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Residual Stress Assessment and its Effect on SCC of Pipelines Steel in Acidic Soil Environment

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ABSTRACT

Effect of residual stresses of multiple welding repairs on API 5L X52 pipeline steel on stress corrosion cracking (SCC) in a simulated acidic soil solution was studied. Four conditions of repairs of the girth weld were evaluated. The residual stresses were measured through X-ray diffraction (XRD) on the internal side of the pipe in longitudinal and circumferential direction. The circumferential and longitudinal residual stresses values are compressive on the inner surface of the welding joints. The highest residual stresses were measured in the hoop direction reaching values of about 98% of the yielding strength (360 MPa). It was observed that its magnitude increases as move away from weld center line. The effect of residuals stresses in the SCC susceptibility of X52 pipeline steel was evaluated through slow strain rate tests (SSRT) in a simulated acidic soil solution. Relation between mechanical properties obtained from SSRT and residual stresses on the SCC susceptibility was analyzed. Results of SCC index taking account the ratios obtained from the mechanical properties of the welding joints evaluate, showed good SCC resistance in acidic soil solution at low pH. Scanning electron microscopy (SEM) observations showed 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.

Keywords: corrosion, steel, fracture, microstructure, stress-strain relationship.

INTRODUCTION

In the last years there is an increasing interest in how the state of residual stress affects the mechanical properties of a material, its structural shape and welding process. The failure of a structure or a mechanical component is not only due to external loads; it is necessary to take account residual stresses. All new process like welding introduces new state of stresses. These stresses can have a positive effect in the case of compressive surface stress, or they can have a negative effect in the case of tensile residual stresses.

Residual stresses can be defined as those stresses that remain in a material after been manufacture and processing, in the absence of external forces or thermal gradients. 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 suffers microstructural changes which are reflected in the mechanical properties.

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. The use of X-rays is one of the more popular techniques for residual stress assessment [1]. It is a non-destructive technique used to evaluate the surface residual stress.

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 [2-6].

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. Therefore, is very important to measure the residual stresses after make several repairs through submerged arc welding (SAW) joining technique or shielded metal arc welding (SMAW). This research work studied the effect of residual stresses on the SCC behavior of X52 pipeline steel with multiple welding repairs in a simulated acid soil solution using SSRT.

EXPERIMENTAL PROCEDURE

A seamless API 5L X52 pipeline steel was used. The dimensions of the pipeline were 8 inches in diameter and 0.437 inches in nominal wall thickness. The chemical composition was shown elsewhere [7].

The girth welds were obtained by qualified welders under a qualified welding procedure according to API 1104 standard, using the SMAW process with V-bevel at 30° as is shown in Figure 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 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.

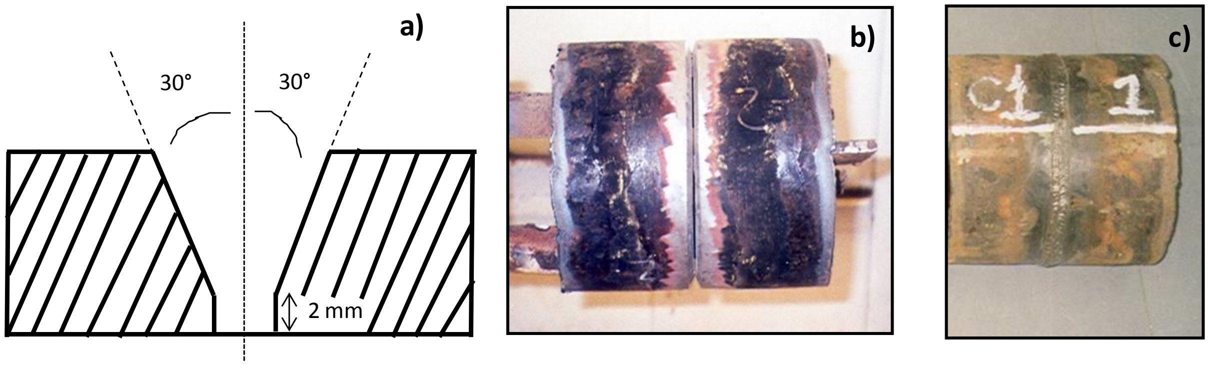

Figure 1. a) Schematic of the V-bevel at 30°C, b) notch after been removed the metal to repair and c) piece of pipe after been welded.

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.

Residual stress measurement was carried out in order to determine its magnitude and stress distribution generated during the repairs through an equipment of X-ray diffraction Phillips brand X-PERT model, which radiation source has Chromium (Cr Kα).

