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INTEGRITY ASSESSMENT OF AMMONIA STORAGE TANK BY NON-DESTRUCTIVE TESTING

PROCENA INTEGRITETA REZERVOARA ZA AMONIJAK ISPITIVANJEM BEZ RAZARANJA

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Abstract

Ammonia is a very dangerous fluid, and it is so important that its storage tanks are safe. Fusion welded joints (in further text: welded joints) are the 'weakest' location in some structures, in this case - tanks, and the detection of defects in welded joints during manufacture is also very important, since defects may cause failure with catastrophic events. NDT techniques that have been performed on welded joints show insight into the quality of the performed welding technique, and results imply whether tanks are safe to be put into exploitation. Three different methods are used for testing: visual, penetrant, and ultrasonic (in this case a new method is used). The first two methods show no irregularities, but third NDT method shows the necessity for tank repair. All of these tests are performed in accordance with relevant standards that are discussed, as well as the used NDT methods in general, with their ability and restrictions.

Izvod

Amonijak je veoma opasan radni fluid i bezbednost rezervoara za njegovo skladištenje je od velike važnosti. Zavareni spojevi predstavljaju 'najslabija' mesta u nekoj konstrukciji, u ovom konkretnom primeru - na rezervoarima. Detekcija grešaka u zavarenim spojevima tokom izrade predstavlja važnu stavku, s obzirom na to da posledice loše izrade mogu biti katastrofalne. Korišćene IBR metode pokazuju kvalitet izrade zavarenih spojeva kao i uvid u potencijalne greške, a rezultati IBR ispitivanja utiču na odluku o konačnom puštanju rezervoara u rad. Tri metode su korišćene za ispitivanje: vizuelna, penetrantska i ultrazvučna. Prve dve metode nisu pokazale nepravilnosti, dok je treća metoda pokazala neophodnost reparaturnog zavarivanja. Sva ova ispitivanja su urađena prema odgovarajućim standardima koji su takođe diskutovani u radu, kao i same IBR metode, sa svojim mogućnostima i ograničenjima primene.

INTRODUCTION

High- and low pressure vessels are essential for storing ammonia, mainly because of the mechanical properties of the materials they are built of. The reasons why this is crucial are numerous, e.g. environmental safety. It is recommended to design ammonia storage tanks in accordance with relevant standards, e.g. EN 14620:2008 /1/.

Non-destructive testing (NDT) of pressure vessels is very important for both economic and safety reasons. The lifespan of any pressure vessel depends on the absence of harmful defects, /2/, presence of residual stresses within acceptable levels, if they cannot be eliminated /3/, and the presence of a proper microstructure with desired mechanical properties that does not degrade under operating conditions /4/. Therefore, it is easy to notice the importance of non-destructive assessment of components for defects, residual stresses, and microstructure, and it plays a very important role in the pre-service and in-service inspection for the integrity assessment of pressure vessels, /5/.

The primary goal of NDT methods is to determine the defects in the material, and the secondary goal is the possibility to determine some material properties, such as microstructure, chemical composition, or hardness. All NDT methods have advantages and disadvantages, and reliable evaluation of defects, important for the integrity of welded pressure vessels, cannot be obtained from the results of only one particular method /6/. The third goal of NDT is the objective pressure vessel life management, and its safe and economic operation, which can greatly improve life expectancy, /7/. That is why three different NDT methods are included in this paper.

In this particular case an ammonia plant in Kingisepp is considered, located 130 km from St. Petersburg. Additional information on the facility is given in /8/. The storage tanks (Fig. 1) are manufactured in accordance with parts of standard EN 14620:2008. Tankmont d.o.o., Belgrade, is responsible for the construction of ammonia storage tanks, /9/.

