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Effect of Prebending Strain on $CuNb/Nb_3Sn$ Superconducting Coils Using a React and Wind Method

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***Abstract*—We have found that superconducting properties such as a critical current for bronze route Nb_3Sn superconducting wires were enhanced by prebending strain (ε_{pb}), which is the repeated bending strain at room temperature. In this study, four kinds of react and wind (R&W) processed CuNb reinforced bronze route Nb_3Sn coils with $\varepsilon_{pb} = 1.0$, 0.8, 0.5 and 0% were prepared. We investigated the effect of prebending strain for the coils. In the electromagnetic compressive stress condition, a critical current (I_c) of the R&W processed coil was enhanced by the prebending strain. These I_c values are larger than those of a short sample wire without prebending strain. In the hoop stress condition, the I_c of four coils revealed a similar value. Therefore, it is considered that the I_c was limited by the large tensile stress for all coils in the hoop stress states. These results suggest that the I_c enhanced by the effect of prebending strain is applicable for the R&W coil design without degradation in large stress and strain states.**

***Index Terms*—Critical current, Nb_3Sn, prebending strain, react and wind processed coils.**

I. Introduction

THE SUPERCONDUCTING properties of the A15 compounds are very sensitive to stress and strain [1]. Especially, the properties of a Nb_3Sn wire were deteriorated by the compressive residual strain, which was given at cooling from the heat treatment temperature to 4.2 K by the thermal contraction difference between Nb_3Sn and other composed materials.

However, we have found that the repeated bending load at room temperature largely enhances a critical current (I_c), an upper critical field (B_{c2}) and a critical temperature (T_c) of bronze route Nb_3Sn wires [2]–[8]. We called the repeated bending strain as "prebending strain" and the repeated bending load as "prebending treatment". It was understood qualitatively that the prebending strain reduces the residual strain of the Nb_3Sn wires. Thus, the superconducting properties of the wire are enhanced.

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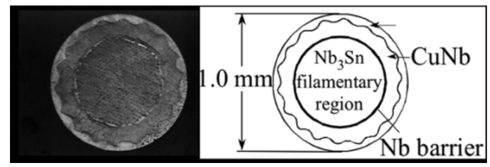

Fig. 1. Cross sectional view of $CuNb/Nb_3Sn$ wire.

It is expected that the effect of prebending strain is beneficial for a react and wind (R&W) processed Nb_3Sn coil, i.e., the superconducting properties of the Nb_3Sn coils are enhanced by the effect of prebending strain. In this study, we prepared four kinds of R&W processed CuNb reinforced Nb_3Sn ($CuNb/Nb_3Sn$) coils with prebending strain. We investigated the effect of prebending strain on I_c of the coils. This paper describes the performance of the R&W $CuNb/Nb_3Sn$ coil using the prebending treatment.

II. Experimental Procedure

A. Preparation for the Sample Wires

A bronze route multifilamentary $CuNb/Nb_3Sn$ wire as shown in Fig. 1 was prepared. The wire was wound on the 440 mm diameter reel and heat-treated at 670°C for 96 hours. The wire parameters of the $CuNb/Nb_3Sn$ superconductor are the outer diameter of 1.0 mm, filament diameter of 3.5 μm, number of filaments of 10165, copper/CuNb reinforcement/non-Cu ratio of 20.7/34.5/44.8, and twist pitch of 30 mm. Straight short samples were also prepared to evaluate the standard properties.

