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Development of Advanced Superconducting Coil Technologies for the National Centralized Tokamak

K. Kizu [1], Y.M. Miura [1], K. Tsuchiya [1], T. Ando [2], N. Koizumi [1], K. Matsui [1], A. Sakasai [1], H. Tamai [1], M. Matsukawa [1], S. Ishida [1], K. Okuno [1]

[1] Japan Atomic Energy Research Institute, Naka Fusion Research Establishment, Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken, 311-0193 Japan
E-mail:kizuka@fusion.naka.jaeri.go.jp

[2] Nippon Advanced Technology, 812-43 Funaishikawa, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1111 Japan

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K. Kizu 1), Y.M. Miura 1), K. Tsuchiya 1), T. Ando 2), N. Koizumi 1), K. Matsui 1), A. Sakasai 1), H. Tamai 1), M. Matsukawa 1), S. Ishida 1), K. Okuno 1)

1) Japan Atomic Energy Research Institute, Ibaraki-ken, Japan
2) Nippon Advanced Technology, Ibaraki-ken, Japan

e-mail contact of main author: kizuka@fusion.naka.jaeri.go.jp

Abstract. Advanced technologies for fabrication of superconducting coils have been developed for the National Centralized Tokamak which is based on modification of JT-60. One of the developed technologies is the application of the react-and-wind (R&W) method to fabrication of a Nb_3Al D-shaped coil. The bending strain of 0.4% due to the R&W method did not affect the critical current characteristics. This finding indicates the possibilities that manufacturing cost of large size coils can be reduced further by downsizing the heat treatment furnace, and complicated shape coils can be manufactured by using the Nb_3Al conductor. Another technology is an advanced winding technique for the reduction of the AC losses of a Nb_3Sn coil by loading bending strain on the conductor. It was found that 0.2% bending strain is enough to reduce the AC losses to one fifth at the virgin state. Newly developed NbTi conductor attained the low AC loss of 116 ms in coupling time constant and low cost owing to the stainless steel wrap of the sub-cables and Ni plated NbTi strands with 11μm filaments.

1. Introduction

Modification of JT-60 is planned as a full superconducting coil tokamak referred as National Centralized Tokamak (NCT) [1]. Previous design of JT-60 superconducting tokamak [2] was extended to attain the wide operation regime for high beta steady-state research. The superconducting coil system is composed of toroidal field (TF) coils, central solenoid (CS) and equilibrium field (EF) coils. The device size of NCT is limited by present JT-60 facilities such as NBI units. Therefore, in order to attain compact coils with high current density, developments of Nb_3Al, Nb_3Sn and NbTi strand with higher Cu/non-Cu ratio than ITER have been required.

A Nb_3Al cable-in-conduit (CIC) conductor is a promising conductor for TF coils, because of its low strain sensitivity on superconducting performance. The critical current (I_c) decrease of Nb_3Al by strain is smaller than that of Nb_3Sn. There is a possibility that the TF coil is fabricated by a react-and-wind (R&W) method [3]. In the R&W method, the winding is carried out after heat treatment. The required furnace size is smaller than that of a wind-and-react (W&R) method which needs the furnace with coil size. This indicates that the total heat reaction cost becomes lower than that of the W&R method.

A Nb_3Sn CIC conductor was designed for CS and divertor coil, because these coils undergo relatively high magnetic fields of 7.4 T and operate in pulse mode. Reduction of AC losses for this conductor is one of the key issues. For Nb_3Sn strands, it has been verified that the Cr plating is effective in reducing inter-strand coupling loss. However, it was reported that the inter-strand coupling loss is very large immediately after heat treatment (virgin state) [4]. It may be attributed to sintering of strands with Cr plating during the heat treatment that decreases an inter-strand resistance. Therefore, an advanced winding technique for the reduction of the AC losses of a Nb_3Sn coil was developed.

