Investigations on Corrosion Behaviour of Welded Joint in ASTM A355P5 Alloy Steel Pipe

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In this paper an investigation on corrosion behaviour of welded joints was performed to facilitate determination the causes of preferential degradation by corrosion of the welded metal (WM) and the heat affected zone (HAZ), in a welded pipeline of grade ASTM A355P5, used in a petrochemical plant as transfer line between a thermal cracking heater and a column which are part of an atmospheric distillation and vacuum (DAV) unit. Mechanical testing, structural and chemical analyses were performed and a heat treatment procedure was applied to reduce the corrosion of WM and HAZ. Besides classical tests and analyses, electrochemical tests were performed in order to study the influence of heat treatment on the welded joints. Measurements were carried out at the open-circuit potential (OCP) on specimens immersed in 3% NaCl solution to observe the change of potential and qualitatively appreciate the dissolution and/or creation of a protective layer on the component surface. It was found that the corrosion of the weld analyzed in this research has resulted due to its dendritic structure (pearlite, ferrite, complex carbide, bainite and martensite in localized areas), which reveals the lack of post welding heat treatment (PWHT). A promising solution to this problem represents proper PWHT. The corrosion resistance of HAZ and WM increases after temperature treatment, as a result of the structure improvement as well as hardness reduction in the weld and adjacent areas.

Keywords: Corrosion, Pipeline, Petrochemical equipment, Structural Integrity, Failure

1. INTRODUCTION

Petrochemical equipment and systems are composed of complex components at which age, wear, and generally the uncertainty linked to their technical condition are the main issues facing their management system, considering new safety and environmental protection requirements.

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Iron and steel alloys are materials commonly used in manufacturing a series of industrial equipments including pipelines because they offer excellent weldability, fine mechanical properties *etc.*[1,2] The use of heat resistant chromium-molybdenum steels for manufacture of structures operating at higher temperatures (up to +475 °C) is caused by their low cost compared to the top performing steels. A335 is often called chrome-moly pipe because the chemical composition contains Molybdenum (Mo) and Chromium (Cr). Molybdenum adds strength, elastic limit and resistance to wear, impact properties, and hardness to steel, increases the resistance to softening, restrains grain growth and makes chromium steel less susceptible to embrittlement. It also enhances the high temperature creep strength, corrosion resistance and inhibits pitting of steel. As a result of the very high costs associated to their replacement with completely new construction, remaining life assessment and exploitation prolongation in safety condition of components, failure analysis and prevention [1], especially referring to those working in severe stress conditions (high temperatures and pressures, vibration, aggressive environment), are still the current topics of research in the present.

A key problem in the applications of these materials in the pipeline industry remains the corrosion of these materials in the presence of aggressive factors [3 - 7], because of the cost and technical difficulties in repairing the corroded parts [8]. Since, in some cases, indirect costs of corrosion were more or less equal to direct costs [2], corrosion is the most significant cost related technical challenge that provides strong motivation for researchers to understand and identify the corrosion mechanisms, predict the corrosion behaviour and find appropriate solutions for preventing and mitigation of corrosion effects on susceptible components. Corrosion of metals and alloys in aqueous environments or other ionically conducting liquids is mostly electrochemical type. It takes place when various electrochemical reactions occur on a metal surface. One of these reactions results in the change of the metal or some elements in the metal alloy from a metallic state into a non-metallic state. Corrosion products consist of solid or dissolved species. There are well-known different types of corrosion, including "Localized Corrosion", "Generalized Corrosion" and "Metallurgically Influenced Corrosion". The corrosion behaviour of metals and alloys and their associated mechanisms are influenced by the chemical composition, metallographic structure, mechanical characteristics, stress level and impurities.

