Cracking Failure Analysis of Pipe to Flange Weld Joint

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Abstract. Cracking failures occurred frequently in blowdown pipe to flange weld joint, and the root crack appeared on the blowdown pipe side of the weld joint and extend into the base metal of pipe. To explore the reason why cracking failures occurred on the blowdown pipe side of the weld joint, the weld joint was analyzed via macroscopic and metallographic structure observation, and blowdown pipe was tested by physical and chemical property testing, and corrosion scale was analyzed by SEM, EDS, and XRD. The dent and thinner wall thickness of pipe are found in the internal pipe to flange weld joint. Widmanstatten metallographic structure is found in heat affected zone (HAZ), fusion zone (FZ) and weld metal zone (WZ) of weld joint. Stress concentration form in the weld joint at blowdown pipe side during welding due to the dent and different wall thickness. Under the action of gas vortex in the dent of weld joint, corrosive droplets aggravate the localized corrosion of the weld joint. Stress corrosion cracking (SCC) were initiated in FZ and WZ from the surface of weld joint and propagated into the base metal of pipe under the combined actions of stress resulting from weld process and during operation, and corrosion.

Keywords: Hydrogen sulfide; Pipe; Weld; Stress Corrosion Cracking; Failure.

1. Introduction
During the construction of pipeline in sour gas station, welding is often used to joint pipe sections. At present, corrosion in weld joint of pipe is the biggest internal corrosion problem in sour gas station [1], which is detriment of the safety operation and integrity management of sour gas station [2]. Different types of metallographic structures with different distributions and ratios are generated at the weld joint of pipe in sour station due to heat input during welding [3-5]. Thereby, the weld joint can be divided into base metal zone (BZ), heat affected zone (HAZ) and weld metal zone (WZ), among which HAZ is the most sensitive to corrosion [1]. In recent years, frequent failures of weld joint in sour gas stations [6-9] have gained more attentions. Unlike the long-distance pipelines that are butt welded by using the same steel grades and wall thicknesses pipes, most pipe sections in sour stations are butt welded by using different steel grades or different inner diameter pipe sections [10]. At present, there are rare studies on pipe to flange weld joint especially in sour gas station, and the reason of the failure is unclear, which severely delay the development of integrity management of sour gas station.
In sour stations, the pig receiver flange and the blowdown pipe are connected by welding. After service for over ten years, cracking frequently occurred at the root of weld joints near to the blowdown pipe side. It is necessary to find out the causes of cracking through failure analysis of weld joint. The blowdown pipe is made of No. 20 carbon steel with size of Φ57×4.5, as while the flange model DN50 PN10MPa behave thicker wall thickness and the same steel grades. The material performance met the standards [11-12] during the construction of the sour stations. However, there were no requirement about post-weld heat treatment and hardness test. In some sour station, the operation temperature was 20℃ and the operation pressure was 5.6MPa. The natural gas is composed of 92.9% methane, 0.13% ethane, 1.46% hydrogen sulfide, and 3.56% carbon dioxide. The water type is NaHCO$_3$. When gas transmission is off, the pipes are directly exposed to the atmosphere.

In this paper, the metallographic structure and cracks in weld joint, as well as the macro and micro morphology and corrosion products formed on the inner wall were analyzed in order to find out the cause of cracking failure.

2. Experimental analysis

2.1. Appearance analysis
Cracks appear at the root of weld joint near to the blowdown pipe side and away from it (by about 1cm). Crack with a length of 95mm display in the weld joint (Fig. 1), and the two step-shaped cracks connect together, which is shown in the arrow area (Fig. 1(a)). Cut out a section of the failed weld joint, and it is found that the wall thickness of flange neck is obviously thicker than that of blowdown pipe (Fig. 1(b)). The wall thickness of flange neck is 4.26-4.54mm, while the wall thickness of blowdown pipe is 1.28-2.22mm. Corrosion morphology of weld joint after the removal of scale was observed by S-3700N Scanning Electron Microscope (SEM) equipped by EDS. Distinct dent appears near to blowdown pipe side in the inner wall of weld joint and maximum width of dent reaches about 4mm (Fig. 1(c)). At the same time, the surface in BZB is smoother than in WZ (Fig.1 (c)).