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 Figure 2a. The diffraction peak used to measure residual stresses was a ferrite peak (211) located at an angle of 156.81° in axis 2θ. For each point measurements were taken at an angle of: a) $\psi = 0$ ° (measured in the circumferential direction and b) $\psi = 90$ ° (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).

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=3 at room temperature and at constant elongation rate of 1.0 $x10^{-6}$ s^{-1}. Cylindrical tensile specimens were transversal machined to the direction of the application to the girth weld as is shown in Figure 2b.

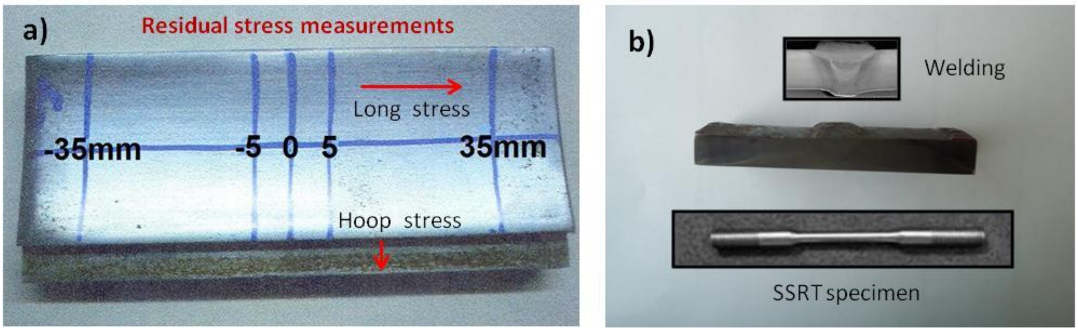

Figure 2. a) Location of the residual stress measurements, b) Cross section of the welding and SSRT specimen.

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 pH solution was around 8.5 and after was adjusted with HCl.

RESULTS AND DISCUSSION

Microstructure

Microstructural characterization through optical microscopy of the welding joint is shown in Figure 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 pearlite in the grain boundary. Optical micrographs of the coarse grained heat affected zone (CGHAZ) revealed that increasing the number of weld repairs promotes grain growth in the CGHAZ.

The mechanical properties obtained for the different weld repair condition were shown elsewhere [7]. The yield strength and the ultimate tensile strength was 380 and 484 MPa, respectively.

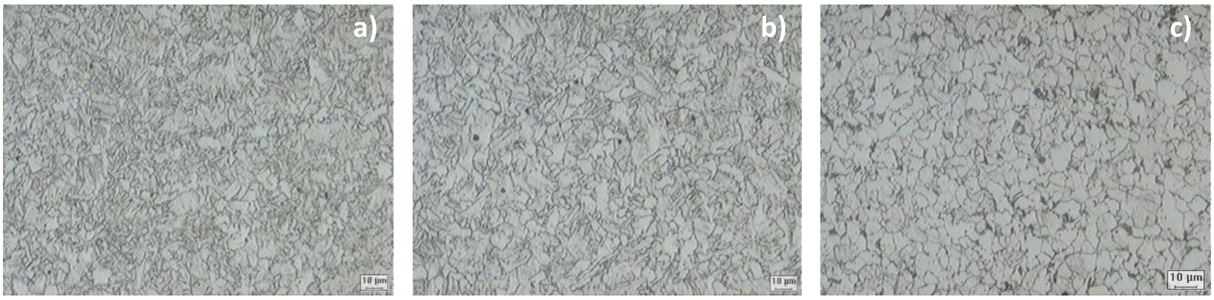

Figure 3. Typical weld joint microstructures, a) weld bead, b) heat affected zone and c) base metal.

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 was shown in Figure 2a.

<u>Hoop residual stresses</u>

To assess the effects of the number of welding repairs, residual stress distributions in the hoop direction through five measurements were performed. Figure 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 joints. 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. The higher stresses (first repair) in the circumferential direction reach values of about 98% of the yield strength (360 MPa).

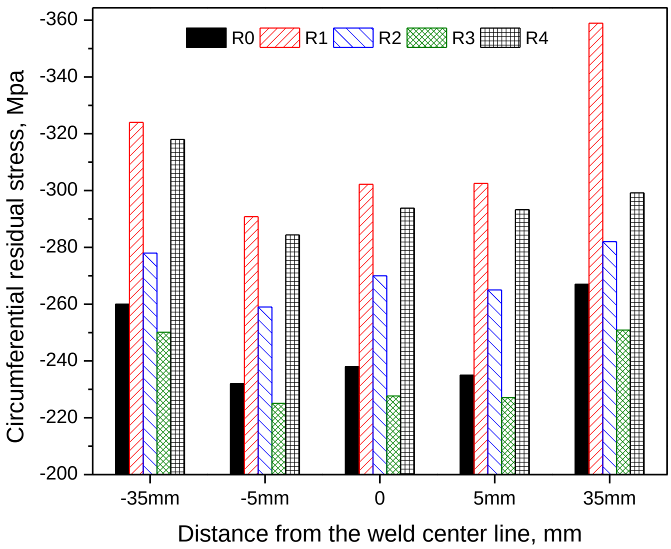

Figure 4. Circumferential residual stresses.

