Suitability Evaluation of X100 Steel Pipes for High Pressure Gas Transportation Pipelines by Full Scale Tests

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Abstracts.
The interest of gas companies in the possible use of high grade steel pipes (Yield Strength ≥ 690 MPa, equivalent to X100 and higher) for the construction of long distance gas pipelines is now a consolidated trend in the world. In response to this potential demand steel makers have developed new classes of steel for pipelines in grades up to X100, for large diameter pipes (up to 56"); steels showing high toughness values, a low brittle / ductile transition temperature and a limited carbon equivalent.

A recently completed ECSC program of work investigated the suitability of X100 grade steels for high pressure pipeline use, with the main emphasis placed upon establishing the fracture behaviour of this new class of steels. The results of the work provided a basis for a new in-progress "ECSC-Demonstration Project" (*DemoPipe Project*), partially sponsored by *EPRG*.

The *DemoPipe* project examines, by means of full-scale tests, the expected problems which can met in building new high steel grade on-shore gas pipeline. Specific tasks of the project are:

- Development of Welding Procedure Specifications for in-field manual and automatic welding technologies for this class of pipes;
- Definition of the required mechanical properties, in terms of both strength and toughness of the girth joints, in order to optimise the in-service performance of very high strength steels in the presence of possible weld defects;
- Development of a specific know-how regarding the field cold bending behaviour of X100 pipes;
- Consolidation and validation of existing know-how about the definition of the minimum toughness required to guarantee safe high strength pipeline service in terms of ductile fracture propagation.

This paper presents the results obtained to date, together with a preliminary discussion about their applicability for future X100 lines.

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INTRODUCTION

In recent years, gas companies have shown an increasing interest in the possible use of higher grade steel pipes (Yield Strength ≥ 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 (≥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 fracture behaviour of these pipes was good. Concerning specific fracture issues, the main results obtained in the research were the following:

- The Battelle /8/ flow stress dependent formula for assessing the resistance of steel linepipes to fracture initiation from part wall axial defects, correctly predicts the failure stress value even for the high strength, high Y/T ratio (> 0.90 on round bar un-flattened specimen) 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 /9/.
- The toughness characteristics of the X100 tested pipes, in terms of Charpy V energy, proved sufficient to arrest a long running shear fracture at hoop stress levels up to 517 MPa (75% of SMYS). The toughness required to arrest the fracture was equivalent to approximately 260 Joules of Charpy V energy for both pipe geometry/test conditions examined. With regard to the correction factor to be used for both the Battelle /10/ simplified equation and the *Two Curves* approach, the burst test results indicated values of 1.4 and 1.7 respectively. These are higher values than those previously derived from past experience on lower grade steels, and further experimental activity is necessary to confirm such values as toughness requirements to arrest a running ductile fracture for X100 gas pipeline.

The results of this 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 girth weld defect tolerance, field cold bending, and the fracture propagation behaviour in high-pressure natural gas pipeline. In order to achieve the general aim, the following specific tasks are included into the project:

- Selection of the field welding technologies and parameters to weld very high strength pipeline. Both manual and automatic welding technologies will be used, with specific Welding Procedure Specifications (WPS) developed to produce the required toughness and strength for the field welded joints.
- Definition of the required mechanical properties, in terms of both strength and toughness of the girth joints, in order to optimise in-service performance of these classes of welded joints on very high strength steels in the presence of possible weld defects.
- Definition of the field cold bending behaviour of units selected in the project, and evaluation of their mechanical properties after forming.

- Consolidation and validation of existing know-how about the definition of the minimum toughness required to guarantee safe high strength pipeline service in terms of ductile fracture propagation; toughness evaluated using Charpy V shelf energy, DWTT shelf energy, and new promising toughness parameters such as the DWTT specific propagation energy and the Crack Tip Opening Angle.

The project commenced in 2001 and the experimental activities are now in progress. This paper presents the results obtained to date in the DemoPipe project.

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 Muelheim 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 /11/ /12/. 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 were developed with respect to the selection of chemical composition and cooling conditions. *Approach A,* which involves a relatively high carbon content (about 0.08%) and high carbon equivalent (about 0.49) in combination with a mild 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 content (about 0.05%) and low carbon equivalent (about 0.43) 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, without additional heat treatment, 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.

HEAT-No.	C	Mn	Si	Mo	Ni	Cu	Nb	Ti	N	Al	Cr	CE_{IIW}	P_{CM}
16155	0.059	1.93	0.35	0.30	0.24	0.020	0.046	0.019	0.006	0.031	0.023	0.464	0.19
16156	0.055	1.97	0.31	0.31	0.24	0.025	0.047	0.019	0.005	0.035	0.021	0.467	0.19
16157	0.057	1.95	0.33	0.30	0.24	0.024	0.046	0.019	0.004	0.035	0.022	0.464	0.19
18438	0.058	1.91	0.31	0.30	0.24	0.018	0.048	0.019	0.005	0.030	0.033	0.461	0.19

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

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 % and the carbon equivalent (CE_{IIW}) is in the range 0.46 - 0.47.

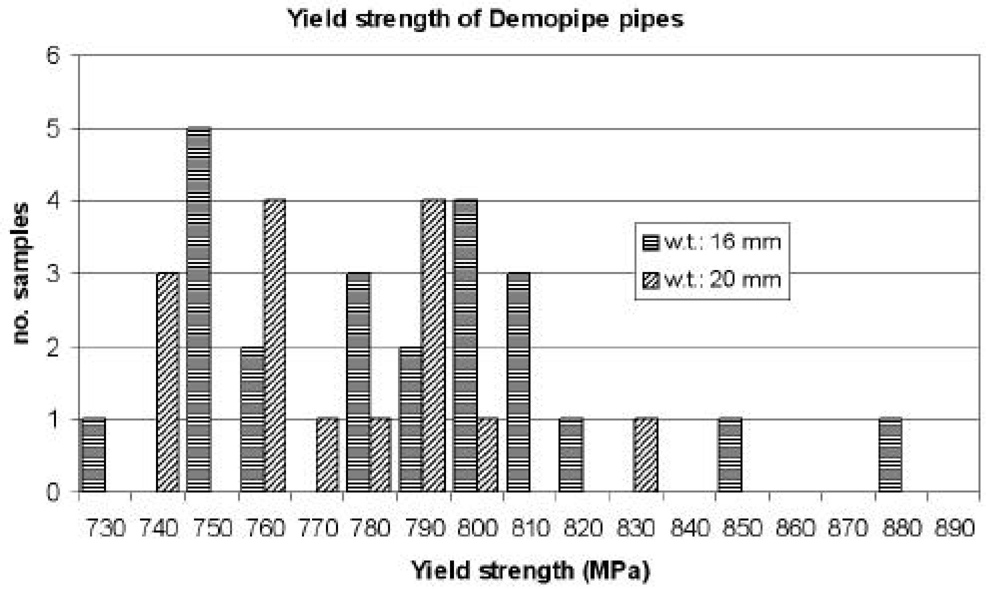


Figure 1: Yield strength (Rt0.5) of produced X100 pipes (thickness 16.0 and 20.0 mm), in MPa.

