Residual Resistance Ratio in Nb_3Sn Strands During ITER TF Conductor Manufacture and After SULTAN Tests

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***Abstract*—The residual resistance ratio (RRR) is an important parameter affecting the stability of superconductors and the quench protection properties of magnets. During the manufacture of cable-in-conduit-conductors based on Nb_3Sn strands, RRR may change noticeably. We studied the RRR of strands in as-received condition and at different stages of the TF conductor manufacturing (cleaning and Cr-plating of strands, cabling and final compaction). The RRR of strands extracted from a TF conductor sample after electromagnetic and thermal cycling at the SULTAN test facility has been studied also. For this purpose after testing at SULTAN the strand samples were extracted from different locations in the cross-section of the TF conductor and from different positions along the axis. The results about the RRR variation during the conductor manufacturing process and after SULTAN tests are presented and discussed.**

***Index Terms*—ITER, measurement technique, Nb_3Sn, residual resistance ratio (RRR) parameter, strands.**

I. Introduction

TOROIDAL FIELDS (TF) coils of the ITER Magnet System will be manufactured with conductors based on superconducting Nb_3Sn strands [1]. The amount and quality of the stabilizing copper incorporated in the Nb_3Sn strands play the important roles in protection the magnet system against quenches and of improvement its stability. The quality of copper is primarily defined by the parameter RRR (R273 K/R20 K), which is very sensitive to the amount of impurities and the microstructure of the copper in the strand. As a consequence, the RRR is also very sensitive to the plating process [2], the heat treatment for the formation of Nb3Sn, [3], and the electromagnetic and thermal cycling of the final conductor [4]. The requirement for RRR $\geq$ 100 is included in the ITER technical specification for the Nb_3Sn strands to be used in the TF coils [5].

In the ITER Project the Russian Federation is one of the parties responsible for the production of strands and conductors for the TF coils. The production of bare Nb_3Sn (bronze route) strands for ITER (totaling $\sim$100 tons) takes place at the Chepetsky Mechanical Plant (ChMP), while the production of the TF conductors is being performed at the Russian Scientific R&D Cable Institute (VNIIKP) [6]. VNIIKP is also responsible for the Cr-plating and cabling of strands as well as for the final measurement of the Cr-plated strands' RRR after diffusion heat treatment.

It is found that RRR reduction after heat treatment is associated with chromium and oxygen diffusion from the Cr layer. In order to keep the RRR of strand higher than 100, the duration of the final stage of the heat treatment was reduced from 200 hours (Cycle A) to 100 hours (Cycle B). With this, any noticeable decrease of the critical current [7]. We have performed a lot of RRR measurements for the samples heat treated both by Cycle A and Cycle B. At present we have enough data for the Cycle B heat treatment to compare results and to estimate the improvement in RRR values.

Another issue we have studied was the impact of electromagnetic forces and thermal cycling during SULTAN tests on RRR of Nb_3Sn strands inside TF conductor. There is evidence that cold work in Cu sheath structure of the TF strands occurred after electromagnetic and thermal cycling [8] which could result in RRR reduction. We have performed direct measurements of RRR of strands extracted from the TF conductor sample after it was tested at SULTAN.

With high-end measuring facility in hand we have also decided to trace the evolution of RRR of Nb_3Sn strands during the main stages of the TF conductor technology production, from as-received bare strands through cleaning and Cr-plating of strands up to the final compaction of a conductor. Earlier, similar work was partly performed with NbTi strand for the ITER PF coils [9], in which the RRR degradation associated with the bending of the strands on the guide rollers of the coating facility was studied.

In this paper, we present some RRR measurements at various stages of the TF conductor production as well as after full-cycle test of a TF conductor sample at SULTAN facility.