Ammonia is one of the most hazardous chemicals in the world, its release in the atmosphere causes severe injuries and in some extreme cases even death, and due to its high corrosivity usually causes huge damage to property /10-11/, and because there are no large changes and damages of the inspected object, NDT methods are very valuable techniques that usually save both money and time by in-situ inspection and troubleshooting. In this case, three techniques are performed: visual, penetrant, and ultrasonic testing. Naturally, this is done after the welding, /12/.

Visual inspection (VT) is the most used method for quality control. In addition, data acquisition and data analysis can be performed in this way. This includes inspection methods of equipment and structures by using basic human senses (vision, hearing, and touch).

Penetrant testing (PT) is a frequently used non-destructive testing method for non-porous materials and is used to check surface-damaging defects. The penetrant may be applied to both ferrous and non-ferrous material. PT is used for surface defects such as surface porosity, cracks, and leaks in new products, and also for fatigue cracks for in-service components.

Ultrasonic testing (UT) is based on the propagation of ultrasonic waves in the object or material tested, and represents a whole family of non-destructive tests. Phased Array Ultrasonic Technique (PAUT) method of ultrasonic testing is used in this particular case due to its accuracy and sensitivity when testing welds for defects /13/. A more detailed discussion will follow that will show how mentioned methods are used in the particular case.

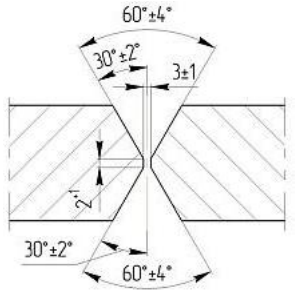
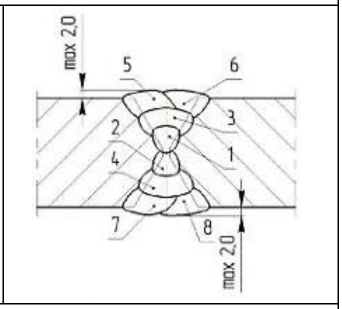
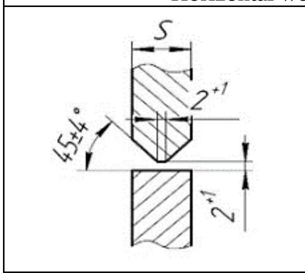
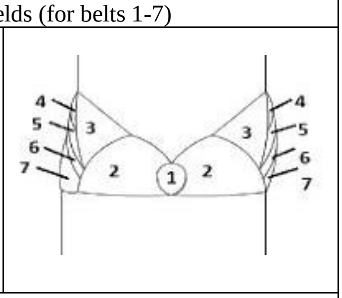
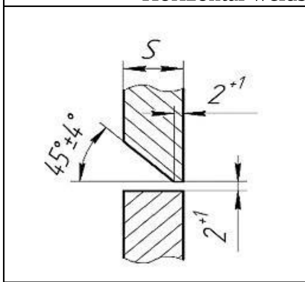
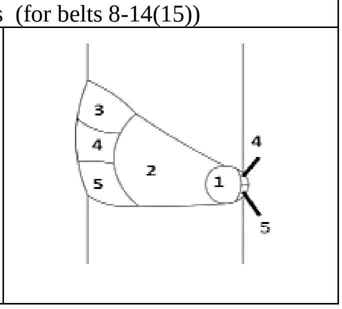
Figure 1. Ammonia storage tank in the Kingisepp facilities.

Welding of Kingisepp ammonia storage tank

Pressure vessels used for storing ammonia have somewhat more strict demands in terms of welded joint quality due to the hazardous nature of ammonia. Thus, particular attention needs to be devoted to the proper selection of welding technologies. In a previous paper /8/, the complete welding technology is shown in great detail. Only a brief review of the most important parameters for fusion welded joints used in the aforementioned ammonia tanks in Kingisepp are given here. Grooves are produced by grinding preparations of vertical and horizontal joints for both walls accordingly and are shown in Table 1. The groove geometry depends on the thickness of both sheet and belt. Welding plans for groove filling are also given in Table 1.