2.2. Physical and chemical property testing
According to GB/T 228.1-2010 standard [13], five samples with the dimension of 77mm × 13mm × 2mm and with 32mm original gauge length and 10mm original gauge width are taken in the base metal zone of blowdown pipe with no crack for tensile test. The stress-strain curve of the blowdown pipe is tested by the Rigel RGM-4300 electronic universal testing machine. The test results show that blowdown pipe behaves 447-480MPa tensile strength and 13%-15% elongation, among which the tensile strength met the standard recommended value (410-540MPa) stipulated by GB/T 8163-1999 standard [11], but elongation is lower than the standard recommended value (20%) by GB/T 8163-1999 standard [11].

![Fig. 1 Macro appearance of fracture surface (a) and wall thickness of welding joints (b)
Samples were cut along the directions parallel to the pipe axis at different o'clock positions. According to GB/T 4340.1-2009 standard [14], the average hardness of BZ, HAZ, WZ of each sample at different o’clock position was tested for three times with a digital micro hardness tester (HVS-1000) with 200g load. As can be seen in Table 1, the average hardness value of WZ is the hardest one, followed by HAZ, and BZ has the least hardness. SY/T 0599-1997 standard [12] requires that the hardness in weld, heat-affected and base materials zones should be less than or equal to 22HRC. After converted by GB/T1172-1999 standard [15], it should be less than or equal to 235HV. By comparing with the standard values, it is found that the hardness of BM met the required value, but the hardness of HAZ and WZ did not meet the required value.

Table 1. Results of hardness test (HV)

| Location, o’clock | 0    | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
|-------------------|------|------|------|------|------|------|------|------|------|------|------|------|
| Base materials zone | 208.8 | 210.7 | 210.8 | 203.1 | 207.4 | 201.6 | 215.3 | 214.1 | 212.9 | 209.7 | 213.3 | 208.7 |
| Heat-affected zone | 243.5 | 222.6 | 237.6 | 222.1 | 241.8 | 234.4 | 228.9 | 246.7 | 238.6 | 240.0 | 228.9 | 233.4 |
| Weld zone         | 282.2 | 282.4 | 278.2 | 263.8 | 273.7 | 284.7 | 272.3 | 276.6 | 285.7 | 282.7 | 276.8 | 280.1 |
| Standard value    |      |      |      |      |      |      |      |      |      |      |      |      |
| Less than or equal to 235HV (or 22HRC) |

2.3. Metallographic analysis

Testing according to GB/T 13298-2015 standard [16], the metallographic structure of weld joint was observed by OLYMPUS GX71 metallurgical optical microscope (OM). According to Fig. 2 (a) and Fig. 2 (b), the weld joint consists of base metal zone of flange (BZF), fusion zone of flange (FZF), heat-affected zone of flange (HAZF), weld metal zone (WZ), fusion zone of blowdown pipe (FZB), heat-affected zone of blowdown pipe (HAZB), and base metal zone of blowdown pipe (BZB). The maximum width of HAZF is 1.1mm, but the maximum width of HAZB is 3.0mm. The BZF and BZB of weld joint are both composed of white ferrite equiaxed grains and black lamellar pearlite, but BZF contains more pearlite. Using TIGER3000 metallographic image system, the content of pearlite in BZB metallographic structure is tested as 22%, which is in consistent with standard structure of the No. 20 steel. Meanwhile, the metallographic structure of WZ is composed of Widmanstatten structure (white proeutectoid ferrite and pearlite, and there is acicular ferrite and granular bainite in crystals) (Fig. 2 (c)). FZB is also composed of Widmanstatten structure, but the content of acicular ferrite reaches 54% (Fig. 2 (d)). Based on Fig. 2 (c) and Fig. 2 (d) HAZB can be divided into coarse-grained heat-affected zone (CHAZB) and fine-grained heat-affected zone (FAHZB). CHAZB has a coarse structure and obvious networked grain boundaries, and the grain sizes reach 200-300μm. HAZB is composed of white ferrite equiaxed crystals and black flaky pearlite, but some of the crystal grains contain obvious Widmanstattenite structure. The metallographic structure of FAHZB is the same as that of BZB, aside from obviously finer grains.
2.4. Cracks and fracture morphology analysis

The dent of weld joint was observed by SEM. There exist distinct different corrosion morphologies in BZB and WZ of weld joint (Fig.3(a)). Cracks extend along circumferential weld between BZB and WZ, and some cracks extend into BZB (Fig.3(b)).

