Analysis for the welding crack leakage of deethanizer

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Abstract: A deethanizer made of 16MnDR steel was found medium leakage used by a company shortly after weld repair. The cause of the welding crack leakage was analyzed by means of morphology examination, chemical composition analysis and hardness test, residual stress test, metallographic examination, and microscopic metallographic analysis. The results show that the crack produced by the 16MnDR pressure vessel after weld repair is a typical liquefaction crack of weld metal. Improper control of repair operation process results in abnormal microstructure, excessive hardness and excessive residual stress at repair welding position, which leads to the formation of longitudinal microcrack, and further expansion in use to form penetrative crack leakage.

1. Introduction

A deethanizer was found medium leakage used by a company in Nanjing in 2018. The deethanizer is a main pressure vessel in the ethylene-ethane distillation system. An obvious crack was inspected on the welding joint between the ellipsoidal head and the cylinder shell after the deethanizer was stopped. The total length of the crack was about 25.5mm, and the crack direction was about 80° from the weld direction, as shown in Fig.1.

Fig.1 Leakage location of the deethanizer

The deethanizer had the design pressure of 3MPa, the design temperature of -25 ~ 90°C, the working pressure of 2.59 (top)/2.61(bottom)MPa, the working temperature of -14 ~ 63°C. The working medium...
was hydrocarbon, which was mildly harmful, flammable and explosive. The pressure vessel was designed and manufactured in accordance with GB 150-2011 and put into use in 2015. The shell material of the deethanizer was 16MnDR with the thickness of 40mm. After inspection of the manufacture document of the vessel, the leak position was RT film of B1-8. During the first periodic inspection in 2018, a crack was found in the depth of 26mm near the leak position. After on-site weld repair, it passed RT test and put it into use subsequently.

16MnDR steel is a steel smelted by adding trace alloying elements such as niobium, nickel, vanadium on the basis of the original main strengthening elements manganese and silicon, and adopting measures of smelting high-purity steel and micro-alloying. 16MnDR steel has sufficient strength and excellent low-temperature toughness and the lowest operating temperature can reach -40 °C [1]. At present, 16MnDR steel is used in low-temperature storage vessels, transportation pipelines and service equipment in cold areas such as liquefied petroleum gas, liquid ammonia, liquid oxygen and liquid nitrogen. It has been widely used in pressure vessels, refrigeration, chemical equipment, vehicles and other industries[2]. However, the structure of low-temperature pressure vessels made of 16MnDR steel are complex, and the shells thickness are relatively thick. Thus the microstructures of weld seam and heat-affected zone are not uniform in the welding process, and there is a large residual stress after welding, which leads to many types of cracks in the weld joints. Especially in the partial repair weld process of 16MnDR pressure vessel, the preheating condition and the whole heat treatment effect in the manufacturing process cannot be achieved because the conditions of pressure vessel in service are limited, which aggravate the serious problems[3].

2. Document examination

According to the document of the product quality assurance, the shell thickness of the circumferential butt joint B1 was 40mm. The groove of the joint was V-shaped of 60° with the blunt edge 6mm, and the butt clearance was 0~1mm. A crack was found in the joint during the first periodic inspection. The crack was eliminated by mechanical polishing, and then repaired by gas tungsten arc welding. The repaired welding wire was ER50-G with the diameter of 1.6mm, and the welding current was 80~120A. The repaired preheating measure and post weld heat treatment adopted local electrical heating method. The chemical composition and mechanical property of the shell at the joint B1 and the welding wire were shown in Tab.1 to Tab.4. The local heat treatment procedure after repaired welding were shown in Fig.2.

| Table 1 Chemical composition of the 16MnDR shell at the joint (%) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Elements        | C   | Si  | Mn  | P   | S   | Ni  | Alt |
| Standard specified values | ≤0.20 | 0.15~0.5 | 1.2~1.6 | ≤0.025 | ≤0.012 | ≤0.4 | ≥0.02 |
| Measured values  | 0.17 | 0.31 | 1.35 | 0.022 | 0.008 | <0.01 | 0.02 |

| Table 2 Mechanical property of the 16MnDR shell at the joint |
|-----------------|----------------|----------------|----------------|----------------|
| Items           | Yield strength $R_{p0.2}$ (Mpa) | Tensile strength $R_m$ (Mpa) | Elongation after fracture A (%) | Impact value AKV-40°C/ (J) |
| Standard specified values | ≥285 | 460~590 | ≥21 | ≥47 |
| Measured values  | 315 | 564 | 37 | 77, 83, 81 |