For EF coils, a NbTi CIC conductor was selected because these coils experience relatively low field of 5 T. Since the EF coils suffer rapid field change up to +2.7 T/s, reduction of AC losses is one of the important issues. From this viewpoint, three approaches were adopted. The first was selection of Ni for the strand plating material that realizes acceptable coupling loss and cost reduction, and the second was the development of the strand with fine filaments for reduction of hysteresis loss and the third was the adoption of the cable composed of 6 sub-cables separated by stainless steel (SS) tape to reduce the coupling current among the sub-cables.

In this paper, the experimental results of Nb_3Al D-shaped coil made by R&W method, the AC loss reduction method of Nb_3Sn coil and the AC loss measurements of newly developed NbTi full size conductor are described.

2. Nb_3Al Conductor for Toroidal Field Coil and D-shaped Coil

The operational current and the maximum magnetic field and operational temperature of TF coil are 19.4 kA, 7.4 T and 4.6 K, respectively. The Nb_3Al conductor for TF coil consists of 216 Nb_3Al strands and 108 copper wires inserted into the circular hole of a rectangular stainless steel conduit. In order to withstand the large electromagnetic force acting on the superconductors in the TF coil, a CIC conductor cooled by forced flow (supercritical helium) was designed. The photograph of the developed Nb_3Al conductor is shown in *FIG. 1*. Nb_3Al strand produced by jellyroll process was 0.74 mm in diameter with a high Cu/non-Cu ratio of 4.05 made by Hitachi Cable. Table I shows the major design parameters of the Nb_3Al strand and conductor.

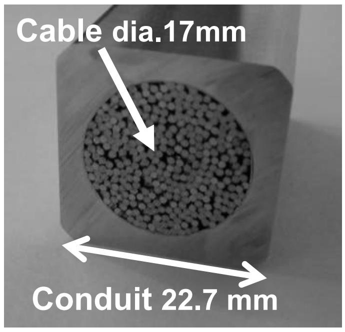


FIG. 1. 20-kA Nb_3Al cable-in-conduit conductor for TF coil.

TABLE I: MAJOR PARAMETERS OF Nb_3Al CIC CONDUCTOR

Strand	
Diameter	0.74 mm
Thickness of Cr plating	2 μm
Cu/non-Cu ratio	4.0
Conductor	
Outer size of conduit	22.7 × 22.7 mm
Cable diameter	17 mm
Number of Nb_3Al strands	216
Number of Cu wires	108
Cabling pattern	3×3×3×3×4=324
Conduit material	SS316LN
Void fraction	~36 %

In order to demonstrate the R&W method, a D-shaped coil with Nb_3Al conductor was developed as shown in *FIG. 2* [5]. The D-shaped coil was fabricated by winding the CIC conductor of 13.3 m into a two-turn coil. For the heat treatment, the CIC conductor was formed into a circular shape with a bending radius of 2125 mm. The heat treatment temperature was 750 ºC for 50 hours. After the heat treatment, bending was applied. The bending radius in the I_c test section was 1062.5 mm. The bending strain was defined from the Nb_3Al cable radius divided by the winding radius. The bending strain defined from the shape is 0.4% at I_c test section that was equivalent to the maximum bending strain of the actual TF coil. However, it underwent the bending strain up to 0.6% transiently due to over bending.

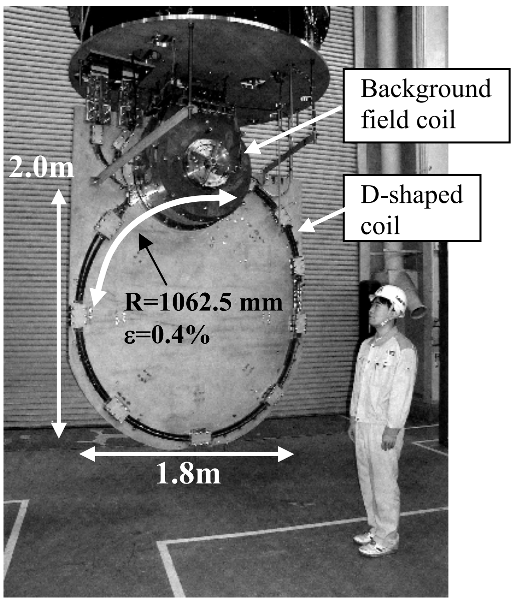


FIG. 2. D-shaped coil fabricated by R&W method.

