Relationship between Strain Effect and Martensitic Transformation in Multifilamentary Nb3Sn Wires

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Relationship between strain effect and martensitic transformation in multifilamentary Nb_3Sn wires

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For bronze-processed multifilamentary pure Nb_3Sn and 2.3 at. % Ti added $(Nb,Ti)_3Sn$ wires, which were prepared under the condition of the same wire parameters such as the filament size, filament number, and bronze ratio, the strain effects on the critical current density were measured. The large difference of the residual strain between Nb_3Sn and $(Nb,Ti)_3Sn$ wires was obtained. It was found that the martensitic transformation for Nb_3Sn compound largely contributes to the residual strain through the variation of the elastic modulus in bronze-processed multifilamentary Nb_3Sn wires. It was verified that the ternary element addition of Ti surely suppresses the martensitic transformation in the bronze processed multifilamentary Nb_3Sn wire.

I. INTRODUCTION

In multifilamentary Nb_3Sn superconducting wires, many efforts for improvement of the critical current density J_c in high magnetic fields up to 20 T have been made. The flux pinning mechanism which is responsible for J_c is well known to be due to grain boundaries in Nb_3Sn.[1] Since the J_c value in fields largely depends on the characteristics of pinning centers, it is of importance to control the microstructure such as stoichiometric composition or fine grain boundaries. In addition, the upper critical field B_{c2} principally affects the performance of J_c in high fields. Therefore, the effects of ternary element addition such as Ti or Ta in the bronze-processed Nb_3Sn wires have been investigated, in order to improve pinning centers and increase B_{c2}.[2–4] Up to now, Ti-added Nb_3Sn superconducting wires successfully contribute to realization of high-field superconducting magnets over 20 T.[5,6]

On the other hand, the martensitic transformation from a cubic to a tetragonal phase for the A15-Nb_3Sn compound has been widely identified at low temperatures.[7–10] When the martensitic transformation occurs at low temperature, the B_{c2} value at 4.2 K for tetragonal Nb_3Sn is by about 5 T lower than that for cubic one.[11] This lower B_{c2} value is the inferior point for the improvement of the high-field J_c characteristics. The transition temperature of the martensitic transformation sensitively depends on the specimen quality. The transformation can be suppressed by deviation from the stoichiometry[9] or by the ternary element addition[12] such as Ti or Ta. From the standpoint mentioned above, a detailed investigation on the martensitic transformation in Nb_3Sn wires using an internal friction technique was reported by Kumakura *et al.*[13] The point of interest in their report is that the suppression of the martensitic transformation by the ternary element additions is not a dominant factor in the improvement of B_{c2}. Their results suggest that the improvement of B_{c2} is mainly attributed to the increase of the resistivity ρ_n which is related to the temperature slope of B_{c2}. In the practical multifilamentary Nb_3Sn wires, it is very difficult to directly measure the resistivity of Nb_3Sn and the martensitic transformation temperature of Nb_3Sn by a resistive method because of a Cu stabilizer and a bronze matrix. Therefore, the subject on the effect of ternary element additions in Nb_3Sn still remains unsettled for the martensitic transformation.

Moreover, there exists a strain effect on the superconducting properties such as T_c, B_{c2}, and J_c in A15 compound. Especially, the large strain effect in Nb_3Sn wires[14] attracts special attention as a crucial issue for practical use. The martensitic transformation is also sensitive to such strain, and the uniaxial stress for multifilamentary Nb_3Sn wires induces a cubic-to-tetragonal phase transition.[15] Thereby, in the case of the bronze-processed multifilamentary Nb_3Sn wires accompanying a large residual strain, the influence due to the martensitic transformation for the strain effect on J_c must be made clear. This is because the effect of the ternary element addition for the B_{c2} enhancement is complicatedly changed by both phenomena of the martensitic transformation and the strain effect.

The aim of the present work is to clarify the relationship between the martensitic transformation and the strain effect in bronze-processed multifilamentary Nb_3Sn superconducting wires. The strain effects on J_c for pure Nb_3Sn and Ti-added $(Nb,Ti)_3Sn$ wires were studied in detail. The residual strains obtained for Nb_3Sn and $(Nb,Ti)_3Sn$ wires are elucidated, and the relationship between the martensitic transformation and the strain effect is discussed.