Welding is a necessary and frequently used method for pipeline assembly. The microstructure and the mechanical properties of materials subjected to a welding process are modified and usually three evident zones can be highlighted [3, 4]. One is associated with the unchanged part of the welded joint with properties as the base metal (BM). An intermediary zone is represented by the base metal area affected by the generated heat due to the welding process, followed by a re-cooling process, known as the heat affected zone (HAZ). In HAZ, the microstructure and properties can be critically altered. The third zone is represented by the weld metal (WM). Microstructure of the WM is a specific moulding complex structure. Thus, WM is a dendritic structure that solidified from a molten state. Adjacent to the WM is the fusion line that makes the transition to HAZ. In multipass welding, the microstructure of these zones could be affected by thermal field produced due to successive weld passes. Thus, welding produces localized changes in the composition, structure, stress level and impurities in the joined metals and alloys and implicitly can also affect corrosion resistance. The corrosion products can form a layer capable to protect further the steel surface of the generated species through physically blocking the effect of corrosive attack [9, 10]. The corrosion of different steel grades and in different aggressive environments has been presented in [11-14]. Chloride is an excellent rust cause with a little moisture. The protective layer produced on the metal surface frequently fails in the presence of the chloride ions in different pH [1, 13, 14]. In sodium chloride solution the iron corrodes through dissolution into ferrous and ferric cations. Chloride ions after adsorption on the base metal surface penetrate the protective layer mainly at its point defects [13].

Metallurgical effects could affect the corrosion resistance of carbon steel weldments [15], thus preferential corrosion appear in HAZ or WM. Also, geometrical shape of the component, associated with stress concentration factor, play an important role on corrosion resistance behaviour. Usually, alloys with high hardness are most severely damaged by corrosion, while those that are overaged are fairly less susceptible [16]. Thus, in case of welded structures, the post weld heat treatments (PWHT) are beneficial since they control the hardness characteristics and the size and distribution of intergranular precipitates. Due to the exploitation condition and pollutants that could be found in the system, such as: hydrogen sulphide, gaseous hydrocarbons, carbon monoxide and carbon dioxide, High Temperature Hydrogen Attack (HTHA) and Stress Corrosion Cracking (SCC) phenomena [17,18] could affect the material of pipelines.

The goal of this paper is to study the corrosion nature of a pipeline which transports light products by mechanical, optical and electrochemical methods. The results indicate the importance of PWHT. An improper PWHT presents a direct negative impact on the operation safety of inspected components by increasing the risk of failure.

2. EXPERIMENTAL

2.1 Material and methods

The experimental study was performed on samples taken from the transfer line $\emptyset 508 \ge 15.09$ mm between the thermal cracking heater H1 and the column C1 of the DAV installation, which generates light products (gasoline, diesel or gas) by atmospheric and vacuum distillation of crude oil. A part of these pipeline welds were affected by preferential corrosion at the weld and HAZ. The pipeline is working under a temperature of 355 °C and pressure of 0.3 MPa and is made of feritic alloy-steel according to ASTM A355P5 - Standard Specification for Seamless Ferritic Alloy-Steel Pipe for High-Temperature Service. Two coupons were taken from the transfer line, each containing both a portion of pipe $\emptyset 508 \ge 15.09$ mm and a portion of the welded joint and a portion of an elbow 90R = 1.5D, $\emptyset 508 \ge 15.09$ mm, placed between the two welds, Figure 1.



a) Coupon containing a portion of the weld no.23b) Coupon containing a portion of the weld no.24 between elbow 90 R=1.5D, Ø508×15.09mm and between elbow 90 R=1.5D, Ø508×15.09mm and pipe Ø508×15.09mm pipe Ø508×15.09mm

Figure 1. Samples for the experimental program, taken from desalinate oil transfer line between the heater H1 and the column C1.

Filler materials used to create the welded joints were:

- Welding wire: CM5 -IG Boehler (WCrMo5Si), Ø2.40x1000 mm;
- Welding electrodes: Boehler Fox CM5-Kb (ECrMo5B42H5), Ø2.50x250 mm;

The welding process should have been realized with a PWHT.

An extensive experimental investigation has been carried out, including mechanical tests, macro and microstructural examinations, chemical and electrochemical analyses on the specimens extracted from the two coupons, according to the sampling plan presented in Figure 2.



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A 6		1	11 12			Λ 3
	T4		M1.2			Т
	T5			T8		T
	T6			T9		1
	1.4	 A	7			1
	1.5	Ā	9	T7		1
	1.6		M1.1	1		1

a) Coupon containing a portion of the weld no.23 between elbow 90 R=1.5D, Ø508×15.09mm and pipe Ø508×15.09mm



Figure 2. Sampling plan for the specimens.

The chemical composition of the pipe, according to ASTM A335 P5, is shown in Table 1.

Table 1. Chemical composition, ma	nanufacturer's data [%]	

Steel Grade	С	Mn	Р	S	Si	Cr	Mo
ASTM A335 Grade P5	Max. 0.15	0.30 - 0.60	Max. 0.025	Max. 0.025	Max. 0.50	4.00 - 6.00	0.45 - 0.65

The main reference mechanical properties of the material, according to ASTM A335 P5, are presented in Table 2.

