Pipeline renewal
or lifetime extension?

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IN 2014, the Rotterdam - Rijn Pijpleiding (RRP) Maatschappij decided to conduct a vast experimental test programme with the objective to demonstrate that the lifetime of the pipe sections with channeling corrosion in their 54 years old 24" grade API5L X52 oil product pipeline is sufficiently high for the future safe operation of the pipeline. The experimental work included material characterization testing, full-scale fatigue testing under cyclic internal pressure, hydrostatic / burst testing and wide plate testing. The experimental programme, details of which are presented in the paper, is still ongoing but the provisional analysis of the data suggests that the detected channeling corrosion in the pipeline has no detrimental effect on fracture and fatigue resistance provided the original design and current operational conditions are satisfied.

THE ROTTERDAM - RIJN Pijpleiding (RRP) Maatschappij, The Netherlands, operates a 36 inch crude oil and a 24 inch oil product transportation pipelines from Rotterdam to the Rhine - Ruhr area (Germany).

The Pernis (Rotterdam) to Venlo (German border) portion of the oil product pipeline from Pernis to Köln (Germany) has a total length of 153 km. The pipeline, constructed in 1959 and 1960, and put in operation on July 1, 1960 is built up of API 5L X 52 pipes with an outer diameter (OD) of 24" (609.6 mm) and a wall thickness of 5/16" (7.9 mm). The pipeline is operated at a design pressure (maximum allowable operation pressure - MAOP) of 62 bars and a design temperature of 38°C.

In 2011, after 51 years of operation and a high of number of pressure cycles, the 24" oil product pipeline was inspected by a high definition ultrasonic (US) intelligent pig. The inspection revealed girth weld anomalies and a high number of channeling corrosion (or internal axial corrosion -metal loss- along the 6 o'clock position), which often extended over several pipe lengths. Channeling corrosion is characterised by a smooth and uniform reduction in wall thickness.

During 2012 and 2013 RRP has replaced and/or repaired (installion of clock-springs) a number of pipe sections, which were, according to ASME B31G most critically affected. In 2014, RRP decided to conduct a full-scale test based study with the objective to demonstrate that the fatigue resistance of the corroded pipe sections which has not yet been repaired, is sufficiently high for the future safe operation of the pipeline. To generate reliable and conservative information, the feature list resulting from the UT in-line inspection was re-assessed to select the 'worst' pipe sections, which were subsequently cut and both destructively and non-destructively examined.

The experimental work yielded a vast amount of information, including material characterization testing, full-scale fatigue testing under cyclic internal pressure, hydrostatic / burst testing and wide plate testing.

Experimental programme

Test materials

RRP supplied four plain pipe, three pipe sections with a girth weld and four pipe sections with a 2" nipple at mid-length for testing in 2014. These nipples had been welded to the pipes by a partial penetration fillet weld (incomplete root penetration). The pipes were API grade LX52, 24 inch (609.8 mm) in outer diameter and 7.9 mm in wall thickness. These sections have been in service for 54 years. The pipe sections contained, according ASME B31G, unacceptable internal corrosion attack. Table 1 identifies the pipe sections and the particulars of the detected anomalies.

Type of specimen	Test vessel number	Length (mm)	Extent of metal loss at 6 o'oclock
Cold bend (radius: 25 m) plain pipe	# 6-897-Part2	3000	Full length - intermittent * Width: 192 mm Remaining wall thickness: 6.0 mm
	# 6-341	4020	Full length - intermittent * Width: 123 mm Remaining wall thickness: 6.9 mm
Plain pipe	# 6-13310*	1735	Full length - intermittent * Width: 311 mm Remaining wall thickness: 5.2 mm
Pipes / vessel with girth weld	# 6-896 & 6-897	1020 + 2020	Full length - intermittent * Width: 125 mm Remaining wall thickness: 6.0 mm AND Lack of root penetration in girth weld at 6 o'clock
	# 6-897 & 6-898	1200 + 2010	Full length - intermittent * Width: 120 mm Remaining wall thickness: 6.9 mm
	# 6-341 & 6-342	1010 + 2200	Full length - intermittent * Width: 160 mm Remaining wall thickness: 6.9 mm
	# 6-340 & 6-341	1015 + 1500	Full length - intermittent * Width: 123 mm Remaining wall thickness: 6.9 mm

* : Test vessel contained also two linear crack-like indications at the D-SAW weld 130 mm long) and in the pipe body (135 mm long - gauge - mechanical damage). Fractographic analysis is still ongoing.

			D-SAW position at
Pipe with 2" nipple	#6-13716	1000	335 mm from nipple
	#6-13561	965	485 mm from nipple
	#6-0249	1050	500 mm from nipple Outer side SAW ground flush
	#6-0251	875	at 130 mm from nipple

Table 1 / Test materials .

Extent of testing

The material property tests were conducted to characterize the chemical composition, the pipe and weld metal microstructures, the tensile properties of the plate and weld metals, and the notch toughness (Charpy V) properties of the pipe metals, weld metals and adjacent heat affected zones (HAZs). The specimen blanks were extracted from randomly selected pup-pieces. Each of these pieces was subjected to the same test matrix, Table 1. The blanks for tensile testing were extracted at several positions around the circumference to produce information on the spread of the pipe and girth weld properties around the pipe circumference. The metallographic samples and Charpy test specimens were extracted at the 3 o'clock position.

	Pipe sections	Chemical analysis	Metallography		
			Micro	Macro	
			Pipe	Long. Weld	Girth Weld
Plain pipe	1	1	1	1	-
	2	1	1	1	-
Pipe with girth weld	1	1	1	1	1
	2	1	1	1	1
	3	1	1	1	1
Total		5	5	5	3

	Tensile testing					Charpy V testing			
	Base metal		Weld metal		Cross weld	Base metal		Weld metal	
	Long[1].	Trans[1].	Long. Weld	Girth Weld[2]		Long[3].	Trans[3].	WMC[4]	HAZ[4]
Plain pipe	3	3	1	-	2	9	9	6	6
	3	3	1	-	2	9	9	6	6
Pipe with girth weld	3	3	1	2	4	9	9	12	12
	3	3	1	2	4	9	9	12	12
	3	3	1	2	4	9	9	12	12
Total	15	15	5	6	16	45	45	48	48

Sampled at 3, 6 and 9 o'clock
Sampled at 3, 6 and 9 o'clock
Tested at -20, 0 and +20 ºC - sampling position: 3 o'clock
Tested at -20 and 0 ºC - sampling position: 3 o'clock

Table 2. Testing matrix.

Furthermore, full-scale fatigue tests and a curved wide plate test were carried out. The aim of the full-scale tests was to determine the fatigue resistance of the corroded pipe sections and the axial strain capacity of a girth weld with natural weld anomalies. Full-scale fatigue testing included seven tests. The test specimen which did not fail after 500000 cycles was further hydrostatically loaded to failure.

Material properties tests

Metallography

The microstructures at pipe subsurface (outer wall) and at pipe mid-thickness, were characterized by optical metallography at magnifications of x 200 and x 500. For the welds (longitudinal D-SAW seams and girth welds), macro and microphotographs were taken at magnification of x5 (macro section), x50 and x100 (microstructure). The microphotographs covered the heat affected zone (HAZ) and weld metal microstructures at the outer and inner pipe wall. The pipe metal and D-SAW samples were taken transverse to the pipe axis at the 3 o'clock position making an angle of 90° with the longitudinal D-SAW weld seam. Standard metallographic procedures for grinding, polishing and etching were used to prepare the samples for light optical microscopy.

Standard tensile tests

The pipe and all-weld metal tensile tests were performed to (a) verify whether the measured properties complied with the requirements and to (b) determine the actual levels of weld metal strength mismatch. The longitudinal and transverse pipe tensile properties were measured using full-wall flat-strip dog-bone shaped specimens with a reduced section 200 mm long and 25 mm wide. Uniform elongation was measured over a 50 mm gauge length. The transverse specimen were flattened before testing. All-weld metal tensile testing was conducted using a round bar (Φ 6 mm) geometry with threaded ends. The test section sampled the mid-thickness of the weld deposit.

To determine the uniform elongation (uEL) or the strain at ultimate strength, full stress-strain curves were generated for each tensile test. Note that the uEL is a useful parameter to evaluate the post yield strain capacity. In contrast, the Y/T ratio, being an alternative (engineering) measure for estimating the strain hardening capacity, can be used to evaluate the tearing resistance. When defects occur, lack of strain hardening or a high Y/T ratio leads to strain localization and premature failure.

