Properties of Toroidal Field Nb_3Sn Strands Made for the ITER Chinese Domestic Agency

Fang Liu, Huajun Liu, Yu Wu, Xiangbin Li, Yi Shi, Yibing Zhang, Hongjun Ma, Xintao Zhang, Jinggang Qin, Huan Jin, and Lei Lei

***Abstract*—China was responsible for supplying 7.5% of ITER toroidal field (TF) Nb_3Sn conductors. It has delivered all the required conductors unit lengths and fulfilled the TF conductor package. The conductor package delivery consisted of four phases, in terms of phase I (call for tender), II (qualification process), III (pre-production process), and IV (production process). This paper focuses on work from phases II to IV. The Superconducting Strand Test Laboratory of the Institute of Plasma Physics Chinese Academy of Sciences (ASIPP) was the reference laboratory of the Chinese Domestic Agency and undertook the task of Nb_3Sn strands verification based on the requirements of ITER procurement arrangements. The verification results showed that the strands properties fulfill ITER specifications. In addition, in order to know well the strand properties and supply essential data for conductors' performance prediction and analysis, the mechanical properties and critical current I_c as a function of axial strain, temperature, and magnetic field for the TF strands have been tested and summarized.**

***Index Terms*—Nb_3Sn, benchmarking, verification, scaling, CNDA.**

I. Introduction

The ITER TF system, which consists of 18 independent coils, is one of the main parts of the ITER magnet system. All the TF coils have the same dimension and are made of Cable-In-Conduit Conductor (CICC). Nb_3Sn-based superconducting strands and pure copper strands are used for TF conductors [1], [2].

The TF conductor package that was agreed on by ITER and CNDA, assigned procurement of 7.5% of the TF conductors to CNDA. This amount corresponds to 11 unit lengths (ULs). The execution has been in four main phases [3]. China started the TF conductor task in 2006, finished phase I successfully in 2009, and continued the following phases in 2010. At present, China has finished the TF package and all the conductor performances fulfill the PA requirements.

In total about 6,000 km Nb_3Sn strands have been supplied for CNDA and used for the TF conductors fabrication. ASIPP has undertaken the task of ITER strands verification. In order to verify the experimental set-up and procedure for measuring Nb_3Sn strands, four rounds of benchmarking have been organized by ITER International Organization (IO) and ASIPP took part in all of them [4]–[6]. All the results from ASIPP were acceptable.

The TF Nb_3Sn strands verifications included four test items at room temperature on un-reacted strand samples and three test items at low temperature on reacted strand samples [7]. In addition, in order to supply basic parameters for conductor performance prediction and analysis, the mechanical properties and I_c characteristics as a function of axial strain ε, temperature T and magnetic field B have been tested and the scaling parameters according to the ITER scaling law (the deviatoric strain model) were given [8].

In this paper, we summarize all performances of the CNDA Nb_3Sn strands, including verification results, I_c characterization, and mechanical properties.

II. Samples

The TF CICCs rely on multifilamentary Nb_3Sn-based composite strands. The strands were twisted and plated with chromium. Two manufacturing routes (bronze route (BR) and internal tin (IT)) are typically used for ITER. The strands fabricated for CNDA were IT Nb_3Sn strands**.** During qualification process (phase II), five TF samples were manufactured and tested in the SULTAN facility [9]. Only the strands used in the Chinese first TF conductor sample TFCN1 were produced by Oxford Superconducting Technology (OST). The other strands were all fabricated by Western Superconducting Technologies Co., Ltd (WST). Micrographs of the transverse cross-sections of the OST and WST Nb_3Sn strands are shown in Fig. 1.

The ITER PA has specified the sampling requirements for the factory tests by the strands suppliers and the least level for the verification tests [3]. The verification level limits were 100% for phase II, 50% for phase III and 25% for phase IV. During the TF package execution, ASIPP verified the strands performance with the sampling level no less than the limits set by ITER PA.

