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EFFECTS OF CATHODIC OVER PROTECTION ON RESIDUAL STRENGTH OF DAMAGED PIPES
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ABSTRACT

Underground pipelines are protected from soil corrosion by an outer barrier (i.e. the external coating) enhanced by cathodic protection (CP). However, buried pipeline are exposed to potential damages by third party and local over cathodic potentials may be present (down to -1450 mV vs $Cu/CuSO_4$).
In this context, the hydrogen from cathodic (over) protection may play an important role: its entrance in the pipe material is facilitated when stresses are applied, causing local embrittlement and allowing the growth of cracks in the damaged area, that often undergoes a re-transformed microstructure, with higher hardness and lower toughness properties, as a consequence of the damaging process.
In such a scenario, EPRG performed a number of projects on the effect of hydrogen produced by cathodic over protection on pipes damaged by third party activities. Pipes representative of modern pipelines (no sour service) were involved and full scale tests performed.

An innovative full scale approach was designed, to include the full extension of the damaged area, the relevant stress – strain fields in the pipe wall, the stress concentration factors, the environment (non-sour), the cathodic protection and the cyclic internal pressure.
Thus, the effects of the damaging process, cathodic protection potential, pipe coating, environment, tooth wear, pipe forming process and cyclic pressure were investigated in three full scale tests, for a total of 28 damages and 20 months testing, in conditions reproducing a real in-service damaged pipeline.
The aim was to assess the effects of the listed variables on presence, extension and characteristics of cracks in the damaged areas, provide a preliminary quantification of crack growth rate and show the effects of cathodic (over) protection (according to the applied potential).
Results of the full scale tests are summarized in the this paper with evidence of experimental observations.

DISCLAIMER

Papers shall be treated as confidential documents and may not be cited in papers or reports except those published under the auspices of EPRG, PRCI or APGA-RSC.

1. BACKGROUND

Failure due to external damage was the most frequent cause of incidents in a pipeline system over the years (Figure *1*). In this regard, the EGIG 11th report [1] confirms that the external damage may cause dangerous consequences *("Incidents caused by external interference and ground movement are characterised by potentially severe consequences. This emphasises the importance of measures to prevent these incidents taken by pipeline operators and authorities"*), and it represent the most frequent failure cause of the last 10 years (*"Over the last ten years, external interference, corrosion, construction defects and ground movement, represent 27%, 27%, 16% and 16% respectively of the pipeline incidents reported"*), although reduced with respect to past, and presently at the same level of corrosion.

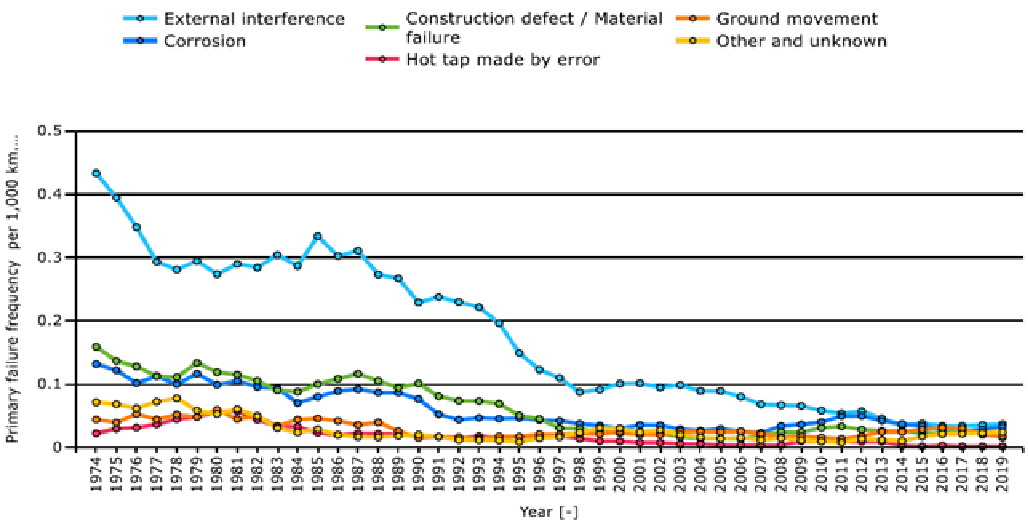


Figure 1: Primary failure frequencies per cause (five year moving average).

Furthermore, the delayed failures of damaged gas pipes may occur, in a time period (weeks or months) that cannot be related only to pure mechanic fatigue, since this would require thousands of cycles, that is years of in-service operating conditions. In such a context, the hydrogen generated by cathodic (over) protection may play an important role: in fact, the entrance of the hydrogen inside the material lattice is facilitated when stresses are applied (pipe internal pressure), causing the local embrittlement of the pipe material and allowing the growth of micro-cracks in the damaged area, that often undergoes a re-transformed microstructure, with higher hardness and lower toughness properties, as a consequence of the damaging process.

2. INTRODUCTION

EPRG performed a number of projects on the effect of hydrogen from cathodic protection on damaged pipes. The aim was to assess the effect of cathodic protection on damages from third party activities, and to assess if cracks may be present and develop. Hence, three full scale projects were performed, for a total of 28 damages and 20 months testing (Table 1).
Testing progressively converged to most relevant variables according to results from first project (being the 151 the first and the 196 the last), focusing on one type of damage (dent&gouge), one excavator tooth wear (new), one level of cathodic protection (-1450 mV vs $Cu/CuSO_4$), one environment (ground water), and increasing the testing time from four months to eight months.

Project #	151	174	196
Pipes	2	2	1
Grade	X70	X70	X70
Type	LSAW	LSAW	HSAW
OD (mm)	1219	1219	1219
Th (mm)	17,5	17,5	17,5
Length (m)	8	4	8
Damages per pipe	8	4	4
Total number of damages	16	8	4
Type of damages	Dent&gouge + gouge	Dent&gouge	Dent&gouge
Coating	3LPE	3LPE	No coating
Simulated excavator (ton)	35	35	35
Excavator tooth	New and worn	New	New
Cathodic protection potential vs $Cu/CuSO_4$ (mV)	-850 and -1450	-1150 and -1450	-1450
Environment	Ground water and brackish water	Ground water	Ground water
Max pressure (bar)	100	100	100
Min pressure (bar)	90	90	90
R (P_{min} / P_{max})	0,9	0,9	0,9
UF (hoop stress / SMYS) (%)	72	72	72
Strain rate	~ $6,0 \times 10^{-8}$	~ $6,0 \times 10^{-8}$	~ $6,0 \times 10^{-8}$
Testing time (months)	4	8	8
Cycles per month	~1000	~1000	~1000
Total number of cycles	~3600	~9000	~7000

Table 1: Characteristics of full scale tests

Pipes and damages were characterized as follows:

- Before full scale testing:
  - Mechanical characterization (tensile and Charpy tests);
  - Chemical analysis;
  - Damages geometry;
  - Damages NDT;
- During full scale testing:
  - Pressure;
  - Temperature;
  - Potential;
  - Current density;
- After full scale testing:
  - Damages NDT;
  - Microstructural analysis.

