INTEGRITY ASSESSMENT OF TANKS WITH MICROCRACKS IN WELDED JOINTS

OCENA INTEGRITETA REZERVOARA SA MIKROPRSLINAMA U ZAVARENOM SPOJU

Abstract

During the exploitation of the vertical tank used for storing liquid carbon dioxide, there was a need for the installation of two new connectors on one of the lids. The tank is made of micro-alloyed steel and its connectors are made of high-alloyed austenite steel. The same welding technology and added materials are used for both the tank and connectors. Non-destructive testing methods of welded joints in new connectors revealed microcracks in the heat-affected zone of micro-alloyed steel. By applying the procedure given in standard BSI PD 6493 "Manual for assessment of acceptability of flaws in welded structures", it is possible to estimate the effect of these microcracks on the integrity of welded joints in new connectors, and therefore their effect on the integrity of the tank.

INTRODUCTION

During the exploitation of the vertical tank used for storing liquid carbon dioxide, there was a need for the installation of two new connectors on its upper lid. The connectors were meant to connect the external freon unit with the internal heat exchanger. The carbon dioxide gas phase is cooled down through the heat exchanger, which lowers the temperature and pressure in the tank, therefore reducing the losses caused by releasing carbon dioxide into the atmosphere through the safety valve. The connectors were installed at the location of tank exploitation.

INSTALLATION OF CONNECTORS

The tank is a cylindrical, heat isolated pressure vessel with a volume of 25 m³. It is made of micro-alloyed steel P460 NL1, with thickness of 12 mm. Other basic information about the tank includes: maximum working pressure of 25 bar, test pressure of 32.5 bar, lowest working temperature −50°C, outer diameter of 2000 mm, total height of 10080 mm and vessel class II, /1/.

The welding technology and materials used for the making of new connectors are the same as used by the tank manufacturer, /1/. The connectors are made using high-alloyed austenite steel X6CrNiTi 18 10, with guaranteed toughness at −50°C and of good weldability. According to calculations, /2/, for working pressures in the tank and the exchanger, the required connector diameter is 26.9 mm and the wall thickness is 2.6 mm. However, since it is difficult to achieve a quality welded joint between materials with such significant difference in thickness (12 mm for the lid, 2.6 mm for the connector), it was decided to weld reinforced connectors to the lid, with wall thickness similar to that of the lid, Fig. 1, and then weld connector pipes to the reinforcement. Connector reinforcements are mechanically made from solid pieces.

New connectors are welded using the SMAW procedure. A rutile coated electrode E 29 9 R 1s2 (standard EN 1600) is used. The shape and dimensions of the grooves are shown in Fig. 1. Chemical composition and mechanical properties of the base and added materials are given in /3, 4/ and Tables 1 and 2.
RESULTS OF WELDED JOINT TESTING

According to regulations /5, 6/, new connector joints should be tested using non-destructive methods upon welding, including visual examination, magnetic particle, penetrants and ultrasound on both outer and inner sides of the tank. The required level of quality for these joints is level C according to /7/, which defines the acceptability criteria for detected flaws. Welded joints are tested using provided NDT methods immediately after welding, and prior to internal pressure testing of the tank. The above methods did not reveal any flaws other than small edge etches of acceptable size, /8/.

However, the NDT procedure prescribed by regulations in case of joints between micro-alloyed and high-alloyed steels does not always give a reliable result, because in this case of joint types, there are limitations in the possibilities of above mentioned methods, /9/. Hence, the prescribed NDT procedure is expanded by microstructure testing using the replicas and hardness test. A replica is made on each of the connectors in a way that includes the base metal (BM) of the lid, its heat affected zone (HAZ) and weld metal (WM). Microstructural tests /8/ determined that the BM of the lid has a non-homogeneous distribution of microconstituents and noticeably larger grain size than usual for micro-alloyed steels, where coarse grain structures occur in heat affected zones of both connectors. It has also revealed traces of martensite in the bainite matrix, along with microcracks and that the microstructure of the WM is austenitic with around 35% δ-ferrite. Figure 2 shows the largest microcrack detected. Its real length is 2.1 mm. The light area in the figure represents non-eroded austenitic WM. The figure actually shows two microcracks that continue onto each other. The end of one microcrack is located in the flaw on the fusion line.

