X100 - GIRTH WELDING, JOINT PROPERTIES AND DEFECT TOLERANCE

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ABSTRACT

The following paper describes some of the work undertaken within the Demopipe X100 project for the evaluation of X100 pipeline steels. The specific areas of interest described are the development of suitable girth welding procedures using mechanised GMAW and SMAW processes, the resultant joint properties and the assessment of defect tolerance levels applicable to X100 line pipe and girth welds. Numerous weld metal chemistries were examined with the two welding processes typical of field-welding construction, such that various strength, toughness and hardness levels could be assessed. Preheating and interpass temperature requirements for the various consumable and base material combinations were assessed using Tekken testing. The final output of the consumable evaluation programme resulted in the selection of several weld metal chemical compositions and welding procedures suitable for the in-field construction of two X100 pipe strings for burst testing. The resultant field weldability and joint integrity was proved through their exemplary performance in the two burst tests conducted within the project.

The defect tolerance work centred on the production of wide plate tests and full scale bend tests in conjunction with numerous small scale CTOD and impact toughness tests, all of which incorporated mechanised GMAW and SMAW girth welds. Assessment of the data using classical failure assessment diagrams has led to a conservative result as is commonly found for pipeline applications. The results of the curved wide plate testing undertaken have, in general, indicated that it will be possible to obtain adequate levels of defect tolerance in X100 pipeline girth welds, although in the short term project specific testing may be required to optimise the acceptance criteria for a specific application and design conditions.

KEYWORDS

Pipeline, Girth Welding, X100, ECA, Defect Tolerance, High Strength Steel, Mechanised GMAW, Gas Metal Arc Welding, SMAW, Shielded Metal Arc Welding, Mechanical Properties, Pipeline Weld Procedure Specifications.

INTRODUCTION

The last decade has shown increasing interest by gas transmission companies in the possible use of higher strength steel pipes (yield strength ≥ 690MPa, equivalent to an API 5L X100 steel grade if it were to exist) for the construction of long distance gas pipelines [1,2,3,4]. The use of a high strength grade offers potential benefits, in terms of using a higher service pressure (≥ 15MPa) without increasing the pipe wall thickness. This in turn offers financial benefits arising from lower material, transportation and fabrication costs.

The following paper summarises several aspects of work conducted within the X100 DEMOPIPE project. The project was funded by the European Coal and Steel Community (ECSC) and the

HOME

European Pipeline Research Group (EPRG), with the programme managed by Centro Sviluppo Materiali (CSM) in Rome. The overall aim of the project was to increase the knowledge required to promote the use of grade X100 pipeline steels, and to consolidate the preliminary indications regarding the value of toughness needed to control running ductile fracture propagation within X100 pipelines. This paper will concentrate on the girth welding techniques employed, the joint properties achieved and the defect tolerance assessments conducted during the project. The welding development work culminated in the in-field construction of two X100 pipe strings (9 pipes in each) for running ductile fracture evaluation through burst testing, thereby providing a suitable goal for this aspect of the project. The defect tolerance work was considered an essential aspect of ensuring the safe use over the specified design life of any future X100 pipeline.

1 X100 PIPE MATERIAL

The X100 plate used throughout the project was manufactured by Dillinger Hütte. Several approaches were evaluated regarding the chemical composition and thermo-mechanical controlled processing (TMCP) route of the steel before an optimum was selected [5]. The final composition and TMCP route involved a carbon content of 0.055-0.060%, a carbon equivalent (CE_{IIW}) of 0.46-0.47%, with a cooling stop temperature of ~400°C and cooling rate in the range of 30-50°C/s (dependant on the final plate wall thickness). The microstructure consisted predominantly of fine acicular ferrite (granular bainite).

Pipes were manufactured by Europipe using UOE pipe forming technology with SAW longitudinal seams. Two wall thicknesses (WT) were selected for the majority of welding trials; 16mm and 20mm, both having an outer diameter of 914mm (36”). These represented the wall thicknesses to be used in the burst test programme. The pipe body exhibited transverse round bar yield strengths ($Rt_{0.5}$) averaging 770MPa (20mm WT) and 780MPa (16mm WT), transverse tensile strengths (Rm) averaging 815MPa (20mm WT) and 840MPa (16mm WT), with typical $Rt_{0.5}$/Rm ratios of 0.94-0.95 and elongation values (A) of 16%. Average pipe body Charpy impact toughness levels at -20°C were ~220J for both pipe WT variants.

2 WELDING PROCEDURE SPECIFICATION DEVELOPMENT

A major objective of the DEMOPIPE project was to enable the selection of suitable field welding processes and parameters to weld X100 linepipe. Definition of the required girth weld mechanical properties centred on the pipe yield strength, such that various conditions of weld metal yield strength relative to the pipe longitudinal yield strength were investigated. High levels of toughness were considered desirable, and would form the basis of optimum welding consumable selection if more than one type was capable of the required strength level. Conventional manual and mechanised welding technologies were examined, with the specific aim of generating weld procedure specifications (WPS) suitable for construction of the burst test sections. This was achieved via a comprehensive evaluation of numerous commercially available welding consumable chemistries for each process, in order to generate the required toughness and strength levels for an X100 field weld.

Mechanised girth weld compositions were selected on the basis of providing even-matching/ light overmatching (Procedure I), and appreciable over-matching (Procedure II) with respect to the nominal (all-weld metal electrode classification test) properties. Two manufacturers were approached to provide suitable gas metal arc welding (GMAW) consumables fulfilling these criteria, as shown in Table 1. Shielded metal arc welding (SMAW) was performed using three electrode manufacturers’ consumables. The fill and cap electrodes were chosen so as to provide even-matching or light over-matching, with the coating types designated as low hydrogen (<5ml diffusible H_2/ 100g deposited weld metal).

