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The Influence of Multiple Welding Repairs of Pipelines in Residual Stress Assessment Related to Stress Corrosion Cracking

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Authors' contributions

This work was carried out in collaboration between all authors. Author AC designed the study, supervise all the work, perform analysis of experimental results and reviewed the final manuscript. Author OV performed the experimental studies, make the analysis of results and wrote the first draft of the manuscript. Authors SLH and RG help to carried out the SSRT, analysis results and literature searches. All authors read and approved the final manuscript.

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Original Research Article

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ABSTRACT

The effect of residual stress of multiple welding repairs in seamless API 5L X52 on the stress corrosion cracking (SCC) susceptibility was evaluated. Four repairs of the girth weld were evaluated through X-ray diffraction (XRD) on the internal face of the pipe to measure residual stresses in longitudinal and circumferential direction. Residual stresses in the circumferential and longitudinal direction reach values of about 77% and 58% of the UTS (460 MPa) respectively, approaching to the YS of the steel (360 MPa). It was observed that its magnitude increases as move away from weld center line. SCC susceptibility of X52 steel welded joints with the residual

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stresses generated was evaluated through slow strain rate tests (SSRT) in a soil solution at low and high pH. Relation between mechanical properties and residual stresses on the SCC susceptibility was analyzed. SCC index obtained from the mechanical properties of SSRT indicate good SCC resistance of X52 steel exposed to soil solution at low and high pH. From these results, it is suggested that the region with high residual stresses before to generate cracks in the steel surface due to the combination of soil solution and the strain applied, should favor pitting formation and not cracking. Initiation of micro-cracks from these pits will depend on the geometrical form of the pit and the stresses state can be established at given pitting. It is suggested that initiation of micro-cracks from these pits may depend on the dissolution rate and morphology of the pitting and stresses on the bottom of the pitting. This favorable condition could appear increasing the soil exposition time of the steel and reducing the strain rate applied on the SSRT.

Keywords: Steel; welding; x-ray diffraction; residual stresses; stress corrosion cracking (SCC).

1. INTRODUCTION

Residual stresses can be defined as those stresses that remain within a material after been manufactured, processed, heat treated or welded in the absence of external forces or thermal gradients [1]. The magnitude of residual stresses must be known when the integrity of a structure is assessed. Mostly, surface tensile residual stresses are undesirable. Welding, machining and grinding are examples of operations that generate surface tensile stresses. In almost every step of material processing residual stresses can be arise due to mechanical effects (generate by plastic deformation as a result of processes during production), thermal effects (generated as a result of heating or cooling processes), and chemical effects (generate by reaction such as precipitation or chemical surface treatment [2].

Residual stresses are categorized based on the length scale over which they equilibrate [3,4]. Type I which refers to macro residual stresses that develop in the body of a component on a scale larger than the grain size of the material. Type II are micro residual stresses found at the grain-size level, which vary on the scale of an individual grain. Such stresses may be expected to exist in single phase materials because of anisotropy behavior of each grain. They may also develop in multi-phase materials because of the different properties of the different phases. Type III is generated at the atomic level. They are micro residuals stresses that exist within a grain, essentially as a result of the presence of dislocations and other crystalline defects. Types II and III are often grouped together as micro stresses.

Welding process generally involves the deposition of molten filler metal and the presence of high temperatures close to the weld bead. Consequently, the surrounding parent material suffer microstructural changes which is reflected in the mechanical properties such as elastic modulus, elongation, yielding strength, hardness and ultimate tensile strength. When a defect is detected in a weld by means of some nondestructive test, the weld must be remove and repaired [5]. Generally, the girth weld metal is removed by grinding and the groove is prepared again in order to re-weld under a qualified welding procedure.

The welding process generates large residual stress gradients around the weld bead, which can be particularly detrimental to the structural integrity of a pipeline. In order to be able to predict the service life of a pipeline, it is important to have a proper knowledge of the residual stress distribution in the vicinity of the weld region. Among the nondestructive evaluation (NDE) techniques available for this purpose, X-ray diffraction (XRD) offers the more interesting perspectives, since it can deliver relevant information about the strain network state and microstructural changes. The XRD technique is used to evaluate microdeformations, characterized by the XRD peak. X-ray diffraction can directly measure this inter-planar atomic spacing; from this quantity, the total stress on the metal can then be obtained [6]. It is also an efficient tool in studying the evolution of residual stress in a mechanical structure under static or dynamic loading. The disadvantage for this technique is the low deep of analysis (superficial assessment). For deeper analysis the neutron diffraction is used [7,8]. The main advantage of the neutron diffraction method is its high penetration capacity for inspection materials up to several millimeters in depth. The disadvantage of such a technique is the high cost. There is another method like finite element method (FEM) used to simulated the numerical description of residual stresses in welded structural components (including pipelines) which uses the thermal–mechanical analysis approach [9,10].

In many cases in pipelines where unexpected failure has occurred, this has been due to the presence of residual stresses which have been combined with the service stresses to induce cracks that growth with the time until produce a suddenly failure (commonly rupture) [11]. In multiphase materials, residual stresses can arise from differences in thermal expansion, yield stress, or stiffness [5,12].

