pipe n. 846129) with an angle of about 45° respect to the girth weld, till they joined causing the severance of the test line and the ejection of the pipe n. 846129 out of the trench, more than 100 m away. Due to the severance and the consequent ejection of part of the test line, no information about West test side were available.

- **East side**: The crack propagated through the initiation pipe along the top generatrix, kept on running in the second pipe and arrested at the end of the third pipe (260 J of Charpy V energy) in correspondence of the girth weld. It is important to underline the examination of the weld zone involved in the fracture showed that the crack was always propagated in the base metal.

In figure 5 can be observed the *Fan diagram and Crack velocity on East test side*, i.e. the plot of the time of rupture of the Timing Wires versus their distance from the initiation point and, from the combination of these two type of data, the crack speed at its different position on pipes.

As mentioned above, no reliable data from West test side are available, and this figure deals only with the East test side. Making reference to the figure, the crack was initiated in the middle pipe with speed up to 300 m/s and then propagated in the 1st pipe (n.846058) with a decreasing velocity down to about 200 m/s. Afterwards the crack entered in the 2nd pipe (n. 846157) and then it kept on slowing down till the arrest. At that moment the crack speed was about 100 m/s, and then rapidly decreased to zero. This speed value is in agreement with the previous burst tests results performed on high grade modern TMCP steels (API X80) that indicate 100 m/s as the limit value before the arrest /1/. Finally the results obtained from pressure transducers assure that the crack arrest in East part was not affected by the reflection of the first decompression wave because the crack arrest occurred after the first decompression wave arrived at the end of the East reservoir.

On the base of the full scale burst test performed it can be said the toughness characteristics of X100 56" x 19.1 mm pipes, in terms of Charpy V energy, are sufficient to avoid a long running shear fracture, at the hoop stress chosen (470 MPa). In particular the toughness required to arrest the fracture in the test conditions was about 260 J, i.e. 40 % higher of predicted value of Battelle formula.

This result is in agreement with previous experience on high grade/high hoop stress pipelines /1/. Therefore in order to use the conventional Battelle predictive simplified formula /7/, based on CharpyV values, an appropriate correction factor should be used.

On the base of the full scale test results (obviously this test and also the most recent burst tests results /1/ on API X80 grade steel performed at high pressure) has been evaluated a correction factor of about 1.4, as indicated in the diagram of figure 8, where *Actual vs. Battelle predicted CharpyV energy for high grade/ large diameter steel pipes* are reported (CSM database).

**EVALUATION OF DEFECT TOLERANCE REQUIREMENTS**

The criteria for assessing the resistance of linepipes to initiation of fracture from axial defects are well established, although based on a semi-empirical approach. This implies that their reliability is limited by the experimental database used to establish the relevant equations. So the widely used Battelle formula /6/ has
been validated by full-scale tests on different classes of pipe steels with a general value of yield to tensile ratio max of about 0.87 and a Charpy V toughness in the range 30 -120 J even if a negligible fraction of the material collected refers to high grade steels (> X70) and none of them to “modern” low-carbon TMCP ultra high grade steels (> X80). In order to check if existing plastic failure criteria are still applicable for API XI00 pipeline, two hydraulic full scale tests until failure have been carried on two single pipes with a machined axial surface defect with different length/depth ratio.

The mechanical properties of the pipes tested, in terms of tensile (both longitudinal and transversal direction with round bar specimens) and Charpy V shelf energy, are reported in table 5.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>840677</td>
<td>740</td>
<td>774</td>
<td>261</td>
</tr>
<tr>
<td>846014</td>
<td>795</td>
<td>840</td>
<td>171</td>
</tr>
</tbody>
</table>

Table 5: Main mechanical properties of pipes used in defect tolerance tests.

Both tests have been performed at room temperature; the main test conditions and results are summarised in table 6. In both case a very limited plastic deformation was observed and the tests resulted in break.

