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Advanced ultrasonic examination of heavy–gauge high strength studs for the ITER toroidal field gravity supports

I. Aviles Santillana [a,*], G. Arnau Izquierdo [a], S. Bonnin [b], M. Celuch [a], E. Rodriguez Castro [a,f], S. Sgobba [a], C. Beemsterboer [c], M. Liao [c], T. Schild [c], S. Han [c], P. Brun [d], V. Roque [d], J.M. Coulet [e]

[a] *CERN, CH-1211 Geneva 23, Switzerland*
[b] *Foselev Suisse SA, Chemin des Batailles 22, Vernier 1214, Switzerland*
[c] *ITER Organization, Route de Vinon sur Verdon, CS 90 046 - 13067 St. Paul lez Durance cedex, France*
[d] *Framatome / Intercontrôle, BP 70 385 – Chalon sur Saône cedex, France*
[e] *Framatome - IBPER-F Department - CNPE Consortium - ITER Project TAC1, Route de Vinon sur Verdon, CS 90 046 - 13067 St. Paul lez Durance cedex, France*
[f] *Universidad Carlos III de Madrid, Campus de Leganés, Av. De la Universidad 30, Leganés, Madrid 28911, España*

A R T I C L E I N F O

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The ITER Tokamak will include the largest superconducting magnet system ever built, with 50 GJ of stored energy. A series of structural elements guarantee its integrity under extreme load and temperature conditions. Key structural components to support the superconducting magnet coils are the Toroidal Field Gravity Supports (TFGS), which not only must sustain the deadweight of the magnetic system (11000 tonnes), but also withstand large electromagnetic forces during operation and accelerations induced by possible seismic events. Each of the 18 TFGS is secured to the cryostat's base by a set of 26 heavy – gauge (M60 to M85) studs. The selected alloy for these fasteners is the high-strength precipitation–hardening Ni-base superalloy UNS N07718, featuring a suitable combination of strength and fracture toughness. An essential characteristic of these studs is internal soundness, which must be guaranteed thanks to a 100 % volumetric non–destructive inspection by ultrasonic testing (UT). Due to the very stringent reliability requirements imposed on these components, the UT procedures gathered in industrial standards for this size of products proved to be insufficient to guarantee the absence of internal flaws of detrimental size. Thus, a special procedure was developed and tailored to inspect every single stud installed in the TFGS. This paper describes the implemented UT procedure to assure the internal soundness of the studs, with a focus on control parameters, calibration procedures, and acceptance criteria. Additionally, the results of UT testing obtained on a selection of studs using such procedure is presented, moreover cross-checked by other volumetric NDE techniques such as computed microtomography to confirm the nature and size of imperfections.

1. Introduction

The 18 Toroidal Field (TF) coils of the ITER magnets system supply a constant toroidal field of 5.3 T to confine the plasma during an ITER pulse [1,2]. The interlinked toroidal field coils provide the superstructure that anchors the entire superconducting magnet system, including six poloidal field coils, the central solenoid, and an array of correction coils. From their position at the bottom of the machine, the toroidal field coil gravity supports will withstand about 11,000 tonnes of magnet dead weight [1,2,3]. But the TFGS not only support the dead weight of the whole magnet system, but also carry the forces such as the thermal stress from the relative thermal motion of the magnet system during cooling down and warming up, the electromagnetic loads (end of burning, disruption of plasma) during the different operation steps of the ITER device, and the possible seismic loads in vertical and horizontal directions [4]. Each of the 18 TFGS (Fig. 1) is secured at the cryostats' base with 26 UNS N07718 heavy gauge forged bolts (14 x M60 and 12 x M85) with a rolled thread. A stringent quality control of these bolts was put in place by ITER Organization (IO) to guarantee the reliability of the components in service conditions for a 20 year operation period. It included requirements of chemical composition, forging reduction, macro and microstructure, mechanical (tensile, hardness, proof load, fracture toughness), penetrant testing (PT), visual examination (VT) and ultrasonic examination (UT)). UT inspection was performed in accordance with ASME Section V Article 5. The examination procedure and acceptance standard are in accordance with ASME Section III, NB-2542. The size of the artificial defects in the calibration reference blocks, depending on the products' diameter, was 5 mm for the M60 and 8 mm

* Corresponding author.
E-mail address: ignacio.aviles.santillana@cern.ch (I.A. Santillana).

