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## EVALUATION OF THE SUITABILITY OF X100 STEEL PIPES FOR HIGH PRESSURE GAS TRANSPORTATION PIPELINES BY FULL SCALE TESTS

BY EPRG

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### ABSTRACT

In order to increase the knowledge necessary for the utilisation of grade X100 steel pipes, and to consolidate preliminary indications regarding the safe level of toughness required to control the ductile fracture propagation event within X100 gas pipeline, an ECSC-Demonstration Project, (DemoPipe Project), partially sponsored by EPRG, has been performed (2001 - 2004) using TMCP X100 pipes with a diameter of 36". The project examines the problems of building a new high grade steel on-shore gas pipeline, with special emphasis given to the issues of the field welding technologies and selection of consumables, girth weld defect tolerance, field cold bending, and the fracture propagation behaviour in a high-pressure natural gas pipeline. In order to achieve these stated aims, a dedicated laboratory and full scale tests programme was included into the project. This paper presents a summary of some results obtained, together with a discussion regarding their applicability to future X100 pipelines.

### INTRODUCTION

In recent years, gas companies have shown an increasing interest in the possible use of higher grade steel pipes (Yield Strength  $\geq 690$  MPa, equivalent to X100 steel grade and higher) for the construction of long distance gas pipelines /1/ /2/ /3/ /4/ /5/. The use of a high strength grade offers potential benefits, in terms of using a higher service pressure ( $\geq 15$  MPa) without increasing the pipe wall thickness. This, in turn, offers financial benefits arising from lower material, transportation and fabrication costs.

A completed ECSC sponsored research program /6/ /7/ performed by CSM and Corus investigated the suitability of equivalent X100 grade steels for high pressure pipeline use, with the main emphasis placed upon establishing the fracture behaviour of this high grade steel. One of the essential points was dealing with the general fracture behaviour of these new materials, including defect tolerance, ductile to brittle transition and ductile fracture arrest capability. The X100 grade large diameter steel pipes (56" x 19.1mm and 36" x 16.0mm) were produced by Europipe using controlled-rolled and accelerated-cooled plates made by Dillinger Hutte.

The results of this ECSC work were encouraging, and provided a basis for a new ECSC-Demonstration Project, (DemoPipe Project), currently in progress, and partially sponsored by EPRG. The general aim of the DemoPipe project is both to increase the knowledge needed to utilise grade X100 steel pipes, and to consolidate the first preliminary indications about the value of safety toughness needed to control the fracture propagation event within X100 gas pipeline. The project examines the problems of building a new high steel grade on-shore gas pipeline, with special emphasis on the issues of the field welding technologies and selection of consumables, girth weld defect tolerance, field cold bending, and the fracture propagation behaviour in high-pressure natural gas pipeline. In order to achieve this general aim, a dedicated laboratory and full scale tests programme was included into the project.

The project commenced in July 2001 and the experimental activities have been concluded in spring 2004. This paper presents some results obtained in the DemoPipe project, in particular as regards the pipes produced, selection of consumables and ductile fracture propagation events.

## PIPES PRODUCED

The materials used are high strength, micro-alloyed steels, obtained by means of a suitable combination of chemical composition and thermo-mechanical 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, prior to Europipe forming the plates to pipes in their Mulheim UOE pipe mill. In the overall programme of work, four series of X100 plates of different nominal thickness (12.7, 16.0, 20.0 and 25.0 mm) with a range of toughness values (150-300 J) were formed into 36" diameter pipe. Approximately 50 pipes have been produced.

The criteria for an optimised metallurgical design and fabrication route in terms of chemical analysis and plate rolling and cooling parameters for the manufacture of high strength pipes up to grade X100 are shown in references /8/. In general, there are no technological break-throughs, such as thermo-mechanical rolling and accelerated cooling which increased the strength and toughness respectively, but instead, improvements in the existing technology were involved in the production of these grade X 100 plates. As a result, the production window is quite narrow. Heat treatment of plate or pipe is obviously not advisable. The work done to date has shown the limits of technical feasibility for the properties of grade X100. The required yield strength and tensile strength can be achieved relatively easily, but the yield-to-tensile ratio increases with increasing material grade. Uniform elongation and elongation at rupture also decrease as the strength increases. Optimised steel making practices, together with optimised rolling and cooling schedules, enable the base material to achieve toughness values that are far superior to those envisaged earlier with the present-day chemical composition. The major objective of Europipe/Dillinger was to optimise further the chemical composition in conjunction with improved rolling and cooling conditions to achieve the goals defined within an adequately large window of production parameters.