II. Test Facility to Measure RRR

A. Measuring System

The test facility consists of helium flow cryostat and electrical measuring system. Helium flow cryostat has the temperature controller that permitted to keep a specified temperature in the

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TABLE I
HELIUM FLOW CRYOSTAT PARAMETERS

Temperature range: ~2 K - 300 K (LHe); 78 K - 300 K (LN2)
Initial cooldown time: ~ 30 minutes
Cryogen consumption: 1.1 l/hr at 5 K
Sample changeover time: 2 minutes or less

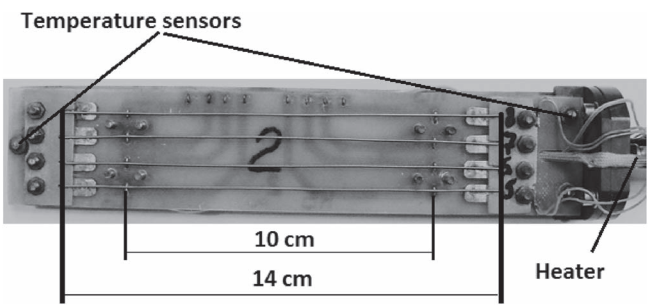

Fig. 1. Samples holder (view from one side).

measuring area. The temperature gradient along the length of samples did not exceed 0.5 K, the measuring current does not exceed 0.5 A. As a current source we used power supply Instec PSS-2005 with 5 A–20 V ratings. The signals from voltage taps and current shunt are measured by use of nanovoltmeter Keithley 2182A. Sensitivity of channels is 10 nV. Our measuring system and measuring method successfully passed the benchmarking organized by the IO ITER [10].

B. Helium Flow Cryostat

We used the continuous flow non-optical cryostat system from Janis Research Co., where samples can be placed into flow of cold helium vapor (Model STVP-200) [11]. Main parameters of the cryostat are presented in Table I.

C. Insert to Measure RRR

For testing, samples are mounted on the sample holder shown in Fig. 1, we use clamping contacts. The total length of each sample is about 14 cm. The samples holder allows performing measurements of eight samples at the same time. Samples are connected in series that allows using one power supply. The distance between voltage taps is 10 cm.

III. Materials and Experimental Procedure

To study RRR changes in process of the TF conductor manufacture, the strand samples were taken: (1) during the incoming inspection of bare strands as-received from the ChMP; (2) after their electrochemical cleaning; (3) after Cr-plating; and (4) during the destructive examination of the conductor after the final compaction. In addition, RRR values which were submitted by the ChMP in certificates for bare strands were also used for the analysis of RRR changes.

To study the effect of electromagnetic and thermal loads, the strands were extracted from the sample of TFRF3 conductor, which after having been heat treated with the cycle “B” was tested in the SULTAN facility [4].

TABLE II
SAMPLES DESCRIPTION

Sample	Quantity	Description	Heat Treatment
Sample-1	~ 470	Data taken from ChMP certificates on Nb_3Sn strand	500°C, 0.5 h
Sample-2	~ 16	As-received	Annealing in through-type furnace for a few min
Sample-3	~ 20	After electrochemical cleaning	NO
Sample-4	~ 20	After Cr- plating	NO
Sample-5	~ 40	After compaction of conductor	NO
Sample-6	~ 200	Supplier data of Cr-plated strand	Diffusion heat treatment of strand (Cycle "A")
Sample-7	~ 200	Supplier data of Cr-plated strand	Diffusion heat treatment of strand (Cycle "B")
Sample-8	~ 30	Strand taken from SULTAN conductor sample (Low field zone)	Diffusion heat treatment of conductor sample (Cycle "B")
Sample-9	~ 16	Strand taken from SULTAN conductor sample (High field zone, near spiral)	Diffusion heat treatment of conductor sample (Cycle "B")
Sample-10	~ 16	Strand taken from SULTAN conductor sample (High field zone, near jacket)	Diffusion heat treatment of conductor sample (Cycle "B")

To avoid damage of the samples intended for RRR measurement after testing in the SULTAN, at first, the 140–150 mm pieces corresponding to high field zone (external field 10.78 T) and low-field zone (external field 0.4 T) were cut of the conductor by using electric discharging machine (EDM).

After that the jacket was removed (also by using EDM), the cable and the sub-cables wraps were also removed and the strands were accurately separated. Descriptions of the samples studied and their amounts are listed in Table II.