In addition, in order to supply basic parameters for conductor performance prediction and analysis, the mechanical properties

Manuscript received October 21, 2018; accepted January 29, 2019. Date of publication February 4, 2019; date of current version February 25, 2019. This work was supported in part by the National Natural Science Foundation of China under Grant 51477172 and in part by the National Magnetic Confinement Fusion Science Program under Grant 2014GB105004. *(Corresponding author: Fang Liu.)*

F. Liu, H. Liu, Y. Wu, Y. Shi, H. Ma, X. Zhang, J. Qin, H. Jin, and L. Lei are with the Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China (e-mail: liuhj@ipp.ac.cn).

X. Li is with the Acting ITER China Domestic Agency, Ministry of Science and Technology, Beijing 100862, China.

Y. Zhang is with the Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, China.

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Digital Object Identifier 10.1109/TASC.2019.2897097

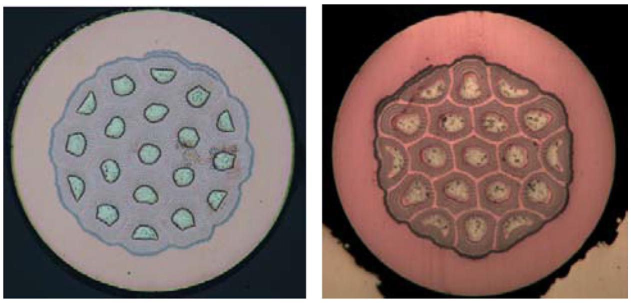

Fig. 1. Transverse cross-section of ITER TF Nb_3Sn strands made by OST (left) and WST (right).

and $I_c(B, T, \varepsilon)$ characteristics were measured. TFCN1 conductor sample was made of three OST IT Nb_3Sn strands (three billets) for qualification process. Three samples from these billets were tested by use of a strain device (referred to as "Pacman") at Twente University [10], [11].

All the other conductors were made of WST strands. For WST strands, two identical samples in total were prepared and used for $I_c(B,\ T,\ \varepsilon)$ characterization. The results of the sample, whose I_c was close to the average value obtained from the strands verification results, were used for conductor performance prediction and analysis [11]. In addition, one sample from WST strands was used to benchmark ASIPP Pacman device against that of University of Twente [12]. Several samples were prepared and used for mechanical properties determination.

III. Experiments

A. Verification

The parameters, including diameter *D*, copper to non-copper volume ratio R_{cu-ncu}, chromium plating thickness, twist pitch T_p, were obtained by measurements at room temperature on un-reacted Nb_3Sn strand samples. A micrometer with accuracy of 0.001 mm was used for diameter measurements. Metallographic techniques were used for plating thickness determination. Weighting method was used for the R_{cu-ncu} measurements. Two methods were used for T_P measurements, which included angle method for phase II and rotation method for phases III and IV [13].

The verification test items, which should be done at low temperature on reacted strand samples, included: I_c and *n*-value, residual resistance ratio (*RRR*) and hysteresis loss. Cycle B (650 °C with 100 h) was used for heat-treating samples according to PA recommendation [3].

The standard ITER barrel was used for I_c and *n*-value tests. Measurements were performed at 12 T. The electric-field criterion 10 μV/m was used for I_c determination and the range of 10 μV/m to 100 μV/m was used for the *n*-value determination. When the sample temperature was not 4.22 K, the supplied I_c values were corrected by an equation based on the sample temperature and measured I_c [5].

RRR is the ratio of the sample resistance at 273 K and that at 20 K. *RRR* was tested on heat-treated, 5 mm long, straight samples [7].