Three main different approaches are possible with respect to the selection of chemical composition and cooling conditions. Approach A, which involves a relatively high carbon (about 0.08%) and medium carbon equivalent (about 0.49) contents, together with a soft accelerated-cooling process: reheating temperature 1140 - 1220°C, finish rolling temperature 680 - 780 °C, high cooling stop temperature (about 500°C) and low cooling rate (about 20°C/s), has the disadvantage that the requirements for toughness to ensure crack arrest, i.e. prevention of long running cracks, may not be fulfilled; moreover, this approach is also detrimental in terms of field weldability. Approach B, which involves a relatively low carbon (about 0.05%) and low carbon equivalent (about 0.48) contents, together with a low cooling stop temperature (minimum value 300°C) and high cooling rate (maximum value 60°C/s), which result in the formation of uncontrolled fractions of martensite in the microstructure, which, in turn, have a detrimental effect on toughness properties. This effect cannot be adequately compensated for, even with extremely low carbon contents, without adversely affecting productivity.

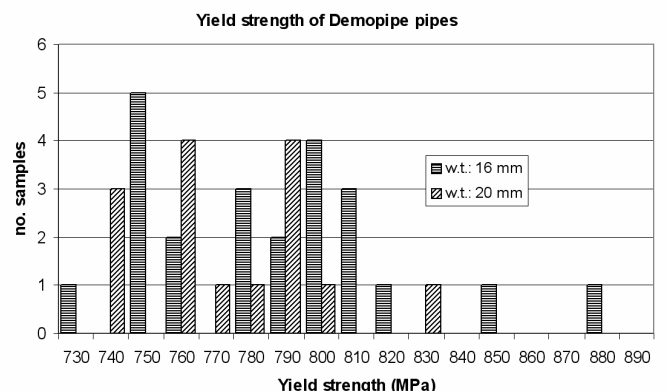
Moreover, it is very difficult to produce pipe with adequate uniformity of strength properties. This problem cannot be attributed solely to the Bauschinger effect associated with the variation in local deformation occurring during the intensive straightening operation required in the case of relatively thin section plate, which distorts heavily during direct quenching. Approach C, involves a medium carbon and medium carbon equivalent content, together with a medium cooling stop temperature (about 400°C) and medium cooling rate (in range 30°- 50°C/s). This approach ensures excellent toughness and fully satisfactory field weldability, despite the relatively high carbon equivalent of the chemical composition.

Based on the experience gained from previous trials of X100 pipe production, in order to produce the DemoPipe X100 pipes, Approach C has been followed and a further optimisation of the chemical composition on the one hand, and further optimisation of rolling and cooling conditions on the other hand has been performed. In particular four heats have been produced. In Table I the chemical composition of each heat is reported; in particular the carbon content is in the range 0.055 - 0.059 %, the carbon equivalent ( $CE_{IIW}$ ) is in the range 0.46 - 0.47 %, and the  $P_{CM}$  is about 0.19 %. The range of rolling cooling parameter values: cooling rate: 15° to 35°C/s; cooling stop temperature: 80 to 450 °C. The reason for the choice of such a large range of cooling rate and cooling stop temperature was the requirement to produce plates with different toughness levels for the planned full-scale burst tests.

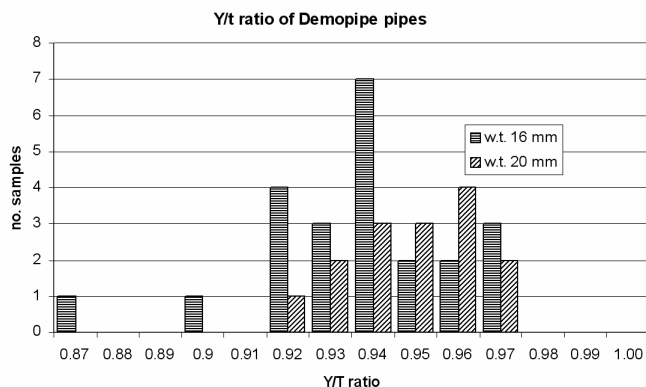
HEAT-No.	C	Mn	Si	Mo	Ni	Cu	Nb	Ti	N	Al	Cr
16155	.059	1.93	.35	.30	.24	.020	.046	.019	.006	.031	.023
16156	.055	1.97	.31	.31	.24	.025	.047	.019	.005	.035	.021
16157	.057	1.95	.33	.30	.24	.024	.046	.019	.004	.035	.022
18438	.058	1.91	.31	.30	.24	.018	.048	.019	.005	.030	.033

**Table I:** Chemical composition and carbon equivalent of industrial heats used for X100, in wt %.

For wall thicknesses 16 mm and 20 mm in Figures 1 and 2 the mechanical properties in terms of yield strength (Rt0.5), Y/T ratio are reported (the indicated tensile test results have been obtained on transverse round bar specimens taken from one end of pipe).



**Figure 1:** Yield strength (Rt0.5) of produced X100 pipes (thickness 16.0 and 20.0 mm), in MPa.



**Figure 2:** Y/T ratio of produced X100 pipes (thickness 16.0 and 20.0 mm).

### SELECTION OF THE IN-FIELD WELDING TECHNOLOGIES, CONSUMABLES AND PARAMETERS.

In order to develop specific welding procedure specifications (WPS) to produce, using both SMAW and GMAW technologies, the in-field welded joints with a “good” toughness and strength, a set of different classes of consumables have been selected, in Table II indications on required classes are reported.

