Development of Conforming Ultrasonic Probe for Inspection of ITER Experimental Reactor

Josipa Delaš, Nikola Pavlović, Nikola Babić
“INETEC” Institute for Nuclear Technology
Dolenica 28, 10250 Lučko, Croatia
Josipa.Delas@inetec.hr, Nikola.Pavlovic@inetec.hr, Nikola.Babic@inetec.hr

ABSTRACT

This paper presents the development of an ultrasonic probe for inspection of welded joints between two, 60 mm thick, sector plates of the ITER (International Thermonuclear Experimental Reactor) vacuum vessel. Several points were raised during the analysis of the welded joint specification and environmental conditions that limit the use of conventional UT probes for this purpose. These points include inspection of the weld from the weld root side that’s unmachined, significant weld thickness of 60 mm and medium around weld being air. The development consisted of three mutually dependent parts, of which the first one is the choice of flexible material adequate for conforming to complex surfaces. Parallel to this, it was necessary to simulate the ultrasonic signal to determine probe geometry considering the weld dimensions and specifications of the material AISI 316L(N)-IG being inspected. Finally, the couplant problem was approached. Without couplant, air trapped between conforming material and inspected material prevents the propagation of the ultrasound waves. Due to ITER vacuum restrictions, it was imperative to develop a solution that uses the minimum amount of couplant that still provides a satisfactory ultrasonic signal. The development process included computational analysis, probe prototyping, test blocks manufacturing and experimental tests. Once developed, the probe was subjected to comprehensive tests on qualification blocks matching inspection objects with intentionally implemented artificial defects.

Keywords: *ITER project, Non-destructive testing (NDT), Ultrasonic Testing (UT), UT probe development*

1 INTRODUCTION

ITER is the world’s largest fusion experiment that aims at advancing fusion science and bringing us closer to fusion power plants [1]. The machine used to harness fusion energy is called a tokamak. The centrepiece of the tokamak is the stainless steel vacuum vessel (VV in further text) that houses the fusion reaction and acts as a first safety containment barrier. The vacuum vessel is a toroidal structure assembled by welding nine sectors (400 tonnes per sector) together in-situ. Stress assessment was conducted considering possible types of failure to analyse the critical sections [2]. The structural analysis determined the field weld joint between Sector 3 and Sector 4 as one of the critical points since it is the last weld connecting the VV assembly. Inspection of this weld is a part of periodic inspection and periodic requalification of the VV NPE (Nuclear Pressure Equipment), as required by the ESPN – Regulations of the Under Pressure Nuclear Equipment in France. The inspection technique is also subject to the RCC-MR code [3].

One of the required non-destructive examination (NDE) techniques is the volumetric examination. The chosen volumetric method is ultrasonic examination. The outer field weld joint that is the inspection target connects two 60 mm thick plates between two sectors. Material of plates and weld is austenitic steel with controlled nitrogen contents and tight limitation of impurities such as cobalt, niobium and boron, commercial name SS316L(N)-ITER Grade [4]. This weld material is very challenging to inspect with ultrasound due to anisotropy, high attenuation and its dispersive nature [5]. Additionally, the weld can only be inspected from the weld root side. Previous examination experience of thick austenitic steel welds accessible from one side is limited to plates half the thickness in the petrochemical reactors and nuclear power plants [6]. In addition to the large thickness, the examination is also more difficult because the weld root side is unmachined. A rough surface causes additional signal dispersion and might cause unsteady operation if a conventional UT probe was used. Environmental conditions during examination are in Table 1.1 below. The main obstacle is air as a medium for inspection. Temperature, pressure and other conditions don't impose significant issues on UT probe design and operation. Issues related to air in ultrasonic examination will be addressed later on.

Table 1.1: Environmental conditions during examination

Environmental condition during examination	
Medium around weld	Air
Pressure	Atmospheric
Residual magnetic field	1 mT
Temperature	20 °C (range 10°C to 50°C)
Activation of components	yes
Radiation dose rate	5 mGy/h

The limitations set above demanded the development of a new probe. Paper presents the development steps taken and testing conducted with the finished probe.

2 METHODOLOGY

To tackle the problem explained in the previous section, the development was split into several mutually dependent parts. Entire methodology is presented in Figure 1. A crucial step was to select a technique for volumetric examination. After choosing the technique, it was possible to start defining UT probe specifications and work on the simulation of probe operation.