TABLE I
VERIFICATION RESULTS FOR THE TF WST Nb_3Sn STRANDS

	PA requirement	Mean	Max	Min	σ_s	Number of samples
Diameter, mm	0.82±0.005	0.821	0.825	0.819	0.0008	953
Twist Pitch, mm	15±2	16.0	17.0	13.9	0.58	624
Cu/non-Cu Ratio	1.0±0.1	1.01	1.10	0.91	0.042	590
Plating thickness, µm	1-2	1.5	2.0	1.2	0.13	952
Ic(12T,4.22K), A	>190	261.2	291.8	235.6	9.47	745
n(12T,4.22K)	>20	31.6	41.7	25.5	2.25	745
Hysteresis Loss ,mJ/cc	<600	469.8	608.7	361.9	38.24	275
RRR	>100	182.7	247.1	133.4	21.06	551

A six-turn section of a helical-shaped sample, wound around a 5 mm diameter screw for heat treatment, was used for measuring hysteresis loss. The area under the magnetization curve was used for the hysteresis loss determination [7].

B. $I_c(B,\ T,\ \varepsilon)$ Characterization

$I_c(B,\ T,\ \varepsilon)$ characterizations for Nb_3Sn samples were tested by the Pacman device.

These samples were also heat-treated following cycle B. The sample holder for heat-treatment was made of Ti-6Al-4V. Heat-treated sample was transferred onto the Pacman spring and soldered to it [12].

Measurements were performed in magnetic field. The field was perpendicular to the strand. The sample was strained by applying a torque to the spring. Two strain gauges were attached to the device to measure the applied strain. Temperature was varied by covering the Pacman spring and sample with a polyimide insulator and heating up the helium gas enclosed within. Two heaters were placed symmetrically on the spring and two thermometers were used to monitor temperature. Balancing of cooling and heating allowed to control temperature (within $\pm$20 mK) over the measured sample length.

C. Mechanical Tests

Several straight samples were also tested to determine the tensile characteristics. The tensile force applied to the sample wire was measured by a load cell while the sample elongation was determined by a pair of extensometers.

Heat-treated samples were measured at room temperature (300 K), liquid nitrogen temperature (77 K) and liquid helium temperature (4.2 K). The measurements were done at Twente University, and some samples were double checked by ASIPP using the device shown in reference [14].

IV. Strand Performance and Discussion

A. Verification Results

The verification results of the TF Nb_3Sn strands (including 14 billets for Phase II, 150 billets for Phase III and 687 billets for Phase IV) from ASIPP are summarized and listed in Table I.