Hardness is measured using the portable Vickers method on locations of microstructural testing, on a polished and eroded surface after the removal of replicas, /8/. Based on the difference in the coloration of BM, HAZ and WM, locations of measuring points are accurately determined. Highest hardness (310 HV) is measured in the HAZ and can be considered acceptable.

Table 1. Chemical compositions of base materials and consumables (%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Al</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>P460NL1</td>
<td>≤0.20</td>
<td>0.40</td>
<td>1.45</td>
<td>≤0.020</td>
<td>≤0.020</td>
<td>-</td>
<td>-</td>
<td>≥0.020</td>
<td>-</td>
</tr>
<tr>
<td>X6CrNiTi 18 10</td>
<td>≤0.08</td>
<td>≤1.0</td>
<td>≤2.0</td>
<td>≤0.035</td>
<td>≤0.025</td>
<td>17.0–19.0</td>
<td>9.0–11.0</td>
<td>-</td>
<td>5x%C</td>
</tr>
<tr>
<td>E29 9 R 12</td>
<td>0.15</td>
<td>≤0.9</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>29</td>
<td>9</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of base materials and consumables.

<table>
<thead>
<tr>
<th></th>
<th>Yield strength $R_{0.2}$ (MPa), min.</th>
<th>Tensile strength $R_m$ (MPa)</th>
<th>Elongation $A_5$ (%), min.</th>
<th>Toughness ISO–V min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>P460NL1</td>
<td>470</td>
<td>540–740</td>
<td>19</td>
<td>27 J at –40°C</td>
</tr>
<tr>
<td>X6CrNiTi 18 10</td>
<td>205</td>
<td>490–740</td>
<td>40</td>
<td>27 J at –40°C</td>
</tr>
<tr>
<td>E29 9 R 12</td>
<td>500</td>
<td>740–840</td>
<td>20</td>
<td>27 J at –40°C</td>
</tr>
</tbody>
</table>
ASSESSMENT OF MICRO-Crack ACCEPTABILITY

The replica method revealed multiple microcracks. It is assumed that these microcracks can connect to each other during pressure testing or tank exploitation, and as a result, form larger cracks, which in turn can lead to tank leakage or failure. Removal of microcracks by cutting out or repair welding does not guarantee that they will not reappear, possibly in even greater number and larger dimensions. Hence, the effect of existing microcracks on the integrity of welded joints in the connector is assessed. The procedure given in literature /9/, is used for this assessment.

In order to apply this procedure, it is necessary to reduce the cracks to one of the forms for which analytical solutions for stress states exist. Based on the description of microcracks and Fig. 2, it can be concluded that the cracks in question are on the surface which lies in a plane perpendicular to the direction of principal stress. Due to a small distance between them, both microcracks will be treated as a single surface semi-elliptical crack, whose real length is 2c = 2.1 mm. Depth of the microcracks was impossible to measure, and it is estimated based on NDT results. The ultrasound method has one dead zone with depth of 1 mm along the testing surface where flaws could not be detected. The sensitivity of the method is in this case reduced because of microcracks appearing immediately next to the fusion line, i.e. the boundary between two steels of different densities which results in additional ultrasound damping, which then ‚conceals‘ flaws along that surface. Penetrant testing results also confirm that the cracks in question are not of large depth. Despite sufficiently large length, microcracks are not detected using these methods, presumably because of small depth, hence the penetrants do not reveal them. Based on the above, a crack depth of a = 1 mm is adopted, although in reality it is probably much smaller. Fracture risk assessment with a slightly greater crack depth than the real value gives a more reliable result.

There are two different modes of loading that the tank can be subjected to. One mode includes internal pressure tests, and the other includes working conditions. During internal pressure tests, this tank is exposed to the test medium temperature (water, 10–20°C) and is subjected to a test pressure of 32.5 bar. In working conditions, the tank is exposed to temperatures between –20 and –30°C and is subjected to a pressure of 14–20 bar. Considering that a tank can be subjected to. One mode includes internal pressure tests, this tank is exposed to the test medium (water, 10–20°C) and is subjected to a pressure of 32.5 bar. In working conditions, the tank is exposed to temperatures between –20 and –30°C and is subjected to a pressure of 14–20 bar. Considering that a

\[
P_m = \frac{PD}{4B}
\]

where \(P_m\) is the membrane stress caused by pressure in the tank, and \(M_s\) is the shape coefficient. Since welded joints are located on a spherical lid, the membrane stress is determined according to the following formula:

