ISSN 0543-5846
METABK 46 (3) 173-178 (2007)
UDC - UDK 669.15:624.953.634:621.791=111

ERECTION OF A STAINLESS-STEEL TANK FOR STORING A PHOSPHORIC ACID

Received - Primljeno: 2006-06-26
Accepted - Prihvaćeno: 2006-12-27
Preliminary Note - Prethodno priopćenje

A storage tank for 93 % phosphoric acid was built in Luka Koper from 7 mm thick ground hot-rolled plates of 316L stainless steel. The capacity of the storage tank is of the 750 m^3, diameter of 11 m and the height of 8,2 m. The shell plates were welded manually using the shielded metal-arc and gas-metal-arc processes. Before the erection, welding procedure tests according to EN 288-3 were carried out. During the construction several non-destructive examination methods were used, such as radiographic testing and visual and liquid penetrant examination. After the entire tank and roof structure were completed, a hydrostatic leak test was carried out. The surfaces of all the welds on the internal surface of the vessel were ground and the roughness was checked on site. The surfaces of the base material and the ground welds were passivated and tested for resistance to corrosion with electrochemical measurements.

***Key words**: stainless steel, phosphoric acid, cylindrical storage tank, welding*

Izgradnja rezervoara iz nehrđajućeg čelika za skladištenje fosforne kiseline. U Luci Koper je izgrađen rezervoar za 93 % fosfornu kiselinu iz toplo valjanog lima nehrđajućeg čelika debljine 7 mm i kvalitete 316L. Volumen rezervoara je 750 m^3, promjer 11 m i visina plašta 8,2 m. Za zavarivanje plašta rezervoara je korišten ručni elektrolučni postupak zavarivanja obloženim elektrodama i zavarivanje taljivom elektrodom u zaštitnoj atmosferi plina. Prije izgradnje rezervoara je načinjen atest postupka zavarivanja u skladu s EN 288-3. U toku izgradnje rezervoara su upotrebljavane različite kontrole materijala bez razaranja, kao što su radiografska kontrola, vizualna kontrola i kontrola tekućim penetrantima. Poslije završetka radova na plaštu i krovu rezervoara je izveden hidrotest rezervoara. Sve površine zavara na unutarnjoj površini rezervoara su obrušene i polirane, a potom je provjerena hrapavost. Površine osnovnog materijala i obrušeni zavari su pasivizirani te ispitani na otpornost koroziji s pomoću elektrokemijskih mjerenja.

***Ključne riječi**: nehrđajući čelik, fosforna kiselina, cilindrični rezervoar, zavarivanje*

INTRODUCTION

Since 1986 phosphoric acid has been stored at the liquid-cargoes terminal in Luka Koper in a six reinforced polyester above-ground storage tanks, with a volume of 750 m^3 each. Since these tanks are reaching the end of projected explotation time, it was decided to gradually replace them with tanks from 316L (X2CrNiMo 17-12-2) stainless steel.

DESCRIPTION OF THE STRUCTURE

The new, stainless-steel storage tank has a nominal volume of 750 m^3, an inside diameter of 11 m, a shell height of 8,2 mm and a maximum liquid level of 8 m. The stored liquid is 93 % phosphoric acid with a specific gravity of 1,78 t/m^3. The normal operational temperature is of 35 °C and the design temperature is of 95 °C [1].

Figure 1. **The liquid cargoes terminal at Luka Koper**
Slika 1. **Skladište tekućih kemikalija u Luci Koper**

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The tank is equipped with a bottom- and shell-heating coil and the whole of the tank is covered with heat insulation of a 100 mm thick material, with a protective aluminium foil and 0.6-mm-thick steel plates covered with a paint resistant in marine environment. The bottom annular ring has a width of 200 mm and it is 7 mm thick [2]. The whole of the steel structure is anchored to a reinforced concrete foundation with twenty M16 bolts. The shell consists of a five 1,5 m high courses and with upper course of 0,7 m high. The roof of the tank is designed as a self-supporting cone of membrane type.