One of the mainly adverse effect of residuals stresses are in the susceptibility of stress corrosion cracking (SCC) of buried pipelines. The SCC failures are due to the fracture of metallic materials when they are subjected to stress (that can be residual, operational, etc) in a corrosive solution that can be acidic, neutral or basic. These failures are more likely in acidic media, and there are many studies on the effect of concentration, temperature, the stress in the metal, roughness and the microstructure of the material [13-17].

The stress exerted on the pressured transmission pipeline is complex in nature. The stresses generally speaking are a combination of stresses related to the internal operating pressure, residual stress from pipe fabrication and construction and external forces.

The tensile stresses are a necessary parameter for initiate SCC, however little research has focused on defining the role of stresses in crack initiation and growth [18,19]. For example, NACE SP 204 and ASME B31.8S [20,21] establish a criterion of 60% of the specified minimum yield strength (SMYS) in order to nucleate cracks on the surface of a pipeline. However, it has been found failures in pipelines with operation pressure less than 60% of the SMYS [22,23]. This suggests that SCC in pipelines is a multifactorial phenomenon and of course time dependant.

Weldments in pipelines are critical to maintain structural integrity, but unfortunately these weldments produce residual stresses, therefore assessment of residual stresses play a key role in operating pipelines. In the case of pipelines operating under cyclic load or at high temperature, the presence of tensile residual stresses can increase the likelihood of time dependent failure by acting as a driving force for the initiation and growth of cracks. Therefore, is very important to evaluate the residual stresses after make several repairs in the pipelines through submerged arc welding (SAW) or shielded metal arc welding (SMAW) joining technique.

This research work analyzed the effect of residual stresses produced by multiple welding repairs on the SCC behavior of X52 pipeline steel exposed to a soil solution with low and high pH using SSRT.

2. EXPERIMENTAL DETAILS

2.1 Steel Used

The material used in this work was a seamless API X52 pipeline steel. The dimensions of the pipeline were 8 inches in diameter and 0.437 inches in nominal wall thickness. The chemical composition is shown in Table 1.

Optical and scanning electron microscopy (SEM) observations of the microstructure for the different welding repairs were carried out. Additionally, SEM analysis of the failure zone was performed.

2.2 Welding Procedure

The girth welds were obtained from the quality control department of the company CMM-PROTEXA, carried out by qualified welders under a qualified welding procedure according to API 1104 standard [24], using the SMAW process with V-bevel at 30º as is shown in Fig. 1. To simulate multiple welding repairs, the repaired weld was removed and welded again, to obtain a second, third and fourth welding repair. The specimens obtained according to the number of welding 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.

The qualification of welding procedures was according to API 1104 and ASME Section IX which are applicable standards to the welding of pipelines. The specifications and procedures used in welding establish that in order to make welding repairs in areas previously repaired indicate that the welding repair should be carried out with a qualified procedure.

Table 1. Chemical composition of API X52 pipeline steel (wt.%)

C	Mn	Si	P	S	Cu	Cr	Ni	Mo	Al	V	T	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

Fig. 1. a) Schematic of the V-bevel at 30º, b) notch after been removed the metal to repair and c) piece of pipe after been welded

2.3 Residual Stress Assessment

Most of techniques used to evaluated residual stresses, measure strains instead of stresses, and the residual stresses are then deduced using the appropriate material parameters such as Young modulus and Poisson ratio [1,3,4,9]. During this assessment is very common obtain only a single stress value and this value is constant assumed within the measurement volume, both in the surface plane and through the depth.

Residual stress measurement was carried out in order to determine its magnitude and stress distribution generated during the welding repairs. These measurements were made in the experimental laboratory of Engineering Center Industrial Development (CIDESI, Queretaro México) through an equipment of X-ray diffraction Phillips brand X-PERT model, which radiation source has Chromium (Cr Kα). The data were analyzed by the X'PERT PRO software.

The residual stresses measurement was made inside of the weld joint in five points located at: a) welding center, b) 5 mm away from the center of the weld bead to both ends c) 35 mm away from the center of welding toward both ends, as illustrated in Fig. 2a. The diffraction peak used to measure residual stresses was a ferrite peak (211) located at an angle of 156.81º in axis 2θ. For each point measurements were taken at an angle of: a) ψ= 0º (measured in the circumferential direction and b) ψ = 90º (measured in the axial direction). In the calculation of the residual stresses are using an elastic modulus of 201 GPa and a Poisson's ratio of 0.3 (values tabulated in software for steel).

2.4 Stress Corrosion Cracking Assessment

The susceptibility to stress corrosion cracking (SCC) of welded joints of API X52 pipeline steel with up to four repairs was evaluated using SSRT according to NACE TM-0198 standard [25]. The SSRT were performed in air as reference, and in soil solution called NS4 at low and high pH, both at room temperature and at strain rate of $1x10^{-6}$ s^{-1}. The NS4 solution contain $NaHCO_3$:0.483g/L, $CaCl_2$:0.181 g/L, $MgSO_4$:0.131 g/L and KCl:0.122 g/L. The NS4 pH solution was around 8.5 and after was adjusted with HCl and NaOH.

The SSR specimens were machined according the dimensions established in NACE TM 198 [25]. Cylindrical tensile specimens were transversal machined to the girth weld as is shown in Fig. 2b.

