Slow strain rate corrosion of multiple repairs of girth welds in line pipes

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The susceptibility to stress corrosion cracking (SCC) in girth welds of seamless API X52 steel pipe containing multiple shielded metal arc welding (SMAW) repairs and one as-welded condition were evaluated using slow strain rate tests (SSRT) according to NACE TM-0198 standard. The SSRT were performed in air and NS4 solution at pH=10 (basic) and pH=3 (acid) at room temperature and at constant elongation rate of 25.4×10^{-6} mm s^{-1}. Cylindrical tensile specimens were transversal machined to the direction of the application to the girth weld. The SCC susceptibility was expressed in function of the reduction in area ratio (RAR) and elongation ratio (ER). The yield strength, tensile strength and ductility of the welded joints shown a decrease when they are exposed to the NS4 solution. The tests carried out at pH=10 show a greater aggressiveness. No indication of lateral corrosion and secondary cracking was observed. The metallographic observations of the fractured specimens show that the most susceptibility area to SCC was the base metal/heat affected zone interface (HAZ).

Keywords: stress corrosion cracking (SCC); slow strain rate tests (SSRT); shielded metal arc welding (SMAW); API X-52 steel.

En este trabajo se evaluó la susceptibilidad al agrietamiento por corrosión y esfuerzo (SCC) en uniones soldadas de un ducto de acero API X-52 con múltiples reparaciones por la técnica de soldadura de arco protegido (SMAW), empleando pruebas de tensión a velocidad de deformación lenta (SSRT) de acuerdo a la norma NACE TM-0198. Las pruebas SSRT fueron realizadas en aire y en una solución NS4 con pH-3 y pH-10 a temperatura ambiente y una velocidad de deformación constante de 25.4×10^{-6} mm s^{-1}. Se emplearon especimenes de forma cilíndrica maquinados de forma transversal a la dirección de aplicación del cordón de soldadura. La susceptibilidad al SCC fue evaluada en función de la relación de reducción de área (RAR) y la relación de elongación (ER). El esfuerzo de cedencia, resistencia máxima y ductilidad de las uniones soldadas disminuyen cuando son expuestas a la solución NS4. Las probetas expuestas en la solución con pH-10 mostraron mayor agresividad. No se observaron indicaciones de corrosión lateral ni grietas secundarias. Las observaciones metalográficas de las fracturas muestran que el área mas susceptible al SCC fue la interfase metal/zona afectada por el calor (ZAC).

Descriptores: agrietamiento por corrosión bajo esfuerzo (SCC); pruebas de tensión a velocidad de deformación lenta (SSRT); soldadura por arco metálico protegido (SMAW); acero API X-52.

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1. Introduction

The SCC phenomena have been studied extensively in last 20 years by Canada and USA mainly. Results of these investigations classify the SCC in two types: High pH SCC and near-neutral pH SCC [1-4]. Although the majority of SCC occurs on the body of a pipe, cracking also have a high tendency to occur adjacent to the weld beads. There are some reasons for the occurrence of SCC near to the weld bead; the first is due to the residual stresses in that area and the highly susceptible microstructure in the heat affected zone.

SCC may be associated with intergranular (IGSCC) or transgranular (TGSCC) paths through the metal and in some case with a mixture of both modes [5-7]. High pH SCC generally produces intergranular cracking and occurs only in a relative narrow cathodic potential range and at pH greater than 9. For near neutral pH SCC the fracture is generally transgranular with pH from 6 to 8 [1,2,8,9]. The cracks in both types of fracture occur usually in the outside surface of the pipeline in colonies oriented longitudinally. Mechanism of SCC has been studied for many years; even though continue widely discussed. Most of them suggest a process

TABLE I. Chemical composition of the API X-52 steel (wt%).

C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Al	V	Ti	N
0.09	0.89	0.30	0.006	0.0015	0.12	0.07	0.05	0.05	0.025	0.036	0.016	0.0045

of localized embrittlement of the metal in the vicinity of the crack tip or localized dissolution in that region. It is possible that with some environments both dissolution and hydrogen ingress may facilitate crack growth.