As is shown in Fig.4, cracks appear in WZ and FZB respectively, which shows that WZ and FZB are sensitive zones. Crack is found in WZ and they have penetrated the wall (Fig.4(a)). Cracks are also found in FZB, but they have not penetrated the wall (Fig.4(b)) and the crack extends from the surface of weld joint into matrix material and through grains, as indicates that transgranular corrosion occur in FZB.
2.5. Analysis of corrosion products

It is observed that inner wall of the blowdown pipes is coarse, and covered by loose, brittle dark gray corrosion scale. The loose corrosion products in the dents are composed of many particles and (Fig. 5(a)). Corrosion product was also analyzed by DX-2700 XRD, the chemical composition of corrosion scale in the inner wall consists of ferrous sulfide and polysulfide (Fig. 5(b)).

3. Discussion

3.1. Corrosion factor of failure

Due to temperature and pressure changes, the gaseous water in the natural gas turns into liquid water droplets. Hydrogen sulfide and carbon dioxide are dissolved in the liquid water droplets, which forms corrosive droplets. Then the corrosion droplets collide with the pipe wall and condensate, hydrogen sulfide and carbon dioxide corrosion occur. According to the reaction (1) and the reaction (2), ferrous sulfide and ferrous carbonate corrosion products are generated. In acid environment, the solubility product constant of ferrous sulfide is much smaller than that of ferrous carbonate, thus ferrous sulfide is preferentially precipitated [17]. As a result, the corrosion products are mainly composed of ferrous sulfide or iron polysulfide, and ferrous carbonate has not been tested out [17].

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Fe + H_2S \rightarrow FeS + 2H_{ad} \quad (1)
\]

\[
Fe + H_2CO_3 \rightarrow FeCO_3 + 2H_{ad} \quad (2)
\]

Since there exit dent at the inner side of weld joint, vortex will be generated at weld joint [18] when natural gas flows from the flange to the blowdown pipe. Accordingly, the vortex causes corrosive droplets and particles to circulate at the weld joint, increasing the chance of collision and friction between the droplets or particles and inner pipe wall. Such collision and friction bring out two results, firstly, corrosive droplets condense on the inner pipe wall, which leads to electrochemical corrosion, and finally forms corrosion products. Secondly, corrosion products fall off due to the friction and collision, accelerating corrosion in the dents of the weld joint. Therefore, worse corrosion came out near to blowdown pipe.
3.2. Stress factors of failure

For weld joint, the axial stress and hoop stress formed during welding and operation are concentrated on the inner wall of the weld joint [19]. Moreover, stress concentration focuses at weld joint near to the side of blowdown pipe due to the thinner wall thickness than that of flange, where cracks initiate and propagate.

3.3. Cracking mechanism

Compared to the metallographic structure in BZB, there is more Widmanstatten structure in WZ, fusion zone (FZ) and HAZ of the weld joint, and the highest content of Widmanstatten structure and coarse grains with a large amount of acicular ferrite come out in FZ. At the same time, the hardness in HAZ and WZ display over the required hardness. Therefore, the toughness and plasticity of the weld joint decrease rapidly when stress concentrated at weld joint. The stress concentration in the dent promotes the distortion of the material structure lattice, enhances the reaction activity of the deformed parts in HAZ, FZ and WZ, and accelerates the local corrosion of the weld joint. Under the combined action of stress and corrosion, the local corrosion area tears to initiate microcracks. The material structure lattice at the microcrack tip is plastically deformed under tensile stress. The corrosion always occurs resulting from the internal stress concentration field and exfoliation of corrosion scale at microcrack tip. Stress corrosion cracking (SCC) propagate constantly under the combined actions of corrosion and stress. Finally, the cracks propagate through wall thickness and the circumferent direction at the same time. For FZB, these two different crystals of HAZ and WZ are combined together and result in forming unmatched the crystal lattice, as is prone to produce stress concentration. Stress concentration in FZ promotes the extend of cracking under the action of transgranular corrosion.

Fig.4 Corrosion morphology and corrosion products of weld joint
4. Conclusion
Stress concentration forms in the dent of weld joint during welding and operation, especially in FZB, HAZB and WZ of failed weld joint, as results in the lattice distortion. Under the action of stress, the lattice distortion at the Widmanstatten structure in FZB, HAZB and WZ will accelerate the dissolution in corrosive environment and cause distinct localized corrosion. Under the action of gas vortex due to dent in weld joint, corrosive droplets aggravate the localized corrosion of the weld joint. SCC occurs in the dent of weld joint under the influence of corrosion and stress concentration.

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