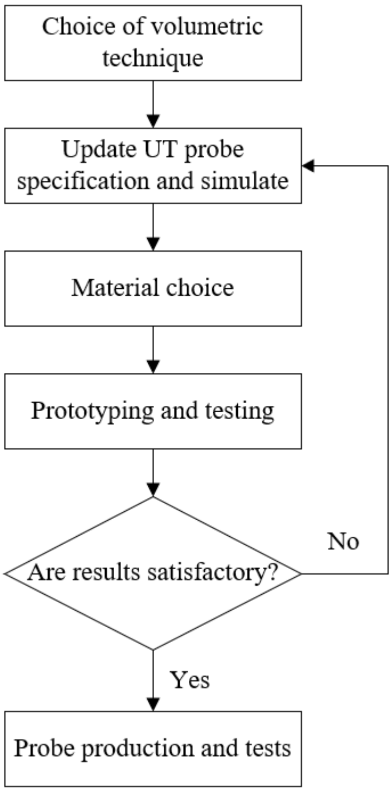


Figure 1: Methodology applied for development of UT probe

Probe geometry heavily depended on solving conformance to unmachined weld and inspection of the dry surface. Preliminary probe specifications were altered based on design changes imposed by these restrictions. Certain components needed to be produced for testing to supplement development. Therefore, development was iterative with a cycle: update of UT probe specifications and simulations, material choice, prototyping and testing.

Once individual aspects of the probe were tested or otherwise validated, the final design of the probe was made, produced and tested. Results from probe final design are presented in Section 4. Despite the iterative nature of the process, in the subsequent sections the issues will be discussed separately for clarity.

3 APPLICATION OF PROPOSED METHODOLOGY

Choice of volumetric technique was made considering limitations imposed on the probe and that the inspection is subject to ESPN and RCC-MR code. Main criterions were sensitivity, radiation resistance and remote handling capabilities. Remote handling refers to complexity of equipment that will handle the probe, but also the size of the probe itself since the access to inspection area is difficult. Pulsed Echo Phased Array was chosen as the most adequate technique.

3.1 Ultrasonic probe aspects and simulations

The probe is dual, meaning that it has a transducer for transmitting the signal, and another one for receiving. The dual transmit/receive configuration offers benefits like better sensitivity and signal to noise ratio, elimination of “ghost echoes” caused by internal reflections in the wedge and absence of near-surface “dead-zone” that a single probe is unable to see. Each transducer has a separate housing that enables safe and easy alteration of the angle between them. The overview of specifications for the probe's final design is shown in Table 3.1. Due to space restrictions, it is not possible to use several conventional probes with various angles of incidence or several phased array probes. The 16 elements probe enables good coverage of the 60 mm deep weld with respect to its size. Low frequency of 2.25 MHz was chosen due to previously emphasized material properties, especially high attenuation of ultrasonic signal.

Table 3.1: Summary of final probe specifications

Final probe specifications	
Number of elements	16
Frequency	2.25 MHz
Pitch	1.6 mm
Element size	1.35 mm
Wedge angle	10°
Roof angle	4°

Wedge and roof angle were iterated in the program for simulating ultrasonic signal. Other geometry important for ultrasonic signal refraction includes pitch and element size, wedge height and height of first element. Once a close estimate was made considering all geometry, the probe (transducer component) and initial wedge were produced and tested. Signal quality was analysed and the final wedge and roof angle are now 10° and 4°, respectively.

3.2 Choice of wedge material

Wedge on UT probe is usually made of Rexolite, a special type of cross-linked polystyrene, due to its good acoustic properties. However, it is rigid and not adequate for usage on unmachined weld root in a dry atmosphere. That represents two points for wedge material choice: conformity to surface and inspection in a dry atmosphere. Air as a medium around weld represents a major obstacle for ultrasonic probes because the ultrasonic wave cannot travel through the air to the material behind it. The attenuation is high because of the air's low density and large difference in the acoustic impedance between the transducer and air. To overcome this, dry surfaces are usually covered with a couplant (ultrasonic gel, water etc.) that facilitates the transmission of ultrasound waves from the transducer into the inspection target.