After RRR measurements the histogram of RRR values for all the samples were determined.

IV. Experimental Results

A. RRR Before Diffusion Heat Treatment

According to the procedure adopted, after manufacture of the bare strands, the specimens for RRR measurements are cut of the strands and annealed in vacuum at 500 °C for 30 min. RRR of these specimens are collected in the certificates of the Nb_3Sn strands that are delivered to VNIIKP for Cr-plating and manufacture of cables and conductors. The histogram of RRR values in the certificates for the bare Nb_3Sn strands (Sample-1 in Table II) is shown in Fig. 2. The average value of RRR is about 320.

After cutting the Sample-1, all remaining strands underwent to soft annealing in through-type furnaces for several minutes at ChMP before delivery to VNIIKP. Fig. 3 shows RRR of these strands measured during the input control at VNIIKP (in as-received condition).RRR data after electrochemical cleaning and Cr-plating are shown in Fig. 3 as well. The average

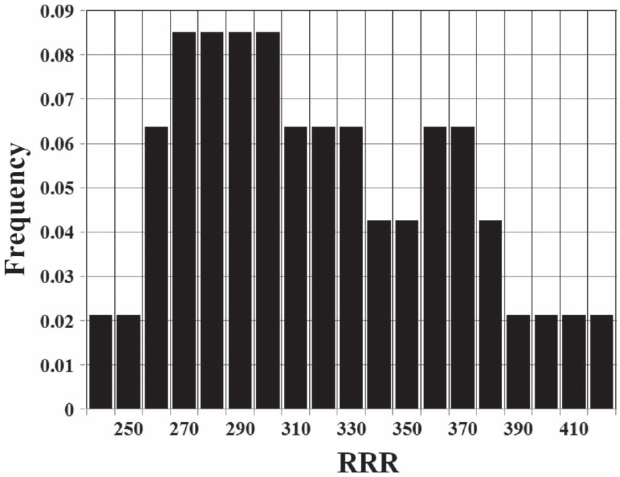

Fig. 2. The histogram of RRR values in certificates of Nb_3Sn strands **(Sample-1)**.

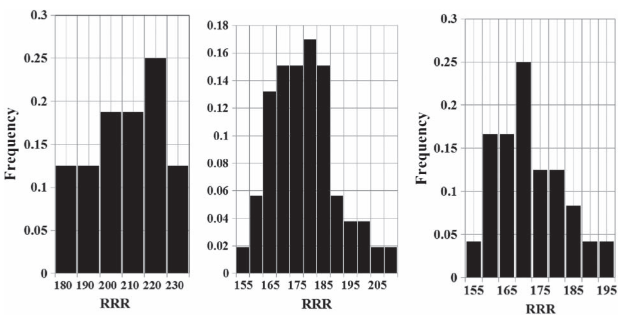

Fig. 3. The histograms of RRR values of Nb_3Sn strands before and after electrochemical cleaning and Cr-plating **(Samples-2,3,4)**.

RRR of strands as-received is 208 (Sample-2). After the electrochemical cleaning the average RRR reduces by about 30 (Sample-3), similar results were obtained in the case of NbTi strands [9]. This could be associated with the bending deformation on the guide rollers of the cleaning and Cr-plating line. After Cr-plating the average RRR of strands reduces by another 11 units (Sample-4). Nevertheless, RRR of strands, entering to the cable and conductor manufacturing, still remains well above 100 with an average value of about 170.

The next stage, in which the measurements of RRR were performed, was the Destructive Examination of the conductor sample after the final compaction. Fig. 4 presents the histogram of RRR values for strands taken from the compacted TFRF3 conductor. The average RRR value is 145, i.e., after cabling, pulling into the conductor jacket and compacting, the average value of RRR decreases by 25 units.

B. RRR After Diffusion Heat Treatment

Fig. 5 shows the distribution of RRR values for Nb_3Sn strands annealed by Cycles A and B.