3. FULL SCALE APPROACH

In order to be representative, testing relies on two main needs:

1. Realistic damages, to reproduce geometry, stress and strain fields, cracks and microstructural alteration of pipe material as in a real pipe hit by a real excavator [3, 4, 5, 6];
2. Realistic environment full scale tests, reproducing in service conditions, like potential, currents, environment, cyclic pressure and strain rate [6].

The first need has been addressed by using a special device to reproduce the digging modality of crawler excavator [3, 4, 5]. By such device, named "Simulator" (Figure 2), it is possible to produce third party damages under controlled conditions (computer controlled trajectory), in order to replicate real damages and to achieve damages target geometry. Different sizes of crawler excavator can be reproduced, from 7 ton to 35 ton, by controlling the device forces, trajectory, lateral stiffness and tooth dimensions and wear (Figure 3).
An example of damage produced for the present projects is shown in Figure 4 (left), together with the pipe external surface appearance in the gouge (Figure 4, right). The blue color indicates the high temperature reached by the pipe material (estimated in the range from 290°C to 330°C) during the damaging process and caused by the friction between the pipe steel and the impacting tooth.
Due to the heating and quick cooling, the pipe material undergoes a local change in the microstructure, according to Figure 5 (left), where higher hardness is detected too (Figure 5, right. Highest values are due to the white tooth material attached to the pipe surface). In such conditions, cracks may be found (Figure 6) since this step, that is just after damage creation.

The environment full scale test has been realized according to sketch and layout in Figure 7: each damage has its own cell with solution and applied cathodic protection. Potential, current density and temperature were measured in every cell.
The pipe pressure is cycled between P_{max} (100 bar, corresponding to hoop stress/SMYS = UF = 72%) and P_{min} (90 bar, P_{min} / P_{max} = R = 0,9), the applied strain rate is about 6,0 x 10^{-8}, and then the cycle period is about 45 minutes. Such values were selected in order to simulate gas pipeline in-service conditions, quite different from oil pipelines, where R is lower and the strain rate higher, thus emphasizing the mechanical contribution and limiting the environment effect.
Cathodic potentials (Table 1), chosen basing on EPRG members experience and ISO 13623 [1], is applied via potenziostatic device to all cells and balanced, in order to reach the target potential in each cell (Figure 8).
According to Table 1, two different environments were used (in project 151 only):

- Artificial ground water: aimed at representing not polluted ground. It contains bicarbonate ion for buffering the solution at the target pH. The solution is characterized as follows:
    - solution: 50 g/l Na_2SO_4 + 5 g/l $NaHCO_3$;
    - gas: 1 bar mixture CO_2/N_2 with CO_2 at 10%;
    - pH: 8.0;
    - Conductivity: 44 mS/cm.
- Artificial brackish water: designed to represent an environment similar to the one that can be found in slightly polluted ground (i.e. industrial discharge, waste water or acid rains); hence lower pH, slightly acid, and higher conductivity. The chloride ion enhances the conductivity and the bicarbonate ion is used for buffering the solution. The solution is characterized as follows:
    - solution: 50 g/l Na_2SO_4 + 5 g/l $NaHCO_3$ + 5 g/l NaCl;
    - gas: 1 bar mixture CO_2/N_2 with CO_2 al 10%;
    - pH: 6.5;
    - Conductivity: 52 mS/cm.

Basing on results of Project 151, in the following Project 174 and Project 196, the testing focused on the most relevant variables only (Table 1).

Figure 2: View of the RINA-CSM's full scale external damage testing facility (Simulator).

Figure 3: 33 tons excavator tooth: new (left) and worn (right).

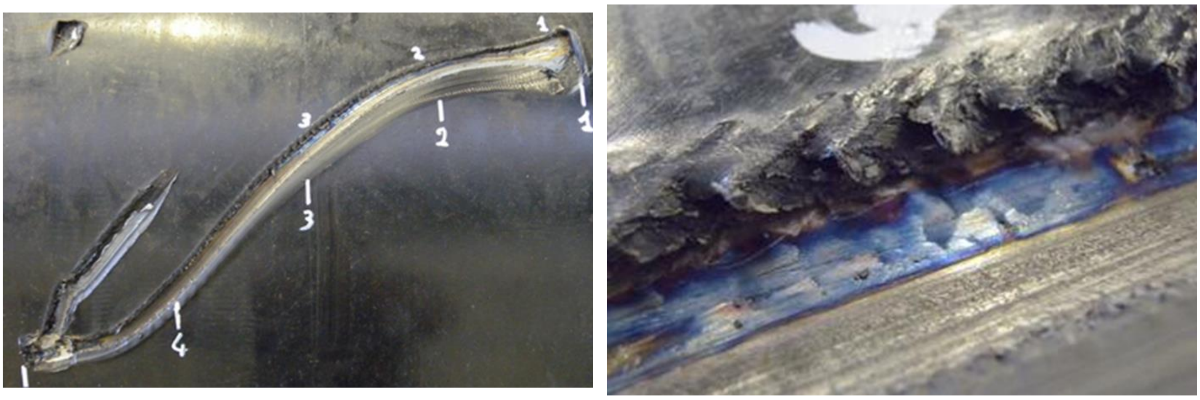
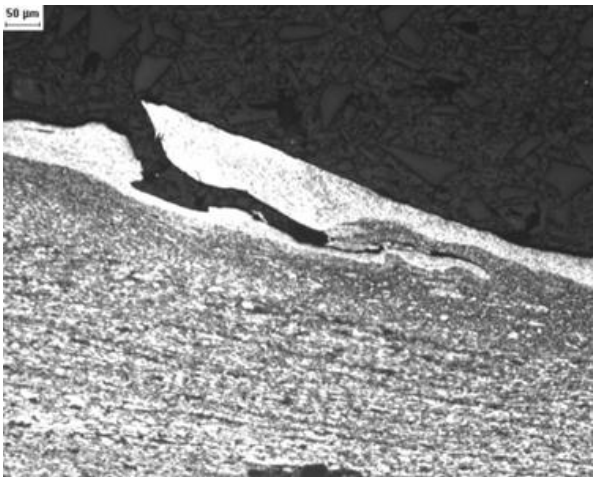


Figure 4: Damage from Simulator (left) and damaged surface (right).