B. Measurements for Short Wires

We investigated the effect of prebending strain on I_c for the wire. Prebending strain $\varepsilon_{pb} = 0$, 0.5, 0.8, 1.0, 1.2 and 1.5% was applied 10 times by using a former with a curved surface. The wire was bent along the curved surface [2]. The number of prebending treatment (N_{pb}) is similar to the number of pulleys in a R&W coil fabrication process for a superconducting magnet. We investigate the N_{pb} dependence of I_c for the wires with $\varepsilon_{pb} = 0.5$ and 0.8%, and $N_{pb} = 5$, 10, 15, 20, 30, 50, and 100, respectively. In these experiments, I_c was measured by a four-terminal method in liquid helium. A short sample wire was 40 mm in length with the voltage tap separation of 10 mm. Magnetic fields were applied by a 15 T cryogen-free superconducting magnet [9] or a 28 T hybrid magnet at the High Field Laboratory for Superconducting Materials (HFLSM), IMR, Tohoku University.

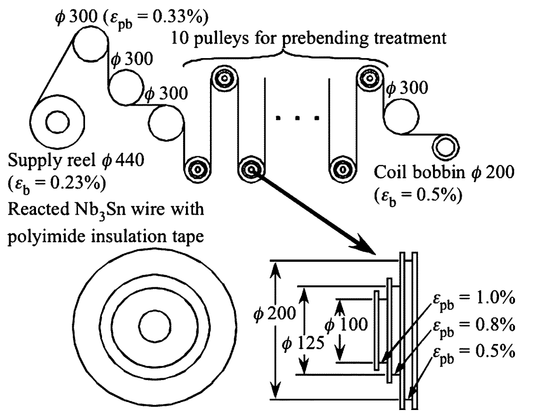

Fig. 2. Winding process for a R&W processed coil. The prebending strain was applied by 10 pulleys.

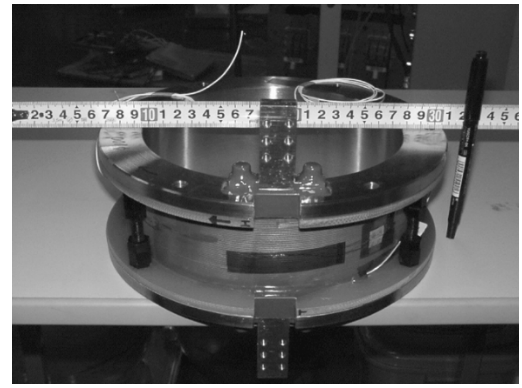

Fig. 3. The photograph of the R&W processed $CuNb/Nb_3Sn$ coil.

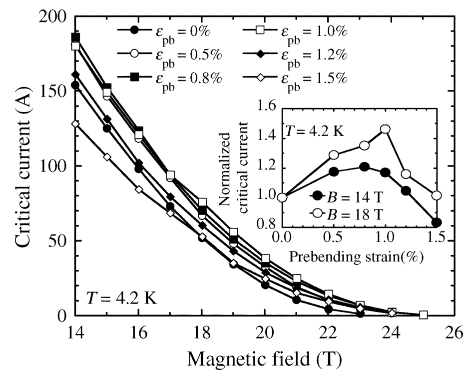

Fig. 4. I_c as a function of magnetic field for $CuNb/Nb_3Sn$ short wires. An inset shows the normalized I_c (I_{c0}) as a function of ε_{pb} at 14 T and 18 T.

TABLE I
SPECIFICATIONS FOR FOUR KINDS OF THE R&W PROCESSED $CuNb/Nb_3Sn$ SUPERCONDUCTING COILS

	Coil1	Coil2	Coil3	Coil4
ε_{pb}(%)	1.0	0.8	0.5	0
Diameter of pulleys (mm)	100	125	200	-
Inner diameter (mm)	200			
Outer diameter (mm)	202			
Height (mm)	54.5			
Number of turns	49	49	48	49
Number of layers	1			
Winding tension (MPa)	31-37			