STORAGE TANK CALCULATION

For the design and construction of the storage tank the following codes and standards were used [3, 4]:

- API 650 - Welded Steel Tanks for Oil Storage, 1998. add. 2001;
- DIN 18800 - Steel structures, T1-Design and construction, T4 - Stability, Buckling of shells, 1992;
- BS 2654 - Manufacture of vertical steel-welded non-refrigerated storage tanks with but welded sheets for the petroleum industry, 1998;
- EN 1991-1-1: Actions On Structures. General actions. Densities, Self-Weight, Buildings;
- EN 1991-1-2: Actions On Structures. General actions. Densities, Actions on Structures;
- EN 1991-1-3: Actions On Structures. General actions. Snow Loads;
- EN 1991-1-4: Actions On Structures. General actions. Wind Action;
- EN 1993-1-1: Design of steel structures. General requirements;
- EN 1993-1-1: Design of steel structures. General rules - Supplementary rules for stainless steel;
- EN 1993-1-6: Design of steel structures. General - Strength and stability of shell structures;
- EN 1993-4-2: Design of steel structures. Silos, tanks and pipelines. Tanks.

The loads [5] taken into consideration were:

- the dead load of the storage tank and equipment,
- the static pressure of the phosphoric acid with g = 17,8 kN/m^3,
- the snow load (0,35 kN/m^2),
- the water's hydrostatic pressure during the hydrotest, with g = 9,81 kN/m^3,
- the wind load at a design velocity of 160 km/h,
- the internal pressure load of a 200-mm water column,
- the seismic load for VIII earthquake zone according to MCS.

The storage-tank data:

- the inside tank diameter D = 11 m,
- the shell height H_{pl} = 8,2 m,
- the design liquid height H_m = 8 m,
- the design specific gravity of phosphoric acid G = 1,78 kg/dm^3,
- the minimum allowed thickness of the shell plate t = 5 mm,
- the corrosion allowance CA = 0,5 mm,
- the design temperature T = 95 °C,
- the allowable stress for the design condition S_d = 137 N/mm^2,
- the allowable stress for the hydrostatic test conditions S_t = 114 N/mm^2,
- the specific density of the steel ρ = 7.85 kg/dm^3.

According to API 650 3.6.3.2 the required minimum thickness of the shell plates must be greater than the values computed with Equation (1):

$$t_d = \frac{4,9 \cdot (H_i - 0,3048) \cdot G}{S_d} + CA. \tag{1}$$

The hydrostatic test-shell thickness must be greater than the values computed with Equation (2):

$$t_t = \frac{4,9 \cdot (H_i - 0,3048)}{S_t}. \tag{2}$$

Table 1. shows the results of the shell-thickness calculation for each course. For the calculation the following data were taken into consideration: a height of 8,2 m, the whole mass of the shell courses 15 580 kg, and a calculated volume of 779 m^3.

Table 1. **Thickness calculation for the storage-tank shell courses**
Tablica 1. **Izračun debljine plašta rezervoara**

course no.	H_p / m	S_d / N/mm^2	S_t / N/mm^2	H_i / m	t_d' / mm
1	1,5	137	114	8,00	5,89
2	1,5	137	114	6,50	4,84
3	1,5	137	114	5,00	3,79
4	1,5	137	114	3,50	2,74
5	1,5	137	114	2,00	1,69
6	0,7	137	114	0,50	0,64
course no.	t_d / mm	t_t' / mm	t_t / mm	t / mm	mass / kg
1	5,89	3,64	5,50	7	2850
2	5,50	2,93	5,50	7	2850
3	5,50	2,22	5,50	7	2850
4	5,50	1,51	5,50	7	2850
5	5,50	0,80	5,50	7	2850
6	5,50	0,09	5,50	7	1330

where:

H_p - the shell-course height,
H_i - the height from the bottom of the course under consideration to the top of the shell,
t_d' - the calculated shell thickness,
t_d - the selected shell thickness,
t_t' - the calculated hydrostatic test-shell thickness,
t_t - the selected hydrostatic test-shell thickness,
t - the design shell thickness.