<table>
<thead>
<tr>
<th>Pipe Number</th>
<th>846077</th>
<th>846014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defect length [mm]</td>
<td>180</td>
<td>385</td>
</tr>
<tr>
<td>Defect depth [mm]</td>
<td>10.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Burst hoop stress [MPa]</td>
<td>566</td>
<td>712</td>
</tr>
<tr>
<td>Burst pressure [MPa]</td>
<td>15.35</td>
<td>20.12</td>
</tr>
<tr>
<td>Maximum circumferential strain in the central section after burst</td>
<td>≈0.3 %</td>
<td>≈0.3 %</td>
</tr>
</tbody>
</table>

Table 6: Defect tolerance main test conditions and results (tests performed at room temperature).

The burst pressure of a pipe containing an axial surface flaw can be calculated using the mathematical formula reported below (developed by Kiefner at al.) /8/. This equation can be applied when the bursting behaviour is flow stress dependent, that is, for all practical purposes, the pipe failure stress is independent by the material toughness. This is historically assumed to be applicable for pipe material with Charpy V toughness above 40 Joule.

\[
\sigma_f = \frac{d}{t} \\
\sigma_0 = 1 - \frac{d}{(M \cdot t)}
\]

In literature can be found several formulas for the flow stress and Folias factor. In particular in this work the following expressions have been considered:

\[
\sigma_s = \frac{YS + TS}{2}
\]

\[
M = \sqrt{1 + 0.4025 \left( \frac{2C}{\sqrt{Rt}} \right)^2}
\]

where:
- \( \sigma_f \) = failure stress;
- \( \sigma_0 \) = flow stress;
- \( d \) = defect depth;
- \( t \) = wall thickness;
- \( M \) = Folias factor.
- \( 2C \) = defect length;
- \( R \) = pipe radius.

In figure 7 the comparison of the present X100 results with the available database CSM/SNAM of burst tests results on pipes with axial surface flaws and Charpy V toughness energy above 40 Joule is made. It can be clearly observed, for the two API XI00 pipes tested the Battelle flow-stress-dependent equation well predict the failure stress value.

**CONCLUSIONS**

The API X100 steel grade for large diameter pipes (56”x19.1mm) produced by Europipe with the process of controlled rolling plus a subsequent on line accelerate cooling, exhibited a good fracture behaviour.

The main results obtained are the subsequent:

- The pipe material shows a full ductile fracture behaviour down to -20°C.
- The validity of the DWT Test, according to the Battelle criterion, in order to evaluate the full scale pipe ductile to brittle transition temperature, has been assessed for this very high strength linepipes steel.
- The toughness characteristics of the API X100 steel grade linepipes, in terms of Charpy V energy, proved enough to warrant the arrest of a long running shear fracture on pipeline with 56” diameter, at operating pressure over 12.6 MPa, corresponding to hoop stresses about 470 MPa. The arrest Charpy V energy is about 260 J, 40% higher than Battelle formula predicted value. As regard the correction factor to be used with the Battelle simplified formula for the API X100 grade steel pipes tested in this burst test, the assumed correction factor equal to 1.4 proved sufficient.
For the pipe grade API X100 with Y/T ratio ≥ 0.93 and high Charpy V toughness ≥ 200 J, the Battelle flow-stress-dependent criteria for assessing the resistance of linepipes to initiation of fracture from axial defects well predicts the failure stress value.

Acknowledgments

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REFERENCES


4. European Coal and Steel Community Contract n. 7210-PR/058.


APPENDIX

![Figure 1: Comparison between DWTT and WJ tests results.](http://electrochemical.asmedigitalcollection.asme.org/IPC/proceedings-pdf/IPC2000/40245/V001T05A011/2507479/v001t05a011-ipc2000-168.pdf)
Figure 2: Fracture surface of both DWT and West Jefferson tests carried out at -20 °C

Figure 3: Full scale ductile fracture propagation test lay-out.
Figure 4: View of the test line after the burst (from West to East side); the severance zone is in the foreground.

Figure 5: Fracture speed, and fan diagram for the East side.
Figure 6: Actual vs. Battelle predicted CharpyV energy for high grade steel pipes (CSM database)

Figure 7: Comparison of the present X100 results with the available database