Table 2. Mechanical properties (on the longitudinal direction)

		Tensile characteristics				
Steel Grade	Yield strength at +20°C R _{p0,2} [N/mm ²]	Tensile strength at +20°C R _m [N/mm ²]	Elongation at break at +20°C A ₅ [%]	Vickers [HV]		
ASTM A335 Grade P5	Min. 205	Min. 415	Min. 30	Max. 265		

2.2 Experimental setup

In order to evaluate the current mechanical and structural characteristics of the samples taken from the transfer line Ø508x15.09 mm, universal testing machine and optical microscopes were use such as: universal testing machine EDZ 40 and ZD10/90, Charpy pendulum PSW 30, hardness apparatus ZWICK 3212, stereo microscope MAK-MS, optical microscope MeF2.

Electrochemical tests were performed by using Autolab 302N EcoChemie after submerging the iron electrode for 1h in 3% NaCl solution. OCP measurements were carried out at the Open-Circuit Potential (OCP), the curves were recorded starting from the first moment of specimens sinking in a free saline aerated test solution to observe the potential behaviour and qualitatively appreciate the dissolution and/or creation of a protective film on the iron surface.

Potentiodynamic polarization testing allowed to calculate the corrosion parameters such as corrosion potential (Ecorr), corrosion current (Jcorr), polarization resistance (Rp) and corrosion rate (Rcorr) for specimens. The polarization curves were achieved by scanning the potential of iron from - 1200 to 200 mV at a scan rate of 1 mV/s. EW the equivalent weight in grams/equivalent of iron alloy ($E_W = 27.93$ grams/equivalent), d the density in g/cm³ (=7.86), and A the area of the exposed surface of the electrode in cm² (0.785 cm²). The polarization resistance, *Rp* (Ω), was achieved from the slope of the plots of the applied potential against the measured current and the corrosion current Icorr (A) is calculated using the Stern-Geary relationship with equation (1):

Icorr = $\beta_a x \beta_c / [Rp 2.3(\beta_a + \beta_c)]$ (1)

where: Tafel constants β_a and β_c represents the slope of the linear regions in V/decade of current.

3. RESULTS AND DISCUSSION

Gravimetric methods were used to determine the chemical composition of specimens extracted from the pipeline and welding zone. The specimen's notation and obtained results are given in Table 3.

The chemical composition of specimens was determined similarly to the reference specifications. By analyzing the chemical composition of the WM, it is noted that the WM is compatible with materials of pipes and elbows.

	Specimen		Mn	Cr	Mo	Ni	W	Ti	Cu	Bi
1	Base material pipeline	BM	0.38	4.80	0.45	-	0.61	-	0.08	0.33
2	Heat affected zone (elbow side)	HAZ _e	0.32	5.10	0.48	0.10	0.38	-	-	0.33
3	Welded metal	WM	0.47	5.13	0.52	0.10	-	0.37	-	0.10
4	Heat affected zone (pipe side)	HAZ _p	0.48	5.00	0.46	0.01	0.62	-	-	0.32

Table 3. Chemical composition of the main components of the specimens

The macroscopic analysis has revealed that the inner surface of the component is degraded by selective corrosion phenomenon localized to the welded joint and adjacent areas, Figure 3. The presence of active areas (areas with metallic gloss and colour change by corrosion products), and passivated areas (dark) has been found. It appears that degradation was initiated in the weld (Figure 3a) and has propagated to the BM of the two components. Also, in the BM, pitting degradation has been identified (Figure 3b).



a) Weld no.24 – WM and HAZ areas (detail)

b) Weld no.24 - HAZ and BM areas (detail)

Figure 3. Macroscopic images of WELD no. 24 (inner surface).

The elbow BM (Figure 4a) has a ferritic structure with punctiform complex carbides and non-metallic inclusions (oxides, silicates) with a grain size of 8-9. BM of the pipe (Figure 4b) has a ferritic structure with complex carbides with a grain size of 6-7.



a) BM - elbow



Figure 4. Microscopic images of pipeline's BM.

Evidenced structures are normal for these materials. The microstructures of HAZ and WM zones from pipeline before and after PWHT are presented in Figures 5a -f. It was observed that the structures before PWHT are not homogenous and presents rough seeds with a rather fibrous morphology (Figures 5a, 5c and 5d).

