Analysis and treatment of cracks in LPG spherical tank

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Abstract: During the first periodic inspection of the LPG spherical tank, a crack was inspected when the inner shell was detected by fluorescent magnetic powder test. The cause of the crack was analyzed by macromorphology examination, chemical composition analysis, hardness test and metallographic examination. Analysis results show that unreasonable welding procedure, no preheating process, improper storage of weld rods result in martensite structure of the welded joint, welding residual stress and diffusible hydrogen, which is the typical characteristic of the welding cold crack. The repair measures are taken to solve the problem and reduce the hidden dangers.

1. Induction

During the first periodic inspection of a LPG spherical tank, inspection by the fluorescent particle magnetic test (MT) was conducted on the internal longitudinal weld seams of the spherical tank in accordance with the specification of TSG 21-2016 “Safety Supervision Regulations for Stationary Pressure Vessels”. The test ratio of the internal longitudinal weld seams was 20%. A crack was found originated from the fusion line of a longitudinal weld seam. The crack was intermittent, dendritic, and approximately 500mm in combined length, as shown in Fig.1. The spherical tank was installed and put into use on July, 2016. The registration certificate of the tank had been issued as required. The manufacture parameters of the tank are shown in Tab.1. According to the inspection plan, this longitudinal seam was tested by MT, and no other cracks were found in the weld joint. Then the five adjacent longitudinal joints by the same welder were supplementary MT tested, and there was a short dendritic crack in one longitudinal seam.
Tab.1 Manufacture parameters of the spherical tanks

| Tank items                        | Manufacture parameters                      |
|----------------------------------|---------------------------------------------|
| Pressure vessel Name             | 200m³ LPG spherical tank                    |
| Production standard              | GB 150-2011                                 |
| Operation parameters             | 1.60MPa, room temperature                   |
| Design parameters                | 1.77MPa, 50℃                               |
| Material                         | Q345R(HIC) (GB/T 713-2014)                  |
| Thickness of the shell plate     | 48mm                                        |
| Date of periodic inspection      | Nov., 2019                                  |

Fig.1 The crack detected by MT

2. Test and documentation examination

2.1 Macromorphology examination and chemical composition analysis

There was no large area of corrosion at the inner shell and only slight local corrosion was observed by macroscopic examination and thickness measurement. After the weld joint at the crack in Fig.1 was polished, the base metal and the weld seam were found had a clear boundary - fusion line. The weld seam was darker than the base metal, but the width of the weld seam was irregular. Cracks exposed on the metal surface of the joint was herringbone and present shiny, and there was no obvious trace of oxidation on the crack surface. Main bifurcations of the crack extend to both sides from the fusion line, where the bifurcations of the crack extending to the weld seam on one side and a crack bifurcation extending to about 15mm inside the base metal through the heat-affected zone on the other side, as shown in Fig.2.

Handheld alloy analyzer was used to analyze the metal chemical composition of the joint, as shown in Tab.2. It can be seen from the table that the base metal and the weld material basically comply with the material standard of Q345R[1]. The Mn content of the weld seam was in excess of the standard specified, which should be related to the excessive Mn element in the weld material. A high Mn content will result in the increase in carbon equivalent of the material, and thus the weldability of the material was decrease, also the welding cold cracks are easy to occur[2].

Fig.2 macromorphology of the welded joint at the crack site after polishing
Tab.2 chemical composition analysis by Handheld Alloy Analyzer

| Location     | Chemical compositions (%) |
|--------------|---------------------------|
|              | Fe | Mn | Cu | Ni | Cr | Mo |
| Standard specified value | Margin | 1.2~1.7 | ≤0.3 | ≤0.3 | ≤0.08 |
| Base metal   | 96.4 | 1.6 | 0.2 | 0.18 | 0.1 | 0.05 |
| Weld seam    | 95.9 | 2.1 | 0.22 | 0.19 | 0.08 | — |

2.2. Hardness test
In the vertical direction of the crack origin, a portable Vicker Hardness Tester was used to test the hardness of the weld seam, the heat-affected zone and the base metal respectively on the joint. The test results showed that the hardness of the heat-affected zone near the fusion line was the highest, as shown in Tab.3. In the hardness values of each position of the welding joint tested, the hardness values of heat-affected zone > weld seam > base metal. But the hardness value of the heat-affected zone was too high obviously and exceeded design requirements of 200HB (approximately equal to 210 HV), which was far exceeded the hardness of the base metal.