The inner walls base material for both tanks is the steel P355NL2. This normalised high-strength low-alloyed steel is used for both pressure vessels and pipelines due to its increased strength and service at lower temperatures. Tables 2 and 3 show the chemical composition and mechanical properties of the material, respectively.

Table 1. Vertical and horizontal groove geometry for both walls of tanks, including the welding plans, /8/.

Vertical welds	
	
Horizontal welds (for belts 1-7)	
	
Horizontal welds (for belts 8-14(15))	
	

Vertical welds of these tanks are performed with electrode OK73.56 using manual arc welding and parameters as given in Table 4.

Horizontal welds are made in the following way /8/:

- the root pass is performed with self-shielded flux core arc welding method, whose welding parameters are shown in Table 5. Fabshield Offshore 71Ni wire, manufactured by Hobart was used as the filler material,
- fill and final passes are done with submerged arc welding and parameters are shown in Table 6. Filler materials that were used include ESAB wire, along with OK Autrod 13.27 powder, and OK flux 10.62 powder.

Electrode chemical composition and mechanical properties are given in the paper /8/.

Table 2. Chemical composition of steel P355NL2, /11/.

Element	C	Si (max)	Mn	P (max)	S (max)	Al (max)	Cr	Ni	Mo	Cu	Ti	Nb	V	N
%	0.18	0.50	1.1-1.7	0.025	0.005	0.02	0.30	0.50	0.08	0.30	0.03	0.05	0.10	0.012

Table 3. Mechanical properties of steel.

P355NL /11/	Tensile strength R_m (MPa)	Yield stress $R_{p0.2}$ (MPa)	Elongation A (%)
P355NL2	490-630	≥ 355	≥ 22

However, the main focus of this paper is the geometry of fused welded joints shown in the aforementioned table, and the reason for this is the focus on non-destructive testing (NDT), performed after welding is finished.

Table 4. Welding parameters for manual arc welding of vertical welded joint, /8/.

	Current (A)	Voltage (V)	Welding speed (cm/min)	Wire diameter (mm)	Polarity	Heat input (kJ/mm)
Root pass	70-90	21-23	4.1-4.3	2.6	Indirect	1.7-1.9
Filling pass	90-130	21-23	7.2-7.4	3.2	Indirect	1.2-1.6
Final pass	90-130	24-40	8-8.2	4.0	Indirect	1.2-1.7

Table 5. Welding parameters for root pass using the 114 procedure (horizontal welded joints).

Current (A)	Voltage (V)	Welding speed (mm/s)	Welding procedure
180-240	23-27	7-12	114

Table 6. Welding parameters for semi-automated welding procedure, for horizontal welded joints.

Sheet thickness (mm)	Groove type	Number of passes	Current (A)	Voltage (V)	Welding speed (mm/s)
26	K-groove	4 filling/8 final	340-420	25-28	14-20
24	K- groove	4 filling/8 final	340-420	25-28	14-20
22	K-groove	4 filling/8 final	340-420	25-28	14-20
20	K-groove	4 filling/8 final	340-420	25-28	14-20
18	K-groove	2 filling/6 final	340-420	25-28	14-20
16	K-groove	2 filling/6 final	340-420	25-28	14-20
14	K-groove	2 filling/6 final	340-420	25-28	14-20
12	half V-groove	1 filling/5 final	340-420	25-28	14-20

Because the environmental temperature is 20 °C, there is no need for the preheating of base material at 50-80 °C. Welding is performed by alternating between welded joint sides in order to reduce deformation, while using indirect polarity. Before and after welding, the workpiece is cleaned by machine grinding. Due to geometry and deformation, the welding technique used in this case is upward vertical.