3. RESULTS AND DISCUSSION

3.1 Microstructure

Microstructural characterization through optical microscopy of the welding joint is shown in Fig. 3. This characterization was made in the three different regions of the weldments. The microstructure of the weld is ferritic–bainitic acicular. The heat affected zone (HAZ) and base metal microstructure shows a structure of grains of ferrite with perlite in the grain boundary. The characterization of the microstructure in the HAZ for each weld repair condition does not reveal significant changes in the type of microstructural constituents, in comparison with the microstructure found in the as-welded condition. Optical micrographs of the coarse grained heat affected zone (CGHAZ) revealed that increasing the number of weld repairs promotes grain growth in the CGHAZ [5].

Mechanical properties obtained for the different weld repair condition were shown elsewhere [26]. The yield strength and the ultimate tensile strength was 380 and 484 MPa, respectively. The values of yield strength (YS) and ultimate tensile strength (UTS) satisfy the specified minimum values of the material according to the API 5L standard [27], whose values are 359 and 455 MPa for YS and UTS respectively.

After carried out the welding repairs, each welding was subjected to internal surface residual stress measurements using the X-ray diffraction technique. Five residual stress measurements were made on the inner surface of the pipe for both circumferential and longitudinal direction in reference to the pipe and not the weld as is shown in Fig. 2a.

3.2 Hoop Residual Stresses

To assess the effects of the number of welding repairs, residual stress distributions in the hoop direction through five measurements were performed. Fig. 4 show the distribution of hoop residual stresses for each welding repair. In general, the hoop residual stress values are compressive on the inside surface of the welding joint. The compressive residual stresses in the hoop orientation are less damaging than tensile on the inner surface when considering the structural integrity of girth welds.

The surface measurements of residual stresses are in the range of 225–358 MPa. It is observed that residual stresses are greater in the first repair reaching values from 290 to 358 MPa, which can be attributed to grain growth due to heat input from the welding process. In the subsequent repairs the welding process generates a grain refinement, which reduces residual stresses. Residual stresses can also be affected by thermal cycles and its analysis provides a potential for estimating the hardening of the weld zone, however the other parameter such as carbon equivalent in composition of steel alloy must be also considered. Preheat effect on thermal cycle and residual stress was studied by Aalami et al. [28].

The higher stresses (first repair) in the hoop direction reach values of about 77% of the ultimate tensile strength (460 MPa), approaching to the yield strength of the steel (360 MPa).

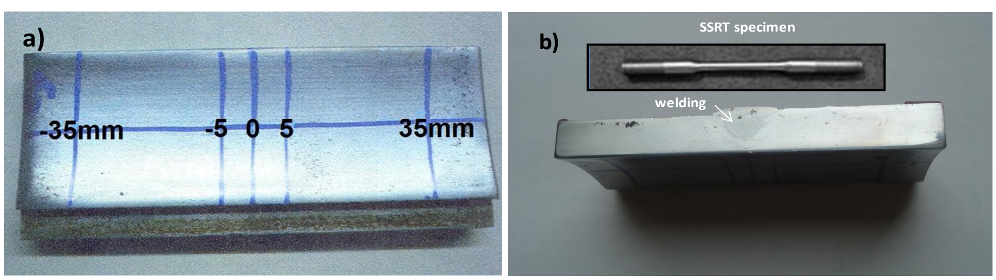

Fig. 2. a) Location of the residual stress measurements, b) cross section of the welding and SSRT specimen

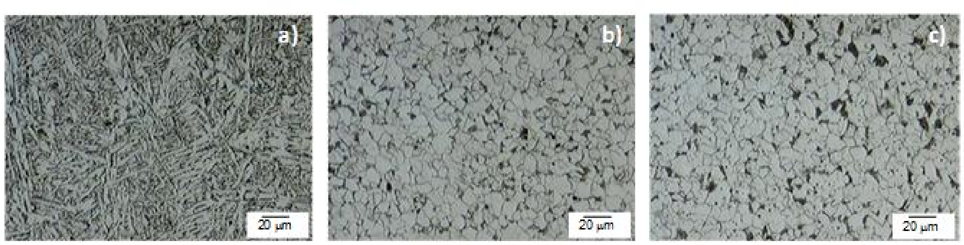

Fig. 3. Typical weld joint microstructures for X52 steel, a) weld bead, b) heat affected zone and c) base metal

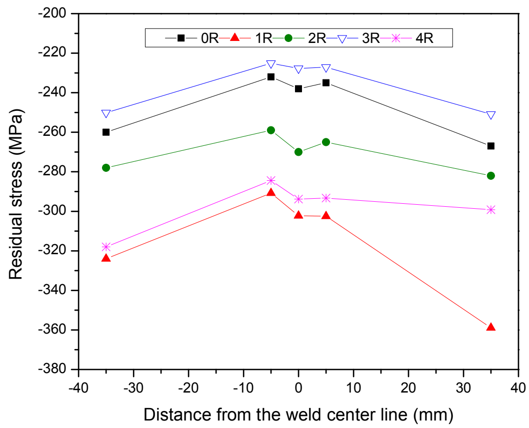

Fig. 4. Hoop residual stresses distribution

The hoop stresses are generally more severe than the longitudinal stresses particularly on the inner surface of the pipe. The most severe residual stresses are generated for the first and four welding, and its magnitude increase as move away from weld center line. These changes can be attribute to the difference in the number of welding bead required for each repair and additionally to the size of the welding beads produced [29-31].