| Table 3 Chemical composition of the welding wire ER50-G (%) |
|-----------------|-----|-----|-----|-----|-----|-----|-----|
| Elements        | C   | Si  | Mn  | P   | S   | Cr  | Ni  |
| Standard specified values | 0.06~0.15 | 0.8~1.15 | 1.4~1.85 | ≤0.025 | ≤0.01 | ≤0.15 | ≤0.15 |
| Measured values  | 0.11 | 0.24 | 1.64 | 0.013 | 0.005 | 0.02 | 0.10 | 0.07 |
### Table 4  Mechanical property of the welding wire ER50-G

| Items                      | Yield strength $R_{p0.2}$ (Mpa) | Tensile strength $R_m$ (Mpa) | Elongation after fracture $A$ (%) | $A_KV$ / -30℃ (J) |
|----------------------------|-----------------------------------|-------------------------------|-----------------------------------|-------------------|
| Standard specified values  | ≥420                              | ≥500                          | ≥22                               | ≥27               |
| Measured values            | 435                               | 580                           | 37                                | 76, 74, 79        |

![Fig.2](image-url) Local heat treatment procedure after repaired welding

### 3. Test analysis

#### 3.1. Macromorphology examination

The leakage position of the deethanizer was at the bottom of the connecting circumferential weld joint between the head and the cylinder shell. There was a crack near the circumferential welding seam, which started from the weld seam through the heat affected zone and extended to the base metal. The location of the repair welding part and the crack morphology are shown in Fig.3 and Fig.4. The crack was linear and showed 11.3mm in length on the inner shell and 25.5mm in length on the outer shell. After grinding, the heating traces could be observed near the weld seam, which were approximately ellipse (about 700mm along long axis, about 400mm along short axis). The heating area presented different colors, which should be caused by uneven heating.

![Fig.3](image-url) Diagram of the crack location on the outer shell
![Fig.4](image-url) Crack morphology on the inner shell

#### 3.2. Chemical composition and hardness test analysis

Handheld alloy analyzer was used to analyze the metal chemical composition of the joint. The results show that the materials of the shell and weld joint are basically comply with 16MnDR of the material standard GB 713-2014 ‘steel plates for boilers and pressure vessels’.

Along the crack in the weld joint thickness direction, a portable Vicker Hardness Tester was used to test the hardness of the bottom of the weld joint, the middle of the weld joint and the top of the weld joint respectively. The test results show that the hardness at the crack-repaired site is the highest in the weld seam depth of 25mm, up to 347 HV, and the heat-affected zone and other site of the weld seam are high, as shown in Tab.5. In the hardness values of each position of the welding joint tested, the hardness
values of weld seam > heat-affected zone > base metal. The hardness value of the crack-repaired site is too high obviously and exceeds design requirements of 200HB (approximately equal to 210 HV), which is also far exceeded the hardness of the base metal.

Table 5  Hardness test results

| Location                  | Hardness value (HV5) |
|---------------------------|----------------------|
| Outside of the weld joint | 153, 147, 152        |
| Middle of the weld joint  | 144, 146, 143        |
| Inside of the weld joint  | 150, 149, 153        |
| Base metal                | 297, 295, 293        |
| HAZ                       | 216, 209, 211        |
| Weld seam                 | 286, 285, 294        |
| Crack repaired site       | 286, 285, 294        |

3.3. Residual stress test

The residual stresses of metal materials are different in the process of machining and hot working (casting, welding, forging). The residual stress has a great influence on the mechanical properties of materials, especially in the process of welding and heat treatment. On one hand, the pressure vessels will reduce the strength, and cracking or other defects will be generated in manufacturing of the pressure vessel; On the other hand, the fatigue strength, stress corrosion and other mechanical properties of the material will be reduced in the natural release process of the residual stresses after pressure vessels manufacturing[4]. Therefore, the detection of residual stress is very important for stress relief technology and welding crack analysis.

According to ASTM E837-2013 ‘Standard Test Method for Solving Residual Stresses of the Hole Wall’, two holes with a diameter of 2.0mm and a depth of 2.5mm were drilled in the weld seam and heat affected zone (HAZ) of the outer and inner shell at the repair welding position respectively, which were near the leakage crack. The strain gauges were pasted on the holes, and the residual stresses of the hole wall were calculated by measuring the linear strain. The test results are shown in Tab.6. The results show that the residual stress in the weld seam and heat affected zone of the outer and inner shell at the repair welding position are large. The maximum tested residual stress is 265MPa, which is close to the yield strength of 16MnDR steel.