HOME

Table 1: Electrode types and nominal compositions used throughout the programme

Process	Manufacturer 1	Manufacturer 2	Manufacturer 3
GMAW Light over-matching (Procedure I)	AWS 5.28 ER100S-G 0.1C, 1.7Mn, 0.5Si, 0.1Cu, 0.3Mo	AWS 5.28 ER80S-G 0.1C, 1.4Mn, 0.8Si, 0.8Ni, 0.3Cu, 0.2Cr	N/A
GMAW High over-matching (Procedure II)	AWS 5.28 ER110S-1 0.1C, 1.7Mn, 0.75Si, 2.0Ni, 0.55Mo, 0.3 Cr	AWS 5.28 ER100S-G 0.1C, 1.4Mn, 0.7Si, 0.6Ni, 0.2Mo, 0.6Cr	N/A
SMAW (root)	AWS 5.1 E6010 0.12C, 0.6Mn, 0.3Si	AWS 5.1 E6010 0.1C, 0.45Mn, 0.2Si,	AWS 5.1 E6010 0.1C, 0.5Mn, 0.2Si
SMAW (hot pass)	AWS 5.5 E8018-G 0.05C, 1.2Mn, 0.5Si, 1.6Ni	AWS 5.1 E9010-G 0.09C, 0.07Mn, 0.2Si, 0.65Ni, 0.25Mo	N/A
SMAW (fill and cap)	AWS 5.5 E11018-M 0.06C, 1.6Mn, 0.35Si, 2.0 Ni, 0.4Mo	AWS 5.5 E10018-G 0.08C, 1.8Mn, 0.5Si, 0.75Ni (ϕ3.2),1.45Ni(ϕ4)	AWS 5.5 E11018-G 0.07C, 1.5Mn, 0.4Si, 2.0Ni, 0.3Mo
SMAW (fill and cap)	AWS 5.5 E12018-M 0.07C, 1.6Mn, 0.30Si, 2.0 Ni, 0.45Mo	N/A	N/A

The root pass electrodes were low strength cellulosic types, chosen due to their ability to produce low levels of residual stress in the weld metal coupled with a high capability to generate optimum penetration and root profile characteristics. Specific procedures in the 20mm WT pipe utilised an E9010 or E8018 electrode for the hot pass, in accordance with typical field-welding practice to ensure optimum penetration and weldability for this position within the welding sequence.

Preheat and Interpass Determination

Initial investigations focused on the determination of suitable SMAW preheat and interpass temperatures to avoid the occurrence of cold (hydrogen) cracking for the X100 material and consumables listed in Table 1. Of particular concern was the cellulosic root pass due to the high levels of hydrogen initially present in the weldment, coupled with the high strength of the pipeline steel. The Tekken test was selected for weldability evaluation due to its similar geometry (Y-groove) to a typical SMAW joint (60° included angle). Previous experience had also shown that the Implant test gave excessively conservative results for this welding process, parameters and geometry.

Preliminary WPSs were determined by CSM and the welding contractor for the programme, SICIM Spa. Special attention was focused on the maximum allowable arc energy; this was fixed at 1.5kJ/mm for the fill passes to reduce the chances of mechanical property decay through precipitation of second phases and grain coarsening effects, with the consequent benefit of high toughness maintenance and reduced cold cracking susceptibility.

Tests were undertaken on 16mm, 20mm and 25mm WT X100 pipe. Ring sections were extracted and cold flattened prior to machining the Y-groove specimens. Tests were carried out in accordance with JIS Z 3158 [7]; 60mm anchorage welds were made at either end of the 80mm test section using a GMAW procedure with AWS ER 100S-G consumables. Preheat was applied somewhat higher than the required level to ensure all of the plate material reached the required temperature; the test started when the plate reached the correct value on cooling. Preheat/ interpass temperatures of 150°C, 100°C and room temperature were selected, with either a single weld bead (majority case) or two beads (representing root and hot pass) deposited in the groove at the specified arc energy. Recorded arc energies ranged from 1.0 to 1.4 kJ/mm. The test welds were left for 24 hours to allow hydrogen diffusion and the potential formation of any cracking; each test deposit was subsequently cut transverse to the welding direction to provide four metallographic sections. After polishing each section, optical microscopy in the range of 20X to 200X was carried out with a simple crack/ no crack criteria applied to any given section.

The results of the Tekken tests using the 16mm WT X100 exhibited cracking within the cellulosic electrode weld metals and the basic coated E10018-G of Manufacturer 2 when no preheat was used. However, a 100°C preheat resulted in no visible cracking for all electrode types. The additional tests utilising two beads representing a root (E6010) and hot pass (E10018/ E11018) with 100°C preheat/interpass also exhibited no cracking. Hardness levels after applying a preheat of 100°C resulted in a peak of 281 HV10 in the HAZ of the base material, and 299 HV10 within the weld metal of one of the basic coated electrodes.

Results from the trials carried out using the 20mm WT X100 again showed cracking for all of the cellulosic electrodes when no preheat was applied. A preheat of 100°C resulted in no observed cracking for all electrode types, including the 25mm WT pipe. Hardness levels peaked at 301 HV10 in the HAZ of the base material and 298 HV10 for the E10018-G weld metal when a preheat of 100°C was applied (25mm WT).

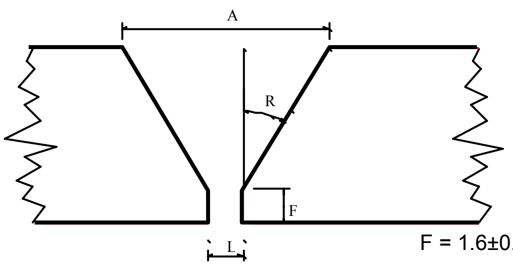
The conclusion of this work resulted in the application of a preheat/ interpass minimum to at least 100°C for the SMAW and GMAW girth weld procedures undertaken with the X100 material examined in this programme. In reality, a higher preheat level was used in the numerous welding consumable evaluation trials to ensure that all passes of the procedure were made above the 100°C minimum.

