Benchmarking of Mechanical Test Facilities Related to ITER CICC Steel Jackets

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***Abstract*—The International Thermonuclear Experimental Reactor (ITER) cable-in-conduit conductor used in the superconducting magnet system consists of a cable made of 300 to 1440 strands housed in a stainless steel tube (called as jacket or conduit). There are circular, square, as well as circle-in-square jackets, made of either a very low carbon AISI 316LN and AISI 316L grade stainless steels, or a high Mn austenitic stainless steel developed for ITER called JK2LB. Selected mechanical properties of the base material and weld joint were tested at room temperature and/or cryogenic temperatures ($<$ 7 K) at predefined mechanical deformation and heat treatment condition. The domestic agencies' reference laboratories and the ITER-IO appointed reference laboratories, CERN and Karlsruhe Institute of Technology performed mechanical tests such as tensile strength, fracture toughness, and fatigue crack growth rate. This paper will compare the test results (e.g., elongation to failure) from different laboratories, present the statistics, and identify any systematic differences.**

***Index Terms*—Austenitic steel, fatigue, ITER, mechanical properties, stress.**

I. Introduction

THE ITER magnet system consists of several different conductor types relying on NbTi or Nb_3Sn superconductors. Depending on the specific magnet requirements the conductors are designed for 10 kA at a few Tesla background field up to 68 kA at around 11 T as required for the Toroidal Field (TF) Coil system [1]. Each system is based on the Cable-in-Conduit-Conductor (CICC) design and the seamless jackets are produced by extrusion and cold drawing. Furthermore, after the primary casting a re-melting step by Electroslag Remelting (ESR) is required to limit non-metallic inclusions and macro-inclusions. Apart from the same production process the conduit material and shape vary from round 316LN tube as used for the TF conductors to circle-in-square JK2LB for the Central Solenoid (CS) conductors. A summary of the ITER jacket types and their dimensions at final stage after compaction is given in Table I.

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TABLE I
ITER Conductor Jackets

Conductor Type	Steel grade	Outer dimensions (mm)	Thickness/inner dimensions (mm)
TF	Low C 316LN	Ø 43.7	2
CC[a]	316L	19.2 x 19.2	2.2
MB	316L	Ø 44.5	2
CB	316L	Ø 22	2
PF1/6	316L	53.8 x 53.8	Inner Ø 37.7
PF2-5	316L	51.9 x 51.9	Inner Ø 35.3
CS	JK2LB	49 x 49	Inner Ø 32.6

[a] The CC conductor is manufactured by compacting a round tube to square dimensions.

In addition to the different shapes and stainless steel grades, a further variation is caused by the involvement of different steel suppliers all around the world. In the case of the TF conductors, 6 different Domestic Agencies (DAs) are involved in the supply leading to several different TF jacket suppliers [2]. The DAs have to qualify laboratories which are in charge of performing all the required mechanical testing to confirm that the material meets the specifications. In order to ensure the same quality standards and performances the ITER IO has appointed reference laboratories to benchmark institutes and cross-check test results.

II. TF Jacket

A. Standardization of Sample Preparation and Test

The required mechanical tests to be performed on the jackets are defined in the Procurement Arrangements (PAs) signed between ITER IO and the DAs and are conducted according to national standards such as ASTM or JIS. However, the first comparisons of the tensile test results showed significant variations despite the fact that test procedures and specimen geometries were according to applicable standards [3]. As a consequence, several parameters had to be agreed and standardized for the TF jacket mechanical tests.

1) Material Preparation: The mechanical test results have to be representative for the final conductor and therefore, the

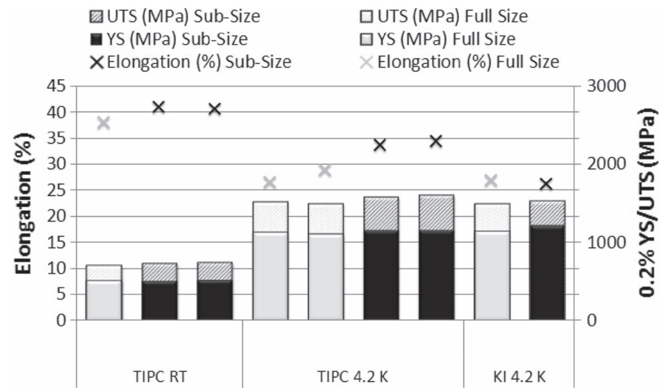

Fig. 1. Comparison between results of full-size and subsize tensile test results carried out at KI [6] and TIPC [7].

