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Large T_c, B_{c2} and I_c Enhancement Effect Due to the Prebending Treatment for Bronze Route Nb_3Sn Wires

K. Watanabe, S. Awaji, H. Oguro, G. Nishijima, K. Miyoshi, and S. Meguro

***Abstract*—In order to develop a react-and-wind (R&W) processed Nb_3Sn superconducting magnet, we investigated the influence on the superconducting properties due to the prebending treatment. Since a reacted Nb_3Sn superconducting wire reveals a very sensitive response from stress and strain, we focus on the prebending treatment which is repeatedly applied to the Nb_3Sn wire through several pulleys in the R&W coil winding process. We found that the prebending treatment doubles the I_c value at 20 T and 4.2 K for bronze route Nb_3Sn wires. This I_c enhancement effect comes from the T_c and B_{c2} enhancement. It turned out that T_c increases from 17.4 to 17.9 K and as a result B_{c2} also increases from 23.7 to 25.2 T at 4.5 K for bronze route multifilamentary Nb_3Sn wires prebent at bending strain of 1.0% and at 5 repeated times.**

***Index Terms*—Bending strain, critical current density, CuNb reinforcement, Nb_3Sn, react and wind process.**

I. Introduction

SINCE the superconducting properties of reacted Nb_3Sn wires are very sensitive for stress and strain [1], a coil is generally heat-treated to form the desired Nb_3Sn compound after the coil winding with unreacted Nb-Sn wires for the safety, which is the so-called wind-and-react (W&R) process. Such a W&R process requires two kinds of vacuum furnaces for the coil heat-treatment and the epoxy impregnation process. The long-time heat-treatment at high temperature is needed in the A15 compound formation reaction of bronze-route Nb_3Sn superconducting wires. These long term fabrication methods using special vacuum furnaces for Nb_3Sn superconducting magnets partly cause high costs for a high field superconducting magnet employing Nb_3Sn wires. In addition, it is difficult to make a large Nb_3Sn superconducting magnet with a wide bore, because of the equipment with very large furnaces.

On the other hand, we have developed mechanically strong Nb_3Sn superconducting wires with CuNb composite reinforcing stabilizer ($CuNb/Nb_3Sn$) [2], [3]. The multifilamentary Nb_3Sn wire reinforced with Cu-20 wt.% Nb composite reveals about twice the yield strength of a conventional Nb_3Sn wire without reinforcement (Cu/Nb_3Sn). In order to reduce a coil fabrication cost and time, we intended to adopt a react and wind (R&W) method for a Nb_3Sn superconducting magnet, employing the high strength $CuNb/Nb_3Sn$ wire. In the R&W process, the $CuNb/Nb_3Sn$ wire has to overcome the repeated bending strains about 10 times in the electric insulating treatment and the coil winding one. Therefore, we focused our concentration on the repeated bending strain effect of the superconducting critical temperature T_c, the upper critical field B_{c2}, and the critical current density J_c of the $CuNb/Nb_3Sn$ wires. Up to now, there exist many reports dealing with the uni-axial stress and strain effect for bronze-route Nb_3Sn wires [4], [5]. Moreover, the repeated tensile strain effect through loading and unloading treatments for Nb_3Sn wires has been also investigated in detail [6]. However, the repeated bending strain effect for Nb_3Sn wires has been hardly reported so far. This is because the R&W method for a Nb_3Sn superconducting magnet has not been common to fabricate laboratory-scale magnets.

In this report, the large enhancement effect for the critical current density due to the repeated bending strain is described for high strength $CuNb/Nb_3Sn$ superconducting wires. It is exhibited that the J_c enhancement is surely related to the T_c and B_{c2} enhancement by the prebending treatment.

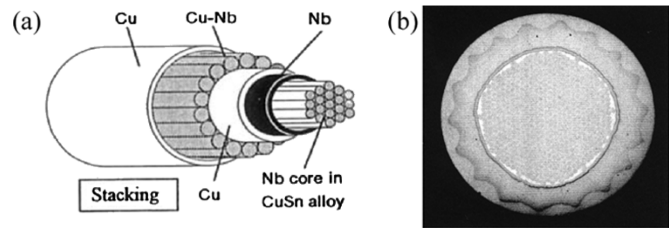

Fig. 1. Structural elements (a) and an overall cross sectional photograph (b) of a high strength Nb_3Sn wire with internal reinforcement of CuNb composite.