C. Fabrication of R&W Processed Coils

We prepared four kinds of monolayer coils with $\varepsilon_{pb} = 1.0$, 0.8, 0.5 and 0%. In the coil fabrication, the test coil was made in the following process. Fig. 2 shows the winding process of the R&W processed coil. The wire, which was insulated with polyimide tapes beforehand, was pulled out from a 440 mm diameter reel (bending strain $\varepsilon_b = 0.23\%$) by 300 mm diameter pulleys ($\varepsilon_{pb} = 0.33\%$). The prebending strain was applied through 10 pulleys with diameter of 100 mm ($\varepsilon_{pb} = 1.0\%$), 125 mm ($\varepsilon_{pb} = 0.8\%$) and 200 mm ($\varepsilon_{pb} = 0.5\%$), respectively. The coil with $\varepsilon_{pb} = 0\%$ (a normal R&W coil) was made without passing the 10 pulleys. After the prebending treatment, the wire was wound on a 200 mm diameter bobbin with epoxy-resin molding, corresponding to $\varepsilon_b = 0.5\%$.

Specifications of the coils are shown in Table I. The number of turns was 49 for each coil. The height of the coil was 54.5 mm. The tensile stress was under the control of 31–37 MPa during coil winding. The photograph of the test coil is shown in Fig. 3.

D. Measurements of the Test Coils

I_c of the test coils was measured by the four-terminal method in liquid helium. Voltage taps were soldered at both ends of the coil and at 1 turn apart from both ends of the coil. The test coil was set in a 12 T large bore superconducting magnet at the HFLSM, IMR, Tohoku University. I_c was evaluated in fields up to 11 T.

We measured I_c at two kinds of conditions. One was a compressive stress test. The direction of the magnetic field produced by the test coil was opposite to the external field, thus the compressive electromagnetic force was applied to the coil. In this way, the actual compressive strain was not applied to the wire because the bobbin supported the compressive force.

The other was a hoop stress test. The direction of the magnetic field generated by the test coil is the same direction as an external field. This was the tensile stress test for the coil wire because the hoop stress was applied to the test coil.

III. RESULTS

A. The Short Wires

Fig. 4 shows the magnetic field dependence of the I_c for $CuNb/Nb_3Sn$ short wires with $\varepsilon_{pb} = 0$, 0.5, 0.8, 1.0, 1.2 and 1.5%. I_c's of the wires were determined by using a 1.0 $\mu V/cm$ electrical criterion. One notes that the prebending strain surely enhanced the I_c value of the short wires. It is expected that I_c of the coils also will be enhanced by the effect of prebending strain. An inset indicates that the enhancement ratio reaches to around 1.5 at $\varepsilon_{pb} = 0.8\%$ and $B = 18$ T.

Fig. 5 shows the N_{pb} dependence of I_c for short wires in the case of $\varepsilon_{pb} = 0.5$ and 0.8%. I_c showed the maximum enhancement at $N_{pb} = 15$. I_c decreased gradually in the region of $N_{pb} \leq 50$, and it became zero at $N_{pb} = 100$. The result suggests that $N_{pb} = 10$ is effective for the I_c enhancement in a R&W processed coil. It is considered that the I_c degradation due to the large N_{pb} may be released to the micro crack generation.

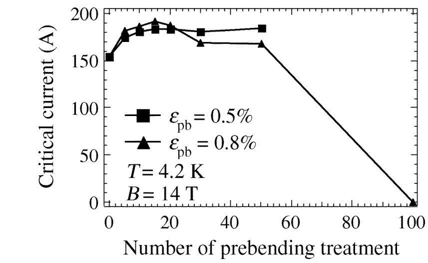

Fig. 5. I_c as a function of number of prebending treatment (N_{pb}) for $CuNb/Nb_3Sn$ short wires.

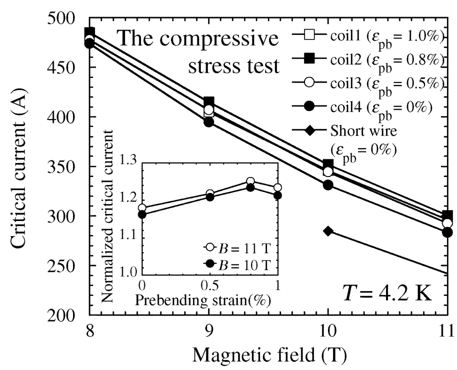

Fig. 6. I_c as a function of magnetic field for the R&W processed $CuNb/Nb_3Sn$ coils in the compressive stress test. An inset shows normalized I_c as a function of ε_{pb} at 11 T and 10 T.