Tab.3 hardness test of the welded joint

| Location | hardness value (HV10) |
|----------|-----------------------|
| Base metal | 153 147 152 |
| HAZ  | 250 256 270 |
| Weld seam | 214 206 218 |
| HAZ  | 263 269 255 |
| Base metal | 157 145 149 |

2.3. 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 was carried out on the weld joint at the crack site.

The microstructure of the base metal was ferrite plus pearlite\textsuperscript{[3]}, as shown in Fig.3. Ferrite plus pearlite are the normal tissues of the spherical tank manufacturing material Q345R at room temperature. However, the characteristic of uneven structure in the microstructure of the base metal was observed.

Fig.3 metallographic structure of base metal
Fig.4 metallographic structure of weld seam and fusion zone
The metallographic structure of the weld seam was different from the base metal, as shown in Fig.4. The weld seam above the fusion line had the lamellar pearlite microstructure, while the heat-affected zone under the fusion line had martensite microstructure. The martensite structure was in the shape of plate stripe, with more dense organizations than the base metal. Then the metallographic structure of the heat-affected zone was observed clearly, and a long microcrack was clearly visible, as shown in Fig.5. The microcrack was extending from the fusion zone to the heat-affected zone. The microcrack characterized along the grain boundary extension, but also had some transgranular cracking. The microcrack was also observed in the heat-affected zone at the short dendritic crack site, as shown in Fig.6.

MT and metallographic examination were carried out on the longitude weld joints of the upper poles, lower poles and the equator of this spherical tank. The microcracks in martensite structure was sometimes found in heat-affected zones too, but the cracks by MT test was not observed. Then metallographic examination was conducted on circular joints which were selected randomly at each location. The martensite structure was also observed, but microcracks were not observed. Compared with the results of MT test, although it was within the detection range of MT, such microcracks were not grown enough to be found even when fluorescent magnetic powder test with the highest sensitivity for ferromagnetic materials.

The martensite structure is a sublatturated solid solution of carbon in $\alpha$-Fe. It is the product of non-diffusible phase transition of steel after austenitizing and rapid cooling to below the temperature point of martensite. Therefore, great stress by phase transition has been generated since its formation\cite{4}. The spherical tank is made of Q345R. The martensite structure formed by this material is hardened and brittle, which has a very bad impact on the strength, plasticity and toughness of the material.

Q345R is a good welding material, but it has a slightly high alloying content than ordinary low-carbon steel. Therefore, its hardening tendency and the tendency of welding cold crack are slightly larger than ordinary low-carbon steel when it was welded\cite{5}. Martensite structure and even cracks may appear if welding process is not done according to the specification in the conditions of low temperature environment, large stiffness and large thickness structure. When the locations of the cracks by MT and microcracks by metallographic examination were analyzed, it was found that the cracks and microcracks were always at the location with high stiffness during the assembly of the spherical tank. It could be inferred that the immediate reason of the martensite structure appeared in the heat-affected zone of weld joints was the improper welding process.