Optical micrographs of HAZ elbow and side show pearlite-ferrite structures with complex carbide and localized areas of bainite and martensite. The micrographs of weld sample show a dendritic structure (pearlite, ferrite, complex carbide, bainite and martensite in localized areas) and revealed in the ferrite part the presence of uniform polygonal ferrite seeds and the formation of some globular carbide particles between the ferrite seeds. This could be connected with precipitation of chromium carbide during the thermal treatment and be a source of inter-granular corrosion. Because the Cr content in the sample was the same as in BM, the corrosion is rather a result of the lack of PWHT (or improper realization on site at the elbow replacement).



a) HAZ_e- elbow side



b) HAZ_e – elbow side (after PWHT)



Figure 5. Influence of PWHT at the microstructural level. The indices "e" and "p" signify the elbow or pipe

Very high (unaccepted) values of hardness in the WM and HAZ_e were measured, a maximum of 405HV10 in WM and 397HV10 in HAZ_e has been determined. The material brittleness depends on the martensite quantity, thus an optimum quantity is required because too much martensite makes the material brittle and too little yields a soft material.

These measured values are over two times higher than the highest value of BM (199HV10) and the increase of hardness is a result of the increase of martensite content over the optimum quantity, due to the welding process. This demonstrates that in this circumstance the welding induced a sharp local stress state. The local hardening estimator calculated with equation (2) demonstrates that, at the boundary, the conditions are met for brittle fracture of the joint (Δ HV10> 50%).

$$\Delta HV10 = \frac{HV10_{\text{max}} - HV10_{\text{min}}}{HV10_{\text{max}}} \cdot 100 = \frac{405 - 199}{405} \cdot 100 = 50.9 \%$$
(2)

By varying heat treatment, improvement in the hardness of the specimens can be attained, mainly depending upon the amount of martensite in the structure.

In order to emphasize the influence of a correctly carried out PWHT, the sample was subjected to heat treatment by heating up to + 725 °C with 60 minutes holding and controlled cooling at a rate of 100 °C/h up to 300 °C, followed by a free cooling in air (Figure 6). After the PWHT more homogenous structures than those before heat treatment have been observed, with an island distribution of martensite in a ferrite matrix (Figure 5f). The HAZ_e and HAZ_p of the elbow and pipe side present a pearlite-ferritic structure, with sorbite areas, and the WM a fine dendritic structure (pearlite, ferrite and sorbite).



Figure 6. Schematic illustration of the PWHT cycle.

By applying of PWHT, the maximum hardness of the WM was reduced up to 268HV10 and in HAZ_p up to 266 HV10 and the maximum value determined for BM was 192HV10. In this case, the local hardening estimator (relative to the BM) is (3):

 $\Delta HV10 = \frac{268 - 192}{268} \cdot 100 = 28.4\% (3)$

It is noted that the local tension induced by welding and the likelihood of brittle fracture has been considerably reduced. The results of the local hardening estimator are correlated with the values obtained by notch impact tests, as follows:

• Although for this material the notch impact characteristics are not guaranteed, at the notch impact tests carried out it appears that the BM of the pipe and the elbow has a very good toughness property, the fracture energy being 278-294 J for BM of pipes and 277-292 J for BM of elbows.

• Unlike the BM, in case of WM and HAZ_e , toughness characteristics have been drastically reduced, to 80 - 228 J for HAZ and only 19 - 39 J for WM. This demonstrates that the WM is fragile.

The changes of morphologies and mechanical properties induced by welding and heat treatment are reflected in the electrochemical behaviour of the specimens. Corrosion measurements can be used in evaluation of the quality of welding and to appreciate if the weld material and welding process guarantee a service without failures. The variation of OCP potential in time for the specimens immersed in 3% NaCl solution are presented in Figure 7.

The potential of pipelines specimens in chloride solution are shifted toward the negative direction in the first minutes of iron immersion. The potential shift is due to the dissolution of iron as aggressive chloride ions attack the surface. In time the corrosion products formed a layer on the surface and partially protected the iron from further attack.



Figure 7. OCP curves for specimens recorded in 3.0% NaCl solution.

As a consequence, in time the slight shift in the potential towards the less negative values appears. It was observed that the WM specimen showed a rapid negative shift in the first few minutes and the highest shifts of the potential toward the negative value comparatively with the BM, HAZ_e and HAZ_p specimens. This means that WM is more prone to chloride attach, due to modification of structure of the surface. Figure 8 shows Tafel polarization curves for pipeline specimens BM, WM, HAZ_e , and HAZ_p after 90 min immersion in 3.0 wt % NaCl solutions.