The average RRR for strands annealed by Cycle B is 138 against 110 when using the Cycle A. Also, the scattering of RRR values decreases significantly to range from 120 to 160, while with the heat treatment by Cycle A RRR values ranged from 70 to 155, i.e., some strands had to be subjected to rejection due to mismatch to the requirement on RRR.

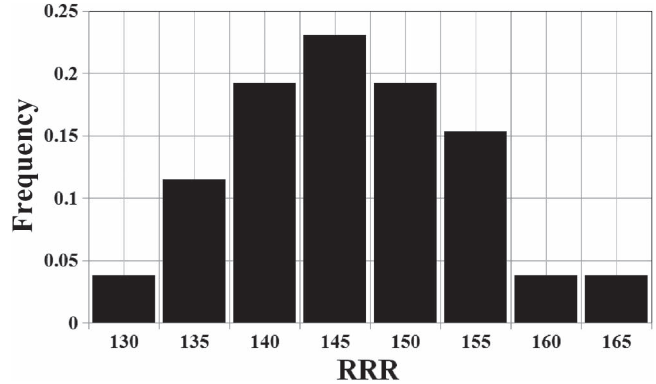

Fig. 4. The histogram of RRR values of Nb_3Sn strands taken from compacted TF conductor sample in the course of Destructive Examination **(Sample-5)**.

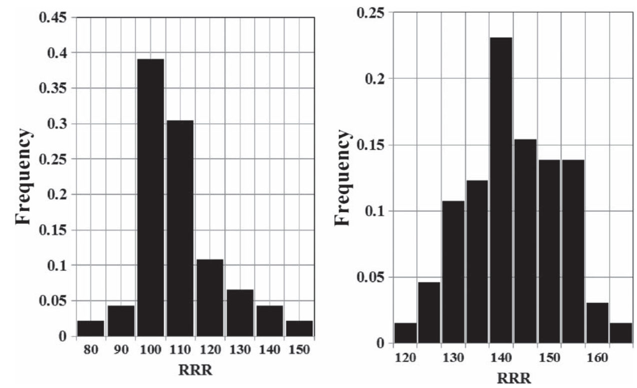

Fig. 5. The histograms of RRR values for Nb_3Sn strands heat treated by Cycle A **(Samples-6)** and Cycle B **(Samples 7)**.

C. RRR After Testing at SULTAN

For the measurements of RRR of strands taken from TFRF3 conductor sample [4] tested in the SULTAN, the strand samples were selected not only in different areas from the viewpoint of the magnetic field—high field zone (external field 10.78 T) and low-field zone (external field 0.4 T), but also from different locations in the cross section of the conductor. Particularly, the samples were taken from different petals of the cable, and for each petal—from its center, near the central cooling spiral, near the jacket (in the middle position) and in the corners of the petal from the jacket side.

Fig. 6 shows the histogram of RRR measurement results for the strands taken from the low- field zone. For the samples corresponding to the low-field zone we could not find any dependence of RRR on a position of a strand in a petal and from one petal to others. The average RRR value for strands of low-field zone is 120.

Some dependence of RRR on the position in cross section was found for strands taken from high field zone of TFRF3 conductor. Thus, under the electromagnetic and thermal loads in the SULTAN the lowest RRR was obtained for samples taken near the spiral and the conductor jacket. The results of RRR measurement for the strands from high-field zone are shown in Fig. 7. RRR of strands near the jacket is somehow higher (113) than that for strands near the spiral (102).

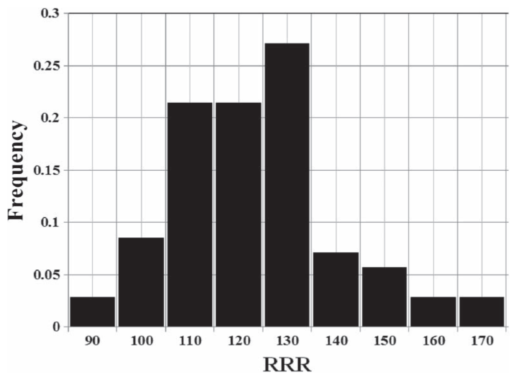

Fig. 6. The histogram of RRR values for Nb_3Sn strands taken from low field zone (**Sample-8**).