2.4 Documentation examination
The installation inspector of the spherical tank, the construction responsible manager of the installation company and the quality engineer of the user were consulted and investigated, and relevant records were collected and checked. The content of H$_2$S in LPG stored in the spherical tank is not higher than 10ppm,
and the spherical shell plate is made of Q345R steel with the function of resistance to hydrogen-induced cracking, so the possibility of stress corrosion cracking of wet H2S is basically ruled out\[6\]. The welding parameters and status of the preheating treatment and post welding heat treatment during installation of the tank were examined carefully. The relevant records on preheating treatment and dehydrogenation heat treatment after welding had no way to verify, while the other record documents were available. Preheating treatment and dehydrogenation heat treatment are essential factors in welding procedure qualification. No preheating treatment or insufficient preheating will lead to hardening tendency, and in severe cases, cracks will be directly generated. In particular, the welding work took place in January and the ambient temperature was low. Lack of dehydrogenation heat treatment after welding will lead to that hydrogen in welding seam and heat-affected zone cannot escape in time, and it will gather in weld seam and fusion line. When the hydrogen gathers to a certain extent, it will cause cold cracks (including delayed cracks) in weld heat-affected zone under welding stress.

According to the specification of GB 12337-2014, preheating measures and dehydrogenation heat treatment must be taken for spherical tanks with shell thickness of 48mm and material of Q345R. The preheating temperature should be maintained at 125℃~175℃, and the preheating range should be at least 144mm beyond the center line of welding seams. The temperature of dehydrogenation heat treatment should be maintained at 200℃~250℃ for 0.5~1 hour.

(2) According to the installation inspection records, the installation inspector found there was no heat insulation barrels many times when welders used the procedure of Shielded Metal Arc Welding. When the electrodes exposed time to air is too long or the welding environment is unfavorable, the electrode will absorb moisture from the air and lead to free hydrogen existing in the weld joint. Then the free hydrogen will spread to heat-affected zone in the process of crystallization and cooling. According to RT reports issued by the installation company, most of the defects were pores, likely generated by hydrogen in the weld joint. Different amounts of hydrogen were captured at different weld locations, and cold cracks would appeared when a certain amount of diffused hydrogen was gathered\[7\].

3. Conclusions

Based on the above tests, the analysis conclusions are summarized as follows:

(1) According to the chemical composition analysis, the excessive content of Mn element above the standard in the welding material increases the hardness of the weld joint.

(2) The bifurcations of the crack extend from the fusion line to the weld seam and base metal, and the surface hardness of the heat-affected zone seriously exceeds the standard.

(3) The martensite structure is found in the heat-affected zone of the weld joint by metallographic examination at many positions of the spherical tank.

(4) The preheating treatment and dehydrogenation heat treatment after welding had no way to verify and there was no heat insulation barrels by examining the installation documents and surveying the relevant people.

The results show that the crack inspected in the spherical tank is a typical cold crack (including delayed crack). The reason of the cold crack are the lack of preheating treatment and dehydrogenation heat treatment, which leads to the rapid cooling speed of the weld joint. Thus the typical hardened structure -martensite is appeared as the main metallographic structure in the heat-affected zone of the weld joint. The heat treatment and weld material management is out of control, resulting in the free hydrogen existing in the heat-affected zone. Finally the microcracks are generated under the welding residual stress and develop into macroscopic cold cracks.

4. Defects handling measures

The defects found in this periodic inspection was cost more than 500,000 RMB for repair measures. The repair measures was taken according to the regulations and standards as follows:

(1) The fluorescent MT was carried out on all inner shall weld joints. The repair welding was carried out after the observed cracks were eliminated and polished, and then nondestructive testing methods of RT, MT and metallographic examination were carried out to confirm that the cracks were completely
eliminated and no other defects exceeding the standard were generated. Preheating measures should be taken before welding. Transportation and storage measures of welding rods should be strictly controlled in heat insulation barrels, and welding parameters should be carried out in strict accordance with the welding procedure specification and the standards.

(2) Integral heat treatment on the spherical tank was carried out again to improve the microstructure of the weld joints and reduce the residual stress. The daily operation, annual inspection and periodic inspection shall be conducted and recorded in detail. In order to detect occurrence and development of microcracks in time, the fluorescent MT and metallographic examination should be carried out regularly and the detection ratio should be increased.

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