Toughness tests

The longitudinal and transverse pipe metal, weld metal (WM) and HAZ/FL notch toughness properties were determined by testing of 'sub-sized' (10 mm*6.66 mm) Charpy V specimens. The WM and HAZ/FL CVN specimens were taken out transverse to either the longitudinal or the girth weld. All specimens were extracted from the 3 o'clock position. Testing was done in triplicate at -20 °C, 0 °C and +20 °C. The CVN tests were performed according to EN 10045 Part 1, with the values of the percentage shear area and the lateral expansion being measured.

Large scale tests

Fatigue tests

Fatigue testing under cyclic internal water pressure was performed with a hydraulic actuator - water cylinder combination. The testing unit, shown in Figure 1, has a maximum pressure capacity (water side) of 75 bars and a stroke of maximum 350 mm. UGent provided the pipe and welded assemblies (further termed as test vessels) with tubulars for the inlet of the pressurizing medium (water), for purging and for the installation of a pressure transducer.

Fig.1. Test vessel ready for fatigue testing under cyclic internal pressure .

During testing, the water pressure in the test vessel was continuously measured. Depending on the length of the test vessel, the frequency of the (sinusoidal) pressure cycles ranged from 0.50 Hz (4 meters long test vessels) to 1.20 Hz (test vessels of 1 meter). Fatigue testing was continued until the occurrence of a leak, at which moment the installation was automatically stopped. Upon completion of testing, the D-SAW weld seam was inspected from the outside with dye penetrants to verify whether fatigue cracks had initiated at other locations along the pipe. Finally, the portion with the leak was extracted by plasma cutting, cooled down in liquid nitrogen and subsequently opened up in three-point bending. This procedure allowed to visualize the crack profile and to determine dimension(s) of any weld anomaly and the lengths of the fatigue crack at the inner and outer pipe walls.

CWP test

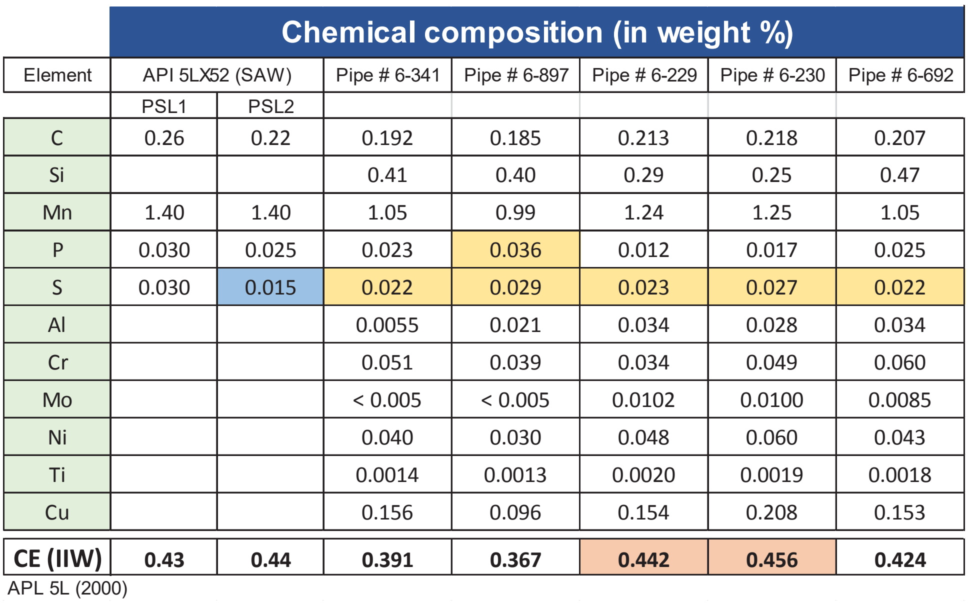
The curved wide plate test specimen was extracted traverse to the girth weld. The girth weld was located in the middle of the test section. The girth contained a pinhole and a lack of penetration defect. These defects were detected during inspections. The CWP specimens had an overall length of 1200 mm (with the girth weld at mid-length) and a width (arc length) of 440 mm. The test section was 900 mm long by 250 mm wide. The weld reinforcements at either side of girth weld were not removed. The overall elongation (gauge length of 750 mm straddling the weld and the notch at mid-span), the pipe metal elongations (gauge length: 200 mm) and the CMOD or crack mouth opening displacement on a gauge length of 20 mm straddling the pinhole were measured.

The CWP specimen was strained (under displacement control) to failure at 0 °C. Cooling was achieved by circulating chilled ethyl-methyl alcohol through chambers clamped onto the specimen. Upon completion of testing, the load and CMOD versus elongation records were used to determine the gross section stress, the overall and the remote pipe metal strain, the pipe metal strains of both pipes and the CMOD at failure. After testing, the fracture faces and the macro section through the pinhole were photographed.

Material property test results

Chemical composition

The chemical composition of the selected pipes, together with the API 5LX52 requirements (PSL1 and PSL2), is given in Table 3. As shown, the carbon equivalent (CE) of these pipes was also determined.



Chemical composition (in weight %)

Element	API 5LX52 (SAW)		Pipe # 6-341	Pipe # 6-897	Pipe # 6-229	Pipe # 6-230	Pipe # 6-692
	PSL1	PSL2					
C	0.26	0.22	0.192	0.185	0.213	0.218	0.207
Si			0.41	0.40	0.29	0.25	0.47
Mn	1.40	1.40	1.05	0.99	1.24	1.25	1.05
P	0.030	0.025	0.023	0.036	0.012	0.017	0.025
S	0.030	0.015	0.022	0.029	0.023	0.027	0.022
Al			0.0055	0.021	0.034	0.028	0.034
Cr			0.051	0.039	0.034	0.049	0.060
Mo			< 0.005	< 0.005	0.0102	0.0100	0.0085
Ni			0.040	0.030	0.048	0.060	0.043
Ti			0.0014	0.0013	0.0020	0.0019	0.0018
Cu			0.156	0.096	0.154	0.208	0.153
CE (IIW)	**0.43**	**0.44**	**0.391**	**0.367**	**0.442**	**0.456**	**0.424**

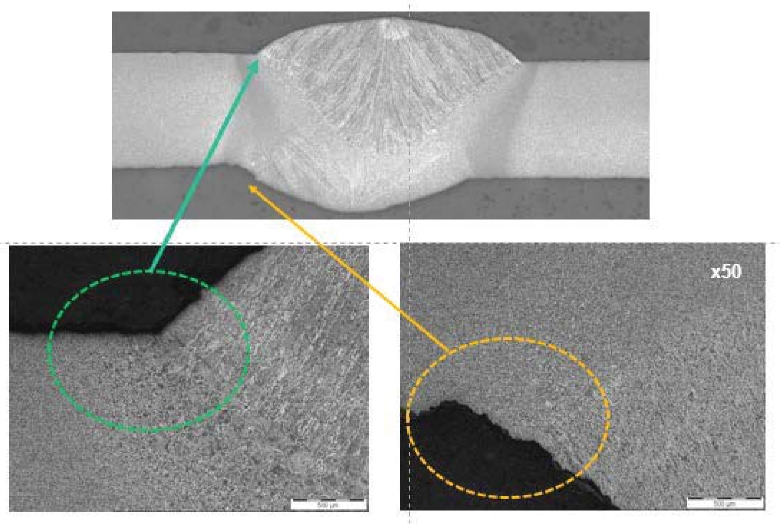
APL 5L (2000)

Table 3. Chemical composition of the pipe metals.

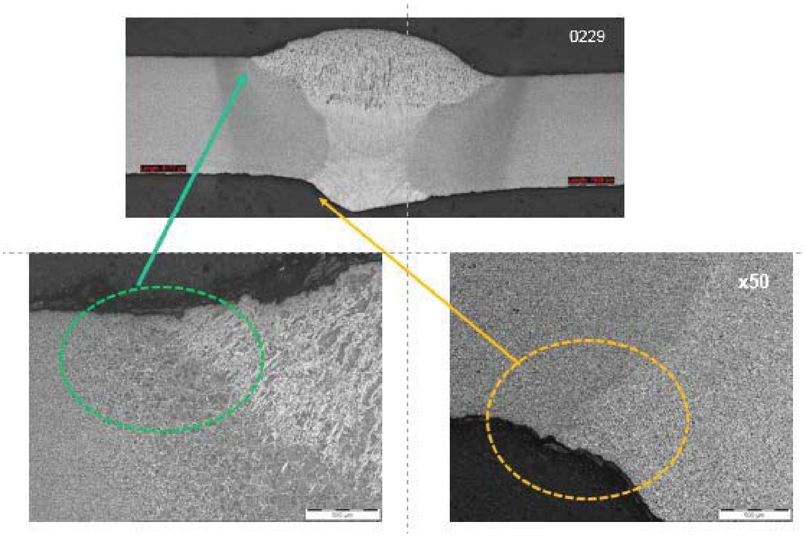
The steels used for the pipes were carbon-manganese steels with carbon contents between 0.18 and 0.22 %. The phosphorus content in pipe #6-896 exceeded the requirements of 0.030 % (PSL1) and 0.025 % (PSL2). Except for the sulphur content (PSL2 pipe requirement), the composition of the pipes complied with the API 5LX52. In comparing the carbon equivalent (CE) values, used to estimate the weldability and hardenability of steels, with the API 5L requirement (0.43) it can concluded that the CE was slightly exceeded for two pipes.

