Development of Cu-Nb Reinforced Nb_3Sn Wires

Masahiro Sugimoto, Ryo Taniguchi*, Koichi Ebisawa*, Ka Kei Mun*, Hiroyuki Fukushima*, Kengo Nakao*, Hidekazu Hara*, Kiyoshige Hirose*, Hirokazu Tsubouchi**

ABSTRACT We have developed Nb-rod method Cu-Nb reinforced Nb_3Sn wires (Cu-Nb/Nb_3Sn wires), which have significantly improved superconducting characteristics under mechanical stress compared to conventional Nb_3Sn wires. Cu-Nb/Nb_3Sn wires can be manufactured into coils not only with the conventional wind-and-react (W&R) method but also with the react-and-wind (R&W) method, and the superconducting performance and the mechanical characteristics are both improved by a strain control through pre-bending treatment. Furthermore, elemental technology developments for a higher strength, a higher critical current density, a rectangularization, an enamel coating, a thinner wire for small radius bending, and a stranded wire have made them practical wires with an excellent manufacturability. In the future, Cu-Nb/Nb_3Sn wires will be expected to be applied in advanced superconducting equipment such as a high magnetic field NMR/MRI, a particle accelerator, and a large fusion reactor.

1. INTRODUCTION

Alloy-based NbTi wires and A15-based intermetallic compound Nb_3Sn wires are in practical use in many superconducting devices. In particular, Nb_3Sn wires are used in superconducting magnets that generate high magnetic fields of 10 T or more, which exceed the critical magnetic field of NbTi wires. However, Nb_3Sn wires require elemental technologies different from Nb-Ti superconducting wires, such as an Nb_3Sn generation heat treatment according to the structural design after processing them into wires made by combining Nb filaments with a Cu-Sn alloy (unreacted Nb_3Sn wires). Also, wires after Nb_3Sn generation heat treatment (reacted Nb_3Sn wires) are not only mechanically fragile, but also have superconducting characteristics that change due to external strain[1], so, the wind and react (W&R) method, which applies Nb_3Sn generation heat treatment after winding unreacted Nb_3Sn wires into coils, are commonly used. Furthermore, as improvements in current-carrying characteristics under large electromagnetic stress are required in order to improve the performance of magnets for higher magnetic fields and larger sizes, it is necessary to increase the strength of the Nb_3Sn wire itself and to develop a conductor made by twisting Nb_3Sn wires together.

Through joint research with Tohoku University, Furukawa Electric Co., Ltd. has developed Nb_3Sn wires reinforced with a Cu-Nb composite material (Cu-Nb/Nb_3Sn wires)[2] produced using a new method (Nb-rod method), which is different from the conventional In-situ method for Cu-Nb alloys[3)-5)]. The Cu-Nb/Nb_3Sn wires have improved superconducting characteristics under high stress by applying the pre-bending strain application treatment (pre-bending treatment)[6)-8)], which is described later, in the react-and-wind (R&W) method of winding a reacted Nb_3Sn wire into a coil, which has been thought to be difficult to put into practical use until now.

In order to achieve the required characteristics for various Nb_3Sn superconducting coils in which not only the R&W method but also the W&R method is used, we carried out elemental technology developments for increasing critical current density, increasing strength, rectangularization, enamel insulation, small diameter bending, and conductorization of Cu-Nb/Nb_3Sn wires[9)-18)]. This paper describes the development results of the Cu-Nb/Nb_3Sn wires to date and their future prospects.

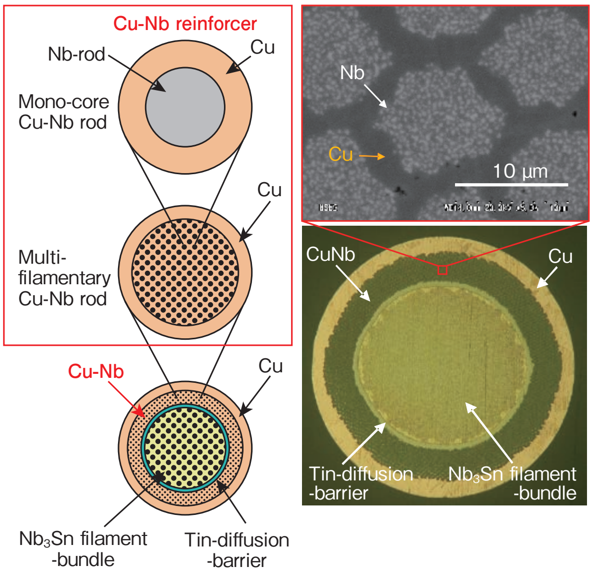
2. CHARACTERISTICS OF THE Cu-Nb REINFORCED Nb_3Sn WIRES