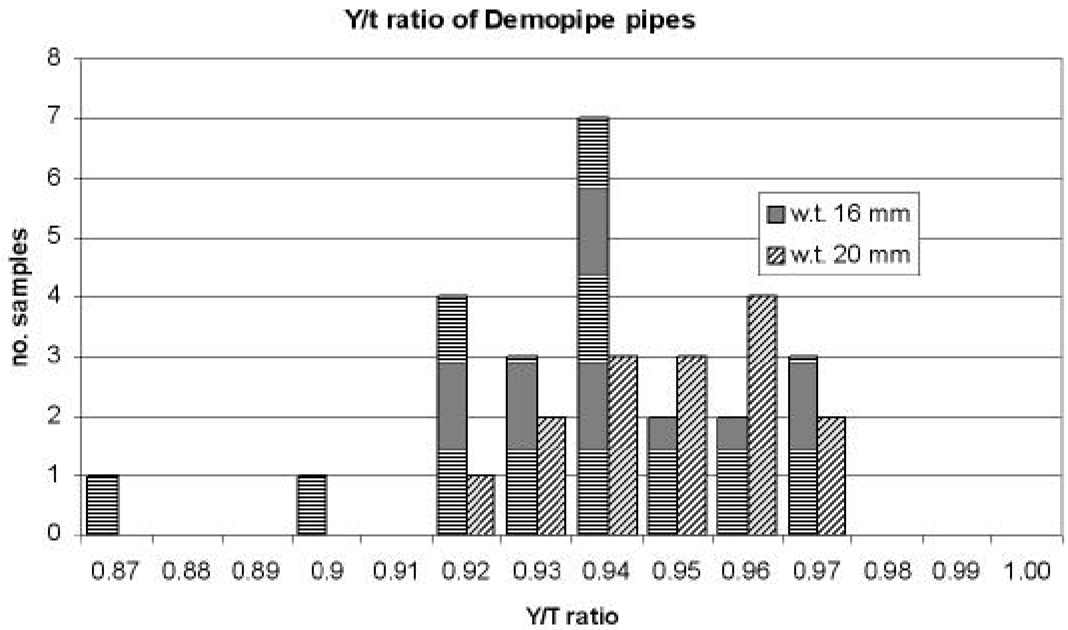


Figure 2: Y/T ratio of produced X100 pipes (thickness 16.0 and 20.0 mm).

The range of cooling parameter values was: 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. For wall thicknesses 16 mm and 20 mm in Figures 1 and 2 the mechanical properties in terms of yield strength (Rt0.5) and Y/T ratio are reported (the indicated tensile test results have been obtained on transverse round bar specimens taken from one end of pipe). High Y/T ratios are also a result of extreme cooling conditions to reach different toughness levels.

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. 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 *Boehler Thyssen)*. 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.

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

Table II: Required consumables classes.

	ETC	*ESAB*	*Boehler Thyssen*
GMAW Light over-matching	116 S	OK Autrod 13.26	***
GMAW High over-matching	120	OK Autrod 13.13	***
SMAW	PH 118 PH 128	Filarc 108	Fox BVD 110

Table III: Solution proposed by different consumable producers.

The WPS have been developed jointly with a 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 optimised 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			SMAW		
Preheat temperature:	min 100°C.		**Preheat temperature:**	min 200°C.	
Inter-pass temperature:	min 100°C max 250°C		**Inter-pass temperature:**	min 120°C max 250°C	
Heat input	**Root pass:**	0.60 KJ/mm	**Heat input**	**Root pass:**	1.0 KJ/mm
	Hot pass:	0.70- 0.75 KJ/mm		**Hot pass:**	1.0 KJ/mm
	Fill passes:	0.75 KJ/mm		**Fill passes:**	1.5 KJ/mm
	Cap passes:	0.80 - 1.0 KJ/mm		**Cap passes:**	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. In Tables V and VI the specific values for all the developed WPS are reported for both wall thicknesses (16.0 mm and 20.0 mm).

		WPS1	WPS2	WPS3	WPS4	WPS5	WPS6	WPS7	WPS8	WPS A	WPS B	WPS Y
	WT 16 mm	**ESAB Filarc 108**	**ETC PH 118**	**ESAB Filarc 108**	**ETC PH 118**	**ESAB OK Autrod 13.26**	**ESAB OK Autrod 13.13**	**ETC 116S**	**ETC 120**	**Boehler Thyssen FOX BVD 110**	**Boehler Thyssen FOX BVD 110**	**ETC PH 128**
Tens [MPa]	**Rt0.5 av.**	660	647	650.5	653.5	676.5	752	744	839.5	726.5	732.5	727
	Rm av.	726.5	750	723	750.5	734.5	807	803.5	900.5	775.5	775	842
	A% av.	25.85	21	23.7	24.4	26.05	19.6	24.35	21.1	18.85	20.3	19.6
Ch V [J]	**R T av.**	154	133	135	142	113	124	101	113	140	136	105
	min	*146*	*128*	*118*	*140*	*108*	*120*	*98*	*108*	*138*	*130*	*102*
	0°C av.	123	118	121	120	105	105	87	98	122	104	102
	min	*120*	*108*	*108*	*116*	*100*	*90*	*84*	*94*	*120*	*94*	*85*
	-20°C av.	93	93	93	106	97	95	77	81	94	79	72
	min	*82*	*80*	*86*	*102*	*86*	*84*	*76*	*78*	*90*	*60*	*62*
CTOD [mm]	**R T av.**	0.454	0.313	0.285	0.327	0.292	0.276	0.201	0.183	0.372	0.244	0.15
	min	*0.443*	*0.298*	*0.285*	*0.259*	*0.267*	*0.263*	*0.185*	*0.164*	*0.340*	*0.244*	
	0°C av.	0.274	0.347	0.358	0.294	0.230	0.251	0.183	0.165	0.233	0.245	0.15
	min	*0.258*	*0.324*	*0.318*	*0.260*	*0.212*	*0.204*	*0.149*	*0.151*	*0.208*	*0.192*	
	-20°C av.	0.275	0.391	0.364	0.163	0.207	0.227	0.143	0.164	0.207	0.193	0.14
	min	*0.265*	*0.335*	*0.337*	*0.109*	*0.190*	*0.227*	*0.133*	*0.139*	*0.207*	*0.182*	

Table V: Weld metal mechanical characterisation of developed WPS on 16.0 mm wall thickness pipes.