3.3 Longitudinal Residual Stresses

To evaluate the effects of welding repair number on the inner surface of the pipeline, residual stress distributions in the longitudinal direction through five measurements were carried out. Fig. 5 show the distribution of longitudinal residual stresses for each welding repair. As well as hoop residual stress values are compressive inside surface of the pipe, the stresses in the longitudinal direction are compressive too. A lower magnitude of residual stresses was found along the weld joint in the longitudinal direction than in hoop direction. The stresses measured in the longitudinal direction reach values of about 58% of the ultimate tensile strength (460 MPa) in comparison with 77% in hoop direction.

The longitudinal residual stresses in the inner pipe surface did not follow a consistent pattern as in the hoop direction. But it is clear that its magnitude increases as move away from weld center line, obtaining the major residual stresses at 35 mm from the centerline. This fluctuation in the longitudinal residual stresses could be attributed to several factors like different microstructure, which is produced by the application of several girth welds, which is more noticeable in the first and second repair. Additionally, in the longitudinal direction always will be more variability by the anisotropy of the material.

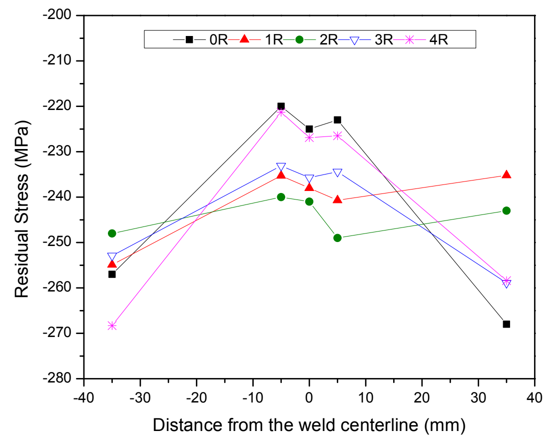

Fig. 5. Longitudinal residual stresses distribution

Different behavior in the longitudinal residual stress distribution on the inner surface was reported by Rybicki [32], who evaluated the effect of pipe thickness on residual stresses in circumferential welds of 304 stainless steel, in nominal diameter of 4” and thickness of 0.120", 0.237", 0.337" and 0.531"; and in nominal diameter of 10" in thicknesses of 0.165", 0.365", 0.593" and 1.125". In the case of pipe of 10" in diameter and thickness of 1.125" it was observed compressive longitudinal residual stress distribution in the centerline of the welding, increasing the stress magnitude as the distance increases from the weld.

Rybicki [32] explain this difference in the stress distribution in terms of rigidity of the system. A circumferential welding with thin thickness exhibits greater local deformation to the center, close to the weld, than thicker pipelines. This local deformation is caused by the combination of shrinkage during cooling of the weld and decrease in stiffness of the system (lower thickness). This strain causes local flexion towards the center and this generates tension residual stresses toward the inside of the pipe and compressive residual stresses to the outer side. On thicker pipes this phenomenon is minimized or not generated, being the case for the pipe of 10" in diameter and 1.125" of thickness, that resists welding shrinkage during the cooling, creating compressive stresses on the internal face of the pipe.

3.4 Assessment of SCC Susceptibility

One of the principal effects of residual stresses is to accelerate (tensile stresses), or in some cases retard (compressive stresses), the nucleation and growth of cracking in pipelines and structures subject to cyclic loading and exposed to corrosive environments. Residual stresses can alter the shape of surface cracks in thick welds, causing them to grow in the time and when they reach a threshold size suddenly produce a failure. They can cause crack growth to occur in regions subject to purely compressive cycling where fatigue would normally not be a problem [33]. They have also been shown to accelerate environmentally assisted cracking in structures subject to static loading.

SCC susceptibility in welded joints of API X52 steel pipe with up to four welding repairs was evaluated using slow strain rate tests (SSRT) according to NACE TM-0198 standard [25]. The tensile specimens were exposed to the soil solution at low and high pH. Results obtained from these tests are shown in Fig. 6.

Table 2 show a summary of the mechanical properties obtained from the curves of Fig. 6. Considering the yielding strength (YS), ultimate tensile strength (UTS), reduction in area (RA), elongation plastic (EP) and strain (e), there is a tendency to increases in the first and second repair, but in third repair decrease with a slight increase in the fourth repair.

The SCC susceptibility was evaluated obtaining SCC index of the mechanical properties from SSRT. SCC index from yielding strength ratio (YSR), ultimate tensile strength ratio (UTSR), the reduction in area ratio (RAR), elongation plastic ratio (EPR) and strain ratio (eR) were obtained as is shown in Fig. 7. These ratios are obtained from comparing the mechanical properties obtained in the NS4 solution with the mechanical properties obtained in the controlled environment (air). When the X52 steel is exposed to NS4 solution YS, UTS and ductility of the welded joints shown a decrease [5]. SEM observations of SSRT specimen revealed absence of lateral corrosion and neither secondary cracking was observed. The metallographic observations of the fractured specimens show that most SSRT specimens failed in the base metal/heat affected zone interface.