Macrographic examinations

Representative macro-sections of both a longitudinal and a girth weld, supplemented with two optical microphotographs (at x 50), depicting the microstructures at the inner and outer weld toes, are shown in Figure 1. The pictures also illustrate the weld pass sequence, the microstructure of the as-deposited and grain refined weldmetals, the fusion line profiles and the extent of the HAZs.



Longitudinal D-SAW seam weld



Girth weld

Fig.2. Typical macro (x5) and micro (x50) photographs of a longitudinal D-SAW seam weld and a girth weld.

Furthermore, the microphotographs illustrate the smooth transition between the pipe surfaces and the deposited weld metal, both at the outer and inner pipe wall. Note also that in none of the sections investigated, fatigue cracks, which might possibly have initiated at the weld toes during the 54 years of operation of the pipeline, were observed.

Pipe metal microstructure

Hot-rolled microstructures were revealed using the 2 % nital etchant. The optical microphotographs (at x 500) in Figure 3 depict the characteristic pipe metal microstructures at pipe sub-surface and pipe mid-thickness.

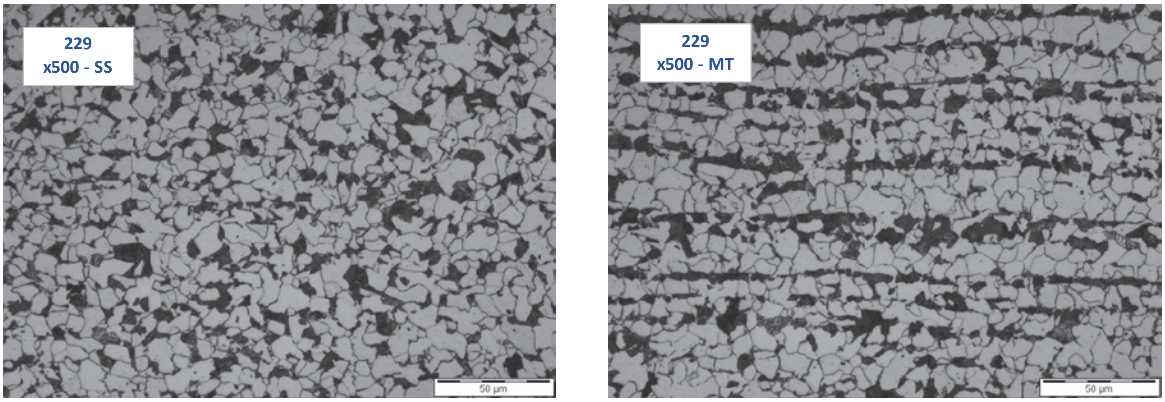


Fig.3. Microstructures of pipe 229 (C = 0.213 and CE = 0.442).

As can be observed, the pipe metal exhibited a fine grained ferrite-pearlite microstructure. At mid-thickness, some banding was sometimes observed.

Pipe and weld metal tensile properties

Representative curves which typify stress-strain behaviour of the pipe and weld metal test pieces at yield point and up to failure are shown in Figure 4. The minimum and mean yield and tensile strengths of the pipe all-weld metals involved in the material characterization study are, along with API 5LX52 requirements for specimens taken in the transverse (hoop) direction, presented in the bar chart plots in Figures 5 and 6. Despite the fact that the longitudinal properties are needed to evaluate the level of girth weld strength mismatch, it can be noted that no provisions for tensile testing in the longitudinal direction are given.

Stress-strain response

The expanded view of the typical pipe metals stress-strain curves, identified by the decorated lines, shown in Figure 4 illustrates that the stress-strain response in the transverse direction displayed a continuous behavior at the onset of yielding and in the post yield loading range. In contrast, the stress-strain response in the longitudinal direction had a Luders plateau (discontinuous yield point behavior), which contributes to crack tip blunting if a defect occurs. It can also be observed that the pipe metals exhibited a high strain hardening capacity (see also Figure 7).

Further, Figure 4 reveals that the girth welds were overmatching in yield strength and matching in tensile strength. The longitudinal (D-SAW) welds were matching (see also Figure 8). Note also that the weld metals displayed a discontinuous yield point behavior.

Figure 5 demonstrates that the sampling location around the pipe circumference had a negligible effect on the measured tensile properties. As in the case of the pipe metal, the variation of the all weld metal tensile properties was also low. The transverse pipe metal tensile strengths largely exceeded the requirement of 455 MPa. The highest values were also below 758 MPa being the maximum allowable tensile strength specified by API 5LX52 (PSL2). In contrast, the yield strength in the transverse direction, which is the API 5L specified test orientation for base (pipe) metal testing did not meet the specified requirement of 359 MPa. The longitudinal strength properties exceeded the requirements specified for the transverse direction.

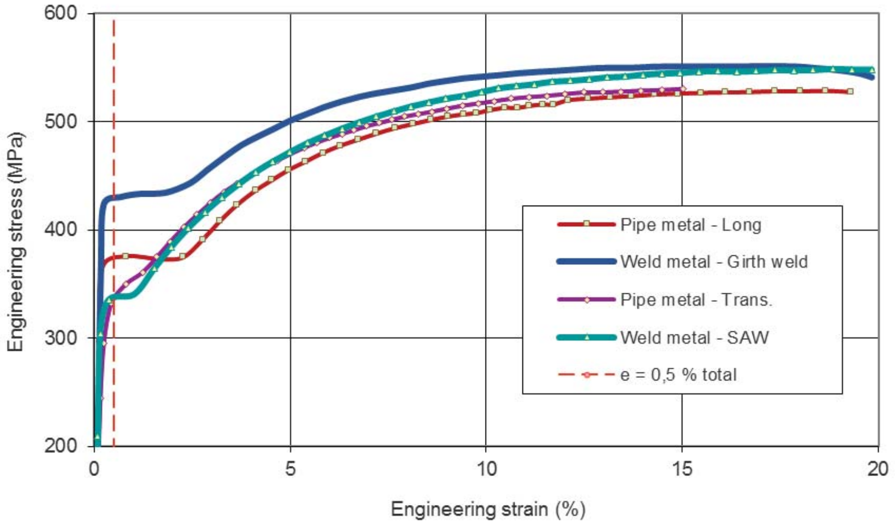


Fig.4. Comparison of representative pipe (longitudinal and transverse) and weld (SAW and girth) metal stress-strain curves.

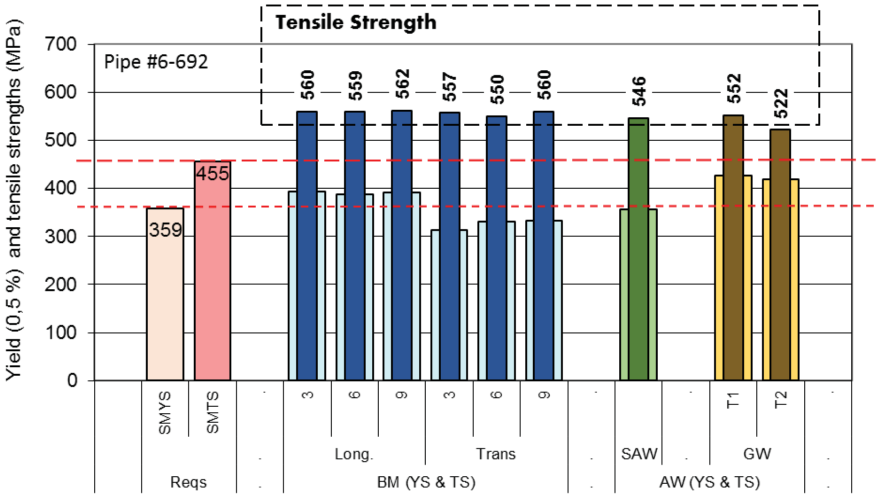


Fig.5. Effect of sampling location on the pipe metal yield and tensile strength properties and the variation of the girth weld tensile properties.