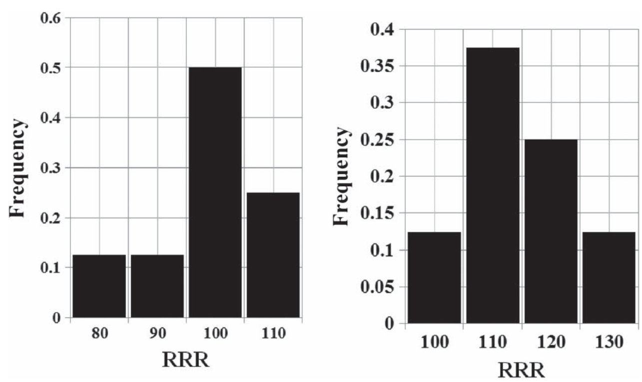

Fig. 7. The histograms of RRR values for Nb_3Sn strands taken from high field zone (**Sample-9**—near spiral, **Sample-10**—near jacket).

V. Discussion

The average values of RRR obtained at different stages of study are summarized in Table III. RRR of the bare strand (Sample-1) heat treated at 500 °C, 0.5 hour (see also Fig. 2) indicates a significant difference in RRR of initial copper. RRR of the bare strand as-received (Sample-2) reduces by 19% after electrochemical cleaning (Sample-3) and Cr-plating (Sample-4), and by another 14% during following cabling and conductor manufacture (Sample-5). Thus, since the supply of bare strands the statistical average RRR decreases by 33%, that indirectly indicates the degree of cold deformation that strands receive during the manufacture of the TF conductor. Comparison of Sample-6 and Sample-7 show that the decision to change the heat treatment to Cycle B (to reduce twice the duration of the high-temperature annealing step) beneficially impacted on RRR in Nb_3Sn strands.

Comparison of Sample-8 and (Sample-9 + Sample-10 data shows that the average RRR for strands taken from high-field zone is lower than the average RRR for strands from low-field zone, that reflects the difference between mechanical stresses arising from the electromagnetic and thermal cycling during tests at the SULTAN. The RRR of strands located near the jacket (Sample-10) is higher than that for strands taken near the spiral (Sample-9), that can reflect the difference in mechanical stresses impacted on the strands located in these areas of petals. However, the average RRR of strands is above 100 even in the areas most exposed by mechanical stresses.

TABLE III
RRR OF Nb_3Sn STRAND AT DIFFERENT STAGES OF PROCESSING

Stage	Average RRR	Std. deviation
Bare strand heat treated at 500° C, 0.5 hour (Sample-1)	320	50
Bare strand as-received for Cr-plating (Sample-2)	208	15
Bare strand after cleaning (Sample-3)	180	17
Cr-plated strand (Sample-4)	169	11
Strand taken from compacted TF conductor (Sample-5)	145	11
Cr-plated strand heat treated by Cycle A (Sample-6)	110	18
Cr-plated strand heat treated by Cycle B (Sample-7)	138	10
Strand from LFZ at SULTAN (Sample-8)	120	20
Strand from HFZ at SULTAN (Sample-9 – near spiral)	102	13
Strand from HFZ at SULTAN (Sample-10 –near jacket)	113	10

VI. Conclusion

The evaluation of changes in RRR of Nb_3Sn strands during manufacture and testing of the ITER TF conductor have been performed on the basis of a representative number of samples.

It has been found that the statistical average RRR degradation by 33% takes place during Cr-plating and the production of TF conductor.

Then, the advantage of Cycle B heat treatment from the strands RRR point of view has been confirmed statistically.

The impacts of strand position in the conductor cross section and the conductor position during testing at the SULTAN (low-field zone or high-field zone) on RRR degradation have been revealed statistically. Nevertheless, the average RRR of strands extracted from SULTAN sample is above 100, even in the areas most exposed by mechanical stresses.

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