Most of the studies about SCC have been performed using the slow strain rate tests (SSRT), these have been used the last 30 years for evaluation of the environmentally cracking using uniaxially loaded tensile specimens [10-13], due to SSRT offer a rapid method to screening materials for specific applications [14-15].

The experimental research about SCC in pipelines considering the external environment have been studied using solutions NS4 [7-9,16-18], this as results of investigations about the chemical composition of the solution on the surface of the pipeline failed by SCC. The main goal using NS4 solution is to simulate the chemical composition of the soil. Some other solutions have been used in minor grade like NOVA solution [19], sodium nitrate solution ($NaNO_2$) [20], bicarbonate-carbonate solution (HCO_3-CO_3) [21-23], NaOH [24], etc. The great majority of these studies were made in the base metal of pipeline steels; there are few studies on the longitudinal and circumferential welding but none reported in function of the number of repairs.

The objective of the present work was to study the effect of NS4 solution on the circumferential weldments of X-52 pipeline steel, a room temperature and different pH's in order to assess the susceptibility to stress corrosion cracking.

2. Experimental procedure

A seamless API X-52 steel pipe was used in this work. The dimensions of the test pipe were 219.10 mm in diameter and 11.10 mm of nominal wall thickness. The chemical composition is shown in Table I. Girth welds were obtained from the quality control department of the company Construcciones Maritimas Mexicanas (CMM-PROTEXA), under a qualified welding procedure according to API 1104 standard [25], us-

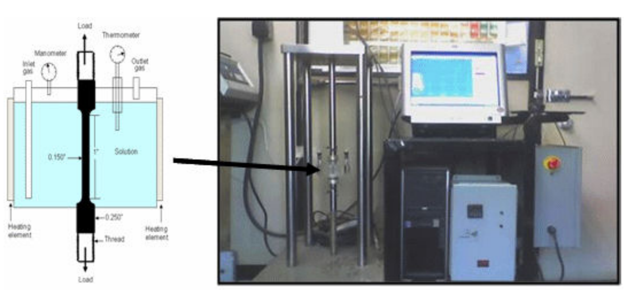

FIGURE 1. Experimental set up used to perform the SSRT.

TABLE II. Chemical composition of the NS4 solution (gr/L).

KCl	**$NaHCO_3$**	**$CaCl_2.2H_2O$**	**$MgSO_4.7H_2O$**
0.122	0.483	0.181	0.131

ing the SMAW process with a consumable electrode E-6010 of 3.1 mm for the root and hot pass and 4.7 mm E-7010G electrode for the subsequent weld beads. The heat input was estimated in the interval of l.2 to 1.5 kJ/mm.

The as-welded material was repaired using arc-air to remove the weld, and using the same SMAW procedure to reweld. In order to simulate multiple weld repairs, the welds were removed similarly and re-weld, in order to obtain second, third and fourth weld repairs. The specimens according to the number of repairs were identified as 0R (as-welded), 1R, 2R, 3R, and 4R, respectively. The repair was made on the whole circumference of the pipe specimen. X-ray inspection was used to verify the quality of the welds after each weld repair according to the requirements of API-1104 standard.

The SSRT were performed in an Intercorr machine type M-Cert with load capacity of 44 KN and total extension of 50 mm. The test vessel was an autoclave of glass with capacity of 0.5 liters and solution volume to specimen surface area > 30 ml cm^{-2} as is shown in Fig. 1.

The tests were carried out at room temperature in air and in a NS4 solution to a constant extension rate of 25.4×10^{-6} mm s^{-1}. The chemical composition of the NS4 solution is shown in Table II. Several tests were carried out for each one of the welding repair conditions, for both, in air and in NS4 solution. Round bar tensile specimens of 3.81 mm of diameter and 25.4 mm of length of gauged section were machined transversely to the direction of application to the girth weld.

The SSC susceptibility was expressed in function of the reduction in area ratio (RAR) and elongation ratio (ER) calculated by the following expressions according to the NACE TM0198 standard [10].

$$RA(\%) = \frac{\left(D_i^2 - D_f^2\right)}{D_i^2} \times 100 \qquad (1)$$

RA is the reduction in area; D_f and D_i are the final and initial diameters of the tensile specimen respectively. The reduction in area ratio after fracture in the test environment (RA_E) to the corresponding value in the control environment (RA_A) was calculated according to the following expression:

$$RAR(\%) = \left(\frac{RA_E}{RA_A}\right) \times 100 \qquad (2)$$

TABLE III. Assessment of the susceptibility to SCC obtained from the SSR tests.

