Abstract. Through the technical analysis of many cracks and leaks occurred in the pressure vessel attached to the gas injection compressor during its long service period at high pressure, the chemical analysis, metallographic analysis, hardness measurement, finite element analysis and vibration monitoring of the three-stage outlet spherical tank were carried out. Finally, it is determined that the causes of the defects are the high hardness and stress values of the weld seam and heat affected zone of the nozzle, and the mechanical fatigue caused by the alternating load caused by the vibration of the unit.

1 Introduction

Reciprocating compressor is widely used in chemical industry, steelmaking, petroleum and other industries because of its high exhaust pressure and strong practicability.[1-3] However, in the actual use process, the intermittent and periodic working characteristics of reciprocating compressor will lead to vibration of the vessels, pipes and other accessories attached to the back end of the compressor. Strong vibration will cause fatigue damage to the equipment.[4-6]

Seven Cooper Superior 16SGT/MH-66 split type natural gas engine compressor units are used in the gas injection compressor in Yaha operation area of PetroChina Tarim Oilfield Company.[7-9] At present, they have been operating for more than 18 years under the conditions of high pressure and unit vibration. During the inspection over the years, 99 surface cracks and punctures were found, including 76 secondary and tertiary cylinder bodies and 23 auxiliary pressure vessels. In view of this situation, Tarim Oilfield took the lead in the detailed inspection and evaluation of the auxiliary pressure vessel of the compressor, carried out chemical analysis, metallographic analysis and hardness test on the three-stage outlet spherical tank with the most frequent cracks, determined the causes of the cracks, and provided technical reference for the operation and inspection of the gas injection compressor.
2 Inspection

2.1 Macroscopic inspection and wall thickness measurement

Macroscopic inspection was carried out on the outside of the pressure vessel attached to the compressor. The anticorrosive coating was good and the paint was even. The internal macroscopical inspection of three-stage outlet spherical tank C2103a/b was carried out with endoscope, and the surface was smooth without obvious corrosion. The thickness of three-stage outlet spherical tank C2103a/b was measured intensively by ultrasonic thickness gauge, and compared with the measurement results of wall thickness over the years, no obvious thinning was found.

2.2 Surface nondestructive testing

The auxiliary containers of gas injection compressor are polished to expose metallic luster and then nondestructive testing of the surface is carried out. Three surface defects were found.

A crack was found at the weld of the reinforcing ring of nozzle of three-stage outlet spherical tank A2102b, the length of which was 70 mm. The location is shown in figure 1.

A surface crack was found in the heat-affected zone of base metal near the reinforcing ring of nozzle for three-stage outlet spherical tank A2103a. The crack length is 7mm and the location is shown in figure 2.

A surface defect was found in the weld joint between the head and the cylinder of the three-stage outlet stabilization tank C2101. The defect length was 28 mm and the defect location was shown in figure 3.

Figure 1. Surface defects of grade three outlet spherical tank A2102b.

Figure 2. Surface defects of grade three outlet spherical tank A2102a.
2.3 Hardness Measurement

The hardness of the three-stage outlet spherical tank C2103a/b is measured. The location and value of the hardness are shown in Table 1. The hardness of the weld seam and the heat affected zone of the nozzle is slightly higher than that of other locations.

Table 1. Hardness Measurement Location and Value.

<table>
<thead>
<tr>
<th>Detection location</th>
<th>Measured value (HB)</th>
<th>Average value (HB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2103a weld</td>
<td>202, 206, 184, 208</td>
<td>200</td>
</tr>
<tr>
<td>C2103a heat affected zone</td>
<td>188, 184, 169, 182</td>
<td>180</td>
</tr>
<tr>
<td>C2103a base metal</td>
<td>181, 171, 169, 180</td>
<td>175</td>
</tr>
<tr>
<td>C2103b weld</td>
<td>210, 220, 212, 224</td>
<td>216</td>
</tr>
<tr>
<td>C2103b heat affected zone</td>
<td>184, 178, 204, 201</td>
<td>191</td>
</tr>
<tr>
<td>C2103b base metal</td>
<td>176, 180, 167, 179</td>
<td>175</td>
</tr>
<tr>
<td>Nozzle</td>
<td>196, 173, 204, 188</td>
<td>190</td>
</tr>
</tbody>
</table>

2.4 Chemical analysis

The chemical analysis of the three-stage outlet spherical tank C2103a/b is carried out. The results are shown in Table 2. The chemical composition meets the requirements of SA-516Gr70/SA-105Gr70.

Table 2. Chemical composition analysis table.

<table>
<thead>
<tr>
<th>Detection location</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2103a base metal</td>
<td>0.17</td>
<td>0.26</td>
<td>1.11</td>
<td>0.008</td>
<td>0.014</td>
</tr>
<tr>
<td>C2103a weld</td>
<td>0.11</td>
<td>0.36</td>
<td>1.34</td>
<td>0.012</td>
<td>0.021</td>
</tr>
<tr>
<td>C2103b base metal</td>
<td>0.17</td>
<td>0.25</td>
<td>1.13</td>
<td>0.007</td>
<td>0.008</td>
</tr>
<tr>
<td>C2103b weld</td>
<td>0.068</td>
<td>0.83</td>
<td>1.80</td>
<td>0.018</td>
<td>0.060</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.13</td>
<td>0.25</td>
<td>0.77</td>
<td>0.017</td>
<td>0.015</td>
</tr>
</tbody>
</table>