2.1 Structure of the Cu-Nb Reinforced Nb_3Sn Wire[5),10)]

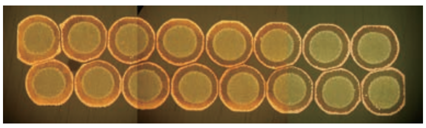
The structure of the Nb-rod method Cu-Nb/Nb_3Sn wire (diameter 0.80 mm) is shown in Figure 1(a). A Cu-Nb composite material with a structure in which multiple Cu-sheathed Nb mono-core wires are embedded in a Cu matrix is placed around the Nb_3Sn filament group. The submicron-sized or less Nb filaments in the Cu-Nb composite material have a fiber-reinforcement function, and the Cu matrix functions as a stabilizing material. The Cu-Nb reinforcement material part in the Cu-Nb/Nb_3Sn

* Superconducting Products Department, R&D Division.

wire shares the external stress (tensile stress, compressive stress, bending stress), which reduces the strain that the Nb_3Sn filament receives and suppresses the occurrence of damage. This Nb-rod method Cu-Nb reinforcement material is superior to conventional In-situ method Cu-Nb alloys in terms of mechanical characteristics, residual resistance characteristics, and manufacturability[2]. Figure 1 (b) shows the R&W type Cu-Nb/Nb_3Sn Rutherford cables (width 6.45 mm x thickness 1.53 mm) used in the Tohoku University 25 T-cryogen-free superconducting magnet (25 T-CSM). The superconducting characteristics under tensile stress and compressive stress has been improved by applying pre-bending strain as described below after Nb_3Sn generation heat treatment[4), 5)].



(a) Cross-sectional structure of Nb-rod method Cu-Nb reinforced Nb_3Sn wires



(b) Nb-rod method Cu-Nb reinforced Nb_3Sn Rutherford cable for 25 T-CSM

Figure 1 Structure of the Nb_3Sn wire reinforced with Cu-Nb manufactured by the Nb-rod method and the Rutherford cables for the 25 T-CSM.

2.2 Processing Methods of the Nb_3Sn Wires (W&R Method and R&W Method)

In both the W&R and the R&W methods described above, the Nb_3Sn superconductor in the Nb_3Sn wire is subject to complex strains due to at least the following three types of stress: (1) Cooling compressive residual strain that remains due to the difference in thermal contraction between the Nb_3Sn superconductor and the composite material inside the wire when cooling from the Nb_3Sn generation heat treatment temperature through room temperature to critical temperature and less, (2) Residual strain after winding due to tensile stress and bending stress when winding the wire into a coil, (3) External stress strain consisting of axial tensile stress, lateral compressive stress, and bending stress due to the electromagnetic force during coil operation.

Figure 2 shows a comparison of the process flow diagrams for manufacturing Nb_3Sn coils using the W&R method and the R&W method. In the W&R method, a gap of the thermal contraction coefficient with the coil components is created by the temperature difference (900°C or more) that occurs when cooling from the Nb_3Sn generation heat treatment temperature (up to 700°C) through room temperature to an extremely low temperature (up to –269°C). Due to the difference in the thermal contraction coefficients, the Nb_3Sn filament undergoes large residual compressive strain. On the other hand, in the R&W method, the compressive strain applied to the wire can be released by separating the Nb_3Sn wire from the structural members such as a winding frame, which is used during heat treatment at room temperature, after Nb_3Sn generation heat treatment. After that treatment, the coil is wound at room temperature and cooled to an extremely low temperature (up to –269°C), so the residual compressive strain generated in the Nb_3Sn filament due to the difference in thermal contraction with the component parts becomes significantly smaller than in the W&R method, which improves the superconducting characteristics. Furthermore, by applying pre-bending strain[6)-8)], which will be described later, in order to optimize the strain that is applied to the Nb_3Sn filament during cooling operation before and during coil winding, to bring out current carrying performance that is higher than that of the coils manufactured with the W&R method becomes possible. On the other hand, the R&W method Nb_3Sn wire has the advantage that polyimide tape, PVF, polyester braid, etc., can be used in addition to heat resistant materials such as glass braid which is commonly used in the R&W method Nb_3Sn wires, and that materials other than metal and ceramic can be selected for coil manufacturing components.

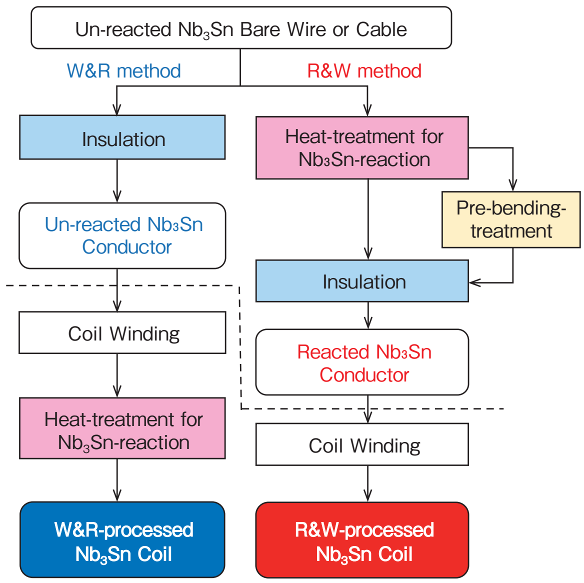


Figure 2 Comparison of the Nb_3Sn coil manufacturing flow between the W&R method and the R&W method.

