Ultrasonic Testing of ITER Toroidal Field Coil Cases Closure Welds

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Abstract. The ITER Toroidal Field Coil Cases (TFCC) are massive components made of austenitic stainless steel with a “D”-shape and composed of a winding pack enclosed in a welded coil case. Closure welds range from 35 mm to over 120 mm in thickness, making more than 70 m of fused metal per coil.

To ensure the mechanical integrity of these components, all the ITER TFCC closure welds have to be 100% examined. As a result of its inherent nature, closure welding can only be inspected from one side, ultrasonic testing (UT) being the method chosen. Postulated defects include volumetric flaws and open, sub-surface and embedded planar flaws (from 10 mm²), with orientations parallel and transversal to the weld centre line.

It is recognized that ultrasonic testing of austenitic stainless steel welds are severely hampered by the anisotropy and sound scattering at the grain boundaries. In the present case, weld inspection is also subject to restricted accessibility, large and variable thicknesses, and highly demanding qualification requirements. Since the inspection conditions are exceptionally challenging, devoted qualified ultrasonic techniques are needed.

To overcome these challenges, Tecnatom has proposed ultrasonic techniques based on Dual Matrix Arrays (DMA) which combine the advantages of TRL (Transmit-Receive-Longitudinal) probes with those of phased-array (PA) technology. Dual probes create a natural focus in which sensitivity is maximized, while unwanted wedge echoes are minimized. On the other hand, two-dimensional PA probes allow electronic steering in the primary axis along with skewing the beam in the secondary axis with the main purpose of focalizing at different depths.

The present paper presents the performance of DMA techniques for the inspection of thick austenitic welds aimed at the qualification of ultrasonic procedures for the non-destructive testing of the ITER TFCC closure welds.

1. Introduction

1.1 Background

Ultrasonic inspections of welded austenitic components present major problems due to significant wave scattering and anisotropy; causing attenuation, beam skewing and beam splitting [1], [2].
ITER Toroidal Field Coil Cases (TFCC) are massive components made of 316 LN austenitic stainless steel with closure welds ranging from 35 mm to over 120 mm in thickness. As a result of its inherent nature, TFCC closure welds can only be inspected from the outer surface and only at half skip. To ensure the mechanical integrity of these components, ultrasonic techniques for the inspection of the 100% welded volume, with the most challenging qualification requirements, have been requested.

1.2 Component

Fusion for Energy, the European domestic agency of ITER, is responsible for the supply of 10 out of the 19 TF coils. SIMIC S.p.A. (Italy) will carry out the final step of the TF procurement, including the closure welding of the coil cases, and delivery to ITER construction site.

The Toroidal Field coils have a “D” shape and are composed of a winding pack (WP) enclosed in a coil case. To allow insertion of the WP during manufacturing, the TFCC is split into four main subassemblies: two U-shaped (AU and BU) and two flat plates (AP and BP).

Fig. 1 shows the TFCC structure with the four main parts (AU, BU, AP, BP) and the two splice plates (TSP, BSP). Three different chamfer geometries are used depending on the welding process (automatic or manual) and the weld orientation (poloidal or toroidal).

![Fig. 1. Closure welding of the ITER TFCC.](image-url)
1.3 Postulated flaws

Postulated flaws are perpendicular and parallel to the weld centre line, including:

- Notches (top and bottom): 2x10 mm in 80 mm thickness, and 3x15 mm in 120 mm thickness
- Sub-surface defects (top and bottom): 14 mm$^2$ in 80 mm thickness, and 20 mm$^2$ in 120 mm thickness
- Planar defects in the centre of the weld: 100 mm$^2$ in 80 mm thickness, and 150 mm$^2$ in 120 mm thickness
- Planar defects at the interface base/welded metals: 20 mm$^2$ in 80 mm thickness, and 35 mm$^2$ in 120 mm thickness
- Volumetric defects of 3 mm in diameter in 120 mm thickness

Embedded postulated defects are located at different depths in the qualification coupons (¼, ½, ¾) and have an aspect ratio of 3:1. Different inspection criteria are applied depending on the zone of the TF coil weld.

