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An experimental investigation of the nature of longitudinal cracks in oil and gas transmission pipelines

Hamid reza Hajibagheri [a], Ali Heidari [a, *], Rasool Amini [b]

[a] Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Khomeinishahr/Isfahan, Iran
[b] Department of Materials Science and Engineering, Shiraz University of Technology, Shiraz/Fars, Iran

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ABSTRACT

Oil and gas pipeline maintenance and monitoring are of utmost importance. Therefore, being aware of the pipeline conditions, predicting their failure, planning to manage emergencies and evaluating their conditions are essential. In this study, Magnetic Particle test inspection was performed on a 52-year-old, 6 inch steel pipeline, which was primarily used as an oil transmission pipeline but was repurposed to a gas transmission pipeline later. Longitudinal cracks were found on the pipes during the inspection. Several tests were conducted aiming to clarify the nature of these cracks. The tests included chemical analysis, tensile test, impact test, hardness measurement to determine the type of steel, soil tests to specify the elements present in the soil and to evaluate corrosion conditions of the soil, SEM imaging, optical microscopy, and Energy-Dispersive X-ray Spectroscopy (EDS). The steel was found to be of X46 grade and the tests did not suggest the presence of aerobic as well as anaerobic bacteria in the environment. Moreover, the EDS results did not show any signs of corrosion in the samples. The depth of cracks was measured to be 80 μm. No evidence of hydrogen induced cracking (HIC) and stress corrosion cracking (SCC) which are the main cracking mechanisms of steel transmission pipelines was appeared in the present study. Overall, it is safe to conclude that the longitudinal cracks were formed during fabrication.

1. Introduction

Nowadays, oil and gas transmission pipelines are crucial to every country, making their maintenance obviously important. Various faults such as longitudinal and circumferential cracks and corrosion are some of the challenges associated with pipelines [1,2]. It is well known that the most important damage modes in the underground steels pipelines are stress–corrosion cracking (SCC) and hydrogen induced cracking (HIC) [3–5]. Among different forms of damage in pipeline steel, HIC has been recognized as an important technological challenge to steel manufacturers and the petroleum industry [6]. It has been recognized as the most important failure mode in the transmission pipelines, provided that they buried in the acidic soils. In the acidic soils, due to the corrosion phenomenon, H_2 gas can be produced and arrested between the pipe surface and coating. Under these conditions, the hydrogen gas can be converted to hydrogen atoms which penetrate inside the pipe body due to several reasons [7]. This phenomenon was became intensify when the pipe was cathodically over-protected in the acidic soils. Hejazi et al. [8] studied the role of different types of inclusions on HIC susceptibility in pipeline steels and concluded that aluminum oxide, aluminum-calcium-silicon oxide and elongated manganese sulfide can initiate HIC cracks. Since elongated manganese sulfide provides high stress concentration region, it is often considered the most detrimental of all. Also, Mohtadi-Bonab et al. [7] investigated the effect of different microstructural parameters on HIC in an API X70 steel pipeline. They studied the surface and cross section of an as-received API X70 steel pipeline by SEM and EDS techniques in order to categorize the shape and morphology of inclusions. The results showed that inclusions were randomly distributed in the cross section of tested specimens. Moreover, different types of inclusions in as-received X70 steel were found. However, only inclusions which were hard, brittle and incoherent with the metal matrix, such as manganese sulfide and carbonitride precipitates, were recognized to be harmful to HIC phenomenon.

Alternatively, SCC is known to be one of the most damaging factors to oil and gas pipelines, directly affecting their service life

* Corresponding author.
E-mail address: heidari@iaukhsh.ac.ir (A. Heidari).

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[9]. Two types of corrosion have been identified for buried pipes [10], namely stress corrosion under high pH [11] and neutral or low pH conditions [12]. Cracks grow perpendicular to stress direction; therefore, most SCCs are longitudinal as a result of the hoop stress. However, 10–20% of the cracks are circumferential and are known as C-SCC [13]. In 1985, a different type of stress corrosion was introduced by TransCanada Pipelines (TSPL). Extensive studies showed that wide transgranular fracture and corrosion on crack walls are a characteristic of this type of stress corrosion [14], which is known as the near-neutral pH stress corrosion [15].