Girth Welding Consumable Evaluation Trials

The preliminary WPSs selected by CSM and the welding contractor for the manual and mechanised welding processes were used to evaluate the various consumables listed in Table 1. Typical procedures for SMAW and GMAW are shown in Table 2 and Table 3. A total of 13 SMAW and 8 GMAW procedures were evaluated, with each full pipe circumference comprising two procedures (each welded from 12 to 6 o'clock). Both vertical up and vertical down welding techniques were examined for the SMAW procedures, whereas all the mechanised GMAW was carried out using the conventional vertical down technique. An internal line-up clamp with integral copper backing was used for the GMAW procedures, such that all passes were deposited using a single consumable composition from the outside of the pipe.

Table 2: Typical SMAW WPS

WPS:	WPS SIC CSM 01
PROCESS:	111 – SMAW
POSITION:	PG (5G)
FILLER METALS:	ROOT – DOWNHILL Manufacturer 2 E6010 OTHER PASSES – DOWNHILL Manufacturer 2 E10018-G
BASE METAL:	API 5L X100 - O.D. 36" (914 mm) - W.T. 16 mm

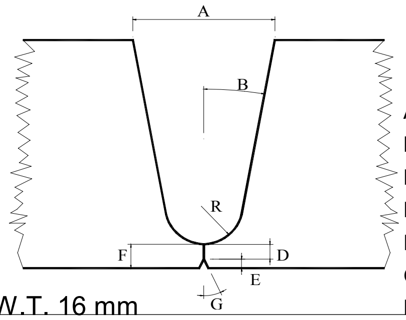


F = 1.6±0.4mm
R = 30° (+5°, -0°)
L = 3.0±0.5mm

Preheat temperature:	min 200°C	Heat input	Root pass:	1.0 KJ/mm
Interpass temperature:	min 120°C max 250°C		Hot pass:	1.0 KJ/mm
			Fill passes:	1.5 KJ/mm
			Cap passes:	1.0 KJ/mm

HOME

Table 3: Typical GMAW WPS

WPS:	WPS SIC CSM 06		A = 9±1mm B = 8±2° W.T. D = 1.2±0.2mm E = 0.2(-0.0+0.2)mm F = 2.0±0.4mm G = 25°±1° R = 3.2±2mm
PROCESS:	135 - GMAW		
POSITION:	PG (5G)		
FILLER METALS:	ALL PASSES DOWNHILL Manufacturer 2 ER100S-G		
ALL EXTERNAL WELDING: Internal line-up clamp with Cu backing ring			
BASE METAL:	API 5L X100 - O.D. 36” (914 mm) - W.T. 16 mm		
Preheat temperature:	min 100°C	Heat input	Root pass: 0.6 KJ/mm Hot pass: 0.7 KJ/mm
Interpass temperature:	min 100°C max 250°C		Fill passes: 0.75 KJ/mm Cap passes: 1.0 KJ/mm

Each completed weld was non-destructively tested using X-radiography in accordance with EN 288-9; the resultant films were assessed such that global effects were noted (e.g. scattered porosity). The aim was not to ensure compliance with a given pipeline welding specification at this point in the programme, but to provide assurance that the series of welds were produced to a similar standard such that the mechanical results were assessing only the effects of varying weld metals.

The mechanical properties evaluated from each girth weld comprised:

- Cross weld strip tensile specimen;
- All weld metal round bar specimen extracted from the pipe wall mid thickness;
- Charpy V impact toughness tests: weld metal centreline, pipe wall mid thickness notched transverse to welding direction and tested at room temperature, 0°C and minus 20°C.
- CTOD toughness tests: weld metal centreline notched transverse to welding direction, standard B x 2B geometry and tested at room temperature, 0°C and minus 20°C.

Results of the laboratory welding programme are shown in Table 4 and Table 5.

Hardness surveys (HV10) were carried out on all the trial weld procedures except WPS Y. Traverses were conducted in the cap, pipe mid-thickness and root, with particular attention focussed on the HAZ. Additional indents were made in the coarse grained HAZ in a vertical traverse through the pipe wall depth. Figure 1 shows typical hardness traverses for an SMAW and GMAW girth weld; softening of the HAZ is clearly evident in both cases.

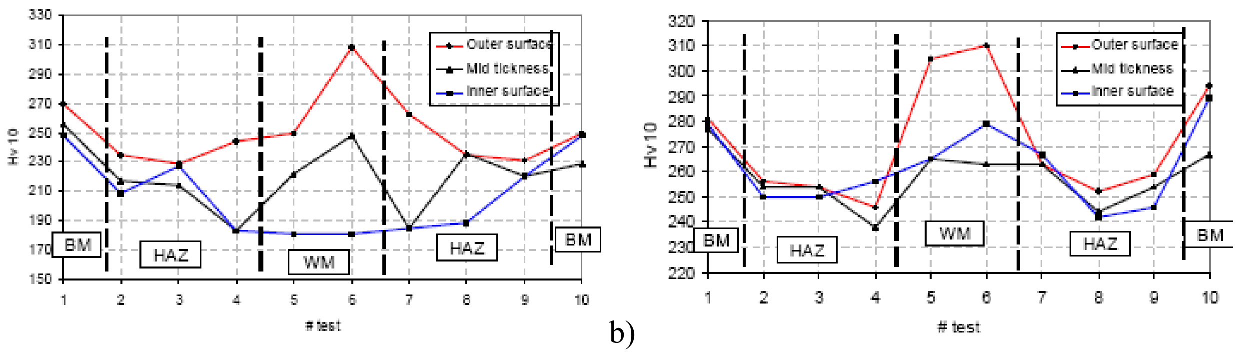


Figure 1: Typical girth weld hardness survey profiles a) SMAW 16mm WT X100 + AWS 5.5 E11018-M (WPS 4) b) GMAW 16mm WT X100 + AWS 5.28 ER100S-G (WPS 6)