2. Material and methods

2.1 Calibration, reference and validation blocks

Calibration, reference and validation blocks have been supplied by SIMIC S.p.A. (Italy).

2.1.1 Calibration blocks

Calibration blocks are made up of base metal, without welding material. The distance calibration block contains a 90° segment of 100 mm radius. Two side-drilled holes of 3 mm in diameter enable refraction angles of 45° and 60° to be checked. The sensitivity calibration block (140 mm in thickness) has two notches and thirteen side-drilled holes (SDH). Holes are drilled every 20 mm (alternating from each side). This block is used to construct automatic Time-Corrected Gain curves.

2.1.2 Reference blocks

Side-drilled holes and notches have been machined in five reference blocks with weld chamfers W2 and W3, and thicknesses of 80 mm and 120 mm. These blocks are asymmetric in order to reproduce ultrasonic testing from the exploration surface parallel to the weld (surface S3). Reflectors are located at the weld centre line and at the interface base/fused metals: SDHs have been alternately drilled from each side every 20 mm in depth, and notches have been produced open to top and bottom surfaces by electrical discharge machining (EDM).

2.1.3 Validation blocks

Besides welded reference blocks, seven validation/qualification coupons, fully representative of the final component, have been manufactured with thicknesses ranging from 80 mm up to 120 mm. Test pieces include all the postulated defects in all the chamfer geometries. Volumetric defects have been represented by semi-spherical bottom holes.
Surface-breaking notches have been machined by EDM. Sub-surface and embedded planar reflectors have been buried after electrical discharge machining. Every qualification coupon has been produced in multiple steps by the collaborative work between welding and machining workshops.

An example of the arrangement of reflectors in a validation test piece can be seen in the drawing depicted in Fig. 2.

![Fig. 2. Example of validation test piece (UT-VAL-02).](image)

2.2 Mechanical scanners

Two mechanical scanners have been designed for the inspection of poloidal and toroidal welds to meet the following technical requirements (Fig. 3):

- 2-axis (x-y) encoding system
- Curvatures in x-direction from $\infty$ up to $R=2076$ mm (poloidal welds)
- Curvatures in y-direction from $\infty$ up to $R=3800$ mm (toroidal welds)
- 100% volume coverage
- Raster scans parallel to the weld centre line
- Smooth movement in x-direction
- Fine/precise movement in y-direction with clamping system
- Probe holders for PA probes that allow 0°, 90°, 180°, 270° skews
- x-axis stroke > 1.5 m, y-axis stroke > 0.3 m
- Able to function on walls and roofs (weightless, secure…)
- Fixable to stainless steel components
- Easily manipulated by a single operator
- External tools not required for operation

Both scanners use magnetic encoders, which are contactless and provide resolutions and repeatabilities with a 0.1 mm range.

The scanners are placed parallel to the weld centre line with the assistance from positioning devices.

An additional ultrasonic scanner, utilizing wire-actuated encoders, has been designed to record positions when manual re-tests are to be carried out.
2.3 Ultrasonic techniques

2.3.1 Longitudinal flaws

Perpendicular ultrasonic scans are carried out from surfaces S1, S2 and S3 (when available) as shown in Fig. 4.

Inspections from surfaces S1 and S2 are performed with a Dual Matrix Array probe using several ultrasonic techniques:
- Creep wave technique, for the detection of sub-surface/open defects on the top surface
- Shear wave technique, for the detection of sub-surface/open defects on the backwall, and within parent material
- Longitudinal wave technique, for the detection of internal defects

Inspections from surface S3 are performed using a normal incidence pulse-echo technique with a linear phased-array probe. The beam is steered from -30° to 30° in the direction of the depth for the detection of sub-surface/open defects.
2.3.2 Transverse flaws

Parallel ultrasonic scans are carried out using a DMA 1.5 MHz pitch-and-catch technique with a probe on each side of the weld (surfaces S1 and S2). The squint angle, probe centre separation and delay laws have been defined using CIVA simulations and optimized experimentally.