Condition	Environment	YS (MPa)	UTS (MPa)	RA (%)	E_P (%)	RAR	ER
BM	Air	386.1	475.2	89.10	23.26		
0 rep		356.0	437.5	85.74	15.00		
1° rep		379.9	464.2	88.10	16.18		
2° rep		384.1	456.2	88.53	16.69		
3° rep		359.7	427.4	84.60	14.37		
4° rep		379.2	455.9	86.34	15.51		
BM	NS4, pH=3	396.8	464.8	88.13	19.72	0.98	0.84
0 rep		325.9	423.0	84.10	14.17	0.98	0.94
1° rep		322.5	427.5	86.84	15.47	0.98	0.95
2° rep		351.8	438.2	86.90	16.69	0.98	1.00
3° rep		318.1	354.9	83.91	13.78	0.99	0.95
4° rep		329.7	428.8	85.01	15.00	0.98	0.96
BM	NS4, pH=10	357.0	467.7	87.62	18.34	0.98	0.78
0 rep		316.0	428.4	83.16	14.98	0.96	0.99
1° rep		324.9	446.3	86.86	15.51	0.98	0.95
2° rep		340.6	415.2	86.88	16.22	0.98	0.97
3° rep		344.6	436.8	82.30	12.99	0.97	0.90
4° rep		318.0	412.1	86.10	14.60	0.99	0.94

The plastic elongation (E_p) is defined as the elongation from the proportional limit on the curve (point of deviation from linear behavior) up to failure. If a load versus elongation curve is used, E_p shall be calculated using:

$$E_P(\%) = \frac{(E_F - E_{PL})}{L_I} \times 100 \qquad (3)$$

E_F and E_{PL} are the elongation at failure and elongation at proportional limit respectively and L_I is the initial gauge length (usually 25.4 mm). The elongation ratio was calculated using:

$$ER(\%) = \left(\frac{E_E}{E_A}\right) \times 100 \qquad (4)$$

E_A is the elongation in air and E_E is the elongation in the test environment.

After failure, the fracture surfaces were observed in a JEOL-6300 scanning electron microscope in order to determine the type of fracture. In addition, the specimens were longitudinally cut and polished and subsequently etched with nital at 2% to reveal the microstructure and failure zone, as well as to observe the presence of secondary crack in the gauge section.

3. Results and Discussion

3.1. Microstructural Characterization

Figures 2a to 2e shows optical micrographs of cross sections for the different welding repair conditions. These micrographs show typically three different zones: base metal (BM), weld metal (WM) and heat affected zone (HAZ). The microstructure of the weld is ferritic-bainitic. The HAZ microstructure shows grains of polygonal ferrite with pearlite in the acicular ferrite. The characterization of the microstructure in the HAZ for each weld repair condition does not reveal significant changes. It was observed a tendency to increasing the number of weld repairs promotes grain growth in the coarse grained heat affected zone (CGHAZ). The microstructure as well as the mechanical properties obtained for the different weld repair condition were shown elsewhere [26].

3.2. Slow Strain Rate Tests

Stress vs. Strain profiles obtained from the SSRT tests performed in air and in the NS4 solution both at room temperature for the different welding repair conditions are shown in Fig. 3. Results of reduction in area (RA), plastic elongation (E_P), reduction in area ratio (RAR) and elongation ratio (ER) are shown in Table III. The reduction in area ratio after fracture was calculated using Eq. (2). Ratios in the range of 0.8-1.0 normally denote high resistance to EAC, whereas low values (*i.e.* <0.5) show high susceptibility. The specimens tested in air showed the maximum %RA. Base metal (BM) presented the maximum strain for SSRT carried out in air and in NS4 solution in comparison with the four weldments. Specimens tested in air showed a strain about 16-19% meanwhile the specimens tested in NS4 showed a strain between 14-19% with pH=3 y pH=10 respectively.