The D-shaped coil was installed in a superconducting split coil system which consists of two pairs of co-axial coils which can generate a magnetic field of up to 12 T in the I_c test section. The D-shaped coil was cooled by pool cooling together with split coil system. The critical currents were measured by applying magnetic fields of 6.5-12 T to the test section. I_c measurements were carried out with both normal operation and reverse operation modes. These current transportation directions were opposite each other under the fixed external magnetic field direction. The I_c was defined from the voltage-current curve using an electric field criterion of 0.1 μV/cm. *FIG. 3* shows I_c measurement results as a function of maximum magnetic field including the conductor's self field. The points of I_c showed almost same values for the normal operation (black circles) and reverse operation modes (white circles). The I_c attained 31.4 kA at 7.3 T, 4.2 K which is almost 89% of strand I_c times number of strands in cables of 216. The low strain sensitivity of Nb_3Al was realized again through the actual coil fabrication method.

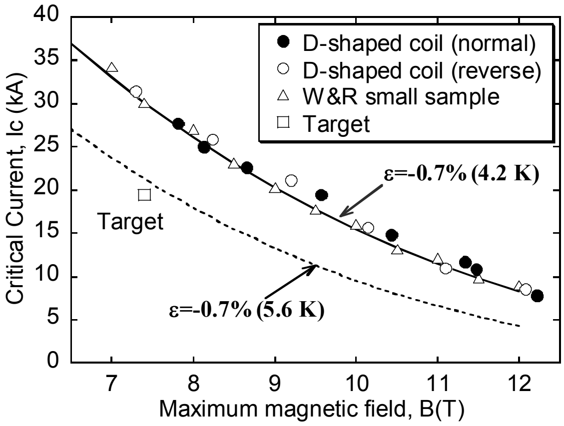


FIG. 3. Magnetic field dependence of I_c for D-shaped coil.

In comparison, I_c of a "W&R small sample" which is CIC conductor sample made by W&R method is also shown in *FIG. 3* as white triangles. The thermal strain of W&R small sample was estimated to be –0.7 % by the empirical equation [6] and I_c of strand. The I_c values of the D-shaped coil agreed with that of W&R small sample. This means that the effective strain (ε_{eff}) of the D-shaped coil was also about -0.7%. It seems that bending did not influence the I_c in spite of the bending after heat treatment by R&W method.

To guarantee a 1 K margin, I_c has to be larger than operational current of 19.4 kA even at 5.6 K which is sum of 4.6 K in operational temperature and 1 K. Using the empirical equation, the magnetic field dependence of I_c at 5.6 K was calculated and is shown as a dotted line in *FIG. 3*. It was found that the I_c at 5.6 K became larger than the target value shown as white square [7].This result indicates that the R&W method are quite appropriate for the TF coil fabrication of NCT.

In the case of the D-shaped coil, the cable suffers the compressive strain due to the thermal strain (ε_{th}) caused by the different thermal expansion coefficient between the cable and SS conduit. The cable also suffers the bending strain (ε_b) caused by bending of the conductor after the heat treatment. In order to investigate the distribution of the ε_b to the ε_{eff} of -0.7%, the effect of ε_b on the I_c performance was calculated. On the calculation, the cross-section of the cable was divided into 81 meshes. Generated voltages of each mesh were calculated by the magnetic field and strain at them. I_c was obtained from the current value when average voltage of conductor reaches 0.1 μV/cm. Thirty was used as n-index from the I_c result of strand. Thermal strain of Nb_3Al strand from Cu matrix was assumed to be -0.05% [8].