Based on the results presented in Table 1., a uniform thickness, for all the shell courses, of 7 mm was selected. The storage-tank bottom thickness was determined according to the clause 3.4.1 API 650, in which it is stated that all the bottom plates must have a minimum nominal thickness of 6 mm. After considering the corrosion allowance, a thickness of 7 mm for the bottom plates was finally selected by the designer.

THE BASE MATERIAL

For the storage-tank shell, the roof, the annular ring and the bottom, a X2CrNiMo 17-12-2 stainless steel (316L according to ASTM-A240/a) was selected. This is an austenitic chromium - nickel - molybdenum stainless steel with a low carbon content, with good corrosion resistance to some organic and inorganic acids [6]. Steel is also easy to polish, which increases corrosion resistance [7 - 9].

The steel has good weldability, if the welding is performed in inert atmosphere to prevent weld-pool carburization. The solidified weld has to have some δ-ferrite in the austenitic microstructure to prevent the occurrence of intercrystaline voids during the solidification of the weld pool [10].

The welding parameters must ensoure the prevention of carbide formation in the heat-affected zone. The chemical analysis results of the sample base material are presented in Table 2.

Table 2. **Stainless-steel chemical composition (in weight %)**
Tablica 2. **Kemijski sastav nehrđajućeg čelika (mas. %)**

C	Si	Mn	S	P	Cr
0,020	0,510	0,960	0,003	0,032	17,0
Ni	Mo	Cu	Ti	Nb	Co
10,3	2,0	0,320	0,010	0,030	0,170

Chromium provides the basic corrosion resistance for the stainless steel with the formation of a very thin and stable oxide film of Cr_2O_3 on the steel's surface. In this way, the stainless steel's surface becomes passivated oxide layer preventing the diffusion between the steel and agent and the corrosion processes.

The addition of molybdenum and copper improves the corrosion resistance while the content of nickel ensures the stability of the austenite matrix and the hot and cold workability of the steel.

Figure 2. shows the microstructure of the base material with austenitic matrix and thin elongated bands of δ-ferrite.

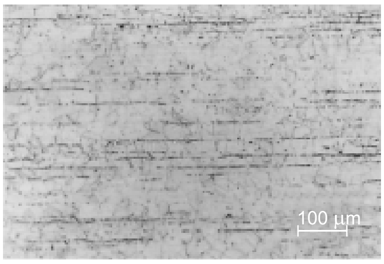

Figure 2. **Stainless-steel microstructure**
Slika 2. **Mikrostruktura nehrđajućeg čelika**

Measurements at 24 points were carried out for the content of δ-ferrite in the base material. The average measured value was 0,78 % of δ-ferrite and its distribution in the stainless steel plates was very homogeneous. It is not expected that the very low content of δ -ferrite could affect the corrosion resistance of the steel, since not surface corrosion attack was observed which could be related to the presence of this phase in the steel.

Table 3. **The base material δ-ferrite content**
Tablica 3. **Sadržaj δ-ferita osnovnog materijala**

0,86	0,73	0,73	0,83	0,80	0,70
0,93	0,67	0,83	0,83	0,78	0,79
0,77	0,86	0,85	0,87	0,76	0,66
0,82	0,89	0,67	0,74	0,61	0,75