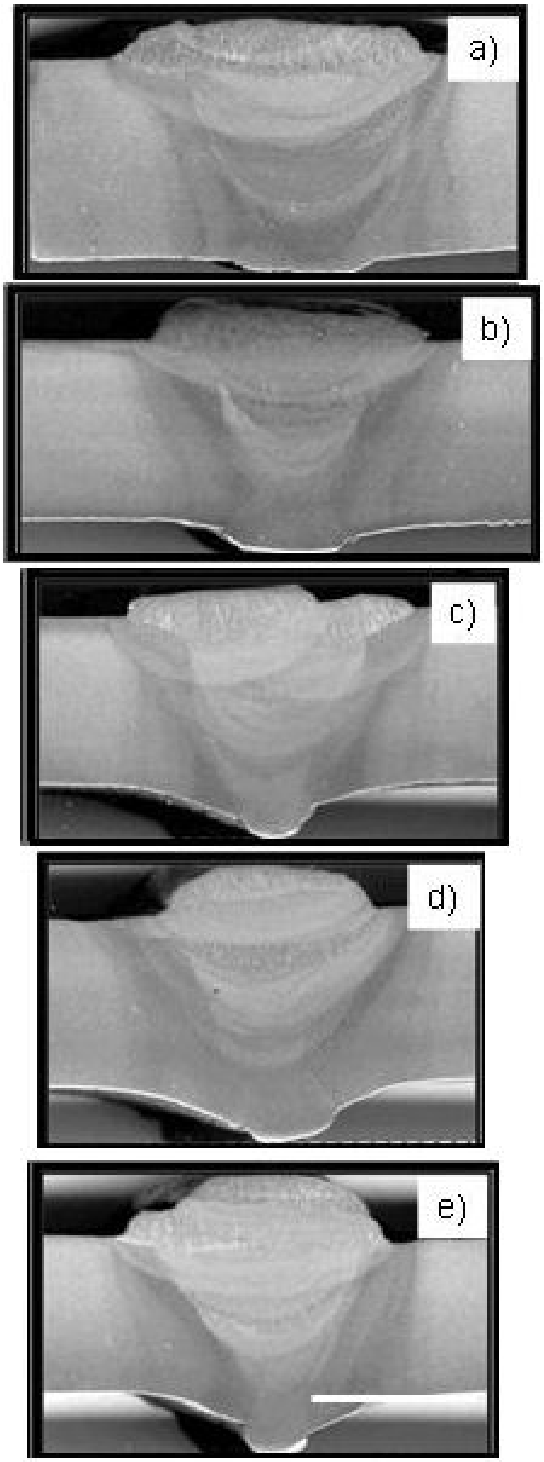

FIGURE 2. Optical micrographs of cross-sections for different welding repair conditions. a) as welded; b) first repair; c) second repair; d) third repair; e) fourth repair.