		WPS9	WPS10	WPS11	WPS12	WPS13	WPS14	WPS15	WPS16	WPS C	WPS D
	WT 20 mm	**ESAB Filarc 108**	**ETC PH 118**	**ESAB Filarc 108**	**ETC PH 118**	**ESAB OK Autrod 13.26**	**ESAB OK Autrod 13.13**	**ETC 116S**	**ETC 120**	**Boehler Thyssen FOX BVD 110**	**Boehler Thyssen FOX BVD 110**
Tens	**Rt0.5 av.**	692.5	676.5	705	661.5	676.5	770	780.5	940	763	777
	Rm av.	776	745.5	770	772	752.5	834	857	1021.5	828	828.5
	A% av.	24.5	21.35	18.5	18.4	29.4	19.9	21.2	18.35	20.5	17.6
Ch V [J]	**R T av.**	127	121	119	117	102	117	97	97	121	123
	min	*116*	*110*	*118*	*112*	*92*	*112*	*88*	*94*	*106*	*108*
	0°C av.	96	95	83	101	110	111	89	91	99	111
	min	*68*	*88*	*70*	*100*	*102*	*110*	*78*	*82*	*90*	*108*
	-20°C av.	85	79	67	83	85	101	70	75	79	77
	min	*80*	*66*	*60*	*78*	*82*	*94*	*62*	*70*	*68*	*64*
CTOD [mm]	**R T av.**	0.355*	0.270	0.302	0.256	0.266*	0.218	0.14	0.113	0.276*	0.270*
	min	*0.332**	*0.263*	*0.283*	*0.22*	*0.241**	*0.187*	*0.14*	*0.078*	*0.203**	*0.194**
	0°C av.	0.327	0.249	0.277	0.233	0.214	0.183	0.123	0.069	0.261	0.209
	min	*0.256*	*0.238*	*0.265*	*0.201*	*0.198*	*0.183*	*0.107*	*0.068*	*0.226*	*0.209*
	-20°C av.	0.271*	0.194*	0.225*	0.140	0.189	0.185*	0.135	0.0845	0.134*	0.104*
	min	*0.263**	*0.164**	*0.223**	*0.140*	*0.189*	*0.166**	*0.124*	*0.077*	*0.067**	*0.043**

((*):using also specimens with crack shape not in agreement with BS 7448)

Table VI: Weld metal mechanical characterisation of developed WPS on 20.0 mm wall thickness pipes.

A summary of the hardness tests are reported in Figures 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.

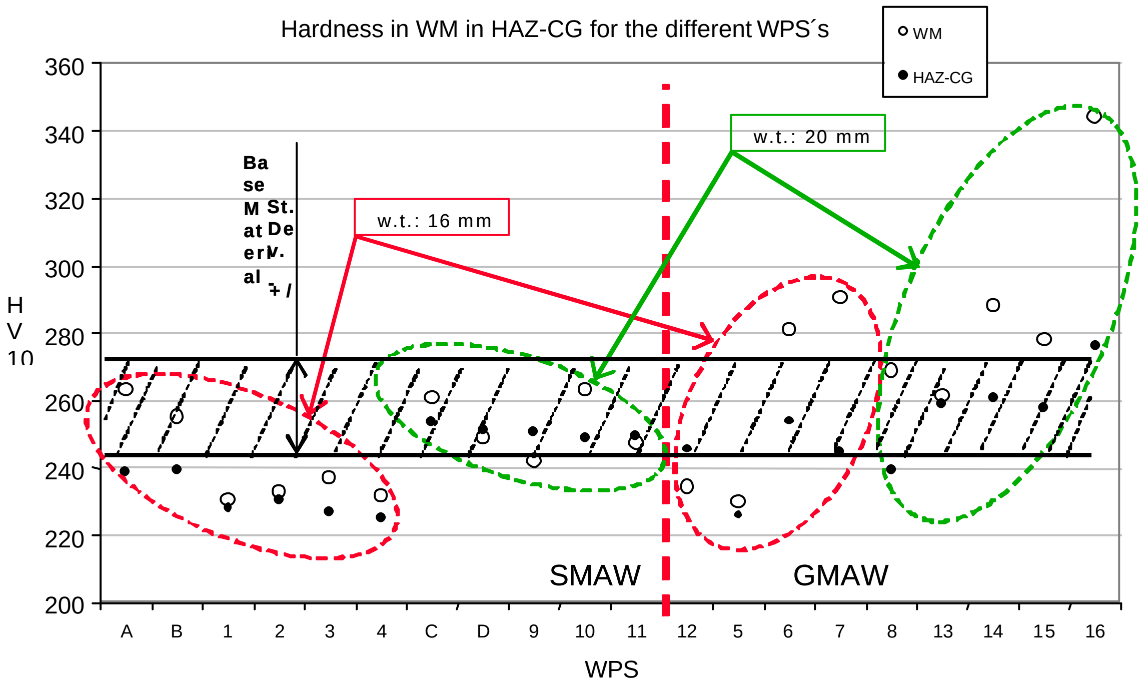


Figure 3: Average hardness values of both HAZ-CG and weld metals (WM) for the developed WPS, compared with the base materials range hardness values.

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.