	Consumables Class	Notes
GMAW I	AWS ER 100	Even-matching/Over-matching conditions
GMAW II	AWS ER 110	Over-matching condition.
SMAW	AWS 6010	Root pass
	AWS 9010	Hot pass
	AWS E100/ E110	Fill and cap passes

**Table II:** Required consumables classes.

The consumables classes have been chosen on the basis of nominal weld metal properties to obtain a condition of even-matching or light over-matching for the SMAW joints, and two different matching conditions for the GMAW joints: a condition of even-matching or light over-matching (procedure I), and a condition of appreciable over-matching (procedure II, weld metal yield strength at least 10% higher than base material yield strength).

To meet these requirements, Table III shows the possible solutions proposed by different consumable producers (ECT, ESAB and *Boheler Tyssen*).

	ETC	ESAB	Boehler Tyssen
GMAW I	116 S	OK Autrod 13.26	***
GMAW II	120	OK Autrod 13.13	***
SMAW	PH 118	Filar 108	Fox BVD 110
	PH 128		

**Table III:** Solution proposed by different consumable producers.

This choice has been used for pipes with both 16 mm and 20 mm wall thickness. In particular, for the SMAW procedure, a cellulosic matching consumable is provided for the root pass, in order to guarantee a good penetration (otherwise a cellulosic soft strength electrode produces a low level of residual stresses into the weld metal, reducing the risks of cold cracking), moreover in the case of SMAW, both “vertical down” and “vertical up” procedures have been used.

The WPS have been developed jointly with an Italian contractor (SICIM Spa) and six pipe girth welds of 16mm wall thickness steel, and six pipe girth welds of 20mm wall thickness steel have been made. In particular, for each ring of pipe, a half-length of girth joint has been used to “test” a different WPS. The entire girth weld joints have been subjected to NDT control (X-rays).

For all consumables, the same range of optimized pre- and inter-pass temperature and heat input values have been found, and in Table IV these values are reported for both the GMAW and SMAW technologies.

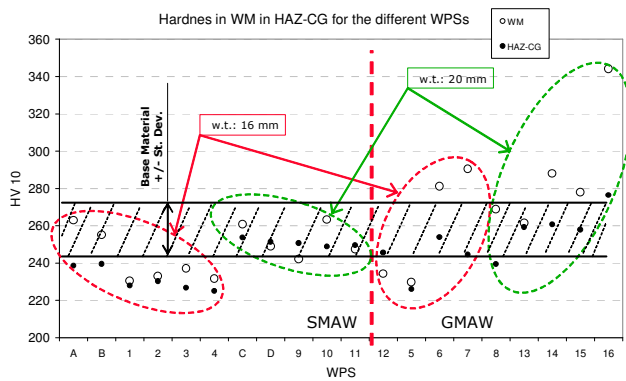
GMAW			
<b>Preheat temperature:</b>		min 100°C.	
<b>Inter-pass temperature:</b>		min 100°C max 250°C	
<b>Heat input</b>	<b>Root pass:</b>	0.60	KJ/mm
	<b>Hot pass:</b>	0.70- 0.75 KJ/mm	
	<b>Fill passes:</b>	0.75	KJ/mm
	<b>Cap passes:</b>	0.80 - 1.0 KJ/mm	
SMAW			
<b>Preheat temperature:</b>		min 200°C.	
<b>Inter-pass temperature:</b>		min 120°C max 250°C	
<b>Heat input</b>	<b>Root pass:</b>	1.0 KJ/mm	
	<b>Hot pass:</b>	1.0 KJ/mm	
	<b>Fill passes:</b>	1.5 KJ/mm	
	<b>Cap passes:</b>	1.0 KJ/mm	

**Table IV:** Optimized pre- and inter-pass temperature and heat input values for GMAW and SMAW

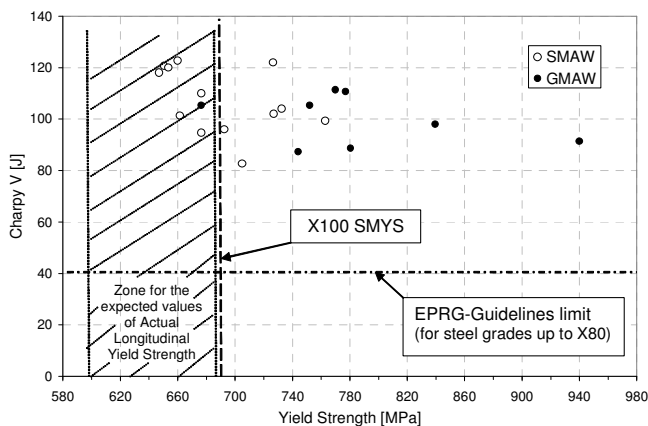
A weld metal mechanical characterisation of all welded joints has been performed, in particular, tensile tests, hardness and fracture toughness tests. For the latter, Charpy V and Bx2B CTOD tests have been performed at room temperature, 0°C and -20°C.

