NbTi Strands Verification for ITER PF CICC Process Qualification of CNDA

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Abstract. China is in charge of most of Poloidal Field (PF) conductors production for the International Thermonuclear Experimental Reactor (ITER). The execution for PF conductors shall be in three main phases. According to ITER Procurement Arrangement (PA), the Domestic Agency (DA) shall be required to verify the room and low temperature acceptance tests carried out by the strand suppliers. As the reference laboratory of Chinese DA (CNDA), the superconducting strands test laboratory of Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) was undertaking the task of strands verification for ITER conductors. The verification test includes: diameter, Nickel plating thickness, copper-to-non-copper volume ratio, twist pitch direction and length, standard critical current (I_C) and resistive transition index (n), residual resistance ration (RRR), and hysteresis loss. 48 NbTi strands with 7 billets were supplied for the PF Cable-In-Conduit Conductor (CICC) process qualification. In total, 54 samples were measured. The verification level for PF CICC process qualification was 100%. The test method, facility and results of each item are described in detail in this publication.

1. Introduction

The CICCs for the ITER PF Coils uses twisted, multifilament, Nickel-plated, NbTi based composite strands [1, 2]. China is in charge of most of the ITER PF conductors, including all the Unit Lengths (ULs) for PF2 through PF5. According to ITER PA, the execution for PF conductors shall be in three main phases: phase 1: call for tender, phase 2: supplier disclosure and process qualification and phase 3: production of all conductor ULs. In addition to Cu dummies, process qualification calls for the manufacturing of NbTi conductor qualification lengths.

At the start of process qualification, DA is required to conduct a benchmarking of the room and low temperature acceptance tests. As the reference laboratory of CNDA, ASIPP is undertaking the task of superconducting strands verification for ITER conductors, which has successfully passed the world-wide benchmarking for NbTi strands [3, 4].The verification for the room and low temperature acceptance tests carried out by the strand suppliers is being organized. All the strands used for PF CICC process qualification have been verified. The test method, facility and results of each item are described in this paper.

2. Samples and sample preparation

This work was partially supported by the Equipment Function Developing and Technical Innovation project of the Chinese Academy of Sciences under Grant Y25ZB13291.

For the PF CICC process qualification of CNDA, 2 ULs were required to manufacture, include 1 UL with 425m for PF2-4 and 1 UL with 100 m for PF5. 48 NbTi strands with 7 billets were used. All the strands were fabricated and supplied by the Western Superconducting Technology Co. Ltd (WST). And all the strands are the same type. A micrograph of the transverse cross-section of the WST NbTi strand is shown in figure 1.

The sampling requirements for the strands suppliers are detailed in Table 1. The strand supplier shall ensure that all acceptance tests are carried out at the proper frequency and with the proper procedures and shall compare the test results with the acceptance criteria. According to the test requirements of CNDA, the verification level for each test item was 100%.

The maximum field considering the Lorenz force direction calculated with a 2-D model was around 0.146T when the applied current was 306A for the I_C test barrel we used. The *RRR* testing sample was cut from the straight strand. The hysteresis loss sample shape was a spiral with ~ 5 mm inner diameter and ~1 mm pitch. At least six turns (~100 mm) were required. The strand was wound on a bolt. A section of the spiral was cut and used as hysteresis loss specimen after fixing on the bolt for at least 2 days. A few parameters were required to be measured at room temperature.

Table 1. Acceptance requirements for Nickel-plated, NbTi-based strands.

Verification item	Sampling
Strand diameter	every piece length and over entire length
Twist pitch and twist direction	at minimum: point or tail of every piece length
Ni plating thickness	at minimum: start and end of every Cr plating process
Cu/non-Cu Ratio	at minimum: point and tail of every billet
RRR	at minimum: point and tail of every billet
I_C and *n*	phase 2: point and tail of every billet plus one sample per breakage
Hysteresis loss	every billet

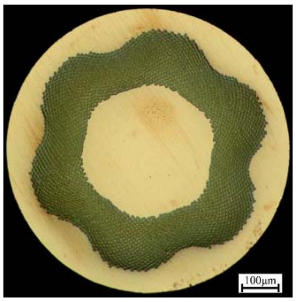

Figure 1. Transverse cross-section micrograph of the NbTi strand used for ITER PF2-5 conductor.

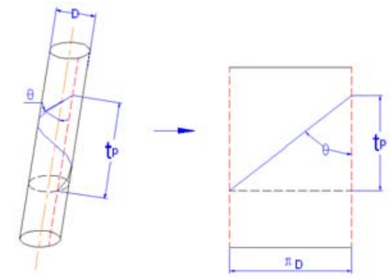

Figure 2. Schematic diagram of twist pitch measurements

3. Experimental methods and test facility

3.1. Room temperature Tests

The room temperature tests include: diameter, Nickel plating thickness, copper-to-non-copper volume ratio, twist pitch direction and length.

Diameters of strands were measured by micrometer, which has been calibrated with the accuracy 0.001mm.

Plating thickness was measured by metallographic techniques. For each cross section, the thickness of the Ni layer was measured with the scanning electron microscope (SEM) at six locations, at 60° each, with an accuracy better than 0.1μm.

The copper-to-non-copper volume ratio *Rcu-ncu* was measured by chemical etching and weighting, and calculated by equation 1.

$$R_{cu-ncu} = V_1/V_2$$
$$V_1 = (D/2)^2 \times \pi \times L \quad (1)$$
$$V_2 = (W_1 - W_2)/\rho_{Cu}$$

where, L, V and W were the sample length, volume and weight, respectively. The subscript 1 and 2 expressed the sample before and after etching, respectively. D was the diameter of the strand while ρ_{Cu} was the density of Copper which was designated to be 8.93g/cm^3.