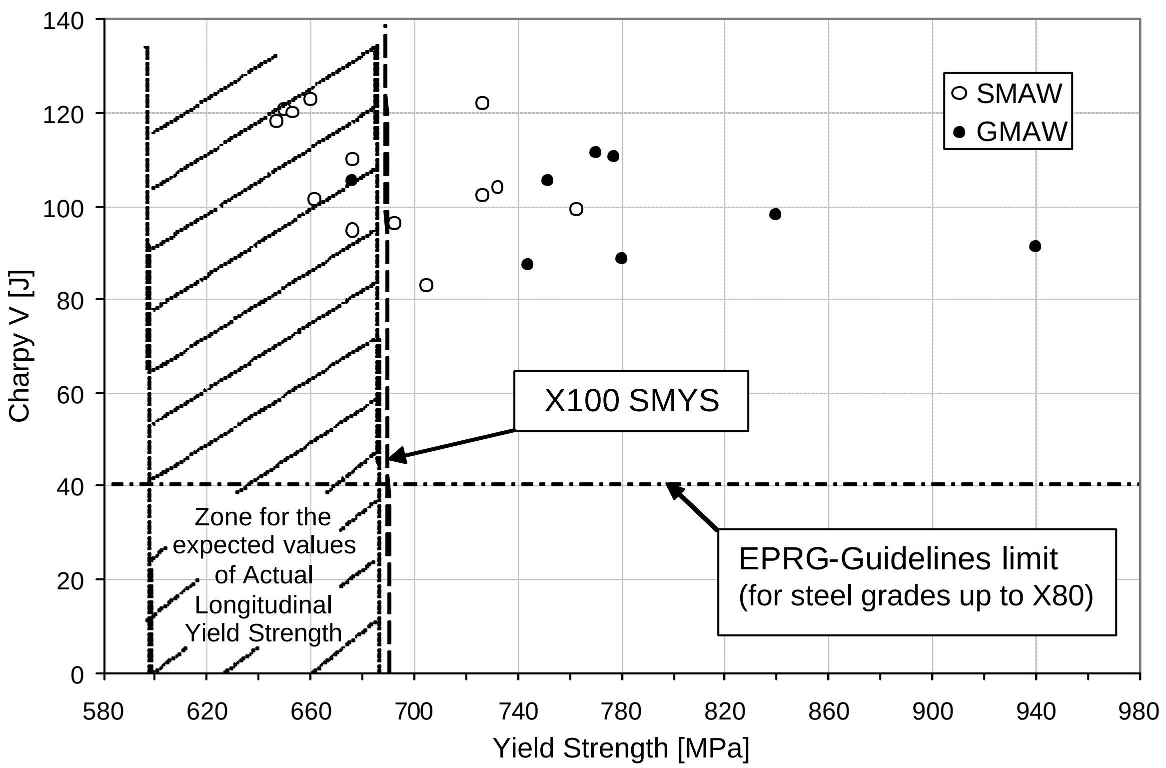


Figure 4: WM Charpy V energy (measured at 0°C) vs. Yield Strength, for all developed WPS.

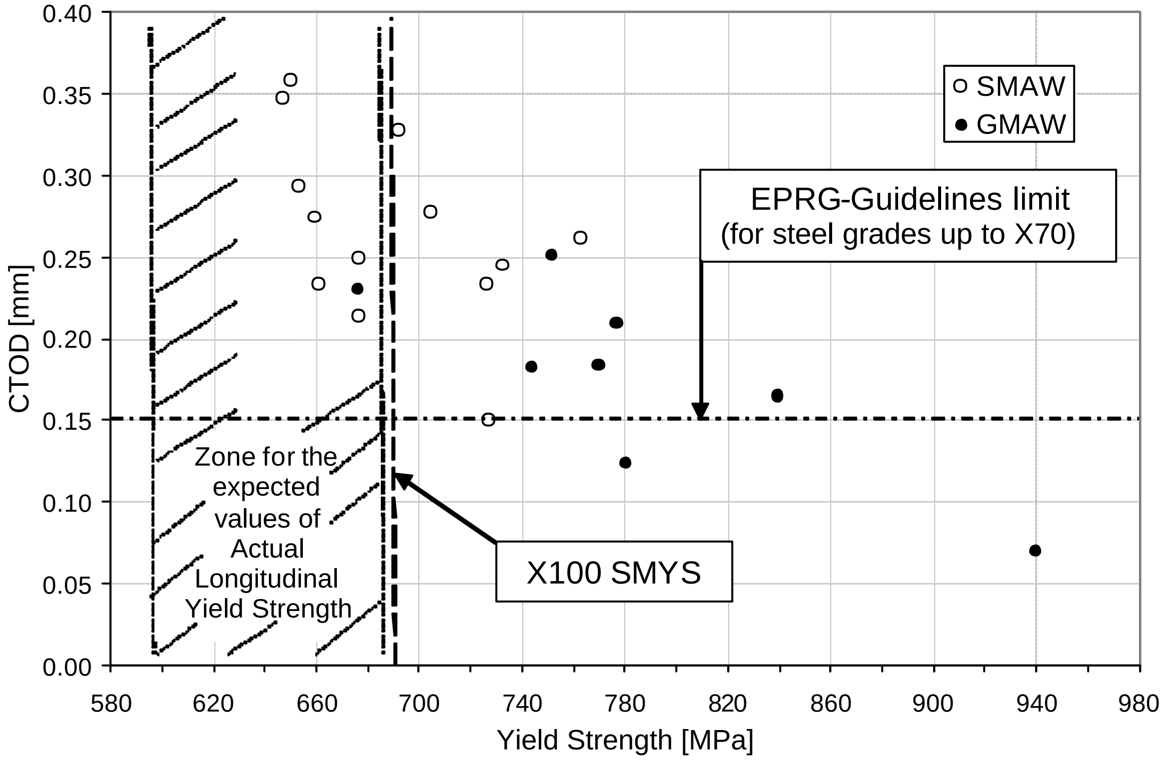


Figure 5: WM CTOD values (measured at 0°C) vs. Yield Strength, for all developed WPS.

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 Boehler Thyssen 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 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 ETC 120 (ER 110 wire), however, 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, WPS n.7 and 6, and one WPS for manual welding, WPS n. 2 in Table V. 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 CE_{IIW}); 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 behaviour 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 contractor 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 VII.

Pipe		Round bar transverse				Round bar longitudinal			
PIPE-No.	WT actual (mm)	**A%**	**Rt0,5**	**Rm**	**Y/T**	**A%**	**Rt0,5**	**Rm**	**Y/T**
8771	13.0	16.3	755	775	0.98	17.0	620	819	0.75
8822	13.0	15.8	730	765	0.96	20.0	581	709	0.82
8823	13.0	14.5	840	890	0.95	17.5	610	706	0.86
8772	13.1	16.3	733	752	0.98	18.5	643	827	0.78

Table VII: Mechanical properties

A bending machine 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 x OD (for OD = 36”, pipe R_{min} corresponds to 36.58 m). In these conditions, for a single pipe of 12m length, $L_{bend}=L_{pipe}-2*(2OD)$, the theoretical maximum overall bend angle is approximately 13°.

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 VIII.

Pipe n.	Bending sequence	Bent length, approx. (m)	Number of steps	Step distance (mm)	Overall bent angle, approx. (°)	Damage
8771	1	6.3	14	450	7	None
8772	2	6.3	14	450	10	Inward wrinkle/ Outward wrinkle*
8823	3	5.9	13	450	8	Wrinkle in step 13°
8822	4	3.6	12	300	6	Wrinkle in step 1°

** = damage created and pushed back by the subsequent bending.*

Table VIII: Cold bending results

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.