3.5 Relation Between Residual Stresses and Stress Corrosion Cracking Index (SCC)

SCC index obtained from the mechanical properties of SSRT at low and high pH showed in Table 2 are plotted in Fig. 7 and they are related to residual stresses. Ratios in the range of 0.8-1.0 normally denote high resistance to SCC, whereas low values (i.e. <0.5) show high susceptibility [25]. The specimens tested in air showed the maximum %RA. SSR specimens tested in air exhibit a strain about 16-19% meanwhile the specimens tested in NS4 solution showed a strain between 14-18%. It is clear that corrosive solution has an effect on the mechanical properties.

Table 2. Mechanical properties obtained from the SSR tests to assess the SCC

Condition	Environment	YS (MPa)	UTS (MPa)	RA (%)	EP (%)	e (%)
BM	Air	386.1	475.2	89.10	23.26	25.72
0 Rep		356.0	437.5	85.74	15.00	17.39
1º Rep		379.9	464.2	88.10	16.18	18.14
2º Rep		384.1	456.2	88.53	16.69	18.69
3º Rep		359.7	427.4	84.60	14.37	15.94
4º Rep		379.2	455.9	86.34	15.51	17.84
BM	NS4, pH 3	396.8	464.8	88.13	19.72	20.03
0 Rep		325.9	423.0	84.10	14.17	16.39
1º Rep		322.5	427.5	86.84	15.47	16.86
2º Rep		351.8	438.2	86.90	16.69	17.75
3º Rep		318.1	354.9	83.91	13.78	14.55
4º Rep		329.7	428.8	85.01	15.00	15.98
BM	NS4, pH 10	357.0	467.7	87.62	18.34	22.67
0 Rep		316.0	428.4	83.16	14.98	17.05
1º Rep		324.9	446.3	86.86	15.51	15.74
2º Rep		340.6	415.2	86.88	16.22	18.50
3º Rep		344.6	436.8	82.30	12.99	16.45
4ºRep		318.0	412.1	86.10	14.60	14.99

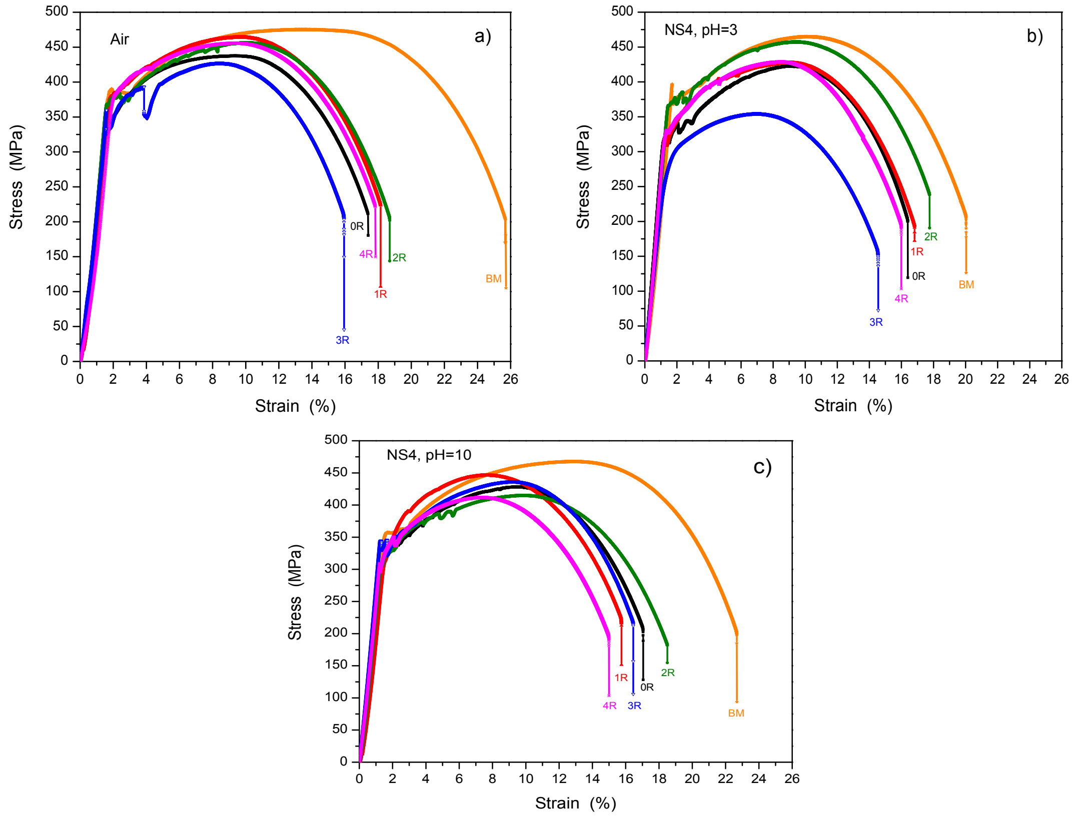

Fig. 6. Stress-strain profiles obtained from the SSRT in function of pH and number of repairs

The strength, elongation and reduction in area decreases slightly when the samples are exposed to the NS4 solution [5]. According to SCC index, it is clear that the specimens tested in the NS4 solution does not exhibited susceptibility to SCC. Additionally, secondary cracks or corrosion in the gauge section of SSRT specimens were not observed.