A summary of the hardness tests are reported in Figure 3, where for all the WPS developed, the average hardness values of both HAZ and weld metals are compared with the range hardness values measured on base materials.

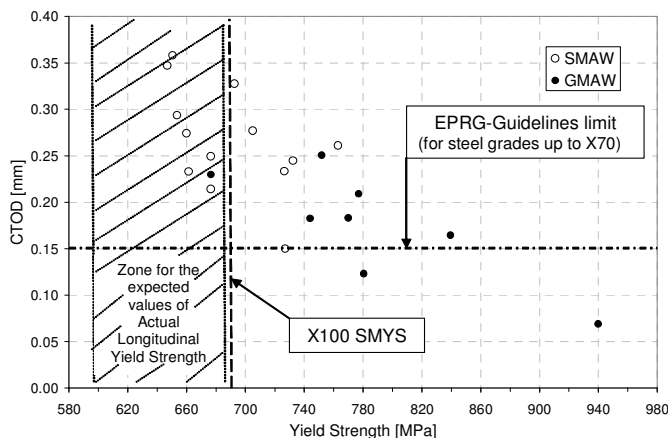
Finally, in Figures 4 and 5, for all the developed WPS, both the Charpy V energy (measured at 0°C) vs. Yield Strength and CTOD (measured at 0°C) vs. Yield Strength are shown.



**Figure 3:** Average hardness values of both HAZ-CG and weld metals (WM) for the developed WPS, compared with the base materials range hardness values.



**Figure 4:** Charpy V energy (measured at 0°C) vs. Yield Strength, for all developed WPS.



**Figure 5:** CTOD (measured at 0°C) values vs. Yield Strength, for all developed WPS.

From the analysis of these experimental data the matching condition in a joint has to be verified with respect to the pipe yield strength in the longitudinal direction, which, for this kind of material, is expected to be significantly lower than the actual pipe yield strength in the transverse direction; if these last values are taken into consideration, higher values of over-matching are difficult to be achieved on the basis of existing

consumables, without a detrimental effect on toughness/transition temperature values (this trend is confirmed also if the hardness values are used to evaluate the matching conditions). In particular, about the strength of consumables:

- SMAW joints offer at least a condition of expected Even-Matching. On 16 mm wall thickness joints only Böheler BVD 110 and the higher grade ETC PH 128 give a marked Over-Matching condition.
- Altogether three different classes of consumables have been tested for GMAW joints. The softest wire offers a condition of expected Even-Matching, while the others give Over-Matching (ER 100) and strong Over-Matching (ER 110).

Moreover, passing from 16 mm to 20 mm wall thickness joints, a general increase of yield strength offered by the same consumable is observed for both the SMAW and the GMAW techniques. This results in an increase of the levels of Over-Matching obtainable with the same consumables (also hardness test results confirm this trend). For example, on 20 mm wall thickness joints, a very high level of Over-Matching is obtained with ER 110 wire, however, in this specific case, this improvement of strength is reflected in lower values of toughness.

Three of the developed WPSs have been selected, and used to produce the in-field welded joints for the test line for the first full-scale burst propagation test: two WPSs for automatic welding, and one WPS for manual welding. The results have been satisfactory, with the in-field welds of X100 pipes not appearing to show any particular problem. So, these X100 base materials have shown a good weldability, even though their Carbon Equivalent values are in the range of 0.46 - 0.47 (in CEIIW); therefore these results could be considered as a base for suitable guidelines for the maximum Permitted Carbon Equivalent for X100 large diameter steel pipes.

### FIELD COLD BENDING

To define the in-field cold bending behavior of the large diameter X100 pipes selected for the project, experimental and analytical activities have been performed: four X100, 36"x12.7mm pipes were cold bent by a contactor using a real in-field bending machine, in parallel, a finite element analysis was started in order to simulate the forming process, and to provide an analytical device for the performing of parametric studies on the cold bending operation of high grade pipes. The main mechanical properties of the selected pipes are reported in Table V.

Pipe No.	Round bar transverse			Round bar longitudinal		
	A%	Rt0,5	Y/T	A%	Rt0,5	Y/T
8771	16.3	755	0.98	17.0	620	0.75
8822	15.8	730	0.96	20.0	581	0.82
8823	14.5	840	0.95	17.5	610	0.86
8772	16.3	733	0.98	18.5	643	0.78

**Table V:** Mechanical properties

A bending machines belonging to SICIM Spa, designed to bend pipe with a diameters ranging from 38 to 48 inches, has been used; in general this facility has not shown any significant differences with the better known CRC-EVANS pipe bending machine. During each bending cycle the pressure and the displacement of the cylinders were measured, in particular two pressure transducers were used to indicate the in-board and out-board cylinder pressure, with two LVDT transducers used to measure the cylinders displacement.