The circumferential 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 welding, and its magnitude increase as move away from weld center line.

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. Figure 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 in the longitudinal direction reach values of about 74% of the yielding strength (360 MPa).

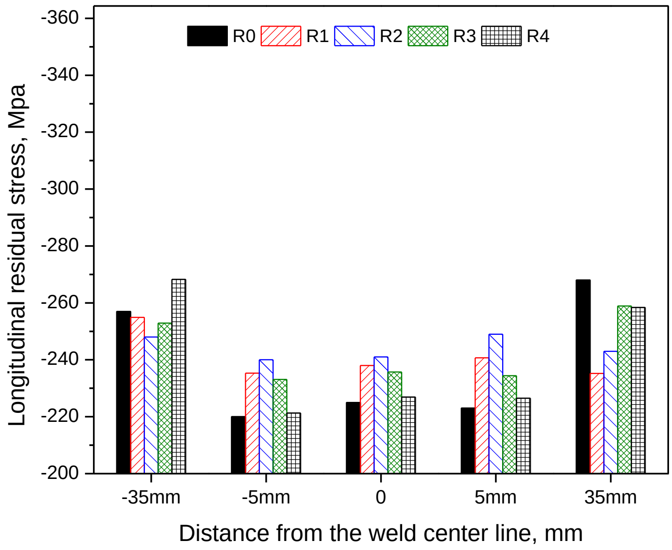

Figure 5. Longitudinal residual stresses.

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 35mm from the centerline. For the longitudinal direction there is a light tendency that increasing the number of repairs increases the residual stresses.

Different behavior in the longitudinal residual stress distribution on the inner surface was reported by Rybicki [8]. He explains 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.

Effect of residual stresses on low pH SCC

Residual stress have key role in the evolution of SCC. One of the most principal effects of residual stress is to accelerate (tensile stresses), or in some cases retard (compressive stresses), the nucleation and growth of cracking in pipelines subject to cyclic loading. Residual stress 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 [9]. They have also been shown to accelerate environmentally assisted cracking in structures subject to static loading.

The susceptibility to stress corrosion cracking (SCC) in girth welds of seamless API X52 steel pipe containing multiple repairs was evaluated using slow strain rate tests (SSRT) according to NACE TM-0198 standard. Cylindrical tensile specimens were transversal machined to the direction of the application to the girth weld.

Table I show a summary of the mechanical properties obtained from the SSRT carried out in air and acid soil solution for the different repair conditions. The SCC susceptibility was expressed in function of yielding strength ratio (YSR), ultimate tensile strength ratio (UTSR), the reduction in area ratio (RAR), elongation plastic ratio (EPR) and strain ratio (εR) as is shown in Table II. These ratios are obtained from comparing the mechanical properties obtained in the NS4 solution with the mechanical properties obtained in the controlled environment (air). The yield strength, tensile strength and ductility of the welded joints shown a decrease when they are exposed to the NS4 solution.

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

Condition	**Environment**	**YS (MPa)**	**UTS (MPa)**	**RA (%)**	**EP (%)**	**ε (%)**
BM	Air	386.1	475.2	89.10	23.26	25.72
As welded		356.0	437.5	85.74	15.00	17.39
1R		379.9	464.2	88.10	16.18	18.14
2R		384.1	456.2	88.53	16.69	18.69
3R		359.7	427.4	84.60	14.37	15.94
4R		379.2	455.9	86.34	15.51	17.84
BM	NS4, pH 3 (acidic soil solution)	396.8	464.8	88.13	19.72	20.03
As welded		325.9	423.0	84.10	14.17	16.39
1R		322.5	427.5	86.84	15.47	16.86
2R		351.8	438.2	86.90	16.69	17.75
3R		318.1	354.9	83.91	13.78	14.55
4R		329.7	428.8	85.01	15.00	15.98

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. 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 welding repairs. Specimens tested in air showed a strain about 16-19% meanwhile the specimens tested in NS4 with pH 3 showed a strain between 14-20%.

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 carried out the tests.

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.

Table II. SCC assessment obtained from the SSR tests.

