Fracture properties of API X 100 gas pipeline steels

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FRACTURE PROPERTIES OF API X100 GAS PIPELINE STEELS

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ABSTRACT

The paper deals with the fracture behaviour of API X100 UOE pipes produced by Europipe using TMCP high grade plates.

Experimental results obtained by an extensive full scale test activity carried out on both single pipes and pipeline test sections have been used to establish the criteria for defect tolerance, ductile/brittle transition temperature evaluation and the crack arrest behaviour of X100 pipes. Moreover the effect of the plate to pipe forming process on the tensile and fracture properties has been evaluated by laboratory tests.

The results show the real feasibility of these very high-grade pipeline steels for new high pressure (>150 bar) long distance gas transmission pipelines.
INTRODUCTION

API X100 steel pipes are nowadays industrially producible /1/, and their use has been demonstrated to be economically viable. But limitations might occur to their application if important aspects related to their structural reliability are not clarified. One of the essential points is dealing with the general fracture behaviour of these new materials, like defect tolerance, ductile to brittle transition and fracture arrest capability.

A research programme, partially funded by the ECSC (European Coal and Steel Community) was launched by a joint co-operation between Centro Sviluppo Materiali (CSM), Corus (formerly British Steel) Snam ENI Group and Europipe in order to investigate these aspects.

The project was focused on the definition of safety criteria against fracture phenomena on base material for large diameter, API X100 grade steel pipes operated at very high pressure (>15 MPa).

Specific objectives of the research were:

- Quantify the plate to pipe forming effect on mechanical properties and fracture resistance.
- Determine the defect tolerance requirements to prevent initiation of fracture from an axial flaw, and verify if provisional formulas currently used (based upon the Battelle flow stress dependent criterion) for lower steel grade materials are still applicable.
- The extension of current criteria regarding the ductile/brittle transition (i.e. the Battelle criterion that assumes a fully ductile behaviour on pipe at a temperature corresponding to 85% shear area on Drop Weight Tear Test specimen fracture surface) to API X100 linepipes.
- The definition of the toughness requirements for arresting fast propagating ductile fracture, in particular to verify the applicability of the existing Charpy V approaches of characterising fracture resistance for these high-grade linepipe steels.

No specific work was planned in this project concerning field weldability issues; an exploring project on X100 field weldability, together with last developments respect to X100 pipe production, has been carried out separately, and the results are illustrated in a paper presented at this conference /2/.

MATERIALS

The materials used were high strength-micro alloyed steels obtained by means of a suitable combination of chemical composition and thermomechanical treatment parameters in order to have a correct 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 /1/.

In the overall programme of work, two series of X100 plates of different thickness with a range of toughness values (150-300 J) were formed into pipe, using two different diameters, and obtaining the dimensions detailed below:
1. 56” OD x 19.1 mm wall thickness;
2. 36” OD x 16 mm wall thickness.

The typical chemical composition of both pipe geometries is reported in Table 1.

<table>
<thead>
<tr>
<th>Pipe size ODxwt</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Mo</th>
<th>Ni</th>
<th>Cu</th>
<th>Nb</th>
<th>Ti</th>
<th>N</th>
<th>CE_{jw}</th>
<th>P_{CM}</th>
</tr>
</thead>
<tbody>
<tr>
<td>56”x19.1 mm</td>
<td>0.07</td>
<td>1.90</td>
<td>0.30</td>
<td>0.17</td>
<td>0.33</td>
<td>0.20</td>
<td>0.05</td>
<td>0.018</td>
<td>0.005</td>
<td>0.46</td>
<td>0.20</td>
</tr>
<tr>
<td>36”x16mm</td>
<td>0.06</td>
<td>1.90</td>
<td>0.35</td>
<td>0.28</td>
<td>0.25</td>
<td>-</td>
<td>0.05</td>
<td>0.018</td>
<td>0.004</td>
<td>0.46</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 1 – Typical chemical compositions in wt. % (X100 base material).

The reference mechanical properties for both pipe geometries are in table 2.