The material susceptibility to SCC depends of many factors such as elemental composition, metallurgical factors, corrosive environment, pH and residual stresses mainly. According to the results of residual stress assessment it is clear that the level of stresses did not show a significant effect on the SCC susceptibility.

As mentioned above, and according to Fig. 4 and 5 for the different welding repair conditions, stress values in the longitudinal and circumferential direction are compressive on the inner surface of the pipeline. These residual stress results at the inner face of the pipe do not match those reported by McGaughy [29,30] or with some other repairs concerning circumferential welds [34-43]. They all reported that both residual stresses resulting from repair are tensile on the inner side of the pipe on the center line of welding, decreases as moving away from this and become compressive toward areas away from the weld. This difference in the distribution of residual stress on the inner surface can be explained according to the work of Rybicki [32] in terms of the stiffness of the system and based on the work of Dong [34,39,40,42,43], Bouchard [36,37] and Elcoate [38] relating to the length of repair. Compared to McGaughy work [29,30], the thickness used in this work is about twice (6.52 mm versus 11.1 mm) so that the thicker tubing can withstand shrinkage during cooling welding. Respect to the length of repair, the length reported by McGaughy was 203 mm (120° arc lengths) and in this study the repair was the entire circumference (360°), so it is expected to generate lower levels of residual stresses. This combined effect of increased stiffness and repair longer favor the generation of compressive residual stresses on the inner face of the pipe as indicated by the results reported in Figs. 4 and 5.

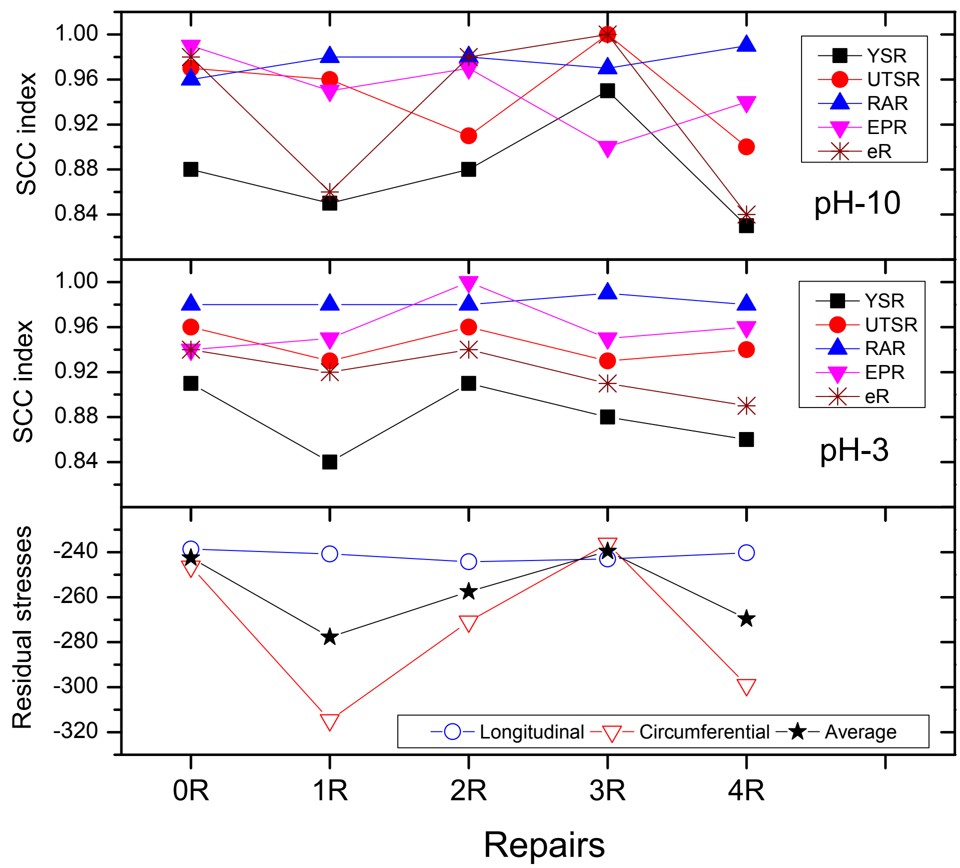

Fig. 7. SCC index obtained from the mechanical properties of SSRT related to residual stresses

The longitudinal residual stress reach values of 58% and 77% for the hoop residual stress relate to the steel strength, but all them are compressive and they are not enough to produce SCC. The stresses exerted on the pipelines steels are complex in nature, and should be a combination of stresses related to the internal operating pressure, residual stress from the pipe fabrication, residual stress from the welding and all the possible external stresses.

An attempt to relate the residual stresses with the SCC index is shown in Fig. 8. The average of residual stresses (longitudinal and circumferential) in function of welding repairs was plotted in order to compare with the average of SCC index obtained from the different mechanical properties (YSR, UTSR, RAR, EPR and eR). It is observed that welding repair with higher residual stresses presented the lower SCC index. That is to say, increasing the residual stresses the SCC susceptibility increases. However, it should be noted that compressive residual stresses measured did not generate SCC in the API X52 steel under the conditions studied. In all the cases the SCC index was above 0.8 and not secondary cracks were observed in the gauge section of the specimens.