HOME

Table 4: 16mm WT laboratory girth weld trials – mechanical test results

		SMAW Procedures							GMAW Procedures			
		WPS 1	WPS 2	WPS 3	WPS 4	WPS A	WPS B	WPS Y	WPS 5	WPS 6	WPS 7	WPS 8
	16 mm WT X100	Manufacturer 2 VD E10018-G (E6010 VD root)	Manufacturer 1 VU E11018-M (E6010 VD root)	Manufacturer 2 VD E10018-G (E6101 VU root)	Manufacturer 1 VU E11018-M (E6010 VU root)	Manufacturer 3 VD E11018-G (E6010 VD root)	Manufacturer 3 VD E11018-G (E6010 VU root)	Manufacturer 1 VU E12018-G (E6010 VD root)	Manufacturer 2 VD ER80S-G	Manufacturer 2 VD ER100S-G	Manufacturer 1 VD ER100S-G	Manufacturer 1 VD ER110S-1
All-Weld Tensile [MPa]	**Rt0.5 av.**	660	647	651	654	727	733	727	677	752	744	840
	Rm av.	727	750	723	751	776	775	842	735	807	804	901
	A% av.	25.9	21	23.7	24.4	18.9	20.3	19.6	26.1	19.6	24.4	21.1
X-Weld Tensile (MPa)	**Rm**	786	769	777	777	796	808	NA	809	821	776	783
	Fracture location	WM/HAZ	BM	WM/HAZ	WM/HAZ	BM	BM	NA	WM/HAZ	BM	BM	BM
Impact Toughness, Cv [J]	**R T av.**	154	133	135	142	140	136	105	113	124	101	113
	RT Min	*146*	*128*	*118*	*140*	*138*	*130*	*102*	*108*	*120*	*98*	*108*
	0°C av.	123	118	121	120	122	104	102	105	105	87	98
	0°C *Min*	*120*	*108*	*108*	*116*	*120*	*94*	*85*	*100*	*90*	*84*	*94*
	-20°C av.	93	93	93	106	94	79	72	97	95	77	81
	-20°C min	*82*	*80*	*86*	*102*	*90*	*60*	*62*	*86*	*84*	*76*	*78*
CTOD [mm]	**R T av.**	0.454	0.313	0.285	0.327	0.372	0.244	0.14	0.292	0.276	0.201	0.183
	RT Min	*0.443*	*0.298*	*0.285*	*0.259*	*0.34*	*0.244*	*NA*	*0.267*	*0.263*	*0.185*	*0.164*
	0°C av.	0.274	0.347	0.358	0.294	0.233	0.245	0.14	0.23	0.251	0.183	0.165
	0°C *Min*	*0.258*	*0.324*	*0.318*	*0.26*	*0.208*	*0.192*	*NA*	*0.212*	*0.204*	*0.149*	*0.151*
	-20°C av.	0.275	0.391	0.364	0.163	0.207	0.193	0.07	0.207	0.227	0.143	0.164
	-20°C min	*0.265*	*0.335*	*0.337*	*0.109*	*0.207*	*0.182*	*NA*	*0.19*	*0.227*	*0.133*	*0.139*

Note: VD = vertical down, VU = vertical up, BM = base material, WM = weld metal, FL = fusion line, HAZ = heat affected zone, NA = not available

Table 5: 20mm WT laboratory girth weld trials – mechanical test results

		SMAW Procedures						GMAW Procedures			
		WPS 9	WPS 10	WPS 11	WPS 12	WPS C	WPS D	WPS 13	WPS 14	WPS 15	WPS 16
	20 mm WT X100	Manufacturer 2 VD E10018-G (E6010 VD root, E9010 VD HP)	Manufacturer 1 VU E11018-M (E6010 VD root, E8010 VD HP)	Manufacturer 2 VD E10018-G (E6101 VU root, E9010 VD HP)	Manufacturer 1 VU E11018-M (E6010 VU root, E8010 VD HP)	Manufacturer 3 VD E11018-G (E6010 VD root)	Manufacturer 3 VD E11018-G (E6010 VU root)	Manufacturer 2 VD ER80S-G	Manufacturer 2 VD ER100S-G	Manufacturer 1 VD ER100S-G	Manufacturer 1 VD ER110S-1
All-Weld Tensile [MPa]	**Rt0.5 av.**	693	677	705	662	763	777	677	770	781	940
	Rm av.	776	746	770	772	828	829	753	834	857	1022
	A% av.	24.5	21.4	18.5	18.4	20.5	17.6	29.4	19.9	21.2	18.4
X-Weld Tensile (MPa)	**Rm**	776	770	771	775	777	778	779	780	781	778
	Fracture location	WM	BM	FL/HAZ	FL/HAZ	FL/HAZ	FL/HAZ	BM	BM	BM	BM
Impact Toughness, Cv [J]	**R T av.**	127	121	119	117	121	123	102	117	97	97
	RT Min	*116*	*110*	*118*	*112*	*106*	*108*	*92*	*112*	*88*	*94*
	0°C av.	96	95	83	101	99	111	110	111	89	91
	0°C *Min*	*68*	*88*	*70*	*100*	*90*	*108*	*102*	*110*	*78*	*82*
	-20°C av.	85	79	67	83	79	77	85	101	70	75
	-20°C min	*80*	*66*	*60*	*78*	*68*	*64*	*82*	*94*	*62*	*70*
CTOD [mm]	**R T av.**	0.355*	0.27	0.302	0.256	0.276*	0.270*	0.266*	0.218	0.14	0.113
	RT Min	*0.332**	0.263	0.283	0.22	*0.203**	*0.194**	*0.241**	0.187	0.14	0.078
	0°C av.	0.327	0.249	0.277	0.233	0.261	0.209	0.214	0.183	0.123	0.069
	0°C *Min*	0.256	0.238	0.265	0.201	0.226	0.209	0.198	0.183	0.107	0.068
	-20°C av.	0.271*	0.194*	0.225*	0.14	0.134*	0.104*	0.189	0.185*	0.135	0.0845
	-20°C min	*0.263**	*0.164**	*0.223**	0.14	*0.067**	*0.043**	0.189	*0.166**	0.124	0.077

Note: Abbreviations as per Table 4. * indicates a CTOD crack front not conforming to the validity requirement of BS 7448

The pipe wall thickness, in combination with the bevel angle and welding process, plays an important part in the resultant HAZ hardness levels as illustrated in Figure 2. The narrow gap mechanised welds tend to give a narrower HAZ due to the lower arc energy and more efficient heat extraction than the SMAW procedures, leading to overall higher cooling rates and lower transformation temperatures with consequent higher hardness values [6]. However, for a given welding process, the pipe wall thickness is the only major change in Figure 2 that can account for the ability to group the resultant hardness values; thereby highlighting the criticality of this variable for a given weld procedure.