<table>
<thead>
<tr>
<th>Yield strength(R_{t0.5}) (MPa)</th>
<th>Tensile strength(R_{m}) (MPa)</th>
<th>Y/T ratio(Y_m)</th>
<th>Charpy(V) upper shelf energy (J)</th>
<th>DWTT 85% shear area (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 690</td>
<td>≥ 770</td>
<td>≤ 0.93</td>
<td>&gt; 150</td>
<td>≤ -20</td>
</tr>
</tbody>
</table>

Table 2 – Tensile and toughness requirements for both pipe geometries

1. on round bar not flattened transverse specimen
2. on full-size CharpyV transverse specimen

PLATE TO PIPE FORMING EFFECT

During pipe forming, inner surface compressive and outer surface tensile, strains are produced at the “U” and “O” press stages. The radius of the skelp after “U” forming is smaller than that of the pipe after the subsequent “O” forming stage, and this will produce some strain reversal at points in the lower half of the pipe. In addition to these bending strains, small compressive strains are generally applied to the pipe during “O” forming. The pipe forming and final expansion processes will therefore involve work hardening, together with the possibility of softening associated with the Bauschinger effect in regions of strain reversal.

Despite these complications, if the relatively small compression strain is ignored, the surface strains after “O” forming can be approximated to ± t/D, where “t” is the pipe wall thickness and “D” the pipe diameter. The mechanical expansion will subsequently produce a further tensile strain of ~ 1% at both the inner and outer surfaces.

Selected plate and corresponding pipe sections were supplied to the Swinden Technology Centre for an evaluation of the changes in the mechanical properties and fracture resistance occurring as a consequence of the forming operations. Details of the sections, from both the 19.1mm and 16mm plate/pipe supplies are shown in Table 3.
<table>
<thead>
<tr>
<th>Plate / pipe thickness</th>
<th>Material Form</th>
<th>Plate/pip Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.1mm (56°Ø pipe)</td>
<td>Plate</td>
<td>38546</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>846083</td>
</tr>
<tr>
<td></td>
<td>Plate</td>
<td>38542</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>846099</td>
</tr>
<tr>
<td></td>
<td>Plate</td>
<td>35832</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>846104</td>
</tr>
<tr>
<td>16mm (36°Ø pipe)</td>
<td>Plate</td>
<td>81576</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>99449</td>
</tr>
<tr>
<td></td>
<td>Plate</td>
<td>55416</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>99450</td>
</tr>
<tr>
<td></td>
<td>Plate</td>
<td>62847</td>
</tr>
<tr>
<td></td>
<td>Pipe</td>
<td>99451</td>
</tr>
</tbody>
</table>

Table 3 - Details of the X100 plate and pipe sections tested at STC for the evaluation of the plate-to-pipe forming effect on tensile and fracture properties

The mechanical properties of the two API X100 geometries were determined in accordance with BS EN 10002 – Part 1 using round bar not flattened test pieces. Plots of the change in transverse proof stress ($R_{0.5}$) occurring from plate to pipe for the three plate/pipe combinations from the two API X100 geometries (19.1mm and 16mm) are shown in Figure 1. Both plots show that a judicious selection of the micro-alloying content and plate processing parameters raise the plate strengths from below the X100 level, to a range of levels in the corresponding pipes which all meet the X100 requirement. The average increase in strength due to pipe forming at the 19.1mm wall thickness was approximately 20%, with a 24% average increase shown by the 16mm material. The latter plate undergoes a higher bending strain ($t/D \sim +1.75\%$) during “U” and “O” forming than the 19.1mm thick plate ($t/D \sim +1.34\%$), and probably accounts for the greater strength increase observed as a consequence of forming.

![Graph](image_url)

(a) 19.1mm wall thickness
(b) 16mm wall thickness

Figure 1 – Proof stress ($R_{0.5}$) change from plate to pipe round bar not flattened test pieces, transverse orientation
Once again a comparison was made between the results of tests carried out on plate and corresponding pipe material, using Charpy “V” notch test pieces taken from equivalent positions within the plate (quarter width location) and pipe (90° location), and tested in accordance with BS EN 10045-1:1990.

