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Prebending Strain Effect on $CuNb/Nb_3Sn$ Superconducting Wire During Practical React-and-Wind Process

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***Abstract*—To demonstrate the applicability of the prebending strain effect to the R&W coil winding process, we have developed the prebent react-and-wind (R&W) process, which is the combination of the conventional R&W process and the prebending treatment. The superconducting and mechanical characteristics were investigated for $CuNb/Nb_3Sn$ superconducting wires which were picked up from the prebent R&W coil winding process. The results were compared with that of $CuNb/Nb_3Sn$ wires which were prebent manually using a prebending former.**

The prebending treatment using pulleys enhanced I_c more than the manual prebending treatment. This is explained qualitatively by a difference of the prebending strain distribution. The prebending strain distribution is plain symmetric and axis symmetric in cases of the manual prebending and the pulleyed prebending, respectively. The axis symmetrically distributed prebending strain reduces the residual strain more than the plain symmetrical one.

The mechanical property was also enhanced. The slope of the stress-strain curve for the pulleyed prebent samples were steeper than that of as-heat-treated sample. The maximum I_c of the I_c-strain curve was enhanced and the strain value corresponding to the maximum I_c shifted to smaller strain by the pulleyed prebending treatment.

Though in the large stress region over 200 MPa, the I_c-stress curves of pulleyed prebent samples and as-heat-treated sample were in good agreement, suggesting that the I_c enhancement effect by the prebending treatment was not beneficial, in the small stress region, it is quite beneficial.

***Index Terms*—Critical current, $CuNb/Nb_3Sn$ superconducting wire, mechanical property, prebending strain effect, react-and-wind process.**

I. Introduction

THE PREBENDING treatment, which consists of the repeated bending at room temperature, largely enhances the superconducting properties as the critical current (I_c), upper critical field (B_{c2}) and critical temperature (T_c) of Nb_3Sn superconducting wires fabricated by the bronze process [1].

The mechanism of the prebending strain effect is being understood qualitatively as follows; the repeated prebending strain reduces the residual compressive strain of the Nb_3Sn filaments, thus the intrinsic superconducting properties appear. Furthermore, neutron diffraction measurement provides that the prebending treatment affects not only the axial strain but also the radial strain distribution [2].

The next step in the study of the prebending strain effect is its application. Two kinds of application candidates are being focused. One is an application to the Nb_3Sn superconducting coil fabricated by a react-and-wind (R&W) process, which is described in this paper, the other is to the Nb_3Sn superconducting cable, which is to be studied.

We have explored transport and mechanical properties of CuNb-reinforced $Nb_3Sn(CuNb/Nb_3Sn)$ coils fabricated by a R&W method to establish the react-and-wind technique with $CuNb/Nb_3Sn$ wire [3]–[5]. The advantage of the R&W method is a coil fabrication cost reduction. In the case of the wind-and-react (W&R) method, the furnace enlarges with enlarging coil volume, causing an increase of the cost. On the contrary, in the case of the R&W method, the furnace size depends on the heat-treatment reel size, thus a huge furnace is not needed.

In the practical R&W method, the reacted superconducting Nb_3Sn wire is pulled out from a supply reel, passed through several fixed pulleys which lead to the final winding bobbin. The wire is bent by the pulleys during the process. We have developed the 'prebent R&W process,' which is the combination of the conventional R&W process and the prebending treatment. The prebending strain value can be controlled by optimizing diameters of the pulleys. If the prebending strain effect is well applicable for the R&W process, an enhancement of the I_c is expected.

The goal of the work is to establish the R&W technique combined with the prebending strain effect. In the present paper, we have investigated the superconducting and mechanical characteristics of superconducting $CuNb/Nb_3Sn$ short samples picked up from the R&W coil fabrication process.

II. Experimental

A. Sample Preparation

A 1.0-mm diameter, bronze-route Nb_3Sn wire reinforced with CuNb composite was prepared. Specifications and a

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TABLE I
SPECIFICATION OF $CuNb/Nb_3Sn$ SUPERCONDUCTING WIRE

Wire diameter	1.0 mm
Filament twist pitch	30 mm
Superconductor/(Cu+CuNb) ratio	45/55
RRR	80
Heat treatment	670 °C×96 hrs

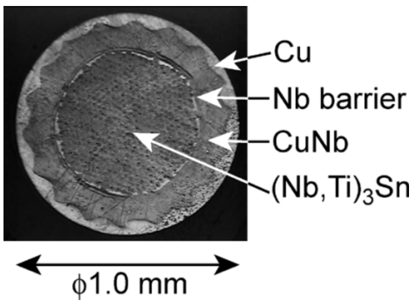

Fig. 1. Cross sectional view of $CuNb/Nb_3Sn$ superconducting wire. The Ti added Nb_3Sn filaments are surrounded by the Nb barrier and the reinforcing material of Cu-20 wt%Nb. The outermost sheath is Cu stabilizer.

cross-sectional view of the wire are shown in Table I and Fig. 1, respectively. The reinforcing material of Cu-20 wt%Nb surrounds the Ti added Nb_3Sn filaments and bronze matrix. The outermost sheath is Cu stabilizer. The wire was wound on a 440-mm diameter reel and was heat-treated at 670 °C for 96 hours.