Condition	Environment	YS-R (MPa)	UTS-R (MPa)	RAR (%)	EPR (%)	εR (%)
BM	Air	386.1	475.2	89.10	23.26	25.72
As welded		356.0	437.5	85.74	15.00	17.39
1R		379.9	464.2	88.10	16.18	18.14
2R		384.1	456.2	88.53	16.69	18.69
3R		359.7	427.4	84.60	14.37	15.94
4R		379.2	455.9	86.34	15.51	17.84
BM	NS4, pH 3 (acidic soil solution)	1.02	0.97	0.98	0.84	0.77
As welded		0.91	0.96	0.98	0.94	0.94
1R		0.84	0.93	0.98	0.95	0.92
2R		0.91	0.96	0.98	1.0	0.94
3R		0.88	0.93	0.99	0.95	0.91
4R		0.86	0.94	0.98	0.96	0.89

As mentioned above, and according to Figure 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 [10-11] or with some other repairs concerning circumferential welds [12-18]. 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 [8] in terms of the stiffness of the system and based on the work of Dong [12, 16, 18], Bouchard [14] and Elcoate [15] relating to the length of repair.

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.

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 0.77 and not secondary cracks were observed in the gauge section of the specimens. 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.

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.

Fracture behavior

In order to complete the SCC assessment, longitudinal gauge section were polished and observed in SEM. The mechanical fracture has been used to assess the stress effects together with the environment in the susceptibility to cracking. The fracture surfaces of specimens tested in NS4 solution with pH 3 showed a ductile type of fracture by microvoids coalescence for all the conditions studied. The neck formation before the samples failed was observed. This was reflected in the assessment of reduction area on the fracture surface.

Optical micrographs of the longitudinal sections for SSRT specimens tested in NS4 solution with pH 3 showing the failure zone are shown in Figure 6. The specimens tested in NS4 solution with pH of 3 for the different conditions of repair, the failure occurred in the base metal and BM/HAZ interface without presence of secondary cracks in the gauge section. These observations are agreed with the results obtained from YSR, UTSR, RAR, EPR and εR.

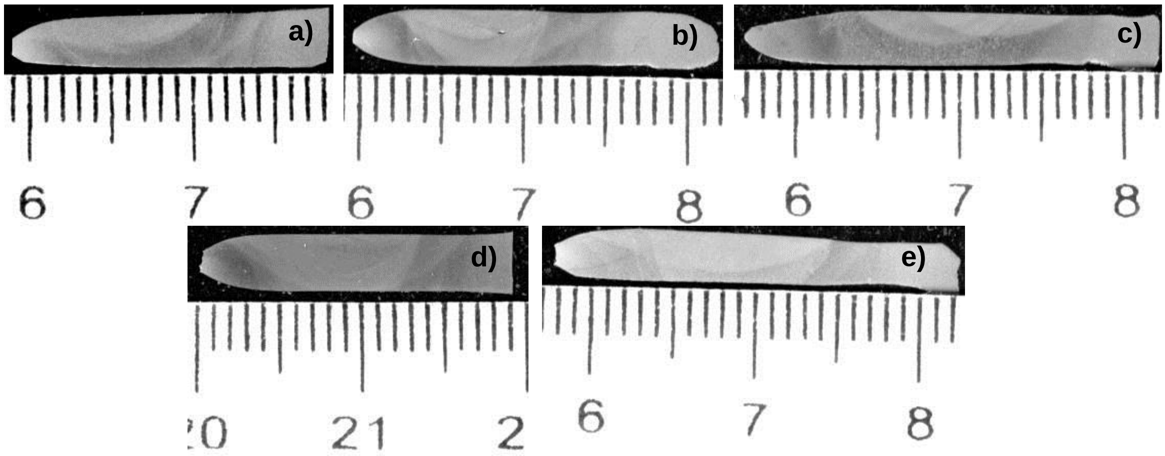

Figure 6. Optical micrographs of longitudinal section of fracture samples from SSRT performed in NS4 solution with pH-3 showing failure zone, a) as welded; b) first repair; c) second repair; d) third repair; e) fourth repair.

Conclusions

This work presents the residual stress assessment of multiple welding repairs in the same area in API X52 pipeline steel and its effect on SCC susceptibility in acid soil solution. Four conditions of repairs and one as welded specimen of the girth weld were evaluated to determine changes in the residuals stresses. Relation between microstructure, mechanical properties and residual stresses on the welding joint does not show any significant effect on SCC susceptibility. The welding joint evaluated presenting different levels of residual stresses, offering good SCC resistance in acidic soil solution at low pH. Presence of cracks was not observed along the gauge section specimen, thus no SCC was found due to the surface compressive stresses measured. These results are agree with the results from ratios of mechanical properties (YSR, UTSR, RAR, EPR, εR) which presented high ratios (0.77-1), indicative that X52 steel with the residual stress measured not contribute to generate SCC. For all the SSRT specimens the failure occurs in the base metal and BM/HAZ interface.

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