Results of three representative cases such as (I) ε_{th}=-0.7%, ε_b=±0%, (II) ε_{th}=-0.7%, ε_b=±0.4%, (III) ε_{th}=-0.3%, ε_b=±0.4% are shown in *FIG. 4*

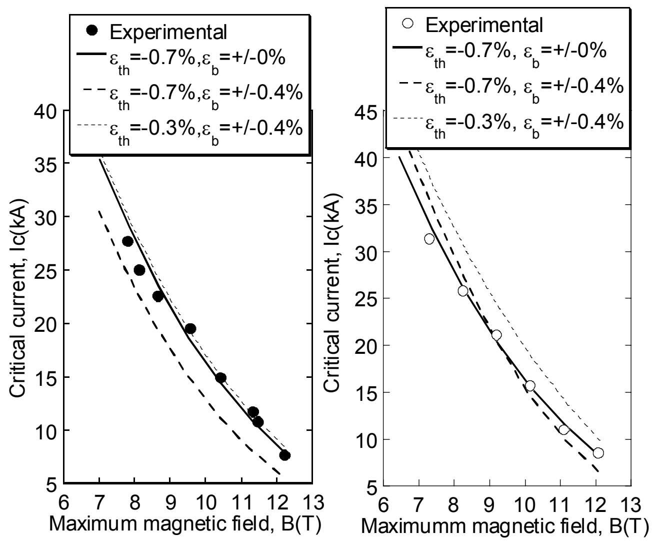


FIG. 4. The comparison between calculated and the experimental I_c for (a) normal and (b) reverse current mode.

[9]. Case I means that the bending does not affect the I_c. Case II and III mean that the cable is fully bonded to each other indicating that the bending strain (ε_b) in the cable at the I_c test section is distributed from -0.4 to 0.4%. The magnetic field distribution is different between normal and reverse transport currents due to self-field of the conductor. The maximum magnetic field within the cable is located in the maximum strain in the case of the normal current mode, and the maximum magnetic field is in the minimum strain in the case of the reverse current mode. Therefore, the different behavior was expected by current direction for the ε_b dependence on I_c. However, the experimental I_c almost agreed with the I_c calculation curve in the case of the ε_b of 0. Thus, it was concluded that ε_{th} is -0.7% and the ε_b is 0%.

These results indicates that some relaxation of the bending strain in the strands can be expected due to cabling effect making strands in the cable slip each other during the bending work. There is great possibility that complicated shape coils can be manufactured by Nb_3Al conductor using the R&W method. In order to confirm this idea, experiments for measuring the bending dependence of I_c of Nb_3Al conductor is planning now.

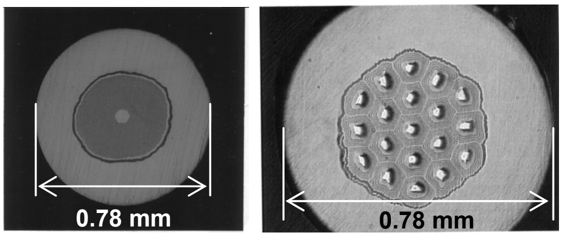
3. Nb_3Sn Conductor for Central Solenoid and Divertor Coil

The Nb_3Sn conductor for CS and divertor coil experience the maximum magnetic field of 7.4 T and changing field rate up to 2.2 T/s during pulse operation. Operating current and temperature are 20 kA and 5.0 K, respectively. This conductor has a square conduit with a circular hole, and conduit material is SS316LN. The conductor has 216 superconducting strands and 108 copper wires with a diameter of 0.78 mm. The conductor design parameters are summarized in Table II. The Cu/non-Cu ratio of the strand is relatively high (2.3) to ensure the high stability margin. Cr with 2µm in thickness was employed for the strands plating. Two types of the strands were successfully manufactured. One was made by bronze process, and the other was made by internal-tin process. The suppliers were Furukawa Electric and Mitsubishi Electric, respectively. Critical current density (J_c) at 4.2 K, 12 T and hysteresis loss of ±3 T of bronze type were 610 A/mm^2 and 224 mJ/cm^3, respectively. On the other hand, critical current density and hysteresis loss of ±3 T of internal-tin type were 655 A/mm^2 and 132 mJ/cm^3, respectively. The cross sectional views of these strands are shown in *FIG. 5*.