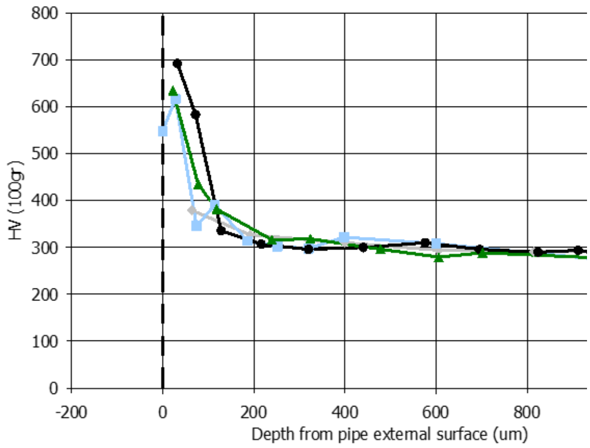
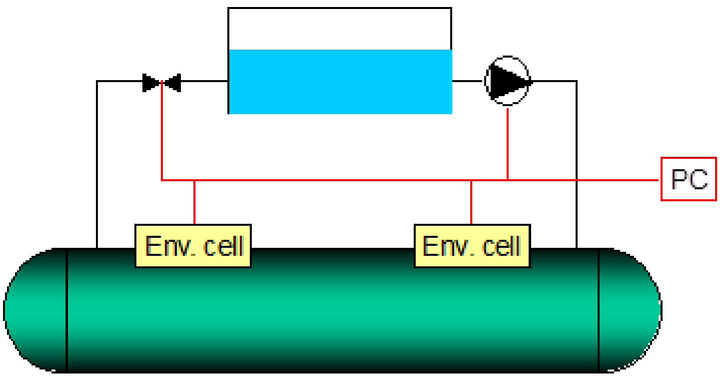


Figure 5: Microstructure of pipe material in Figure 4 (left), and relevant hardness measurements (right).

Figure 6: Cracks after damage creation.



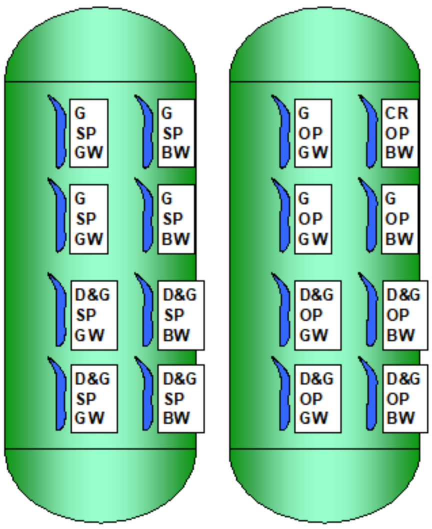


Figure 7: Sketch of the environment full scale test (left), and layout of damages on the pipe (right).

Figure 8: Pipe with cells ready for environment full scale test.

4. CHARACTERIZATION

In all three projects, the following characterization was performed before starting activities:

- Pipe material mechanical characterization;
- Chemical analysis;
- Damages geometry.

4.1. Mechanical characterization

The pipes material was characterized both with tensile tests and Charpy impact tests. Results are summarized in Table 2. Tensile tests were performed on transversal specimens, flattened and full thickness. LSAW pipes for projects 151 and 174 exhibit yield values slightly higher than requirement in ISO3183 [7], but ultimate stress and Y/T ratio are within the range. HSAW pipe for project 196 showed lower values of yield and ultimate stresses, close to the lower limit of the ISO3183. The Y/T is lower too.

Impact energies, measured on Charpy specimens (transversal with trough thickness V notch), are good for all pipes.

Project #	151		174	196
Grade	X70		X70	X70
Type	LSAW		LSAW	HSAW
OD (mm)	1219		1219	1219
Th (mm)	17		17	17,5
Pipe material	A	C	C	E
Pipe sample ID	1	2	3, 4	5
Yield stress (MPa)	648	637	637	488
Ultimate stress (MPa)	744	727	727	616
Y/T ratio	0.87	0.88	0.88	0,79
Elongation (%)	15,5	16,5	16,5	19,0
CV energy (J)	158	181	181	291

Table 2: Results from tensile and impact tests.

4.2. Chemical analysis

Chemical analysis was performed on all pipes and results are summarized in Table 3. All of the values are within the limits from ISO 3183.

	Project #		
Element	151	174	196
C	0,084		0,055
Si	0,29		0,27
Mn	1,50		1,71
P	0,01		0,011
S	0,0007		0,0015
V	0,05		< 0,01
Nb	0,03		0,093
Ti	0,003		0,021

Table 3: Chemical analysis.

4.3. Damages dimensions

Geometry of damages produced in Project 151, Project 174 and Project 196 are reported in Table 4, Table 5 and Table 6 respectively. Damage CR1 in Table 4 is not actually a damage; it is a cut in the coating to expose the pipe surface to have a blank reference (that is pipe surface with no damage). It is worth noting that the damaging process modifies the shape of the impacting tooth due to contact forces and friction and, as a consequence, damages are not exactly equal, but some scatter is found in their dimensions.

			BG1	BG2	BG3	BG4	G1	G2	G3	CR1
Pipe 1	Damage type		Dent&gouge				Gouge			Coating removal
	Dent (mm)	Depth	6,7	6,0	6,0	6,8	< 1,0	< 1,0	< 1,0	-----
	Gouge (mm)	Depth 1	5,6	5,6	5,6	5,4	5,6	5,6	5,4	-----
		Depth 2	5,6	5,8	5,7	5,6	5,7	5,9	5,5	-----
		Length	450	460	440	450	440	440	440	-----
Pipe 2			BG1	BG2	BG3	BG4	G1	G2	G3	G4
	Damage type		Dent&gouge				Gouge			
	Dent (mm)	Depth	5,5	5,1	8,0	5,4	< 1,0	< 1,0	< 1,0	< 1,0
	Gouge (mm)	Depth 1	5,1	5,0	4,5	4,8	4,7	5,0	5,2	5,2
		Depth 2	4,3	4,5	4,5	5,2	4,1	5,1	4,6	5,4
		Length	470	440	462	450	455	470	455	450

Table 4: Geometry of damages in Project 151.

Pipe 3			BG1	BG2	BG3	BG4
	Damage type		Dent&gouge			
	Dent (mm)	Depth	1,9	1,5	1,8	2,0
	Gouge (mm)	Depth 1	0,5	0,5	0,6	0,9
		Depth 2	0,6	0,8	0,7	0,6
		Length	460	470	450	470
Pipe 4			BG1	BG2	BG3	BG4
	Damage type		Dent&gouge			
	Dent (mm)	Depth	2,5	1,9	2,7	3,0
	Gouge (mm)	Depth 1	0,4	0,3	0,5	1,0
		Depth 2	0,4	0,4	0,4	0,6
		Length	450	450	460	450

Table 5: Geometry of damages in Project 174.

Pipe 5			BG1	BG2	BG3	BG4
	Damage type		Dent&gouge			
	Dent (mm)	Depth	3,4	4,1	3,7	3,6
	Gouge (mm)	Depth 1	0,5	0,4	1,0	0,9
		Depth 2	1,6	1,6	1,5	1,3
		Length	455	470	470	460

Table 6: Geometry of damages in Project 196.

5. MONITORING OF THE ENVIRONMENT FULL SCALE TEST

During the environment full scale tests, a number of parameters were monitord and acquired, like: potential, current density, temperature, pressure. In the following tables, the features of the full scale tests are reported, including target and actually measured values.