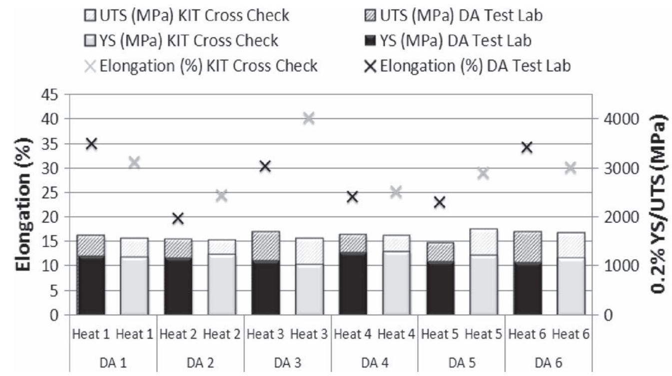

Fig. 2. Comparison of YS and max. elongation of TF jacket sections at cryogenic temperatures. (Note that the heat identification is not related to actual production.)

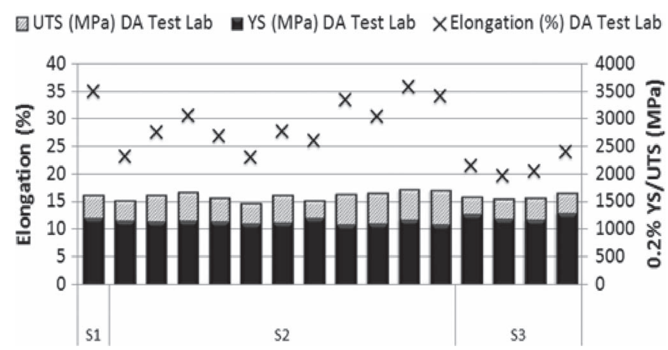

Fig. 3. YS and maximum elongation at cryogenic temperatures of TF jacket sections taken from different primary heats (melts) of the three jacket suppliers called S1, S2, and S3. The acceptance limits are at least 20% and 950 MPa for the elongation and YS, respectively.

test specimens have to undergo equivalent processing steps as the conductor during coil fabrication [2]. The steps defined are:

- compaction (by diameter reduction) to final dimensions
- stretching by 2.5% to mimic bending and straightening processes as experienced during coil winding
- Heat treatment for 200 h at 650 °C in Ar or vacuum tomimic the reaction heat treatment of Nb_3Sn.
- If applicable: cutting of sub-size samples out of thejacket by water jet or electro-discharge machining.

2) Specimen Geometry: Considering the size of TF jacket tubes (see Table I) and the requirement of measuring the ultimate tensile strength (UTS), 0.2% yield strength (YS) and elongation at cryogenic temperatures, full scale tensile tests are difficult and not available in many laboratories. Therefore, testing of sub-size specimens is permitted but the specimens have to be made according to the standard ASTM E8M [4, Fig. 13].

Sub-size vs. full size tensile tests have been performed at the Kurchatov Institute (KI, Russian Federation) [5], [6] and Technical Institute of Physics and Chemistry (TIPC, China) [7]. Fig. 1 provides a comparison of tensile results obtained by the two labs, confirming good agreement and representative-ness of sub size sample results. It has to be noted that elongation measurements in general do show large variations even among specimens taken from the same tube (see below). The slight tendency of getting lower elongation values for full size specimens is explained by the larger variation of material properties and non-homogeneity of the thickness around the perimeter.

3) Test Procedure and Assessment: The cryogenic tensile test in liquid helium has to be conducted in accordance with ASTM E1450 or an equivalent standard (e.g., JIS Z2277). A strain rate below 5×10^{-4}/s is recommended. The upper limit has been set to 1×10^{-3}/s.

The assessment of the results has to follow the procedure of ASTM A370; if the fracture occurs outside the middle 50% of the gauge length, then the sample has to be discarded. The reference value is derived from results obtained from at least two sub-size samples taken from the same jacket tube. In order to ensure a higher confidence level of measurement accuracy and consistency, some limits of the difference in the results between samples taken from the same jacket tube have been defined. If the difference amongst samples in YS and elongation is more than 10% and 20% respectively, two more samples from the same tube are required to be tested.