The entire ITER Vacuum Vessel is inside the high-vacuum pressure chamber called a cryostat. Therefore, the weld root, which is the inspection target, will be exposed to a vacuum during ITER machine operation. Special restrictions are placed on the equipment conducting the inspection. One of which states that all liquids used during inspection need to be recovered. This includes the couplant used for ultrasonic examination. The weld is along the poloidal direction of the vessel, meaning that the probe is used almost vertically along a large radius. If a standard amount of couplant was used in such a position, collecting it is difficult. To overcome this restriction, INETEC has considered and prototyped a few solutions. Multiple tests have shown that couplant recovery systems don't have high reliability for required probe movements and inspection target geometry. It was necessary to change the approach to the problem. Instead of having a standard amount of couplant that would need to be recovered after, it was decided to use as little couplant as possible. INETEC developed a system for producing very fine mist by combining pressurized air and water. The mist would provide sufficient coupling but would not leave a water trail behind and create problems for the vacuum. With finalized mist system, we measured water production per inspected meter. ITER accepted the amount of water required to complete the entire inspection.

Having couplant only solved the problem partially. Because the small amount of couplant was used, we needed to have a very conformable material that would contain the water under the probe. However, the main aspects of the wedge material are its acoustic properties. Since rubber properties are very manufacturer dependent, it was decided to acquire several different rubbers from the same manufacturer and test their acoustic properties. Rubbers that were tested include SBR (styrene-butadiene rubber), NBR (nitrile butadiene rubber) and EPDM (ethylene propylene diene monomer). Multiple samples were made in different hardness from the same material to obtain relevant results. Samples were also in various thicknesses to observe changes in acoustic properties related to that parameter. SBR rubber showed the best acoustic properties. However, even SBR rubber has high attenuation, and ultrasound waves wouldn’t reach the inspection target through a wedge with a large cross-section made entirely of rubber. To overcome this problem, INETEC made a hollow wedge out of rubber and then filled it with water, which has better acoustic properties.

Another problem occurred after defining the couplant supply system and defining the rubber as the contact material. Rubber has very high static friction. It was necessary to check whether the rubber probe can be dragged along the surface of the inspection target. SBR rubber has the smallest coefficient of friction in cases when the surface is both dry and wet, compared to other tested rubbers.

3.3 Prototyping

As emphasized in previous sections, prototyping and testing continually supplemented probe development. Testing of rubber samples was conducted with the entire system submerged in water. For testing, it was necessary to have an adequate probe, calibration block, UT instrument and means to hold the probe and rubbers firmly in place. The probe used for testing rubbers has a 2.25 MHz frequency and 0° wedge angle. The probe was calibrated on the calibration block, submerged in water at a distance fixed with a frame. Once the probe was calibrated, rubber was added at half the distance between the probe and the calibration block. Both positions are shown in Figure 2. The amplitude of each rubber sample was recorded and later compared to the initial signal response from the calibration block. The measurements were used to calculate rubbers attenuation.

Additionally, acoustic impedance Z was calculated by multiplying material density ρ and speed of sound through the material v:

$$Z = \rho \cdot v \tag{1}$$

To get accurate results, density was calculated for every rubber sample individually. Volume was calculated by measuring exact thickness and diameter, and every sample was weighted. Speed of sound was measured with ultrasound.

Figure 2: Probe calibration (left) and rubber testing (right)

Testing for the coefficient of friction required a dynamometer, weights and metal plate with lower or equal roughness to that of the vacuum vessel surface. Rubber was placed in the center of the metal plate. Weights mass was checked before it was placed upon the rubber. Next, the dynamometer was connected to the rubber, and the rubber was dragged along the surface. Rubber had an emphasized stick-slip effect when completely dry. Due to the stick-slip effect, it wasn’t possible to accurately measure the dynamic coefficient of friction. Once the dry tests were done, the surface was sprayed with small amounts of water, and the tests were repeated. Tests showed that the coefficient of friction between wet stainless steel plate and rubber is sufficiently low for the rubber to be used as the wedge material.

In both tests, SBR rubber showed the best properties and was chosen for the final design of the probe. The next step was to produce the entire probe with all partially accepted solutions and test it. Minor changes were made to the probe's initial version to perfect it. Finally, the qualification block was produced, and the probe was tested again.

4 RESULTS

Final design of the probe has non-return valves for filling the wedge with water and spacers to prevent the rubber from bending too much and affecting the wave travel path. Figure 3 shows the probe with the holder for the scanner attached.