Charpy fracture energy values, plotted as a function of test temperature for the three 19.1mm and three 16mm thick plate/pipe pairings, are shown in Figs 2 and 3 respectively. Whilst significant differences in transition behaviour can be observed between individual plates, particularly for the 16mm wall thickness data, the differences between plates and their corresponding pipes are less marked.

In most cases the pipe forming produces a slight raising of the transition temperature, and in one case (pipe no. 846083) a possible reduction in the shelf energy.

Drop weight tear test (DWTT) pieces, again taken from equivalent positions within the plate and pipe sections, were tested in accordance with BS EN 10274:1999. Data generated in the tests are presented in the form of specific fracture energy (energy per unit area) values plotted as a function of test temperature in Figs 4 and 5 for the 19.1mm and 16mm plate/pipe pairings respectively.

The three plots in Figure 4 (19.1mm) show a close agreement between the plate and pipe data, with no discernible shift in either the transition temperature or upper shelf energy values. For the 16mm plate and pipe data, the only major difference between the pairs occurs in plate no. 81576 / pipe no. 99449 (Figure 5a), where the upper shelf energy is reduced in the pipe tests. This was not picked up in the Charpy tests due to the test machine’s inability to break either plate or pipe specimens in the relevant temperature range.

The other point worthy of note in Figure 5 is the rising shelf behaviour and relatively low toughness at ambient temperature in plate no. 55416 / pipe no. 99450 (Fig. 5b), a feature noted earlier in the Charpy tests, and associated with the appearance of separations on the fracture surfaces.
Figure 3 – CharpyV fracture energy plotted as a function of test temperature for the three 16mm plate and pipe combinations (transverse orientation)

Figure 4 – Specific DWTT fracture energy plotted as a function of test temperature for the three 19.1mm plate and pipe combinations (transverse orientation)
By careful selection of alloying content and plate processing parameters, pipes have been produced which comfortably meet the API X100 strength requirement, and also exhibit high levels of toughness, as measured in Charpy V notch and DWTT tests. The cold forming processes involved in pipe production have been shown to be responsible for significant increases in proof stress from the original plate to the finished pipe. These strength increases do not appear to seriously affect the pipe toughness, which show relatively minimal changes to the levels established in plate material.

DEFECT TOLERANCE REQUIREMENTS

The criteria for assessing the resistance of steel linepipes to initiation of fracture from axial defects are well established, although based on semi-empirical approaches. This implies that their range of applicability is limited by the experimental database used to establish the relevant equations.

The widely used Battelle formula, for example, 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 to 120 J. However, only a negligible fraction of these refer to high-grade steels (> X70) and none of them to “modern” low-carbon TMCP ultra high-grade steels (> X80). This class of high grade steels shows high toughness (>200J) and at the same time a high value of yield to tensile ratio (>0.90), and therefore a devoted study concerning their final failure in the presence of axial surface defects has particular and strategic relevance in order to check if existing plastic failure criteria are still applicable.

With the aim of filling this gap, the activities were focused on the evaluation of the defect tolerance requirements to prevent initiation of fracture from axial surface flaws in base material, by carrying out four hydraulic tests on single pipes on both geometries (56”x19.1mm and 36”x16mm) with machined axial surface defect with different length/depth ratio. All the tests were carried out at room temperature, filling the samples with water (100%) until failure occurred.
When the bursting behaviour is flow stress dependent the criterion for the failure of the pipe containing a surface flaw is given by the well known Battelle formula (equation 1 /3/). This is historically assumed to be applicable for pipe material with Charpy V toughness levels above 40 Joules, which clearly is the for the X100 materials tested in this project.

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

Equation 1 – Battelle flow stress dependent formula

Where:
\( \sigma_f \) = failure stress;
\( \sigma_0 \) = flow stress;
\( d \) = defect depth;
\( t \) = wall thickness;
\( M \) = Folias factor, which accounts for stress amplification at the ends of the flaw resulting from outward radial deflection along the flaw.