Table 6  Residual stresses tested results at the repair welding position

| Location                  | Residual stresses values (MPa) |
|---------------------------|-------------------------------|
| Weld seam of the outer shell | 173, 177, 169               |
| Weld seam of the inner shell | 224, 221,220               |
| HAZ of the outer shell    | 198, 202, 203               |
| HAZ of the inner shell    | 265, 259, 261               |

3.4. Metallographic examination

In the analysis methods of cracking failure of pressure equipment, metallographic examination is always an effective means to analyze the causes of cracking. The metallographic examination of the base material and the weld seam was carried out on the repair welding joint at the crack site, as shown in Fig.5.

The microstructure of the base material was ferrite plus pearlite, and the pearlite was distributed as banded and block. The microstructure of the repaired weld seam was bainite plus ferrite, and most ferrite was precipitated along the columnar grain boundary. There was a few acicular ferrite and granular bainite distributed in the grain boundary, and the slight overheating widmanstatten structure can be found. All these indicated that the welding heat input was too high in the repair welding process[5]. The leakage place was where the welding heat cycle and repeated heating occurred. In the unmixed melting zone, there were spherical droplets and microscopic holes produced by the remelting production of non-metallic inclusions, which were the typical characteristic of the weld liquefaction crack.
3.5. Microscopic metallographic analysis of the fracture section

The micromorphology pictures of the crack opening section at the leakage position were shown in Fig. 6. Discontinuous crack microstructure could be seen on the opening section, which was characterized by dendritic microstructure and solidification traces of liquid phase along grain boundary. The crack was originated in the interlamination position of the multilayer weld seams at the bottom of the back bead. That was also the typical characteristic of the weld liquefaction crack[6]. The origin shape of the crack was observed basically perpendicular to the weld surface, so the microcrack could not be detected by RT process after the repaired weld.

4. Analysis and conclusions

Based on the above tests, the chemical composition of the shell material and weld joint material are basically comply with 16MnDR of the material standard. But the hardness at the crack-repaired site is far exceeded design requirements, and the residual stress in the weld seam and heat affected zone of the outer and inner shell at the repair welding position are too high. The microstructure of the base material is ferrite plus pearlite, while the microstructure of the repaired weld seam was bainite plus ferrite and the slight overheating widmanstatten. According to the above test results, it is inferred that the repair operation process was not properly controlled last time. In the unmixed melting zone of the repaired position, there are spherical droplets produced by remelting non-metallic inclusions. The crack has the characteristic of dendritic morphology, and there are solidification traces of the low-melting point liquid along the grain boundary, which are typical characteristics of liquefaction crack of weld metal.

The crack originates in the interlamellar position of the multilayer weld at the bottom of the back bead, where is the removed root position by repaired carbon arc gouging. Carbon arc gouging is a method of machining grooves on the metal surface by melting the metal with the arc generated between carbon rod or graphite and workpiece and blowing the melting metal off with compressed air. Defects such as carbon inclusion, slime and gouging groove nonuniformity often occur when carbon arc gouging is not operated properly, which will be easy to produce pores, shrinkage holes and non-fusion defects in
the subsequent welding process. At the same time, there is a large welding heat input in the repair process, which is easy to cause the material with low melting point in the weld seam to liquefaction at the grain boundary under the condition of high repair temperature. In addition, the local heating method is adopted in the process of preheating and post-welding heat treatment, which leads to the excessively high hardness and residual stress at the welding repair position. All these are the reasons of formation of the longitudinal microcrack, and the microcrack further expansion in use to form penetrative crack leakage.

5. Repair measures on the leakage

The repair measures was recommended according to the regulations and standards as follows:

(1) The cracks found at the leakage are polished to eliminate, and then take repaired welding at the grinding place. Radiographic test and dye penetrant test are carried out again to confirm that the crack is completely eliminated and no other defects exceed the standard are produced. Hardness test and surface metallographic test is performed. Preheating measures should be taken before welding, and the welding process should be strictly controlled, especially the carbon arc gouging and cleaning work in the process of sealing the welding bead. Rust, grease, moisture and other substances should not be left between the welding beads. At the same time, the welding heat input should be controlled strictly in accordance with the welding procedure when the root bead is welding. Local post welding heat treatment should be carried out at the welding repair place and its upper and lower extension 800mm. The heat treatment temperature, holding time and other parameters should meet the heat treatment procedure.

(2) In use, the procedure parameters monitoring of the ethylene-ethane distillation system and the inspection of the equipment should be strengthened. Regular inspection should be carried out on time, and frequent inspection should be carried out on the leakage repair position.

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