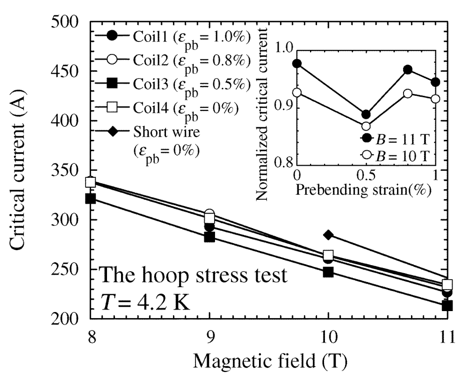

Fig. 7. I_c as a function of magnetic field for the R&W processed $CuNb/Nb_3Sn$ coils in the hoop stress test. An inset shows normalized I_c as a function of ε_{pb} at 11 T and 10 T.

The investigation on the relationship between the I_c degradation and microstructure is now in progress.

B. The R&W Processed Coils

Figs. 6 and 7 show the magnetic field dependence of I_c for four test coils in the compressive stress and the hoop stress test, respectively. The obtained I_c values of the coils were determined by using a 0.1 $\mu V/cm$ electrical criterion. When the coil quenched below 0.1 $\mu V/cm$, I_c was deduced from an extrapolation. In the measurement, the quenched current increases gradually because of mechanical disturbances, which were mainly epoxy cracking and wire movements. Therefore, the epoxy did not give any influence to the I_c of the test coils. After the hoop stress test, we measured the I_c in the compressive stress state again and confirmed that I_c's were the same as the data before the hoop stress test.

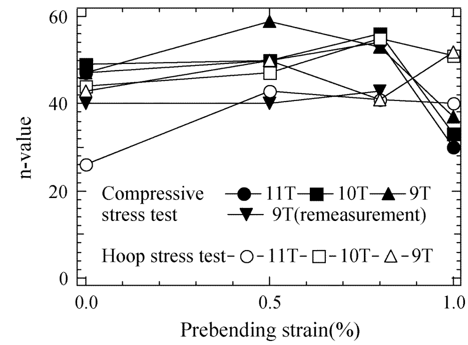

Fig. 8. The n-value as a function of ε_{pb} for the R&W processed $CuNb/Nb_3Sn$ coils.

In the compressive stress test, I_c of four kinds of coils was enhanced. I_c of the coil2 ($\varepsilon_{pb} = 0.8\%$), which was 351.8 A at 10 T, showed the maximum enhancement, and was 25% larger than $I_c = 284.9$ A at 10 T for the short wire with $\varepsilon_{pb} = 0\%$. I_c of the coil4 ($\varepsilon_{pb} = 0\%$), which was 331 A at 10 T, was also larger than that of the short wire with $\varepsilon_{pb} = 0\%$. This is because 300 mm diameter pulleys ($\varepsilon_{pb} = 0.33\%$) probably enhanced I_c of the coil4 during coil winding. The I_c enhancement of the coil4 suggests that the I_c of a normal R&W processed coil within a small prebending strain state is always enhanced. Furthermore, I_c of the R&W processed coil with prebending strain was much larger than that of the normal R&W processed coil. This result implies that the effect of prebending strain is maintained in a R&W processed coil.

In the hoop stress test, the I_c values of the four coils lie in almost the same level though the experienced ε_{pb} was different. This experimental result implies that the I_c was limited by not the prebending strain value, but the hoop stress value. When the hoop stress is estimated by using $\sigma = BJR$, where, B, J and R are the magnetic field, current density and the coil radius, respectively, the maximum hoop stress was 330 MPa at 11 T and 360 MPa at 9 T. This result shows that large hoop stress was applied to the coils.