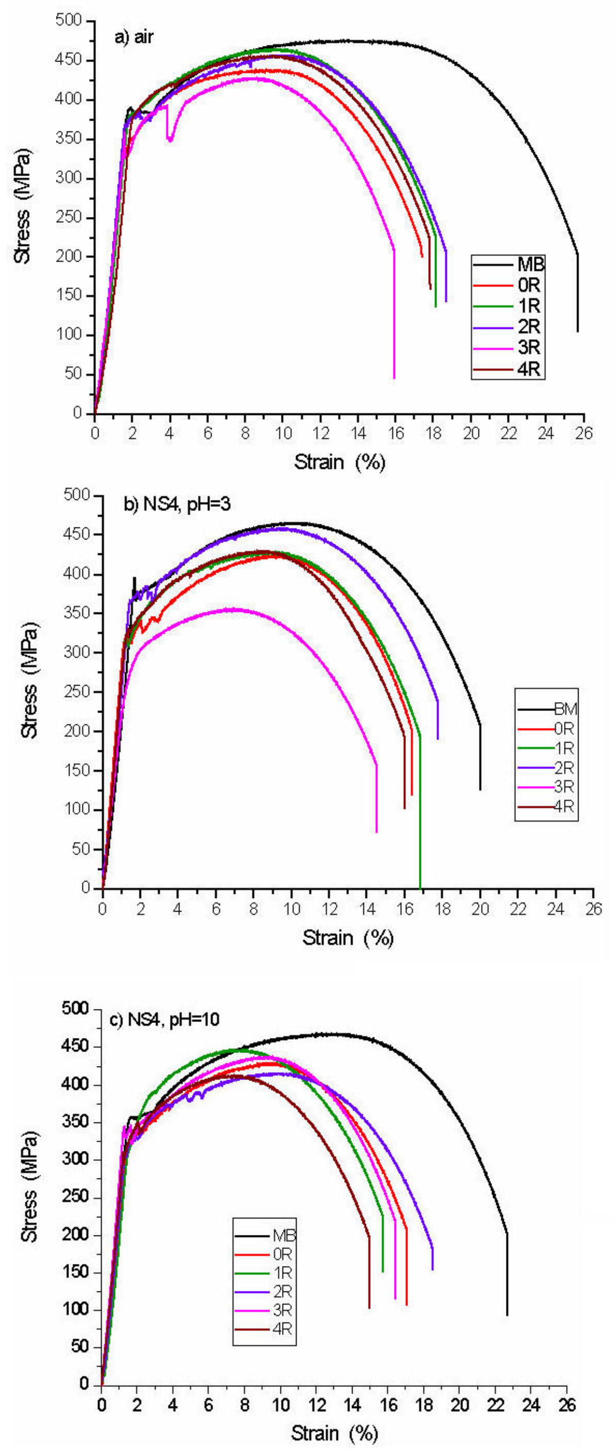

FIGURE 3. Stress versus strain profiles obtained from the SSRT in function of pH and number of repairs.

The strength, elongation and reduction in area decreases slightly when the samples are exposed to the NS4 solution. According to these results, it is clear that the specimens tested in the NS4 solution does not exhibited susceptibility to SCC. In addition, secondary cracks or corrosion were not observed in the specimens after made the SSR tests.

The material susceptibility to SCC depends of many factors such as elemental composition, metallurgical factors, corrosive environment, pH, temperature and electrochemical potential. Therefore for a given material, there may be necessary to investigate the effect alone of each one of these parameters on their SSC susceptibility [9,16,24]. Passive film rupture, anodic dissolution and repassivation are the genera-

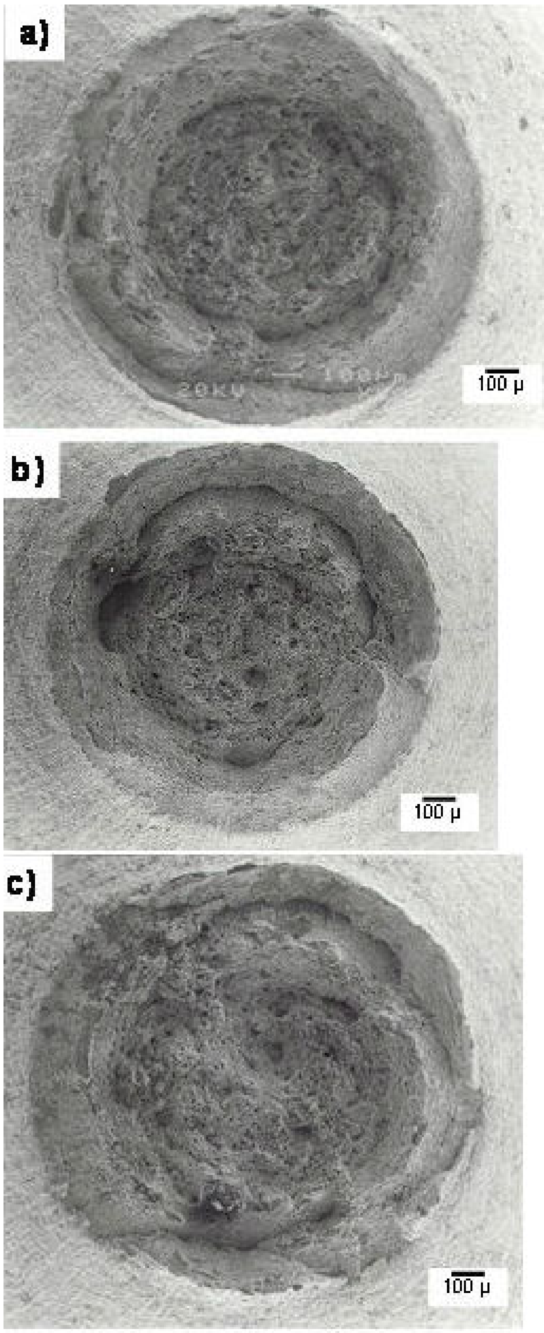

FIGURE 4. Fracture surfaces after made the SSRT, a) in air, b) NS4-pH-3 solution and c) NS4-pH-10 solution.