\[
P_m = \frac{PD}{4B}
\]

where \(P = 32.5\) bar is the test pressure; \(D = 2000\) mm–outer lid diameter; \(B = 12\) mm–lid wall thickness; hence \(P_m = 135\) MPa. Shape coefficient \(M_s\) is calculated as:

\[
M_s = 1 - \frac{a}{BM_t} - \frac{1}{(a/B)}
\]

where \(B = 12\) mm, \(a = 1\) mm is the estimated crack depth; \(c = 1.05\) mm is the crack half-length and factor \(M_s:\)

\[
M_s = \left[1 + 3.2 \left(\frac{c^2}{DB}\right)\right]^{-0.5}
\]

Calculation gives the following values: \(P_m = 133\) MPa; \(M_s = 1.00\); \(M_t = 1.00\); \(a = 162\) MPa.

Hardening stress \(\sigma_f\) is the half-sum of yield stress and tensile strength of the material around the crack tip. The crack is located within the HAZ, however the replica method was unable to determine accurately which of the temperature zones of HAZ contains the crack tip. Hence, integrity will be assessed for two cases. The first case will include the zone of highest strength and lowest toughness (A) and the second case will include the zone of lowest strength and highest toughness (B). Values of yield stress, tensile strength and crack opening for these zones, obtained by testing of specimens by simulating a thermal cycle in specific parts of the HAZ of steel P460 NL1, are given in literature /11/, and in Table 3.

Table 3. Crack opening for specific zones in HAZ of steel P460NL1

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<thead>
<tr>
<th>Simulation temperature °C</th>
<th>1350</th>
<th>1100</th>
<th>950</th>
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<td>Yield stress (\sigma_f) (MPa)</td>
<td>1101</td>
<td>943</td>
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<td>936</td>
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<tr>
<td>Crack opening (\delta) (20°C) (mm)</td>
<td>0.007</td>
<td>0.002</td>
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Document PD 6493 /10/ provides three levels of fracture risk assessment, depending on the possibility of measuring and accuracy of evaluation of all stresses appearing around the crack tip. In this case, fracture risk will be assessed based on level II. For the application of level II it is necessary to know the values of \(S_r\), \(K_r\) and \(\delta\) parameters. Parameter \(S_r\) is calculated from the following equation:

\[
S_r = \frac{\sigma_n}{\sigma_f}
\]

where \(\sigma_n\) is the effective stress in the net section and \(\sigma_f\) represents the material hardening stress, i.e. the half-sum of yield stress \(\sigma_f\) and tensile strength \(\sigma_t\), which in case of level II assessment is adopted as a maximum of 1.2\(\sigma_f\). Effective stress in the net section is calculated as:

\[
\sigma_n = 1.2M_sP_m
\]

where \(P_m\) is the membrane stress caused by pressure in the tank, and \(M_s\) is the shape coefficient. Since welded joints are located on a spherical lid, the membrane stress is determined according to the following formula:

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Regulation /10/ prescribes that, in cases where the consequences of fracture are moderate, stress that is estimated in any way, should be multiplied by a safety factor of 1.2, and the stress measured should be multiplied by a safety factor of 1.1. In:

- case A, temperature zone 1350°C, \( \sigma_f = (\sigma_y + \sigma_m)/2 = 1101 \text{ MPa}, \) where \( \sigma_y = 1101 \text{ MPa}, \) \( \sigma_m = 1101 \text{ MPa}; \) by substituting into Eq.(1), \( S_{IA} = 1.2 \times 162/1.1 - 1101 = 0.161 \)
- case B, temperature zone 850°C, \( \sigma_f = (\sigma_y + \sigma_m)/2 = 798 \text{ MPa}, \) where \( \sigma_y = 660 \text{ MPa}, \) \( \sigma_m = 936 \text{ MPa}; \) by substituting into Eq.(1), \( S_{IB} = 1.2 \times 162/1.1 - 798 = 0.221. \)

The crack opening value \( \delta \) for level II assessment is calculated as:

\[
\delta = \frac{K_I^2}{\sigma_y E} + \rho
\]

where \( \delta \) is the acting crack opening, which is calculated from the following expression:

\[
\delta = K_I^2 \sigma_y E
\]

