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Mechanical and environmental effects on stress corrosion cracking of low carbon pipeline steel in a soil solution

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ABSTRACT

Mechanical and environmental effects on stress corrosion cracking (SCC) susceptibility of X52 pipeline steel were investigated using slow strain rate tests (SSRT) performed in a glass autoclave containing a soil solution at strain rate of 1×10^{-6} in./s at room temperature. Polarization potentials of −100, −200 and −400 mV referred to open circuit potential (OCP) was applied in order to establish the effectiveness of cathodic protection in mitigating SCC of X52 pipeline steel. Electrochemical impedance spectroscopy (EIS) tests and scanning electron microscopy (SEM) observations were done in order to analyze the SCC process. SSRT results indicate that X52 pipeline steel was susceptible to SCC. Susceptibility to SCC increase as the yielding stress (YS) and ultimate tensile stress (UTS) increase. The EIS results showed that the highest corrosion of the steel sample was obtained when the highest cathodic over potential was applied. SEM observations of these specimens showed a brittle type of fracture with transgranular appearance. The failure and SCC of X52 steel in soil solution was explained by hydrogen mechanism.

1. Introduction

Stress corrosion cracking (SCC) can occur in both liquid and gas transmission pipelines but is more common and catastrophic in Gas Pipelines. SCC is the most unexpected form of pipeline failure that can involve no metal loss and must not be confused with wall thinning rupture. Although there is a few understanding of the types and causes of SCC, the prediction and location of SCC cracks on operational pipelines is not so well developed. However, the location and removal of SCC cracks before the pipeline bursts uncontrollably is vital for safe operations.

The two common forms of SCC are low pH-SCC and high pH SCC [1–3]. Both forms require a coating failure exposing the steel pipe to the local soil environment where conditions propitiate to SCC exist. SCC has been observed on pipeline coated with tape, coal tar and bitumen [4]. Although all pipeline steels are susceptible to SCC, most of the failures were observed with X52 and X60 low carbon steels.

SCC in buried pipelines is a serious problem that may cause significant economic, environmental and human losses. Despite of many research works to understand the crack initiation and propagation mechanisms, due to mechanical and environmental effects, these cracking mechanisms are still being debated. The complexity of cracking phenomena results from the dependence of metallurgical, mechanical and environmental parameters that may influence both crack initiation and propagation.

For high pH SCC it is well accepted that the mechanism involves anodic dissolution for crack initiation and propagation. In contrast, it has been suggested that the low pH SCC is associated with the dissolution of the crack tip and sides, accompanied by the ingress of hydrogen in the steel [1–3]. The hydrogen concentration plays an important role in this type of cracking. It is believed that applied stresses to the pipe surface are the cyclic nature (fatigue) due to the internal pressure fluctuations and cracking occurs due to synergistic interaction between hydrogen embrittlement corrosion (HIC) and fatigue loading. Cracks propagate as a result of anodic dissolution in front of their tip in SCC process, due to the embrittlement of their tip by hydrogen based mechanism. It was revealed that cracking behaviour of pipeline steel in the soil environment depends of the cathodic protection applied. Studies of potential effects on SCC were developed by Liu et al. [5]. They found that applying different potentials the dominance of SCC process changes. At relatively low potential, the SCC is based primarily on the anodic dissolution mechanism. With the further decrease of the applied potential, hydrogen is involved in the cracking process, resulting in a transgranular cracking mode. With the further negative shift of applied potential, the SCC of the steel follows completely a hydrogen base mechanism, with a river-bed shaped brittle feature of the fracture surface.

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Highest internal cracks were seen in the steel as highest level of cathodic protection was applied, which contribute in cracking mechanism due to hydrogen embrittlement effect. It is recognized that there is two forms of external SCC on underground pipelines. The intergranular form of cracking generally is presented in environments with high pH, this type of cracking proceeds along grain boundaries. By other hand, the transgranular form of cracking is presented in soils with near neutral pH and proceeds across the grain [6,7]. SCC cracks can be either intergranular or transgranular and they propagate in the direction normal to the applied stress.

Cathodic protection applied to the pipeline surface is a factor that influences the SCC mechanism. The mechanism in high pH SCC is known to be related to the passive film formation and anodic dissolution. In this case, intergranular crack morphology was observed. At low pH SCC the mechanism of cracking have been less studied. Crack morphology in this type of SCC is transgranular with a quasi-cleavage fracture surface and secondary internal cracks on the fracture surface [1–3,6–12].