Twist pitch measurement was by chemically etching away the stabilizing Cu with the two ends of samples fixed before etching. The photos were getting by SEM. The twisting angle θ was gotten by the image editing software based on the SEM photos. The schematic diagram was shown in figure 2.

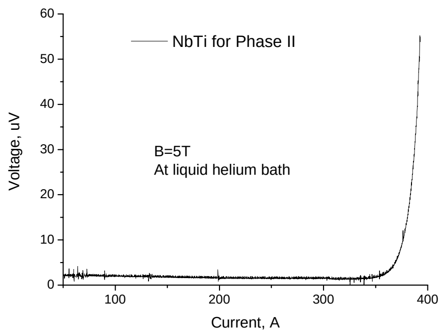

Figure 3. *V-I* curve of one NbTi sample with voltage tap length 50cm.

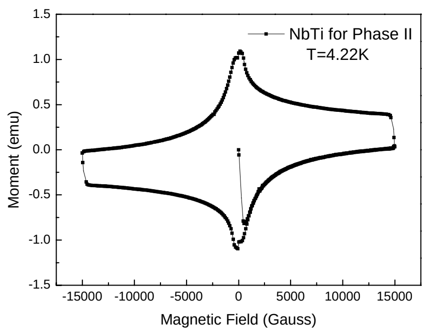

Figure 4. Magnetization curve of one NbTi sample

3.2. Ic, n

For NbTi strand, I_C measurements were required at 5.0 T and 4.22K. The electric field criterion we used was 0.1uV/cm. A voltage-current (*V-I*) curve of one NbTi sample with voltage tap length 50cm was shown in figure 3.

The samples were measured at liquid helium. For liquid helium, when the vapor pressure is around 101.325kPa (1atm), the temperature/pressure relation can be approximated with a linear function [5].

ITER Organization (IO) applied temperature correction using equation 2 [6], since temperature accuracy is important in the *B-T* range concerned.

$$\frac{I_c}{I_m} = \frac{T_c(B) - 4.22}{T_c(B) - T_m} \quad (2)$$

where $T_c(B)$ is the critical temperature at the specified magnetic field

$$T_c(B) = 9.2 \times (1 - \frac{B}{14.5})^{0.59} \quad (3)$$

3.3. RRR

RRR sample is mounted on a thermal substrate. The *RRR* of the composite wire was obtained in equation 4 below, where the resistance at 273K (R_{273K}) was divided by the resistance at specified temperature (R_L).

$$RRR = \frac{R_{273k}}{R_L} \quad (4)$$

RRR for NbTi strands, whose T_C at zero field is approximately 9 K, is defined as the ratio of resistance at 273 K to 10 K. The temperature accuracy at 10 K was less critical, albeit important, than it was at 20 K, because the copper resistivity dependency on temperature was much smaller at 10 K.

3.4. Hysteresis loss

The hysteresis losses were measured by VSM in Ningbo Institute of Material Technology & Engineering Chinese Academy of Sciences (IMTE).

For NbTi strand, the field range requested was ±1.5 T at 4.2 K. The field ramp rate was 50Gs/s. The integration of the magnetization loop was performed and no smoothing of the curves was applied. The magnetization curve of one NbTi sample for PF CICC process qualification was shown in figure 4.The hysteresis loss density Q_{hyst} may be given by the area under the magnetization curve.

4. Test results and conclusions

The verification results of NbTi strands for PF conductors process qualification are summarized in Table 2.

Table 2 Summary of verification results for the NbTi strands with 7 billets

	PA requirement	Mean	Max	Min	σ_s
Diameter, mm	0.73±0.005	0.731	0.733	0.730	0.0006
Twist Pitch, mm Cu/	15±2	14.66	15.22	14.01	0.309
non-Cu Ratio Plating	2.35±0.1	2.316	2.405	2.265	0.0394
thickness, µm	2+0-1	1.5	2.0	1.1	0.22
Ic(5T,4.22K), A	⩾339	366.6	379.6	356.2	5.83
n(5T,4.22K)	⩾20	43.4	51.6	36.2	3.76
Hysteresis Loss ,mJ/	<45	40.5	42.2	39.3	0.97
cc RRR	>100	157.8	162.0	150.1	3.36

As shown in Table 2, the average diameter after plating of all the NbTi strands which have been supplied is 0.731mm with standard deviation (σ_s) of 0.0001mm. And the difference between maximum and minimum (Δ) is 0.003mm. The average plating thickness is 1.5µm with σ_s of 0.22µm and Δ of 0.9µm. The average Copper to non-Copper ratio is 2.316 with σ_s of 0.0394 and Δ of 0.140. And the average twist pitch is 14.66mm with σ_s of 0.309 mm and Δ of 1.21mm.

The average I_C and n value of all the NbTi strands are 366.6A with σ_s of 5.83A and 43.4 with σ_s of 3.76. The difference between maximum and minimum (Δ) of I_C is 23.4A while Δ of n is 15.4.

The average hysteresis loss is 40.5mJ/cc with σ_s of 0.97mJ/cc and Δ of 2.9mJ/cc.

The average *RRR* of all the NbTi strands is 157.8 with σ_s of 3.36 and Δ of 11.9.

All the data for the strands fit well the requirements for ITER PA. From the feedback from CNDA, most of the results of the strands verification for process qualification showed high agreement with the data from the strand supplier except the twist pitch. The twist pitch verification results showed systematic shift to higher values. That may be caused by the systematic error for the twist pitch method for NbTi strands. A new method was used and verified, and better results were obtained in phase 3.

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