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Application of advanced NDT methods to assess structural integrity of pressure vessel welded joints

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Abstract

The review of non-destructive testing of pressure vessel for compressed air is given, as well as the assessment and analysis of defects on the integrity of the vessel itself. The focus here is on welded joints, as the most critical areas in pressure vessels, especially if thickness is large, like in the case considered here (50 mm), cylindrical air storage vessels made of HSLA steel. Toward this end conventional NDT methods, such as UT and Radiography are used in the first phase of this research, providing valuable data for structural integrity assessment based on detected unacceptable defects in welded joints. Anyhow, since few unacceptable defects were found by conventional UT, there was a need to use advanced NDT UT methods, such as Phased Array Ultrasonic Testing (PAUT), to evaluate defect position and size more precisely. In this way risk of failure can be assessed more reliable, which is of utmost importance for pressure vessel where probability of failure is low, but the consequence of failure is potentially catastrophic, like in the case considered here.

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1. Introduction

Non-destructive testing (NDT) of welded joints plays a very important role during pre-service and in-service inspection of pressure vessels to assess their structural integrity, since the lifespan of any pressure vessel depends on absence of harmful defects [1-5]. Therefore, it is simple to recognize the importance of non-destructive testing of components, especially critical ones, like welded joints in pressure vessels [5].

Primary goal of NDT methods is to find out defects in the material. Different NDT methods have their advantages and disadvantages, and reliable defect evaluation of importance for the integrity of welded pressure vessels cannot be obtained

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from the results of only one particular method [6]. Another goal of NDT is pressure vessel life management, and its safe and economic operation, which can greatly improve life expectancy [7,8].

Conventional NDT includes Ultrasound Testing (UT), Radiography (RT), Magnetic particles (MT) and Penetrants (PT). Conventional UT testing technique is based on decibel drop with its own limitations. Generally speaking, it is considered that the reliability of the results obtained by the conventional UT testing method is not more than 50%, so often size of detected defect is doubled in further analysis to get a conservative assessment of structural integrity. Still, this is one of the most frequently used methods for sizing defects in welded joints of piping, pipe fittings and pressure vessels. To overcome some of conventional UT shortcomings, several new techniques are recently introduced, such as Phase Array (PAUT).

In this paper welded joints in pressure vessels in RHE BB are analysed, since several unacceptable defects were detected by conventional UT and monitored frequently in the meantime, including structural integrity assessment, [9]. Minor changes in size of few defects were detected by conventional UT, so leading to the conclusion that more advanced techniques of UT should be used, such as PAUT.

2. Conventional UT

Inspection and testing of pressure vessels in RHPP Bajina Basta was performed by visual testing according to standard EN ISO 5817:2015, along with magnetic particle testing according to the standard EN ISO 23278 2020. These two NDT methods were applied to investigate presence of surface and subsurface defects. For internal defects, the ultrasound method was applied, according to EN ISO 11666 2018. In total 9 pressure vessels for compressed air in Reversable Hydro Power Plant (RHPP) Bajina Bašta, Serbia, were tested, marked 970-978; here one of them are presented (971), where the most critical defects were detected.

It should be noted that the material for inspected vessels was High Strength Low Alloyed (HSLA) steel NIOVAL 50, one the oldest in this steel class, with history of cracking problems in welded joints [9]. The vessel 971 was inspected by 100% ultrasonic testing on two vertical welded joints, and three circular welded joints, by USM 36XL Krautkramer device. This recent conventional UT testing, indicated several unacceptable defects according to standardSRPS EN ISO 11666:2012, with slightly larger dimensions, compared to the previous testing:

- defect 1.1 with length 2c=180 mm and depth a=32 mm (18-50 mm along the thickness)
- defect 1.2 with length 2c=35 mm and depth a=16 mm (19-35 mm along the thickness)
- defect 1.3 with length 2c=65 mm and depth a=26 mm (24-50 mm along the thickness)
- defect 1.4 with length 2c=65 mm and depth a=26 mm (24-50 mm along the thickness)

One should notice that according to this measurement (april 2022) defects have grown compared to the previous NDT (125x24 - defect 1.1, 35x7 - defect 1.2, 55x26 - defect 1.3, 40x20 - defect 1.4). Anyhow, they have been of the same size afterwards, accoring to the conventional UT, with the last tesing in July 2022.