B. Mechanical Test Result Comparison

After all these details have been agreed and implemented within the framework of the ITER project [8], the benchmarking of the DA laboratories provides consistent results. A comparison between results from the DA laboratories and Karlsruhe Institute of Technology (KIT) is given in Fig. 2. As can be clearly seen there is good agreement among the DA and IO reference laboratories. The largest difference has been observed for the first cross-checking tests (DA 3, Heat 3 in Fig. 2) which was performed before the implementation of the standardization as described in Section II-A above.

To enable efficient monitoring of the quality during jacket production, the sampling rate of the mechanical tests is defined per primary heat. During the TF jacket qualification phase it turned out that the total elongation of a jacket after cold work and ageing is rather sensitive to the chemical composition such that even minor variations within the allowable specification range may lead to different results [9], [10]. Therefore, the total elongation is being used as the key parameter for monitoring jacket production. For the TF jackets, there are 3 different steel suppliers involved in the supply and the production is well controlled meeting the specifications (see Fig. 3).

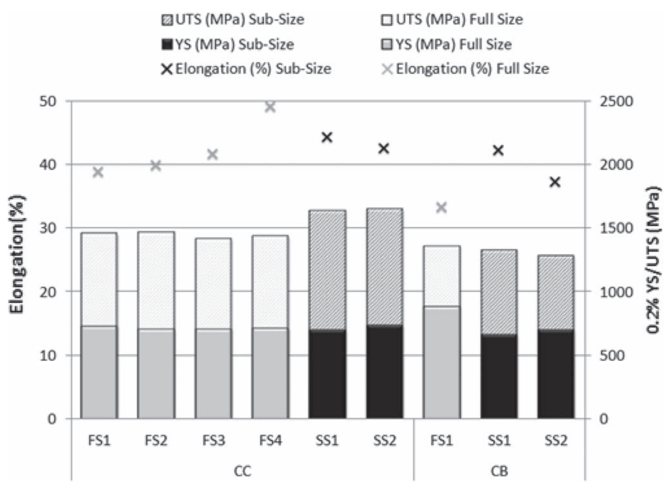

Fig. 4. YS and maximum elongation at cryogenic temperature of CB and CC jacket sections measured on full-size (FS) and subsize (SS) samples. The two subsize specimens (SS1 and SS2) are always taken from the same jacket section.

Data shown in Fig. 3 are taken from all 6 DAs and represent about 100 t of jackets which is more than 50% of the total amount of jackets needed for the TF conductors. As shown for S2 the elongation can vary significantly between different heats despite the fact that all heats meet the chem. composition specification (mod. 316LN).

III. CC and Feeder Busbar Jacket

In contrast to the TF conductors, the Correction Coil (CC) and feeder busbar conductors rely on NbTi strands, meaning that the jackets do not undergo any reaction heat treatment which may otherwise lead to grain boundary sensitization. As a consequence, there are no difficulties in maintaining high elongation values and ductility of the material.

For the main busbar (MB) jacket, the same sub-size approach as for the TF jacket is followed due to the conductor size (see Table I). The difference is that the jackets are only compacted to final dimensions without any stretching or heat treatment.

For the CC and correction coil busbar (CB) jackets, full size sample tests in compliance with ASTM E8M are specified. Due to the smaller steel cross section and the lower material grade (compared to TF), such tests are more readily available. Nevertheless, cross-check tests with sub-size samples were done at KIT to monitor any influence due to specimen size and confirm equivalency. The sub-size specimen design is driven by the square dimensions of the CC jacket after compaction. The selected width and gauge length are 5 and 11 mm, respectively. The comparison of YS and maximum elongation is given in Fig. 4. All CC and feeder conductors are supplied by only one DA and are coming from the same supplier.

The CB results are in good agreement for the elongation. The slightly larger YS obtained on the full size specimen is unexpected and most likely resulting from uncertainties in the determination of the exact material thickness. The differences observed for the CC specimens are related to the square shape since the corners are present only in the full size specimen and this part experiences more deformation. Following the test results sub-size specimens are deemed to be acceptable.