USED STANDARDS

Type and size of imperfections and defects in welded joints depend on the used welding procedures and some of them are specific for certain welding techniques. Imperfections or defects in welded joints can be classified into three major groups: design, welding, and metallurgical. Design defects include issues related to structural details, improper groove preparation for a given application, or undesirable changes of the cross-section. In order to avoid any misunderstanding, these defects are thoroughly described and accompanied with adequate sketches in standard EN ISO 6520-1:2007, /14/. The basis for the numerical designation, given below, determines the name and classification of defects in fusion welded joints.

Defects (imperfections) are divided into six categories, including:
– cracks,
– voids,
– solid inclusion,
– lack of fusion and lack of penetration,
– shape and dimension of defects,
– miscellaneous.

Standard EN ISO 5817:2014 /15/ is of great importance and is used often, since it provides the requirements for imperfection quality level in fusion welded joints, i.e. defines the allowed size of defects, depending on required welded joint quality. Quality levels given in the standards are B, C and D, whereas B quality is the highest /16/. These standards are applicable to the following materials, welded joint geometries, and welding technologies.

Standard EN ISO 17637:2016 /17/ involves the VT of metallic welded joints. Tests are usually performed after welding, although they could be carried out during the procedure if required by standard and/or contract. The testing scope needs to be defined by standard and/or contract before the welding procedure is carried out. Additional requirements include testing from a greater distance using the borescope, a device with optical fibres and cameras. For the purpose of achieving better contrast between imperfections and the background, and additional light source is necessary. Visual testing should be accompanied by other NDT methods if there is doubt about the results.

Examples of VT equipment are given in EN ISO 17637: 2016. Measurement equipment should be selected according to the following list:

1. Ruler or strain gauge with length scale of 1 mm or finer;
2. Mobile measuring device as nonius callipers;
3. Sufficient number of measuring strips with sizes between 0.1 and 3 mm, with a maximum step of 0.1 mm;
4. Radius patterns;
5. Magnifying glasses with magnification of 2-5×.

Standard EN ISO 3452-1:2013 /18/ defines the PT method and is used for detecting surface imperfections and defects (such as cracks, overlaps, porosity, lack of fusion). It is mainly used for metallic materials but can also be used for other materials which are not sensitive to the testing medium and if they are not porous (such as ingots, forgings, seams, ceramics). Herein, the term ‘imperfection’ does not include its acceptability.

Methods for determining and recording main properties of penetrant materials are given by standards EN ISO 3452-2:2013 /19/ and EN ISO 3452-3:2013 /20/. Before PT, the surface needs to be clean and dry. Then, an adequate penetrant is applied that enters open surface imperfections. After a certain penetration period, excessive penetrant is removed from the surface, and a developer is applied that absorbs leftover penetrant in the discontinuity, providing a visible indication of the imperfection. These tests mainly involve the following stages: preparation and cleaning, applying of penetrant, removal of excessive penetrant, applying of the developer, control (inspection) recording, and cleaning after inspection, according to EN ISO 3452-1:2013.

ISO 17640:2017 /21/ is the standard that specifies ultrasonic testing techniques for welded joints in metallic materials (thickness over 8 mm). Is its used on welded joints where both welded and parent material are ferritic. EN ISO 17640:2017 has four testing levels, each for a different level of detecting imperfections - A, B, C, D. It is used for discontinuity detection, by either of the following techniques:

(a) evaluation based primarily on length and echo amplitude of the discontinuity;
(b) evaluation based on characterization and sizing of the discontinuity by probe movement techniques, /21/.

NDT USED FOR AMMONIA STORAGE TANKS

Tanks are used to store large volumes of ammonia with low temperature boiling points. EN 14620 provides the specification for tanks built on site and made of steel. Both liquid and vapour ammonia can be stored, depending on the temperature, and usually a combination of both. The pressure is 120 mbar and temperature of –36 °C. A more detailed explanation of the standard is given in the paper, /8/.