The test plan was to bend the pipe, without damaging it, up to the minimum curvature radius  $R_{min}$  usually adopted in-field (for pipes of lower grade than X100):  $R_{min} = 40 \times OD$  (for  $OD = 36''$ , pipe  $R_{min}$  corresponds to 36.58 m). In these conditions, for a single pipe of 12m length,  $L_{bend} = L_{pipe} - 2 \times (2OD)$ , the theoretical maximum overall bend angle is approximately  $13^\circ$ .

Each bend is composed of many steps, each one of them producing a “single” bend on the pipe. When the bending is complete, by measuring the angular deviation of the pipe’s straight ends it is possible to estimate the overall bend angle. The main results in terms of the bend angle and (possible) damage are reported in Table VI; for pipes 8771, 8772 and 8823 the step length between two single bends was 450 mm, while for pipe 8822 a shorter length, 300 mm, has been tested .

Pipe n.	Bent length, approx. (m)	Number of steps	Overall bent angle, approx. ( $^\circ$ )	Damage
8771	6.3	14	7	None
8772	6.3	14	10	Inward and outward wrinkles*
8823	5.9	13	8	Wrinkle in step 13
8822	3.6	12	6	Wrinkle in step 1

**Table VI:** Cold bending results (\* = damage created and pushed back by the subsequent bending).

A finite element model of a pipe bending operation has been developed using the MARC code. The work performed has focused on the simulation of both the plastic bending and the unloading phase of the bending operation in order to quantify the pipe “spring back” effect after the cold bending process.

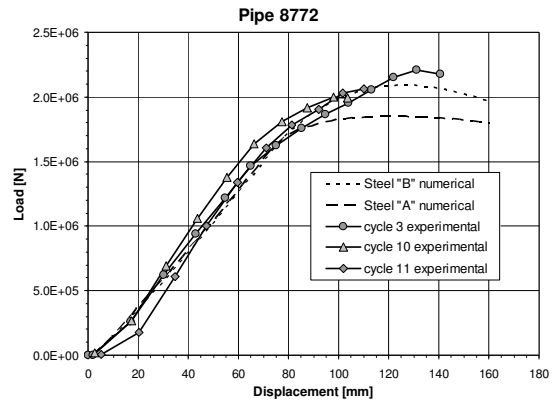
The thickness/radius ratio of the pipe is small enough to allow the use of shell approximation with the “Thickshell” elements (4 nodes, 6 degrees of freedom per node). Due to the geometry and load symmetry, only the half part of the pipe has been schematised. Also, the mandrel has been modelled by means of truss elements; and with this solution, the mandrel is able to flex under the bending force, offering resistance only in the radial direction.

Concerning the material, in order to study the influence of different material strength characteristics, two materials have been analysed:

- grade X80 API 5L (“Steel A”), Longitudinal Yield Stress = 577 MPa, (Yield \Tensile ratio =0.83)

- grade X100 (“Steel B”), Longitudinal Yield Stress = 638 MPa, (Yield \Tensile ratio =0.92)

A first comparison between the experimental results and the numerical calculations, made in terms of the force necessary to bend the pipe, has been carried out. In particular, a comparison between the numerical load-displacement curves with the experimental ones is shown in Figure 6 for the pipe n. 8772, where the bending conditions have been stressed.



**Figure 6:** Comparison between experimental and calculated load vs displacement bending diagram.

Though further investigations are required, the obtained results show that the X100 large diameter pipes can be suitable cold bent, and that for the specific geometry of tested pipes, a deflection angle of about  $8^\circ$  can be achieved (nevertheless, caution during the bending operation has to be taken). Validated finite element models to simulate the bending operation, performed with the pipe bending machine, proved to be suitable to support both a study of the materials and the geometrical parameters required to control the formation of wrinkles, and to define a bending procedure where very high grade steels are involved.

## DUCTILE FRACTURE PROPAGATION

In order to define the material Charpy V 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 X100 grade linepipe steels, two ductile fracture propagation full-scale tests on  $36'' \times 16.0$  mm and  $36'' \times 20.0$  mm pipe geometry have been performed by CSM with natural gas (methane  $\geq 98\%$ ) at the Test Station in Perdasdefogu, Sardinia. Nine pipes were used in both full-scale ductile fracture propagation tests: one initiation pipe and eight test pipes welded together, with an increasing toughness moving from the initiator pipe to the ends. In total, the test line was approximately 90 m long.