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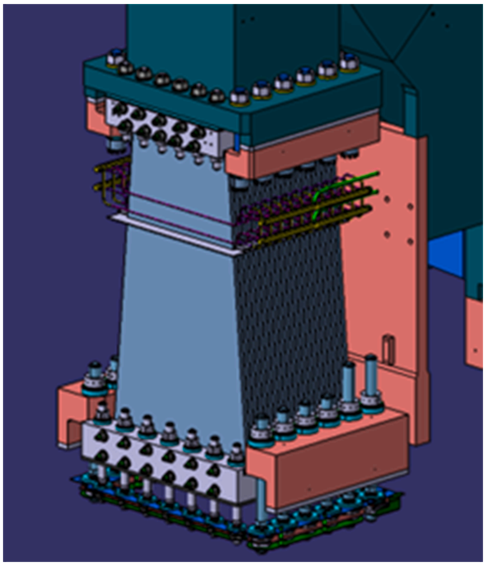

Fig 1. 3D model of a TFGS showing the M60 and M85 studs to secure it to the cryostat's base.

for the M85, according to the above mentioned codes.

In spite of the fact that these examinations were successfully completed, and the bolts were considered suitable for installation, an incident occurred that triggered the catastrophic delayed failure of one of these components. A comprehensive failure analysis was performed [5], and in parallel, a procedure to guarantee the fitness for service of both installed and uninstalled bolts was developed and implemented. The presence of shrinkage cavities at the stud's core together with an imperfect microstructure and the presence of brittle secondary phases seems to be the root cause of this shattering failure [5]. Based on the outcome of the failure analysis, a more stringent volumetric inspection and an acceptance criteria not only based on the detection of imperfections but also on transparency of the material to UT was developed and implemented. A UT examination from the stud's extremity, parallel to their main axis, was considered optimum in order to maximize the analyzed volume and to be able to assess nondestructively the absence of critical defects in uninstalled and installed components. The whole production of M85 studs (228 items) was tested by UT, plus one item of each batch for the M60 studs (8 items) for a total of 236 studs ultrasonically examined.

This paper describes in detail the rationale behind the unconventional UT procedure implemented for the heavy gauge studs of the TFGS and the results obtained for all the analyzed components, providing a reference for UT inspection of critical components demanding extreme reliability.

2. Examination methods and results

For the volumetric assessment of imperfections and microstructural heterogeneities, UT testing was considered as the optimum non - destructive examination technique. The test campaign was deployed in three stages: first, Phased – Array Ultrasonic Testing (PAUT) by immersion of non-installed studs in radial direction, as a complement of the UT examinations carried out by the material supplier but with much more stringent acceptance criteria. In parallel, the second stage consisting in the assessment of the feasibility of a manual UT control of uninstalled studs in axial direction (parallel to the studs' main axis) was carried out. Considering the length of the components (up to 1174 mm), only a very fine and homogeneous microstructure would provide a feebly attenuated backwall echo with no microstructurally induced intermediate reflectors. Once proven its feasibility, dedicated UT control procedures were validated. The axial UT inspection with straight probe imposing a transparence acceptance criterion of the parts is not only innovative for such long components, but also essential to enable the in - situ testing of 87 studs already installed in the tokamak pit. The third stage consists in the application of the control procedures to both uninstalled (ex – situ) and installed (in – situ) components to assess its fitness for operation.

2.1. UT by immersion

Phased array ultrasonic examination (PAUT) by immersion was performed in the radial direction of the studs. Only the central part of the pieces was examined, excluding the shanks and the threaded length (Fig. 2).

A 64 element 5 MHz PAUT probe was used, with a 0.7 mm pitch and a 0.1 mm gap. A measurement in two channels was performed simultaneously: one channel dedicated to the detection of imperfections, and a second one dedicated to assessing the transparency and homogeneity of the pieces (see next paragraphs for more details).

A calibration block was manufactured using a 38 mm slice from a M85 stud, in which two ø 1.5 mm side drilled holes (SDH) were introduced with the aim of building a distance amplitude curve (DAC). The distance from the outer surface at which the SDHs were detected is 18 mm, 30 mm, and 55 mm, respectively (the one found at 30 mm detected from opposite side). By using a DAC, it is possible to build a Time Corrected Gain (TCG), which compensates the gain of the artificial defects detected at different depths so that they all appear at a defined screen height (80 % SH in our case).