Reduction of AC loss is one of the key issues because CS and divertor coil will operate in pulse mode to maintain the plasma current and control the plasma position and shape. The coupling time constants ($n\tau$) of this conductor was designed to be 50 ms to

TABLE II: MAJOR PARAMETERS OF Nb_3Sn CIC CONDUCTOR

Strand	
Diameter	0.78 mm
Thickness of Cr plating	2 µm
Cu/non-Cu ratio	2.3
Conductor	
Outer size of conduit	25.1 × 25.1 mm
Cable diameter	18.1 mm
Number of Nb_3Al strands	216
Number of Cu wires	108
Cabling pattern	3×3×3×3×4=324
Conduit material	SS316L
Void fraction	~36 %



(a) bronze type (b) Internal-tin type

FIG. 5. Cross-sections of two types of the Nb_3Sn strands.

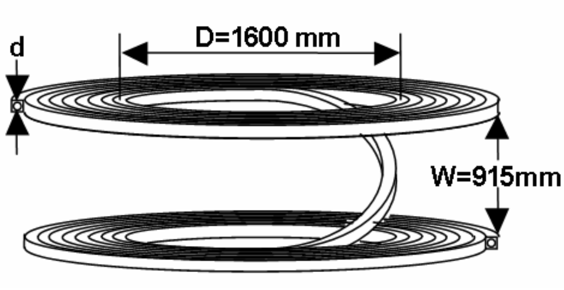


FIG. 6. Technique to apply the strain of 0.2 % to the cable.

realize moderate AC losses. However, because the Nb_3Sn coils are manufactured by the W&R method, in a virgin state after the heat treatment, the conductor tends to generate large AC losses. In the case of CSMC, 250 ms of coupling time constant was initially observed [4]. This phenomenon is probably attributing to the lower inter-strands resistance by sintering of Cr plating among strands due to the heat treatment at high temperature (650°C-240 hours). In order to reduce the AC losses, a novel technique of winding coils was proposed; namely, in the insulation work of the conductor after the heat treatment as shown in *FIG. 6* [10]. The strain was purposely loaded on the conductor to break the sintered parts of the Cr plating. By widely separating the double pancake coil heat treated for the insulation work, the conductor which crosses between the pancakes suffers some strain. The strain (ε_t) is written by

$$\varepsilon_t = \frac{Wd}{\pi D^2}, \qquad (1)$$

where W, D, d are the distance between the pancakes, the diameter of pancake and the diameter of the cable, respectively.

TABLE III: CONDUCTORS DATA (FULL-SIZE SAMPLE)

	Bronze type	Internal-tin type
Cable pitches	31/61/120/ 164/245 mm	60/90/120/ 145/175 mm
Void fraction	36.2%	36.5%
Conduit material	SS304	SS304
Conduit outer diameter	22.0 mm	23.3 mm
Hole diameter	18.1 mm	18.0 mm

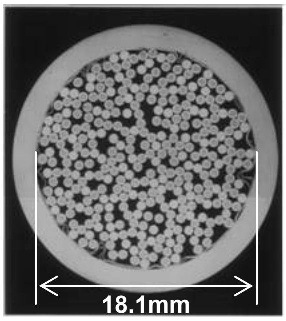


FIG. 7. Cross section of the full-size sample.

In order to demonstrate this technique, AC loss measurements of conductor loaded strain were performed [11]. Two types of Nb_3Sn conductor with full-size were fabricated. One was made by bronze process and the other was made by internal-tin process. The cabling pitch of internal-tin type sample was different from that of bronze type one, to investigate the effect of difference of cabling pitches on the reduction of AC losses. The major parameters of the developed conductors are summarized in Table III, and the cross sectional view of the sample is shown in *FIG.7*. In order to make it easy to manufacture the samples, each sample had a circular conduit with a circular hole unlike the design which is square conduit with a circular hole as Nb_3Al conductor. The length of samples was 740 mm. The thickness of Cr plating was 2 μm. Heat treatment was carried out under the condition of 650°C for 240 hr.