When the mean longitudinal and mean transverse strengths for all pipe metal tested are compared, Figure 6 illustrates that sampling direction (longitudinal vs transverse) has little effect on the yield and tensile strength. Equally, the average yield and tensile properties of the various pipe and weld metals were very consistent. However, 3 out of the 5 transverse pipe metal tests failed to meet the specified requirement of 359 MPa.

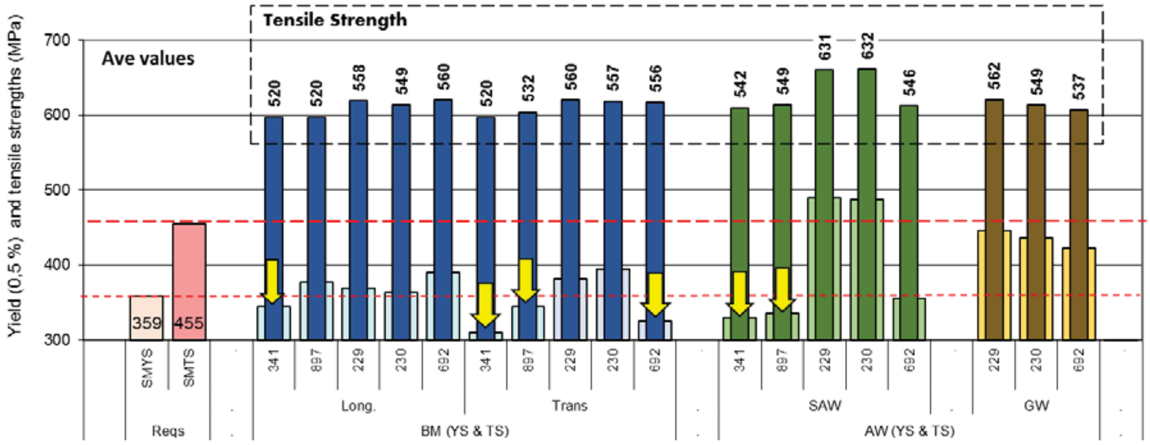


Fig.6. Comparison of mean yield and tensile strength properties of pipe and weld metals tested.

Note also that the variation of the weld metal yield strength of the D-SAW was significant. This variation leads also to a significant variation of yield strength mismatch (see Figure 8).

Y/T ratio

The strain hardening capacity, generally inferred from the yield to tensile strength (Y/T) ratio, is (a) a precondition for achieving remote yielding and (b) an influential variable with regard to the resistance to crack extension. Low Y/T ratio materials ensure remote yielding for larger defects and have a higher resistance to ductile crack extension than their high ratio counterparts. As shown in Figure 7, the average Y/T ratios were distributed from 0.586 to 0.726 (pipe metal), 0.609 to 0.777 (D-SAW welds) and 0.787 to 0.795 (girth weld). These values are well below the 0.85 (0.90/0.93) level.

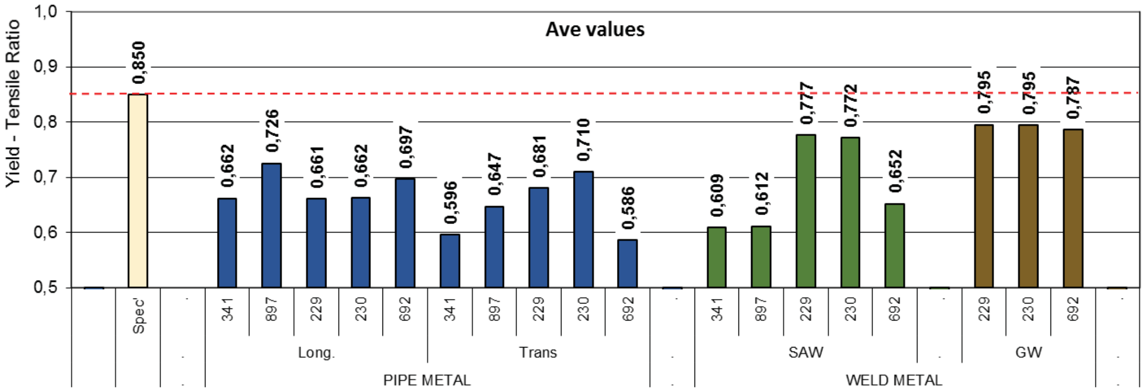


Fig.7. Variation of pipe and weld metal Y/T ratios.

It should also be noted that the uniform elongation (uEL) ranged from 12.0 to 19.7 % (pipe metal long.), 13.7 to 19.5 % (pipe metal trans.), 11.7 to 18.9 % (SAW weld metal) and 9.2 to 15.0 % (girth weld). Consequently, though acceptance testing did not require Y/T and uEL measurements, the pipe and weld metal tests have demonstrated that all pipe and weld metals tested had excellent post yield strain and strain hardening capacity.

Yield and tensile strength mismatch

The mean yield and tensile strength mismatch values for each of the five pipe / weld metal combinations tested are summarized in Figure 8. These values were derived from the mean longitudinal (girth weld mismatch) or transverse pipe (SAW weld mismatch) and the mean weld metal yield and tensile strengths, respectively (Figure 6). The mean values were obtained from three pipe metal and two weld metal (girth weld) tests.

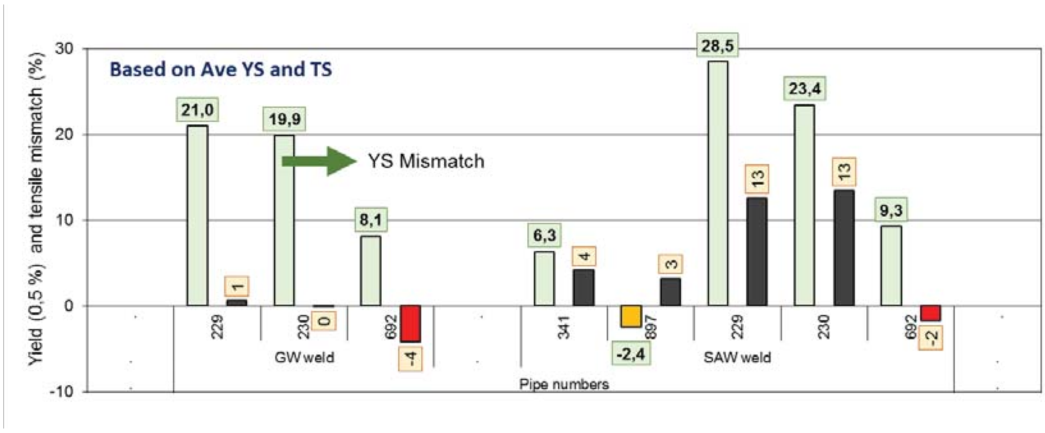


Fig.8. Variation of yield and tensile strength mismatch.

Figure 8 reveals that the girth welds were overmatched in yield strength and matching/slightly undermatching in tensile strength. In contrast, except for two slightly undermatched (2 and 2.4 %) welds, the SAW welds were overmatching both in yield and tensile strength. The measured yield strength undermatch is not a direct issue since (a) the welds had ample weld reinforcements and (b) the weld metals had ample strain hardening capacity (Figure 7).

Another feature is the that level of strength mismatch vary between wide margins. For example, the tensile strength mismatch in the D-SAW girth welds varied from 9.3 to 28.5 %. The significant variation of the strength mismatch levels illustrates that the determination of the actual level of yield / tensile strength mismatch occurring in field welds is a complicated issue. Factors to be accounted for are the natural variability of the pipe and weld metal tensile properties of the various pipes in the pipe string and around the circumference. Consequently, the comparison of the results of a single set of pipe metal and a single set of all-weld metal tensile tests can produce misleading information. This implies that the tests must be performed in sufficient numbers to allow for a correct comparison.

Charpy-V impact properties

At the time of the construction of the pipeline, Charpy testing was not required. However, to appreciate the toughness properties of the 54 years old pipeline, the measured impact energies were compared with currently used requirements.