The acceptance criteria which are described in Table 1 are not only more stringent than the requirements of ASME Section III, NB-2542, only based on the maximum size of the artificial defects for the acceptability of the components, but it also includes strict criteria to assess the transparency of the pieces to ultrasounds which guarantees an excellent detectability of the part.

43 pieces were examined via PAUT by immersion: 8 x M60 and 35 x M85, from which all M60 were acceptable and only three M85 were failing the acceptance criteria. From these three, only one was excluded due to unacceptable indications, whereas the other two were failing the transparency criteria.

2.2. UT in axial direction: in – situ and ex - situ

UT inspection by contact was performed in the longitudinal direction of the studs, with a 4 MHz straight probe of 25.4 mm diameter was used. A single element UT probe was utilized in order to have a less divergent ultrasonic beam, very desirable considering the length of the analyzed pieces. from the accessible extremity of the installed studs, in longitudinal direction. For the in – situ analyses, the pieces were controlled from the accessible extremity of the studs. A schematic view of the controlled area can be seen in (Fig. 3). For the first 40 mm, the accuracy of the measurement is not guaranteed, whereas the last 40 mm are discarded due to an echo found systematically due to the samples' geometry. For the ex – situ analyses, the pieces were controlled also from the top, but if indications were detected, their position was confirmed from the opposite extremity (i.e. from the bottom).

Four calibration blocks coming from Inconel 718 M85 studs were fabricated in order to build the DAC. Sensitivity calibration is performed

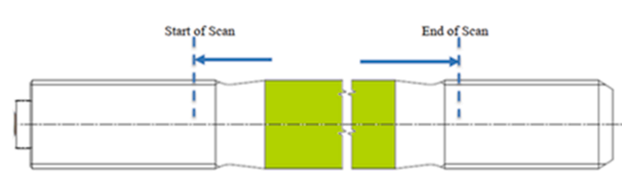

Fig 2. Schematic of the configuration of the UT inspection by immersion. The controlled region is depicted in green.

Table 1
Acceptance criteria for the PAUT inspection by immersion

	Acceptance criteria
Back wall echo	The amplitude of the backwall echo must not decrease more than 6dB with respect to a sound region
Indication echo	The amplitude of the indication must be lower than TCG – 6dB

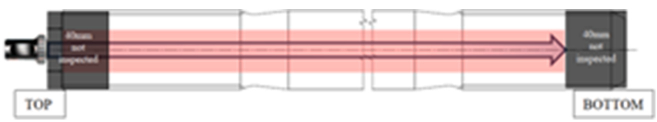

Fig 3. Schematic of the configuration of the UT inspection by contact, with the position of the probe at the top. The exclusion regions are shown, as well as the control volume (in red).

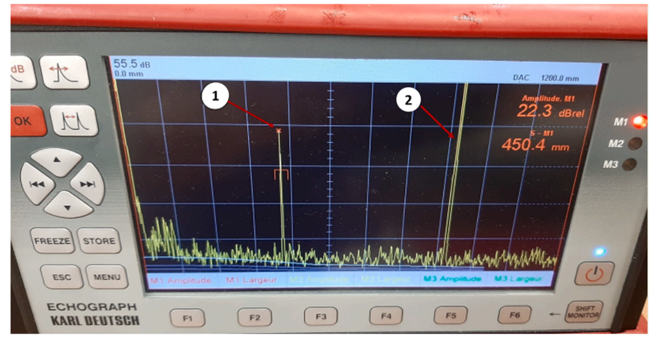

Fig 4. A - scan of the indication observed for XL - GS - 182 – 160 as observed from the top (indication echo marked with a '1'). The back – wall echo (marked with a '2') is also detected, with an amplitude of 100% FSH. The amplitude of the indication at this gain is around 80% FSH.

from a DAC with 4 Flat – bottomed holes (FBH's) of Ø1.5 mm (one FBH per block), whose distances between FBH and scanning surface are respectively 1124 mm, 550 mm, 250 mm and 70 mm. The instrument gain was adjusted such that the indication from the flat-bottom hole producing the highest indication amplitude, is 80% ± 5% full screen height (FSH) for each FBH. A DAC shall be established using the indications from the four FBHs and shall be extended to cover the full length of the material being examined.

