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INTEGRITY ASSESSMENT OF TANKS WITH MICROCRACKS IN WELDED JOINTS

OCENA INTEGRITETA REZERVOARA SA MIKROPRSLINAMA U ZAVARENOM SPOJU

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Abstract

During the exploitation of tanks used for storing liquid carbon dioxide there was a need to install 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.

Rezime

Tokom eksploatacije rezervoara za skladištenje tečnog ugljendioksida ukazala se potreba za ugradnjom dva nova priključka u jedno od danaca. Rezervoar je izrađen od mikrolegiranog čelika, a priključci od visokolegiranog austenitnog čelika. Za izradu novih priključaka izabrani su isti dodatni materijali i ista tehnologija zavarivanja, koji su korišćeni i pri izradi rezervoara. Ispitivanjima metodama bez razaranja zavarenih spojeva novih priključaka otkrivene su mikroprsline u zoni uticaja toplote mikrolegiranog čelika. Primenom postupka prikazanom u standardu BSI PD 6493 „Uputstvo za ocenu prihvatljivosti grešaka u zavarenim konstrukcijama", ocenjen je uticaj ovih mikroprslina na integritet zavarenih spojeva novih priključaka i time i na integritet rezervoara.

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 onto 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 m^3. 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.

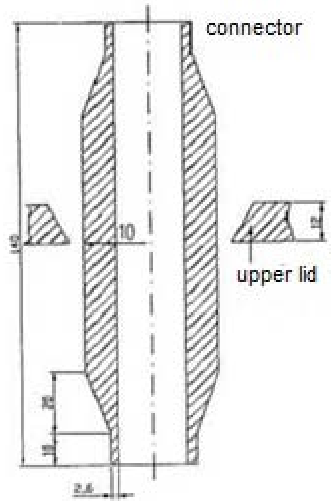

Figure 1. Shape and dimensions of the connector reinforcement and welded joint groove.
Slika 1. Izgled i dimenzije ojačanja priključka i žleba zavarenog spoja

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 (%).
Tabela 1. Hemijski sastavi osnovnih i dodatnog materijala (%)

	C	Si	Mn	P	S	Cr	Ni	Al	Ti
P460NL1	≤ 0.20	0.40	1.45	≤ 0.020	≤ 0.020	-	-	≥ 0.020	-
X6CrNiTi 18 10	≤ 0.08	≤ 1.0	≤ 2.0	≤ 0.035	≤ 0.025	17.0–19.0	9.0–11.0	-	5×%C
E29 9 R 12	0.15	≤ 0.9	0.9	-	-	29	9	-	-

Table 2. Mechanical properties of base materials and consumables.
Tabela 2. Mehaničke osobine osnovnih i dodatnog materijala

	Yield strength $R_{p0.2}$ (MPa), min.	Tensile strength R_m (MPa)	Elongation A_5 (%), min.	Toughness ISO–V min.
P460NL1	470	540–740	19	27 J at –40°C
X6CrNiTi 18 10	205	490–740	40	27 J at –40°C
E29 9 R 12	500	740–840	20	27 J at –40°C

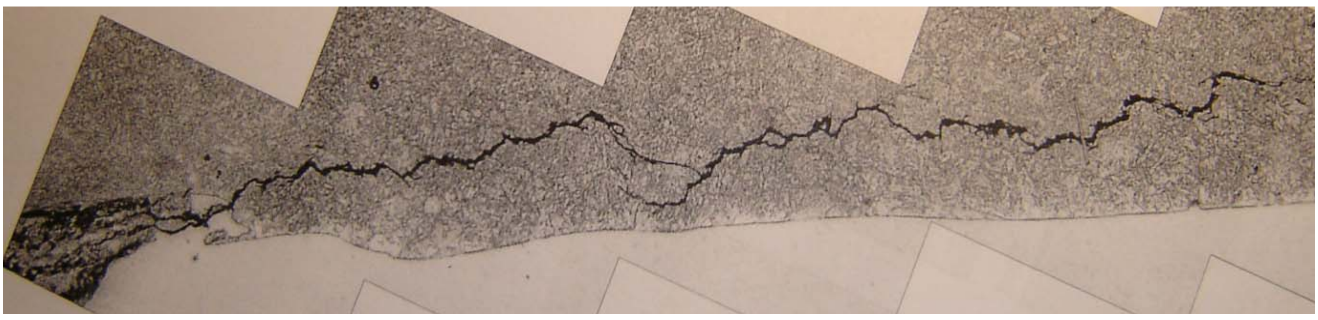

Figure 2. Microcracks in the HAZ of the connector welded joint.
Slika 2. Mikroprsline u ZUT spoja priključka

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 area 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 drop in temperature leads to reduced stresses in the tank wall and reduced material toughness, but not below the minimal guaranteed value (27 J), as well as an increase in material strength up to a certain point, internal pressure test conditions are estimated as most critical, hence effects of cracks on welded joint integrity are assessed for these conditions.

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 δ_r parameters.