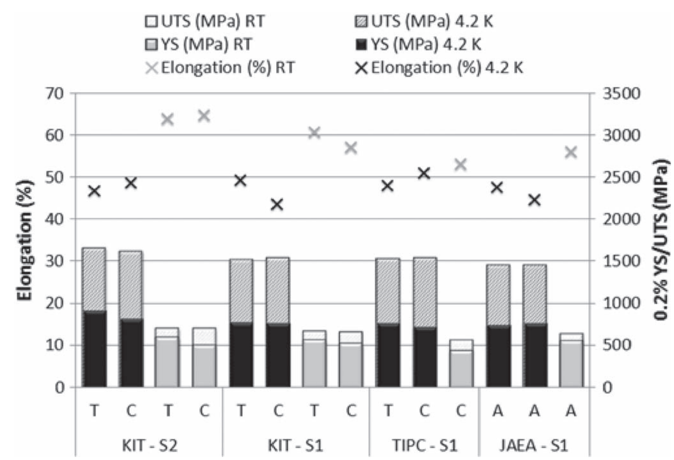

Fig. 5. Tensile test results of PF jackets taken from both suppliers. The data from KIT and JAEA are an average of 2 specimen tests. "T" and "C" represent specimens taken from the tensile and compressive side, respectively. "A" indicates that the specimens are taken from the corner region of the jacket section.

IV. PF Jacket

A. Standardization of Sample Preparation

The Poloidal Field (PF) jacket has a round-in-square profile, i.e., square bar with an inner round bore. Due to the larger thickness, fatigue crack growth rate (FCGR) as well as fracture toughness (K_{1C}) measurements can be performed. Again, the material preparation has to be treated to mimic production steps as for the coil fabrication. The procedure defined is:

- Compaction to final dimensions
- Bending on a radius $r = 2$ m
- Straightening
- Cutting of sub-size specimens according to the corresponding national standards (ASTM E8M, ASTM E647, JIS Z2283, JIS Z2284)

The jacket shape and cold work applied result in inhomogeneous mechanical properties depending on the side of the jacket from which the specimen is taken, i.e., compressive or tensile. They are chosen to represent the most severe conditions for a given mechanical test type, e.g., from the tensile side for FCGR tests.

B. Discussion on Test Results

Examples of tensile test results from the 2 PF jacket suppliers (S1 and S2) are given in Fig. 5. The material from supplier S1 used in the tests shown in Fig. 5 does not come from the same ESR but from the same primary heat. Results obtained from several different ESR heats and primary heats show that the variations of the mechanical properties within a primary heat are very small [11], and therefore a comparison between different ESRs can be made. Furthermore, the location from where the specimens were taken (tensile side, compressive side or corner area) seems to have relatively little impact, at least for supplier S1.

Comparing the results of the two different suppliers, a different behavior can be observed. The higher YS at 4.2 K for supplier S2 is explained by the additional N content

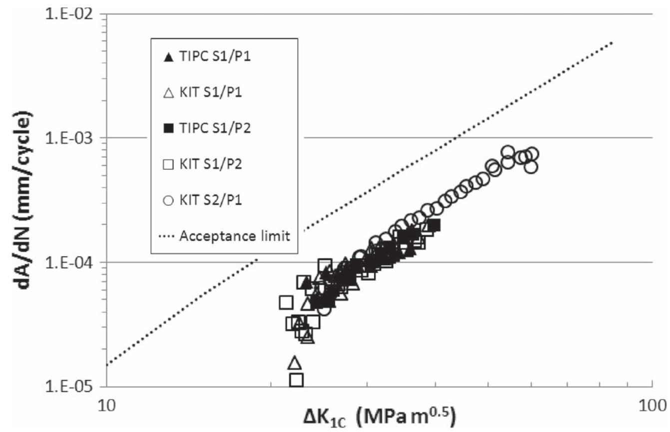

Fig. 6. FCGR measurements on material from suppliers S1 and S2 done by KIT and TIPC at 4.2 K. P1 and P2 are coming from different heats.