In the SCC study it is clear that we only evaluate the residual stress due to the welding repairs, and the stresses evaluated were superficial and compressive inside surface of the pipeline. The maximum values for the residual stresses evaluated belong to 35 mm to the right and 35mm to the left of the weld center line, which reach values between 220 and 270 MPa for the longitudinal residual stresses. Meanwhile for the circumferential direction reach values between 230 and 358MPa. It is obvious that in order to be the X52 steel susceptible to SCC must be reach higher residual stresses. In addition, these stresses must be tensile and not compressive.

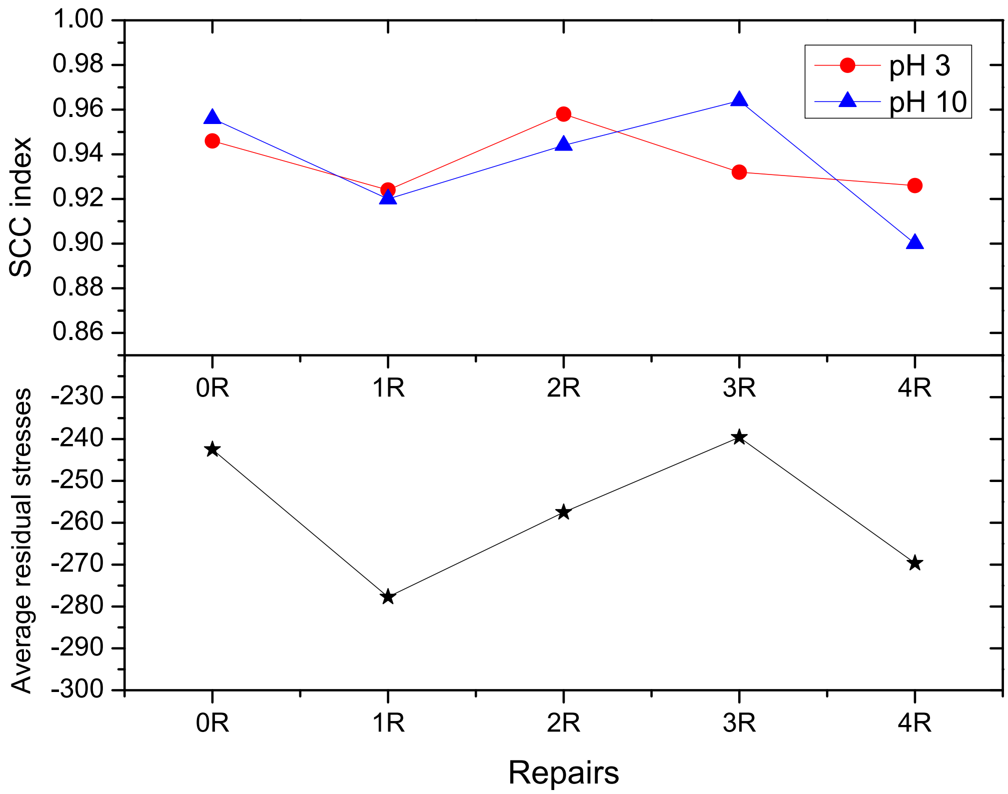

Fig. 8. Average of residual stresses related to average of SCC index

From this asseveration, it is evident that the region with high residual stresses prior to generate cracks in the steel due to the combination of soil solution and the strain exerted, should favor pitting formation and not cracking. Initiation of micro-cracks from these pits may depend on geometrical form of the pit and stresses state can be established at given pitting. This favorable condition can appear with increasing the soil exposition time and reducing the rate of constant load applied on the SSRT. Thus, the pits generate in the high stress regime should be favorable to develop high internal stresses and initiation of cracks from a pit.

The complexity of cracking phenomena results from the dependence of metallurgical, mechanical and environmental parameters that may influence both crack initiation and propagation [44-47]. Previous studies for high pH-SCC demonstrate that mechanism involves anodic dissolution for crack initiation and propagation [48,49]. By the contrary, it has been observed that low pH-SCC is associated with the dissolution of the crack tip and sides, and generally is corrosion products are observed in the crack. This type of SCC is accompanied by the ingress of hydrogen into the steel [5,45-50].

3.6 Fracture Behavior

After carried out the SSR tests, the fracture surfaces were observed by SEM in order to characterize the type of fracture and to assess the stress effects together with the environment in the susceptibility to cracking. The fracture surfaces of specimens tested in NS4 solution with low and high pH exhibited a ductile type of fracture, which was characterized by microvoids coalescence. The neck formation before the samples failed was observed [5]. This was reflected in the assessment of reduction area on the fracture surface. Most studies of SCC in near neutral environments resulted in transgranular fracture type [19,48-51].

Fractured samples from SSR tests were longitudinal cut and polished in order to observe if there are cracks in the gauge section originated by the simultaneous action of corrosive solution and stresses exerted. Optical micrographs from longitudinal sections of SSRT specimens tested in NS4 solution with low and high pH are shown in Figs. 9 and 10. The specimens tested in NS4 solution with low and high pH for the different conditions of repair, the failure generally occurred in the base metal and BM/HAZ interface without presence of secondary cracks in the gauge section. These observations are agreed with the SCC index obtained from mechanical properties evaluated from SSRT (YSR, UTSR, RAR, EPR and eR).