Parameter S_r is calculated from the following equation:

$$S_r = \frac{\sigma_n}{\sigma_f} \tag{1}$$

where σ_n is the effective stress in the net section and σ_f represents the material hardening stress, i.e. the half-sum of yield stress σ_y and tensile strength σ_m, which in case of level II assessment is adopted as a maximum of $1.2\cdot\sigma_y$. Effective stress in the net section is calculated as:

$$\sigma_n = 1.2 M_s P_m \tag{2}$$

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:

$$P_m = \frac{pD}{4B} \tag{3}$$

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:

$$M_s = 1 - (a/BM_t)/1 - (a/B)$$

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

$$M_t = \left[1 + 3.2\left(\frac{c^2}{DB}\right)\right]\cdot 0.5$$

Calculation gives the following values: P_m = 133 MPa; M_t = 1.00; M_s = 1.00; σ_n = 162 MPa.

Hardening stress σ_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
Tabela 3. Otvaranje prsline za pojedine zone ZUT čelika P460NL1

Simulation temperature ^{o}C	1350	1100	950	850
Yield stress σ_y (MPa)	1101	943	818	660
Tensile strength σ_m (MPa)	1101	1189	1036	936
Crack opening δ_c (20^{o}C) (mm)	0.007	0.002	0.164	0.130

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 facture of 1.1. In:

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

The crack opening value δ_r for level II assessment is calculated as:

$$\sqrt{\delta_r} = \sqrt{\frac{\delta_I}{\delta_{mat}} + \rho} \tag{4}$$

where δ_I is the acting crack opening, which is calculated from the following expression

$$\delta_I = \frac{K_I^2}{\sigma_y E} \tag{5}$$

In the above expressions, K_I is the stress intensity factor; δ_{mat}–critical crack opening for the material (δ_c); ρ–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:

$$K_I = \frac{M_m}{\Phi}\sigma_I\sqrt{\pi a} \tag{6}$$

where M_m is the stress increase factor which takes into account the shape of the crack, Fig. 3; Φ is the elliptical integral, Fig. 4. For a crack with length of $2c$ = 2.1 mm and depth a = 1 mm which is located in a wall with thickness of B = 12 mm, M_m = 1.05; Φ = 1,53.

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

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

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

- A, temperature zone 1350°C, $\delta_{IA} = 758^2/1101{\cdot}207000 =$ 0.003; where K_I = 758 MPa√mm, σ_{yA} = 1101 MPa, E = 207 GPa;
- B, temperature zone 850°C, $\delta_{IB} = 758^2/660{\cdot}207000 =$ 0.004; where K_I = 758 MPa√mm, σ_{yB} = 660 MPa, E = 207 GPa.

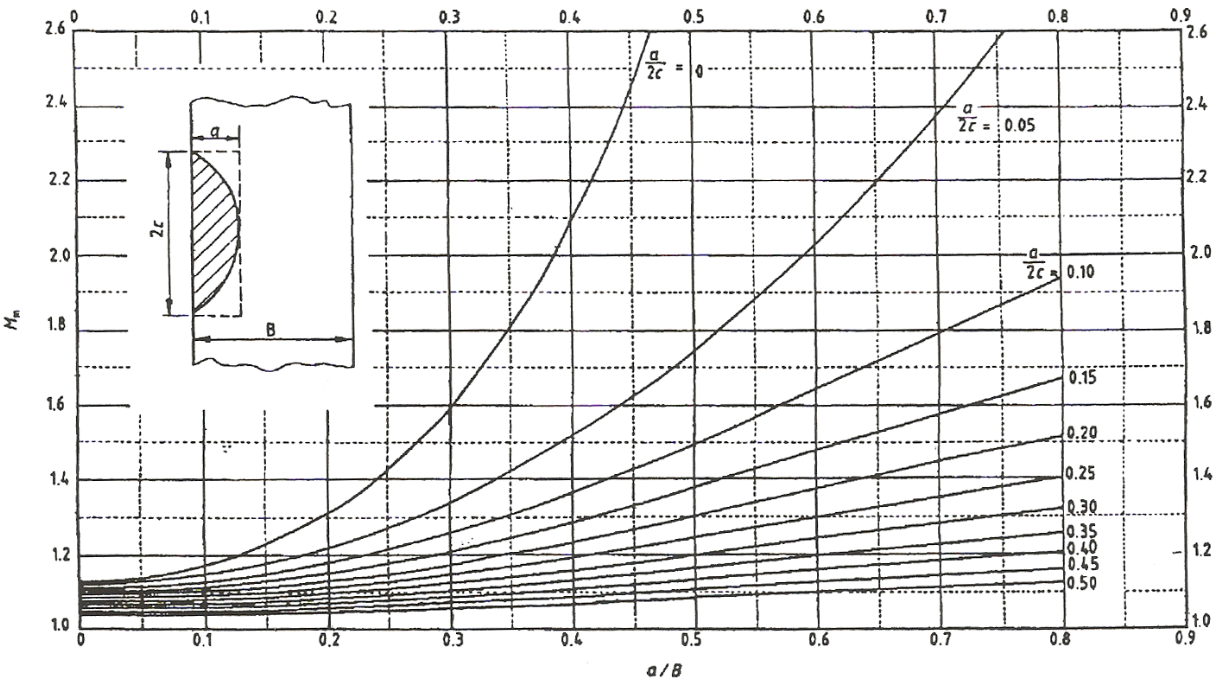

Figure 3. Stress increase factor M_m for a surface crack subjected to tension.
Slika 3. Faktor uvećanja napona M_m za površinsku prslinu izloženu zatezanju