For the further analysis, defect 1.1 was taken as relevant, since it had far the largest dimensions. To assess structural integrity of vessel 971, Failure Analysis Diagramme (FAD) was used, as described in [10-13].

According to the size and position of defect 1.1 (edge surface crack in a circumferential welded joint, the stress intensity factor is defined as: $K_I=Y(a/W,a/c)(pR/2t)\sqrt{\pi a}=1,82(87)\sqrt{32\pi}=1520$ MPa$\sqrt{\text{mm}}$, where Y(a/W,a/c) is the geometry factor, [14], p - operating pressure (8.1 MPa), R - vessel radius, (1075 mm), t - thickness (50 mm). Now one can calculate the ratio $K_I/K_{Ic}=0.96$, knowing that the fracture toughness is $K_{Ic}=1580$ MPa$\sqrt{\text{mm}}$, [9].

The ratio of net stress and it critical value is given: $S_R=\sigma_n/\sigma_F=87x2,78/575=0,42$, taking σ_F=as the half summ of Yield Stress (500 MPa) and Tensile Strength (650 MPa). Now, the coordinates in FAD are (0,42;0,96), so that the corresponding point is the safe region, as shown in Fig. 1. Based on the arguments given in [11] one can estimate the likelihood of failure to be 0.99.

Using this value as the measure for failure probability, and estimating the consequences [12] as the highest level (category 5), one can also estimate the risk of failure, according to the position in the risk matrix, as explained in [11], and shown in Table 1. Since both categories are of level 5, risk is extremely high and requires further attention and analysis. Having this in mind it was decided to apply PAUT as an advanced UT techniques in order to get more precise data about defect 1.1 and to re-assess structural integrity.

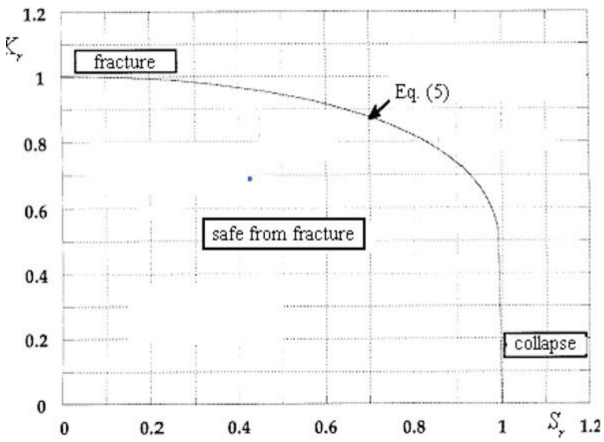

Fig. 1. FAD for vessel 971, defect 1.1 (0.42;0.69) marked by • **0.42,0.96! 0.22,0.27!**

Table 1 Risk matrix for pressure vessel 971

		Consequence category					
		1 very low	2 low	3 medium	4 high	5 very high	**Risk level**
Probability category	≤0.2 very low						**Very low**
	0.2-0.4 low					**Defect 1.1 PAUT**	**Low**
	0.4-0.6 medium						**Medium**
	0.6-0.8 high						**High**
	0.8-1.0 very high					**Defect 1.1 UT**	**Very high**

3. PAUT testing

Testing was done using the ultrasonic device Sonatest Veo+ 32/128. Testing was performed using transversal waves, with sound velocity of 3240 m/s in the material. The Impulse-echo method was used in this case, along with Sector scanning. Test amplification was 45.5 dB. Defect indications are shown in Fig. 2-5. Following results are obtained:

- defect 1.1 with length 2c=185 mm and depth a=15 mm (31-46 mm along the thickness)
- defect 1.2 with length 2c=45 mm and depth a=2 mm (25-27 mm along the thickness)
- defect 1.3 with length 2c=70 mm and depth a=6 mm (29-35 mm along the thickness)
- defect 1.4 with length 2c=44 mm and depth a=7 mm (37-44 mm along the thickness)

Figure 2 – Defect 1.1

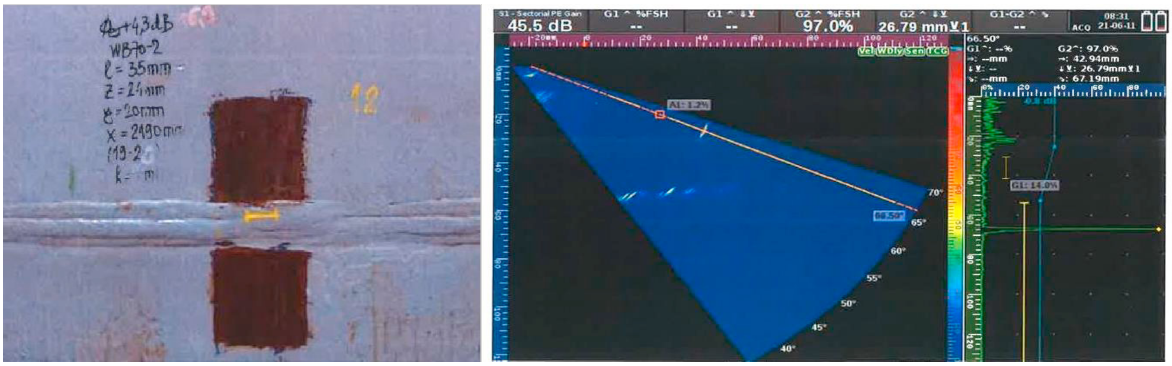

Figure 3 - Defect 1.2

Figure 4- Defect 1.3

Figure 5- Defect 1.4

It is important to notice that defect lengths are in good agreement with those measured by conventional UT, whereas depths are not. Also, very important difference is that PAUT did not detect any of these for defects on the inner side of the vessel, what is consistent with other conventional NDT findings (Magnetic particles and penetrants).

Now, one can evaluate risk level using the same procedure, once again only for the largest defect, 1.1. For a central crack-like defect with 2c=185 mm and 2a=15 mm, one gets: $K_I=Y(a/W,a/c)(pR/2t)\sqrt{\pi a}=1,02(87)\sqrt{7.5\pi}=431$ MPa$\sqrt{mm}$, and the ratio $K_I/K_{Ic}=0.27$.

The ratio of net stress and it critical value is now $S_R=\sigma_n/\sigma_F=87x1,43/575=0,22$, and the coordinates in FAD are (0,22;0,27), Fig. 1, so that the likelihood of failure is just 0.3 and risk is of low level, Table 1.

Discussion

In the case study presented here, one can see that final decision on eventual actions to ensure safe operation of a pressure vessel with unacceptable defects detected in welded joints depends strongly on level of accuracy of method applied for NDT. As it turned out, application of PAUT has reduced risk level significantly, from very high to low, enabling further use of pressure vessel without any action. Not only dimensions, but equally important location of defects was decisive argument, since it turned out that defects are not present at the inner side of the vessel, making them not only smaller, but even more important, not practical for grinding and repair welding.

Conclusions

Based on the results presented here, one can conclude the following:

- It is of utmost importance for structural integrity assessment to use not only conventional NDT, but also advanced methods, like PAUT.
- Simple engineering tolls are efficient in structural integrity assessment of pressure vessels with defecets in welded joints
- Risk-based analysis is useful to bridge the gap between engineers and managers, and can help significantly in decision making process.

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