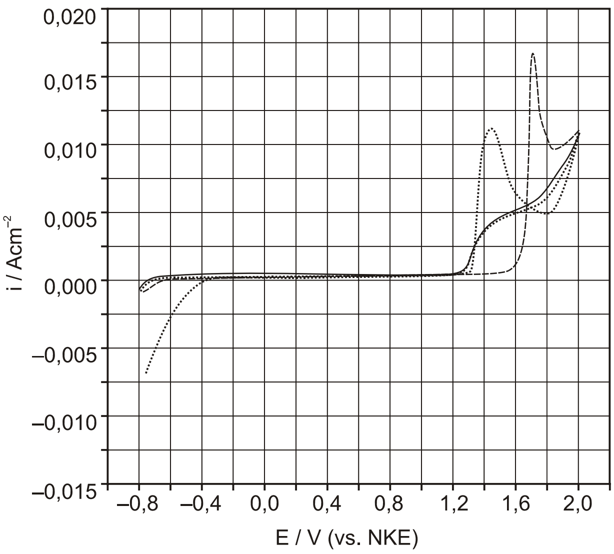

Figure 3. **Polarisation curve, temperature 30 °C, quality of surface grinding R_a 0,6 - 0,9 (specimen 1)**
Slika 3. **Polarizacijska krivulja, temperatura 30 °C, kvalitet brušenja površine R_a 0,6 - 0,9 (uzorak 1)**

Although the steel 316 L is recomended for storage tanks by the producer of the acid, short time corrosion tests were performed on the steel and the weld with the aim to verify the effect of surface condition and temperature on the theoretical corrosion rate. The tests were carried out in the Tacussell cell with the tested steel as working electrode, a platinum measuring electrode and the saturated calomel electrode as reference. The dependences current intensity versus potential similar to those in Figures 3., 4. and 5. were obtained and from the current intensity the theoretical corrosion rate shown in Table 4. was deduced.

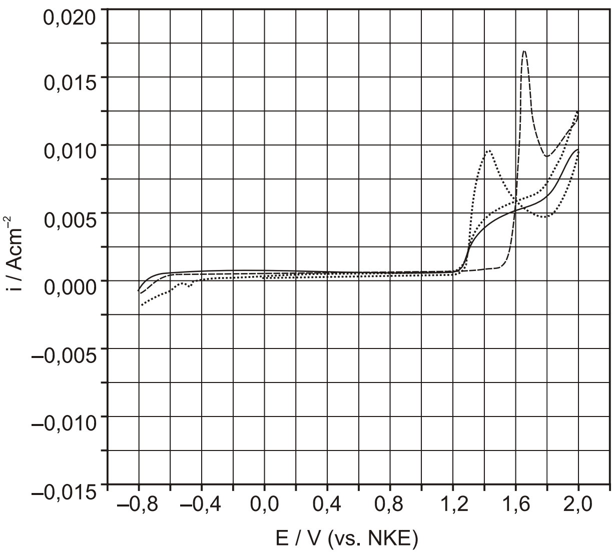

Figure 4. **Polarisation curve, temperature 30 °C, quality of surface grinding R_a 1,5 - 2 (specimen 2)**
Slika 4. **Polarizacijska krivulja, temperatura 30 °C, kvalitet brušenja površine R_a 1,5 - 2 (uzorak 2)**

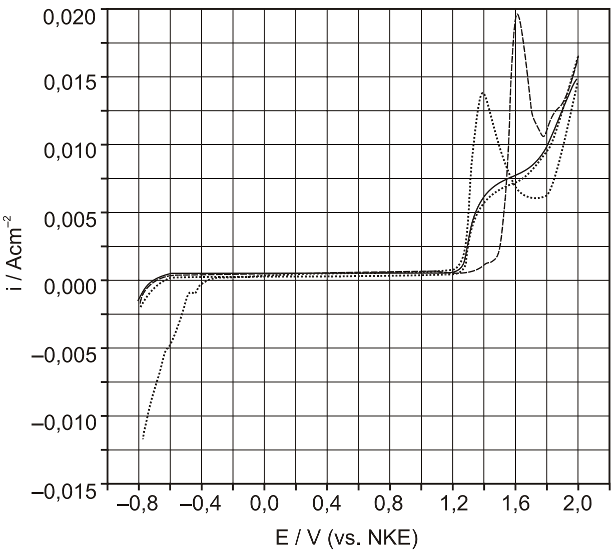

Figure 5. **Polarisation curve, weld material, temperature 30 °C (specimen 3)**
Slika 5. **Polarizacijska krivulja, material zavara, temperatura 30 °C, (uzorak 3)**