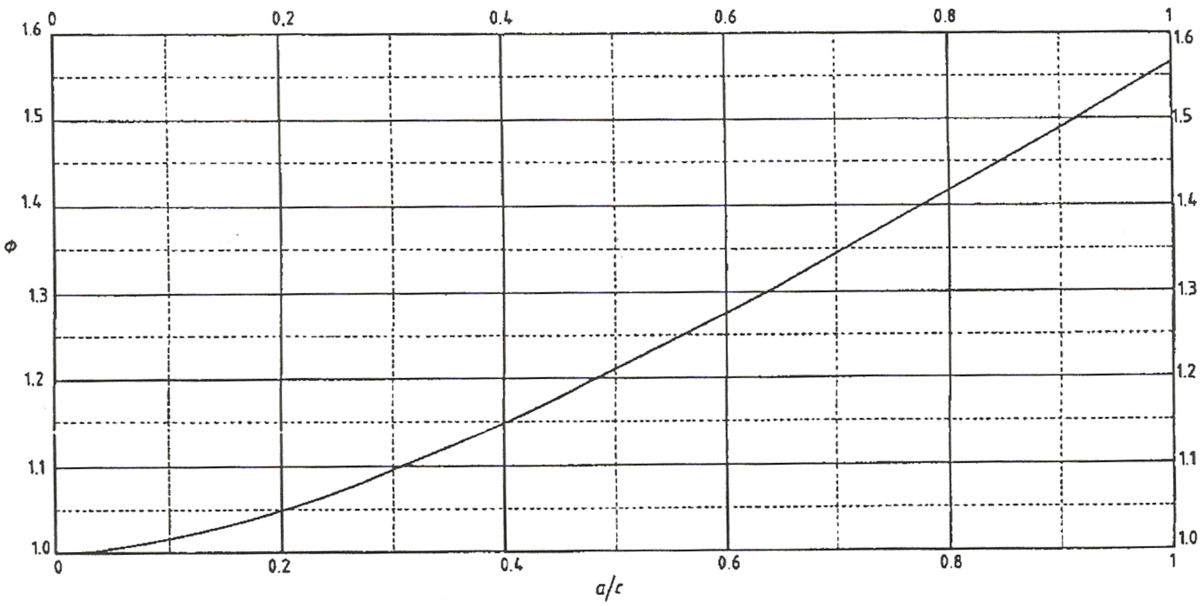

Figure 4. Elliptical integral Φ for a surface crack.
Slika 4. Eliptični integral Φ za površinsku prslinu

Critical values of crack opening δ_c for the considered temperature zones are given in Table 3. Correction factor ρ according to /10/ for this case has a value close to zero. From Eq.(4) it follows that:

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

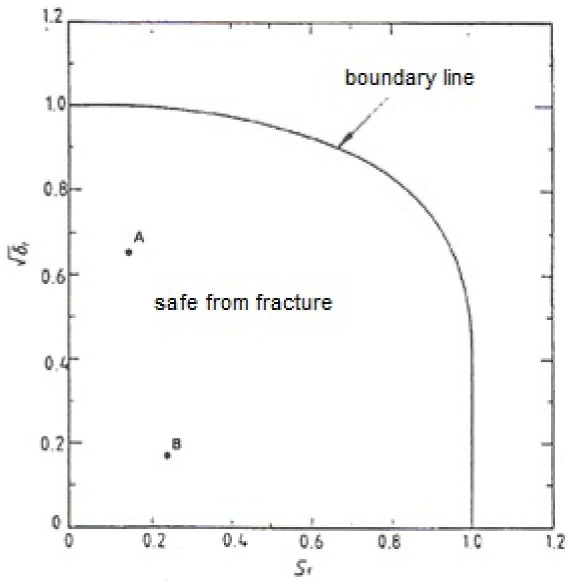

Figure 5. Diagram for level II fracture assessment.
Slika 5. Dijagram ocene loma za nivo II

Appearance of flaws on the fusion line facilitates the growth of microcracks in the lateral direction. Increase in crack length leads to increased values of stress intensity factor, acting crack opening and the δ_r parameter, which moves points A and B closer to the boundary line of fracture risk, Fig. 5. Since the possibility of microcrack growth up to its critical value cannot be excluded, it is prescribed for these joints to be periodically controlled using NDT.

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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