HOME

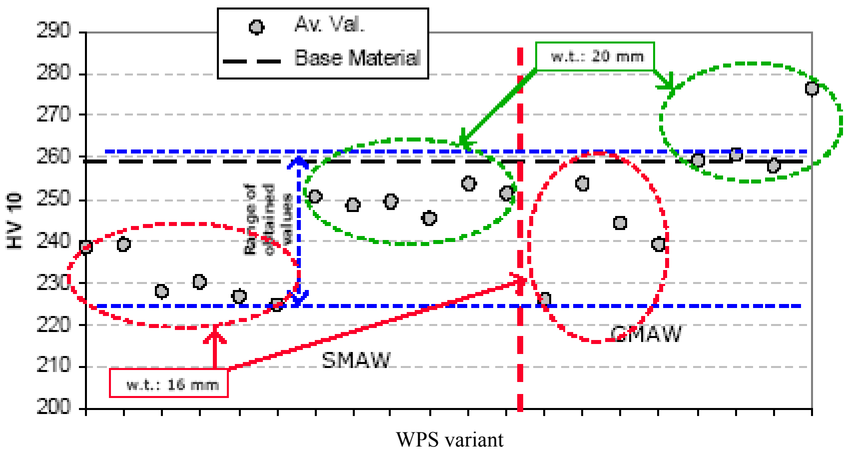


Figure 2: Coarse grained HAZ hardness summary for the various procedure trials

In summarising the laboratory welding programme, it can be stated that all GMAW procedures generated strength levels in excess of the likely pipe longitudinal yield strength, and in all bar one case the pipe transverse yield strength is likely to be overmatched. Charpy impact toughness results exhibited adequate levels at -20°C with respect to the EPRG Tier 2 requirements [12] (these are currently valid up to X80). However, some of the CTOD values (individual and averaged) were below the 0.15mm level of the EPRG Tier 3 requirements, although it should be noted that these requirements have only been validated for steels up to X70 strength levels.

The SMAW trials exhibited strength levels much lower than the GMAW procedures; no electrode tested would guarantee an overmatch of the pipe transverse yield strength (assuming a potential spread of pipe transverse yield strengths in the order of 690MPa to 810MPa). The E11018-G of Manufacturer 3 exhibited the highest strength levels which would overmatch the likely pipe longitudinal strength, but CTOD toughness levels were somewhat lower than the other electrodes.

3 IN-FIELD GIRTH WELDING

The results of the welding consumable evaluation trials allowed the selection of several WPSs to be adopted for the in-field welding of two pipeline sections as per typical field construction techniques currently in use for large diameter pipelines. The pipelines were constructed using the identical X100 materials and procedures as per the consumable evaluation trials: 36" OD, 16mm or 20mm WT. Both SMAW and GMAW procedures were applied as shown in Table 6.

Table 6: Summary of welding procedures adopted for in-field girth welding.

OD x WT	WPS No.	Technique	Fill and Cap Consumable	No. of Joints
36" x 16 mm	7	GMAW	AWS 5.28 ER 100S–G Manufacturer 1	3
36" x 16 mm	6	GMAW	AWS 5.28 ER 100S–G Manufacturer 2	4
36" x 16 mm	2	SMAW	AWS 5.5 E 11018-M Manufacturer 1	3
36" x 20 mm	14	GMAW	AWS 5.28 ER 100S–G Manufacturer 2	7
36" x 20 mm	10	SMAW	AWS 5.5 E 11018-M Manufacturer 1	4

The choice of fill pass consumables reflected a decision to guarantee an overmatch of the pipe longitudinal strength (assumed to be in the range of 610 – 700MPa) for the GMAW (mechanised) procedures (weld metal $Rt_{0.5}$ of 744-770MPa), with some of the individual pipe transverse strengths also overmatched. The SMAW consumable chosen, however, did not necessarily guarantee an overmatch of the pipe longitudinal strength (weld metal $Rt_{0.5}$ of 647-676MPa). This was deliberately undertaken to examine the effects of a potentially undermatching or borderline girth weld strength level in the consequent running ductile fracture burst tests and wide plate tests. The toughness (impact and CTOD) levels of all consumables selected were on the higher end of all electrodes evaluated, thereby providing a greater confidence in their ability to provide a ductile failure mechanism.

The girth weld joints were non-destructively tested using both manual ultrasonic and X-radiography techniques, with the defect acceptance criteria in accordance with an internal CSM specification suitable for burst test pipe strings. Results of both non-destructive test (NDT) methods exhibited an acceptable level of girth weld joint manufacture; the only imperfections encountered were the occasional lack of side wall fusion between the root and hot pass of the mechanised welds. These imperfections were removed and repaired where necessary by the use of a qualified SMAW repair procedure.