The first test layout ( $36'' \times 16.0$  mm), together with the tensile and toughness properties (reported in terms of average Charpy V shelf energy, average drop weight tear test shelf energy, and critical value of crack tip opening angle (CTOA)), is shown in Figure 7a. The test pressure was 193 bar and the test temperature  $\approx 14^\circ\text{C}$ . The arrest Charpy V values, predicted by

both the simplified Battelle equation (with a correction factor of 1.4) and Two Curves Battelle approach (with a correction factor of 1.7) are 295 J and 252 J respectively. The crack, after the initiation by an explosive charge, propagated at high speed in both easterly and westerly directions, through the initiation pipe along the top generatrix, before entering the adjacent pipes, and running at high speed until reaching both ends of the test line. The fracture mode was fully ductile for every pipe. Using the “fan diagram” (the plot of the time of rupture of the timing wires versus their distance from the initiation point), the crack speed diagram shown in Figure 7b has been calculated. It seemed clear that the crack leaves the initiation pipe at high speed (250 m/s); then, in both sides of the test line the pipes (n.8786 and n.8783) adjacent to the initiation pipe indicate a reduction in speed of up to 170 m/s. From this point onwards, the two sides of the test line show a different behavior. On the eastern side, the fracture speed increases in pipe n. 8780, then in pipe n. 8799 runs at a constant speed (210 m/s) before entering the last pipe (n. 8776), where it shows a reduction in speed of up to 110-120 m/s. On the western side, after pipe n. 8786, the fracture runs at a constant speed through pipes 8797 and 8795, before slowing down in the last pipe (8808). The main finding of this full-scale burst test was that all the pipes comprising the test line experienced fracture propagation, with no observed arrests, although in the outermost pipes there are clear indications (given essentially by the observed monotonic decrease in fracture propagation velocity) that these pipes could be close to the arrest condition.

Layout of second full-scale ductile fracture propagation test (36"Ø x 20.0mm) is shown in Figure 8a, together with the main tensile and toughness properties of each pipe. In addition, a composite crack arrestor, provided by Europipe, was positioned after the last pipe in the western side of the line before the reservoir (length 2.0m, fibreglass thickness 40 mm). The test pressure was 225.6 bar and the test temperature  $\approx$  11 °C. For this second test the arrest Charpy V values predicted by both the simplified Battelle equation (with a correction factor of 1.4) and Two Curves Battelle approach (with a correction factor of 1.7) are 280 J and 204 J respectively.

The crack speed diagram, as obtained from experimental “fan diagram”, is shown in Figure 8b. The crack, initiated in pipe n. 8837 by means an explosive charge, propagated at high speed in easterly and westerly directions through the pipe along the top generatrix. At the eastern side of test line, the fracture ran through to the end of the line where a prompt arrest occurred due to the presence of the composite crack arrestor. At the western side, the fracture ran through the instrumented pipe (8831), and subsequently arrested in pipe n.8834. Information from the rupture time of the timing wires, show that the crack on the eastern side propagated very quickly in the first pipe (8835) after the initiation pipe, and then decreased to 120 - 130 m/s on the last three pipes until finally stopping at the beginning of the crack arrestor (within a few centimetres). On the western side, the fracture ran through the instrumented pipe at medium-low speed 110 - 120 m/s, and arrested in the middle of pipe 8834. The arrest was clean, and was preceded by a constant decrease in crack speed down to zero. An analysis of the fracture appearance on the broken pipes, showed fully ductile fracture behaviour.

Determination of the toughness values required for arresting ductile fracture propagation has been historically based upon the use of models in the form of predictive equations, which state the minimum required value of the Charpy V upper shelf energy as a function of both pipe geometry and applied hoop stress. In this context, the Battelle simplified equation and the Two Curves Battelle approach are the most used predictive methods for medium-high strength steel linepipes tested to date. The latter takes into account the decompression behavior of the pressurising medium used in the test at the corresponding pressure and temperature, and is strongly recommended when high pressure and/or rich gas is involved. The former method simply considers the medium as an “ideal gas”. So, for the very high pressure values foreseen for X100 steel pipes, one should use the Battelle Two Curves approach rather than the simplified formula, even when pure methane is the conveyed gas.

A direct applicability of the Battelle equations /9/ to the API X80 grade, and the accompanying level of hoop stress (about 400 MPa), and their straightforward extrapolation to X100 grade operating at very high hoop stress values ( $\geq$  500 MPa) is highly questionable. In fact, for the X100 case, a correction factor of 1.4 times the Charpy V energy predicted by the Battelle simplified equation, and to 1.7 times the Charpy V value predicted by the Battelle Two Curves approach, both derived on the basis of previously performed full-scale burst tests, would be unsuitable. In addition, it is also impossible to detect any satisfactory trend line dividing arrest points from propagation points, in order to derive a new correction factor dedicated to X100 pipes.