Furthermore, an additional gain compensation for the less transparent studs is applied. The gain required for a reference stud to display a backwall echo (BWE) at 80% FSH is compared with the one required for the stud which is being controlled. If the latter is less transparent to ultrasounds, the additional gain needed to obtain an equivalent BWE amplitude with respect to the reference stud will be added to the reference DAC for the inspection.

The acceptance criteria for the axial examinations with straight probe which is gathered in Table 2 is, as in the case of the PAUT by immersion, twofold: on the one hand, there is a criterion for the amplitude of the unacceptable imperfections, which is already very stringent by itself using Ø 1.5 mm FBHs as reference artificial defects. On the other hand, there is a supplementary criterion of one of signal – to – noise ratio, to assess the permeability of the studs to ultrasounds in order to ensure an exceptionally high controllability of the inspected parts.

For the ex – situ examinations, 111 studs were inspected, and a fairly large number (18) were considered unacceptable, from which 11 were due to indications and seven due to an unacceptable controllability. One of these 11 (XL – GS – 182 – 160), clearly exhibiting an unacceptable indication (Fig. 4), was sent to CERN for subsequent analyses.

For the in – situ examinations, 87 studs were inspected and only eight were considered unacceptable, from which only one was exhibiting an unacceptable indication. The other seven were rejected due to criteria of lack of controllability.

2.3. Additional analysis at CERN

In the M85 stud mentioned above, an indication that failed to fulfill the acceptance criteria (DAC + 8 dB) when analyzed in axial direction from the top was found. It was sent to CERN in order to confirm the presence of such indication, and to perform additional NDE to better characterize the geometry and nature of the imperfection via X–ray computed tomography (CT). Once the axial control confirmed the position of the imperfection, a 30 mm slice containing it was extracted. For a better in – plane positioning of the indication, this slice was submitted to immersion UT. The results of this examination are shown in Fig. 5.

The last preparation step was the removal enough material surrounding the imperfection in order to obtain a volume of interest (VOI) exploitable in CT. The VOI was scanned in a Zeiss Metrotom, with an accelerating voltage of 225 kV, to achieve a voxel size of 139 µm. The CT scan which can be observed in Fig. 6 shows a very clear 3D imperfection, which seems to be an extensive network of cavities at the piece's core, with a maximum span of around 8 mm, presumably of the same nature as the one provoking the catastrophic failure of the M85 [5].

Additionally, from one of the most attenuating studs (XL – GS – 182 – 165), a cross section was extracted to perform a metallographic observation. As it is shown in the scanning electron microscope (SEM) image displayed in Fig. 7, a so - called necklace microstructure (a dual structure of small grains surrounding large grains) was observed, with a generalized precipitation of acicular δ – phase at GBs forming a continuous network.

3. Discussion and conclusion

A successful procedure was developed to assess the fitness for

Table 2
Acceptance criteria for the contact UT manual control, valid for both in - situ and ex - situ examinations

	Acceptance criteria
Back wall echo	The signal to noise ratio of the backwall echo must be ≥ 42dB
Indication echo	The amplitude of the indication must be lower than DAC - 6dB

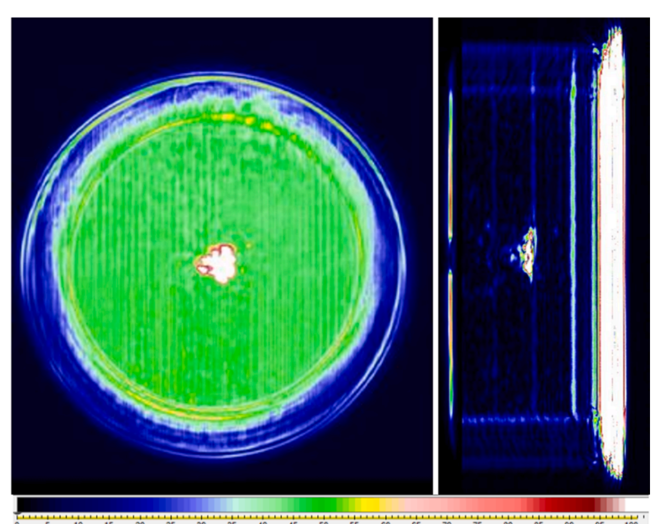

Fig 5. UT by immersion of a 30 mm slice extracted form a M85 stud showing an indication when controlled parallel to the axis (left) and in radial direction (right). Colours represent the amplitude of the signal. Left image shows a CT scan of the cross section. Right image shows a C – scan in radial direction.