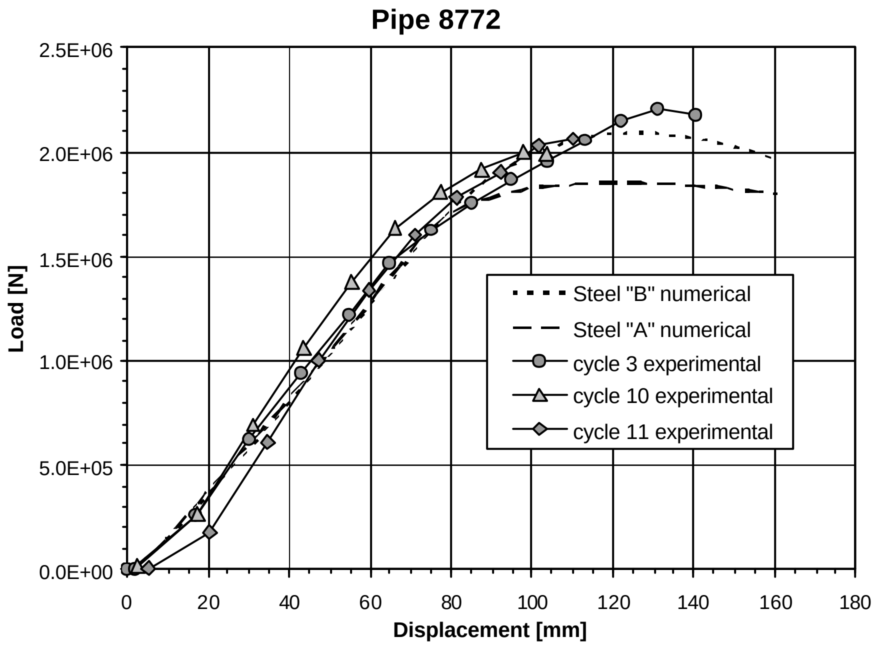


Figure 6: Comparison between experimental and calculated load vs displacement bending diagram.

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° 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”x16.0 mm and 36”x 20.0 mm pipe geometry have been planned. To date, only the first full-scale test has been evaluated, because the second test is scheduled for April 2003. In the meantime, on the basis of these results, the more recently proposed methods/toughness parameters used to predict the ductile fracture propagation event will be validated and/or improved.

Nine pipes were used in the first full-scale ductile fracture propagation test: 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 test layout, together with the tensile and toughness properties (reported in terms of average Charpy V shelf energy, average Drop Weight Tear test shelf energy and Crack Tip Opening Angle (CTOA)), is shown in Figure 7. This last parameters measured as shown in the references /13/ /14/.

The main test conditions for the burst test are reported in Table IX. The medium chosen for pressurising the line was natural gas, predominantly composed of methane (>98%), Table X gives the average value of the actual gas chemical composition.

	WEST					Instrumented			EAST
	A2-W	A1-W	P2-W	P1-W	Initiation	P1-E	P2-E	A1-E	A2-E
FINAL LAYOUT									
Pipe Number	**8808**	**8795**	**8797**	**8786**	**8781**	**8783**	**8780**	**8799**	**8776**
Actual wall thickness (mm)	16.45	16.27	16.28	16.40	16.35	16.15	16.31	16.40	16.45
Actual usage factor*	0.78	0.79	0.79	0.78	0.78	0.79	0.78	0.78	0.78
Actual usage factor**	0.69	0.70	0.68	0.67	0.68	0.70	0.67	0.70	0.72
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
Delta CV (J)	47	50	19	12	21	20	29	28	175
DWTT Tot spec. (J/cm^2)	823	746	761	732	680	796	756	633	791
DWTT Prop. spec. (J/cm^2)	536	483	471	478	472	517	472	403	488
CTOA old	10.6	7.9	10.2	10.8	10.2	9.1	10.1	10.3	8.9
CTOA new	3.1	3.1	5.5	6.0	6.3	4.1	5.8	5.0	2.5

* using actual wt and SMYS
** using actual wt and actual yield strength

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

	X100, 36"x16.0mm burst test
Nominal diameter (inch)	36
Nominal thickness (mm)	16.0
Ground backfill	Soil, >1m
Pressurising medium	Natural gas
Test pressure (bar)	193
Test hoop stress (MPa)	551 (80% of SMYS)
Test temperature (°C)	+14

Table IX: X100 ductile fracture propagation full scale burst test – Main test conditions

Component	**Actual composition [% mole]**
He+N	0.829
CO_2	0.077
CH_4	98.013
C_2H_6	0.716
C_3H_8	0.224
C_4H_{10} I+N	0.105
C_5H_{12} I+N	0.023
C_6+	0.013

Table X: Gas composition.

The instrumentation used was a comprehensive one of thermo-resistances, pressure transducers for measuring both the test pressure and the pressure decay along the test line during the test, and timing wires to determine the crack speed during crack propagation; additionally, electrical strain gages (fixed to the internal and external walls of pipe n. 8783) allowed the measurement of the strain field associated with the running crack, and facilitated the calculation of the pipe cross shape evolution during the fracture process.

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. In this context, it is useful to underline that the Battelle simplified equation and the Two Curve approach are the most adopted predictive method for medium-high strength steel linepipes tested to date; with the latter taking 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 considers the medium as an "ideal gas". In reality, for high pressure values, as those foreseen for X100 steel pipes, even when considering pure methane as the conveyed gas, one should use the Battelle Two Curve approach instead of the simplified formula.

Arrest/Propagation predictions according to the Charpy V Battelle equations referred to above, are reported in Figures 8 and 9; in particular, on the basis of the Battelle Two Curve approach, the predicted arrest condition for both the previous and current DemoPipe project X100 tests is very similar; but it is useful to note the main difference between these two tests is the pressurising medium, with the previous X100 test having been conducted using air as the pressurising medium.