In project 151 (Table 7), the one realized first, a number of variables were investigated at different values (damage type, potential, environment, tooth wear). In particular, the potentials were chosen so to represent strong cathodic over protection (-1450 mV vs $Cu/CuSO_4$) and minimum cathodic protection (-850 mV vs $Cu/CuSO_4$) according to ISO 13623.

Basing on the results of the first project, the following projects 174 (Table 8) and 196 (Table 9) extended the testing time to eight months instead of four and focused on less variables: in fact damage type, tooth wear and environment were set to one value for all tests. Two levels of potential were still applied in Project 174: strong cathodic over protection (-1450 mV vs $Cu/CuSO_4$) and max allowed cathodic protection (-1150 mV vs $Cu/CuSO_4$) according to ISO 13623 [2]. Finally, in Project 196 the potential was set to one value only: -1450 mV vs $Cu/CuSO_4$.

			BG1	BG2	BG3	BG4	G1	G2	G3	CR1
Pipe 1	Damage type		Dent&gouge				Gouge			Coating removal
	Potential (mV) vs $Cu/CuSO_4$	Target	-1450							
		Actual mean	-1378	-1370	-1446	-1401	-1338	-1432	-1383	-1131
	Current density (mA/cm^2)	Target	2,0 – 4,0							
		Actual mean	3,5	3,6	3,6	3,5	3,6	3,6n	3,5	0,8
	Environment		Ground water	Ground water	Ground water	Ground water	Brackish water	Brackish water	Brackish water	Brackish water
Pipe 2			BG1	BG2	BG3	BG4	G1	G2	G3	G4
	Damage type		Dent&gouge				Gouge			
	Potential (mV) vs $Cu/CuSO_4$	Target	-850							
		Actual mean	-823	-838	-850	-846	-842	-829	-838	-842
	Current density (mA/cm^2)	Target	10^{-2}							
		Actual mean	0,013	0,017	0,014	0,013	0,014	0,015	0,014	0,003
	Environment		Ground water	Ground water	Ground water	Ground water	Brackish water	Brackish water	Brackish water	Brackish water
All damages										
Pipe 1 + 2	Temperature (°C)	Min – Max	23,8 – 32,9							
	Pressure (bar)	Min – Max	90 – 100							
	Cycles		3591							

Table 7: Features of environment full scale tests of Project 151.

The target and actual (measured) mean value of potential and current density are shown in the tables. In particular, the current densities range was selected basing on experience of operators inside the EPRG, while the cathodic potentials were selected starting from ISO 13623. Being the tests performed outdoor, the temperature was imposed by the ambient, and so subject to variations due to sun in summer (although shielded) and cold wind in winter. In most cases, potential was very close to the target values for all the tests duration, as well as current densities were in the target ranges.

In order to assess the effect of the coating during the damaging process, Pipe 5 of Project 196 was not coated, while pipes 1 to 4 (Project 151 and 174) were coated. The absence of coating in pipe 5 also allowed to perform NDT just after damage realization and before environment tests, so to check for cracks presence and growth by comparison with NDT after environment tests, as shown in Table 10. Finally, for performing an environmental full scale tests equivalent to tests in projects 151 and 174, in Project 196 coating was applied around the damages before full scale testing to cover the area exposed to the environment.

			BG1	BG2	BG3	BG4
Pipe 3	Damage type		Dent&gouge			
	Potential (mV) Vs $Cu/CuSO_4$	Target	-1100			
		Actual mean	-1129	-1130	-1149	-1120
	Current density (mA/cm^2)	Target	10^{-1}			
		Actual mean	0,4	0,4	0,3	0,4
	Environment		Ground water			
Pipe 4			BG1	BG2	BG3	BG4
	Damage type		Dent&gouge			
	Potential (mV) Vs $Cu/CuSO_4$	Target	-1450			
		Actual mean	-1476	-1500	-1426	-1469
	Current density (mA/cm^2)	Target	2,0 – 4,0			
		Actual mean	4,6	4,7	4,8	4,6
	Environment		Ground water			
Pipe 3 + 4	Temperature (°C)	Min – Max	0,2 – 45,8			
	Pressure (bar)	Min – Max	90 – 100			
	Cycles		9015			

Table 8: Features of environment full scale tests of Project 174.

			BG1	BG2	BG3	BG4
Pipe 5	Damage type		Dent&gouge			
	Potential (mV) Vs $Cu/CuSO_4$	Target	-1450			
		Actual mean	-1410	-1380	-1410	-1370
	Current density (mA/cm^2)	Target	2,0 – 4,0			
		Actual mean	2,6	2,5	2,6	2,63
	Environment		Ground water			
	Temperature (°C)	Min – Max	6,5 – 40,7			
	Pressure (bar)	Min – Max	90 – 100			
	Cycles		7000			

Table 9: Features of environment full scale tests of Project 196.

Damage	Indications	Type	Dimensions (mm)	Position
BG1	1	Group of cracks	70	End of gouge
BG2	1	Group of cracks	50	End of gouge
BG3	1	Group of cracks	10	End of gouge
BG4	0	---	---	---

Table 10: NDT before environment full scale tests of Project 196.

6. ANALYSIS OF RESULTS

After completion of the environmental full scale tests, NDT were performed on all damages and then microstructural analysis was performed on damages with indications of cracks, that were found in most of damages (Table 11 and Table 12). In some cases, although NDT found indications, cracks were not found through the microstructural analysis. Coating removal CR1 (blank test) reported neither corrosion nor cracks.

Indications found on Pipe 5 were confirmed after full scale tests (Table 12), and it was observed a general growth for all of them. In particular for damage BG4, two groups of cracks were observed that were not present before full scale tests, thus demonstrating the possibility of new cracks, namely not created at the moment of damage, to initiate and develop.

Not all of the observed cracks have the same features: some have sharp and complementary edges (showing no plastic deformation), other are branched, other have deformed edges. The latter are due to the applied load, while the former, which exhibit no plastic deformation, are due to the pipe hardened material and/or to hydrogen produced by cathodic (over) protection. Hydrogen from cathodic (over) protection may has been the predominant contributor when cracks are deeper than the pipe material hardened layer.

Results from NDT and microstructural analysis are shown in the following figures:

- Damage BG2 from Pipe 1:
  - NDT (Figure 9): indications of cracks are visible in the gouge;
  - Microstructure (Figure 10): appearance of the damage section at the optical microscope, both polished and etched, to emphasize cracks and microstructure. In particular, the top image shows the tooth material (bright), two layers of pipe base material altered by the damaging process, and finally the pipe base material. The tooth material has very high hardness and the pipe altered material exhibits hardness values higher than the pipe base material. In other words, the damaging process has caused local hardening of the pipe material;
- Damage G1 from Pipe 1:
  - NDT (Figure 11): apparently just a small crack in the end of the gouge;
  - Microstructure (Figure 12): a number of cracks, both in the tooth and pipe material. It is interesting to see that one crack started in the tooth material and extended in the pipe hardened material;
- Damage BG3 from Pipe 1:
  - NDT (Figure 13): crack in the tooth print (impact point);
  - Polished section (Figure 14): a crack, with sharp and complementary edges at the tip;
- Damage BG1 from Pipe 5:
  - NDT (Figure 15): cracks at end of gouge;
  - Microstructure (Figure 16): two branched cracks, with sharp and complementary edges. Both cracks start from pipe hardened material;
- Damage BG2 from Pipe 5:
  - NDT (Figure 17): cracks at end of gouge;

    - Microstructure (Figure 18): the left crack is about 1,75 mm deep, while the right one is about 2,25 mm deep. Both have sharp and complementary edges;
- Damage BG4 from Pipe 5:
    - NDT (Figure 19): cracks at end of gouge;
    - Microstructure (Figure 20): cracks with sharp and complementary edges. Tooth material, pipe altered material and pipe base material.