II. EXPERIMENT

Two kinds of typical bronze-processed multifilamentary Nb_3Sn superconducting wires were prepared for comparison. Table I lists the characteristics of the multifilamentary wires fabricated by a 13 wt. % Sn bronze route. Pure Nb_3Sn and Ti-added $(Nb,Ti)_3Sn$ wires consist of the same structural configuration such as the filament size, filament number, Ta barrier, and Cu ratio with each other, except for a ternary ele-

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TABLE I. Characteristics of bronze-processed multifilamentary Nb_3Sn and $(Nb,Ti)_3Sn$ superconducting wires.

	Nb_3Sn	$(Nb,Ti)_3Sn$
Wire diameter (mm)	0.8	←
Bronze	Cu-13 wt % Sn	←
Core	Nb	Nb-1.2 wt % Ti
Filament diameter (μm)	3.4	←
Number of filaments	5587	←
Bronze/core ratio	4.1	←
Cu/non-Cu ratio	0.78	←
Barrier	Ta	←

ment addition of Ti in the $(Nb,Ti)_3Sn$ wire. The quantity of Ti addition into a Nb core is 1.2 wt. % Ti, which corresponds to 2.3 at. % Ti. The heat treatments were carried out at 750 °C for 192 h in the Nb_3Sn wire and at 670 °C for 192 h in the $(Nb,Ti)_3Sn$ wire, respectively.

Figure 1 shows a cross-sectional view of the multifilamentary wires with the same wire structure, and Fig. 2(a) exhibits its magnification. There is no problem to form Nb_3Sn compound with the Ta barrier. One notes that Nb cores fully reacted and entirely changed into Nb_3Sn or $(Nb,Ti)_3Sn$ compound. There remains no unreacted Nb core in the A15 compound. For comparison, a $(Nb,Ti)_3Sn$ wire with unreacted Nb cores which was heat treated at 670 °C for 120 h is presented in Fig. 2(b).

In order to evaluate the stress-strain effect on J_c, a measuring apparatus equipped with a 15 T superconducting magnet was used.[16] Magnetic fields were applied perpendicular to the transport current. Short straight samples about 40 mm in length and with a gauge length of 17.5 mm were measured. Both ends of the wire sample were soldered to a Cu grip of a current terminal. The axial load of less than 50 kg and the transport current of less than 200 A were applicable. The strain measurement was detected by use of an extensometer, and the accuracy of the strain measurement was within 0.05%. The critical current I_c was determined by a 1 μV/cm criterion between voltage taps soldered at a distance of about 5 mm.

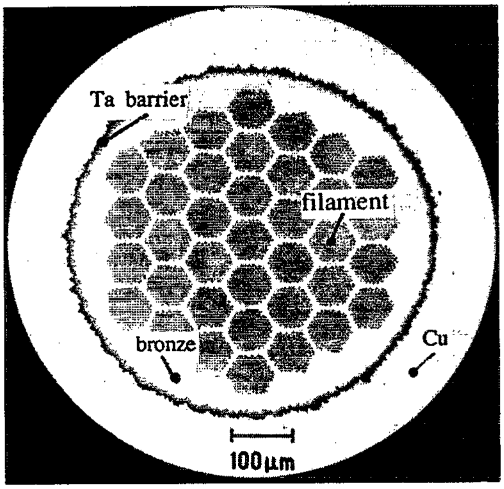

FIG. 1. Cross-sectional view in the bronze-route multifilamentary superconducting Nb_3Sn or $(Nb,Ti)_3Sn$ wire.