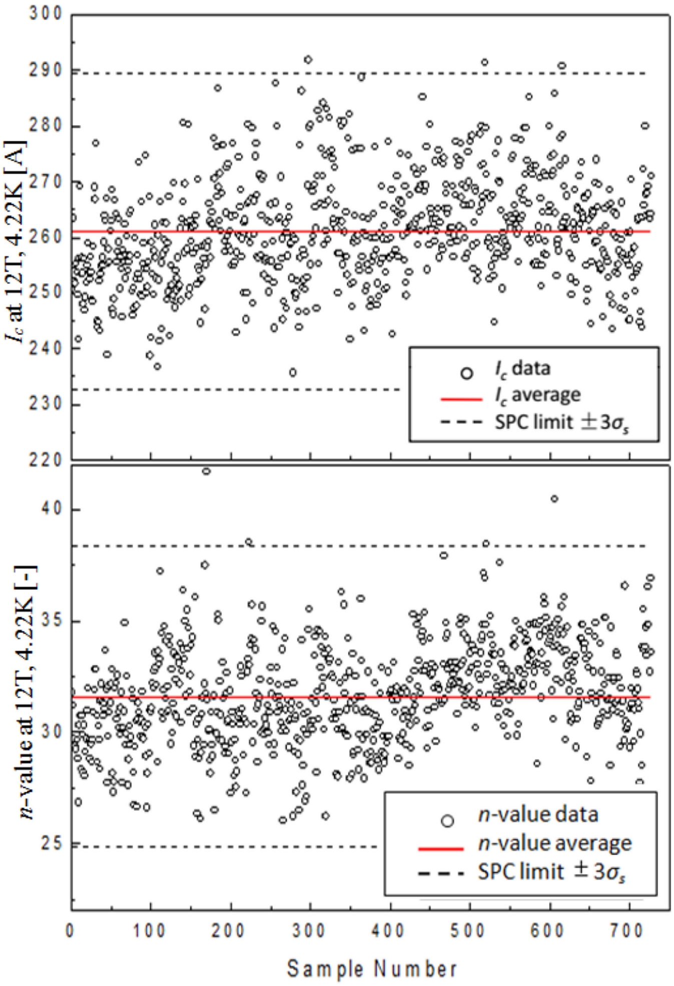

Fig. 2. I_c and n-value distribution in the TF WST Nb_3Sn strands from the verification results.

TABLE II
THE SCALING PARAMETERS ACCORDING TO THE ITER SCALING LAW

Parameter	OST 1	OST 2	OST 3	WST 1
C_{a1}	40.84	44.32	45.18	47.52
C_{a2}	0.00	0.00	0.00	0.00
$\varepsilon_{0,a}$, [%]	0.220%	0.304%	0.311%	0.218%
ε_m, [%]	0.000%	-0.048%	-0.056%	-0.067%
$\mu_0 H_{c2m}(0)$, (T)	31.48	32.86	32.07	34.22
$T_{cm}(0)$, (K)	16.18	16.08	16.11	16.26
C_1, [AT]	21900	22300	22500	20823
p	0.70	0.65	0.66	0.578
q	1.95	2.07	2.02	2.211

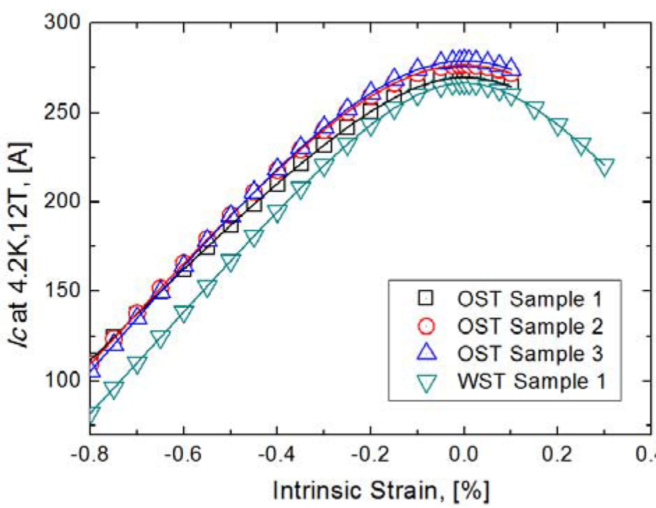

Fig. 3. I_c values as a function of intrinsic strain for the CNDA Nb_3Sn TF strands.

As shown Table I, the mean values of all the samples were 261.2 A with standard deviation (σ_s) of 9.47 A for I_c and 31.6 with σ_s of 2.25 for n-value. The distributions of I_c and n-value from the verification results for all the Nb_3Sn strand samples are shown in Fig. 2.

From the results, except one hysteresis loss data, all the other verification results are within PA requirements. The strands properties have been well controlled, and only few data were out of the statistical process control (SPC) limits.

B. $I_c(B, T, \varepsilon)$ Characterization

The irreversible strain limit, which corresponds to strain where permanent reduction of I_c starts, was around 0.12% applied strain for OST strands. The compressive pre-strain (ε_m) was not exactly similar for all the three strands, for OST 1 strand ε_m was around 0%, for OST 2 strand ε_m was around -0.05% while for OST 3 strand ε_m was around -0.06%. The intrinsic irreversible strain limits for the three samples were around 0.12%, 0.17% and 0.18%, respectively.