Several formulas can be found in the literature for both the flow stress and Folias factor. In previous work /4/ it was demonstrated that there is not relevant influence on the overall accuracy of the Battelle equation in choosing a particular Folias factor definition from amongst those available. The same was demonstrated for the flow stress definition. In the present work the following expressions have been considered:

\[
\sigma_0 = \frac{Y_S + T_S}{2}
\]

Equation 2 – Flow stress

\[
M = \sqrt[3]{1 + 0.4025 \left( \frac{2C}{Rt} \right)^2}
\]

Equation 3- Folias factor

\( Y_S = \text{yield strength}, T_S = \text{tensile strength} \) \( 2C = \text{defect length}, R = \text{pipe radius} \)

The mechanical properties of the tested pipes together with the main test conditions and results are reported in Table 4.

<table>
<thead>
<tr>
<th>Pipe size (OD x WT)</th>
<th>56”x19.1mm</th>
<th>56”x19.1mm</th>
<th>36”x16mm</th>
<th>36”x16mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe n.</td>
<td>846077</td>
<td>846014</td>
<td>99457 (half-pipe)</td>
<td>99457 (half-pipe)</td>
</tr>
<tr>
<td>Actual wall thickness (mm)</td>
<td>19.25</td>
<td>20.1</td>
<td>16.4</td>
<td>16.4</td>
</tr>
<tr>
<td>Yield strength Rt0.5 (MPa)</td>
<td>740</td>
<td>795</td>
<td>739</td>
<td>739</td>
</tr>
<tr>
<td>Tensile strength Rm (MPa)</td>
<td>774</td>
<td>840</td>
<td>813</td>
<td>813</td>
</tr>
<tr>
<td>CharpyV shelf energy (J)</td>
<td>261</td>
<td>171</td>
<td>253</td>
<td>253</td>
</tr>
<tr>
<td>Y/T ratio</td>
<td>0.96</td>
<td>0.95</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Defect length 2C (mm)</td>
<td>180</td>
<td>385</td>
<td>150</td>
<td>450</td>
</tr>
<tr>
<td>Defect depth d (mm)</td>
<td>10.4</td>
<td>3.8</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>Depth/thickness ratio</td>
<td>0.54</td>
<td>0.19</td>
<td>0.55</td>
<td>0.37</td>
</tr>
<tr>
<td>Expected burst stress according to equation 1 (MPa)</td>
<td>568</td>
<td>723</td>
<td>555</td>
<td>551</td>
</tr>
<tr>
<td>Exper. burst pressure (bar)</td>
<td>153.5</td>
<td>201.2</td>
<td>214.0</td>
<td>240.2</td>
</tr>
<tr>
<td>Exper. burst hoop stress (MPa)</td>
<td>567</td>
<td>712</td>
<td>597</td>
<td>670</td>
</tr>
<tr>
<td>Maximum circumferential strain in the central section after burst</td>
<td>≈0.3%</td>
<td>≈0.3%</td>
<td>≈0.3%</td>
<td>≈0.3%</td>
</tr>
</tbody>
</table>

Table 4 – Defect tolerance test conditions and main results
(tensile data on round bar not flattened specimen, transverse orientation)
In Figure 6 the comparison of the present X100 results on both pipe geometries (56” and 36” OD) with the available CSM/Snam database of burst test results on lower grade steel pipes with longitudinally oriented V shaped machined surface flaws and CharpyV toughness above 40 Joule is presented.

![Flow stress dependent Battelle formula](image)

**Figure 6 – Comparison of the present X100 results with the available database**

The main result coming from Figure 6 is that the Battelle formula predicts well the failure stress value of X100 pipes with a slightly higher conservative level for the 36” pipe geometry, which is associated with a lower Y/T ratio (Table 4).

In general the capability of the Battelle equation to correctly predict the failure for the X100 tested pipes is as good as for lower grade steels data.