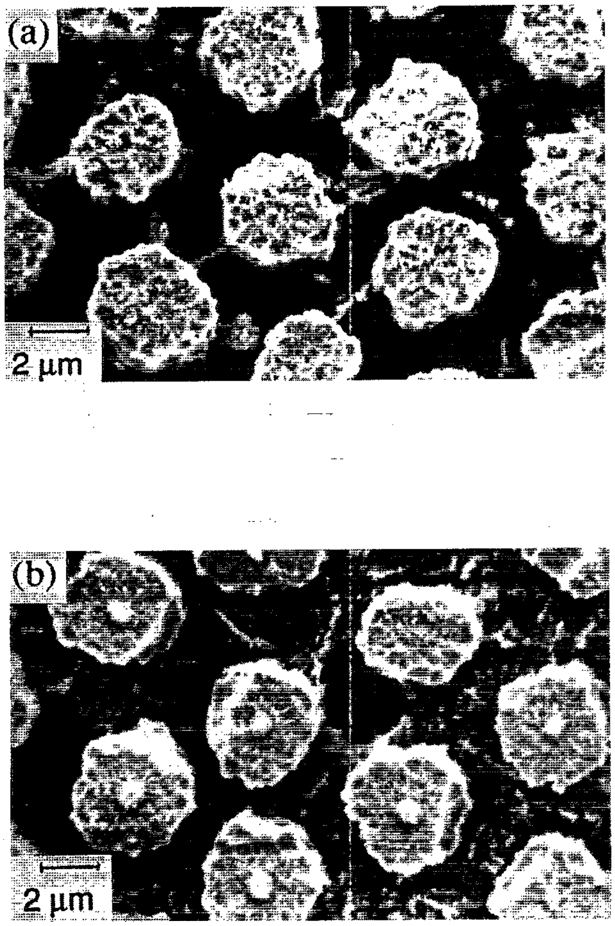

FIG. 2. Scanning electron microscope (SEM) photographs in the bronze-route multifilamentary $(Nb,Ti)_3Sn$ superconducting wires heat treated at 670 °C (a) for 192 h and (b) for 120 h.

III. RESULTS AND DISCUSSION

The J_c properties in fields up to 23 T for Nb_3Sn and $(Nb,Ti)_3Sn$ wires are shown in Fig. 3. The J_c values of about 200 A/mm^2 in a cross-sectional area excloding the Cu stabilizer is obtained at 14 T for the Nb_3Sn wire and at 17 T for the $(Nb,Ti)_3Sn$ wire, respectively. J_c for the Nb_3Sn wire is slightly lower than that for ordinary bronze-processed multifilamentary Nb_3Sn wires, while J_c for the $(Nb,Ti)_3Sn$ wire is comparable with the value reported so far.[17] The irreversibility field B^* at which J_c goes to zero[18] is measured to be about 21.8 T at 4.2 K for the Nb_3Sn wire and also is lower in comparison with ~23 T for the typical Nb_3Sn compound. This degradation of the superconducting properties for the Nb_3Sn wire comes from a large strain effect, which is discussed below.

Figures 4(a) and 4(b) show the strain dependence of I_c for Nb_3Sn and $(Nb,Ti)_3Sn$ wires, respectively. The measurements were performed at 14 T and 4.2 K. I_c measured without applied axial strain corresponds to that shown in Fig. 3. The $(Nb,Ti)_3Sn$ wire exhibits the weaker strain dependence

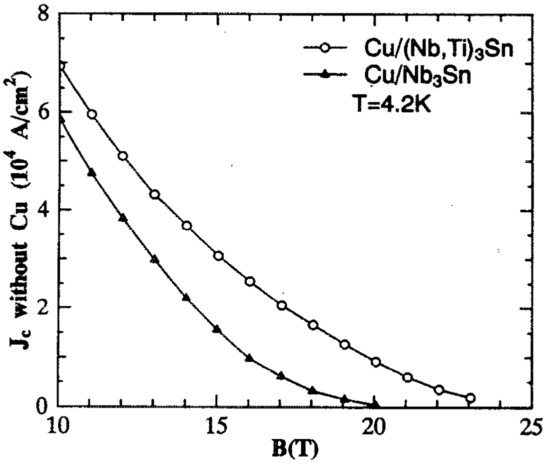

FIG. 3. Critical current density as a function of magnetic field in the bronze-route multifilamentary Nb_3Sn and $(Nb,Ti)_3Sn$ wires.