Also, by adopting alternative fracture parameters more physically related to the fracture process in pipe, such as the DWTT total energy, DWTT propagation energy, and CTOA angle, no unambiguous predictions were found; even if there is a consistent indication that the real fracture behaviour of the material can be obtained from the analysis of load vs displacement DWTT test

At the end of this short analysis of the available results on X100 pipes it is clear that a general criteria to fix the minimum value of steel toughness required to control the ductile fracture propagation event is unavailable at the moment. In this context, one way of overcoming the problem of putting a value to the required arrest toughness, in terms of the well known Charpy V shelf energy parameter, could be to use an appropriate correction factor, calibrated on the basis of experimental evidence corresponding as closely as possible to the situation under evaluation. In practice, this correction factor should be conducted “case by case” by dedicated full-scale burst tests, being dependent upon the material properties and the service conditions within the line. At the same time, the observed results also give support to the hypothesis that the X100 large diameter pipes are working on the upper bound of the arrest/propagation ductile fracture propagation condition, and, that in the near future, dedicated work regarding the use of crack arrestors, as a necessary device to “integrate” the toughness of the base material in terms of the ductile propagation event, could be encouraged, or even deemed necessary for extreme combinations of in-service operating conditions.

<b>FINAL LAYOUT</b>	<b>4-W</b>	<b>3-W</b>	<b>2-W</b>	<b>1-W</b>	<b>Initiation</b>	<b>1-E</b>	<b>2-E</b>	<b>3-E</b>	<b>4-E</b>
Pipe Number	<b>8808</b>	<b>8795</b>	<b>8797</b>	<b>8786</b>	<b>8781</b>	<b>8783</b>	<b>8780</b>	<b>8799</b>	<b>8776</b>
Rt0.5 (MPa)	772	775	792	803	794	784	802	774	750
Rm (MPa)	822	826	844	872	856	847	870	811	773
Y/T	0.94	0.94	0.94	0.92	0.93	0.93	0.92	0.95	0.97
CVav. (J)	291	249	237	215	193	228	223	258	355
CVmin. (J)	265	222	229	209	183	215	213	238	270
CVmax. (J)	312	272	248	221	204	235	242	266	445
DWTT Tot spec. (J/cm <sup>2</sup> )	823	746	761	732	680	796	756	633	791
DWTT Prop. spec. (J/cm <sup>2</sup> )	536	483	471	478	472	517	472	403	488
CTOAc (°)	10.6	7.9	10.2	10.8	10.2	9.1	10.1	10.3	8.9

Figure 7a: Full scale test lay-out for the 36"OD x 16.0 mm, grade X100 pipes.

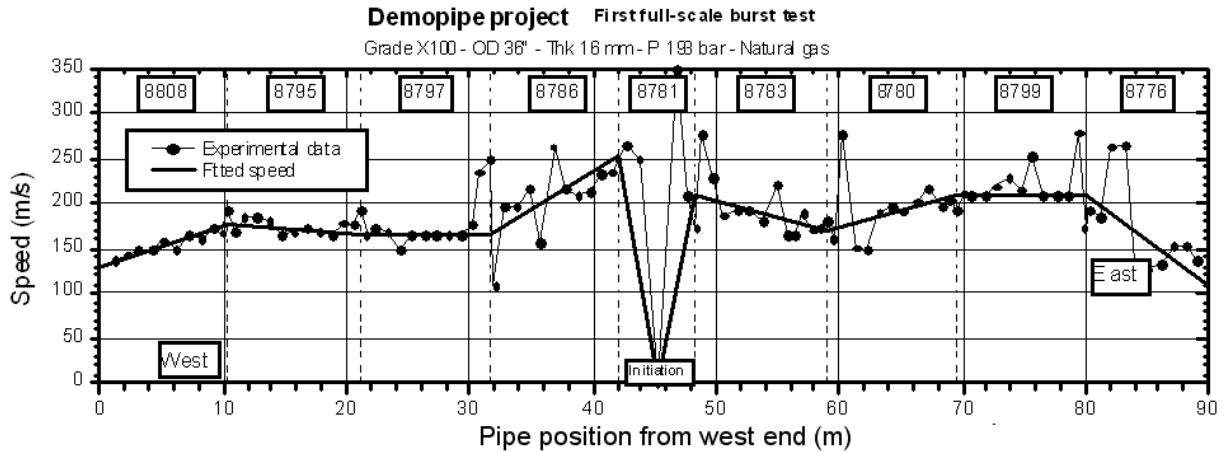


Figure 7b: Crack speed diagram of full scale fracture propagation test on 36"OD x 16.0 mm.