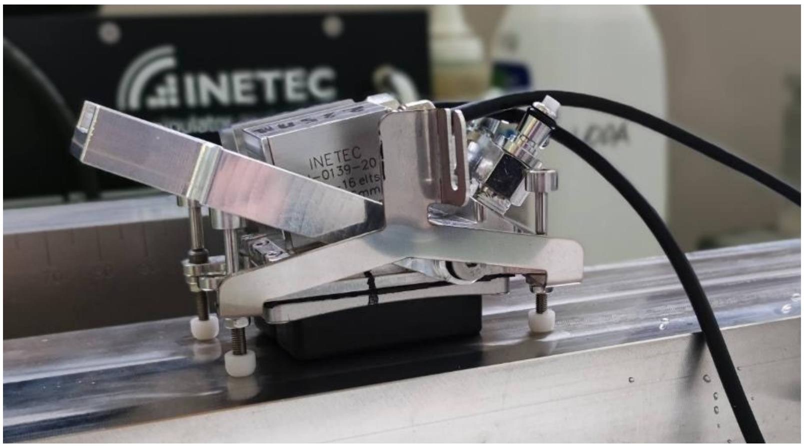


Figure 3: Final design of UT probe developed by INETEC

Qualification blocks are matching inspection objects with intentionally implemented artificial defects. Because ITER grade SS316L(N) is a unique type of steel, it was important to obtain the block from the same material. Additionally, the weld has a significant thickness of 60mm made with the TIG (tungsten inert gas) technique. The welding was also controlled by a specific procedure. Since the block will be used for final qualification of the probe and other equipment, artificial defects needed to be incorporated in the welding procedure. With all of the above carefully implemented, the block represents a realistic inspection target. Figure 4 shows UT probe conforming to the weld root side of the qualification block. The qualification block is placed inside the X-Y scanner developed by INETEC to test probes and scan paths.

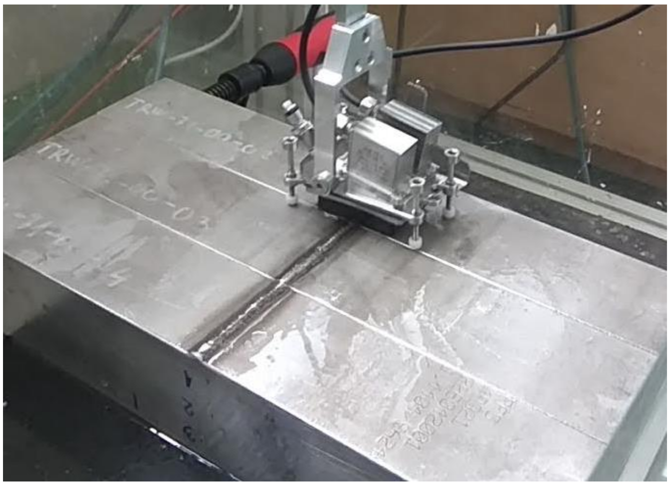
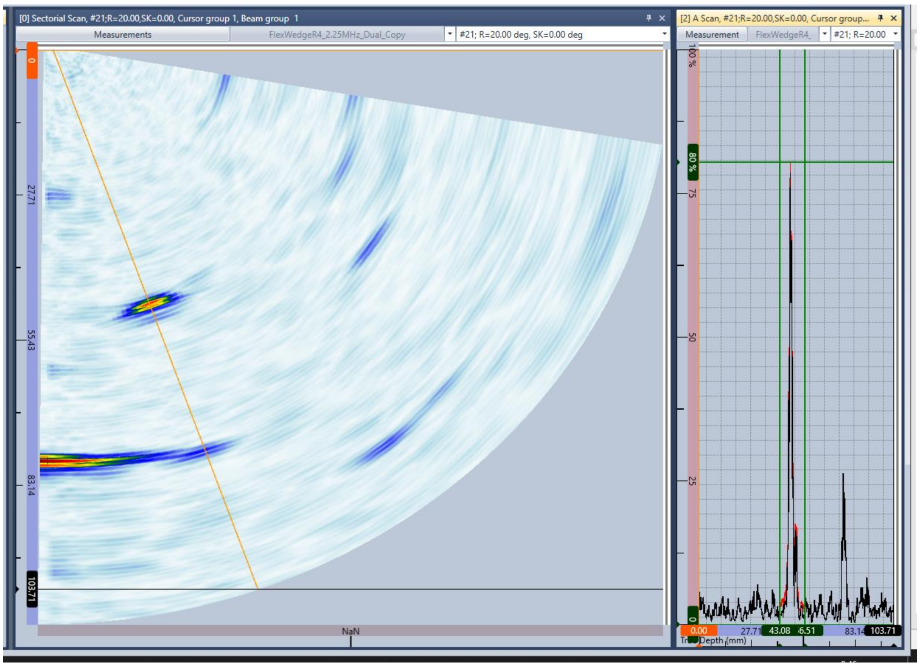