Project 151					
Pipe 1			Pipe 2		
Damage	NDT	Microstructure	Damage	NDT	Microstructure
BG1	No crack	---	BG1	Cracks at end of gouge	Cracks
BG2	No crack	---	BG2	Cracks in the gouge	Cracks
BG3	No crack	---	BG3	Cracks at impact point	Cracks
BG4	Cracks at end of gouge	No crack	BG4	Cracks at end of gouge	Cracks
G1	No crack	---	G1	Cracks at end of gouge	Cracks
G2	No crack	---	G2	No crack	---
G3	Cracks at end of gouge	Cracks	G3	Cracks at end of gouge	Cracks
CR1	No crack	---	G4	No crack	---
Project 174					
Pipe 3			Pipe 4		
Damage	NDT	Microstructure	Damage	NDT	Microstructure
BG1	Crack in the gouge and at the end of gouge	No crack	BG1	Crack at end of gouge	No crack
BG2	Crack in the gouge	No crack	BG2	Crack at end of gouge	Cracks
BG3	Crack in the gouge and at the end of gouge	No crack	BG3	No crack	No cracks
BG4	Crack in the gouge	No crack	BG4	No crack	No cracks

Table 11: NDT after environment full scale tests of Project 151 and Project 174.

Damage	Before full scale test				After full scale test			
	Indications	Type	Dimensions (mm)	Position	Indications	Type	Dimensions (mm)	Position
BG1	1	Group of cracks	70	End of gouge	1	Group of cracks	80	End of gouge
BG2	1	Group of cracks	50	End of gouge	1	Group of cracks	80	End of gouge
BG3	1	Group of cracks	10	End of gouge	1	Group of cracks	70	End of gouge
BG4	0	---	---	---	2	Group of cracks	10 – 80	Print and end of gouge

Table 12: Comparison of NDT investigation before and after full scale test for Project 196.

Figure 9: Crack in the gouge of damage BG2 from Pipe 1.

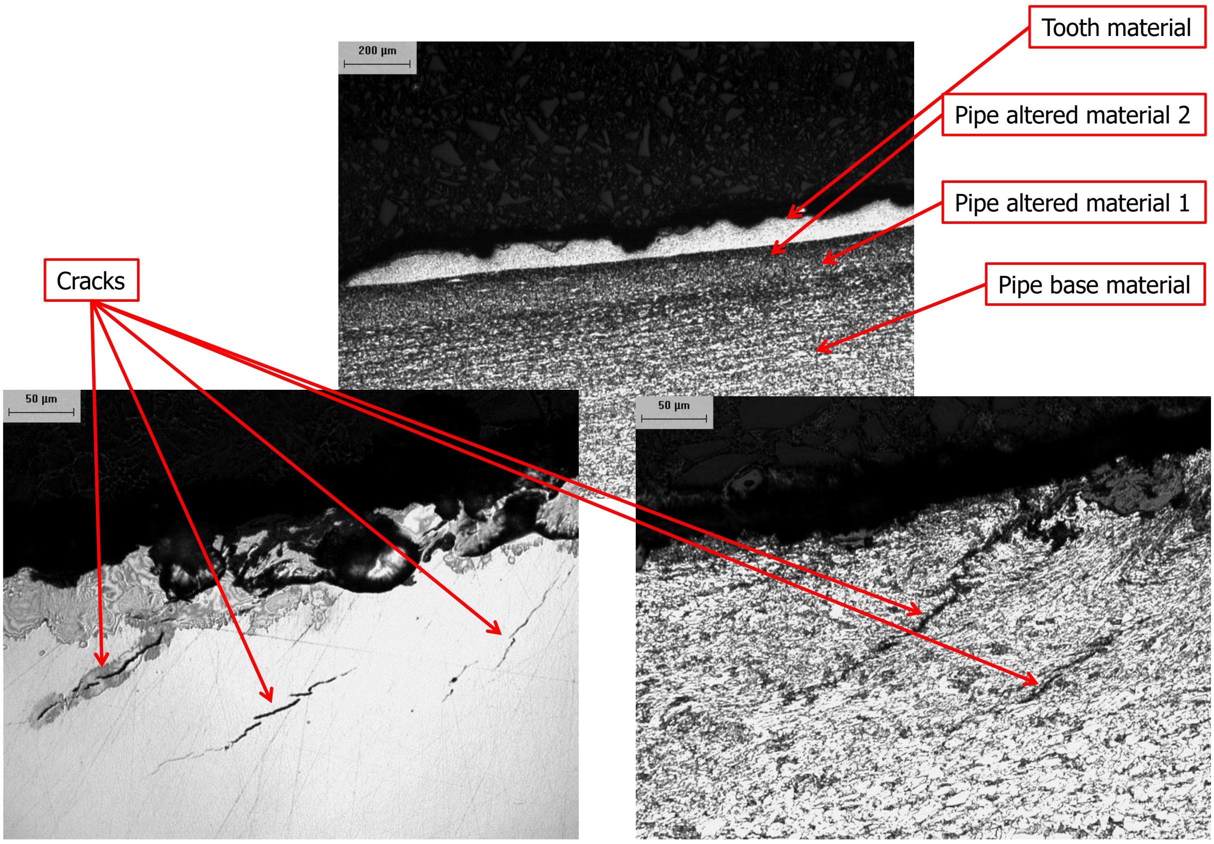


Figure 10: Cracks and pipe altered material in the gouge of damage BG2 from Pipe 1.

Figure 11: Crack in the gouge of damage G1 from Pipe 1.