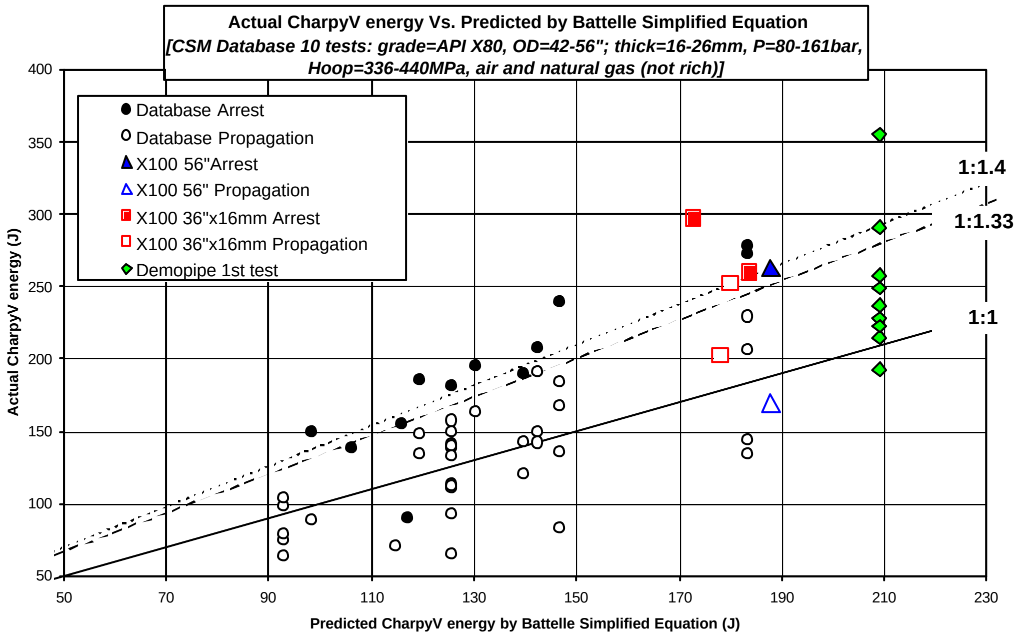


Figure 8: Actual CharpyV energy vs Predicted Battelle simplified equation for large diameter pipes grade = APIX80.

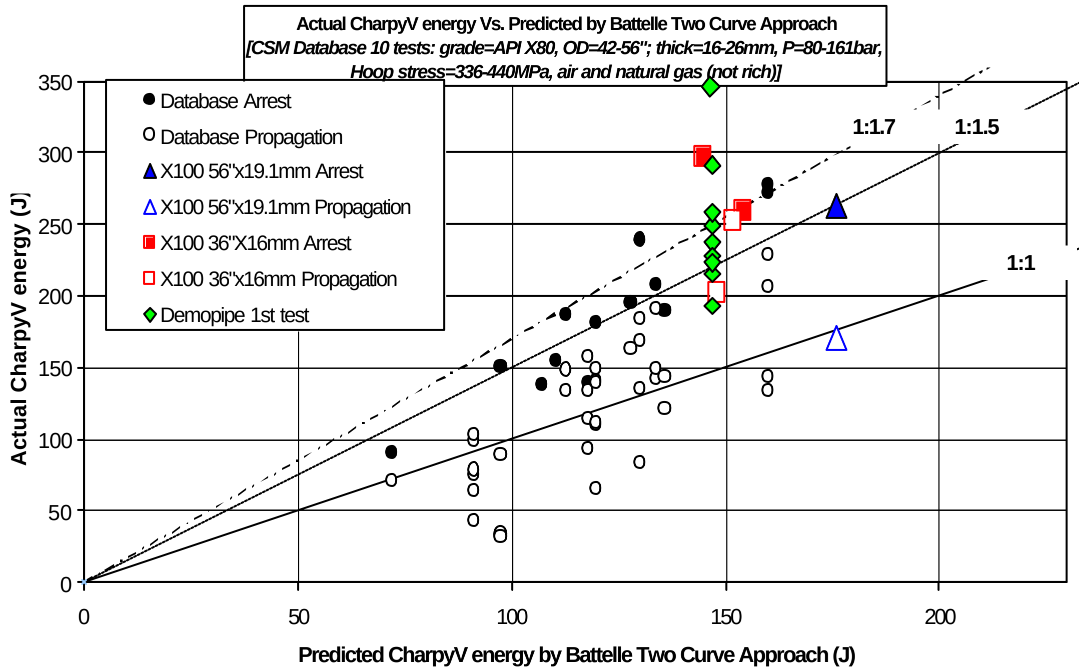


Figure 9: Actual Charpy V energy vs Predicted Battelle Two Curve for large diameter pipes grade = APIX80.

Nevertheless, as shown in the above figures, a directly applicability of the Battelle equations to the API X80 grade, and the consequent level of hoop stress (about 400 MPa), and their straightforward extrapolation to X100 grade operating at very high hoop stress values ($\gtrsim$ 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 evidence, to as close as possible to the situation being evaluated. In practice, this correction factor should be conducted “case by case”, being dependent on the material properties and the test conditions. 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 Curve approach could be suitable.

Also, considering additional toughness requirements such as the DWTT energy and CTOA angle, even if sound predictive methods still do not exist (or they are still under development/validation stage, as the PICPRO model developed by CSM on the base of base on CTOA toughness parameter /13/ /14/), comparison between previous X100 ECSC arrest pipes and the current X100 DemoPipe test pipes indicates, at least for the outermost test pipes, a comparable level of toughness. Calculations made using PICPRO and based upon the CTOAc values, as obtained from standard “Two Specimen” CTOA tests also predicts arrest for the conditions of interest.