2.3 Pre-bending Strain Application Treatment

The pre-bending strain application treatment[6), 7)] in the R&W method coil windings has industrially enabled the improvement of the superconducting characteristics[8)-17)] brought by the pre-strain effect[19)]. In the R&W method, it is necessary to control the pulley diameter, the coil winding diameter and the bending direction that make up the pass line so that the bending strain applied to the wire is below the allowable value. Figure 3 shows a typical example of a pass line configuration for applying pre-bending strain[5)]. When the wire is heat-treated with a bobbin of diameter D_h and then bent by a pulley of diameter D_b, a bending strain ε_b given by equation (1) is applied[20)].

$$\varepsilon_b(y) = \pm d(y) \cdot \left(\pm \frac{1}{D_b^{\pm}} - \frac{1}{D_h}\right) \qquad (1)$$

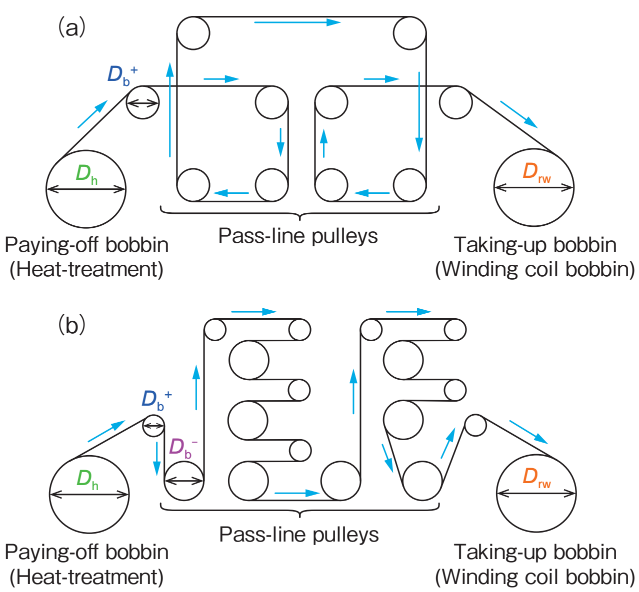


Figure 3 **Schematic diagram of the pass line for applying pre-bending strain; (a) forward bending, (b) bidirectional bending (forward and backward directions)[5)].**

The sign ± represents the winding directions of the heat treatment bobbin, with the forward direction shown as + and the backward direction shown as −. That is, D_b^+ means the pulley diameter of the forward bending, and D_b^- means the pulley diameter of the backward bending. The maximum value of d (y) is the outer diameter of the wire d ($y = d/2$), with the center of the cross section of the wire as the reference point ($y = 0$) (Figure 6 (a) below). In a coil where a wire is wound around a bobbin with a diameter (D_{rw}) different from that of the heat treatment bobbin, pure-bending strain (strain when only a bending moment occurs) is applied to the wire, and the Nb_3Sn filaments located at the diameter d_{fb} of the filament bundle in the wire experiences the maximum bending strain[12)]. When comparing the bending strain characteristics of the wires with different cross-sectional structures, a diameter $d_{non\text{-}Cu}$ of the Non-Cu part including the Sn diffusion barrier may be used[16)].

Figure 4 shows the effect of the pre-bending strain application treatment on the axial tensile strain dependence of the critical current (I_c) in the Cu-Nb/Nb_3Sn wire for 25 T-CSM[5)]. In this report, the wire immediately after the Nb_3Sn generation heat treatment is referred to as As-reacted wire (-AR), and the wire that has been subjected to the pre-bending strain application treatment is referred to as Pre-bent wire (-PB). Due to the pre-bending strain application treatment, the axial strain (ε_m) at which the I_c is maximized shifted from approximately 0.3% to approximately 0.1% to the low strain side, and the I_c value itself increased. This is the effect of improving superconducting characteristics due to three-dimensional relaxation of the compressive residual strain applied to the Nb_3Sn filaments[21)].

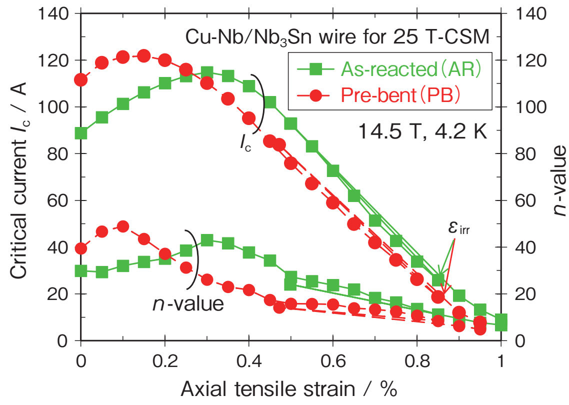


Figure 4 **Transverse compressive stress dependence of the I_c and the n-values of the Cu-Nb/Nb_3Sn in the 25 T-CSM at 14.5 T and 4.2 K[5)].**

A similar effect can be obtained with a conventional Cu/Nb_3Sn wire without reinforcement, but the mechanical strength of a Cu/Nb_3Sn wire at room temperature is considerably lower than that of the Cu-Nb/Nb_3Sn wires[13)], and it causes a greater risk of damage on Nb_3Sn filaments during handling. Therefore, it is difficult to proactively apply the pre-bending strain application treatment on it. In addition, when the pre-bending strain application treatment is applied to a Rutherford cable using Cu-Nb/Nb_3Sn wires (Figure 1 (b))[5)], the adhesive parts between the wire surfaces that occur during heat treatment peel off, causing individual wires to move separately. As a result, the allowable bending strain of the stranded wire becomes equivalent to that of a single wire, and it can be bent to a small diameter.

