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STRESS STATE AROUND IMPERFECTIONS IN WELDED JOINTS

NAPONSKO STANJE OKO GREŠAKA U ZAVARENOM SPOJU

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- stress state
- finite element analysis

Ključne reči
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- naponsko stanje
- analiza konačnim elementima

Abstract

Because of their geometry, welded joints can cause a local increase of stress. In the presence of imperfections in welded joints the local stress additionally increases and can lead to the formation of cracks. Cracks are detected in the welded joint during testing of pressure equipment in service, and the stress state around imperfections is analysed by finite element method. It is concluded that even the imperfections that are acceptable for the highest level of quality, according to the standard SRPS EN ISO 5817, may cause significant higher local stresses than stresses predicted in the design of the structure.

Izvod

Zavareni spojevi, usled svoje geometrije, mogu prouzrokovati lokalno povećanje napona. U prisustvu grešaka u zavarenim spojevima, lokalni napon se dodatno povećava i može dovesti do formiranja prslina. U ovom radu su prikazane prsline otkrivene u zavarenom spoju tokom ispitivanja opreme za rad pod pritiskom u eksploataciji, a naponsko stanje je analizirano primenom metode konačnih elemenata. Zaključeno je da su čak i greške koje su prihvatljive i za najviši nivo kvaliteta prema standardu SRPS EN ISO 5817, izazivaju značajno veće lokalne napone od predviđenih tokom projektovanja konstrukcije.

INTRODUCTION

Welded joints require special attention when assessing the safety of welded structures in service, because the material properties and stress state differ from the rest of the structure, /1/. The stress state in welded joints depends on workload, residual stresses, stresses caused by the shape of welded joint (excess weld metal, sagging, incompletely filled groove, sharp transition from weld metal to base metal etc.) and stresses caused by the presence of defects in the weld such as cracks, inclusions, lack of penetration and undercuts. Some examples of failures caused by the presence of defects in welded joints are given in literature /2-4/.

CRACKS IN THE WELDED JOINT

During in-service testing of the storage tank for liquid carbon-dioxide, cracks are detected in the welded joint between the tank shell and the head, /5/. The storage tank is a horizontal, cylindrical, thermally isolated pressure vessel, with volume of 50 m^3. It is made of 17 mm thick micro-alloyed steel P460NL1 according to standard SRPS EN 10028-3, /6/. Further details on the storage tank are, /5/: outside diameter 3000 mm, total length 7900 mm, maximal operating pressure 2 MPa, testing pressure 2.6 MPa, the lowest operating temperature –50°C and the category of pressure vessel is 2, according to the pressure equipment directive published in the Official Journal of SFRJ, No. 16/83, /7/.

From ref. /5/, the connections of the tank shell, as well as connections between the heads and the shell are made by submerged arc welding procedure. As a filler material, the electrode wire EPP2NiMo2 was used in combination with the flux OP 121 TT, /8/. The chemical compositions and mechanical properties of the base and filler material are given in /8, 9/ and presented in Tables 1 and 2.

Welded joints in the storage tank are subjected to visual, magnetic particle– and ultrasonic testing. Detected cracks are shown in Fig. 1. The image is obtained by taking the print of black magnetic particles from the surface of the ground weld. The top line in the image represents an undercut, and the three lines in the lower part of the image represent three cracks extending along the weld fusion line.

Table 1. Chemical composition of the base and filler material.

Material	Chemical elements (wt. %)							
	C	Si	Mn	P	S	Mo	Ni	Al
P460NL1	≤ 0.20	0.40	1.45	≤ 0.02	≤ 0.02	-	-	≥ 0.02
EPP2NiMo2	0.05-0.08	0.2-0.3	0.7-1.0	-	-	0.45	2.0	

Table 2. Mechanical characteristics of base and filler material.

Material	Yield stress (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Charpy impact energy (J)
P460NL1	460	620	19	27 (–40 °C)
EPP2NiMo2	450	650 - 750	20	30 (–60 °C)

Figure 1. Cracks in welded joint between shell and tank head.

