Large-diameter X 100 gas line pipes: Fracture propagation evaluation by full-scale burst test

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Large Diameter X100 Gas Linepipes: Fracture Propagation Evaluation by Full-Scale Burst Test

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1. INTRODUCTION

In recent years there has been a growing interest amongst gas companies in the possible application of high strength low alloy steels. The move to a high strength steel is obviously very attractive in terms of potential cost savings for pipeline users, because this would allow an increase in the operating pressure up to a doubling of the actual one (15 MPa), but it is of paramount importance that its use should not compromise the structural integrity of the pipeline itself. In order to verify the possible application of high pressure, long distance natural gas transportation, in 1995 E.N.I. sponsored a research program. This activity had been developed by SNAM jointly with CSM in order to assess the fracture behaviour of large diameter (up to 1442 mm), heavy wall thickness (up to 30 mm), high steel grade (API 5L X70 and X80) pipes for operating pressure over 15 MPa by means of both laboratory and full scale tests\textsuperscript{(1)}. The assessment of the fracture behaviour of large diameter, higher steel grade (X100) pipes operated at very high pressure (up to 15 MPa) is meant to be the ideal carrying on of this project. So a research program on behalf of ECSC (European Coal and Steel Community) is being carried out by a joint co-operation among CSM, Snam and Europipe. Aim of this research is to define appropriate safety criteria against fracture phenomena in large diameter, X100 SAW pipes operated at very high pressure by determining a range of fracture properties using both laboratory and full-scale tests.

In particular specific objective of this activity is the definition of material requirements for arresting fast propagating ductile fracture. The Ductile Fracture Propagation control for very high grade pipes is one of the key point to be solved in order to have complete safety in their application. The available knowledge indicate this aspect could be a critical point for future use of large diameter, very high strength steel (\(\geq X80\)) gas pipelines, operated in severe conditions (i.e. hoop stress \(>450\) MPa). On the other hand the conventional methods for assessing the toughness requirements in linepipe are recognised to be inadequate to characterise fracture resistance in modern ultra high grade linepipe steels. No experiences on this innovative high grade steel operated at so high hoop stress levels have been performed in the past, and therefore a specific full-scale experimental activity is necessary to investigate this aspect.
This paper presents the results obtained in a specific testing program concerning the control of long shear ductile fracture propagation for large diameter, high strength steel pipes (X100, 56” x 19.1 mm). The validity of the current approach to ductile fracture propagation control, related on the use of predictive CharpyV formulae, has been investigated by full scale ductile fracture propagation test at very high hoop stress (470 MPa).

2. TEST PIPES

The plates were made by Dillinger Hutte from special microalloyed steel using thermomechanical rolling plus subsequent accelerated cooling. Afterwards Europipe formed the plates to pipes in their Mülheim UOE pipe mill. Seven pipes for the burst test, with different toughness levels required by the particular lay-out of the test line, have been chosen; these different toughnesses were achieved from Europipe by varying rolling parameters. On these pipes an extensive mechanical characterisation has been performed; in particular tensile tests on round bar transversal specimens and CharpyV toughness tests at room temperature have been carried out. The results of the mechanical characterisation are reported in table 1. Finally, the required minimum tensile and toughness properties have been generally achieved, and moreover, in terms of ductility, all pipes revealed more than 90% shear area at -10°C in DWTT tests.