The strain was applied on the sample conductor by a bending. The sample was loaded with 0.1%, 0.2% and 0.3% bending strain which was defined from the Nb_3Sn cable radius divided by the curvature radius of bending. Each load was applied once on the sample in the same direction. After each loading, the sample was released from a bender and spring back of the sample was observed. AC losses of the sample were measured by calorimetric technique in a pulsed dipole. The magnetic field variation in time applied on the samples was trapezoidal wave with amplitudes of 0.5, 0.7, 1.0 T and ramp up/down rate of 0.014~1.73 T/s. The correlation between applied bending strain and the $n\tau$ of bronze process and internal-tin process samples are shown in *FIG. 8*. As expected, both samples initially showed large $n\tau$ of about 330 ms like the ITER CSMC. For the case of bronze process, the $n\tau$ dropped remarkably from 330 ms to 60 ms with bending strain, and it seems

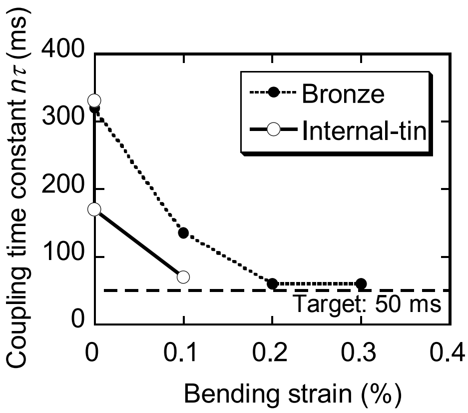


FIG. 8. Reduction effect on AC losses of Nb_3Sn conductor samples by applying bending strain.

to be saturated after 0.2% bending. On the other hand, the $n\tau$ of internal-tin process decreased from 330 ms to 170 ms during measurement although the bending strain had not been applied yet. Finally, it is found that the bending strain of 0.1% was enough to reduce $n\tau$ to acceptable level of 70 ms.

From these results, it was conclude that this technique is sufficiently effective. The effect is irrespective of cabling pitches of conductors. It was found that 0.2% bending strain is enough to reduce the AC losses to one fifth at the virgin state. The bending strain of 0.2% is sufficiently small to reproduce the superconducting performance of the strand [12]. Using this technique, low AC loss coils will be realized from the beginning of operation.

4. NbTi Conductor for Equilibrium Field Coils

The NbTi CIC conductor for EF coils experience 5.0 T. Its nominal current is 20 kA at operating temperature of 4.8 K. EF coils will suffer rapid field change up to +2.7 T/s. Since reduction of AC losses is one of the important issues, the $n\tau$ of EF conductor was designed to be 100 ms. In previous work [5], a CIC conductor with Cr plated NbTi strands was developed. This conductor successfully showed the $n\tau$ of 32 ms. However, cost of Cr plating of NbTi strand is relatively high, since NbTi strand is cheaper than Nb_3Sn and Nb_3Al strands. Cr plating cost occupied from 25 to 40% of NbTi strand cost. Therefore, in previous work [5], in order to study how plating material effects on coupling loss of the conductor, three short CIC conductor samples of which strands were plated with different materials: Cr, Ni, and SnAg with oxidation were developed. Ni plating has moderate resistivity and is expected to reduce the plating cost to be less than one fifth of Cr. However, the $n\tau$ of Ni plating sample was 140 ms which is rather large comparing with the design value of 100 ms. Therefore, in order to attain both low AC loss and low cost conductor, a new NbTi conductor was designed and developed.