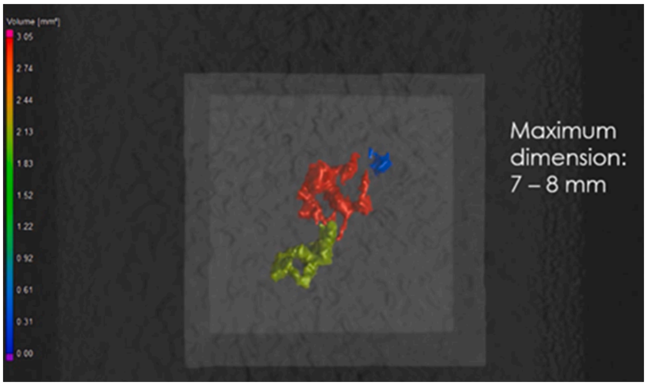

Fig 6. CT scan of piece XL – GS – 182 – 160. At its core, it presents a continuous network of cavities which were not properly closed during the forging operations.

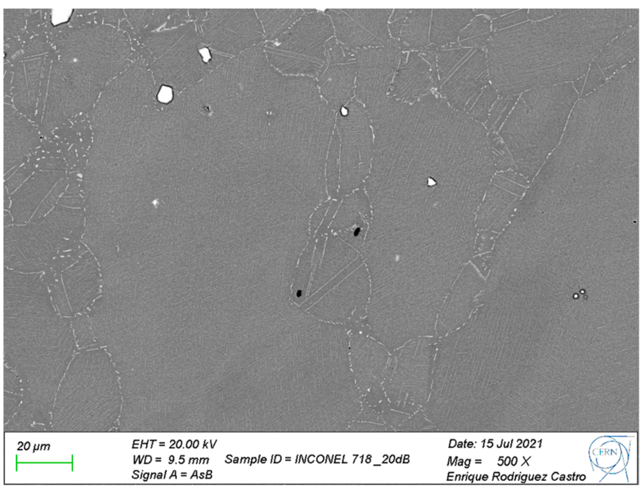

Fig 7. SEM image (backscattered electrons detector) of the microstructure of XL – GS – 182 – 165. Necklace structure is observed, with acicular δ – phase precipitated at GBs.

operation of heavy-gauge, high-strength studs for the ITER TFGS. It involved advanced ultrasonic examination techniques, specifically PAUT by immersion in the radial direction and UT inspection by contact with normal probe in the axial direction. These complementary analyses enhance each other's capabilities: the immersion-based radial control detects sub-superficial and elongated imperfections, while the axial control is better suited for detecting lenticular imperfections, cavities, and assessing microstructural homogeneity.

More specifically, with respect to the original radial examination with relatively large (ø = 8 mm) reference defects, an axial contact examination all along the studs' main axes and a radial examination by immersion was put in place to assess the whole production (228 items) of M85 studs. Independently of the UT approach, the acceptance criteria based on ø = 1.5 mm SDH / FBH is much more stringent than the originally used as reference from ASME Section III, NB-2542. In addition, an innovative part of the UT inspection is the criteria to reject studs which are too opaque to ultrasounds, thus jeopardizing the inspectability of the parts. 29 studs failed the UT assessment (10 studs due to indications and 19 due to lack of transparency), which represents 12.8% of the production. 25 new studs will be procured based on a new technical specification, which includes the UT procedure for axial inspection with straight probe herein described.

Additionally, the improved UT procedure which allowed an axial in – situ examination was essential to guarantee absence of critical defects in the already installed studs, thus assuring the fitness for a 20 year operation of these key structural components of the ITER magnet system. Additionally, one stud of each batch of M60 studs was controlled by immersion UT, with total absence of critical defects and thus, this production was considered as suitable for operation.

An M85 stud rejected after axial UT based on the amplitude of an indication was examined at CERN. The volume containing the indication was isolated and reduced to an exploitable size for a XCT scan, which shows a three dimensional network of interconnected cavities at the core of the stud. It is presumably of the same nature, and it is found at a similar position than the imperfection that triggered the catastrophic failure of an M85 stud, thus proving that the improved UT inspection would be able to detect critical size defects in this production. Furthermore, the dual grain structure observed for an M85 explains its rejection due to its lack of UT transparency and, in turn, inspectability.

"The views and opinions expressed herein do not necessarily reflect those of the ITER Organization"

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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