**DUCTILE TO BRITTLE TRANSITION TEMPERATURE**

Experiments carried out since the 1970’s show that there exists a correlation between the percentage shear area (and the transition temperature) of a Drop Weight Test Test (DWTT) specimen and the full-scale linepipe; the fracture propagation transition temperature on pipe material is normally taken to correspond to the temperature at which a DWTT specimen exhibits at least an 85% shear area fracture (Battelle criterion). This requirement ensures that the linepipe steel cannot exhibit brittle fracture behaviour in full-scale conditions.

Over the last years this approach has been confirmed /5/ on large diameter pipes with mechanical properties corresponding to steel grades from API X65 to X80, and high thickness (26 to 30.5mm).

In order to verify the validity of the DWTT for the prediction of full scale behaviour in X100 linepipes, the ductile to brittle transition curves have been measured and the results compared with those obtained by two West Jefferson (WJ) tests carried out on two 56”x19.1mm samples (two halves of the same X100 pipe n. 846176) at two different low temperatures below zero.
The ductile/brittle transition curves have been established using both Charpy V and full thickness Battelle DWTT specimen with a pressed notch in accordance with the API RP 5L3 Recommendations /6/.

The WJ tests were carried out by CSM at a nominal pressure (133 bar) equivalent to about 72% of the SMYS. The tests were performed using water as a pressurising medium, with a small percentage of air (about 5%) to assure enough energy to propagate the fracture. The temperatures at which the WJ tests were carried out have been selected in order to reproduce the upper and the central part of the DWTT transition curve. The instrumentation used to measure the test temperature consisted of a series of 12 thermocouples placed inside and outside the pipe samples.

The percentage shear area was measured immediately after the test according to the API RP 5L3 Recommendation regarding the presence of separations, i.e. the cleavage fracture on splits angled from the pipe surface was included in the shear area percent rating by looking normal to the surface.

In Figure 7 the transition curves obtained by DWT tests and Charpy V tests are compared with the WJ tests results. It can be noted the Battelle criterion is completely fulfilled and the DWT tests allow the determination of the pipe transition temperature in a conservative way, even if the full-scale results show a little spread. The latter can be a consequence of temperature measurement scatter and the difficulty in measuring the brittle fracture area percentage on the fractured tested steels, which (as is usual for the high strength TMCP materials) have a tendency to show separations on the fracture surface.

![Figure 7 - Comparison between Charpy V, DWTT and WJ test results](image-url)

In Figure 8 the typical fracture surfaces for both DWTT specimen and West Jefferson test carried out at −20°C are shown.
For the X100 pipes tested in the present work the experimental results confirm the validity of the Battelle DWTT 85% SA criterion and the DWT test capability to correctly predict the transition temperature on pipe material.

**DUCTILE FRACTURE PROPAGATION**

The determination of the toughness values required for arresting ductile fracture propagation has been historically based on the use of models in the form of predictive equations, which state the minimum required value of the Charpy upper shelf energy as a function of both pipe geometry and applied hoop stress. These semi-empirical predictive relationships have been developed using a combination of theoretical analysis and available burst test data /7/. In practice their validation range is restricted so far to the API X80 grade and the consequent level of hoop stress (≤ 400 MPa), and therefore their straightforward extrapolation to X100 grade operating at very high hoop stress (≈ 500 MPa) is highly questionable.

One way to overcome this problem could be to use an appropriate correction factor, calibrated on the basis of past experimental evidences as close as possible to the situation being evaluated. In practice this correction factor should be “case by case” evaluated, being dependent on the material properties and the test conditions. For the X100 case, on the basis of the most recent burst test results on lower steel grade (X80) performed by CSM-Snam /8/ a correction factor of 1.33 of CharpyV energy predicted by the Battelle simplified equation and equal to 1.43 of the CharpyV value predicted by the Battelle Two Curve approach could be suitable (see Figures 13 and 14). The Battelle simplified equation and the Two Curve approach /9/ /10/ are in fact the most appreciated predictive methods for medium-high strength steel linepipes so far; the latter takes into account the decompression behaviour of the pressurising medium used in the test at the corresponding pressure and temperature (and it is strongly recommended when high pressure and/or rich gas is involved) whilst the former consider the medium as an “ideal gas”. In reality for high pressure values, as those foreseen for API X100 steel pipes, even considering pure methane as conveyed gas one should use the Battelle Two Curve approach instead of the simplified formula.
In order to define the material toughness requirements for arresting a fast propagating ductile fracture and in particular to verify the applicability of the existing Charpy V methods of characterising fracture resistance for the API X100 grade linepipe steels studied in the project, two ductile fracture propagation full scale tests on 56”x19.1mm and 36”x16mm pipe geometry have been carried out by CSM.