<table>
<thead>
<tr>
<th>Test Line (WEST side)</th>
<th>Pipe N°</th>
<th>YS (MPa)</th>
<th>TS (MPa)</th>
<th>YS/TS</th>
<th>CV (J) Av</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd pipe</td>
<td>846020</td>
<td>707</td>
<td>766</td>
<td>0.92</td>
<td>271</td>
</tr>
<tr>
<td>2nd pipe</td>
<td>846083</td>
<td>719</td>
<td>766</td>
<td>0.94</td>
<td>245</td>
</tr>
<tr>
<td>1st pipe</td>
<td>846129</td>
<td>780</td>
<td>832</td>
<td>0.94</td>
<td>200</td>
</tr>
<tr>
<td>Initiation</td>
<td>846113</td>
<td>773</td>
<td>858</td>
<td>0.90</td>
<td>151</td>
</tr>
<tr>
<td>1st pipe</td>
<td>846058</td>
<td>755</td>
<td>829</td>
<td>0.91</td>
<td>170</td>
</tr>
<tr>
<td>2nd pipe</td>
<td>846157</td>
<td>663</td>
<td>762</td>
<td>0.87</td>
<td>263</td>
</tr>
<tr>
<td>3rd pipe</td>
<td>846061</td>
<td>722</td>
<td>778</td>
<td>0.93</td>
<td>284</td>
</tr>
</tbody>
</table>

(EAST side)

Note: All specimens taken transversally to pipe axis. CharpyV data at room temperature and measured with full size CharpyV specimen.

Table 1 - Mechanical properties of X100 pipes involved in the burst test
3. BURST TEST CONDITIONS AND INSTRUMENTATION

3.1 Arrest/propagation conditions

Arrest/Propagation curves according to the most used formulations (Battelle, AISI, Mannesmann) were calculated\(^{(3,4)}\). In the field of interest the predicted minimum arrest toughness found for X100 56” x 19.1 mm pipe, designed to operate at very high hoop stress levels (up to 500 MPa), has a large spread (figure 1). However it is necessary to underline the valid range of all these provisional formulas is limited on the upper side by the API X80 grade, therefore their straightforward application to X100 gas pipelines operating at very high hoop stress is possible but highly questionable.

Since it is generally recognised that conventional methods, based on CharpyV values, used to characterise fracture resistance in linepipe could be inadequate to assess the toughness requirements for very high grade linepipe steels, an appropriate correction factor should be used. This correction factor should be evaluated considering, above all, the hoop stress applied on the testing line, so the safety factor designed for the test, the most suitable for the steel grade considered, has a great importance. For the present test on the base of the most recent burst tests results on API X80 grade steel performed by CSM at very high pressure level\(^{11}\) (P > 15 MPa) a correction factor of about 1.4 of the value obtained by the Battelle formula could be suitable (see figure 2).

Figure 1 - Predictions of the available predictive formulas for 56”x19.1mm line pipe in comparison with current X100 test results

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3.2 Test pressure and pressurising medium

The main aim of this first burst test on X100 grade steel linepipes was to have, as far as possible, both propagation and arrest pipes. Looking at the available predictive formulas, decision was made to move from 133 bar (corresponding to 72% of SMYS, that is the safety factor usually adopted) to a pressure level of 126 bar (corresponding to 68% of SMYS). In this way there was a reasonable probability for arresting in the outermost higher toughness pipes.

The pressurising medium chosen for the test line was air. Several works have been carried out in the past about the problem of the fluid decompression behaviour in pipeline during the fracture propagation\(^{(5,7)}\), and it is in general recognised that, at the same test conditions (pressure, backfill, ecc.) air represents a more severe medium than natural gas, where “natural gas” means gas with no two-phase behaviour during decompression (pure methane for example) typical of gas rich of heavy components. The conservative behaviour of air respect to natural gas is ascertained for pressure up to about 100 bar, and it has to be verified for the pressure field of interest in the project. In order to check this aspect the Battelle 2-Curves approach\(^{(2)}\) for the evaluation of the toughness required for arresting a fast propagating ductile fracture can be used; this approach allows in fact to compare the Driving Force due to the gas with respect to the Resistance Force represented by the material toughness (i.e. CharpyV energy level). A decompression software called GASMISC, developed by CSM, able to calculate the gas decompression curves at pressure up to 200 bar has been used; the theoretical decompression curves, down from 126 bar, for air and pure methane have been obtained; comparing the results the CharpyV energy level required to arrest fracture in the two pressurising medium is almost the same.
3.3 Test lay-out

Seven pipes have been used in this full scale ductile fracture propagation test: one initiation pipe and six test pipes. The test line was about 70 m long and consisted of pipes having an increasing CharpyV toughness from the centre. The line was placed in the middle of a permanent line formed by two reservoirs long enough to guarantee, during the whole crack propagation on the central test pipes, the same driving force, which would act on a pipeline of indefinite length.