<b>FINAL LAYOUT</b>	<b>4-W</b>	<b>3-W</b>	<b>2-W</b>	<b>1-W</b>	<b>Initiation</b>	<b>1-E</b>	<b>2-E</b>	<b>3-E</b>	<b>4-E</b>	<b>Crack arrester</b>
Pipe Number	<b>824</b>	<b>826</b>	<b>834</b>	<b>831</b>	<b>837</b>	<b>835</b>	<b>839</b>	<b>836</b>	<b>851</b>	
Rt0.5 (MPa)	758	739	739	784	739	782	760	751	760	
Rm (MPa)	788	794	792	824	777	852	800	795	813	
Y/T	0.96	0.93	0.93	0.95	0.95	0.92	0.95	0.94	0.93	
CVav. (J)	267	240	252	247	211	206	223	249	257	
CVmin. (J)	233	231	231	219	199	193	196	233	222	
CVmax. (J)	297	251	260	275	229	214	256	262	293	
DWTT Tot spec. (J/cm <sup>2</sup> )	781	792	779	728	635	565	741	749	809	
DWTT Prop. spec. (J/cm <sup>2</sup> )	499	497	487	427	371	378	438	430	474	
CTOAc (°)	11.5	10.5	8.7	10.5	10.4	9.7	11.9	12.9	11.2	

Figure 8a: Full scale test lay-out for the 36"OD x 20.0 mm, grade X100 pipes,

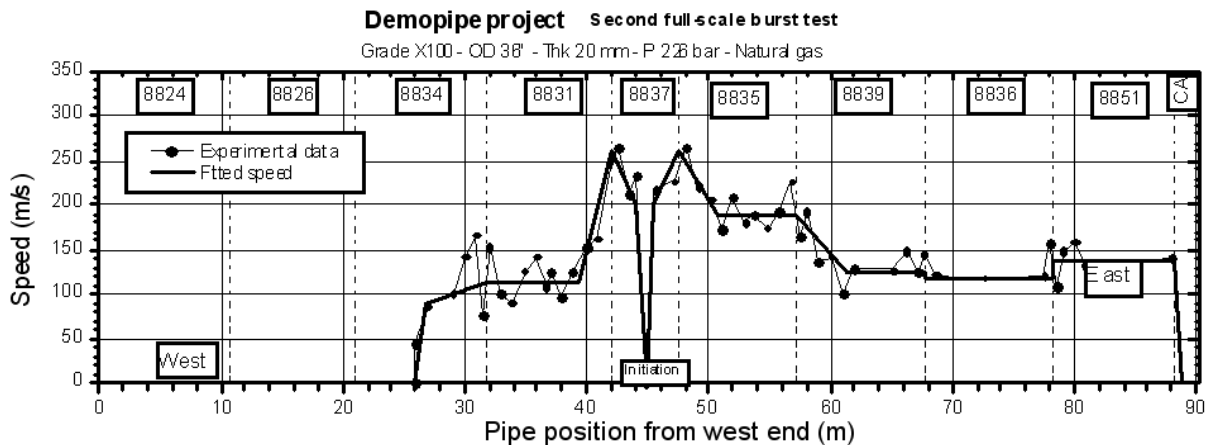


Figure 8b: Crack speed diagram of full scale fracture propagation test on 36"OD x 20.0 mm.

## CONCLUSION

About 50 large diameter steel pipes X100 grade, with a 36" diameter; have been formed by Europipe in their Mulheim UOE pipe mill using controlled-rolled and accelerated-cooled plates of different nominal thickness (12.7, 16.0, 20.0 and 25.0 mm). The strength and toughness properties of pipes have been found to be good, and in agreement with the fixed targets.

Welding Procedure Specifications, using both SMAW and GMAW technologies, to produce in-field welded joints have been developed and tested. The results obtained in terms of strength, hardness and toughness of the welded joints have shown no in-surmountable problems for in-field welds in X100 pipes, and, in fact, consumables with a substantially good performance, including at low temperatures (down to -20°C), are available on the market. In particular, the levels of overmatching generally required for lower grade pipes have been achieved in X100 steel pipes if the longitudinal strength of the pipe is taken into account.

Also the cold bend manufacture is not particularly difficult if a suitable set up of the bend procedures is made. Also, the development of a dedicated finite element analyse code to simulate the cold bending processing gives encouraging initial results.

Two ductile fracture propagation full-scale burst tests were conducted on nominal UOE X100 grade, 36" OD, 16mm and 20 mm wall thickness test lines, using pipes formed from controlled-rolled and accelerated-cooled plates. The results of these two tests, in terms of arrest/propagation conditions, discussed together with available results in the literature on API X80 and X100 pipes, show that the applicability of the Battelle equations, and their straightforward extrapolation from API X80 pipes to X100 grade operating at very high hoop stress values ( $\geq 500$  MPa) is highly questionable.

All these indications give support to the hypothesis that the X100 large diameter pipes are working at the upper bound of the arrest / propagation ductile fracture propagation conditions. In this context, one way to overcome the problem of deriving the required arrest Charpy V toughness (also for alternative fracture parameters from easy-to-measure laboratory test data, such as the DWTT total energy and propagation energy values) is to derive full-scale experimental evidence, under conditions as close as possible to the situation being evaluated. In parallel to this, the use of crack arrestors, as a device to "integrate" the toughness of the base material in terms of ductile fracture propagation, could be adopted, at least for extreme combinations of in-service operating conditions.

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