The cracks are located at small mutual distances, so the total length of cracks and the material in between them (the total length of the imperfection) is 60 mm. The maximal depth of the cracks is determined by ultrasonic testing and it is 3 mm. In the area where the cracks are detected, visual testing of linear misalignment and incorrect weld toe are also determined. According to literature /5, 10/, the required quality level of this welded joint is B. It is concluded that, in this particular case, the acceptable size of linear misalignment is 1.7 mm, while the measured size is 4 mm and the acceptable transition angle from the base metal to the weld metal is 150°, while the measured angle is 120°. Consequently, detected imperfections are unacceptable for the required level of quality of the welded joint, /10/.

Figure 2 shows a cross section through the weld and tank wall in the area with a maximal depth of cracks. It can be seen that the cracks occurred in the area of transition from the weld metal to the base metal, along the fusion zone.

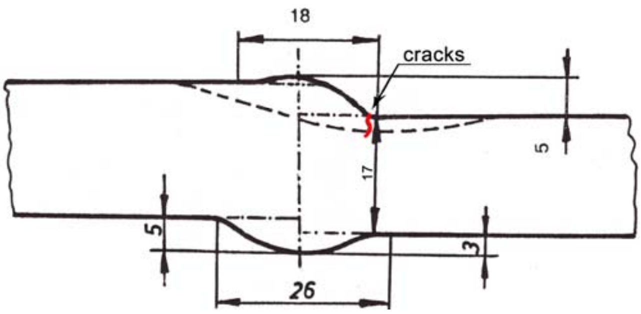

Figure 2. Cross section through the weld with cracks.

STRESS ANALYSIS

The impact of imperfections detected in the welded joint, on the stress state is analysed, and also the influence of the stress state on the possibility of crack formation is analysed.

There are two possible working regimes the tank can be exposed to. The first is the testing regime and the second is the regular working regime, /5/. During the testing regime, the tank is exposed to internal pressure of 2.6 MPa, and the testing fluid in this case is water of temperature in the range from 10°C to 20°C. During the regular working regime the tank is loaded with liquid carbon-dioxide of pressure between 1.4 and 2 MPa, and temperature is in the range from –20 to –30 °C. With a decreasing temperature the pressure decreases, and consequently the stress in the tank wall decreases, the toughness of the material decreases, but not below the minimal guaranteed value of 27 J for used steel, and the strength of the material grows to some extent. This is why the conditions which occur during the pressure test are declared as critical. The integrity of the welded joint with cracks is evaluated for these critical conditions.

The normal stress σ, which is decisive for the initiation and propagation of cracks, /11/, acts in the direction of longitudinal axis of the tank and is determined by the following expression:

$$\sigma = \frac{pD}{4t}, \tag{1}$$

where: test pressure p = 2.6 MPa; thickness of tank wall t = 17 mm; and outside diameter D = 3000 mm. The calculated value of normal stress is σ = 115 MPa.

From literature it can be seen that welded joints in this tank are not annealed, /5/. In this case, according to /11/, it is assumed that the residual stress is approximately equal to the lesser of the two values: the yield stress of the weld metal, or the yield stress of the base metal. From Table 2 it can be seen that the yield stress is lower for the weld metal compared to the base metal and its value is 450 MPa. According to /11, 12/, even in the case of annealing, the residual stress in the welded joints cannot be reduced below 30% of the initial value. However, the value of the residual stress can be significantly reduced by applying various measures during welding (preheating, maintaining interpass temperature, back-step welding, etc.). During the welding of steel P460NL1, preheating and maintenance of the interpass temperature are necessary, /5/. Because the submerged arc welding procedure is used, it was not possible to apply back-step welding. Based on these facts, it was adopted that the residual stress was reduced to the value of 85% of the weld metal yield stress. The value of the residual stress is 383 MPa.

The stress caused by linear misalignment and sharp transition from base- to weld metal is determined by finite element analysis. The part of the tank with cracks in the welded joint is modelled by two-dimensional finite elements. The model is based on dimensions shown in Fig. 2. At the right end of the model the displacement is prevented in a direction of longitudinal axis of pressure vessel (x-axis) while at the left end of the model, the forces that correspond to σ stress of 115 MPa are set. This stress occurs in the longitudinal direction of the tank wall, at test pressure of 2.6 MPa. The results of analysis are shown in Fig. 3. Different colours indicate areas of different stress values. The maximum stress of 279 MPa (red zone in Fig. 3) occurs in the area with linear misalignment, on the surface where cracks are detected. The ratio of maximum stress value (stress acting in the area where imperfections occurred, 279 MPa) and the value of stress caused by internal pressure (σ = 115 MPa, green zone in Fig. 3), represents the stress concentration factor. In this particular case, the value of the stress concentration factor is 2.43. In the blue zones, the normal stress is lower than 100 MPa.

