Grooving corrosion of seam welded oil pipelines

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A B S T R A C T

24” pipeline carrying oil was failed in the form of longitudinal crack at the 6 O’clock position resulting in oil spill. The failed pipe was investigated to reveal the main cause of its failure. The procedure of investigation was built on studying the intact pipe, rupture area, parent material, and intact weld. Results of chemical analysis, mechanical properties, and microstructure of the pipe material were confirmed with the specified standard. Cracks were originated from weld defected sites, initiated by grooving corrosion, propagated by inertia at the normal designed pressure condition, and stopped when stress relief is attained. It is recommended to use high quality ERW pipe, with its seam weld line positioned around the 12 O’clock during installation, to minimize and decelerate grooving corrosion. It is also important to perform regular or routine inspection, on suitable intervals, determined by past experience.

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1. Introduction

An oil pipeline of 24” diameter was installed in the Eastern Desert 25 years ago. It has experienced many leaks. Pipeline and operating data are shown in Table 1. A recent intelligent pig inspection was conducted, revealing that the line was suffering an extensive internal corrosion. Periodic cleaning was adapted to prevent further deterioration; nevertheless, a pipe failure has taken place in the form of 2 m longitudinal crack at the 6 O’clock position. Effective actions and precautions were carried out to prevent polluting the coast.

For steel pipelines, one of the most dominant forms of deterioration is corrosion which decreases the metal cross-section. This results in a reduction of pipeline carrying capacity and safety. Electric resistance welded (ERW) carbon and low alloy steel pipes may suffer preferential corrosion attack in the weld area when exposed to neutral, salt-containing waters resulting in premature leaking. The selective and localized corrosion prefers to occur in the weld, especially close to the fusion line. ERW seams in the presence of a corrosive environment are susceptible to preferential attack at the bond line. Because of alloying element mismatch existing between the base metal and the weld resulting from the ERW process, the weld generally becomes less resistance to corrosion due to the small decrease of alloying elements, as demonstrated by Zongyue et al. [1]. Chemical composition, microstructure, and the use of post-weld heat treatment can greatly affect the grooving tendency of ERW pipes, through formation of non-metallic, MnS inclusions and redistribution of sulfur by the thermal cycle of the ERW, as demonstrated by Lee et al. [2], Lee and Lee [3], and Wang [4,5]. The material at the bond line is anodic to the surrounding material and the result is a V-shaped groove with the apex of the V centered on the bond line, as demonstrated by Quickel et al. [6].

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The post-weld heat treatment with higher temperature can reduce the small change in chemical compositions through the diffusion process and can thus improve the resistance to grooving corrosion. By using a fracture mechanics approach, Feng et al. [7] have shown that the pipeline may leak before break under the normal designed pressure, and the lack of fusion defects in the weld may propagate under the condition of fluctuating pressure. The failure cause of the present case was investigated to establish an overview of whether the failure is related to any aspects of the material or operating conditions.

2. Experimental procedure

Visual inspection of the internal and external surface of the failed pipe was performed. Rupture is located within the seam weld line, suggesting the presence of welding defect which requires full NDT inspection to locate the origin of the first opening. Therefore, magnetic and dye penetrant tests were performed to determine crack extension zone and to identify whether failure has initiated from external surface or not. The radiograph test was performed to detect internal defects such as porosity, lack of side wall fusion, incomplete penetration, and slag inclusions. Scale analysis using XRF and XRD was also performed.

Measurement of the remaining wall thickness was carried out and a contour map around the fracture area was drawn and analyzed. In addition, through examination of fracture surface was carried out using stereoscopy. Material conformity was verified through chemical analysis, mechanical testing; mainly hardness profile, tensile, and Charpy impact tests. Macro and microstructure investigations were performed for different cross sections of both failed and intact segments of the pipe. Also, fracture surface was observed by SEM and analyzed by EDX.