Figure 8. Polarization curves for pipeline samples BM, WM, HAZ_e and HAZ_p after 90 min immersion in 3.0 wt % NaCl solutions.

Parameters obtained from polarization curves presented in Figure 8 are shown in Table 4.

Sample	Jcorr, A/cm ²	βc, V	βa, V	Rp, Ohm,	Ecorr, Ohm	Rcorr. mm/year
BM	1.654x10 ⁻⁶	0.076	0.126	3.208×10^3	-0.860	0.019
WM	2.638×10^{-5}	0.163	0.074	$2.534 \text{x} 10^2$	-0.523	0.307
HAZ _p	9.571x10 ⁻⁷	0.094	0.101	5.462×10^3	-0.751	0.011
HAZ _e	1.676x10 ⁻⁵	0.127	0.082	3.421×10^2	-0.810	0.195

Table 4. Electrochemical parameters for pipeline samples BM, WM, HAZ_e, and HAZ_p after 90 min immersion in 3.0 wt % NaCl solutions at 25 °C.

The values obtained for Ecorr and Jcorr indicate their dependence on the structural modification appeared due to the welding process. Post heat treatment improves mechanical properties but could decrease the corrosion resistance. It is reported for low carbon steel that iced-water reduce procedure generates a fine grained recrystallized structure and enhances the mechanical properties and on the other hand, corrosion resistance decreases [19]. All specimens present a pearlite-ferrite structure and the dissimilarity is a result of the difference in the microstructure (different spacing of the cementite lamellae-ferrite, content and size of ferritic phase). The corrosion potentials determined for BM, HAZ_p , WM are more appropriate to -0.860V (to base material), except the HAZ_e specimen which present a nobler corrosion potential of -0.523 V. The nobler corrosion potential value obtained for WM suggests that this zone is more prone to cover with a protective layer, comparatively with BM, HAZ_p and HAZ_e specimens due to the formation of martensitic phase. It is reported that due to the carbon content martensitic phase frequently shift the corrosion potential to a nobler value than the ferritic matrix [14, 20, 22]. Higher hardness obtained for WM and HAZ_e specimens is also a consequence of the formation of a martensite region. The presence of martensite in steel reduces the corrosion resistance as was observed for WM and HAZ_e specimens. The Jcorr determined from Tafel slope show higher corrosion current density for WM specimens and HAZe and lower corrosion current density HAZ_p and BM. The welding induced in the specimens WM and HAZ_e appropriate conditions to brittle fracture of the joint and is the reason for the higher Jcorr value obtained for these specimens. The WM shows a dendritic structure (pearlite, ferrite, complex carbide, bainite and martensite in localized areas) capable in an easier manner to incite an increase of the corrosion current density. The increase of corrosion current density is 16 times higher comparatively with BM. The pearlite-ferrite structure with complex carbide and localized areas of bainite and martensite observed for HAZe structure show a corrosion current 10 times higher comparatively with BM. Also, in case of WM and HAZe the obtained higher corrosion currents and reduced toughness characteristics are the result of residual stress appeared due to martensite transformation (less homogeneous microstructure); and due to the fine needles or lamellas interconnection path between the martensite and ferrite phases (active corrosion area). This significantly affects the ratio between the nobler and active phases responsible for corrosion. Similar observation was reported in the literature [14]. The cathodic β_c constant for BM,

 HAZ_p are 0.076 and 0.094V/decade. HAZ_e and WM specimens present higher values and this is a result in variable degradation due to breakdown of the passivating film, behaviour characteristic for alloy materials indicating differential Redox reactions. For HAZ_e and WM the cathodic Tafel slopes (β_c) are found to be greater than those anodic Tafel slopes (β_a) and indicate an overall kinetics under cathodic control due to the increased currents on values of anodic part.

After PWHT, the HAZ_p specimen shows reduced local stress state and this is reflected in the value for Ecorr and Jcorr due to increasing in homogeneity of structure. In result, a decrease of Jcorr of HAZ_p with about 17 times lower comparatively with HAZ_e was obtained. Low value for corrosion rate Rcorr are found for HAZ_p and BM specimens.