TABLE IV: MAJOR PARAMETERS OF NbTi CIC CONDUCTOR

Strand	
Diameter	0.70 mm
Thickness of plating	2 μm
Cu/non-Cu ratio	7.0
Conductor	
Outer size of conduit	25.0 × 25.0 mm
Cable size	19.0 × 19.0 mm
Number of NbTi strands	486
Central spiral OD, ID	6 mm, 5 mm
Number of Cu wires	0
Cabling pattern	3×3×3×3×6=486
Conduit material	SS316L
Void fraction	~36 %

The features of this conductor are (i) NbTi strand with fine filaments for reduction of hysteresis loss, (ii) Ni plating strand for acceptable coupling loss and cost reduction and (iii) sub-cables separated by stainless steel tape to reduce the coupling current among the sub-cables. The conductor was designed as a CIC type with a roll-formed square stainless steel conduit. The EF conductor has 486 superconducting strands with a diameter of 0.70 mm, and the strand has high Cu/non-Cu ratio of 7.0 for high thermal stability. Since a central cooling spiral was adopted to reduce pressure drop of coolant (supercritical helium), conductor with long cooling paths could be designed. The unit conductor length of the longest coil is 1146 m in current EF coil design. Coil winding design could also be changed from two-in-hand conductor to one-in-hand conductor with double pancake configuration. Thus, number of joints between pancakes was reduced to half of previous design. Six

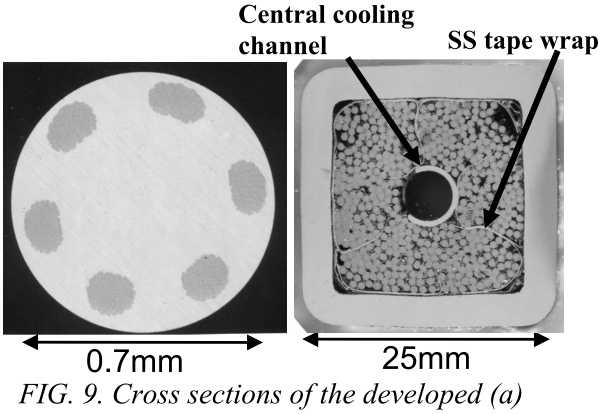


FIG. 9. Cross sections of the developed (a) strand and (b) conductor.

petals are arranged around the spiral. AC losses are controlled by the SS tape wrap on each petal to reduce the coupling current among the petals. Major parameters of the conductor are given in Table IV.

In order to reduce hysteresis losses of the conductor, the strand having fine filaments with a diameter of 11 μm and high Cu/non-Cu ratio of 6.9 was newly developed [13]. The critical current density and n-index at 5 T, 4.2 K are 2973 A/mm^2 and 38, respectively. There are no CuNi internal barriers in the strand that might decrease thermal stability. The strand having a length of 44 km was successfully drawn without breakage. The feasibility of cabling of the 486 strands together with SS tape wraps and the central cooling channel was demonstrated in a trial manufacture of a 28 m length full-size cable. The cross sections of the manufactured strand and conductor are shown in *FIG. 9*. The filament diameter estimated from geometric arrangement before drawing was 11 μm. On the other hand, the effective diameter evaluated from hysteresis loss measurement was 13 μm. Deformation of cross sections of filaments through drawing process of strand is considered as the cause of this degradation. Such filament deformation was actually observed by Scanning Electron Microscope. Cross sections of a large number of filaments were deformed from circle to oval whose aspect ratio is typically about 2.

TABLE V. FULL-SIZE SAMPLE OF NbTi CONDUCTOR FOR AC LOSS MEASUREMENT

Conduit type	square in square
Cable size (mm)	18.9 x 19.0
Void fraction (%)	~ 41
Length of sample (mm)	750
Twisted pitches (mm)	1st 61 2nd 89 3rd 150 4th 265 5th 425
SS tape wrap, thickness (opening gap ratio)	4th stage, 0.1 mm, (46%)

Applying of Ni plate with 2 μm in thickness to the developed NbTi stand, a full-size short sample of the CIC conductor was manufactured. The parameters of this sample are shown in Table V. The conduit type of the sample is "square in square" as shown in *FIG. 9*. Six petals are formed by 6 sub-cables separated by SS tape wraps (0.1 mm thickness) with opening gap ratio of 46%. The magnetic fields of trapezoidal wave with amplitudes of 0.5, 1.0, 1.5 T and ramp up/down rates of 0.043~1.56 T/s were applied on the samples. The results of coupling loss measurement are shown in *FIG. 10* and the measured $n\tau$ was 116 ms.