II. Experimental Procedures

A. Basic Characteristics of High Strength $CuNb/Nb_3Sn$ Wires

Highly strengthened $CuNb/Nb_3Sn$ wires with internal reinforcement were fabricated by an ordinary bronze-route method, as shown in Fig. 1. The wire parameters of the multifilamentary $CuNb/Nb_3Sn$ wire are an outer wire diameter of 1 mm, number of filaments of 8066, filament diameter of 3.5 μm, bronze composition of Cu-14 wt.% Sn-0.2 wt.% Ti, and stabilizer ratio of Cu/CuNb/bronze matrix of 0.41/0.63/1.0. The relationship between stress and strain for the $CuNb/Nb_3Sn$ wire exhibits the yield stress of 250 MPa at 4.2 K. When the mechanical properties of usual Nb_3Sn wires without reinforcing materials were compared, the $CuNb/Nb_3Sn$ wires

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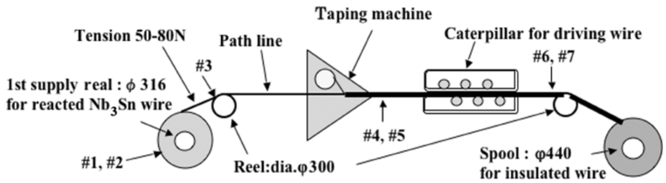

Fig. 2. Polyimide tape insulation process for prereacted Nb_3Sn wires. Indicated number # means the sampling point for the I_c evaluation.

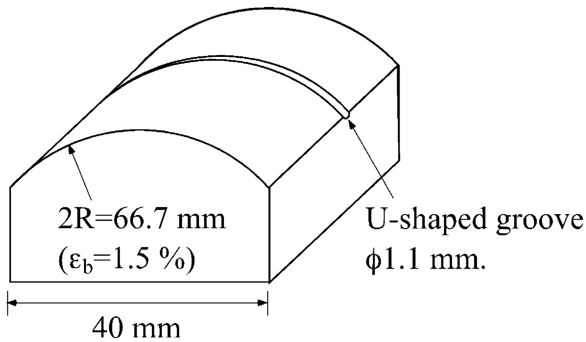

Fig. 3. Bending former with a curved groove to investigate the repeated bending strain effect for prereacted Nb_3Sn wires.

have 1.7 times stronger yield stress than Cu/Nb_3Sn wires. The recent coil design of a high field superconducting magnet requires an electromagnetic stress level of 200 MPa. When the hoop stress of 200 MPa is applied, the 50% degradation of the critical current occurs in Cu/Nb_3Sn wires, but the critical current in $CuNb/Nb_3Sn$ wires in the residual strain state at 200 MPa does not degrade.

B. Repeated Bending Strain in the Practical R&W Process

In order to investigate the effect of the repeated bending strain for high strength $CuNb/Nb_3Sn$ wires, we tentatively adopted the insulating process and the coil winding process for a practical long wire. Through these processes, the fully reacted $CuNb/Nb_3Sn$ wire experiences bending strains repeatedly by several guide pulleys. In the insulating process illustrated in Fig. 2, the un-reacted Nb-Sn wire was heat-treated in a winding situation onto the first supply reel with an outer diameter of 316 mm. After the heat-treatment at 650°C for 240 h, the pre-reacted $CuNb/Nb_3Sn$ wire was wrapped in polyimide insulation tape through a guide reel of 300 mm in diameter, and was finally taken up in the spool of 440 mm in diameter. In the coil winding process, the pre-reacted $CuNb/Nb_3Sn$ wire was wound onto a coil bobbin with 260 mm in diameter through a roller with 310 mm in diameter for a tension monitor and two guide pulleys from the spool. The maximum bending strain during such treatments was less than $\varepsilon_b = 0.4\%$ for the $CuNb/Nb_3Sn$ wire with an outer diameter of 1.0 mm, and the bending treatments were repeated about ten times from the first supply reel to the coil bobbin.