The scaling parameters for the ITER scaling law were determined from the experimental results for applied tensile strain below 0.12%. The parameters for the three OST strands are shown in Table II. One of them (OST 2) was chosen for TFCN1 sample performance analysis [15].

For the WST strands, one sample with I_c close to the average value (as shown in Table I) was used for determining the scaling parameters. The irreversible degradation starts at $+0.30\%$ intrinsic strain. Similar values for the intrinsic irreversible strain limit were also observed on other ITER WST Nb_3Sn samples measured on a Pacman device. All data below $+0.30\%$ intrinsic strain were used to determine the scaling parameters for I_c strain dependence. These parameters are also listed in Table II. Results of I_c as a function of intrinsic axial strain are summarized in Fig. 3 for OST and WST samples.

C. Mechanical Properties

Reacted samples were tested at 300 K, 77 K, and 4.2 K.

The tensile properties include the yield strength (YS) ($\sigma_{0.2}$), the ultimate tensile strength (UTS), elastic modulus (E), and elongation. Typical stress-strain curves are shown in Fig. 4. The mechanical properties are summarized in Table III.

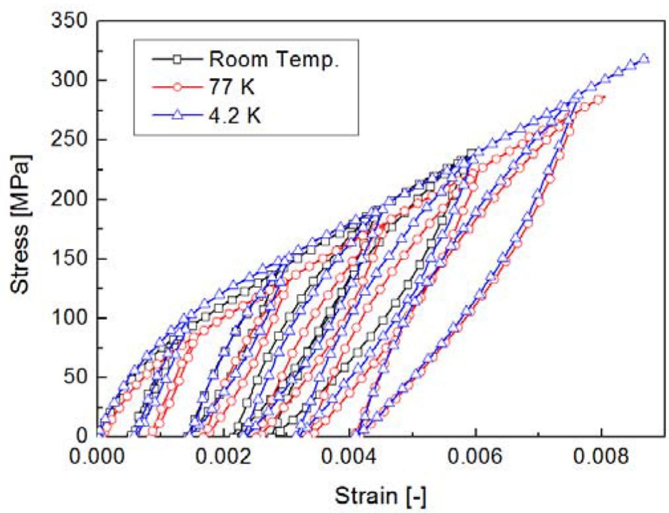

Fig. 4. Typical stress-strain curves for WST Nb_3Sn TF strands.

TABLE III
TENSILE PROPERTIES FOR WST TF Nb_3Sn STRANDS

	E/GPa	YS/MPa	UTS/ MPa	Elongation/%
Room Temperature	118	150	243	0.6
77 K	118	140	288	0.8
4.2 K	115	160	320	0.9

For WST Nb_3Sn strand, UTS is 243 MPa at 300 K, 288 MPa at 77 K, and 320 MPa at 4.2 K. E is 118 GPa at 300 K and 77 K, and 115 GPa at 4.2 K. YS is 150 MPa at 300 K, 140 MPa at 77 K, and 160 MPa at 4.2 K.

As shown from the table, the UTS changed with temperature significantly but YS and E have small dependence on temperature.

Results obtained on other WST TF strands showed similar mechanical properties. Differences were small and can be ignored for the conductors or magnets performance analysis. The values in Table III are applied in further analysis (e.g., cable and CICC performance modeling) for all WST TF strands.

V. CONCLUSIONS

China has finished the ITER TF conductor package. In total about 6,000 km Nb_3Sn strands have been supplied by CNDA for the fabrication of TF CICC cables.

The superconducting strands test laboratory of ASIPP undertook the verification task for CNDA ITER strands. Verification results showed that strands performances were within ITER specifications. The verification includes both room temperature and low temperature tests. We conclude that the quality of the supplied strands has been well controlled.

In addition, in order to predict and analyze the performance of TF conductors, the mechanical properties and I_c characteristics as a function of magnetic field, temperature and axial strain have been tested and the obtained I_c scaling parameters were used in performance analysis of TF conductors.

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