The final twisted pitch of this sample was 425 mm which was longer than that of sample in previous work (250 mm) [5]. However, measured coupling time constant successfully decreased from 140 ms to 116 ms. In order to investigate this reason, conductances between strands in the same petal and between strands in different petals of the CIC sample were measured. The conductances were 3.7×10^6 S/m and 2.5×10^6 S/m, respectively. These were from 1/3 to 1/4 smaller than the sample of previous work that is probably the effect of SS tape wraps. In general, the coupling loss (P) is proportional to the squares of twisted pitch (L_s) and is proportional to the conductance (σ) as following equation.

$$P \propto (L_s)^2 \sigma . \qquad (2)$$

The expectation value of $n\tau$ of sample of this work derived from the $n\tau$ of previous work sample was estimated by using eq (2) as follows.

140 (ms) × (425/250)^2 × (1/3~1/4) = 135~101(ms) ≈118 (ms).

This value close to the measured $n\tau$ of this work sample (116 ms) indicating that the decrease of $n\tau$ attribute to the SS tape wraps and that the eq. (2) can use for designing new conductor. Therefore,

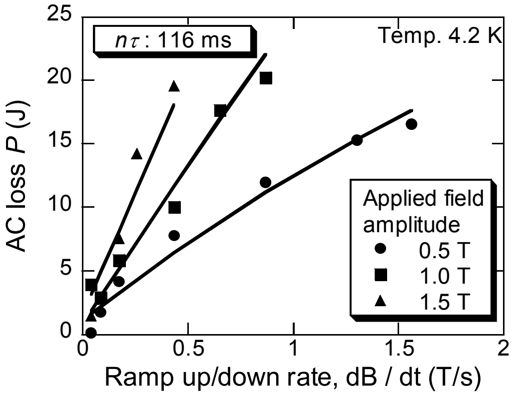


FIG. 10. AC losses of the full-size EF conductor sample.

the target $n\tau$ of 100 ms will be achieved by slight shortening of the last stage twisted pitches from 425 to 394 mm.

5. Conclusions

In order to demonstrate the R&W method, the I_c measurements of Nb_3Al D-shaped coil was performed and the following results were obtained. (i) The I_c attained 31.4 kA at 7.3 T, 4.2 K indicating that the J_c is 89% of strand J_c. Low strain sensitivity of Nb_3Al was confirmed. (ii) The I_c comparison with W&R sample and numerical calculation showed that the effective strain of Nb_3Al conductor was only thermal strain from the SS conduit. The effect of 0.4% in bending strain on I_c was not observed. (iii) The conductor will satisfy the design requirements under the actual TF operational condition.

AC losses of the full-size CS and divertor coil conductor samples of the Nb_3Sn were carried out. Applying of 0.2% bending strain on the Cr plated Nb_3Sn conductor reduced the coupling time constant from 330 to 60 ms. The proposed winding method will be useful for the reduction of AC loss from initial operation.

The Ni plated NbTi CIC conductor was newly developed. Results are summarized as follows. (i) The NbTi strand with a fine filament diameter of 11 μm and high Cu/non-Cu ratio of 6.9 was newly developed. The strand with a length of 44 km was successfully drawn without breakage. (ii) Cabling of the 486 strands together with a central spiral and SS tape wraps was successfully done with a length of 28 m. (iii) The full-size conductor composed of Ni plated strands achieved moderate coupling loss with a coupling time constant $n\tau$ of 116 ms thanks to the SS tape wraps between sub-cables. Target $n\tau$ of 100 ms will be achieved by slight shortening of cabling pitches from 425 to 394 mm.

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