In the above expressions, \( K_I \) is the stress intensity factor; \( \delta_{max} \)-critical crack opening for the material \( (\delta) \); \( \rho \)-correction factor for the interaction between primary and secondary stresses and \( E \)-elasticity modulus of steel. Stress intensity factor of a surface crack is calculated from the following expression:

\[
K_I = M_m \sigma_I \sqrt{\pi a}
\]

where \( M_m \) is the stress increase factor which takes into account the shape of the crack, Fig. 3; \( \Phi \) is the elliptical integral, Fig. 4. For a crack with length of \( 2c = 2.1 \text{ mm} \) and depth \( a = 1 \text{ mm} \) which is located in a wall with thickness of \( B = 12 \text{ mm}, M_m = 1.05; \Phi = 1.53. \)

Maximum tensile stress \( \sigma_I \) equals the sum \( (P_m + P_b + Q + F) \), where \( P_m \) is membrane stress caused by pressure in the tank; \( P_b \) is the bending stress caused by groove edge dislocation; \( Q \) represents secondary stresses which include residual stresses in welded joints and thermal stresses; \( F \) represents tip stresses which occur due to stress concentration at local discontinuities, e.g. connections, transitions from weld face to base metal. In this case, membrane and residual stresses will be taken into account. Visual examination of welded joints determined that there are no sharp transitions from weld faces to the base metal, hence stresses \( P_b \) and \( F \) will be disregarded. For joints that are not stress tempered, residual stresses are approximately equal to the smaller of the yield stress values for WM and BM. Testing of specimens from the WM, /12/, which are welded in the same way as the joints considered, resulted in yield stress of 550 MPa. Yield stress of lid segments where the connectors are being installed is 490 MPa, /1/.

Total tensile stress \( \sigma_I \) in this case is equal to the sum of membrane stress \( P_m = 133 \text{ MPa} \) and residual stresses \( Q = 490 \text{ MPa}, \) i.e. it equals 623 MPa. By substituting into Eq.(6) the following is obtained:

\[
K_I = \frac{1.05}{1.53} \times 623 \sqrt{\pi 1.0} = 758 \text{ MPa} \sqrt{\text{mm}}
\]

Substituting into Eq.(5) gives following results in case:

- A, temperature zone 1350°C, \( \delta_{IA} = 758/1101-207000 = 0.003; \) where \( K_I = 758 \text{ MPa} \sqrt{\text{mm}}, \) \( \sigma_y = 1101 \text{ MPa}, \) \( E = 207 \text{ GPa}; \)
- B, temperature zone 850°C, \( \delta_{IB} = 758/660-207000 = 0.004; \) where \( K_I = 758 \text{ MPa} \sqrt{\text{mm}}, \) \( \sigma_y = 660 \text{ MPa}, \) \( E = 207 \text{ GPa}. \)
Critical values of crack opening $\delta_c$ for the considered temperature zones are given in Table 3. Correction factor $\rho$ according to /10/ for this case has a value close to zero. From Eq.(4) it follows that:

- for zone A, $\sqrt{\delta_{IA}} = (0.003/0.007)^{0.5} = 0.65$; where $\delta_{IA} = 0.003$ and $\delta_{mat} = \delta_c = 0.007$ mm,
- for zone B, $\sqrt{\delta_{IB}} = (0.004/0.130)^{0.5} = 0.175$; where $\delta_{IB} = 0.005$ and $\delta_{mat} = \delta_c = 0.130$ mm.

By entering values for $S_r$ and $\sqrt{\delta_r}$ for both cases, into the fracture assessment diagram, Fig. 5, points that lie in the zone safe from fracture are obtained.

**Figure 4. Elliptical integral $\Phi$ for a surface crack.**

**Slika 4. Eliptični integral $\Phi$ za površinsku prslinu**

**CONCLUSIONS**

By applying the procedure for flaw acceptability assessment of welded joints given in standard BSI PD 6493, it is assessed that microcracks detected in the HAZ of welded joints in the connectors of the tank used for storing liquid carbon dioxide do not present a danger to its safe work. Hence, the tank is subjected to further exploitation with these microcracks.

Certain unreliability is introduced into microcrack acceptability assessment by limitations of NDT methods during the tests of welded joints between micro-alloyed and high-alloyed steels. Therefore, it is provided that during the exploitation of the tank, welded joints of connectors should be periodically tested using these methods to determine if there is any microcrack growth.

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