2.4 Current Carrying Characteristics Under Pure-Bending Strain

The Relationship between the critical current when pure-bending strain is applied to the Cu-Nb/Nb_3Sn wires for 25 T-CSM and the bending strain (peak pure-bending strain) generated in the filament placed in the outermost layer of the Nb_3Sn filament bundle is shown in Figure 5 (a)[12)]. In the range of ±0.5% pure-bending strain, the Pre-bent (-PB) wire had a higher I_c than that of the As-reacted (-AR) wire in the unstrained state.

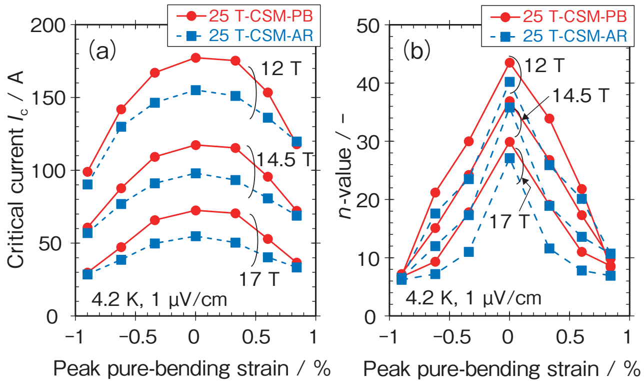


Figure 5 I_c characteristics of the Cu-Nb/Nb_3Sn wire for the 25 T-CSM against the peak pure-bending strain[12].

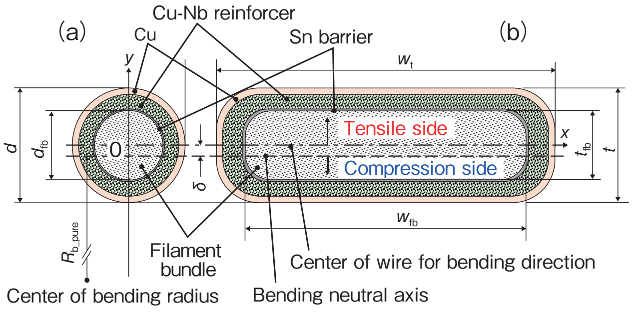


Figure 6 Cross-sectional structure model of the wire for the analysis of the pure-bending strain effect on the I_c of the Cu-Nb/Nb_3Sn wire[17]. (a) round wire, (b) tape wire

This indicates that by applying appropriate pre-bending strain to the Cu-Nb/Nb_3Sn wire and controlling the bending diameter below the allowable bending diameter, the I_c of the R&W method can be improved more than that of the W&R method. However, as shown in Figure 5 (b), consideration must be given to the n-value, which decreases in different degrees depending on the applied magnetic field and the applied bending strain.

Figure 6 shows a cross-sectional structural diagram of Ekin etc.'s analytical model for critical current in a round wire under pure-bending strain[22, 23] applied to a rectangular wire[17]. The permissible bending diameter of the Nb_3Sn wire is limited by the maximum bending strain experienced by the Nb_3Sn filament located at the outer edge of the filament region. Therefore, in order to bend the Nb_3Sn wire to a smaller diameter, it is effective to reduce the area of the Nb_3Sn filament, but there is a problem that reducing the wire diameter reduces the critical current per wire. In addition to a cable with thin strands of 0.4 mm in diameter[15], we have confirmed that a forming a Cu-Nb/Nb_3Sn rectangular wire (tape wire) with a large aspect ratio is an effective method for increasing the critical current value when bent to a small diameter in order to make the Nb_3Sn filament region smaller to the bending direction[17].

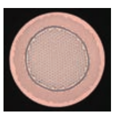
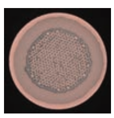
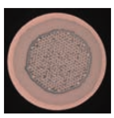
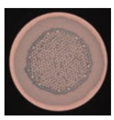
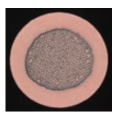
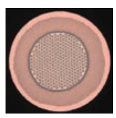
3. PERFORMANCE IMPROVEMENT IN THE Cu-Nb/Nb_3Sn WIRES

3.1 Improvement in the Mechanical Characteristics

When a superconducting coil with a winding radius R (m) is operated in an external magnetic field B (T) and an average current density J_e (A/m^2), the tensile stress σ (Pa) given by BJ_eR is applied to the winding axial direction, and a transverse compressive stress determined by the coil structure is applied to the wire. In order to obtain structural design guidelines for Cu-Nb/Nb_3Sn wires that can achieve both the I_c and the strength required under tensile and transverse compressive stress during coil operation, we made prototype wires with different cross-sectional structures shown in Table 1[5, 15, 16].