B. Prebending Treatment

The prebending strain was applied to the reacted Nb_3Sn superconducting wire in two ways. One is by a manual treatment, and the other is using pulleys.

A schematic illustration of the prebent R&W process is shown in Fig. 2 [6]. The superconducting wire was pulled out from the heat treatment reel, insulated with a polyimide tape half-wrapping, and then, wound on the 440-mm diameter reel, which was the supply reel for the winding process. The insulated superconducting wire was pulled out from the supply reel and passed through ten pulleys. The ten pulleys apply the prebending strain to the wire. After the prebending treatment, the wire was wound on a 200-mm diameter stainless-steel bobbin with epoxy-resin molding.

Short samples, which are 40-mm long each, were picked up from the point A, B and C, which are shown in the figure. Samples picked up from point A correspond to 'after heat treatment,' indicating the virgin state of the reacted $CuNb/Nb_3Sn$ superconducting wire.

The virgin state sample was identified as M0. The samples which were bent manually using a bending former [7] were identified as M1 and M2. Five cycles of alternative bending strain were applied. The prebending strain ϵ_{pb} values were 0.5% and 1.0% for M1 and M2.

A sample picked up from the point B was identified as IW, 'as-insulation-wrapped' sample.

Samples picked up from the point C, which were identified P0, P1 and P2, were mechanically bent by the 10 pulleys during the prebent R&W process. The 10 fixed pulleys bent P1 and P2 10 times, and ϵ_{pb} values of 0.5% and 1.0% were controlled by the pulley diameters. In the case of P0, the superconducting wire passed the 300-mm diameter guide pulleys, but not the 10 pulleys. In other words, P0 was a representative for conventional R&W processed coils. The parameters of all samples are listed in Table II.

C. Measurements

I_c was measured at 4.2 K, in high magnetic fields for all samples. I_c-stress/strain characteristics were measured at 4.2 K, 14 T for M0, P0 and P2. I_c was determined by using a 1.0 $\mu V/cm$ criterion for both measurements.

III. RESULTS AND DISCUSSION

A. Critical Currents

Fig. 3 shows I_c as a function of magnetic field. The right axis indicates non-Cu J_c, which is I_c divided by the cross-sectional area excluding Cu and CuNb. Solid and open markers represent measured I_c for samples which were bent manually by a former and mechanically by pulleys, respectively.

All samples show noticeable I_c enhancement compared with M0. The I_c enhancement ratio is shown in the inset of Fig. 3. I_c of the pulleyed prebent samples were more enhanced than that of the manually prebent samples. Of the three values of ϵ_{pb} (1.0%, 0.5% and 0%), $\epsilon_{pb} = 1.0\%$ induces the largest I_c enhancement, and $\epsilon_{pb} = 0\%$ the smallest for both, the manual and the pulleyed prebending. For example, at 18 T, I_c were 52 A, 76 A, 74 A and 93 A for M0, M2, P0 and P1, respectively. Thus, I_c was enhanced 1.4 times by the manual 1.0% prebending, and 1.8 times by the pulleyed 1.0% prebending.

In this work, the number of applied prebending cycles was fixed to five in the case of manual prebending treatment. We have investigated the dependence of the prebending cycle number for manual prebent samples. As a result, 5–10 prebending cycles gave the maximum enhancement [8]. This result suggests that the 1.4 times enhancement of M2 is the upper limit of the enhancement for a manual prebent sample.

Both IW and P0 did not pass through the 10 pulleys, however they passed through the insulation wrapping process including two pulleys of 300-mm diameter and guide rollers. As a result IW and P0 experienced at least two times prebending strain of $\epsilon_{pb} = 0.3\%$. Though P0 passed not only through the insulation wrapping process, but also through the conventional R&W process including four guide pulleys of 300-mm diameter, I_c of IW and P0 are nearly identical. This suggests that the four 300-mm diameter pulleys did not give rise to any additional I_c enhancement.