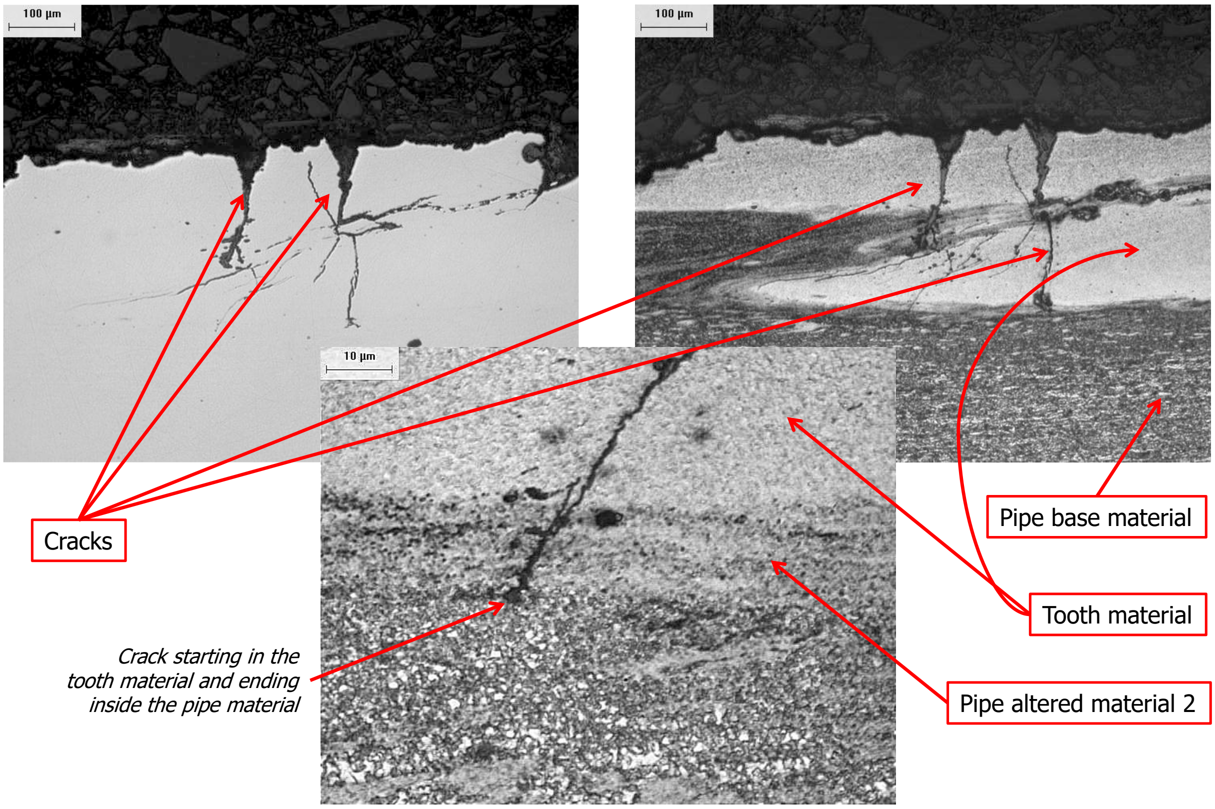


Figure 12: Cracks and pipe altered material in the gouge of damage G1 from Pipe 1.

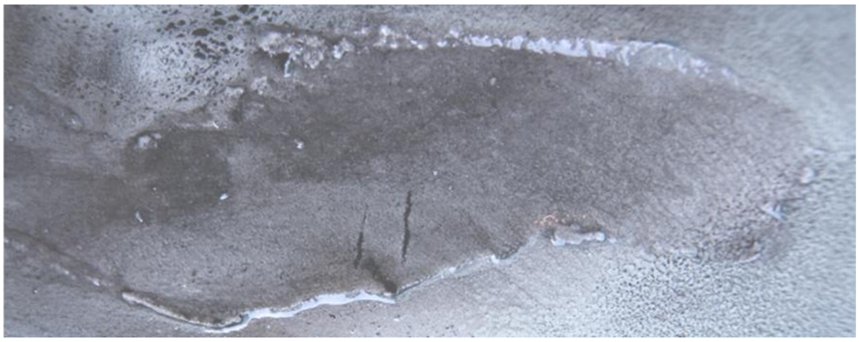


Figure 13: Crack in the print of damage BG3 from Pipe 1.

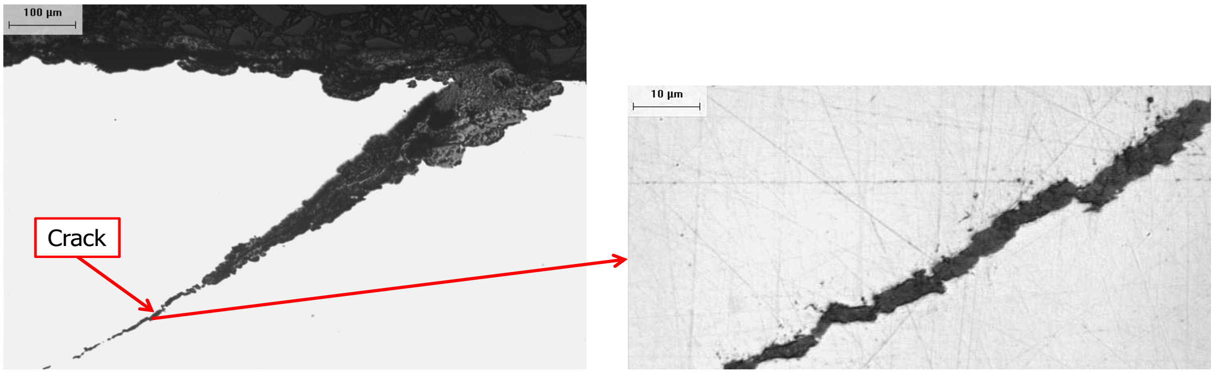


Figure 14: Cracks in the print of damage BG3 from Pipe 1.

Figure 15: Crack in the gouge of damage BG1 from Pipe 5.

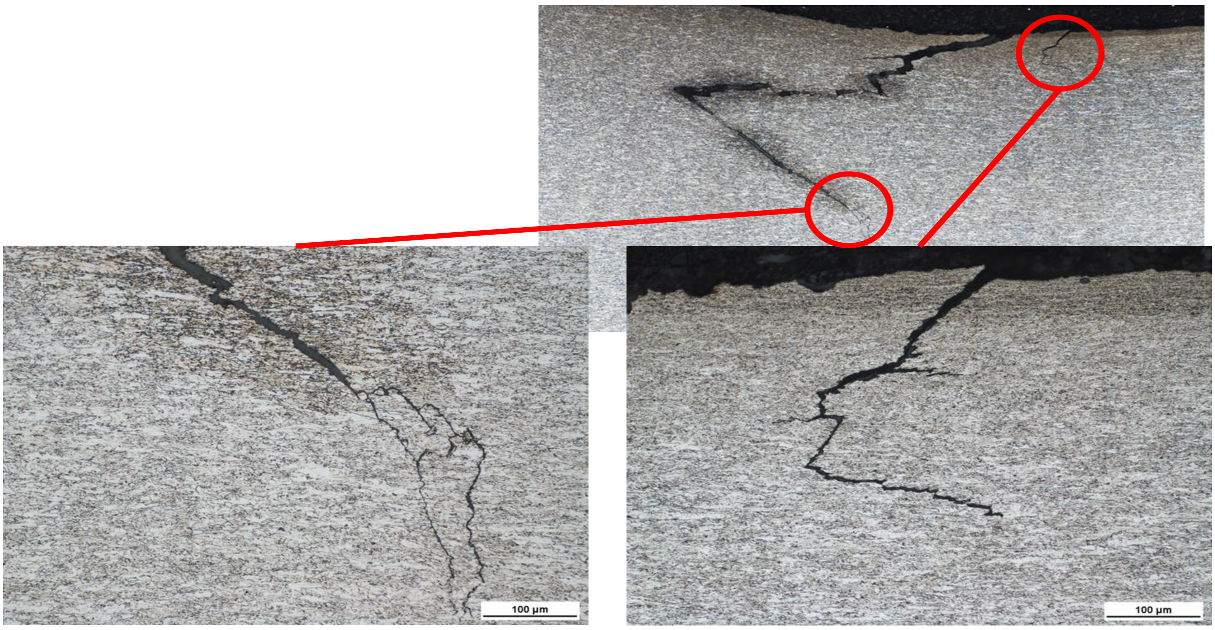


Figure 16: Cracks in the gouge of damage BG1 from Pipe 5.