The pipe metal Charpy impact energies at 0 °C and -20 °C are compared with the specified API 5L (PSL2) requirements of 27 J (transverse specimens) and 41 J (longitudinal specimen) in Figure 9. According to API, these minimum values are to be obtained at 0 °C. For the weld metal / HAZ tests of the longitudinal (D-SAW) and girth (SMAW) welds, the EPRG requirements, at minimum design temperature, of 30 J minimum and 40 J mean were used. Note that the impact energies of the sub-sized specimens were converted to represent the impact energy of a full-sized (10 mm * 10 mm) specimen. Remember also that the pipeline operaties at +38 °C.

Figure 9 reveals that all longitudinal pipe metal specimens met the impact requirement of 41 J (dashed line)at the specified test temperature of 0 °C as well as at -20 °C. Except for one pipe (341), the transverse tests marginally complied with the API requirement of 27 J. Note further that the impact energies at -20 °C were slightly lower than those obtained at 0 °C.

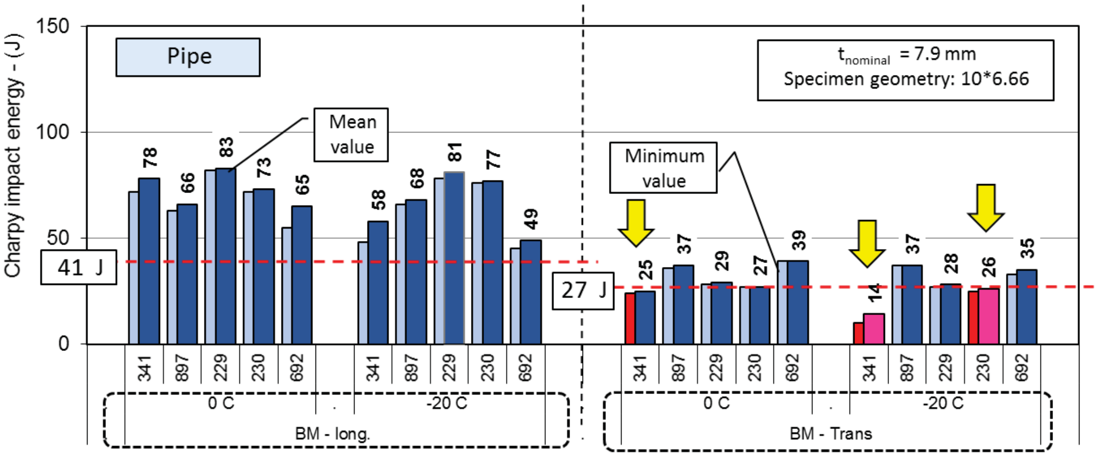


Fig.9. Minimum and mean Charpy impact energies of pipe metals at 0 °C and -20 °C.

The results of the weld metal/HAZ tests showed different trends, Figure 10. The weld metal and HAZ impact properties of the girth (SMAW) welds easily exceeded the EPRG mean requirements (see dashed lines), both 0 °C and -20 °C. Since the EPRG requirements excludes brittle fracture, it can be expected that, for surface breaking girth weld anomalies smaller than 7*wall thickness(length)* 3mm (height), girth weld failure by remote yielding will occur.

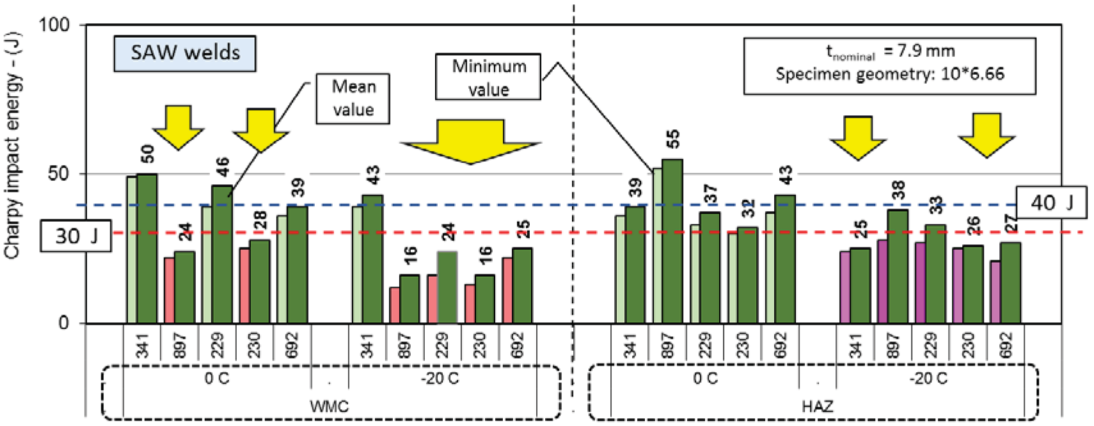


Fig.10. Minimum and mean Charpy impact energies of the weld girth welds (SMAW) at 0 °C and -20 °C.

The impact values of the longitudinal (D-SAW) welds displayed a less consistent trend, Figure 11. They were lower, equal to or greater than 30 J / 40 J. The weld metal tests were also sensitive to testing temperature. The impact values at -20 °C of four out of the five weld metals tested were lower than 30 J. However, the minimum API requirement (27 J – for transverse pipe metal specimens)- at 0 °C was satisfied for all HAZ tests. . However, one can also expect that the impact weld metal and HAZ properties at the operating temperature (38 °C) will be higher and meet the ERPG requirement.

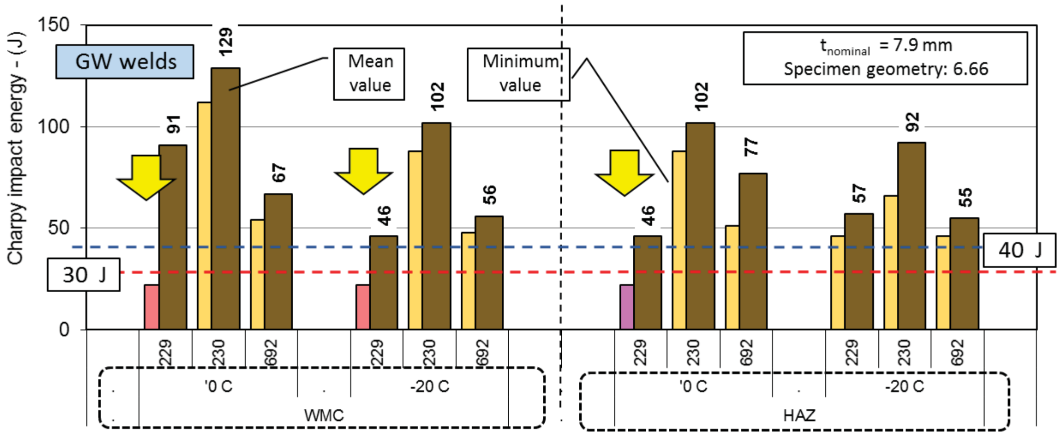


Fig.11. Minimum and mean Charpy impact energies of the longitudinal welds (D-SAW) at 0 °C and -20 °C.

Fatigue and wide plate test results

A detailed presentation of all experimental and photographic documentation gathered during fatigue and wide plate testing is beyond the scope of this paper. Therefore, in what follows, only characteristics results are presented.

Fatigue test performance criterion

The plain pipe sections and the welded test vessels sections were fatigued under cyclic internal pressure with a pressure range, Δp, of 32 bars (62 bars maximum - 30 bars minimum). The statistical rainbow counting analysis of the pressure data recorded during the second half of 2014 have shown that the equivalent number of cycles for Δp = 32 bars is 11748 for 30 years of operation. Applying a safety factor on lifetime of 5, one arrives at 58740 'equivalent' pressure cycles with a range of 32 bars. This number of cycles was used as a 'performance requirement' to quantify the remaining fatigue life of the pipes and vessels which, according to ASME 31G, need to be repaired or replaced.

Plain pipes / cold bends fatigue tests

The fatigue test results of the cold bend pipe sections with intermittent metal loss in the axial direction in the vicinity of the 6 o'clock position and the straight pipe section, which had also suffered third-party mechanical damage, but which had been repaired by the installation of a clock spring are summarized in Table 4.