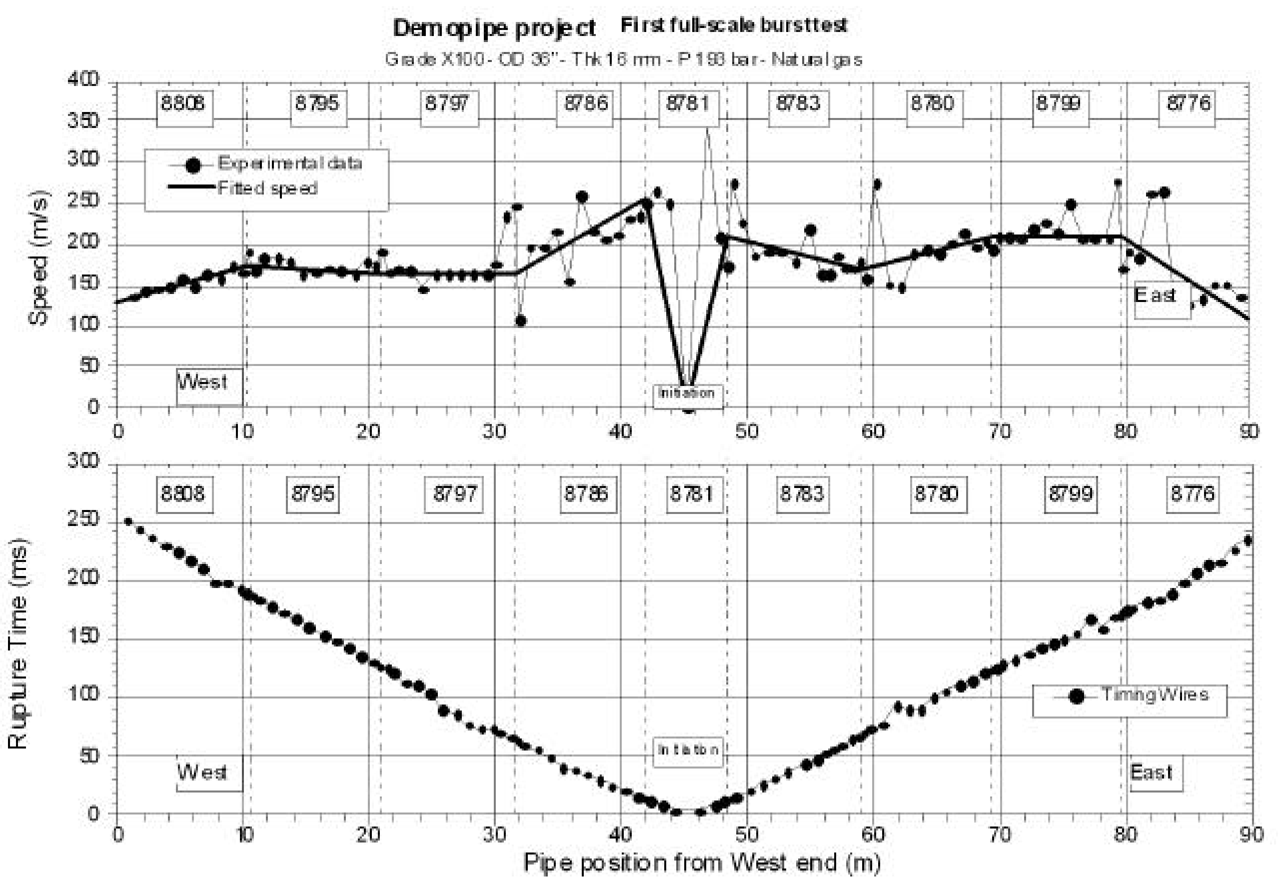


Figure 10: “Fan diagram” and crack speed diagram of full scale fracture propagation test.

The test was performed at the CSM Test Station in Perdasdefogu, Sardinia. The crack, after the initiation by explosive charge, propagated at high speed in both the East and West directions, through the initiation pipe along the top generatrix, entered into the adjacent pipes and ran at high speed until it reached both the ends of the test line, where it caused a “ring-off”, corresponding with the tie-in welds with the reservoirs. The fracture mode was fully ductile for every pipe. Pipe n. 8799 and n. 8776 showed indications of separations on the fracture surface. 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 10 has been calculated. On examining these curves, it seemed clear that the crack leaves the initiation pipe at high speed (250m/s) due to initial overpressure. Then, in both sides of the test line, the two pipes (n. 8786 and n. 8783) nearest the initiation pipe indicate a reduction in speed of up to 170m/s. From this point onwards, the two sides of the test line show different behaviour. On the East side, the fracture speed increases in pipe n. 8780, then in pipe n. 8799 runs at a constant speed (210m/s) before entering the last pipe (n. 8776), where it shows a reduction of speed of up to 110-120 m/s. On the West 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 result of the full-scale burst test was that all the pipes comprising the test line experienced fracture propagation, with no arrests observed, even though in the outermost pipes there are clear indications that these pipes could be close to the arrest conditions. As far as the Charpy V-based predictive methods are concerned, particularly the most quoted Battelle two Curve approach, it proved unable to give correct predictions, even when adopting the correction factor of 1.7 (which had been demonstrated to work well for previous X100 ECSC test results). In addition, looking at Figure 8 (and 9), it is impossible to indicate any satisfactory trend line dividing the arrest points from the propagation points, in order to derive a new correction factor.

An in-depth analysis of the testing conditions has been made, comparing them with those of the previous X100 ECSC test where the tests conditions were very similar, and where arrests were observed: no unexpected extra driving force was found. In particular, the raw pressure transducer data, pressure measured vs time curves, show the typical decompression trend in a gas transmission line during ductile fracture propagation when a single phase gas is used. Moreover, good agreement is shown with the predicted decompression curve obtained using the GASDECOM computer program; used in this specific case to predict the gas decompression curve in the Two Curve Battelle valuation.

Therefore the main issue remaining, concerns the difference in material properties between the two tests:

- the comparison of tensile properties for both X100 tests has shown that the differences are small, with the DemoPipe data indicating slightly higher yield and tensile strengths, and also in terms of Y/T ratio;
- the comparison of DWTT shelf energies (both total and propagation energy) show that the differences are slightly more marked, especially looking at the DWTT energy.

This last point is more physically evident when looking at *Force vs. Displacement curves* from the DWTT tests as shown in Figure 11: the slope of the propagation part of the X100 ECSC arrest pipes are different from all the propagation pipes from both tests, and in particular they correspond to a higher absorbed energy per displacement unit. The same trend can be found looking at the CTOAc angle. With regard to this point, it underlines that the differences found in both DWTT and CTOA fracture parameters are not very great, and practically, they fall within the same level of the scatter within the test lines. Anyway, these differences, that were considered negligible in the test design process, could be responsible for the different behaviour of the two tests.

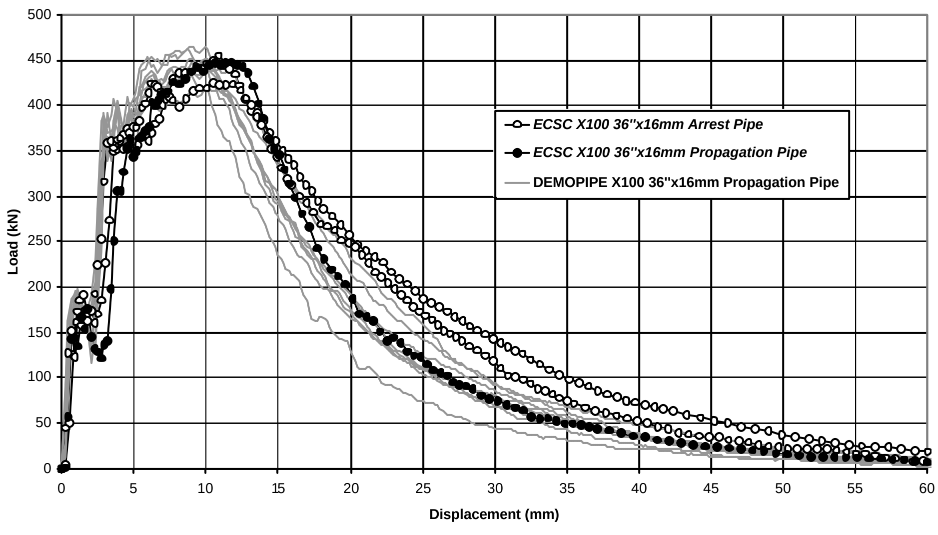


Figure 11: *Force vs. Displacement curves* concerning the DWTT tests on X100 steels.