Figure 4: Developed UT probe positioned across the qualification blocks weld

Adequate qualification block above makes the signal retrieved from the developed UT probe relevant for the inspection itself. The probe signal is visible in Figure 5. The probe was tested with INETEC's equipment. Including the Dolphin 128/128R phased-array ultrasonic instrument and SignyOne software package for ultrasound inspection. Signals from developed UT probe were compared to UT phased-array probes developed by INETEC and already qualified. This helped set a goal for signal quality during development and provided relevant comparison of signals for the final solution.



[0] Sectorial Scan, #21;R=20.00,SK=0.00, Cursor group 1, Beam group 1

FlexWedgeR4_2.25MHz_Dual_Copy

#21; R=20.00 deg, SK=0.00 deg

[2] A Scan, #21;R=20.00,SK=0.00, Cursor group...

FlexWedgeR4_

#21; R=20.00

Figure 5: Defect visible in signal from developed UT probe (screenshot taken in SignyOne)

5 CONCLUSION

Development of the UT probe, presented in this paper, aimed at solving the issue of inspecting a dry unmachined weld from the root side on the ITER Vacuum Vessel. Other challenges such as limited usage of couplant, specific type of austenitic stainless steel and large weld thickness put additional constraints on the development process. The couplant problem was solved by a combination of fine mist producing little water and rubber as the wedge material. Rubber conforms to the rough surface and enables the inspection path to include going over the weld. With conventional probes with a Rexolite wedge, it's not possible to scan across the un-machined root weld. Weld could only be inspected on each side, thus not covering 100% of the inspection target. This issue can usually be overcome by using several different probes with varying roof and wedge angles to change to probe focal depth. In this case, due to limited space around and above the weld, only a single probe could be used. Limited space also affected the choice of probe specifications and final geometry. Even though the probe is intended for usage in ITER, the solution can be applied in various environments. Especially the ones that require little to no couplant and have complex surfaces. The probe can be altered to enable manual handling or it can be fitted on the manipulator as intended for the UT probe above. Development of this probe, together with a qualification block, enabled INETEC to have a complete inspection solution with existing UT instrument Dolphin, SignyOne software and manipulator developed for this specific purpose.

REFERENCES

[1] "In a Few Lines," *ITER Organization*. [Online]. Available: https://www.iter.org/proj/inafewlines. [Accessed: 10-May-2022].

[2] J. Caixas, A. Bayon, E. Fernandez, J. Izquierdo, M. Jimenez, J. M. Zarzalejos, J. Guirao, and J. Polo, "Analysis Strategy of the ITER Vacuum Vessel for the Manufacturing Design," in *Proceeding of the 22nd International Conference on Structural Mechanics in Reactor Technology*, San Francisco, USA, 2013.

[3] AFCEN, "RCC-MRx 2012, Design and Construction Rules for mechanical components of nuclear installations : high-temperature, research and fusion reactors," 2012.

[4] H. J. Ahn, B. C. Kim, J. W. Sa, Y. J. Lee, K. H. Hong, H. S. Kim, J. S. Bak, K. J. Jung, K. H. Park, T. S. Kim, J. S. Lee, Y. K. Kim, H. J. Sung, K. Ioki, B. Giraud, C. H. Choi, and Y. Utin, "Fabrication Design and Code Requirements for the ITER Vacuum Vessel," in *ASME 2011 Pressure Vessels & Piping Division Conference*, Baltimore, USA, 2011.

[5] The American Welding Society, *Handbook on the Ultrasonic Examination of Austenitic Welds*. Miami, USA: The International Institute of Welding, 1986.

[6] R. Martínez-Oña, A. García, M. C. Pérez, G. Pirola, A. Dans, and Á. Bayón, "Ultrasonic inspections in the fabrication of the ITER vacuum vessel sectors," in *Fusion Engineering and Design*, 2013, vol. 88, no. 9–10, pp. 2155–2159.