Figure 17: Cracks at end of gouge of damage BG2 from Pipe 5.

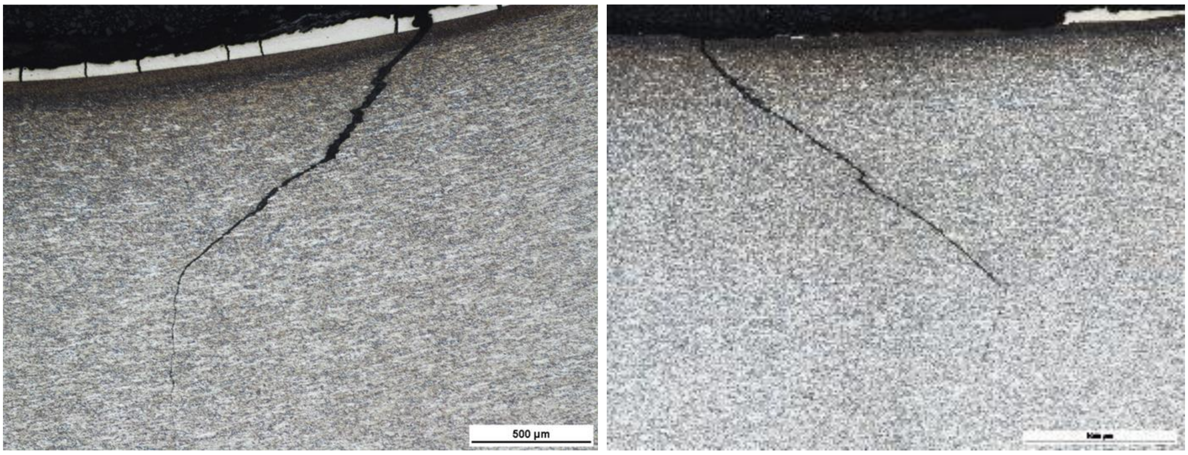


Figure 18: Cracks and pipe altered material at end of gouge of damage BG2 from Pipe 5.

Figure 19: Cracks at end of gouge of damage BG4 from Pipe 5.

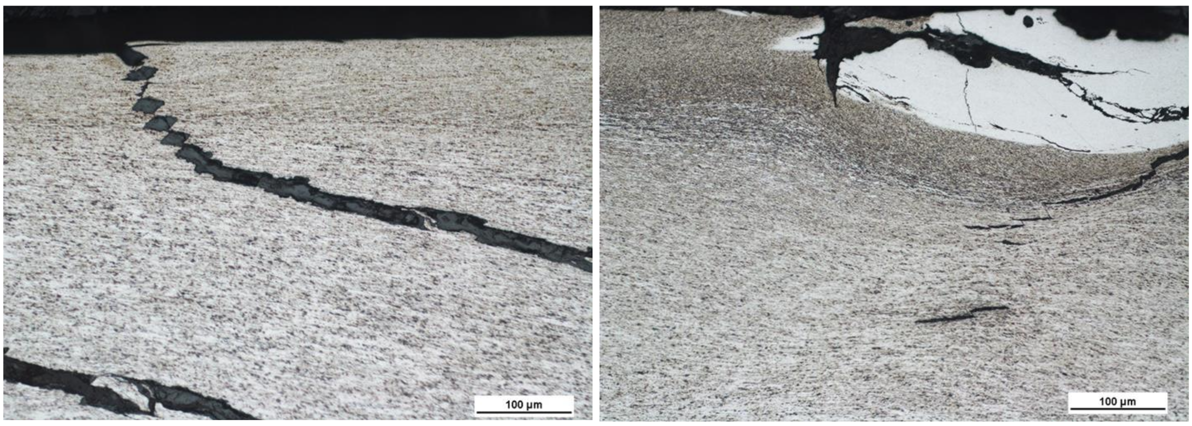


Figure 20: Cracks, pipe altered material and tooth material in the gouge of damage BG4 from Pipe 5.

Based on the number of damages with cracks, the applied potential and the cracks appearance, a statistic can be obtained (Table 13):

- 8 damages were tested at -850 mV vs $Cu/CuSO_4$. 2 revealed cracks at NDT inspection (25%) and, among them, 1 was confirmed at microstructural investigation (12,5%). None of the cracks in this damage is either brittle or branched or deeper than the pipe material hardened layer. Hence, no evidence of cathodic protection detrimental effect is visible;
- 4 damages were tested at -1150 mV vs $Cu/CuSO_4$. Among them, 4 revealed cracks at NDT inspection (100%), but none at microstructural analysis (0%). Hence, no evidence of cathodic protection detrimental effect is visible;
- 15 damages were tested at -1450 mV vs $Cu/CuSO_4$. Among them, 12 revealed cracks at NDT inspection (80%), all confirmed at microstructural analysis. Among them, 9 showed cracks either with sharp edges or branched (60%) and 6 were deeper than the pipe material hardened layer, showing effect of cathodic over protection at least on 40% of tested damages.

Hence, at least 40% of damages showed cracks attributable to hydrogen developed from cathodic over protection (-1450 mV), while at -850 mV and -1150 mV there was no evidence of such effect. Moreover, comparing the cracks depth from external surface, it is found that the depth of the cracks ranges from about 50 µm to about 2,25 mm, as a consequence, the highest estimated crack growth rate is approximately 0,31 µm/cycle.

Potential vs $Cu/CuSO_4$	mV	-850	-1150	-1450
Damages	Total number	8	4	15
NDT	Damages with cracks	2	4	12
	%	25	100	80
Microstructure	Damages with cracks	1	1	12
	%	12,5	25	80
	Brittle or branched cracks	0	0	9
	%	0	0	60
	Cracks deeper than hardened layer	0	0	6
	%	0	0	40

Table 13: Statistics on cracks.

Hardness measurements were performed for all damages that underwent microstructural analysis (Figure 21). Measurements have been performed both close to cracks and far from cracks, including tooth material and pipe hardened material. It is found that hardness of tooth material is quite higher, above 600 HV, than the pipe material. At the same time, the pipe hardened material extends to about 0,4 mm depth from external surface showing values up to 500 HV, higher than 300 HV average beyond 0,5 mm depth and 250 HV beyond 1,0 mm depth.