Let us discuss about the difference between the manual prebent samples and the pulleyed prebent ones. The extra enhancement of I_c of P2 and P1 are caused by the mechanical prebending treatments using the 10 pulleys. In the case of manually prebent samples, the wire was bent in one plane. As a result, ϵ_{pb} was applied plain symmetrically. In contrast, in the case of pulleyed prebent samples, the wire passed through pulleys with rotation, and was bent in several planes. Thus, the prebending strain was applied symmetrically around the

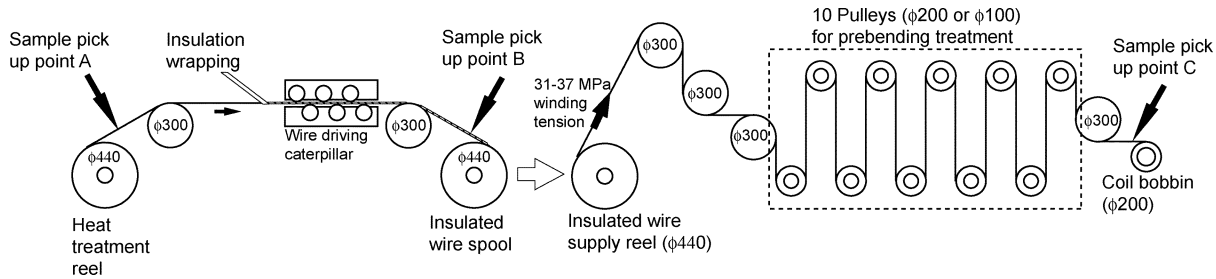

Fig. 2. Schematic illustration of the prebent R&W process. The reacted Nb_3Sn was insulated with polyimide tape wrapping, after that, the insulated wire passes through three guide pulleys and the ten fixed pulleys.

TABLE II
MAJOR PARAMETERS OF MANUAL/PULLEYED PREBENT $CuNb/Nb_3Sn$ SUPERCONDUCTING WIRES

Sample ID	M0[2]	M1	M2	IW[3]	P0	P1	P2
Prebending method[1]	–	M	M	IW	P	P	P
ϵ_{pb} [%]	0	0.5	1.0	–	0	0.5	1.0
Picked up point	A	A	A	B	C	C	C

[1] M and P indicate 'manual prebending' and 'pulleyed prebending,' respectively.
[2] Sample M0 is 'as heat treated,' indicating ϵ_{pb} is accurately zero.
[3] IW indicates 'insulation wrapping.'

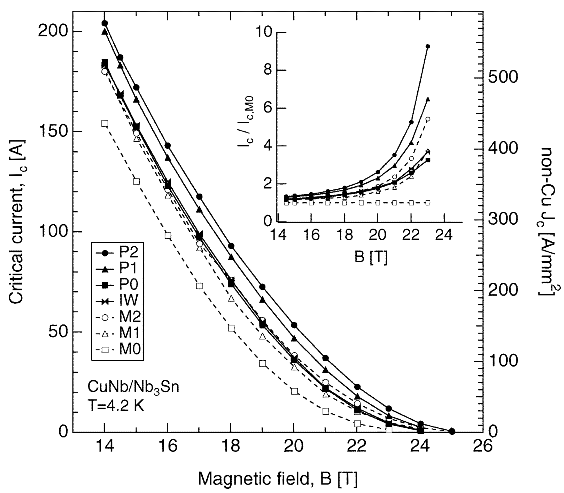

Fig. 3. I_c and non-Cu J_c as a function of magnetic field, B. The inset shows the ratio I_c to $I_{c,M0}$ as a function of B.

wire central axis. The axis symmetrical distribution of ϵ_{pb} reduces the residual strain more than the plain symmetrical one. Therefore I_c of P2 and P1 are larger than those of M2 and M1.

B. Mechanical Properties

Fig. 4 shows the tensile stress test results. (a) and (b) show the stress-strain $(\sigma_t - \epsilon_t)$ curve and ϵ_t dependence of I_c for M0, P0 and P2. The inset shows I_c/I_{cm} as a function of the intrinsic tensile strain ϵ_0. I_{cm} represents the maximum value of the $I_c - \epsilon_t$ curve.

Slopes of the $\sigma_t - \epsilon_t$ curve for P2 and P0 are steeper than that of M0. The initial slopes of $\sigma_t - \epsilon_t$ curves are 60, 100 and 110 GPa for M0, P0 and P2, respectively. It indicates the obvious change of apparent Young's modulus, which was already reported by Awaji *et al.* [9]. The origin of the change is the local