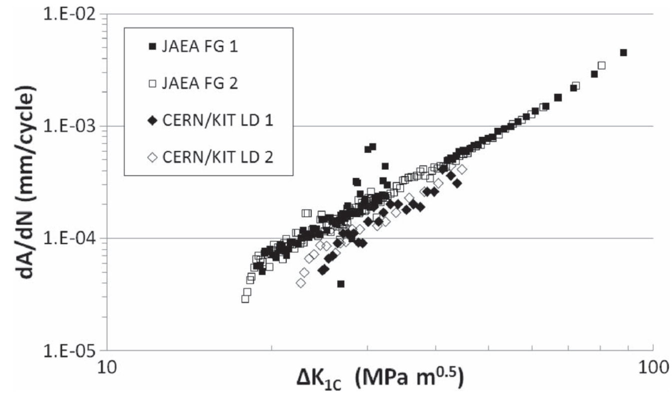

Fig. 7. FCGR data from CERN/KIT and JAEA at cryogenic temperatures for a 316LN candidate material. Data are taken from [16] (Note: in [16] the tests were subcontracted to the company CEME who has done the tests at KIT).

specification range of 0.4%–0.8%. The noticeably higher YS on the tensile side is a consequence of the different cold work applied by bending. However, the extent as observed for supplier S2 is unexpected.

First measurements of the FCGR from different laboratories revealed inconsistencies in the results but after the standardization of the specimen geometry and test procedure, good agreement has been found between KIT and TIPC (Fig. 6).

In addition to the good inter-laboratory agreement of the test results, the jackets from both suppliers meet the specification with ample margin. Consistent with the tensile test results, the stiffer material from supplier S2 reveals slightly poorer fatigue properties.

V. CS Jacket

Like the PF jacket, the CS jacket has a round-in-square profile. An extensive R&D program has been carried out involving CERN, JAEA and KIT with the aim to characterize the mechanical properties of 316LN and high-Mn austenitic steel called JK2LB [12]–[15] jackets for the CS, which were manufactured in different companies. In this program, focus is given on the FCGR behavior of the different steel types since the CS coil is a pulsed coil with demanding requirements on the fatigue properties of the CS jacket. Prior to the start of the measurement campaign a benchmarking of the FCGR and fracture toughness was performed. Reasonable agreement has been found among different laboratories (see e.g., [16]). An example for 316LN is given in Fig. 7.

Irrespective of the steel supplier, the FCGR properties of JK2LB are in average superior to 316LN [14], [16]. As a consequence, and also due to its lower coefficient of thermal expansion between RT and 4 K compared to 316LN, allowing for an additional pre-compression of the CS modules during cooling down, JK2LB has been selected as the reference CS jacket material. Since the CS conductor is made of Nb_3Sn, the material preparation is similar to the one for the TF jacket (see Section II-A1) but also includes a bending prior to the heat treatment like for the PF jackets. Mechanical Tests of Conductor Welds.

TABLE II
Weld and Base Material Test Results Comparison[a]

Type	Specimen	YS (MPa)	UTS (MPa)	Elongation (%)
Base TF	Sub-size	1284	1620	25
Weld TF	Sub-size	1067	1533	26.6
Base CC	Full size	712	1446	42.4
Weld CC	Full size	739	1426	34.7
Base CB	Full size	882	1359	33.3
Weld CB	Full size	784	1472	41
Base PF	Sub-size	752	1448	46
Weld PF	Sub-size	856	1454	47.2

[a] Data presented are the average of 2 – 4 test specimens.

During weld qualification, the weld specimens undergo the same mechanical tests as the base material including material preparation such as compaction or heat treatment. Table II provides a summary comparison of weld and base material tensile properties measured at KIT and JAEA. As expected, the test results indicate that welding can be done without significant degradation of the base material properties.

VI. Conclusion

The large number of suppliers and laboratories involved in the characterization of the mechanical properties of the ITER conductor jacket base and weld materials requires the definition of further details on sample preparation and testing. Such details include the exact procedures of material preparation and sub-size specimen cutting, as well as the sample dimensions and specification like the gauge length, specimen width and thickness, all of which may have significant influences on the experimental results. After having implemented standardized procedures for the material preparation and specimen testing, the inconsistencies observed at the beginning of the benchmarking process have been successfully resolved. Results from tensile tests and FCGR as well as fracture toughness tests (not presented in this paper) are now in good agreement among all DA laboratories for both room and cryogenic temperature measurements.

