Developments of NDE method of jacket welds for ITER In-Vessel coil joints

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Abstract. The ITER facility currently incorporates two types of In Vessel Coils (IVC) as a method of stabilizing “Edge Localized Modes” (ELM) and providing “Vertical Stabilization” (VS). To withstand the severe conditions, the IVCs are made of stainless steel mineral insulated conductor (SSMIC). The jacket of the SSMIC is modified stainless steel 316LN. The diameter is 59mm and thickness is only 2.5mm. In order to join the IVC coils, it is necessary to develop the joints manufacturing. Jacket welding is an important process of the joints manufacturing. Based on the structural analysis, the maximum acceptable defect sizes inside the jacket weld were defined. This paper presents the non-destructive examination (NDE) method developed for jacket weld inspection which has thin thickness. The difficulty in the development of the jacket weld NDE is the thin thickness which will cause the scattering of sound waves and lead the difficulty of effective identification of defects. Phased Array Ultrasonic Test (PAUT) and eddy current test (ECT) were developed for the jacket welds inspection. The results indicated the feasibility of the PAUT and ECT method could solve the problem of the thin thickness tube weld inspection.

1. Introduction
The International Thermonuclear Experimental Reactor (ITER) facility currently under construction at Cadarache in the south of France will be the largest thermonuclear Tokamak fusion reactor in the world. The plasma is created in the toroidally shaped vacuum vessel and confined by strong magnetic fields created by the super conducting magnets located outside the vacuum vessel environment. To withstand the severe conditions, including large transient electromagnetic fields, high radiation flux, and high temperature, and provide the required functionality.

The In Vessel Coils (IVC) are made of stainless steel mineral insulated conductor (SSMIC) as shown in Figure 1. Two specific joint types are required for the SSMIC’s. The first involves joining lengths of SSMIC’s together to form the coils; these are identified as in-line or coil-to-coil joints. The second, coil-to-feeder joints, attaches the coils to the lines which supply coolant and power. There are totally 176 IVC joints for joining the IVC coils, feeders and feedthrough. Every individual vertical stabilization (VS) turn includes 4 joints, thus there are totally 32 joints for the 2 VS coils and 144 joints for the 27 Edge Localized Modes (ELM) coils[1]. The distribution and orientation for IVC joints are given in Figure 2. All of the joints will be manufactured in the ITER vacuum vessel and made of SSMIC to withstand the severe environment as the coils themselves. During assembling the IVC coils,
feeder and feedthrough, the hermeticity of jacket welds is critical, thus the non-destructive examination (NDE) technology is developed for the jacket weld inspection.

**Material description**

1. Jacket: Modified stainless steel 316LN
2. Conductor: Oxygen Free Electronic copper OFE CW009A
3. Insulation: Magnesium Oxide

**Material thickness**

1. Jacket thickness: 3mm
2. Copper thickness: 6.0mm
3. MgO thickness: 3.5mm

**Figure 1.** IVC mineral insulated conductor

2. **Weld design and NDE test requirement**

As described above, the assembled coil, feeder and feedthrough are all made of SSMIC. The jacket of the SSMIC is modified stainless steel 316LN. The diameter is 59mm and thickness is only 3 mm\(^2\). For the joints manufacturing, first step is to join the two adjacent bare Cu conductors, then application of the insulation and jacket after the Cu welding has been performed. Figure 3 gives the schematic of joints manufacturing. Considering the protecting magnesium oxide (MgO) performance during jacket welding, the final design of the jacket welds has been fixed after a long discussion with ITER Organization (IO) which is illustrated in figure 4.

**Figure 2.** Reference distribution and orientation for IVC joints

**Figure 3.** The schematic of joints manufacturing
In the technical specification, an appropriate NDE approach should be established to detect surface and volume defects for the jacket welds. The developed procedure shall take consideration of the limited space of the ITER vacuum vessel inside. Research and development (R&D) activities have been carried out at Institute of Plasma Physics Chinese Academy of Sciences (ASIPP). Phased Array Ultrasonic Test (PAUT) method and Eddy Current Test (ECT) are developed in this paper. A reference specimen with machined semi-elliptical notch will be fabricated to demonstrate the sensitivity which is sufficient to meet the requirements. The acceptance criteria is 50% signal level of machined defect as mentioned above.