The main test parameters were:

- Nominal diameter 56” (1422.4 mm)
- Nominal thickness 19.1 mm
- Nominal grade X100
- 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
- Hydraulic test before burst 48h at 150 bar, corresponding to 80% of SMYS

A simplified sketch of the test line is shown in figure 3, where the actual CharpyV energy values are also reported for all test pipes.

3.4 Test instrumentation

Given that it is necessary to know:

- crack speed during the test;
- gas decompression behaviour inside the test pipes;
- test temperature at the burst time;

the instrumentation used at this purpose was: 92 Timing Wires (spaced 1 meter or less), 8 internal pressure transducers (located at 90° from crack line) and 3 thermocouples were used. Each sensor signal was monitored and recorded by two independent systems, to increase the reliability of the measurement.

4. BURST TEST RESULTS

The test was performed on September the 29th 1998, at the CSM Perdasdefogu Test Station in Sardinia. The instrumented test line was pressurised with air at the desired level; afterwards the burst was initiated using an explosive charge 500 mm long, located on the upper generatrix of the initiation pipe, able to create a through thickness gouge long enough to guarantee the break conditions on the initiation pipe. After the break, the fracture propagated on the upper pipe generatrix at a very high speed in both test line sides, sustained by the driving force assured by the gas decompression at the crack tip. Figure 4 shows a view just after the burst, while a view of the fractured test line is shown in figure 5.
Figure 3 - Test lay-out, actual and predicted toughness ("A" means predicted arrest, "P" means predicted propagation) and crack path after the test

Figure 4 - View just after the burst with the ejection of pipe n. 846129 out of the ditch (see arrow)
Figure 5 - View of the test line after the burst (from West to East side); the severance zone is in the foreground.

4.1 Arrest/Propagation results

The crack, initiated on the pipe n. 846113, had a different propagation behaviour in the West and East direction.

**West side:** The crack, after the explosion, propagated in West direction through the initiation pipe along the top generatrix, as expected. In correspondence of the girth weld with the adjacent pipe n. 846129 it split in two different cracks as sketched in 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 (i.e. in pipe n. 846129) with an angle of about 45° respect to the girth weld (see figure 3), 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 (see figure 4). Due to the severance and the consequent ejection of part of the test line, information from the instrumentation installed on the West test side were not available.
**East side:** The crack, after the initiation, propagated in East direction through the initiation pipe along the top generatrix, entered in pipe n. 846058 (170 J of CharpyV energy) where propagated and in pipe n. 846157 (263 J of CharpyV energy) where it arrested at the end of the pipe in correspondence of the girth weld with pipe n. 846061. The analysis of the last part propagation in pipe n. 846157 shows that the crack began to deviate from the top pipe generatrix about 1.5 m before the girth weld, and then swerved and stopped in correspondence of the welded joint. It is worthy to note that the deviation of the propagation path from the straight line along the top generatrix is in general considered as a sign of the propagation becoming unstable, and hence the arrest conditions were close to be reached. Furthermore the examination of the weld zone involved in the fracture showed that the crack was always propagated in the base metal of pipe n. 846157.

4.2 Crack velocity measurements

The fan diagram, i.e. the plot of the time of rupture of the Timing Wires versus their distance from the initiation point, is shown in figure 6. Fitting these data it is possible to trace the velocity of the crack at its different position on pipes, as also depicted in figure. As above mentioned, 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 pipe n. 846058 with speed less above 300 m/s and then propagated in this pipe with a decreasing velocity down to about 200 m/s. Afterwards the crack entered in pipe n. 846157 with a speed of at about 200 m/s and then it keeps on slowing down till the arrest. In figure 6 the last Timing Wires broken by crack before arrest on last part of pipe n. 846157 are reported; the Timing Wire number 79 is the last before the crack began to deviate from the straight line. At that moment the crack speed was about 100 m/s, and then rapidly decreased to zero. This velocity value is in agreement with the results of previous burst tests (see for example ref. 2.) performed on high grade modern TMCP steels that indicate a velocity value of about 100 m/s as the speed limit sustainable for high toughness, modern TMCP steels during the propagation before the fracture spiralling and arrest.
Figure 6 - Fan diagram and crack speed of the East test side