C. Measurement of the Repeated Bending Strain Effect

We prepared a former with a curved groove as illustrated in Fig. 3. Using this former, pre-bending strains up to $\varepsilon_{pb} = 1.5\%$ were applied by attaching the $CuNb/Nb_3Sn$ wire to the curved

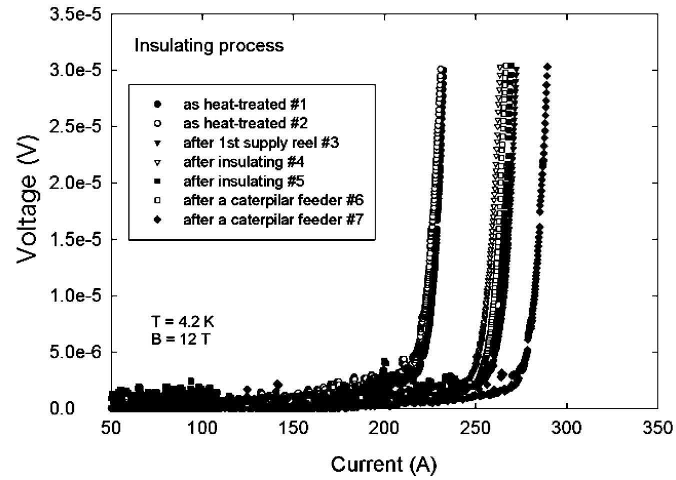

Fig. 4. I_c enhancement effect due to the repeated bending strain in the insulating process for a long $CuNb/Nb_3Sn$ wire. The number # indicates a sampling point in Fig. 2.

groove at room temperature without tension. Such a pre-bending treatment was carried out five times $(N = 5)$ repeatedly.

The prebent wire samples were set onto the measuring holder, keeping the bent wire shapes. T_c and B_{c2} were measured resistively using a vacuum can holder. The temperature of the sample mounted on the Cu holder was monitored with a Cernox thermometer and was controlled precisely by a heater. The value of the measuring current density was 12.7 A/cm^2. I_c was also measured by a four-terminal method in liquid helium and was determined by a 1 $\mu V/cm$ criterion. Magnetic fields were generated by a 15 T superconducting magnet or a 30 T hybrid magnet at the High Field Laboratory for Superconducting Materials.

III. Experimental Results and Discussion

Fig. 4 shows the V-I properties in each stage of the insulating process for the $CuNb/Nb_3Sn$ wires by repeated bending load. It notes that the tendency of the I_c value enhancement becomes larger by repeated bending load. However, the I_c enhancement effect is slightly irregular. These scattering values seem to be associated with the bending strain loading method only on one side of the wire. After the coil winding process, the high strength $CuNb/Nb_3Sn$ superconducting magnet wound with our R&W method showed a good performance as a practical cryogen-free superconducting magnet. This performance test result has been already reported in detail elsewhere [7].

In order to confirm the I_c enhancement effect due to the repeating bending strain for $CuNb/Nb_3Sn$ wires, we used a prebending former which can apply the repeated bending strain on both sides of the wire through bending on one side, releasing naturally, and bending reversely on the opposite side. Fig. 5 shows the I_c enhancement effect for the $CuNb/Nb_3Sn$ wire prebent at $\varepsilon_{pb} = 1.2\%$ and at $N = 5$, together with the wire without prebending for comparison. One notices that the I_c enhancement for the wire with prebending at $\varepsilon_{pb} = 1.2\%$ is twice as large as that without prebending at a high field of 20 T. It is found that the repeated bending strains up to 1.2% at room temperature do not cause a I_c degradation. In addition, I_c enhancements by prebending strain are observed in not only

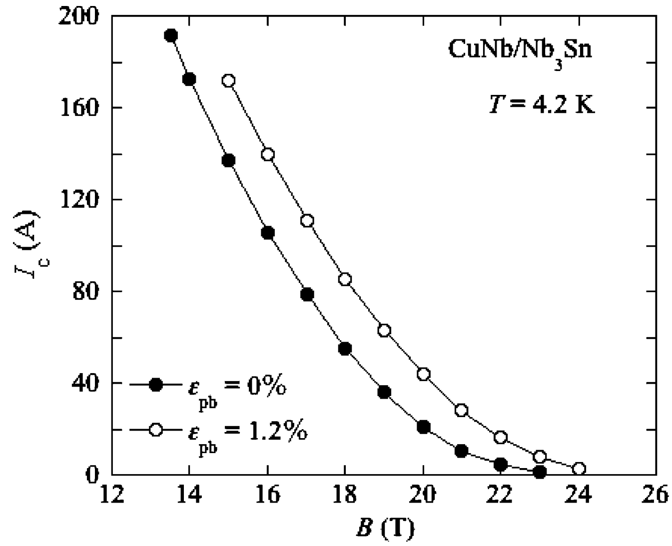

Fig. 5. I_c enhancement effect at $\varepsilon_{pb} = 1.2\%$ and $N = 5$ for a short sample $CuNb/Nb_3Sn$ wire.