3. **Phased array ultrasonic test**

The difficulty in the development of the IVC jacket weld non-destructive examination is mainly the thin thickness which brings obvious defocusing in the wall thickness direction and decrease the sensitivity and signal-to-noise ratio \[3-5\]. Considering the weld is in circle, the wedge should be designed during the PAUT method development.

3.1. **Theoretical calculation of PAUT angle probe for welded joint inspection**

It is critical to check the test space to verify the test feasibility before the PAUT technology development. Theoretical calculation was carried out. Root inspection and full thickness inspection is considered by using the first leg and the second leg. Assuming the angle of the probe is 75 degrees (recommended in the RCC standard), the calculation results is presented in the below. Figure 5 gives the scheme of angle calculation.
For root inspection, at $\theta = 75^\circ$,
\[
\text{HSD} = t \cdot \tan(\theta) = 3 \cdot \tan(75) = 11.19 \text{ mm}. \tag{1}
\]
\[
\text{HSD} + 0.5rg = 11.69 \text{ mm}. \tag{2}
\]
\[
\text{HSBPL} = \frac{t}{\cos(\theta)} = \frac{3}{\cos(75)} = 11.59 \text{ mm} \tag{3}
\]
2) For full thickness inspection (2nd leg)
\[
\text{FSD} = 2\text{HSD} = 22.39 \text{ mm}. \tag{4}
\]
\[
\text{FSD} + 0.5\text{cap} + \text{HAZ} = 30.39 \text{ mm}. \tag{5}
\]
\[
\text{FSBPL} = \frac{2t}{\cos(\theta)} = \frac{6}{\cos(75)} = 23.18 \text{ mm} \tag{6}
\]

From calculation results at probe angle at $75^\circ$, minimum probe distance from the center line is about 12 mm, and maximum probe distance from the center line is about 31 mm. The values will be checked in sound path during the experiment.

3.2. Acoustic field distribution simulation

The simulation of the acoustic filed distribution is performed by using CIVA \cite{6-8} for visualizing the coverage of acoustic fields in this trial. A phased array transducer model which can be excited transversal wave from $35^\circ$ to $75^\circ$ is established. The center frequency for the probe model is 5MHz, 32 elements were excited during the simulation. The way of the sector scanning was utilized during the simulation process. Simulation results are shown in figure 6. The simulation results indicated that a full acoustic field coverage of the weld was achieved by using the proposal probe.

![a. Simulation model of IVC jacket weld](image1)

![b. Simulation of acoustic field coverage](image2)

![c. Simulation results of the sector scanning](image3)

**Figure 6.** Simulation results of acoustic field

3.3. Reference Block

A reference block is designed for the sensitivity verification of the test. Two types of the planner notches are machined in the reference block. The size of the one type notch is 0.25 mm in width, 2 mm in length, and 0.5 mm in depth. The other type is 1mm depth which is machined from the back of the weld to check the root integrity of the weld. The details of the reference defect are presented on the table I.

| Defects | Dimension [L×W×D] [mm³] | Orientation | Position |
|---------|--------------------------|-------------|----------|
| A       | 2×0.25×1                 | Along the weld | on the center line of the weld /inner surface |
| B       | 2×0.25×0.5               | Along the weld | On the weld edge /outer surface |
| C       | 10×0.5×1                 | Along the weld | on the center line of the weld /inner surface |
| D       | 10×0.5×1                 | Along the weld | On the weld edge /inner surface |
| E       | 2×0.25×0.5               | Transversal   | Base material/inner surface |
| F       | 2×0.25×0.5               | Longitudinal  | Base material/inner surface |

3.4. Experiment results

A ZETEC TOPAZ 32/128P and a phased array double crystal transducer made by Olympus were used for the PAUT trails on IVC jacket welds. The transducer contains 32 elements. The test frequency is
5MHz and the gain setting is 34.1dB. Based on the simulation results of the acoustic field distribution, sector scanning is used for the 100% acoustic coverage. In these trials, 1st leg and 2nd leg are used for getting the maximum amplitude of reflection signal from the reference notches on the weld and heat affect zone (HAZ) by moving the probe position. Test diagram is shown in figure 7.