To understand better the mechanism of the crack initiation process on SCC, focus on metallurgical [8,10,13], environmental [2,9,11], applied potential [5,14–16] and mechanical [2,3,9,10,13] properties that can affect the crack initiation and propagation phenomena have been investigated. At least the next three concepts should be considered in the SCC initiation: (1) the sites cracks are initiated in relation to metallurgical factors, such as inclusions, grain boundaries, pits and other defects, (2) the role of applied load, including the effects of stress level, strain rate and elongation, (3) the time dependence of cracking, including existence of an incubation period of time, crack size with time, dormancy and crack growth rate. To understand better the mechanism of the crack initiation process, key metallurgical and environmental elements that can affect the cracking phenomena were investigated and are reviewed in this paper.

The aim of this work is to evaluate the SCC susceptibility on API X52 pipeline steel, in function of the corrosion, mechanical and environmental behaviour in a soil solution at room temperature with near neutral pH and applying different cathodic potentials. Relation between mechanical properties and susceptibility to SCC was studied.

2. Experimental

2.1. Materials

API 5L X52 low carbon steel for this study was used. Steel from this pipeline, which had an external diameter of 36 in. (914.4 mm) and wall thickness of 0.375 in. (9.525 mm), in this work, was studied. Chemical composition of the steel is shown in Table 1. The X52 steel microstructure consisted of fine pearlite and ferrite with a grain size around 10–20 μm. Low carbon steels tend to have a ferrite–pearlite structure containing little pearlite. Additionally, these steels contain a nonnegligible quantity of sulphur forming manganese sulphide inclusions (MnS).

2.2. Test solution

A simulated ground water solution (called NS4) with pH 8.5 as the corrosive environment in this study was used. NS4 synthetic solution has been widely used to simulate the soil solution in the study of near neutral pH-SCC behaviour. However, another synthetic soil solution called NS1, NS2, NS3, NS4, NOVA and C1 has been used in similar studies [9,17,18]. Table 2 shows the chemical composition of the NS4 solution used.

2.3. Applied potentials

An impressed current cathodic protection (CP) system was used to apply the potential of protection and overpotentials. The impressed current anode was a platinum rod. This anode is connected with an insulated cable to the positive terminal of a direct-current (DC) source. The work sample is connected to the negative terminal of the DC source [19].

Three different cathodic overpotentials were used: −100, −200 and −400 mV vs. OCP. It is important to mention that the external corrosion control can be achieved at various levels of cathodic polarization depending on the environmental conditions. However, in the absence of specific data that demonstrate that adequate CP has been achieved, the next criterion is applied: a negative (cathodic) potential of at least −850 mV with the CP applied. This potential is measured with respect to a saturated copper/copper sulphate ($Cu/CuSO_4$) reference electrode [20]. The potential measured with the reference electrode is shown in Table 3.

The main objective of polarized specimen at −1011 mV and −1226 mV vs. $Cu/CuSO_4$ reference electrode mainly was to reach those extreme conditions where pipelines protected by CP in conjunction with coatings could be exposed in service. Those conditions could be promoted by the overpotential near to rectifiers and by the stray current sites that promotes inverse current flow, which reach overpotentials to positive values.

2.4. Corrosion behaviour tests

The electrochemical measurements were performed with an ACM Instruments potentiostat–galvanostat. An electrochemical cell with a three electrodes array was used. Cylindrical tensile samples of X52 steels were used as working electrode, platinum (Pt) rod as counter electrode, while $Cu/CuSO_4$ electrode was used as reference electrode.

Open circuit potential (OCP) was measured during a period of the exposure. According to these measures was possible to found that after 20 min the OCP of the X52 steel showed a stable values. For that reason, the OCP values used in analysis of the presented work were selected after 20 min that the test was begun. All OCP values were measured with a $Cu/CuSO_4$ reference electrode.

The electrochemical impedance spectroscopy (EIS) measures were obtained in NS4 solution at different impressed potential, 0, −100, −200 and −400 mV vs. OCP. In all EIS tests, the frequency range used was 0.01 Hz to 10 kHz with a 10 mV of amplitude. Ten points per decade of frequency were recorded. The EIS were obtained at constant potential applied, the measurement being initiated after reaching the stationary conditions (characterized by a constant current).

2.5. Slow strain rate tests (SSRT)

Slow strain rate tests were carried out on smooth cylindrical tensile samples, which are shown inside of the autoclave in Fig. 1a. These specimens were machined according to the NACE

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

C	Mn	Si	P	S	Cu	Cr	Ni	Nb	V	Ti	Al	Fe
0.08	1.05	0.26	0.019	0.003	0.019	0.02	0.02	0.041	0.054	0.002	0.038	Bal.