Inspection and control of welded joints is performed on both horizontal and vertical seams, on both cisterns and walls, and EN 14620-5 focuses on the tests that need to be done. EN ISO 5817 is used as a quality criterion. This international standard does not address the methods used for the detection of imperfections. Thus, EN ISO 17635 /22/ is also needed as it contains a correlation between the quality and acceptance level for different NDT methods. These standards are applicable directly to visual testing of welds and do not include details recommended for methods of detection. Naturally, nothing can be directly concluded from the aforementioned, and by using these limits shows the befitting criteria applicable to NDT methods such as radiography, ultrasonic, eddy current, magnetic particle or penetrant testing needs to be supplemented by adequate, more precise standards (in this case, EN ISO 3452-1, EN ISO 17637, EN ISO 17640).

VT of fusion welded joints is done within scale of 100%. The correlated standard is EN ISO 17637 that covers visual tests of fusion welds in metallic materials. Also, EN ISO 17637 can be used for visual tests of the joint prior to welding. The surface illumination should be at least 350 lx, but because of conditions in this case, it was 1001 lx. Defects are not detected with this test method (VT), and a surface inspection from the other side is needed, for safety reasons.

PT of welded joints is done in the scale of 100 %, in accordance as explained before in EN ISO 3452-1 standard. This part of EN ISO 3452 specifies a method of PT used to detect discontinuities, e.g. cracks, laps, folds, porosity, and lack of fusion, which are located at the surface of the material being tested. Equipment used is suitable for in-situ testing. The penetrant is applied to the test component by spraying and is removed afterwards and a developer is applied. Illumination was also 1001 lx, the same as in VT. This method also did not reveal any defects.

PAUT is the newest and most advanced method of ultrasonic testing. The PAUT probe usually consists of eight small ultrasonic transducers, and each can be independently pulsed. By making the pulse delay from each transducer in the timely manner, a pattern of constructive interference is set up. To be more precise, by changing the progressive time delay, the beam can be steered electronically, and the data from those beams can be put together to make a visual image that shows a slice through the object /23/. PAUT tests was also performed for all welded joints (100% scale), on both tanks and walls, in accordance with the acceptance criteria as defined by the corresponding standard. During ultrasonic inspection, several defects are noticed in certain welded joints, and these joints are repair welded. Repair welding at the locations of observed defects involved the removal of previous welds (digging) and additional grinding and welding. After this, repaired locations are once again tested, and no defects are found. During the ultrasonic test of a horizontal welded joint of an ammonia storage tank, several unacceptable defects are detected.

Tests are performed using the ultrasonic device OmniScan MX, with OmniPC 4.4R3 software. The tests use transversal waves, with a sound velocity of 3240 m/s in the material. The pulse-echo method is used in this case, along with sector scanning. Test amplification is 33-41 dB. The following images show some of the defects. Figure 2 shows a defect discovered at a depth of 9096 mm from the coordinate origin. This defect is detected at depth of 10.81 mm, at a sound path of 31.61 mm from the probe output point. Test amplification is 39.0 dB. Testing angle is 45-70°, with angle increment of 1°. Echo height is 40.7% screen height. The defect was discovered in the first welded joint located on the second belt of the outer wall of the first tank.