By using the high Sn bronze Cu-15.7wt%Sn-0.3wt%Ti[9], the critical current density (non-Cu-J_c) was increased by about 10% compared to the 25 T-CSM wire using the Cu-14wt%Sn-0.2wt%Ti. In three types of structures with Nb filament volume fractions in Cu-Nb of 20 vol% (LK199), 25 vol% (LK200), and 30 vol% (LK201), and in other three types of structures with Cu-25 vol%Nb reinforcement occupancy per wire cross section of 38% (LK200), 55% (LK202), and 0% (LK206), the current carrying characteristics under external stress were compared

Table 1 Cu-Nb/Nb_3Sn wire rods with various cross-sectional structure designs[5, 15, 16].

Wire ID	25 T-CSM	LK199	LK200	LK201	LK202	LK206	LK224
Cross-sectional structure							
Cu/Cu-Nb/non-Cu (%)	20/35/45	19/39/42	21/38/41	19/39/42	20/55/25	57/0/43	20/45/35
Nb occupancy in Cu-Nb reinforcement material (vol%)	20	20	25	30	25	—	30
Diameter of the Nb_3Sn filament region (mm)	0.52	0.49	0.49	0.49	0.37	0.5	0.45
Wire diameter (mm)	0.80			0.80			0.80
Nb_3Sn filament diameter (μm)	3.3			3.2			3.2
Sn diffusion barrier	Ta			Nb			Ta/Nb
Bronze composition	Cu-14wt%Sn -0.2wt%Ti			Cu-15.7wt%Sn-0.3wt%Ti			
Twist pitch (mm), Twist direction				24, S direction			

respectively. In the LK224, the Nb ratio in the Cu-Nb was increased to 30 vol% and the Cu-Nb cross-sectional area ratio in the wire was increased to 45% in order to improve the current-carrying characteristics under tensile stress exceeding 300 MPa[16].

Figure 7 (a) shows the I_c values (4.2 K, 14.5 T) normalized by the peak I_c value of each bare wire and the I_c value at zero stress against axial tensile stress, respectively. The strain value of the pre-bending strain application treatment was defined per non-Cu area. The tensile stress at which the I_c of each Cu-Nb/Nb_3Sn wire decreased was twice or more than twice that of the Cu/Nb_3Sn wire without reinforcement (LK206-PB±0.3%). The LK201-PB±0.3% and the LK202-PB±0.3% had smaller I_c decrease than in the 25T-CSM-PB±0.3% in the region of tensile stress of 300 MPa or higher, and the LK201-B±0.5% had a significantly restrained I_c decrease at 400 MPa or more. In the LK224-PB±0.38%-D, even with multi-stage heat treatment (575°C x 100 hrs + 670°C x 50 hrs), which increases the critical current density, it maintained the same high mechanical characteristics as with heat treatment at 670°C x 96 hrs.

In the I_c characteristics of each Cu-Nb/Nb_3Sn wire shown in Figure 7 (b) under transverse compressive stress, the transverse compressive stress value at which the I_c decreases by 10% or more was 50 MPa or more larger than that of the Cu/Nb_3Sn wire without a reinforcement material (the LK206-PB±0.3%). This confirmed that Cu-Nb reinforcement is also effective in improving lateral compression characteristics. A comparison of the characteristics of the LK201-PB±0.3% and the LK201-PB±0.5% with different applied pre-bending strain values showed that an increase in pre-bending strain value improved the I_c characteristics under tensile stress, but the I_c characteristics under transverse compressive stress decreased. This indicates that the pre-bending strain application conditions must be selected by taking into consideration the cross-sectional structure of the Cu-Nb/Nb_3Sn wire and the distribution of external stress applied to the wire during actual superconducting magnet operation.

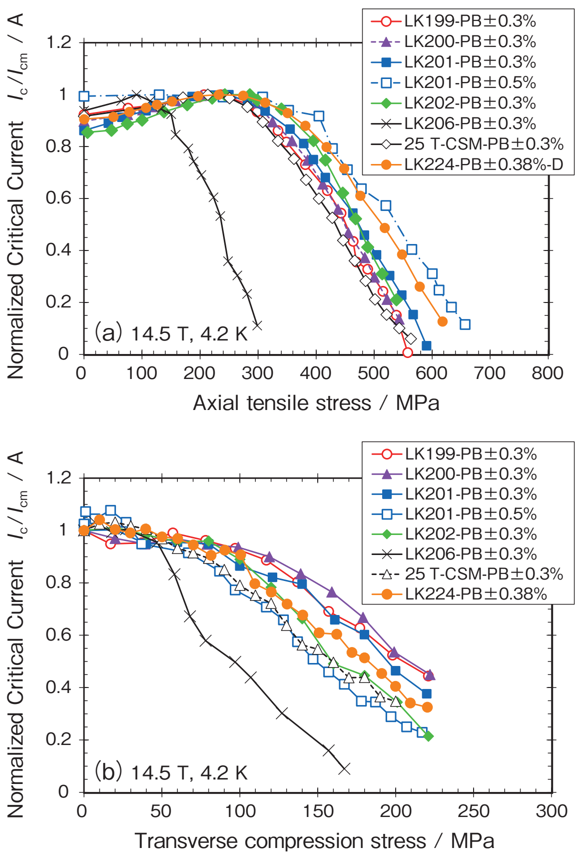


Figure 7 **I_c values normalized at the respective peak I_c values of the Cu-Nb reinforced Nb_3Sn wire and the unreinforced Cu/Nb_3Sn wire at 4.2 K and 14.5 T under tensile stress. (a) Under axial tensile stress. (b) Under transverse compressive stress.**