$CuNb/Nb_3Sn$, but also in commercial Nb_3Sn wires [8]. Here, we examine the influence of the repeated bending strain on T_c and B_{c2} for $CuNb/Nb_3Sn$ wires. The insets in Fig. 6 show the temperature dependence and the magnetic field dependence of the resistivity for $CuNb/Nb_3Sn$ wires, respectively. We found that the repeated bending treatment at $\varepsilon_b = 1.2\%$ and at $N = 5$ enhances T_c of $CuNb/Nb_3Sn$ from 17.4 to 17.9 K and B_{c2} from 23.7 to 25.2 T at 4.5 K. Furthermore, such the enhancement systematically increases with increase of the bending strain, and also a peak of the bending strain dependent critical current appears at around 1.0–1.2%. From the results obtained in T_c and B_{c2} measurements, we notice that the I_c enhancement due to the prebending strain comes from the T_c enhancement for $CuNb/Nb_3Sn$ wires.

In internally reinforced Nb_3Sn wires, Flükiger *et al.* reported that the critical current at the strain free state for a steel reinforced Nb_3Sn wire is 25% lower than for a unreinforced one [9]. They pointed out a three-dimensional stress distribution in the reinforced Nb_3Sn wires. This suggests that the loading of only axial tensile stress cannot release the residual strain in internally reinforced Nb_3Sn wires. According to Luhman and Welch [10], strain effects on the critical temperature of Nb_3Sn are described in the general form including the axial strain ε_z as well as the radial (or azimuthal) strain ε_r (or ε_θ). In particular, the strain dependence of T_c for a nontextured polycrystal in a cylindrically symmetric strain field is described in the form of

$$T_c = T_c(0) + \Gamma_l \varepsilon_z (1+2\xi) + \varepsilon_z^2 \left\{ \frac{1}{2}\Delta_v (1+2\xi)^2 + \frac{4}{15}\Delta_t (1-\xi)^2 \right\}, \quad (1)$$

where $T_c(0)$ is the critical temperature without strain, ξ is the ratio of the radial (or azimuthal) to the axial strain ($\xi = \varepsilon_r/\varepsilon_z = \varepsilon_\theta/\varepsilon_z$), Γ_l and Δ_v are hydrostatic material constants, and Δ_t is the nonhydrostatic material constant. Therefore, T_c is dependent on the three dimensional strain component ε_z, ε_r, ε_θ and the bending strain is mainly related to the nonhydrostatic term.

