

Implication of Fractographic Analysis of the Crack in an Above Ground Pipeline – Potential Role of Hydrogen

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ABSTRACT

A crack was found in 2020 on a 324 mm (12-inch) OD above ground pipeline externally uncoated but insulated with mineral wool with aluminum cladding. The steel grade of the pipeline is CSA Z245.1 Gr 414 Category II with wall thickness of 7.9 mm (0.310-inch) operating since 2013. The product that the pipeline transports is casing gas and the pipeline is operated at a temperature of 150–200 °C. The circumferential crack initiated on the outer diameter (OD) and grew through-wall. Detailed fractographic analysis showed a mixed mode of fracture: predominantly intergranular separation with a small amount of cleavage corresponding to {001} lattice plane, which is confirmed by mated fracture surfaces and the presence of {001} etching pits. Striation-like features were found on the fracture surface; however, these striation-like features are not due to fatigue. Metallographic cross section analysis also showed the crack paths are mainly intergranular with some transgranular that is consistent with micro-fractographic analysis. Classic high-pH stress corrosion cracking (SCC) mechanism cannot explain the presence of transgranular cracking, and other evidence observed such as the lack of corrosion products at the crack tip, lack of corrosion damage on the grain boundary and the lack of SCC colony on the OD surface of the pipe. These findings led to the potential role of hydrogen in the cracking mechanism observed in the above ground insulated pipeline.

Key words: mineral wool insulation, mixed intergranular and cleavage cracking, hydrogen cracking

INTRODUCTION

Fracture surface morphology is useful in determining the mechanisms involved in cracking. Features in the fracture surface of steel like micro-void coalescence or dimples are often related to ductile crack mode, while features like cleavage, and rock-candy showing grain boundary cracking are commonly related to brittle crack mode. Some fracture surface may have a predominant feature, while others may have presence of mixed features. Types of stress corrosion cracking (SCC) are commonly identified by the features present in the fracture surface. Features showing transgranular quasi-cleavage cracking are often related to near-neutral pH SCC, while features that show rock-candy intergranular cracking are often related to high-pH SCC [1]. Fracture surface morphology provides clues related to the history of the failed specimens, and prevalently used by investigators to identify failure mechanism. Therefore, careful evaluation of these fracture surface features is essential in identifying the correct failure mechanism. However, tiny details present in the fracture surface are most of the times overlooked.

A systematic study of fracture surface morphology was performed as part of the failure analysis of an above ground insulated pipeline with a circumferential crack originating from the outer diameter (OD surface). The pipeline section is made up of CSA Z245.1 Gr 414 Category II (equivalent to API 5L X60 carbon steel) 324 mm diameter (NPS12) pipe with a nominal thickness of 7.9 mm. The pipeline transports casing gas with ~20–34 mol% CO₂, ~0.6–1.5 mol% H₂S and 1.3–3.6 mol% H₂. The pipeline is designed to operate at maximum temperature of 230°C, and the actual normal operating temperature ranged from 150 to 200 °C, with some temperature drops to about 16 °C. The pipe is internally and externally uncoated but wrapped with mineral wool insulation and aluminum cladding fixed with stainless steel straps in order to prevent heat dissipation. The mineral wool in the vicinity of the crack was still intact when removed from the sample. However, there was discoloration in the mineral wool adjacent to the surface of the pipe. The cladding in the area of the failure was in good operating condition and showed no signs of degradation or mechanical damage.

Other similar circumferential cracks have been found at random locations in the same pipeline. Initially, it was postulated that the circumferential cracking from the OD surface is related to stress-corrosion cracking (SCC). It was originally postulated that the environment created by the leachate of mineral wool insulation led to high-pH SCC. The fracture surface morphology is predominantly rock-candy intergranular, which is common to high-pH SCC. However, some of the evidences do not support the postulated high-pH SCC mechanism. Published literature [2] indicated that the pH of leachate depends on which layer of the mineral wool— inner (dark) layer close to the pipe OD surface results to pH of ~5–6, and the outer (light) layer results to pH of ~9–10. White calcite deposits, which could be related to high pH SCC, were also found on some locations on the OD surface of the pipe, but not on all locations where the circumferential cracks were found. Other cracking mechanism or other contributing factors were not fully explored.

The objectives of this paper are to show the importance of fractography and fractographic interpretation to determine the cracking mechanism in a failure analysis, and to discuss the potential role of hydrogen in the cracking phenomena of the above-ground insulated pipe. Each feature observed on the fracture surface of the circumferential crack are reported and discussed. In addition, the results of other analyses complementary to fractography are integrated and the plausible cracking mechanism is presented.