The typical test layout was composed by seven pipes (one initiation pipe and six test pipes) the toughness increasing when moving from the centre towards the outermost pipes. The medium chosen for pressurising the line in both tests was air; for the test conditions under consideration there is not substantial difference between the use of air instead of pure methane and hence air was used for sake of safety.

The instrumentation used was a comprehensive one of thermo-resistances for measuring the test temperature, pressure transducers for measuring both the test pressure and the pressure decay during the test along the test line and Timing Wires for crack speed measurement during crack propagation.

The main test conditions for both burst tests are reported in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>X100, 56”x19.1mm burst test</th>
<th>X100, 36”x16mm burst test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal diameter (inch)</td>
<td>56</td>
<td>36</td>
</tr>
<tr>
<td>Nominal thickness (mm)</td>
<td>19.1</td>
<td>16</td>
</tr>
<tr>
<td>Ground backfill</td>
<td>Soil, 1.3m</td>
<td>Soil, 1.3m</td>
</tr>
<tr>
<td>Pressurising medium</td>
<td>Air</td>
<td>Air</td>
</tr>
<tr>
<td>Test pressure (bar)</td>
<td>126</td>
<td>181</td>
</tr>
<tr>
<td>Test hoop stress (MPa)</td>
<td>469 (68% of SMYS)</td>
<td>517 (75% of SMYS)</td>
</tr>
<tr>
<td>Test temperature (°C)</td>
<td>+20</td>
<td>+15</td>
</tr>
</tbody>
</table>

Table 5 – X100 ductile fracture propagation full scale burst tests – Main test conditions

The mechanical properties in terms of tensile data (round bar not flattened specimen, transversal direction) and CharpyV full size toughness values (room temperature, transversal direction) of the examined pipes for both burst tests are shown in Figures 9 and 10 together with the test layout. In the Figures the specific CharpyV energy values calculated by the means of both Battelle simplified formula and Two Curve approach are reported for the various test pipes classified in terms of predicted arrest/propagation events.

The first test on 56”x19.1mm, X100 pipes was performed on September 1998; the second one on 36”x16mm, X100 pipes was performed on June 2000. A view of both test lines after the burst is shown in Figures 11 and 12.
**X100, 56''x19.1mm Burst Test Layout**

<table>
<thead>
<tr>
<th>Pipe number</th>
<th>846020</th>
<th>846038</th>
<th>846129</th>
<th>846113</th>
<th>846058</th>
<th>846157</th>
<th>846061</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile and toughness properties</td>
<td>YS (MPa)</td>
<td>707</td>
<td>719</td>
<td>780</td>
<td>773</td>
<td>755</td>
<td>663</td>
</tr>
<tr>
<td></td>
<td>TS (MPa)</td>
<td>766</td>
<td>766</td>
<td>832</td>
<td>858</td>
<td>829</td>
<td>762</td>
</tr>
<tr>
<td></td>
<td>Y/T ratio</td>
<td>0.92</td>
<td>0.94</td>
<td>0.94</td>
<td>0.90</td>
<td>0.91</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>CharpyV (Joule)</td>
<td>271</td>
<td>245</td>
<td>200</td>
<td>151</td>
<td>170</td>
<td>265</td>
</tr>
</tbody>
</table>

| Arrest predicted CharpyV toughness values with P=126 bar (hoop stress=469 MPa) | Battelle simpl. formula | 188 J | A | A | A | P | P | A | A |
| Battelle Two Curve appr. | 176 J | A | A | A | P | P | A | A |