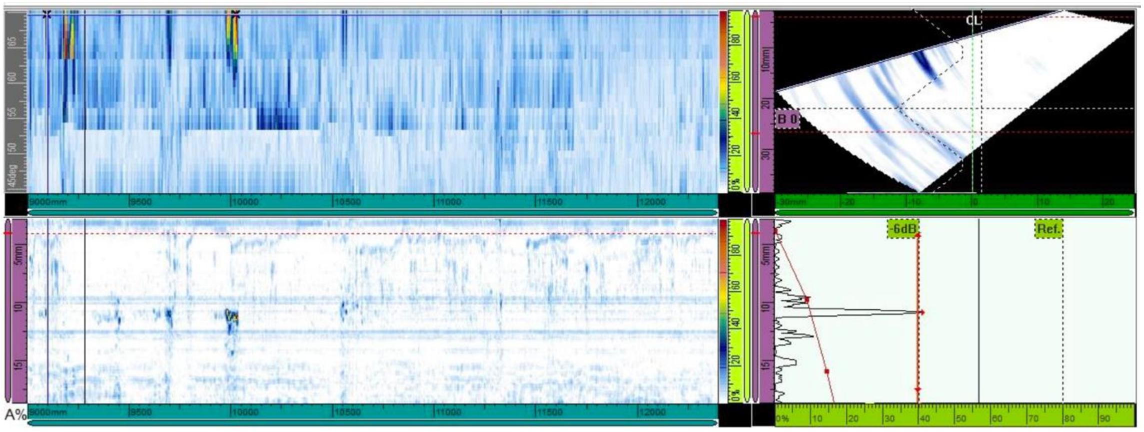


Figure 2. First defect discovered by PAUT at a depth of 9096 mm from the coordinate origin.

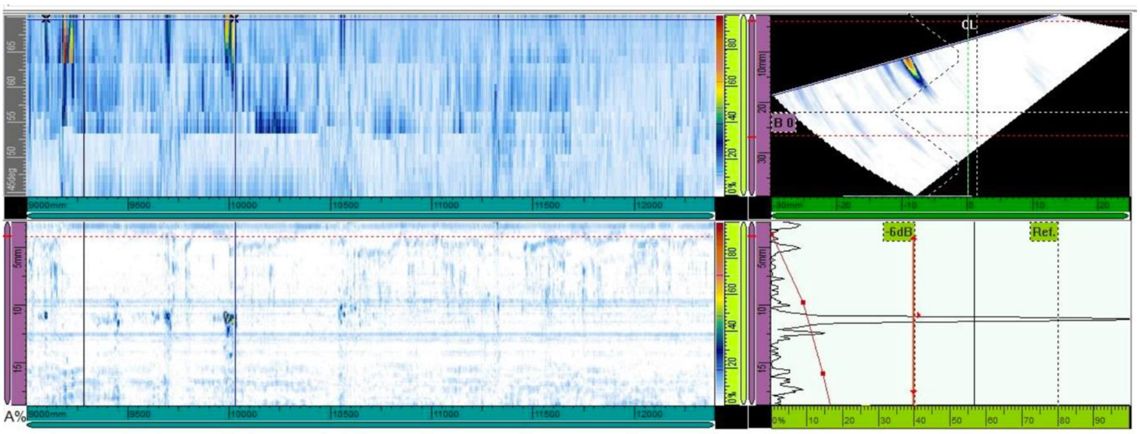


Figure 3. Second defect discovered by PAUT at a depth of 10028 mm from the coordinate origin.