3. Results and discussion

Fig. 1 shows general views for the external and internal surfaces of the failed pipe segment. Visual examination showed that solid debris and rust were covering the external surface, whereas a scale layer of 1.15 mm thickness was found on one side of the inner surface and extensive corrosion on the other side, in areas up to 350 mm on both sides of the crack.
Failure has taken place as longitudinal crack at the 6 O’clock position with noticeable bulging in several sites of the ruptured zone. Crack opening at the outer and inner sides had lengths of 1.90 and 1.99 m respectively, and its maximum opening distance was 150 mm. The inner surfaces of the bulged sites were corroded extensively suggesting anodic weld line. These sites are thought to be areas within the seam weld line containing welding defects such as lack of fusion or inclusions and were preferred sites for crack initiation.

Fig. 2 shows the different non-destructive tests performed on both outer and inner surfaces of the failed pipe segment. Magnetic particles examination of the outer surface 150 mm on both sides of the rupture, detected only hook crack at the end of one side of the rupture (see Fig. 2a). Dye penetrant applied to the internal surface showed incomplete penetration and lack of fusion, deep pitting or cavities and thinning of wall thickness (see Fig. 2b). Meanwhile lack of side wall fusion and incomplete penetration were the dominant defects. Radiographic examination of areas on both sides of the ruptured zones has confirmed the dominant presence of lack of fusion on both sides in addition to the thinning, pits, and scales (see Fig. 2c).

Table 2
Chemical analysis of the pipe material elements results (wt.%).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Results (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (C)</td>
<td>0.144</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td>0.336</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>1.04</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>0.013</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>0.006</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>0.008</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>0.016</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>0.035</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>0.014</td>
</tr>
<tr>
<td>Niobium (Nb)</td>
<td>0.03</td>
</tr>
<tr>
<td>Vanadium (V)</td>
<td>0.005</td>
</tr>
<tr>
<td>Tungsten (W)</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Scale analysis of samples collected around the crack showed high content of Fe₂O₃ and BaO on the inner surface, whereas SiO₂, Cl, CaO, and Fe₂O₃ were obtained on the outer surface.

Thickness measurement was also carried out on the area around the ruptured zone. Fig. 3 shows contour graph and 3-D graph for the actual remaining wall thickness around rupture, noting that the ruptured area represents 0 mm remaining wall thickness. A minimum wall thickness less than 3 mm has taken place exactly on the seam weld line, immediately around rupture, at the root of the seam weld. The 3-D graph shows the change of the internal surface topography into hill and valley form. Maximum reduction in thickness few millimeters in both sides of the seam weld line is indicated by dark blue color.

Fracture surface examination was carried out, after through ultrasonic cleaning. Stereoscopic images of the fracture surface have shown smooth un-melted areas within the fusion zone of the seam line, close to the inner surface of the pipe otherwise, it was nearly rough, full of dull holes and undercuts (see Fig. 4).
Table 3
Results of tensile test.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation % age</th>
<th>Rupture site</th>
</tr>
</thead>
<tbody>
<tr>
<td>L 90</td>
<td>376</td>
<td>539</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>T 90</td>
<td>437</td>
<td>568</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>T 180</td>
<td>446</td>
<td>578</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>228</td>
<td></td>
<td></td>
<td>Seam weld</td>
</tr>
</tbody>
</table>

Chemical analysis of the pipe material is given in Table 2, and the results of tensile test are given in Table 3. The hardness values obtained were almost around 200 Hv, whereas the hardness values of the weld line, measured inside the fusion zone have a mean value of 230 Hv.

Charpy impact test was carried out at room temperature for specimens prepared from intact weld on both sides of ruptured zone, with their V-notch centered in the fusion line. A mean value of 17 J was measured, which corresponds to 85 J of the original specimen size. The fractured surfaces of the impact specimens showed un-melted regions within the seam weld line, supporting the presence of lack of fusion, close to the pipe inner surface (see Fig. 5).