"A" = predicted arrest
"P" = predicted propagation

**Figure 9 – X100, 56''x19.1mm burst test layout and results**

---

<table>
<thead>
<tr>
<th>Pipe number</th>
<th>99447</th>
<th>99458</th>
<th>99460</th>
<th>99461</th>
<th>99456</th>
<th>99457</th>
<th>99446</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile and toughness properties</td>
<td>YS (MPa)</td>
<td>724</td>
<td>750</td>
<td>711</td>
<td>709</td>
<td>761</td>
<td>740</td>
</tr>
<tr>
<td></td>
<td>TS (MPa)</td>
<td>780</td>
<td>819</td>
<td>797</td>
<td>802</td>
<td>844</td>
<td>811</td>
</tr>
<tr>
<td></td>
<td>Y/T ratio</td>
<td>0.93</td>
<td>0.92</td>
<td>0.89</td>
<td>0.88</td>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>CharpyV (Joule)</td>
<td>297</td>
<td>252</td>
<td>202</td>
<td>165</td>
<td>259</td>
<td>253</td>
</tr>
</tbody>
</table>

| Arrest predicted CharpyV toughness values with P=181 bar (hoop stress=517 MPa) | Battelle simpl. formula | 186 J | A | A | A | P | A | A | A |
| Battelle Two Curve appr. | 154 J | A | A | A | A | A | A | A | A |

"A" = predicted arrest
"P" = predicted propagation

**Figure 10 – X100, 36''x16mm burst test layout and results**

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Figure 11 – View of the X100, 56''x19.1mm fractured line from West to East side

Figure 12 – View of the X100, 36''x19.1mm fractured line from West to East side
X100, 56”x19.1mm burst test

The crack, initiated on the pipe n. 846113 by means an explosive charge, had different propagation behaviour in the West and East direction (Figure 9). On the West test side, at the girth weld between pipes 846113 and 846129, the fracture split in two different cracks causing the severance of the test line and the ejection of pipe n. 846129 out of the trench. Due to the severance and the consequent ejection of part of the test line, information from the instrumentation installed on the West test side was not available.

On the other test side the fracture propagated through the pipe n. 846113, 846058 and 846157 with decreasing speed. When the crack speed was down to about 100 m/s, a deviation from the generatrix of pipe 846157 occurred and the crack arrested at the end of that pipe at the girth weld between pipe nos. 846058 and 846061. Examination of the weld zone involved in the fracture showed that the crack always propagated in the base metal. Also the pressure transducer data showed that the crack propagation on East side was regular and not affected by the severance which occurred in the West side.

Pipe n. 846157 can hence be classified as an arrest pipe, with the minimum toughness level required to arrest the fracture equal to 263 Joule of CharpyV energy.

X100, 36”x16mm burst test

The path followed by the crack artificially injected in the test line by means an explosive charge is depicted in Figure 10: two propagations and two clear arrests were observed. In the West direction, the crack, after initiation, propagated through the initiation pipe along the top generatrix (max speed about 310 m/s), entered pipe n. 99460 where it propagated with a constant velocity (about 240 m/s), into pipe n. 99458 where propagation was a constant velocity (about 160 m/s) and into pipe n. 99447 (297 J of Charpy V energy) where it arrested after about 1.5 ÷ 2 metres.

In the East direction the crack, after the initiation, propagated through the initiation pipe along the top generatrix (max speed about 300 m/s), enter in pipe n. 99456 (259 J of Charpy V energy) where it arrested after about 5 metres.

In Figures 13 and 14 the comparison in terms of both the Battelle simplified equation and the Two Curve approach of the present X100 results with the available database of full scale burst tests on high grade (API X80) large diameter steel pipes are presented.