Zhang and Cheng [16] investigated the influence of hydrogen on stress corrosion of X100 steel pipes subjected to the neutral pH range. Using Electrochemical Impedance Spectroscopy (EIS), they examined the impact of hydrogen on the electrochemical corrosion behavior of steel pipes in a solution with neutral pH level. Their results suggested that hydrogen charging promotes local cathodic dissolution of steel and helps formation of corrosion product layer. Tang and Cheng [17] addressed the quantitative characteristics of stress corrosion cracking in pipelines using micro-electrochemical measurement of the synergetic effects of hydrogen, stress, and dissolution in neutral environment. Liu et al. [18] addressed the mechanical aspect of stress corrosion crack formation in x70 steel pipelines under cathodic polarization and found a critical potential range (−920 to −730 V_{SCE}). In case the electrochemical potential assumes more positive or negative values compared to this range, cracking takes place through anodic dissolution or hydrogen embrittlement, respectively. In case the polarization potential is in this range, SCC is influenced by both hydrogen embrittlement and anodic dissolution. Using tensile test with a low strain rate, potentiodynamic polarization test, and fracture analysis, Javidi and Bahalaou [19] investigated the influence of cathodic potentials on stress corrosion behavior of X52 steel in a near-neutral pH environment. Moreover, in order to simulate the behavior of the crack tip and walls, they conducted a polarization test with a low strain rate. Their results suggested ductile failure for low applied potential and brittle failure for cathodic potentials.

In the present study, the longitudinal cracks on a 52-year-old, 6-inch pipeline were investigated. To this end, chemical analysis, impact test, hardness measurement, and tensile test were employed to determine the grade of the steel. Soil tests were performed in order to specify the elements present in the soil and evaluate the corrosion conditions of the soil. Moreover, a closer investigation was carried out using optical microscope (OM) and scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscope (EDS).

2. Material and methods

The test sample was prepared from a 52-year-old, *6-in* seamless steel (unknown grade) pipeline of *0.27-in* thickness, which was fabricated in 1963 and was used for transmission of Iranian petroleum products. However, it was repurposed in 1984 for gas transmission at 1050 *psi*. It should be noted that the pipeline is coated with the hot applied Coal Tar.

To determine the probability of cracking occurred along the pipeline, the type of coating, pipe fabrication date, operational conditions and soil characteristics were considered as main factors of investigation [20]. Given the age of the coating and the date of fabrication, a Non-Destructive Testing (NDT) method (Magnetic Particle Inspection) was performed on the pipeline.

Various experiments containing microstructural studies, chemical analysis, and mechanical properties tests were conducted in order to determine the characteristics of the material, nature of cracks, and cause of their formation. For further investigation, the tests were performed on two samples, one of which was taken from an oil pipeline stored in a warehouse after 20 years of service (before gas injection), and the other was cut from a pipeline after the gas was discharged subsequent to 52 years of service.

The chemical composition of the samples (according to the ASTM E415 standard [21]) was determine by a calibrated quantometer. Afterwards, the tensile test was conducted in order to determine the strength and flexibility of the material (according to ASTM A370 standard [22]). Impact test was also employed to investigate the toughness of the material. Notched samples of $10 \times 5 \times 55$ *mm* dimensions were prepared, on which the Charpy test was conducted at a temperature of $0\,^{\circ}C$ (according to ASTM E23 standard [23]). According to Table 20 of API 5L standard [24], the test was performed on three transversal samples. Subsequently, OM images were taken at different location close to and far from the cracks prior and after etching in Nital 2% solution. Vickers hardness test was conducted by applying 10 *g* force (according to ASTM E384 standard [25]) at different locations. Moreover, the microstructure and microscopic chemical composition of the selected samples were evaluated by SEM and EDS, respectively.

3. Results

3.1. Magnetic Particle Inspection (MT) results

The pipeline was excavated in a number of locations and longitudinal cracks were found (Fig. 1). Observations suggest the presence of these cracks all across the course of the pipeline. It is evident from Fig. 1 that the longitudinal cracks are as long as 4 *cm* in some parts of the pipe. Additionally, no sign of corrosion was seen in the visual inspection of the external surface of the sample, and the coating adhesion to substrate was acceptable, which can be a result of favorable cathodic protection.

3.2. Determining the type of the steel

Since no technical information of the pipeline were available in the documents, it was necessary to specify the type and grade of the steel. Consequently, the chemical analysis (Table 1), tensile (Table 2), impact (Table 3), and hardness (Table 4) tests were performed on the samples prepared from the pipes at selected locations. Comparing the test results with API 5L standard for oil and gas transmission pipelines, the steel was found to be of X46 or L320 grade.

Fig. 2 shows the SEM image of the steel pipeline after the mirror polishing and etching in Nital 2%. The microstructure has been

Fig. 1. Cracks detected on the steel pipeline by Magnetic Particle Inspection.