Type of specimen	Test vessel number	Length (mm)	Extent of metal loss at 6 o'clock	Number of cycles to failure	Results
Cold bend (radius: 25 m) plain pipe	# 6-897-Part2	3000	Full length - intermittent Width: 192 mm Remaining wall thickness: 6.0 mm	**436182**	Leak in the HAZ of the D-SAW weld Initiation from outer wall l_{Outer} = 144 mm - l_{inner} = 87 mm
	# 6-341	4020	Full length - intermittent Width: 123 mm Remaining wall thickness: 6.9 mm	**501888**	Leak in the HAZ of the D-SAW weld Initiation from outer wall l_{Outer} = 114 mm - l_{inner} = 73 mm
Plain pipe	# 6-13310*	1735	Full length - intermittent Width: 311 mm Remaining wall thickness: 5.2 mm	**137191**	Leak in the HAZ of the D-SAW weld Initiation from outer wall To be measured

* : Test vessel contained also two linear crack-like indications at the D-SAW weld of 130 mm long and in the pipe body (135 mm long - gauge - mechanical damage). Fractographic analysis is still ongoing.

Table 4. Fatigue test results of plain pipe and cold bend tests.

All pipe test failed by a leak in the HAZ of the longitudinal D-SAW weld seam. The number of pressure cycles to failure ranged from 137191 to 501888. More importantly, in none of the tests fatigue crack growth from the internal metal loss corrosion defects was observed. Consequently, the D-SAW long seam is the 'weakest link' under fatigue loading. However, all test easily satisfied the performance criterion.

Welded pipe (vessel) fatigue

The test results of the pipe sections incorporating a girth weld and intermittent metal loss in the axial direction in the vicinity of the 6 o'clock position in both (adjacent) pipes are shown in Table 5.

The number of pressure cycles to failure ranged from 170977 to 597717. .As for the plain pipe tests, the D-SAW long seam was again the 'weakest link'. One test failed by leak in the girth weld at 6 o'clock from a lack of root penetration defect after 292723 cycles. Two test failed by a leak in the HAZ of the longitudinal D-SAW weld seam. The fourth test, test vessel # 6-340 & 6-341, remained unbroken after 597717 cycles was subjected to a full-scale burst test, the results of which are presented and discussed below. Thus, all tests exceeded the performance criterion.

Type of specimen	Test vessel number	Length (mm)	Extent of metal loss at 6 o'oclock	Number of cycles to failure	Results
Pipes / vessel with girth weld	# 6-896 & 6-897	1020 + 2020	Full length - intermittent Width: 125 mm Remaining wall thickness: 6.0 mm AND LORP in girth weld at 6 o'clock	**292723**	Leak in the girth weld Fatigue crack had initiated from the LORP defect l = 10 mm - h = 4 mm
	# 6-897 & 6-898	1200 + 2010	Full length - intermittent Width: 120 mm Remaining wall thickness: 6.9 mm	**182311**	Leak in the HAZ of the D-SAW weld, followed by unstable fracture Initiation from inner wall
	# 6-341 & 6-342	1010 + 2200	Full length - intermittent Width: 160 mm Remaining wall thickness: 6.9 mm	**170977**	Leak in the HAZ of the D-SAW weld Initiation from outer wall l_{Outer} = 34 mm - l_{inner} = 115 mm
	# 6-340 & 6-341	1015 + 1500	Full length - intermittent Width: 123 mm Remaining wall thickness: 6.9 mm	**597717**	No leak / failure Subjected to burst testing

Table 5. Fatigue test results of welded vessels.

Figures 12 provide a typical picture illustrating of the shape of fatigue crack in the HAZ of the longitudinal weld in vessel # 6-342 & 6-341.

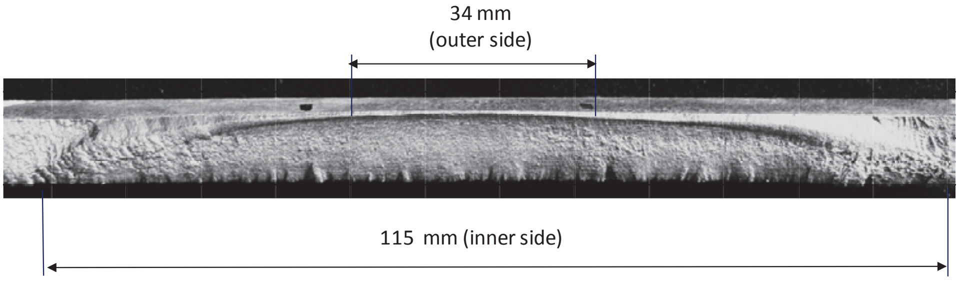


Fig.12. Shape and dimensions of the fatigue crack in the HAZ of the longitudinal weld in vessel # 6-342 & 6-341(number of cycles at leak = 170977) .

Figure 13 shows a picture of the LORP and the fatigue cracking transverse to the girth weld of vessel # 6-896 & 6-897 after fatigue testing. The arrows on the photographs identifies the fatigue cracks.

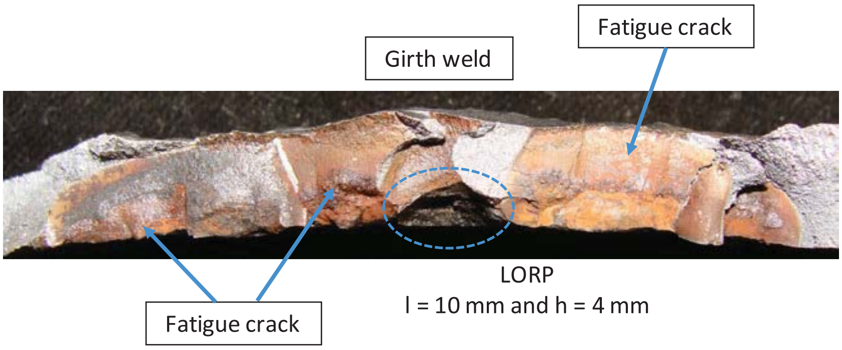


Fig.13. LORP defect of 10 mm x 4 mm and the fatigue crack profile transverse to the girth weld of vessel # 6-896 & 6-897 (number of cycles at leak = 292723 cycles.

Fatigue test of pipe sections with a 2" nipple

The results of the four fatigue tests are summarized in Table 6. As before, the pressure range, Δp, was 32 bar (30 - 62 bar). Table shows that the target number (58740 'equivalent' pressure cycles with a range of 32 bars) of cycles was largely exceeded.

The leak or the failure location was either the toe of that portion of the fillet weld subjected to the highest hoop stress (two tests) or the HAZ of the D-SAW weld seam (one test). In none of the test pieces was fatigue crack growth observed from the lack of root penetration defects. The fourth test, nipple # 13716, was interrupted after 555.780 cycles

Nipple #	Length (mm)	Number of cycles end of test	Results
#6-13716	1000	555.780	No leak / failure
#6-13561	965	298.434	Leak in SAW weld
#6-'0249	1050	243.834	Leak at toe of fillet weld (not from LORP)
6-'0251	875	509.256	Leak at toe of fillet weld (not from LORP)

Table 6. Fatigue test results of pipe sections with a 2" nipple.

Prior to and upon completion of fatigue testing, the nipples were inspected by Phased Array UT. These inspection revealed that in none of the partial penetration welds fatigue cracks had initiated from the incomplete root penetration defects. This was later confirmed by the post-test micro and macrographic examinations. Figures 14 and 15 provide typical pictures illustrating the geometry of the nipple, the location of the leak at the weld toe and the root area of the partially welded fillet weld after fatigue testing.

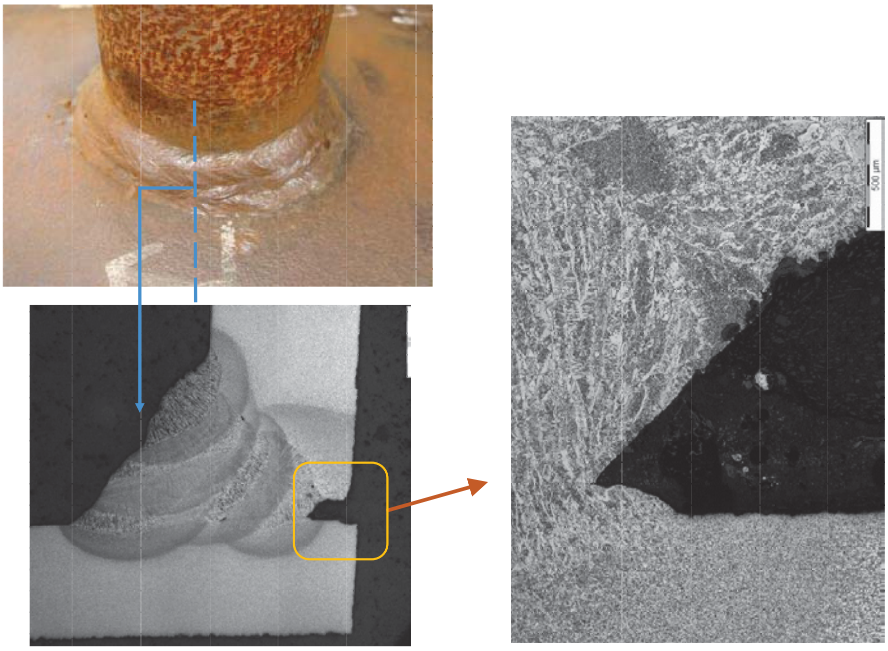


Fig.14. Macro and microphotographs illustrating that the root of the partially welded nipple (#6-13716) and the weld toe remained intact after 555780 cycles.