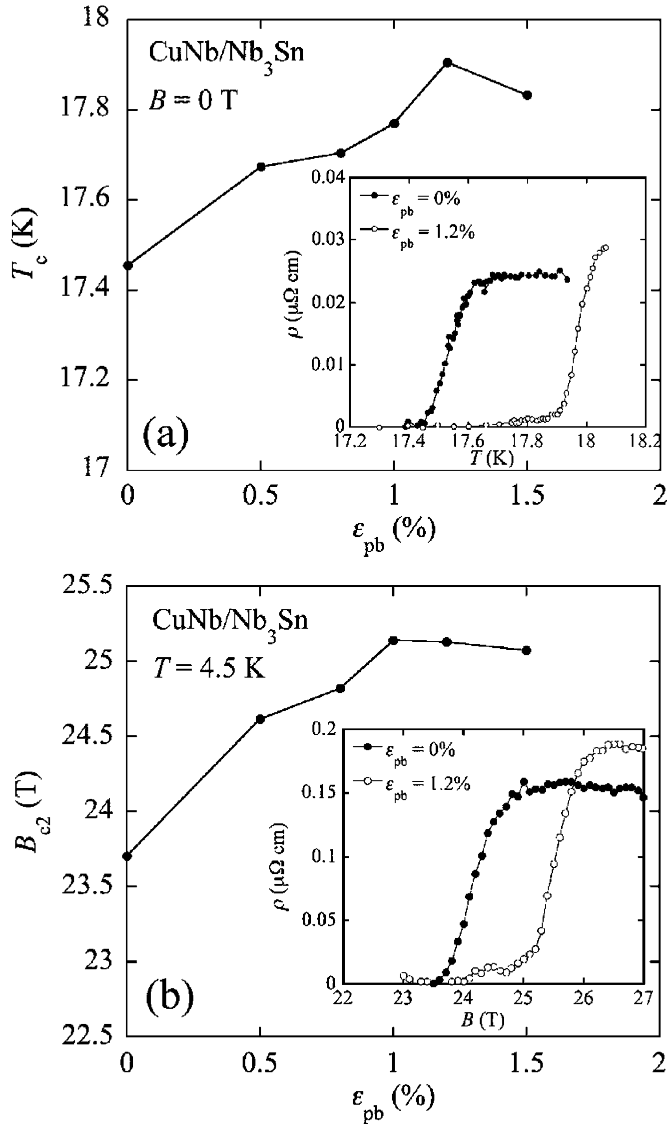

Fig. 6. T_c enhancement (a) and B_{c2} enhancement (b) affected by the prebending treatment for a $CuNb/Nb_3Sn$ wire.

In the bending treatment, it is considered that there exist two prebending effects, the axial residual strain reduction and the radial/azimuthal strain one. Especially the large enhancement of T_c for high strength $CuNb/Nb_3Sn$ wires is related to the reduction of the residual radial/azimuthal strain based on the difference of Poisson's ratios due to the work-hardening of repeated bending treatments.

We found that high strength $CuNb/Nb_3Sn$ wires with the repeated bending treatment shows a great change of the strain dependence on I_c, and that the I_c enhancement due to the repeated bending strain is larger than the effect of the tensile strain [11].

Recently, NMR superconducting magnets have been actively developed to aim a magnetic field generation over 23 T [12]. In this respect, high strength and a large critical current density are inevitably required for the bronze-route Nb_3Sn wires employed in a high field region of 20 T. In order to improve the critical current properties in high fields for Nb_3Sn wires, recent progress enables us to adopt the new bronze-route of high

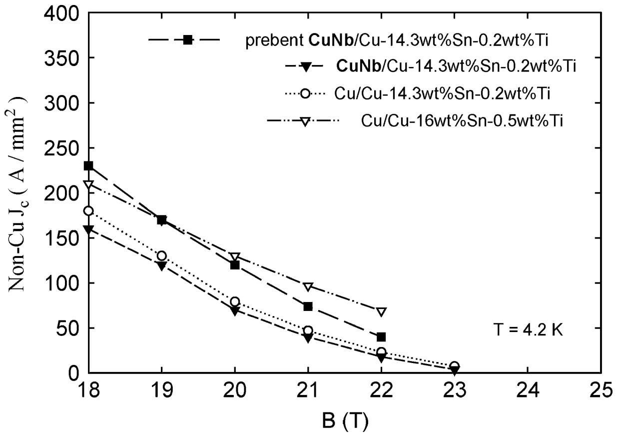

Fig. 7. Non-Cu J_c properties in high fields for various kinds of Nb_3Sn wires. The non-Cu J_c values for the $CuNb/Nb_3Sn$ wires with and without prebending treatments and a high Sn content 16 wt.% bronze-route Nb_3Sn wire are compared to each other.

Sn contents up to 16 wt.% Sn [13]. Fig. 7 shows the comparison of the non-Cu J_c properties in high fields ranging from 18 to 23 T for various kinds of Nb_3Sn wires with and without reinforcement. One should note that the non-Cu J_c value of the prebent $CuNb/Nb_3Sn$ wire is twice as high as that of the nonprebent 14.3 wt.% Sn bronze-route $CuNb/Nb_3Sn$ wire at 20 T and at 4.2 K, and is comparable to that of a 16 wt.% Sn bronze-route Cu/Nb_3Sn wire. When we focus on large I_c enhancement at a high field of 20 T, it is expected that the high strength $CuNb/Nb_3Sn$ wire is a promising high field superconducting wire for the react-and-wind process.

IV. Conclusion

The prebending treatment for the internally reinforced Nb_3Sn wire with CuNb reinforcing stabilizer ($CuNb/Nb_3Sn$) extremely enhances the critical current, and the I_c enhancement achieves twice the critical current value at 20 T and 4.2 K in comparison with an ordinary Nb_3Sn wire without a bending treatment. This I_c enhancement clearly comes from the T_c and B_{c2} enhancement. It is found that the employment of the high strength $CuNb/Nb_3Sn$ wire is very effective for a react-and-wind processed Nb_3Sn superconducting magnet in high fields up to 20 T.

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