2.4 CIVA model

Both base and fused metals have been simulated using a polycrystalline model with random orientation, described by an elastic matrix with cubic symmetry and three independent constants. The elastic constants have been collected from the literature for the type 316 stainless steel single crystal [3], namely, $c_{11}=198$ GPa, $c_{12}=125$ GPa, and $c_{44}=122$ GPa. The average size of the grains has been adjusted based on literature data [4] and the Average Grain Size measured by the supplier. Grain structures have been supposed simple (in contrast to duplex) and without dilatation. The input parameters of the model have been adjusted with acquisitions of the reference blocks.

Longitudinal and transverse wave velocities, $c$, are calculated by CIVA using the polycrystalline model. Ultrasonic velocities, $c$, depend on combinations of the elastic constants:

$$c = \frac{C_{\text{eff}}}{\sqrt{\rho}}$$

where $C_{\text{eff}}$ is an effective elastic constant which depends on the crystal symmetry.

Simulations have taken into account attenuation. Attenuation coefficients for longitudinal and transverse waves were calculated using the Born approximation, which simplifies the description of ultrasonic scattering [5].

3. Results and discussion

3.1 CIVA simulations

The selection of ultrasonic probes has been based on the experimental results of the reference blocks and CIVA simulations. The behaviour (material-based noise, depth penetration, steering capability, axial resolution/bandwidth, sensitivity, divergence and focal capability) of the following probes has been studied:

- P/E Linear PA 2.25 MHz (without refraction wedge)
- Dual Linear PA 1.5 or 2.0 MHz
- Dual Matrix Arrays 1.5, 2.25 or 4.0 MHz

Overall, dual probes have been preferred in terms of SNR, and to avoid spurious echoes and dead zones. Dual linear PA probes required several roof/squint angles to cover all the volume, whereas Dual Matrix Array probes provide the possibility of overlapping T/R beam footprints, without the need of several refraction wedges or mechanical assistance. Both DMA 1.5 MHz and 2.25 MHz probes showed satisfactory results, though the latter seemed more prone to false calls (Fig. 5). CIVA has also been used to examine volume coverage (Fig. 6) and to optimize other inspection parameters such as squint angle or probe centre separation.
3.2 Longitudinal flaws

Fig. 7 shows a volumetric merged B-scan of the validation block UT-VAL-02 using a DMA 1.5 MHz (Creep wave technique). Despite the noisy material, it can be observed that both open and sub-surface defects are satisfactorily detected.
Similar results were obtained for embedded reflectors using a DMA 1.5 MHz (longitudinal wave technique) as shown in Fig. 8.

**Fig. 8.** Detection of embedded planar flaws located at the weld centre line (UT-VAL-02).

Detection of flaws located near the backwall presented added challenge due to the geometrical echo coming from the poloidal chamfers (data not shown).

When S3 is available, ultrasonic testing from this surface provides specular echoes coming from defects parallel to the weld centre line, which significantly improves detection, characterization and sizing capabilities. Experimental data from surface S3 are shown in Fig. 9.

**Fig. 9.** Volumetric merged C-scan from surface S3 (UT-VAL-02).

### 3.3 Transverse flaws

Transverse planar flaws of different sizes have been completely embedded in fused metal so as to assess the limits of the parallel inspection. Test pieces with transverse planar reflectors have been produced by manual welding (W1), since it reproduces the most conservative situation, that is, the “worst-case” from the point of view of ultrasonic testing. Fig. 10 shows a volumetric merged B-scan obtained using a DMA 1.5 MHz in a pitch-and-catch configuration. It can be observed that planar flaws as small as 20 mm² were detected.
4. Conclusions

Advanced ultrasonic techniques have been developed for the non-destructive testing of ITER TFCC closure welds with satisfactory results, which consist of:

- Creep, longitudinal and shear wave techniques, using a Dual Matrix Array probe from the top scanning surfaces (S1 and S2), for the detection of longitudinal flaws.
- Normal incidence P/E technique, using a linear PA probe from the lateral surface (S3), providing specular echoes from longitudinal flaws.
- DMA pitch-and-catch technique, with one probe on each side of the weld (S1 and S2), for the detection of transverse flaws.

5. References