Figure 7 - Pressure decay at transducer n. P8 located at the end of the East test side

4.3 Pressure transducers data
As examples of the pressure data recorded during the test, in figure 7 the *Pressure measured versus Time* curves concerning the transducer P8 is shown. This transducer was located at the end of the East side near on the reservoir at about 34 m from the initiation point. As we can see, regardless of the typical ground noise present in the experimental recordings of pressure data, this figure shows the typical decompression trend in a gas transmission line during ductile fracture propagation when “one-phase” gas is used. The curve exhibits a change in the monotonic decompression behaviour after about 370 ms from initiation. This is due to the reflection of the first decompression wave at the end of the East reservoir; it is important to note that the crack arrest at the end of pipe n. 846157 occurred after about 130 ms from the crack onset, therefore this arrest was not affected by the reflection of the first decompression wave.

4.4 Fracture appearance
The analysis of the fracture appearance on the test pipes involved in the fracture propagation showed a fully ductile behaviour for all pipes with a light presence of small separations on the fracture surface, as shown in figure 8.

![Figure 8 – Typical fracture appearance](image)

5. DISCUSSION
Because of the severance occurred immediately after the entrance of the crack in the first propagation pipe in the West line side, the consideration regarding the resistance to ductile fracture propagation for X100 grade steel pipes involved in the test are to be limited to the East test side, where a propagation and an arrest have been observed. According to the Battelle simplified formula multiplied by 1.4, the actual toughness of the pipe n. 846157 (263 Joule of CharpyV energy) is just the minimum toughness necessary to arrest the fracture; so depending on this theory this pipe is on the borderline between propagation and arrest.
This behaviour has been confirmed by the experimental results, given that:

1. the crack propagated straight through the pipe n. 846157 with a velocity continuously decreasing (deceleration mainly constant), so no steady-state propagation conditions have been reached, till the crack deviated 1.5 m before the girth weld;

2. past experiences with large-diameter, high grade steel pipes at very high hoop stress indicate rapid arrest when crack speed of about 100 m/s is reached and when a deviation from straight propagation occurs, and both these conditions have been observed for pipe n. 846157;

3. after the deviation and before to definitively stop, the crack swerved along the welded joint but involving just the base metal of pipe n. 846157; therefore the crack deviation along the girth weld can be ascribed to a “ring effect”. This action was exerted by the weld joint acting on a crack near to be arrested and so very “sensitive” to the border effects.

These are all clear indications that pipe n. 846157 can be classified as an arrest pipe, with the minimum toughness level required to arrest the fracture equal to 263 Joule of CharpyV energy.

6. CONCLUSIONS

Grade X100 large-diameter pipes in size of 56”x19.1mm were produced by Europipe with thermomechanically rolled and accelerated cooled plates made by Dillinger Hutte. It was the first time that this grade and size was manufactured worldwide. Pipes from this production have been tested in a first X100 fracture propagation test at ambient temperature (+20°C) and they exhibited fully ductile fracture behaviour.

The toughness characteristics of these X100 pipes, in terms of CharpyV energy, proved enough to warrant the arrest of a long running shear fracture, at operating pressure over 12 MPa, corresponding to hoop stresses of about 470 MPa. In particular the toughness required to arrest the fracture in the test conditions was equal to 263 Joule of CharpyV energy.

Concerning the value of the correction factor to be used with the existing Battelle simplified formula for the X100 grade steel pipes tested in this burst test, the assumed correction factor equal to 1.4 proved sufficient.

7. ACKNOWLEDGMENT

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8. REFERENCES


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