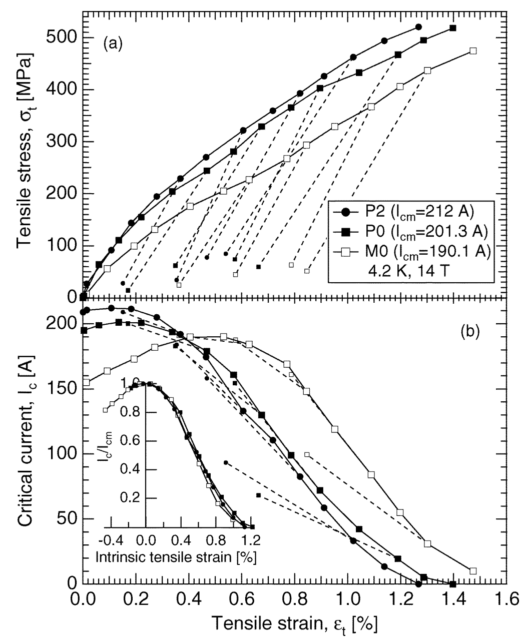

Fig. 4. Tensile stress and critical current as a function of tensile strain. The inset shows the normalized critical current as a function of intrinsic tensile strain.

work-hardening in the superconducting wire. Meanwhile, the slopes of the initial unloading lines (dotted lines) for P0 and P2 do not show any noticeable changes compared with those for M0, being in the range of 77–105 GPa.

In the $I_c - \epsilon_t$ curves for the three samples, the maximum I_c of the $I_c - \epsilon_t$ curve was enhanced. The strain values corresponding to the maximum I_c of the $I_c - \epsilon_t$ curve, ϵ_m, were 0.48%, 0.18% and 0.14% for M0, P0 and P2, respectively. ϵ_m shifted to smaller strain by the pulleyed prebending treatment. From $I_c - \epsilon_t$ curves, the irreversible strain (ϵ_{irr}), which is the upper limit of the I_c-reversible strain region, was estimated to be 1.2%, 0.9% and 0.8% for M0, P0 and P2, respectively. Using these values, one can obtain the upper limit of the intrinsic reversible strain $\epsilon_{0,irr}$ by subtracting ϵ_m from ϵ_{irr}. $\epsilon_{0,irr}$ is 0.72%, 0.72% and 0.66% for M0, P0 and P2, respectively. Note that $\epsilon_{0,irr}$ are nearly identical. This suggests that the prebending treatment did not change the intrinsic mechanical strength of Nb_3Sn. On the other hand, the inset of Fig. 4 suggests that strain sensitivity of I_c does not change by the prebending treatment.

From the viewpoint of superconducting coil design, the $I_c - \sigma_t$ curve is more useful. Fig. 5 shows $I_c - \sigma_t$ curves, which were deduced from Figs. 4(a) and 4(b). The slopes are in good

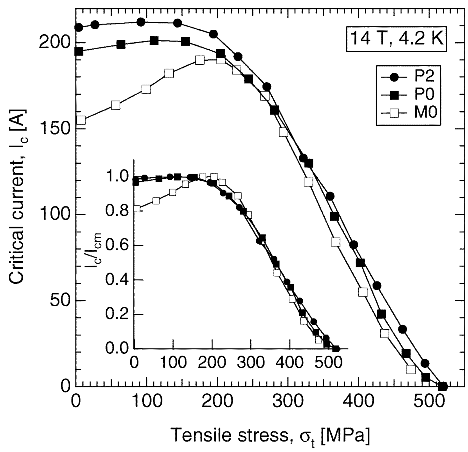

Fig. 5. Critical current as a function of tensile stress. The inset shows the normalized critical current as a function of tensile stress. The slopes for the different samples are in good agreement in the large stress region.

agreement in the large stress region $(\sigma_t > 200\ \mathrm{MPa})$. Hence, the I_c enhancement effect caused by the prebending treatment is not beneficial in the large stress region. On the other hand, in the low stress region of $\sigma_t < 200\ \mathrm{MPa}$, the I_c enhancement effect is quite beneficial.

IV. Summary

To demonstrate the applicability of the prebending strain effect to the R&W coil winding process, superconducting and mechanical characteristics were investigated for $CuNb/Nb_3Sn$ wires which were picked up from the prebent R&W coil winding process. The results were compared with that of $CuNb/Nb_3Sn$ wires which were prebent manually using a prebending former.

I_c of the pulleyed prebent samples were more enhanced than that of the manual prebent samples. This is explained qualitatively that the pulleyed prebending reduced the residual strain more than the manual prebending, so that the superconducting property was enhanced more largely.

The initial slope of the stress-strain curve for the pulleyed prebent samples was steeper than that of as-heat-treated sample. The maximum I_c of the I_c-strain curve was enhanced and the strain value corresponding to the maximum I_c shifted to smaller strain by the pulleyed prebending treatment.

In the large stress region over 200 MPa, the I_c-stress curves of pulleyed prebent samples and as-heat-treated sample are in good agreement, suggesting that the effect of the prebending treatment is not beneficial. In the small stress region below 200 MPa it is quite beneficial.

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