Note: Heat treatment condition was 670°C x 96 hours. However, data of the LK224 under axial tensile stress was obtained by heat treatment at 575°C x 100 hours + 670°C x 50 hours[5), 15), 16)].

3.2 Improvement in the Conductor Current Density

There are various specifications for Nb_3Sn wires used in high-field Nuclear Magnetic Resonance (NMR), accelerators, large-capacity conductors for nuclear fusion, etc., and as their magnetic field becomes higher and they become larger, achieving both the improvement of the conductor current density (current density J_e per wire cross-sectional area: engineering J_c) and high mechanical strength becomes necessary. As shown in Table 2, the LK144 (REC) was manufactured into a rectangular cross-section shape to increase the coil winding density for the application to high-field NMRs[13)]. As the LK145 and the LK288 are considered for application in accelerators and nuclear fusion magnets, they were manufactured to a round wire shape to improve the current density by stranding multiple wires together and applying compression processing[13), 18)]. With respect to the cross-sectional composition ratio, the Cu-Nb reinforcement material was reduced to 20 to 23% and non-Cu part was set to 50% in order to increase the J_e, but the stabilized Cu amount, including Cu in the Cu-Nb reinforcement material, was secured at 45 to 46%.

Table 2 **High critical current density type Cu-Nb/Nb_3Sn wire[13),18)].**

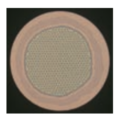
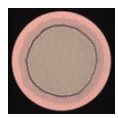
Wire ID	LK144 (REC)	LK145	LK288
Cross sectional structure			
Dimension (mm)	1.13^t x 1.70^w-0.3^R	0.80	0.827
Nb_3Sn filament diameter (μm)	3.2	3	2.3
Twist pitch (mm)	50	24	15
Direction	S direction		Z direction
Sn diffusion barrier	Nb		Ta
Cu/Cu-Nb/non-Cu (%)	30/20/50		27/23/50
Bronze composition	Cu-15.7wt%Sn-0.3wt%Ti		
Cu-Nb reinforcement material	Nb-rod method Cu-20vol%Nb		

Figure 8 (a) shows the magnetic field (B) dependence of the non-Cu-J_c when subjected to the Nb_3Sn generation heat treatment at 575°C x 175 hrs + 650°C x 125 hrs. The non-Cu-J_c value increased by applying the pre-bending strain application treatment (wire surface definition ±0.5%). The LK145-PB had 1115 A/mm^2 at 12 T and 400 A/mm^2 at 17 T, which was about 30% increase to the characteristics of the 25 T-CSM-PB. The rectangular wire LK144 (REC) shown in Figure 8 (b) was evaluated by changing the direction in which the pre-repetitive bending strain of ±0.5% was applied. The non-Cu-J_c of the LK144-PB, which was applied the pre-bending strain alternately from both the flatwise direction and the edgewise direction for five times each, was 355 A/mm^2 at 17 T, which was about 1.6 times that of the LK144-AR. It was approximately 1.1 times when it was applied 10 times from the flatwise direction (PB-f) and from the edgewise direction (PB-e). Using the Kramer model[24], the effective upper critical magnetic field (B^*_{c2}) of the LK144-AR, the LK144-PB-f, and the LK144-PB, calculated from the extrapolation of the J_c values from 18 T to 25 T, were 24.4 T, 24.8 T and 25.0 T respectively. Similar to the Cu-Nb/Nb_3Sn rectangular wire, even when the conductor is made into a stranded wire, pre-bending strain application from two directions is considered to be effective.

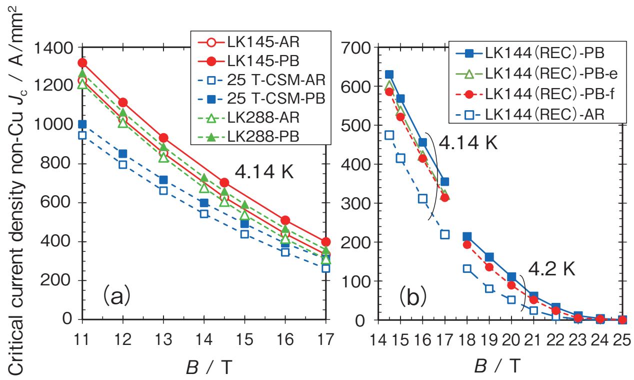


Figure 8 **Magnetic field dependence of the critical current density in the non-Copper part[5), 13), 18)].**
(a) round wire, (b) rectangular wire