2.5 Metallographic analysis

The metallographic analysis of the three-stage outlet spherical tank C2103a/b shows that the base metal is ferrite + pearlite, as shown in figure 4; the heat affected zone is ferrite + pearlite, as shown in figure 5; and the weld metal is proeutectoid ferrite + ferrite + pearlite, as shown in figure 6.
2.6 Vibration Monitoring

Vibration monitoring was carried out on the auxiliary pressure vessel and cylinder block of No.1 and No.7 compressor units in Yaha operation area. The speed, acceleration and displacement of the equipment were measured respectively, and then according to the standard GB/T 6075.6-2002 table I selects vibration intensity level, and the test results show that the vibration of the three-stage inlet spherical tank, the first stage exhaust buffer tank, the first stage outlet buffer tank and the first stage inlet buffer tank of the gas injection machine is large, and the vibration intensity level is 18. As shown in Table 3.
3 Finite element calculation

Finite element calculation is carried out for the three-stage outlet spherical tank C2103a/b. Regular geometry is divided into hexahedral mesh and irregular geometry such as spherical shell is divided into tetrahedral mesh. The total number of mesh nodes is 16349408 and the total number of mesh elements is 6318899, as shown in figure 7.

The calculation model of the device is simplified as follows:

1) The device is in a stable working state, and the pressure and temperature of the inner wall of the device are calculated according to the design pressure of 56.9 MPa and the design temperature of 176.7 °C;

2) The outer surface of the device is exposed to air. According to the convection heat transfer conditions between steel and air, the heat transfer coefficient range is 5-15 W·m⁻²·K⁻¹, and the value here is about 1.5 × 10⁷ W·mm⁻²·℃⁻¹;

3) Fix the gas inlet end faces of the left and right spherical shells, apply the pipe end force to the gas outlet end faces of the tee, and apply the pipe end force to the other end faces of the nozzles, and apply the gravity field to the whole device;

4) Establish the stress boundary conditions of the equipment, as shown in figure 8, where the pipe end force is calculated according to Formula 1 below,

\[ P = \left( P_i \times R_i^2 \right) / \left( R_o^2 - R_i^2 \right) \]  

Where: P is the pipe end force, N; Pi is the end face internal pressure, MPa; Ri is the end face internal radius, mm; Ro is the end face external radius, mm.

The stress results are as shown in figure 9. The maximum stress at the welding position of No.2 instrument connecting pipe and spherical shell is 284.06 MPa. The other positions with large stress are the welding position of connecting pipe and spherical shell, including the welding position of gas inlet straight pipe and spherical shell, which is 234.65 MPa, and the welding position of gas outlet straight pipe and spherical shell, which is 228.94 MPa.

### Table 3. Data sheet of vibration test results of some auxiliary pressure vessels.

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Device location number</th>
<th>displacement (μm)</th>
<th>speed (mm·s⁻¹)</th>
<th>acceleration (m·s⁻²)</th>
<th>Vibrat ion intensity level</th>
<th>Vibrat ion classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A2003A</td>
<td>16.968</td>
<td>13.0</td>
<td>15.55</td>
<td>18</td>
<td>C</td>
</tr>
<tr>
<td>2</td>
<td>A2003B</td>
<td>15.554</td>
<td>14.0</td>
<td>14.14</td>
<td>18</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>G1701</td>
<td>13.433</td>
<td>3.2</td>
<td>21.21</td>
<td>18</td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>G1702</td>
<td>12.019</td>
<td>4.2</td>
<td>18.38</td>
<td>18</td>
<td>C</td>
</tr>
<tr>
<td>5</td>
<td>G1702</td>
<td>5.656</td>
<td>2.8</td>
<td>21.21</td>
<td>18</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>A1601</td>
<td>7.07</td>
<td>3.3</td>
<td>22.62</td>
<td>18</td>
<td>C</td>
</tr>
</tbody>
</table>

Figure 7. Solid model of three-stage outlet spherical tank C2103a/b.
4 Causes of surface cracks

The reciprocating suction and exhaust during the operation of compressor make the speed and pressure of air flow change intermittently, forming a gas column. The gas column is a quality elastomer, which will transmit the vibration to the inlet and outlet spherical tanks, making the fillet welds of the inlet and outlet spherical tanks bear relatively large alternating load.[10-14] The vibration monitoring results also show that the vibration intensity of the equipment is large during the operation of the equipment, not suitable for long-term continuous operation.

The results of hardness measurement show that the hardness of the weld and the nearby heat affected zone of the vessel is higher than that of other parts, the strength of the zone is higher, the elasticity and plasticity are lower, and the cracks and other defects are easy to form under the action of higher stress and external force. The results of the finite element analysis also show that the stress values of the welding parts of the three-stage outlet spherical tank instrument nozzle and the cylinder, and the welding parts of the inlet and outlet nozzle and the cylinder are significantly higher than other parts. On this basis, it can bear the alternating load caused by vibration for a long time, and finally produce fatigue failure.

5 Recommendations

In the process of operation, it is necessary to strengthen the inspection of the connecting pipe and the reinforcing ring of the connecting pipe to prevent cracking and other problems. Once abnormal gas leakage is found, the tag number shall be confirmed and the emergency shutdown shall be handled under the condition of explosion-proof measures.

Vibration monitoring shall be carried out for the gas injection compressor and its auxiliary pressure vessel. If the vibration intensity level is found to be more than 18, the cause of abnormal vibration shall be found out and handled as soon as possible to prevent fatigue damage to the cylinder block and auxiliary pressure vessel.

During the regular inspection and annual inspection, the non-destructive testing of the nozzle fillet weld surface shall be the main method, especially the nozzle fillet weld and
cylinder body of the secondary and tertiary surge tank. If necessary, the inspection cycle shall be shortened.

References