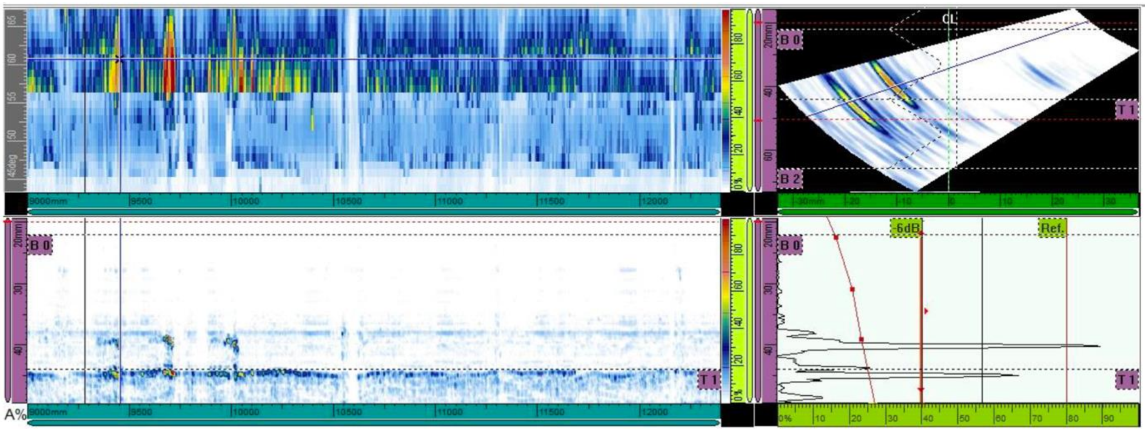


Figure 4. Third defect discovered by PAUT at a depth of 9451 mm from the coordinate origin.

Figure 3 shows a defect discovered at 10028 mm depth from the coordinate origin. This defect is detected at depth of 10.81 mm, at a sound path of 11.19 mm from the probe output point. Test amplification is 33.1 dB. Testing angle is 44-67°, with angle increment of 1°. Echo height is equal to 104.5% screen height. The defect was discovered on the second welded joint, located on the second belt of the outer wall of the first tank.

Figure 4 shows a third defect discovered at a depth of 9451 mm from the coordinate origin. This defect is detected at depth of 3.17 mm, at a sound path of 83.1 mm from the probe output point. Test amplification is 40.4 dB. The testing angle is 40-70°, with angle increment of 1°. Echo height is equal to 104.5% screen height. The defect was discovered in the third fusion welded joint, located on the second belt of the outer wall of the first tank.

CONCLUSIONS

The goal was to perform extensive non-destructive tests of welded joints in a pressure vessel made of high-strength low-alloyed steels. The pressure vessel is an ammonia storage tank, and such structures are especially demanding in terms of welded joint quality. For this reason, NDT methods in this case need to be carried out in detail, taking into account every possible type of defect. NDT methods presented here involve, again a full description, visual tests, penetrant, and ultrasonics tests. All of these tests are performed in accordance with relevant standards, which are presented as well.

Selected NDT methods have covered defects both on the surface and within the welded joints themselves. No noticeable defects of any kind (cracks and other) are detected by VT and PT. Ultrasonic tests detected certain defects which were then repair welded. From this, the advantages of applying 100% scale tests methods of various kind are clear. Test results presented here are also aimed to confirm the need for thorough and extensive testing, due to the conditions the ammonia storage tanks are subjected to in exploitation. Additionally, the results have confirmed the applicability of a relatively new ultrasonic test method (PAUT). With an additional focus on such test methods in the future, reliable structural integrity assessment of welded structures could be carried out in a quick an efficient manner, and repairs can be immediately performed, if needed, like in this particular case.

Even with all their positives, there are also a few shortages of NDT methods in general. A shortcoming of the PT is its ability to detect only surface defects and imperfections. Also, if the exanimated surface is not prepared very well in accordance with requirements, defects can be ‘masked’ or covered by contamination as dirt, oil, grease, etc. Post-cleaning of the PT solvent is very important as well, since too much waiting time, or too short time can have an influence on false indications and totally make the method useless. Having in mind the toxicity of the PT developer, there are mandatory requirements on handling precautions. VT and PT have certain problems and it is quite clear that results and reports after these two test methods depend on experience and eye-sight of an individual operator. On the other side, the PAUT method has none of these shortages. When compared to other UT types, the PAUT has a few important advantages. PAUT can be conducted quickly, much faster than other types of UT, measured in fractions of seconds. Also, it is highly repeatable and can do multiple scans at once, but it also has flaws as any other UT method, it cannot be reliable on thin metals and also has a 'dead zone,' where it cannot transit waves.

All these methods are reliable in the assessment of the structural condition and can help in collecting accurate data that may describe the existing condition of the structure and prolong the operating life of the structure. However, none of these methods provide any information on the properties of materials and structure, or their behaviour and state after prolonged exposure to harsh and corrosive environmental influence.

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