In conclusion, the toughness characteristics of the X100 tested pipes, in terms of CharpyV energy, proved enough to warrant the arrest of a long running shear fracture, at an operating pressure of up to 18 MPa, corresponding to hoop stress level of 517 MPa (75% of SMYS). In particular the toughness required to arrest the fracture was equal to about 260 Joule of CharpyV energy for both pipe geometries and test conditions.

Concerning the value of the correction factor to be used with the existing Battelle simplified equation for the X100 grade steel linepipes tested, a correction factor slightly higher than supposed and equal to 1.4 was found for both tests. On the contrary if the Battelle 2 Curve approach is applied, and it is recommended given the high pressures involved, the correction factor required for the two tests is different: it should be equal to 1.5 for the first X100 test case (56”x19.1mm), and to 1.7 for the second one (36”x16mm).
Actual CharpyV energy Vs. Predicted by Battelle Simplified Equation

[CSM Database 10 tests: grade=API X80, OD=42-56"; thick=16-26mm, P=80-161bar, Hoop stress=336-440MPa, air and natural gas (not rich)]

Figure 13 – Actual vs. Predicted CharpyV energy (Battelle simplified equation) for high-grade steel linepipes (CSM database)

Actual CharpyV energy Vs. Predicted by Battelle Two Curve Approach

[CSM Database 10 tests: grade=API X80, OD=42-56"; thick=16-26mm, P=80-161bar, Hoop stress=336-440MPa, air and natural gas (not rich)]

Figure 14 – Actual vs. Predicted CharpyV energy (Battelle Two Curve Approach) for high-grade steel linepipes (CSM database)
CONCLUSIONS

The X100 grade large diameter steel pipes (56" x 19.1mm and 36" x 16mm) were produced by Europipe using controlled rolled and accelerated cooled plates. The fracture behaviour of these pipes was good.

Concerning specific fracture issues, the main results obtained in the research are the following.

- Pipes produced meet the API X100 strength requirement and exhibit high levels of toughness, as measured in Charpy V notch and DWTT tests. The cold forming processes involved in pipe production have been shown to be responsible for significant increases in proof stress from the original plate to the finished pipe, but it does not appear to seriously affect the pipe toughness, with relatively minimal changes moving from plate to pipe.

- The Battelle flow stress dependent formula for assessing the resistance of steel linepipes to fracture initiation from part wall axial defects predicts well the failure stress value even for the high strength, high Y/T ratio (> 0.90 on round bar not flattened specimen) API X100 pipes examined in the project.

- The West Jefferson full scale test results confirm the validity of the Battelle DWTT 85%SA criterion and the DWT test capability to correctly predict the transition temperature on X100 pipe material.

- The toughness characteristics of the API X100 tested pipes, in terms of CharpyV energy, proved enough to cause the arrest of a long running shear fracture at hoop stress levels up to 517 MPa (75% of SMYS). The toughness required to arrest the fracture was equal to about 260 Joule of CharpyV energy for both pipe geometries/test conditions examined. As regard the correction factor to be used for both the Battelle simplified equation and the Two Curve approach, the burst test results indicate values of 1.4 and 1.7 respectively. These are higher values than those previously supposed from past experience on lower grade steels.

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REFERENCES


AUTHORS’ BIOS

Gianluca Mannucci was born in Roma in 1967 and he graduated in Mechanical Engineering at the University of Rome. Since 1995 he has been working for CSM involved in brittle initiation and ductile fracture propagation problems in high grade/large diameter gas pipeline steels from both theoretical and experimental (labs and full scale burst tests) point of view. He has in charge the Structural Integrity Section.

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Dr. Hans-Georg Hillenbrand hold an MS in mechanical engineering (1979) and a PhD in materials science (1983), both from Ruhr-University, Bochum. In 1983 he started his career in the Mannesmann Research Institute developing steels for large-diameter pipes. From 1986 to 1994 he was first QA/QC manager of Mannesmann heavy plate mill, later Senior Manager Quality for plates and welded pipes of Mannesmann-Röhren. Since 1994 he is a Senior Manager and head of Technical Sales of Europipe GmbH. He is the author of more than 40 papers relating to HSLA steels.