![Testing diagram](image1)

**Figure 7.** Testing diagram

For longitudinal imperfections, scan the PAUT probe along the welded line (sound beam perpendicular to welded line) to ensure that the sound beam covers the welded area and HAZ [9]. For transverse imperfections, place the PAUT probe on the welded area and make the sound beam parallel to welded line. The examples of examination results are presented in the Figure 8 and Figure 9.

![Images of the defects in the base material](image2)

**Figure 8.** Images of the defects in the base material. Part (a) shows transverse defects on the inner surface of base material. Part (b) shows transverse defects on the outer surface of base material
Figure 9. Examples Images of the defects in the weld area. Part (a) shows longitudinal defects on the inner surface of weld area. Part (b) shows longitudinal defects on the outer surface of weld area.

From the experiment results, all the reference defects could be found based on the designed test system. The indication levels of defects can be achieved 60% of full screen height (FSH) with the gain of 30.2dB.

4. Eddy current test (ECT)

Eddy current system was established for the ECT experiment on the IVC jacket weld inspection. ECT inspection system is OLYMPUS MS5800 and MultiView6.0R8 software as well. The reference block used for the following ECT experiment is the described block in section 3.3 which contains 6 different defects as listed in table I. Figure 10 presents the eddy current system which used in the ECT experiment.

Figure 10 Eddy current system

The difficulty in the development of the IVC jacket weld eddy current test is mainly the thin thickness which brings obvious defocusing in the wall thickness direction and decrease the sensitivity and signal-to-noise ratio \[^{10-11}\]. Considering the weld is in circle, the wedge should be designed during the ECT method development.

4.1. Probe design

A specified probe with the curve wedge was designed for the jacket weld with the thin thickness inspection. The coil type is a quadrature coil with a side length of 3mm, and the inductance is 150\(\mu\)H. Comparison trials between the quadrature coil and the pancake coil were performed on the 304L plate block with different depth cracks. The results are given in figure 11 and figure 12. The results provides the information that quadrature coil shows better defect detection capabilities and the inhibition of lift-off signals when the crack depth is greater than 1.0mm. The amplitude of the noise of the quadrature coil is 0.6V as well as the 0.9V for the pancake coil.
4.2. ECT results

Frequency is the most important parameter which affects the depth of eddy current penetration. After a series of R&D experiments, the optimized frequency for the thin thickness weld inspection is 100kHz when the drive signal with the amplitude 8V was applied. The ECT signal of reference defects in the strip chart is displayed in Fig. 13. The defects of A, B, C, D, E, F is listed in Table 2. All the defects reveal a good signal-to-noise (S/N) ratio. Some comparison work also carried out between these 5 reference defects as illustrated in figure 14 and in figure 15. Figure 14 gives the impedance of the five reference defects based on the ECT signal. Figure 15 gives the amplitude comparison of reference defects.
Clear signal of each reference defect was obtained based on the established ECT system. The results also give the eddy current penetration which could be achieved to 3mm. The test system is effective for the notch with 2mm in length, 0.25 mm in width, and 0.5 mm in depth.

5. Conclusion
Results indicated that the developed PAUT method and eddy current method are available for the IVC joints welds inspection. All of indications at welds could be inspection based on the established test system. A special probe and wedge to produce a wide beam in the movement direction was designed and analyzed by simulation and experiment. The results could provide a reference for the inspection of thin-walled tubes of which thickness is less than 3mm.

6. Acknowledgments
This work was supported by National Key R&D Program of China (Grant No. 2017YFE0301404), supported by Research on Non-destructive Examination of superconductor cable (grant No. YZJJ2018QN12) and the Fund of Natural Science Foundation of China (Grant No. 51677184). The authors are very grateful to all the members of the conductor design team in ASIPP.

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