EXPERIMENTAL PROCEDURE

A 1.72 m pipe section with the circumferential crack shown in Figure 1a was cut and retrieved from the existing pipeline. Magnetic particle inspection (MPI) was done to verify the location and the length of the OD surface crack (see Figure 1b). Prior to excising the crack from the pipe section, the hardness within the vicinity of the crack and away from the crack were determined using ultrasonic contact impedance

(UCI), in order to determine if there is hard spot that may have caused the crack to initiate. A grid composed of 25.4 mm x 25.4 mm (1 in. x 1 in.) squares was made around the crack. Triplicate measurements were made for each square. UCI hardness measurements were also done in triplicates in a grid of four squares away from the crack. Figure 1c shows the location of the grids near the crack and away from the crack.

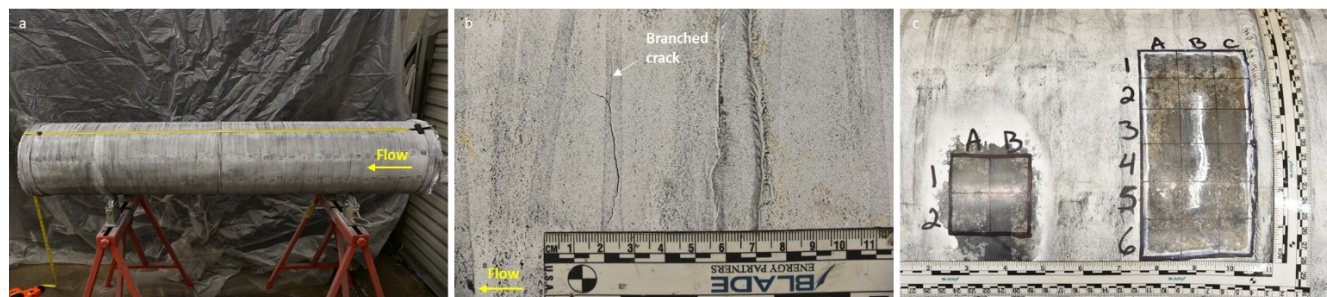


Figure 1: a. Pipe Section, b. OD Circumferential Crack, c. Location of UCI Hardness Measurements

MPI was also done on the inner diameter (ID) of the pipe to show the length and location of the same crack on ID surface. After macro-scale measurements and documentation, a small portion of the crack was cross sectioned and mounted for metallography and Vickers hardness measurements. The pit depths were measured using the mounted specimen. The pit density and pit size (area) in the vicinity of the crack were determined using methods described in ASTM G46 [3]. The remaining part of the crack was broken open in liquid nitrogen temperature for fracture surface investigation.

Characterization of the scale or deposit on the fracture surface was done using Raman spectroscopy. In addition, energy dispersive x-ray spectroscopy (EDS) was used to verify elements present on the fracture surface. Scanning electron microscope (SEM) imaging was done to capture details of the fracture surface morphology. Micro-fractographic analysis of the fracture surfaces was carried out to identify the crack initiation location, to characterize the fracture mode of the crack propagation, and the possible cracking mechanism. The fracture surfaces were investigated in the SEM prior to cleaning to capture features produced in-service condition (those that are with oil deposit), and differentiate with areas produced in the lab (e.g., liquid nitrogen cleavage features). The fracture surfaces were then successively cleaned by sonicating in acetone, and then in 1 wt% Alconox solution to remove the oil deposit on the fracture surface. The samples were rinsed off with distilled water and then methanol.

RESULTS

Hardness and Microstructure

The circumferential crack on the OD surface is slightly curved (as shown in Figure 1b), and is ~35–40 mm away (downstream) from the girth weld. The crack on the OD surface is ~62 mm long including the branched crack. The length of the crack on the ID surface is about ~16 mm long, much shorter than the same crack on the OD surface (~62 mm long). Figure 2 is a side-by-side comparison of the length and location of this through-wall crack on OD and ID surfaces, showing about 16 mm difference between the location of the crack on OD and ID surfaces with respect to the BD edge (see Figure 2, the BD edge served as a common reference for the through-wall crack on OD and ID surface). This means that crack initiates from the OD side and propagates toward the ID in an inclined manner.