The installed pipe strings were subsequently subjected to ductile fracture propagation / arrest testing[5]. Although the propagating fracture behaviour is not the topic of this paper, it is worth noting that no issues relating to the girth welds materialised during the full scale burst tests; in all cases the fracture ran over the welded joints without any crack deviation. The circumferential integrity of all girth welds, both SMAW and GMAW, was preserved even if longitudinal plastic deformations in the crack tip passage zone achieved magnitudes of $\varepsilon_{pl} \geq 5\%$. In Figure 3 examples of crack surfaces after burst testing are shown for a GMAW and SMAW joint. Such pictures are representative of the general behaviour of all the joints involved in the fracture path. The analysis of the fracture appearance traversing the girth joints always exhibited a fully ductile behaviour for both base material and weld metal.

a) b)

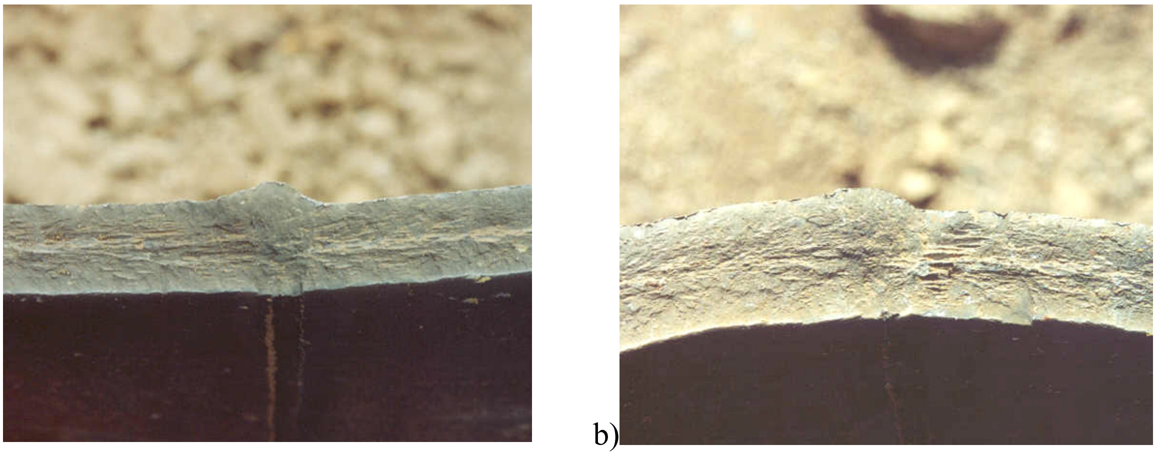


Figure 3: Fracture surface appearance of a) GMAW and b) SMAW joint after burst test.

4 DEFECT TOLERANCE IN X100 PIPELINES

Much effort has been expended by plate and pipe makers in developing very high strength linepipe materials such as X100 and X120. This work has advanced to the stage where the most recent parent materials are able to achieve the required strength levels whilst also achieving upper shelf Charpy impact energies in excess of 250J. A major concern for X100 linepipe has been the toughness of the seam weld, in particular the heat affected zone where very low toughness values have been measured using conventional fracture mechanics tests. However, the structural significance of these low values is less clear. Testing [8] and a constraint based fracture mechanics analysis [9] have shown that even apparently low HAZ toughness values do not affect the performance of the pipe and that the failure pressures can be predicted using models that assume the failure mode will be by plastic collapse.

Assuming that it is possible to obtain adequate mechanical properties in the parent material, it is still necessary to obtain adequate defect tolerance in the completed pipeline. Various types of defect should be considered, both in the linepipe and in the girth welds. These will be considered in more detail below, but first it is instructive to consider the basic effect of increasing grade on the toughness required. If the material toughness is quantified by the CTOD (δ), then using the standard relation between CTOD and stress intensity factor (K_I):

$$\delta = \frac{K_I^2}{\sigma_Y E} \tag{1}$$

If there is a defect of fixed size *a* subject to a stress *σ*, by substituting $K_I = \sigma Y \sqrt{\pi a}$ the toughness can be expressed as:

$$\delta = \left(\frac{\sigma}{\sigma_Y}\right)\frac{\sigma Y^2 \pi a}{E} \tag{2}$$

If, as is usual, the design factor is kept constant, the required toughness will increase linearly with the grade of the material. This analysis is simplified, as it ignores factors such as welding residual stresses, but it does serve to illustrate the challenge when attempting to ensure defect tolerance in a high strength pipeline. Toughness levels which may have been adequate in a pipeline constructed from a conventional grade such as X60 or X65 may no longer be adequate in a very high strength material.

Crack Initiation Resistance

In practice it is usually found that the defect tolerance of pipelines produced from conventional grade materials is not dependent on the toughness, but is controlled by the plastic collapse behaviour. As will be noted below, it is not yet established whether this is the case for the very high strength materials. The most commonly used crack initiation model for pipelines is that originally due to Kiefner *et al*.[10]. For a through–wall defect this model takes the general form:

$$M_T \sigma = \sigma_{flow} \tag{3}$$

where the quantities are defined as:

- σ hoop stress, N/mm^2
- σ_{flow} flow stress, defined below

M_T is the Folias factor, which accounts for the stress concentrating effect of bulging at the ends of the crack, and is a function of the diameter, wall thickness and crack length. The models, and subsequent variations, differ in their definition of the flow stress, and this can have an effect on the tolerable crack length as the pipe grade increases. Shannon [11] defined the flow stress as 1.15 * SMYS, and using this definition it can be seen from (10) that the tolerable crack size is independent of material grade when operating at a constant design factor. A problem with this definition for high strength steels with relatively limited work hardening capability is that it can result in a flow stress that exceeds the tensile strength. For example, with X100 (690 N/mm^2) material the flow stress would become 793 N/mm^2, which is above the typical minimum tensile strength of 770N/mm^2 usually assumed for this material. This can be avoided by adopting the definition used in BS 7910 [13], which defines the flow stress as the average of the yield and ultimate strengths.