Figure 9 shows the non-Cu-J_c characteristics (14.5 T, 4.2 K) of the LK145 and the LK288 (heat treated at 575°C x 175 hrs + 650°C x 125 hrs), and the 25 T-CSM wire (heat treated at 670°C x 96 hrs) with respect to the axial tensile strain and the axial tensile stress. The non-Cu-J_c values of the LK145-PB was higher than that of the LK145-AR at 600 A/mm^2 or more up to an axial strain of 0.3% (stress of 250 MPa), and higher than that of the 25 T-CSM-PB up to approximately 300 MPa. The non-Cu-J_c values of the LK288-PB was higher than that of the 25 T-CSM-PB up to approximately 400 MPa. As the LK288 is expected to have both the improvement in the manufacturability of short-pitch, low-void multi-stranded wires and the maintenance of the superconducting characteristics under high electromagnetic stress due to the excellent stress resistance characteristics of the I_c, it is expected to be applied to cable-in-conduit conductors for large nuclear fusion reactor magnets[18)].

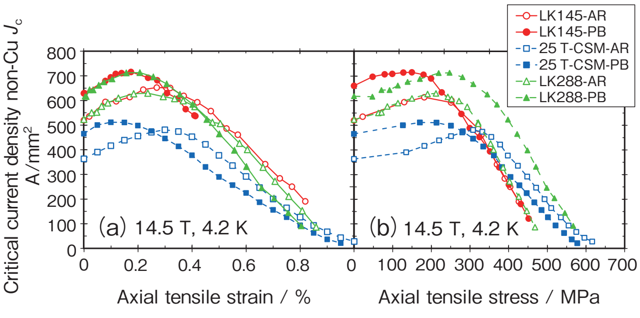


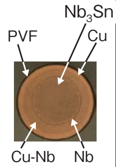
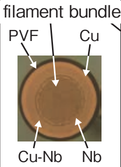
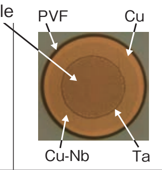
Figure 9 **Comparison of the critical current density characteristics in the non-Copper part at 14.5 T between the high critical current density round wires (LK145, LK288) and the 25 T-CSM wire under axial strain and axial stress[5), 13), 18)].**
(a) Axial tensile strain, (b) Axial tensile stress

3.3 Application of Enamel-coated Insulation

As shown in Figure 1, in the W&R method Nb_3Sn coils, the unreacted Nb_3Sn wire is generally insulated with glass braid and heat treated after winding, but it has the following disadvantages: (1) Glass braiding takes long production time and high cost, (2) Breakdown voltage decreases due to carbonization of the binder in glass braiding, (3) Wire fill factors in the coil decreases due to thick insulation coating and variations in dimensions, etc. On the other hand, in the case of the R&W method, various materials can be used for the insulation of the wire after Nb_3Sn generation heat treatment, including polyimide tapes, polyester braids, and enamel coating such as Polyvinyl Formal (PVF). With respect to enamel-coated Nb_3Sn wires, there has been a report on the development of an R&W method Nb_3Sn coil using a PVF-coated internal tin-diffusion Nb_3Sn wire with a strict control of tension and bending strain[25)], but at present, there has been no practical application yet.

We coated the Cu-Nb/Nb_3Sn wires shown in Table 3 with PVF and evaluated their critical current characteristics under tensile stress[14)]. The applied bending strain was defined as the peak strain at the outer diameter d_{fb} (mm) of the Nb_3Sn filament bundle part, and the bending strain ε_{pb}^+ in the forward direction, which is same as the bending direction during heat treatment, and the bending strain ε_{pb}^- in the backward direction were calculated using the formula (1) mentioned above. The LK165 was wound on a bobbin with a diameter (D_h) of 500 mm and subjected to Nb_3Sn generation heat treatment at 670°C for 96 hrs, after which 10 sets of D_{pb}^+ = 125 mm and D_{pb}^- = 250 mm pulleys were alternately connected and bidirectional bending strain $\varepsilon_{pb}^{\pm}$ = ±0.31% was applied repeatedly (Figure 3 (b)). For the LK179, only the forward bending pulley of D_{pb}^+ = 250 mm was used after heat treated with a bobbin of D_h = 150 mm, and only –0.34% of backward strain that would be experienced when returning to the straight position was applied (Figure 3 (a)). For the LK183, only a forward bending pul-

Table 3 Cu-Nb/Nb_3Sn wire with PVF insulation coating[14].

Wire ID	LK165	LK179	LK183
Cross sectional structure			
Wire diameter after PVF coating (mm)	0.84	0.88	1.39
PVF coating thickness (mm)	20	40	40
Wire diameter before PVF coating (mm)	0.80		1.31
Nb_3Sn filament bundle diameter (mm)	0.51		0.79
Nb_3Sn filament diameter (μm)	3.3		3.3
Twist pitch (mm), direction	24, S direction		36, S direction
Bronze structure	Cu-14wt%Sn -0.2wt%Ti		Cu-15.7wt%Sn -0.3wt%Ti
Sn diffusion barrier	Nb		Ta
Cu/Cu-Nb/non-Cu (%)	20/35/45		20/40/40
Cu-Nb reinforcement material	Nb-rod method Cu-20vol%Nb		

ley with D_{pb}^{+} = 270 mm was used after heat treated with a bobbin of D_h = 700 mm, and a forward bending strain ε_{pb}^{+} = +0.19% and a backward bending strain ε_{pb}^{-} = −0.11% that would be applied when returning to the straight position were applied.