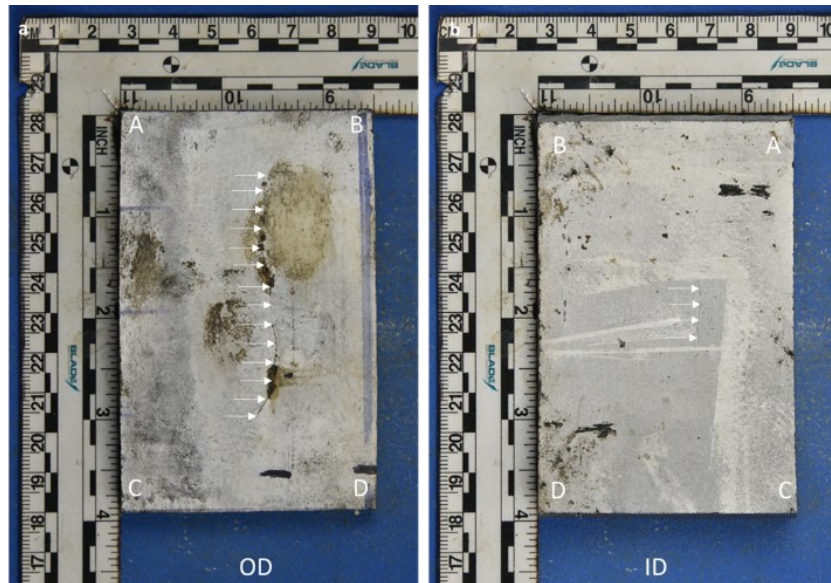


Figure 2: Crack in the a. OD Surface, and b. ID Surface

The average values of UCI Vickers hardness near the crack for columns A, B, and C are 204.56 HV, 205.94 HV, and 205.5 HV, respectively (Figure 1c). The average values of UCI Vickers hardness measured ~110 mm away from the crack for columns A, and B are 200.5 HV, and 199 HV, respectively (Figure 1c). These measurements indicate that there is no hard spot in the vicinity of the crack in accordance with API 5L (2007) hard spot definition of $HV \geq 345$ [4]. Vickers hardness values were verified using indentation of mounted specimen with 0.5 Kg load. Two samples obtained near the crack (Mount 1 crack mouth and Mount 2 crack tip) and one sample 180° away from the crack (Mount 3) were mounted, polished and etched. Hardness measurements were obtained in the OD, ID, and mid-wall. Table 1 shows the values obtained for the three (3) mounted samples. There is no significant difference from the OD Vickers hardness values for Mount 1, Mount 2, and Mount 3. This supports the previous finding that there is no hard spot in the vicinity of the crack.

Table 1: Vickers Hardness Values Obtained Using 0.5 Kg Load (Mean $\pm$ 1 Std Dev)

Sample	ID	Mid-wall	OD
Mount 1 (Crack Mouth)	178.50 $\pm$ 9.70	169.40 $\pm$ 1.49	191.03 $\pm$ 5.08
Mount 2 (Crack Tip)	176.43 $\pm$ 7.97	175.33 $\pm$ 6.70	196.40 $\pm$ 5.72
Mount 3 (180° away)	185.50 $\pm$ 3.14	183.13 $\pm$ 2.13	191.17 $\pm$ 1.70

From Table 1, the hardness in the OD is higher compared to the values obtained from mid-wall and ID. This can be explained by the difference in microstructure along the through wall thickness of the specimens. Figure 3 shows the microstructure of Mount 1 observed under 200 $\times$ magnification. The region near the OD contains fine ferrite, pearlite grains. The mid-wall has coarse ferrite, pearlite grains, while the ID has mixed fine and coarse ferrite, pearlite grains.