Fig. 8 shows the ε_{pb} dependence of the n-value calculated from V-I characteristics. In the compressive stress test, the n-value of the coil2 ($\varepsilon_{pb} = 0.8\%$) showed the maximum enhancement. However, the n-value of the coil1 ($\varepsilon_{pb} = 1.0\%$) was decreased. This result implies that the superconducting properties of coil1 were deteriorated by the large prebending strain. In the hoop stress test, all of the n-value for the four coils have a similar value. When we measured I_c again in the compressive stress state after the hoop stress test, the obtained n-values became smaller than those before the hoop stress test. These results suggest that the large hoop stress about 360 MPa surely deteriorated the superconducting properties of the four coils.

IV. Discussion

The compressive stress test exhibits that the effect of prebending strain enhances the superconducting properties for a R&W processed coil. Moreover, the experimental results

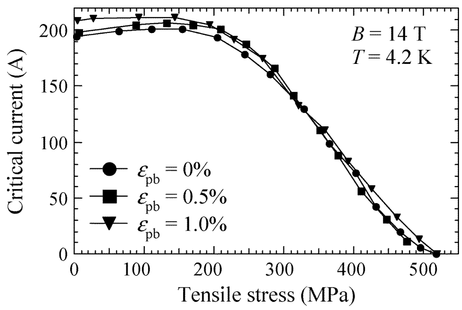

Fig. 9. I_c as a function of axial tensile stress for $CuNb/Nb_3Sn$ short wires with prebending strain by the same process as the coil winding.

showed that the maximum enhancement value of I_c for the coil with prebending strain was higher than that of the short wire. The I_c enhancement of the coil2 ($\varepsilon_{pb} = 0.8\%$) was 25% at 10 T, and the I_c enhancement of the short wire with $\varepsilon_{pb} = 0.8\%$ was 20% at 14 T. As shown in Fig. 3, the I_c enhancement value of the short wire decreased with decreasing a magnetic field. This difference may be associated with the different prebending treatment between the former and the pulley. Using the pulley, a certain tensile load is added during the prebending treatment.

In the hoop stress test, I_c of four coils was the same value in spite of the different ε_{pb}. This result was explained by Fig. 9, which shows the axial tensile stress dependence of I_c for short wires. The short wires were prepared by sampling in the prebending strain state by the same process as the coil winding. One should notice that I_c of all the wires reaches to almost the same value in the large stress state. Moreover, we understand that the effect of prebending strain appears under the small hoop stress state. Consequently, the effect of prebending strain is applicable for a R&W processed coil under the small hoop stress.

V. Summary

We measured the I_c of four kinds of the R&W processed $CuNb/Nb_3Sn$ coils with $\varepsilon_{pb} = 1.0$, 0.8, 0.5 and 0%. In the compressive stress test, the I_c values of the four coils were enhanced. The maximum value of I_c was 351.8 A at the coil with $\varepsilon_{pb} = 0.8\%$. The I_c enhancement was 25% larger than that of the short wire without prebending strain. In the hoop stress test, the I_c values for four coils with different prebending strain were almost the same. This result indicates that I_c was limited by the large hoop stress of 330–360 MPa. The n-value decreased at $\varepsilon_{pb} = 1.0\%$ in the compressive stress test because of degradation of the wire. After the hoop stress tests, the n-value of all coils were decreased because the large hoop stress deteriorated the superconducting properties of the coils. These results suggest that the large prebending strain up to 0.8–1.0% successfully enhances the superconducting properties of Nb_3Sn coils fabricated by a R&W method. Furthermore, we demonstrated that the effect of prebending strain was also beneficial for a R&W processed coil if we used the coil under the small stress below 200 MPa.

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