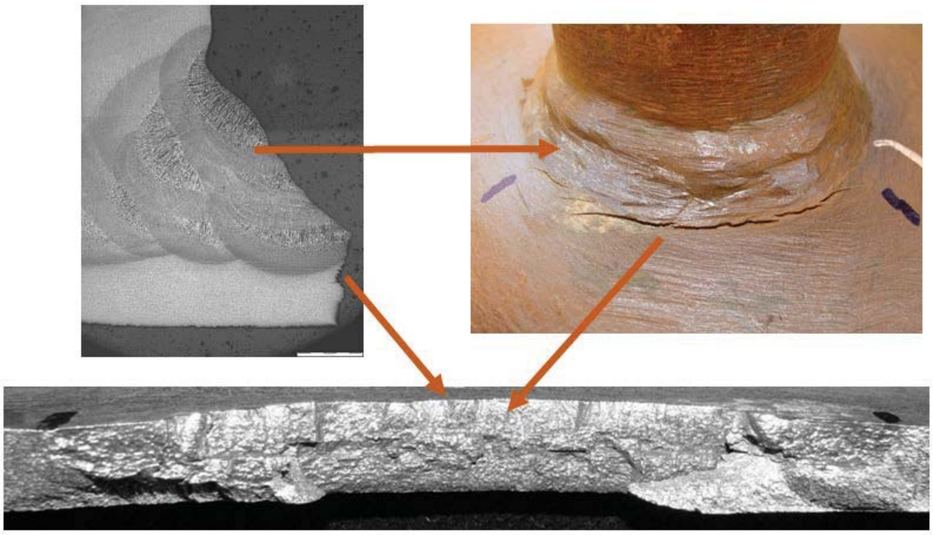


Fig.15. Photograph of nipple # 6-0249 illustrating that failure occurred at the weld toe after testing 243834 cycles.

Full-scale hydrostatic (burst) test

The 2.55 m long test vessel # 6-340 & 6-341, which remained unbroken after 597717 pressure cycles between 30 and 62 bars, was subsequently subjected to burst testing. The vessel failed by a stable pop-through (leakage) at 118.3 bar or 1.91 times the MOAP of 62 bars. The corresponding hoop stress exceeded the pipe metal yield strength and amounted to 456 MPa. The leak initiated from a small transverse fatigue crack located at the outer surface of the girth weld (see arrow in Figure 16). It is also worth noting that failure didn't occur in thinnest portion (6 o'clock position) of the pipe wall.

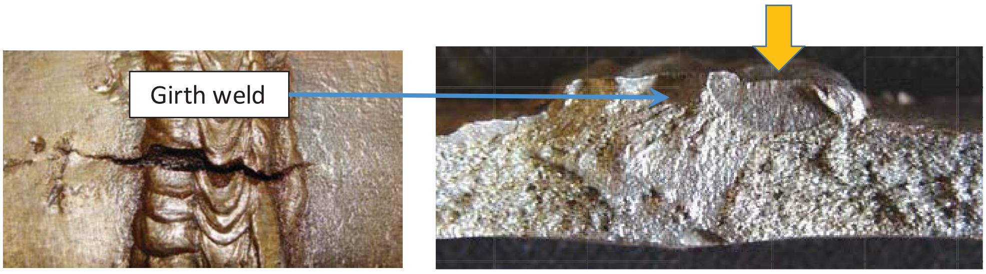


Fig.16. Details of leak at the outer pipe wall and fatigue crack which initiated leak by pop-through

The distribution in the axial direction of the circumferential strains measured after burst testing is shown in Figure 17. The graph illustrates that (a) because of limited length of pip pup pieces the end caps had an effect on the development of plastic strains, (b) the girth weld strength exceeded (overmatched) the strength of the adjacent pipes and (c) pipe # 6-340 was 'softer'(mean plastic strain was approximately 4.5 %) than pipe # 3-341 (mean plastic strain was approximately 3.0 %).

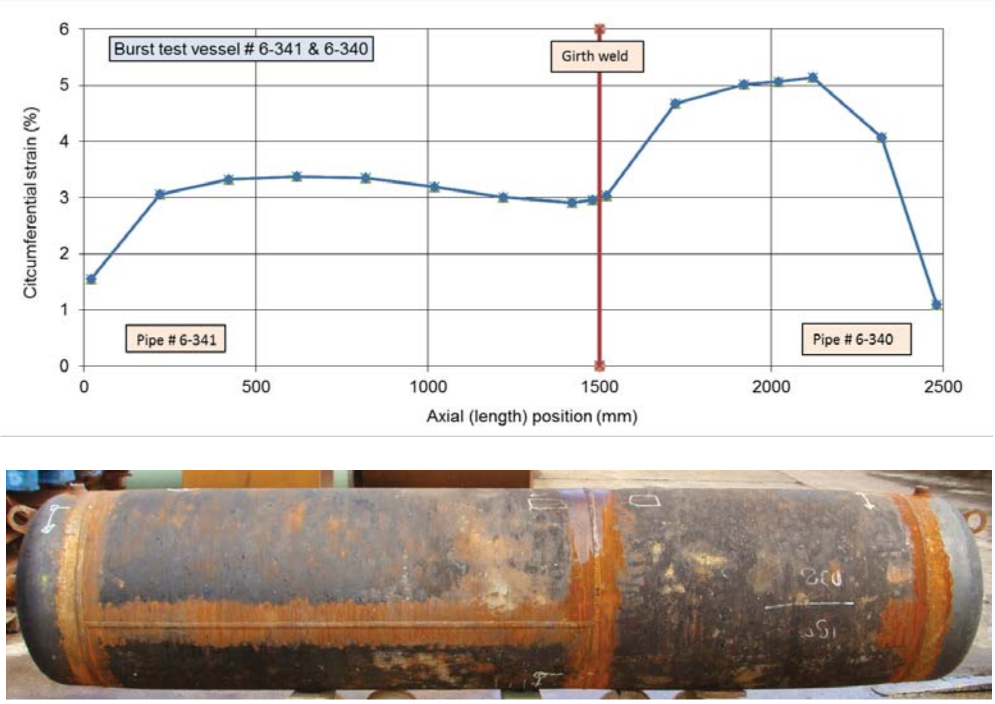


Fig.17. Test vessel after testing and the distribution of the circumferential plastic strains along the length of the test vessel.

After testing, the outer walls of the longitudinal D-SAW welds were inspected with dye penetrants for cracks, if any. This examination revealed multiple cracks in the HAZ of the long seam of the softest pipe (# 6-340). The cracks were then opened up in liquid nitrogen and subsequently photographed, Figure 18. The photographs show that slow stable crack extension occurred during hydrostatic testing.

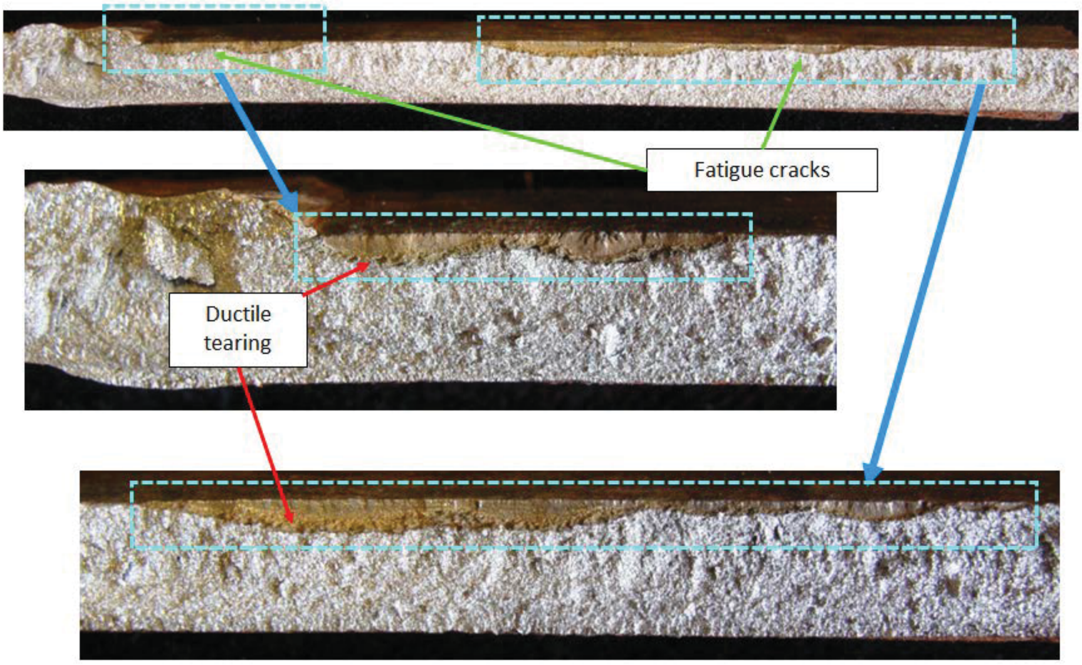


Fig.18. Fatigue cracks in the HAZ (outer wall) of the D-SAW weld in pipe # 6-340.