Microstructure of the intact pipe material has shown a fine grained ferrite–pearlite structure, having no abnormalities (see Fig. 6a). Microstructure of the seam line of ERW process showed extensive deformation of the faced edge grains, with dark undefined inclusions along the seam line (see Fig. 6b). These inclusions could be the origin of the un-melted zones and lack of fusion within the weld line.

Macrograph of a cross section through the weld line at earlier stage has shown grooving corrosion at the root opening (see Fig. 7a), whereas a similar micrograph close to the ruptured zone (see Fig. 7b) has shown a V-shaped grooving at the root of the seam weld, with the apex of the groove located at the center of the fusion zone. It can be noticed that the remaining wall thickness before rupture was 2 mm.

The results obtained from chemical, microstructure, hardness, and tensile tests indicate the conformity of the pipe material with API 5L standard, grade X-42. Non-destructive testing using dye penetrant showed that the lack of side wall fusion and incomplete penetration of the seam weld line were the dominant defects. Radiographic examination has also confirmed the dominant presence of lack of fusion. Fracture surfaces have also shown smooth un-melted areas within the fusion zone close to the inner surface of the pipe. Also, fractured surfaces of the Charpy impact test specimens showed un-melted regions within the seam weld line, close to the pipe inner surface (see Fig. 5).

Incomplete penetration could be related to insufficient heat input and/or wider root opening, whereas lack of side wall fusion could result from wrong upsetting and improper edge cleaning. The later was evident on the microstructure, whereas undefined inclusions were observed along the seam line. These un-melted regions within the seam weld line, related to one or more of the above-mentioned reasons, served as sites for liquid penetration and initiation of localized corrosion.

Presence of grain deformation related to welding process dirty, or undefined inclusions within the seam weld line, provide heterogeneous anodic sites, compared to the pipe homogeneous material, leading to the formation of localized corrosion cell. Preferential attack of the ferrite grain boundaries at the seam weld line took place resulting in material loss until reaching the un-melted weld region and hence crack was opened.

This type of corrosion in the seam weld line of the ERW pipes is known as grooving corrosion. Due to size-effect in the localized galvanic corrosion cell (small anode/large cathode), corrosion initiated in these un-melted pockets propagates rapidly, resulting in excessive wall thinning (loss in metal thickness) within the seam weld line, up to critical values as shown in the contour graphs (see Fig. 3). The thickness of the steel pipe reached values lower than the critical thickness required for supporting the operating stresses, which resulted in ductile failure of the pipe. The bulged sites were evidence for reaching

Fig. 5. Stereoscopic images for the un-melted regions within the seam weld line after impact test.
the critical thickness but could not detected at the proper timing, therefore, the degraded pipe segment was suddenly ruptured, releasing oil. The presence of a main crack, together with smaller ones in the seam weld line, resulted in the formation of an effective autocatalytic corrosion cell. In both cases critical wall thickness is attained, yet crack length is determined by the amount of stress to be released. Therefore, the lack of ERW fusion together with grooving by corrosion
played the main role in crack initiation, while operating pressure with wall thinning were the driving force for crack propagation.

4. Conclusions and recommendations

Based on the results obtained in the investigation, the following conclusions and recommendations could be submitted.

1. Failure of the pipeline segment is directly related to a poor quality ERW process, since incomplete penetration, un-melted zones, and lack of fusion close to the pipe inner surface were present on extended regions along the seam weld line.
2. Grooving corrosion is largely accelerated by the above-mentioned welding defects, leading to rapid thinning in these defective regions of the seam weld. At a critical wall thickness, the radial stress of the flowing fluid exceeds the pipe hoop strength leading to crack initiation and propagation until stress relief is attained.
3. It is recommended to use high quality ERW pipe with its seam weld line positioned around the 12 O’clock during installation, to minimize and decelerate grooving corrosion. Also, alloying additions such as Cr, Ni, Cu, and Ca, if added to steel can decrease its corrosion rate.
4. A suitable monitoring method for detecting bulging of any segment in the line is recommended to avoid sudden failure.
5. Regular or routine inspection, on suitable intervals, determined by past experience, with each pipeline and pipes quality is a must.

References