lly accepted mechanism on SCC, but this is dependent on the strain rate. If the strain rate is too high, the material fails predominantly under mechanical loading, and the environment did not have time to damage the material. By other hand, at too slow strain rate the passive film formed over a longer period of time will be too dense to be ruptured by the slow strain rate.

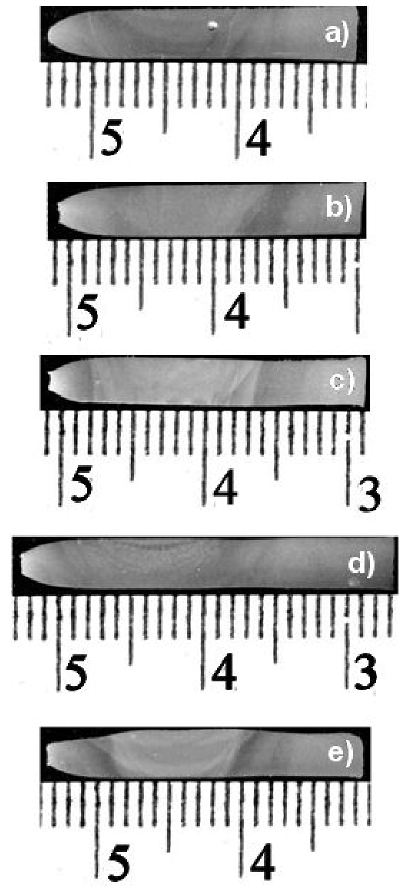

FIGURE 5. Optical micrographs of longitudinal section of fracture samples from SSRT performed in NS4 solution with pH-10 showing failure zone, a) as welded; b) first repair; c) second repair; d) third repair; e) fourth repair.

3.3. Fracture behavior

The mechanical fracture has been used to assess the stress effects together with the environment in the susceptibility to cracking. Fig. 4 shows micrographs of the fracture surfaces of specimens tested in air and NS4 solution with pH's of 3 and 10. It is clear a ductile type of fracture by microvoids coalescence for all the conditions studied. Detailed observation at higher magnifications of the fracture surface show the presence of some inclusions, which were initiation sites to form microvoids, as the strain rise this microvoids coalescent and provoke the reduction in area until the failure occur.

As the strain increases the neck formation in the gauge section before the samples failed was observed. This was reflected in the assessment of reduction area on the fracture surface. On the edge of the fracture surface an intergranular type of fracture was observed, towards the centre of the fracture change to a ductile type.

Optical micrographs of the longitudinal sections for specimens tested in NS4 solution with pH-10 showing the failure zone are shown in Fig. 5. The specimens tested in NS4 solution with pH of 3 and 10 for the different conditions of repair, the failure occurred in the BM/HAZ interface without presence of secondary cracks in the gauge section. These observations are agreed with the results obtained from RAR and ER.

4. Conclusions

The susceptibility to SCC of multiple welding repairs in circumferential girth welds of line pipes was evaluated by means of SSRT in NS4 solution. The SSRT results indicate that yield strength and ultimate tensile strength in presence of NS4 solution have little effect compared with the SSRT results obtained in air. According to the results of RAR and ER, in the NS4 solution at conditions studied the welding joints are not susceptible to SCC, confirmed by the absence of secondary cracks in the gauge section. In presence of NS4 solution, the most susceptible zone to failure in multiple welding repairs in girth welds of line pipes was the MB/HAZ interface. The mechanical properties satisfied the requirements of the different standards, indicating that a fourth weld repair is possible without problems of susceptibility to SCC at the conditions studied.

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