Figure 10 (a) shows the critical current characteristics of the LK165-PVF and the LK179-PVF with PVF coating under tensile stress. With respect to the tensile stress

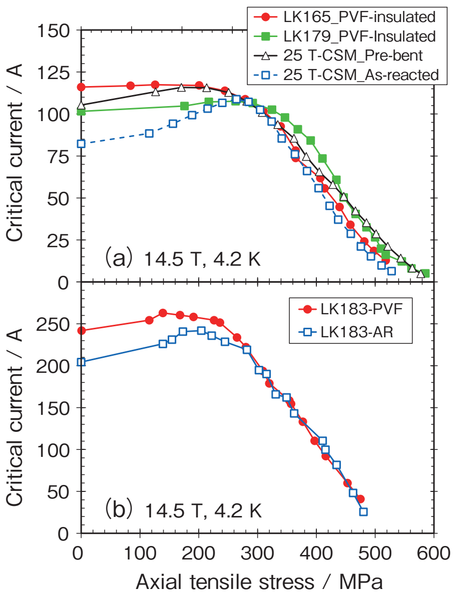


Figure 10 Comparison of critical current characteristics under axial tensile stress of the Cu-Nb/Nb_3Sn wire with PVF insulation coating and the wire without PVF coating[14].
(a) Comparison of the PVF-coated wire K165, the LK179 and the 25 T-CSM wire, (b) Comparison of the PVF-coated wire LK183 and the uncoated wire LK183

dependence of the critical current value of the LK165-PVF, the critical current in the tensile stress region of 260 MPa or less improved compared to that of the 25 T-CSM-AR immediately after heat treatment, and the critical current in the tensile stress region of 150 MPa or less improved compared to that of the 25 T-CSM-PB. Figure 10 (b) shows the critical current characteristics of the LK183-PVF coated with PVF under tensile stress. The critical current value of the LK183-PVF improved compared to that of the LK183-AR immediately after heat treatment in the tensile stress region of 250 MPa or less.

As a result, the Cu-Nb/Nb_3Sn wires can be insulated with enamel such as PVF, and by applying appropriate pre-bending strain, the current carrying characteristics under practical tensile strain and tensile stress can be improved after coating PVF.

4. SUMMARY AND FUTURE OUTLOOK[11]

The effectiveness of the Nb-rod method Cu-Nb/Nb_3Sn wires have been demonstrated in the Tohoku University 25 T-CSM Cu-Nb/Nb_3Sn Rutherford cable, and subsequent development of various elemental technologies has clarified the excellent manufacturability and the high superconducting characteristics in a wide stress range could be achieved not only by the R&W method but also by the W&R method.

In the application for the Nb_3Sn magnets for nuclear fusion, the JA-DEMO-TF conductor (TF conductor for a Japanese demo reactor)[26] utilizes the developmental achievement of the ITER-CS conductor[27)-29], and in order to maintain excellent superconducting characteristics under high electromagnetic stress, a short-pitch and low-void W&R type cable-in-conduit Nb_3Sn conductor structure is promising. To apply the above, it is necessary to improve the stress resistance characteristics and the manufacturability of stranded wires of Nb_3Sn wires. Therefore, the application of Cu-Nb/Nb_3Sn wires is effective[18]. In addition, for EU-DEMO-TF conductors, as an R&W type Nb_3Sn conductor option[30] is being considered, a method of forming a conduit after applying pre-bending strain to the Cu-Nb reinforced Nb_3Sn conductor is an option[10]. On the other hand, for the Future Circular Collider designed under the FCC project of the European Organization for Nuclear Research (CERN)[31], development of manufacturing technologies for a robust high current density type Nb_3Sn magnet that reliably generates a specified magnetic field is necessary. Therefore, in addition to improving the basic coil manufacturing technology, consideration has been given to increasing the strength of the Nb_3Sn wire itself. Based on the characteristics of Nb_3Sn superconducting wires[32], both a high J_c and a high strength can be achieved at the same time by replacing a member of the Nb_3Sn filament bundle part made by the bronze method to the one using an advanced internal tin-diffusion method that achieves high current density. Furthermore, in the fields such as high-field NMRs, Magnetic Resonance Imaging (MRI), and medical accelerators, it is expected that the right material will be used in the right place for coils that cover a wide range of magnetic fields and temperature regions between NbTi wires and high-temperature superconducting wires.

In the future, we will steadily advance the development of elemental technology for application to a variety of Nb_3Sn magnet application devices, taking advantage of the fact that the Cu-Nb/Nb_3Sn wires are practical wires that can be mass-produced at a reasonable cost.

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