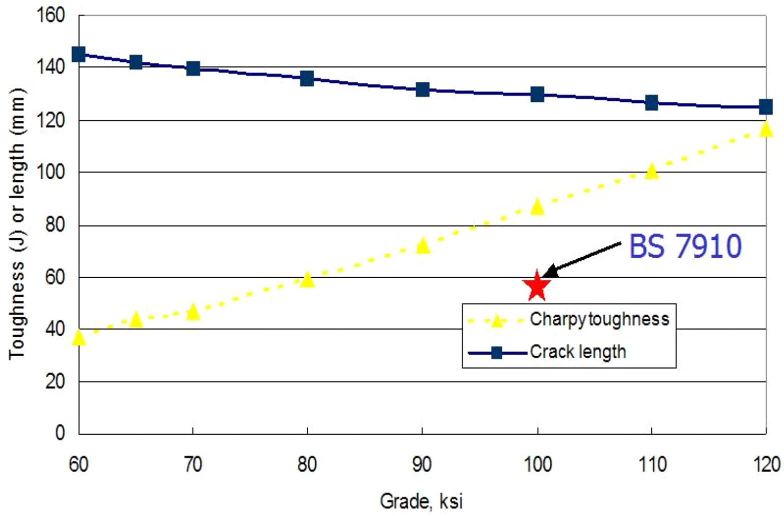


Figure 4: Critical axial through wall crack length for a 914 mm diameter 12.7 mm wall thickness pipeline operating at 80% SMYS

Figure 4 shows the critical through wall crack length using (10) for a typical high strength steel pipeline application as a function of pipe grade. The crack length is not strongly dependent on grade. The upper shelf Charpy toughness required for a collapse controlled failure, calculated using the toughness dependent model in [10], is also shown; the levels exceed 100J for the very high strength grades. These levels are in fact below those typically achieved by the pipe manufacturers. There is only a small amount of published data to show whether these models will apply to very high strength material. Two sets of data with conflicting results are shown in Figure 5; the ring data from [8] show that the collapse model is satisfactory, whilst data from pipe burst tests from [14] show that the toughness dependent variant of the model is unconservative. Further work is required to resolve these issues.

Volumetric Corrosion Defect Resistance

Internal stress corrosion cracking (SCC) is not expected to be a problem for very high strength linepipe as the expected application is sweet dry gas. Hence the resistance of the materials to volumetric corrosion is expected to be the most serious integrity issue related to corrosion. Again, only limited data are available in the public domain for this type of defect. Some of these data are also shown for metal loss defects in Figure 5; they indicate that existing models based on plastic collapse [16] are likely to be satisfactory. Further work is required to confirm this conclusion.

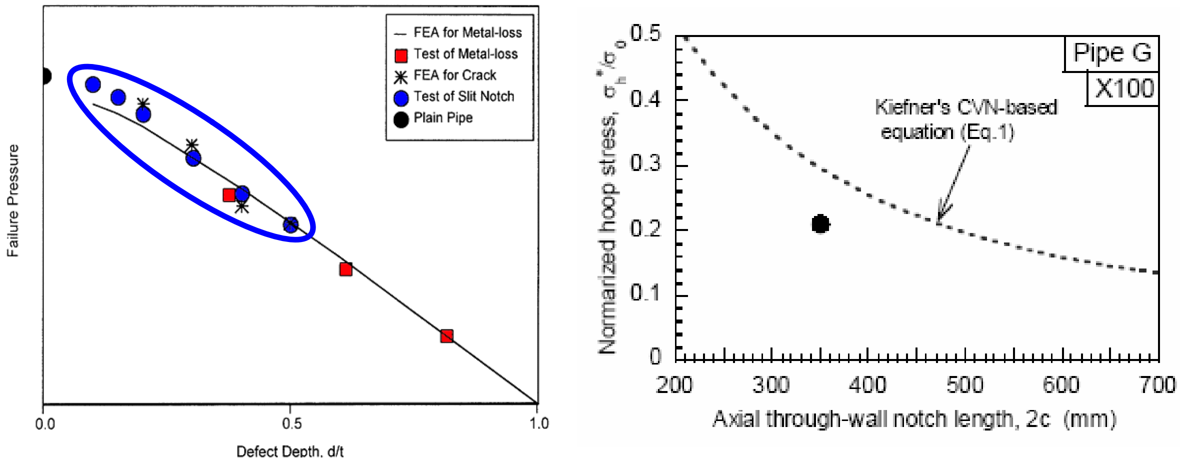


Figure 5: Parent metal axial crack tolerance results for X100 materials. Left, data from [8] for surface breaking cracks; right data from [14] for a through-wall crack

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Girth Weld Defect Tolerance

The curved wide plate test has been widely used for assessing the defect tolerance of pipeline girth welds. The test uses a 300mm wide axial strip with the girth weld located centrally. This is loaded in tension to failure, with the parent metal strain inferred from the overall extension and the crack mouth opening. Figure 6 shows the results obtained in the Demopipe project [5], plotted on axes of parent metal strain and non-dimensional defect area. All tests were carried out at -20°C; all the welds had achieved Charpy impact energies in excess of 40 J average at temperatures of -40°C or lower. The diamond symbols are the Demopipe results. Two out of the ten points are inside the EPRG Tier 2 [12] limits. One of these test welds was significantly undermatched, so can be disregarded, as the EPRG guidelines require an overmatched weld. The other point inside the EPRG limit failed as a brittle fracture. This was a 25 mm thick SMAW procedure which was approximately matching and so should be included in the analysis. The failure initiated in the cellulosic root, which undermatches locally due to the tensile strength of an E6010 consumable. The stronger cap and fill overmatch the parent metal and should have shielded the root. Further work is required to address these issues.