Table 4. **Corrosion rate for different testing conditions**
Tablica 4. **Brzina korozije kod različitih uvjeta testiranja**

	surface as delivered			surface as ground		
	temperature			specimen (temperature 30 °C)		
	25 °C	50 °C	75 °C	1	2	3
corrosion rate / (mm/year)	0,525	1,58	2,93	0,12	0,31	0,21

It is clear from the results in Table 4., that the corrosion rate depends strongly from the quality of the surface and the temperature. In reference (11) a slightly lower corrosion rate of 0,11 mm/year is reported for the steel 316 L in the solution of phosphoric acid. The corrosion rate calculated from the short time tests of the polished surface of 0,12 mm/year is slihtly greater. It is thought, however, that the difference is not significant and probably due to the used tetsing method. It was decided, that the internal surface of the vessel, welds included, will be polished and care will be given also to the protection of the external surface to atmoshperic heating. After polishing the internal surface was passivated with nitric acid and, in this way, the protections against a possible corrosion attack strengthened.

WELDED JOINTS

A combination of tungsten inert-gas arc welding (root weld) and metal-arc welding with a covered electrode (filler welds) was used for all the vertical and horizontal butt welds [11 - 13]. During the welding of the first course of the storage tank a vertical butt-weld test piece according to EN 288-3 was prepared. The testing of the test piece included both, a non-destructive examination and destructive testing. The non-destructive tests included visual, liquid penetrant and a radiographic examination [14]. After all the non-destructive tests had shown satisfactory results, destructive test specimens for a transverse tensile test, a bend test, an impact test, a hardness test and a macro-examination were cut out. Tensile test showed the yield stress of 418 MPa, the tensile stress of 590 MPa, the elongation A_5 of 35 % and the reduction of area of 64 %. Figure 6. shows the section of a weld.

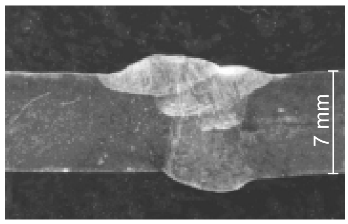

Figure 6. **Section of a weld**
Slika 6. **Presjek zavara**

The hardness measurement results (HV3) from the face side and the root side of the specimen in Figure 3. are presented in Table 5.

Table 5. **Results of the hardness measurements (HV3)**
Tablica 5. **Rezultati mjerenja tvrdoće (HV3)**

face side					
base material	184	189	187	187	187
HAZ *	205	209	202	207	206
weld	180	187	186	187	185
root side					
base material	191	187	188	183	186
HAZ *	210	208	206	207	206
weld	181	189	191	191	190
*heat-affected zone					

The average hardness value in the heat-affected zone is of 206 HV, on the face side and of 207,5 HV, on the root side. Both values are acceptable.

The Charpy V-notch impact-toughness at room temperature was above of 100 J. Four specimens for the transverse bend test were prepared (two face and two root). All four specimens were bent to the angle of 180° without surface cracks.

The microstructure of the heat-affected zone is shown in Figure 7., and the microstructure of the deposited

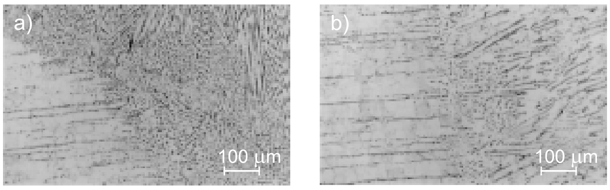

Figure 7. **Microstructure of heat-affected zones: a) weld face heat-affected zone; b) weld root heat-affected zone**
Slika 7. **Mikrostruktura zone utjecaja topline: a) zona utjecaja topline u tjemenu zavar; b) zona utjecaja topline u korijenu zavara**

material (weld) is shown in Figure 8. The microstructure of the heat-affected zone consists of austenite and δ-ferrite. Both phases are also found in the deposited material, however, the content and the distribution of δ -ferrite in the weld deposited material are different and more suited for the prevention of the formation of micro voids during the solidification of the weld pool. The δ -ferrite content in the deposited weld material was measured at six spots with an average value of 7,5 %.