Wide plate test

Plate tensile testing at 0 °C of a girth welded pipe section with a central 'pinhole' defect in the root of 15 mm long by 5.3 mm high, Figure 19, and a lack of root penetration (LORP) defect of 18 mm x 3.8 mm, and scattered porosities, Figure 20, has demonstrated that the welded pipe section failed by remote yielding. Failure initiated from the LORP defect at a remote (axial) stress of 398 MPa (SMYS of X 52 pipe = 359 MPa) and a remote pipe metal plastic strain of 2.46 %.

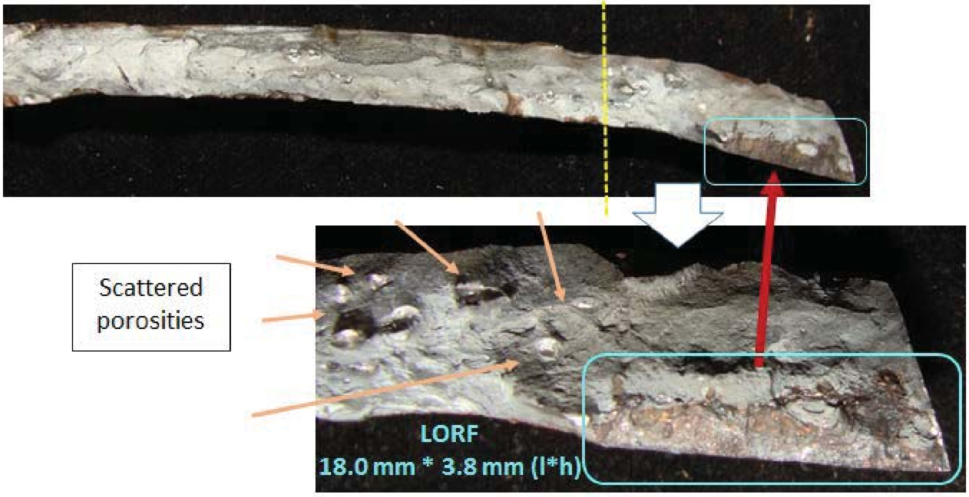


Fig.19. Detailed view of lack of root penetration (LORP) defect.

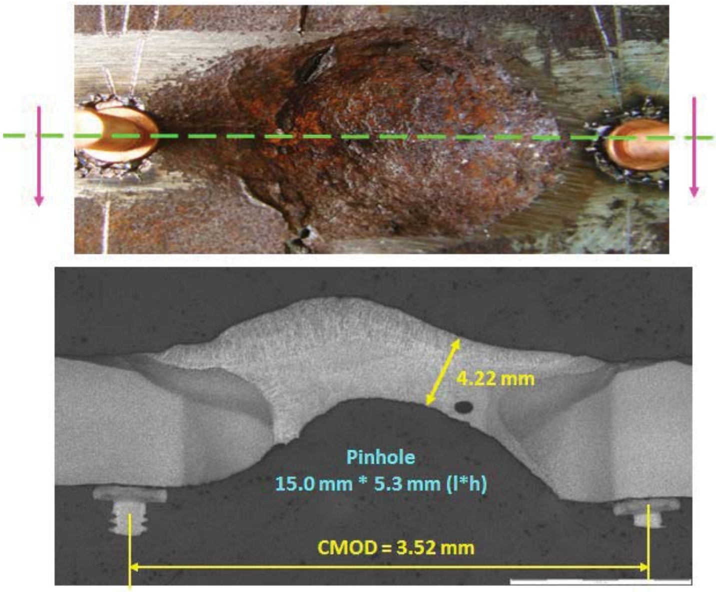


Fig.20 Cross section of pin hole .

Though the specimen was strained well into the post-yield loading range, Figure 20 shows that the pinhole remained intact. Note also that (a) the minimum weld metal section at the end of testing was 4.22 mm and (b) considerable elongation across the pinhole occurred (CMOD = 3.52 m) prior to the fracture initiation at the LORF defect.

Provisional conclusions

In 2014, the Rotterdam - Rijn Pijpleiding (RRP) Maatschappij decided to conduct an extensive experimental test programme focussing on their 54 years old 24" API 5L grade X52 oil product pipeline. The objective was to demonstrate that the fatigue resistance of pipe sections containing channeling corrosion (rejected by ASME B31G) is sufficiently high for the future safe operation of the pipeline. The experimental study involved material characterization, full-scale fatigue testing under cyclic internal pressure, hydrostatic / burst testing and wide plate tensile testing.

Notwithstanding that the analysis of the test data study is ongoing, the following observation can made:

Using the 58740 'equivalent' pressure cycles performance requirement for a pressure range of 32 bars (62 bars maximum - 30 bars minimum) for a 30 years period, the full-scale fatigue tests have demonstrated that seven tested pipe sections with channeling corrosion have adequate fatigue resistance provided the original design (maximum allowable operation pressure - MAOP - of 62 bars) and current operational conditions are satisfied. In particular:

- the number of pressure cycles (30 - 62 bars) to failure ranged from 137191 to 501888. One test was interrupted at 597717 cycles without failure;

- in none of the tests performed, fatigue crack growth from the internal metal loss corrosion defects occurred. For five test performed, failure occurred by leak in the HAZ of the D-SAW weld seam, implying that the D-SAW seam weld is the 'weakest link' with respect to fatigue. The failure in the sixth test inititated from a lack of penetration in the girth weld.

The fatigue testing of pipe sections with a 2" nipple, welded to the pipes by a partial penetration fillet weld, has demonstrated that the fatigue resistance is not adversely affected by the incomplete root penetration of the nipple welds. The number of cycles to leak ranged from 243834 to 555780. The failure location was either the HAZ of the D-SAW weld seam or the toe of the fillet weld. In none of the test pieces fatigue crack growth was observed to initiate from the lack of root penetration (LORP) defects.

In addition, the material characterization, the full-scale burst and the wide plate tests have demonstrated that the pipe sections with channeling corrosion and a girth weld have adequate fracture resistance:

- the burst pressure of the pipe section, which survived 597717 pressure cycles, was 118.3 bars, i.e., 1.91 x MAOP of 62 bars. The corresponding hoop stress was 456 MPa (1.27 x SMYS of 359 MPa). The associated strain in the hoop direction exceeded 5 %. Failure occurred by leak, which had initiated from a transverse fatigue crack in the girth weld. It is also worth noting that failure didn't occur in the thinnest (corroded) portion of the pipe wall;

- wide plate tensile testing at 0 °C of a girth welded pipe section with a central 'pinhole' defect in the root of 15 mm long by 5.3 mm high and a LORP defect of 18 mm x 3.8 mm led to failure by remote yielding. Failure initiated from the LORP defect at a remote (axial) stress of 398 MPa (1.11 x SMYS). The corresponding remote pipe metal plastic strain was 2.46 %.

Finally, material characterization testing of five randomly selected pipe sections has demonstrated that the pipe metals, SMAW girth welds and longitudinal D-SAW weld seams have, after 54 years of operation, tensile and notch toughness properties which comply with the contemporary pipe (API 5LX) and weld metal (EPRG) requirements. In addition, the tensile tests revealed that the Y/T ratio, which has important effect on the material's flow stress, of pipe and weld metals was below 0.80 (0.85/0.90), implying that standard corrosion assessment procedures, such as ASME B31G, will to lead to overly conservative predictions.