Most results about cracking in near neutral environments have origin from pits [52,53]. The location of the cracks in the micro-pits can be related to the stress intensification in this site. Continuous loading produce a micro strain in the bottom of the pit facilitating the pit-to-crack transition in regions with the highest stress concentration. Pitting in neutral pH environment preferentially occurs at surfaces with high residual stresses as a result of galvanic reactions [52].

In welded joints of low carbon steels the HAZ was characterized by a combination of fine and coarse grained polygonal ferrite structure and fine perlite particles [54,55]. In the weld metal, the constituents of complex ferrite were low temperature transformation products formed during continuous cooling such as acicular ferrite and bainite microstructure [14,26].

Optical micrographs of the coarse grained heat affected zone (CGHAZ) revealed that increasing the number of weld repairs promotes grain growth in the CGHAZ [5,54,55], being this zone the most susceptible to failure.

Taking account the results published and considering the standards and recommended practices on pipeline fabrication and installation, not more than two welding repairs may be carried out in the same area. The rule was established perhaps because of a lack of knowledge on the effects of repeated weld repairs on the properties of the weld.

Considering the residual stresses, the corrosive solution (NS4) and X52 steel, the evaluation through the mechanical properties to obtain SCC index and SEM observation in the gauge section of the specimens to find cracks, revealed that X52 steel weldments with up to four repairs are not susceptible to SCC despite of high compressive residual stresses level. The stresses in the inside surface of the weldment are compressive and as such, are no damaging as the tensile residual stresses.

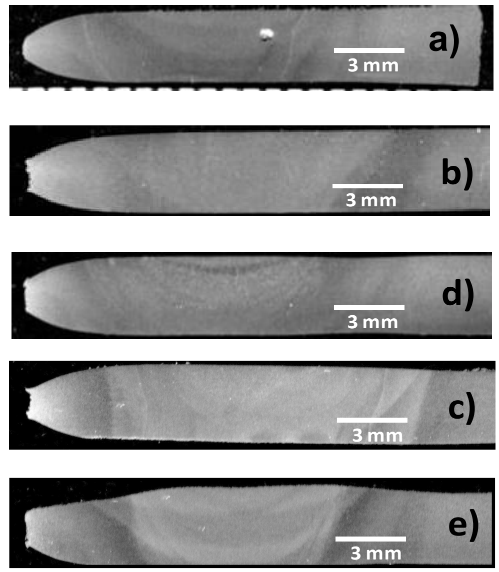

Fig. 9. Optical micrographs of gauge section of fractured samples from SSRT performed in NS4 solution with pH 3 showing failure zone, a) as welded; b) first repair; c) second repair; d) third repair; e) fourth repair

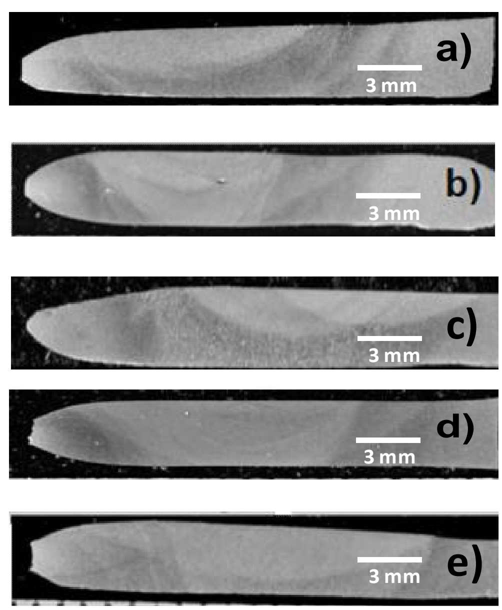

Fig. 10. Optical micrographs of gauge section of fractured samples from SSRT performed in NS4 solution with pH 10 showing failure zone, a) as welded; b) first repair; c) second repair; d) third repair; e) fourth repair

4. CONCLUSIONS

The influence of residual stresses on SCC susceptibility due to multiple welding repairs in X52 pipeline steel was studied. Relation between microstructure, mechanical properties and residual stresses on the welding joint was evaluated. The welding joint evaluated presented different levels of residual stresses, offering good SCC resistance in a synthetic soil solution at low and high pH. Presence of cracks was not observed along the gauge section specimens. These findings are agree with the results obtained from ratios of mechanical properties (YSR, UTSR, RAR, EPR, eR) which resulted in high ratios (0.8-1), indicating that X52 steel with up to four repairs and the residual stress generated not contribute to produce SCC. After carried out the SSRT, the metallographic observations of specimens showed that failure occurs in the base metal and BM/HAZ interface. It is observed that region with high residual stresses before generating cracks in the steel surface due to the combination of soil solution and stress applied, should favor pitting formation and not cracking. It is suggested that initiation of micro-cracks from these pits may depend on the dissolution rate and morphology of the pitting and stresses on the bottom of the pitting. This favorable condition could appear increasing the soil exposition time of the steel and reducing the strain rate applied on the SSRT.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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