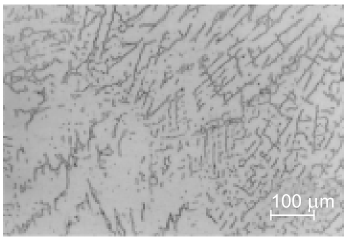

Figure 8. **Weld deposited microstructure**
Slika 8. **Mikrostruktura zavara**

ASSEMBLY OF THE STORAGE TANK

The storage tank shell has five 1500 mm wide courses, while the upper one is 700 mm wide. Each course consisted of five 6000 mm long sheets and an insert for the final diameter adjustment. An insulation layer and a mesh with a 730 m long heating coil were laid on the storage tank's foundation, following the slope layer of the concrete. The heating coil (Figure 9.) was completely covered with a second layer of concrete. The stainless-steel bottom was fitted to the last layer of concrete. Stainless-steel bottom plates with dimensions 7×1500×6000 mm were welded together with full-penetration butt welds and a backup bar. The incline of the storage tank stainless steel bottom is 1 %. The storage tank roof (Figure 10.) is designed as a self-supporting of membrane type.

Figure 9. **Heating coil on the bottom of the tank**
Slika 9. **Sustav zagrijavanja dna rezervoara**

Figure 10. **The storage tank's roof**
Slika 10. **Krov rezervoara**

The on-site quality control consisted of control of the shell erection, retesting of the welding procedure, visual checks, liquid penetrant and the radiographic examination of the welded joints. A leak test of all the welded joints on the bottom and on the roof was carried out using the vacuum-box technique.

Figure 11. shows the storage-tank shell during the erection.

Figure 11. **Erection of the storage-tank shell**
Slika 11. **Montaža plašta rezervoara**

The hydrostatic leak test was carried with fresh water filled to 1/3, to 2/3, and to the maximum design level of 8 m. After each liquid level was reached, the measurements were carried out. The storage tank was full for 24 hours, and then emptied to half of the design level, with complete discharge taking place afterwards. Measurements of the foundation settlement for each liquid level were carried out, as well as a structural integrity inspection of the shell and a visual inspection of the welded joints.

After completion of the construction and the erection of the tank the dimensional tolerances of the storage tank were checked. The maximum out-of-plumbness of the top of the shell is 12 mm and well below the design limit of 80 mm. Control of the roundness was carried out with measurements of the radius at a 0,3 m shell height. The maximum measured radius deviation was +4 mm and below the allowed design value of ± 25 mm.

CONCLUSION

1. For the design, manufacturing, erection and inspection of above-ground storage tanks, in addition to the API standard 650, DIN 18800 and BS 2654, also the Eurocode series standards were used.
2. A 316 L stainless steel storage tank for 93 % phosphoric acid was built. The bottom, shell and the roof are consisted of 7 mm thick plates, for which a chemical analysis was carried out.
3. 316 L steel has good corrosion resistance, good toughness and weldability. The welding procedure was verified according to EN 288-3, and the corrosion resistance tested to 93 % phosphoric acid.
4. During the erection on site non-destructive examination of the welds was carried out with visual examination, liquid penetrant testins and a radiographic examinations.
5. A hydrostatic leak test was performed In accordance with ENV 1993-1-6.
6. After the inspection and testing, the storage tank was filled with 93 % phosphoric acid, and the tank was found to be suitable for its purpose.

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