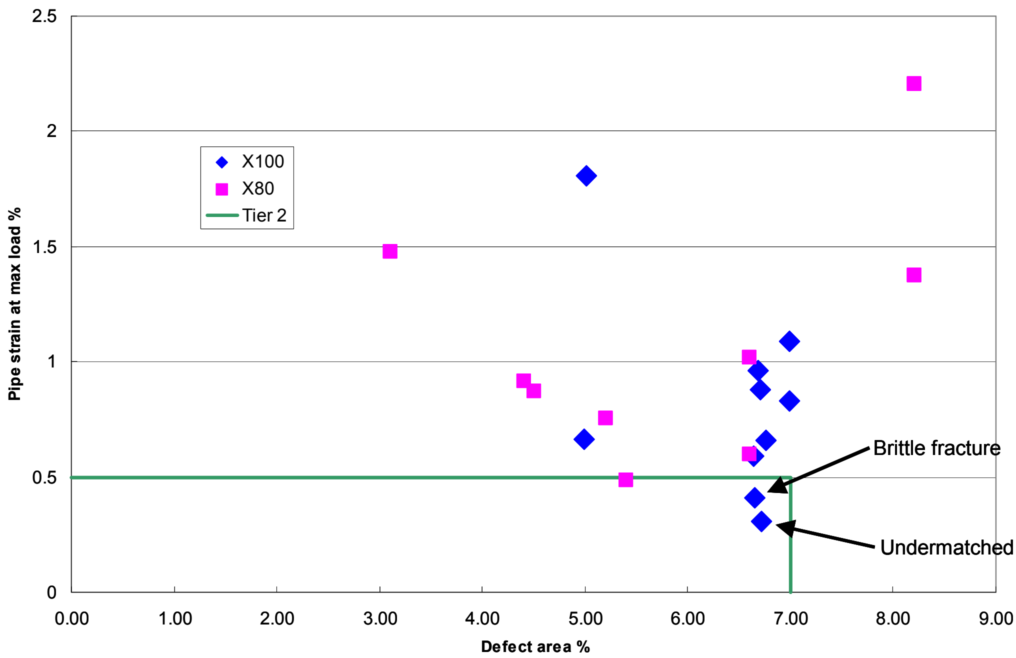

Figure 6: Curved wide plate test results for X100 [5] and X80 [15] girth welds

For comparison, Figure 6 also shows results on large diameter X80 girth welds from [15]. These welds were made using automatic GMAW procedures and show comparable performance levels to the X100 data. Overall, it appears that it will be possible to obtain adequate levels of defect tolerance in X100 pipeline girth welds, although in the short term project specific testing may be required to optimise the acceptance criteria for a specific application and design conditions.

As an alternative to the semi-empirical curved wide plate approach, these test results have also been analysed using the failure assessment diagram approach of BS 7910 [13]. Figure 7, from the final Demopipe report [5], shows the results from the wide plate tests and also four full scale bending tests. The analysis used the Level 2A (generic) assessment diagram using specification minimum tensile properties and the CTOD toughness appropriate to the notch location and weld process. For the wide plate tests the stresses were estimated from the test records as force over area at point of failure, while for the full scale bending tests the local stress was estimated from the strain gauge data and converted into stress using the stress-strain curve. As is commonly found for pipeline applications, the fracture mechanics analysis is conservative. All four of the bending tests achieved 100% SMYS so the EPRG Tier 3 criteria [12] were satisfied. Note that a constraint corrected analysis [9] would expand the collapse region so these might be considered as collapse controlled rather than mixed collapse-fracture failures.

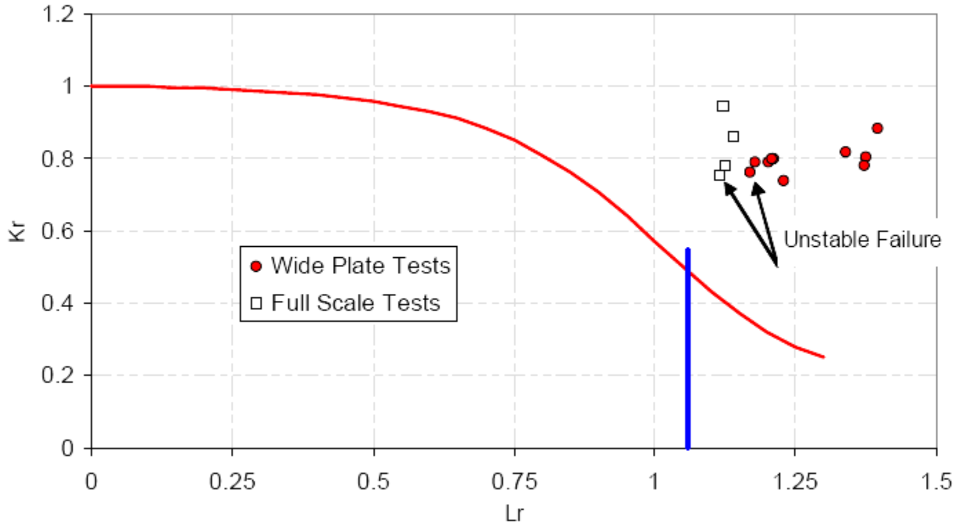

Figure 7: X100 girth weld tests from the Demopipe project [5] plotted using the BS 7910 failure assessment diagram.

5 CONCLUSIONS

- The numerous welding procedure trials undertaken within the Demopipe project have enabled the selection of a range of candidate welding consumables and processes for the construction of X100 pipelines. The final weld metal overmatch required will be subject to the given pipeline design, but the current paper has shown that electrodes exhibiting toughness levels in excess of the EPRG guidelines but with weld metal yield strengths not necessarily overmatching the equivalent pipe longitudinal strength have resulted in burst tests devoid of problems associated with the girth welds.
- As expected, a decrease in toughness (both Charpy V and CTOD) was found with decreasing temperature, but the change was considered to be relatively small in the range of -20°C to +20°C.
- CTOD values exhibited a decrease in value with increasing weld metal yield strength; this was not so prevalent with the impact toughness values.
- An increase of pipe wall thickness indicated a general increase in weld metal yield strength and hardness values when the same SMAW and GMAW consumable/WPS was used, highlighting the important effect of wall thickness within high strength weld metal procedures.
- The results of the curved wide plate testing undertaken within the Demopipe programme have in general indicated that it will be possible to obtain adequate levels of defect tolerance in X100 pipeline girth welds, although in the short term project specific testing may be required to optimise the acceptance criteria for a specific application and design conditions.
- An analysis using the Level 2A assessment diagram of BS7910 incorporating the wide plate tests and full scale bending tests in conjunction with the specification minimum tensile properties and CTOD toughness appropriate to the notch location and weld process resulted

in a conservative result as is commonly found for pipeline applications. All four of the bending tests achieved 100% SMYS such that the EPRG Tier 3 criteria were satisfied.

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