In addition, the CTOA approach under-estimated the capability of the test pipes to arrest the fracture, and consequently a specific analysis has been done. The CTOA-based approach is a "*Driving vs Resistance Force*" method, in the sense that the PICPRO finite element code calculates the driving force, CTOA applied, to be compared with the CTOA as measured in the laboratory. To check the various parts of this method, and in particular the driving force, a comparison was made between the pipe opening shape at the crack tip during the fracture propagation as predicted by the code, and as measured by means of strain gauges, during the burst test. To do that, the crack speed history as measured in the burst test, was given as the input to the code, and the pipe opening shape was worked out as the output. The results are in good agreement with the experimental data, in particular the CTOA value as derived from the code using the

actual crack speed of the burst test, gave a very close agreement with the average value as measured by strain gauges, i.e. about 6°.
This comparison indicates that the PICPRO code tends to provide a good estimation of the applied driving force, and that the main matter of concern is how the CTOA of the material has to be measured in laboratory. The Two Specimen CTOA test developed in the past for lower grade steels, and here used for DemoPipe test pipes CTOAc measurement, could in fact be somewhat unsuitable /15/. In ongoing PRCI sponsored projects /16/, led by CSM, a modification to the test methodology was proposed, based on the observation that some of the hypotheses used at the time for developing the laboratory method were invalid for high strength – high toughness steels. The CTOAc so modified is named CTOAc new (or CTOAnew) and the values for the DemoPipe test pipes are reported in Figure 7. The CTOAc conventional values are higher than the CTOAnew values, and this is lower than the CTOA predicted by PICPRO; so the CTOAnew values can give a prediction in agreement with the full scale test results, but overly conservative. All this can be considered as an indication that the CTOA approach is promising, but further research effort is necessary, within the previously mentioned current PRCI sponsored project /16/.

Finally, the observed results 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.

Conclusion.

About 50 large diameter steel pipes X100 grade, with a 36” diameter; have been produced by Europipe in their Muelheim 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 is in progress, with encouraging initial results.

A ductile fracture propagation full-scale test was conducted on nominal X100, 36” OD, 16mm wall thickness. The results revealed that a fast crack propagated through all the pipes comprising the test line, irrespective of the Charpy V energy levels, which over-estimated the resistance capability of the test pipes at the test conditions. Nevertheless, in the outermost and tougher pipes (average values of shelf energy about 300 J) there were indications of close-to-arrest conditions: with a crack speed that continuously decelerated down to 120-140 m/s, close to the value, generally around 100 m/s, usually considered as the limit for steady-state ductile fracture propagation in high strength/high toughness steel pipes.

Also, by adopting alternative fracture parameters, more physically related to the fracture process in pipe (such as the DWTT energy and CTOA angle), no conservative predictions were found. Possible reasons for such different behaviour to the previous experience on X100 pipes with the same geometry, could be ascribed to small, but clearly relevant, differences in terms of the pipes’ mechanical properties: DemoPipe test pipes exhibited slightly higher tensile characteristics and slightly lower toughness properties in terms of DWTT energy and CTOAc values. All these indications 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 on 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.

Work in progress, last news…

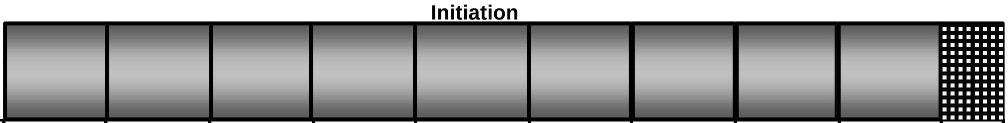
The 2nd full scale burst test has been performed on the 2nd April of this years by CSM at the Test Station in Perdasdefogu, Sardinia. Nine pipes were used in this full-scale ductile fracture propagation test: one initiation pipe and eight test pipes welded together, in total, the test line was approximately 90 m long. The test layout, together with the tensile and toughness properties (reported in terms of average Charpy V shelf energy, average Drop Weight Tear test shelf energy and Crack Tip Opening Angle (CTOA)), is shown in Figure 12. The main test conditions for the burst test are reported in Table XI. In particular at the end of the East side of the test line a crack arrestor has been inserted.

The crack, after the initiation by explosive charge, propagated at high speed in both the East and West directions, through the initiation pipe along the top generatrix, entered into the adjacent pipes. In the East side it ran at high speed until it reached the crack arrestor and it was stopped after few centimeters; in the other side it was stopped in base material within the second West test pipe (pipe n. 834). Generally the obtained arrest/propagation results are in line what the predictions made on the base on first DemoPipe full scale burst test suggestions.

Nominal Diameter (inch)	Nominal thickness (mm)	Ground backfill	Pressurising medium	Test pressure (bar)	hoop stress (MPa)	Test temperature (°C)
36	20	Soil, >1m	Natural gas methane >98%.	225.7	516 (75%SMYS)	+11

Table XI: 2nd X100 ductile fracture propagation full scale burst test – Main test conditions

WEST instrumented Initiation EAST



FINAL LAYOUT										
Pipe Number	**824**	**826**	**834**	**831**	**837**	**835**	**839**	**836**	**851**	Crack arrestor
Actual wall thickness (mm)	20.31	20.37	20.69	20.32	20.42	20.38	20.55	20.48	20.44	
Actual usage factor*	0.74	0.74	0.72	0.74	0.73	0.73	0.73	0.73	0.73	
Actual usage factor**	0.67	0.69	0.68	0.65	0.68	0.65	0.66	0.67	0.67	
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	
Delta CV (J)	64	20	29	56	30	21	60	29	71	
DWTT Tot spec. (J/cm^2)	781	792	779	728	635	565	741	749	809	
DWTT Prop. spec. (J/cm^2)	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	
CTOA new (°)	6.6	6.6	5.7	6.5	7.8	6.2	6.9	9.4	6.4	

* using actual wt and SMYS
** using actual wt and actual yield strength

Figure 11: 2nd X100 ductile fracture propagation full scale burst test – Main test conditions.

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