The value of maximum tensile stress in the area of the welded joint, where imperfections are detected, represents the value of stress which is decisive for the formation of cracks. It is equal to the sum of values of residual stress (383 MPa) and maximum stress caused by internal pressure which occurs in the area with imperfections in the welded joint (279 MPa). The value of maximum tensile stress is 662 MPa. This tensile stress in the welded joint, in the area where imperfections are detected, is higher than the ultimate tensile strength of the base metal, due from which the cracks had occurred in this zone.

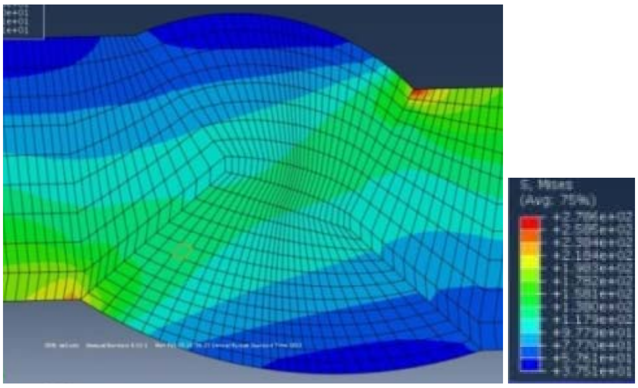

Figure 3. Stress distribution in the cross section of the welded joint with defects.

In other parts of the same welded joint, linear misalignments are discovered by visual tests. However, the dimensions of these imperfections are in the range of acceptable values for the required quality level, /5, 10/. The stress concentration factor is estimated in the same manner as in the previous example. Based on the results shown in Fig. 4 it can be concluded that in this case, the value of stress concentration factor is 1.58. Consequently in the zone of the welded joint with acceptable linear misalignment, the maximum stress caused by internal pressure is 182 MPa. This value is obtained by multiplying the value of σ (115 MPa) with the value of the stress concentration factor (1.58). The value of maximum tensile stress in the area of the welded joint where the acceptable linear misalignment is discovered is equal to the sum of values of the residual stress (383 MPa) and the maximum stress caused by internal pressure (182 MPa), and it's value is 565 MPa. This is less than the tensile strength of a base metal due to which the cracks in this zone of the welded joint did not appear.

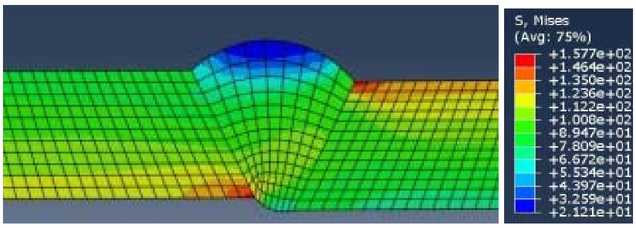

Figure 4. Stress distribution in the cross section of the welded joint with acceptable linear misalignment.

CONCLUSIONS

In the considered example, the size of defects in the welded joint, such as linear misalignment and incorrect weld toe (sharp transition from the weld metal to the base metal), were significantly greater than allowed for the required quality level. Defects caused a 2.4 times increase of the local stress. This stress in a combination with the residual stress in the welded joint resulted in the formation of cracks. Sizes of linear misalignments detected in other parts of the same welded joint are within the range of acceptable values for the required level of quality. These imperfections caused local stress increase up to 60% which, together with the residual stress, is sufficient to exceed the yield stress of the base metal, but is not sufficient for the formation of cracks.

Visual testing of the welded joints is a very important method of testing. This testing method makes it possible to collect: data about defects on the surface of the welded joints; data about completed reparations; and even information on the applied welding technology. In addition, this method provides a fast and inexpensive way to discover zones of increased risk for the formation of cracks in welded joints, which then should be tested by other non-destructive methods.

When considering the safety of welded structures, both the global and the local approach must be taken into account. The global approach involves a calculation of the dimensions of the structure, assuming a regular geometric shape and a homogeneous material. However, welded joints represent places on welded structures where the shape, material properties and homogeneity have locally changed. Because the global approach is not sufficient, the local approach involving stress analysis and material properties around the welded joint applies.

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