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References

[1] N. Mitchell, A. Devred, P. Libeyre, B. Lim, and F. Savary, "The ITER magnets: Design and construction status," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4200809, Jun. 2012.

[2] A. Devred, I. Backbier, D. Bessette, G. Bevillard, M. Gardner, M. Jewell, N. Mitchell, I. Pong, and A. Vostner, "Status of ITER conductor development and production," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4804909, Jun. 2012.

[3] K. Hamada, K. Kawano, T. Saito, M. Iguchi, H. Nakajima, O. Teshima, and H. Matsuda, "Effect of specimen shape on the elongation of 316LN Jacket used in the ITER Toroidal Field Coil," in *Proc. AIP Conf. CEC-ICMC*, 2012, vol. 1435, pp. 55–62.

[4] *E8M-08 Standard Test Methods for Tension Testing of Metallic Materials*, ASTM E8/E8M-08, 2008.

[5] O. P. Anashkin, V. E. Keilin, A. V. Krivykh, D. N. Diev, A. S. Dinisilov, V. I. Shcherbakov, and V. I. Tronza, "Tensile tests of ITER conductors jacket materials," in *Proc. AIP Conf. CEC-ICMC*, 2012, vol. 1435, pp. 117–124.

[6] O. P. Anashkin, A. V. Krivykh, and V. I. Tronza, Tensile Tests on Full Size TF Jacket Tubes, ITER, Cadarache, France, Final Rep. ITER Task Agreement C11TD181FR, ITER IDM #ITER_D_65BLEP. [Online]. Available: https://user.iter.org/?uid=65BLEP

[7] J. Qin, Y. Wu, K.-P. Weiss, and Z. Wu, "Mechanical test on the ITER TF jacket," *Cryogenics*, vol. 52, no. 7–9, pp. 336–339, Jul.–Sep. 2012.

[8] "Standardization of TF conductor jacket mechanical testing procedure," Cadarache, France, ITER IDM #ITER_D_35RKUS, 2010.

[9] K.-P. Weiss, A. Ehrlich, A. della Corte, and A. Vostner, "Tensile test results on compacted and annealed 316LN," in *Proc. AIP Conf.*, 2010, vol. 1219, pp. 3–8.

[10] K. P. Weiss, "Mechanical measurements at KIT," presented at the ITER Cond. Meeting Cadarache, France, Mar. 2010, ITER IDM #ITER_D_3DDGY8. [Online]. Available: https://user.iter.org/?uid=3DDGY8

[11] J. Qin, K.-P. Weiss, Y. Wu, Z. Wu, L. Li, and S. Liu, "Fatigue tests on the ITER PF jacket," *Cryogenics*, vol. 52, no. 10, pp. 486–490, Oct. 2012.

[12] S. Sgobba, J.-M. Dalin, P. Libeyre, D. J. Marcinek, and A. Nyilas, "Progress in production and qualification of stainless steel jacket material for the conductor of the ITER Central Solenoid," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 7800104, Jun. 2012.

[13] K. Hamada, H. Nakajima, K. Kawano, K. Takano, F. Tsutsumi, K. Okuno, T. Suzuki, and N. Fujitsuna, "Optimization of JK2LB chemical composition for ITER Central Solenoid conduit material," *Cryogenics*, vol. 47, no. 3, pp. 174–182, Mar. 2007.

[14] S. Sgobba, P. Libeyre, D. J. Marcinek, and A. Nyilas, "A comparative assessment of metallurgical and mechanical properties of two austenitic stainless steels for the conductor jacket of the ITER central solenoid," presented at the Proc. 27th SOFT Conf., Liege, Belgium, 2012.

[15] K. Hamada, Y. Nunoya, T. Isono, Y. Takahashi, K. Kawano, T. Saito, M. Oshikiri, Y. Uno, N. Koizumi, H. Nakajima, H. Matsuda, Y. Yano, A. Devred, P. Libeyre, D. Bessette, and M. C. Jewell, "Preparation for the ITER central solenoid conductor manufacturing," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, p. 4203404, Jun. 2012.

[16] A. Nyilas, K.-P. Weiss, S. Sgobba, M. Scheubel, and P. Libeyre, "Fatigue crack growth rate and fracture toughness of ITER central solenoid jacket materials at 7 K," in *Proc. AIP Conf.*, 2010, vol. 1435, pp. 47–54.