The microstructural differences are revealing in the EIS spectra. EIS tests were performed in a 3% NaCl solution at 25 °C. Impedance spectra were illustrated in both complex impedance diagrams (Nyquist plot), and Bode amplitude and phase angle plots. In the Nyquist graph (Figure 9a), the imaginary component of the impedance is represented as a function of the real component, whereas the Bode plots (Figure 9b) illustrates the logarithm of the impedance modulus |Z| and phase angle as a function of the frequency f logarithm.



Figure 9. a) Complex Nyquist plane plots and b) Bode plots for the studied specimens.

Electrochemical parameters were extracted using an electric equivalent circuit (EEC) shown in Figure 10.



Figure 10. Schematic representation of the equivalent electric circuit.

The EEC was chosen to fit the data, it included an electrolyte resistance – Rs which is approximately constant in all determinations, the polarization resistance - Rp of the film formed on each specimen surface which represents the coating film resistance as a result of formation of a oxide layer and/or corrosion products and corresponds to the corrosion resistance and Q represents the capacitance of the film. Impedance parameters obtained from fitting the impedance data were shown in Table 5.

			Rs	Q-T	Q-P,	Rp
Specimen	Chi-Sqr	Sum-Sqr	$\Omega.cm^2$	$F/cm^2/s\phi^{-1}$	(ф)	$\Omega.cm^2$
BM	2.76E-03	9.755	9.755	1.97E-03	0.631	1696
WM	1.35E-02	9.706	9.706	4.11E-03	0.630	324.3
HAZe	4.37E-03	4.603	4.603	1.17E-02	0.600	1276
HAZ _p	7.94E-03	6.034	6.034	2.88E-03	0.490	6882

Table 5. Values of the electric circuit elements for the studied specimens.

The Q values are correlated with the local dielectric constant and/or thickness of the electrical double layer variation. The capacitance value could decrease due to an increase of protective layer thickness or to decrease in dielectric constant of protective layer. Higher Q values are obtained for HAZ_e and WM specimens and indicate a decrease in thickness of the protective layer.

An increase for the parameter Q-T and a decrease for Rp value the case of HAZ_e and WM pointed out a passive layer with more defects or less thickness. The values of Rp and Q-T for the HAZ_p suggest a thicker surface or with enhanced density with fewer defects.

The results reveal that the Rp value also depends on the microstructural patterns. The Rp is affected by the thickness and composition of the passive layer formed on surfaces and affect their corrosion resistance. Electrochemical parameters indicate that, the WM presents lower Rp value. The Rp value of WM pointed to the formation of a passive layer with more defects or less thickness than the BM, due to the microstructural changes produced by the thermal flux introduced into the welding area (unproper PWHT). The microstructural change could be associated with the apearance of martensitic phase, and the martensitic transformation is possible to be less uniform in the whole part (Figure 5a, c and d). Similar observation was reported for austenitic stainless steel deformation induced α ' martensitic transformation arises by plastic deformation, which does not occur in the whole part [21, 22]. By changing the PWHT an increase by 5.4 times in the Rp was achieved as can be seen for HAZ_p comparatively with BM and HAZ_e specimens, pointing out an increase tendency to cover with a protective oxide film, due to the formation of martensitic phase in an optimum quantity and grain size. These results confirm that the proper PWHT leads to a high resistance to the weld-decay. The results of potentiodynamic polarization further support the results of electrochemical impedance spectroscopy and also indicate that the proper PWHT determines a proper corrosion resistance of the welded material.

4. CONCLUSIONS

The paper present the importance of convergence of the mechanical testing results with those of microstructural analysis, chemical and electrochemical evaluation, to achieve relevant information on corrosion behaviour of welded joints, which could lead to the cause of pipeline failures, related to the actual material degradation condition and technological process parameters: temperature, loading conditions and working environment.

It is demonstrates that hardened steel (consisting of ferrite and martensite and carbides) corrode much faster than a material in a state of balance (normalized). The results of the performed experimental program lead to the conclusion that preferential corrosion of pipeline at the WM and the HAZ was possible due to the metallurgical effect and the stress concentration in the adjacent area of the weld, due to the presence in the fluid of corrosive compounds, under normal operating conditions of the system at elevated temperatures. The metallurgical effect refers to the significant alteration of the corrosion rate of the intrinsic material, due to the microstructural changes produced by the thermal flux introduced into the welding area (inappropriate linear energy using, high cooling rate, the absence of a PWHT, or incorrect PWHT performed).

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