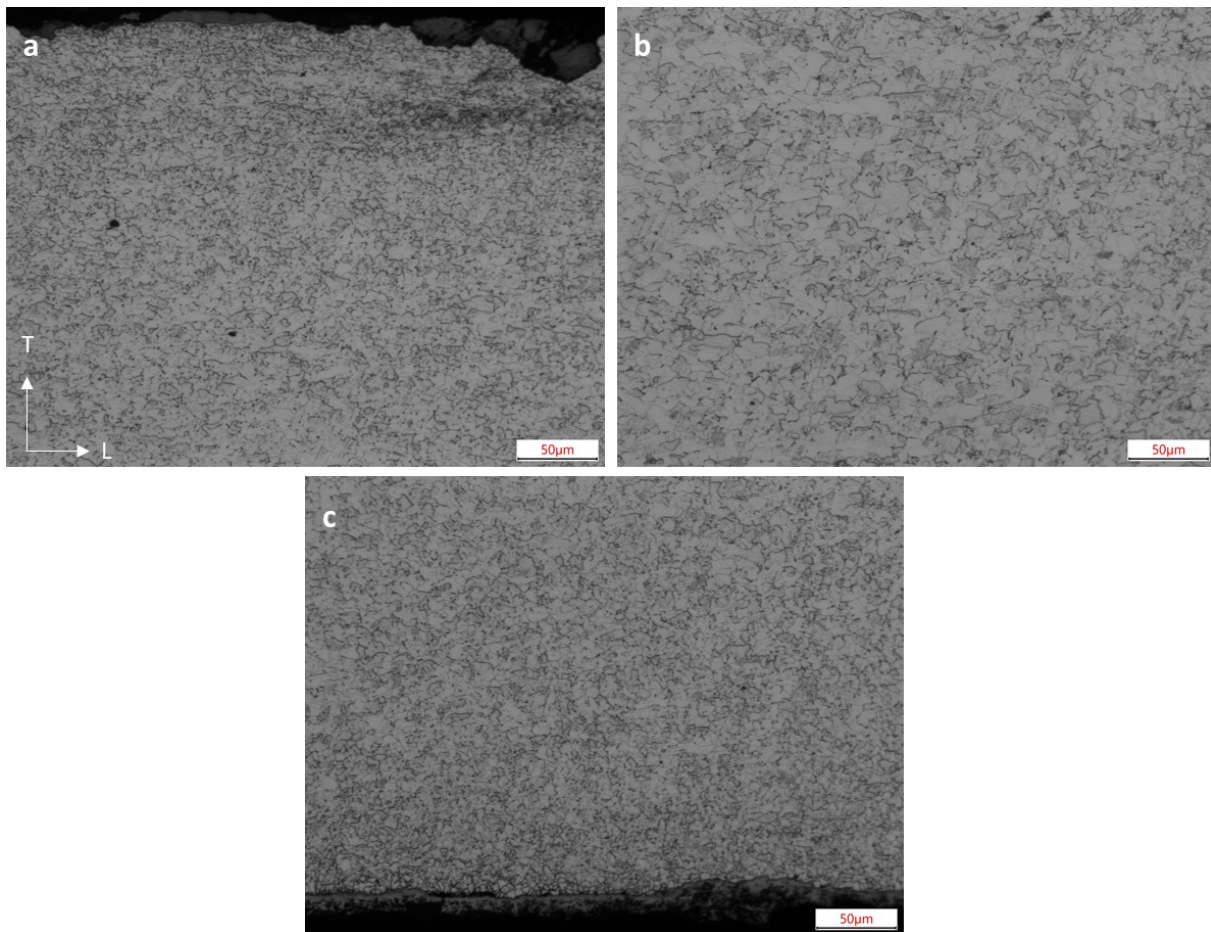


Figure 3: Microstructure of Mount 1 Crack Mouth at 200× a. OD, b. Mid-wall, c. ID

Figure 4 shows OD surface of the Mount 1 viewed at 400× under optical microscope (Figure 4a) and at 1000× in the SEM. The images show that there is no decarburized layer present in the OD surface in the vicinity of the crack.

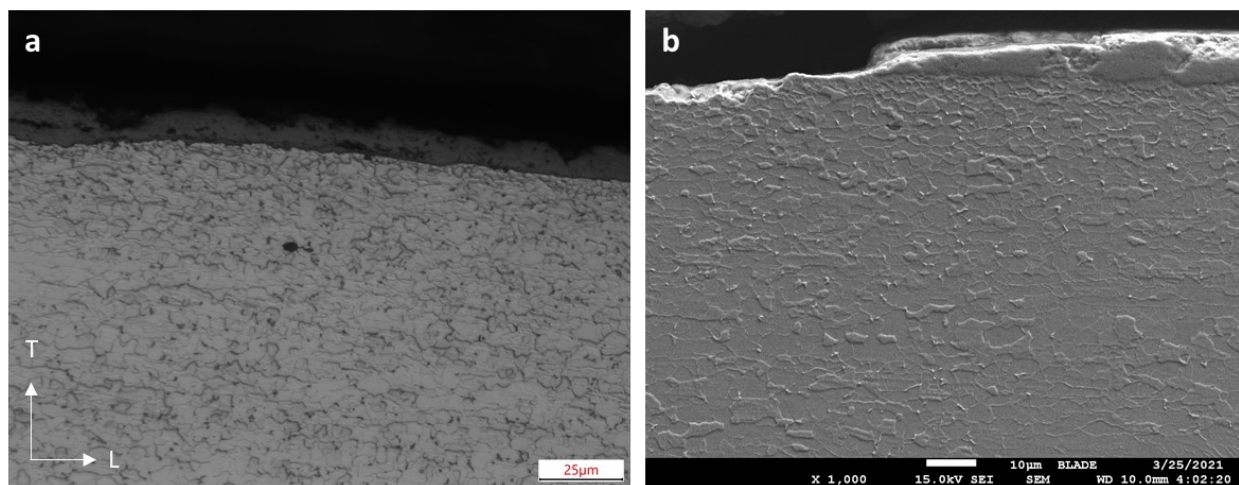


Figure 4: High Magnification Images of Mount 1 OD Surface a. 400× Optical Image; b. 1000× SEM Image