As a consequence, the cracks in Figure 18 extend from pipe surface with high hardness to about 2,0 mm depth, where hardness is lower and there is no evidence of microstructural alteration of pipe material. Such extension of the cracks in the pipe base material may be explained considering local embrittlement at the crack tip due to hydrogen developed by cathodic over protection at -1450 mV.

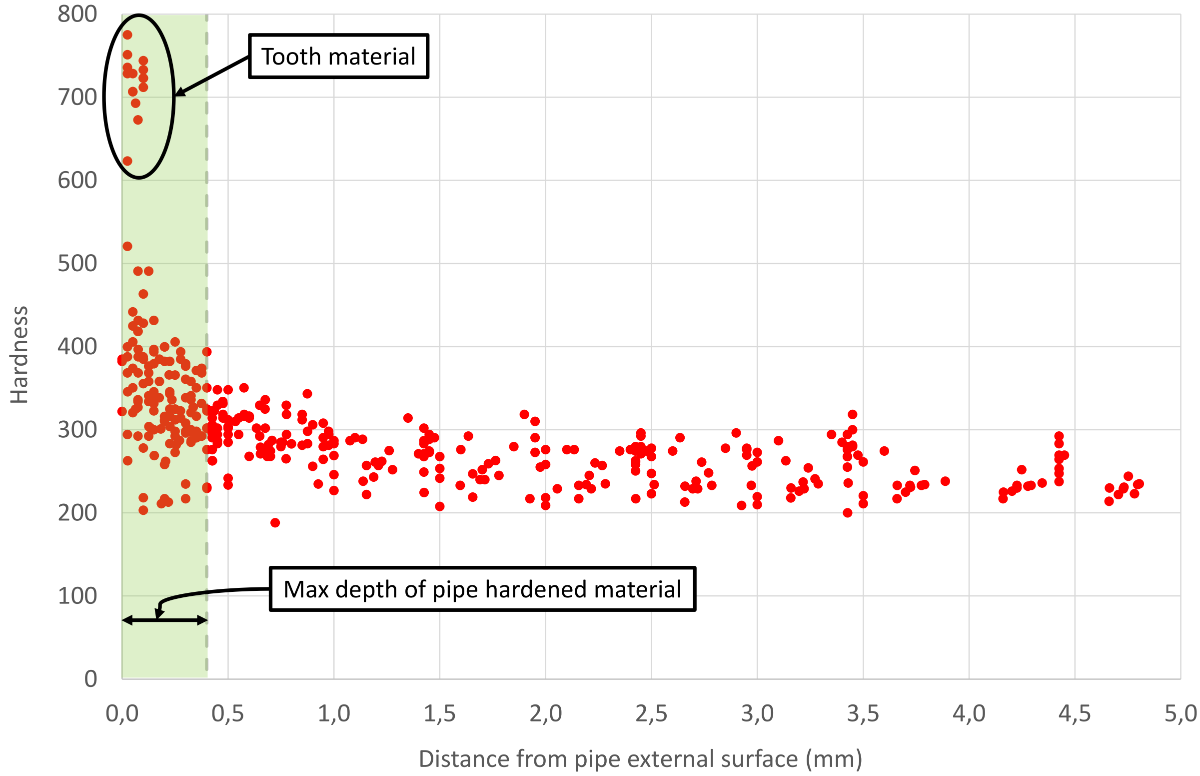


Figure 21: Hardness measurements.

7. CONCLUSIONS

Damages and environment full scale tests performed in these projects investigated a number of variables that may affect the behaviour of damaged pipes with cathodic protection. In particular, the effects of damage type (dent&goue or only gouge), tooth wear (new or worn), coating (with or without), cathodic protection potentials (-850 mV, -1150 mV and -1450 mV vs Cu/$CuSO_4$), environment (ground water and brackish water), pipe forming process (LSAW and HSAW) were investigated on 28 damages and 20 months full scale testing.
It arose that the most important variable that can affect the results of the analysis is the cathodic protection potential and then, during the development of the projects, attention was paid specifically to it, by focusing on one potential (-1450 mV) in the last project.
At the end of the three projects, main outcomes are:

- Cracks may be present since damage creation or initiate and develop at a later time, even in non-sour environment. Depending on the tooth geometry, excavator size and coating, cracks may have different geometry and size;
- In the cracks area (gouge in most of cases), the pipe material exhibits microstructural alteration and hardening, due to the strong heating caused by friction in the contact between impacting tooth and pipe external surface. The pipe altered material is quite harder than the base material (500 HV vs 200 – 300 HV in the base material) and the tooth material, sometime attached on the pipe external surface is even harder (above 600 HV);
- Coating (3 LPE) may act as a sort of lubricant between excavator tooth and pipe surface, so to reduce aggressivity of damages. In some cases, a thin layer of melted coating may still act as a protection of the damaged area and prevent crack formation. Nevertheless, in most cases of the present study, the coating was removed by the impacting tooth;
- Some cracks are branched, other have sharp edges, but in both cases with no plastic deformation. Such characteristics are attributable to the effect of hydrogen from cathodic over protection, especially if cracks grow deeper than the pipe hardened material;

- In general, cathodic over protection potentials (-1450 mV vs $Cu/CuSO_4$) cause higher number of cracks with respect to standard cathodic protection potentials (-850 mV and -1150 mV vs $Cu/CuSO_4$), where no evidence of cathodic protection detrimental effect was found;
- Cracks may grow with high R values (0,9) of pressure cycling, representative of gas pipelines;
- The deepest cracks detected range from 1,75 mm to about 2,25 mm (depth from pipe external surface), that is 10 - 12,5% of the pipe wall thickness, to be added to the thickness reduction due to the gouge. In such a case, the total depth is up to 3,85 mm, that is about 22% of the pipe wall thickness;
- Basing on the size of the deepest crack, the highest estimated crack growth rate is approximately 0,31 µm/cycle.

In conclusions, cracks on third party damaged pipes under cathodic protection may be found even when considering modern pipe, not high grade, compliant to ISO 3183. Such cracks start from the hard material on the pipe surface (tooth material or hardened pipe material), can initiate at the moment of damage creation or at a later time. Hence, in case of evidence of third party damage, the hardened material should be removed in order to prevent crack growth or initiation.
Furthermore, cracks grow or initiate especially at cathodic over protection potentials (-1450 mV vs $Cu/CuSO_4$), while at lower potentials (up to -1150 $Cu/CuSO_4$) there is no evidence of growth or initiation (potentials refer to local values in the crack zone).
When cathodic over protection is present locally on the damages area, the crack growth rate may reach 0,31 µm/cycle at the testing conditions applied (UF = 72% SMYS and R = 0,9, representative of gas pipelines service conditions), and the cracks may extend to 10 – 12% of the pipe wall thickness inside the pipe base material. As a consequence, the total depth, crack and gouge, may by more than 20% of the pipe wall thickness and potentially affect the pipe resistance to internal pressure.

8. REFERENCES

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