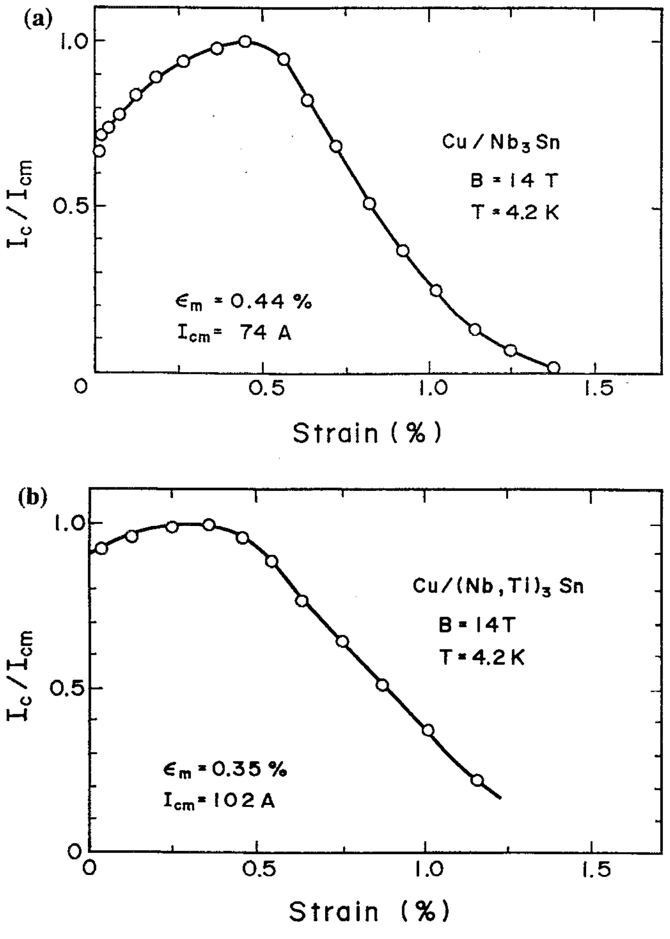

FIG. 4. Strain effect on the critical current in the bronze-route multifilamentary wires of (a) Nb_3Sn and (b) $(Nb,Ti)_3Sn$.

TABLE II. Volume fractions (in %) for each component in Nb_3Sn composites.

	Nb_3Sn	$(Nb,Ti)_3Sn$
V_{Cu}	43.8	←
V_{BZ}	41.3	←
V_{Nb}	0	←
V_{Nb_3Sn}	10.1	←
V_{Ta}	4.84	←

of J_c than the Nb_3Sn wire, owing to the higher B_{c2} value in the $(Nb,Ti)_3Sn$ wire. The peak of I_c as a function of axial strain represents a strain-free state in bronze-processed multifilamentary Nb_3Sn wires. The value of the residual strain was obtained to be 0.44% for the Nb_3Sn wire and 0.35% for the $(Nb,Ti)_3Sn$ wire. Note that the residual strain for the Nb_3Sn wire is larger than that for the $(Nb,Ti)_3Sn$ wire. The large residual strain for the Nb_3Sn wire is consistent with slightly lower J_c and B^* values.

Now a great interest was focused on the difference between the residual strains obtained for Nb_3Sn and $(Nb,Ti)_3Sn$ wires. In order to calculate the residual strain in bronze-processed multifilamentary Nb_3Sn superconducting wires, we follow a simple analytical method presented by Easton *et al.*[19] The model is based on the volume fraction of each component treated individually in multifilamentary composites. It is considered that the Cu stabilizer and bronze matrix have much larger thermal contraction than the Nb_3Sn compound, Nb core, and Ta barrier from reaction temperature to 4.2 K. Since the thermal-expansion coefficients of Nb_3Sn, Nb, and Ta are nearly equal, the filament system combined with the Nb_3Sn compound, Nb core, and Ta barrier can be regarded as undergoing the compressive stress. Therefore, the force balance in the absence of external applied stress is described as follows:

$$-\sigma_f=(V_{Cu}\sigma_{Cu}+V_{BZ}\sigma_{BZ})/V_f, \qquad (1)$$

where V_f, V_{Cu}, and V_{BZ} and σ_f, σ_{Cu}, and σ_{BZ} are the volume fraction and the residual stress of the filament system, Cu stabilizer, and bronze matrix, respectively. In addition, the combined modulus E_f in the filament system with the similar values of the thermal-expansion coefficient is given by

$$E_f=(V_{Nb}E_{Nb}+V_{Nb_3Sn}E_{Nb_3Sn}+V_{Ta}E_{Ta})/V_f, \qquad (2)$$

where V_{Nb}, V_{Nb_3Sn}, and V_{Ta} and E_{Nb}, E_{Nb_3Sn}, and E_{Ta} are the volume fraction and the elastic modulus of the Nb core, Nb_3Sn compound, and Ta barrier, respectively. Then the residual strain ϵ_r in the filament system of Nb, Nb_3Sn, and Ta is derived from Hooke's law,

$$\epsilon_r=\sigma_f/E_f. \qquad (3)$$

To perform the analytical method for the prediction of the residual strain in bronze processed multifilamentary Nb_3Sn wires, the volume fractions of each component were obtained from the conductor structure shown in Table I and Fig. 1. Table II lists the volume percentages of each component in Nb_3Sn and $(Nb,Ti)_3Sn$ wires. Since there is no unreacted Nb core in both wire samples as already mentioned, the volume faction of Nb is $V_{Nb}=0$. Therefore, the volume fraction of the filament system (V_{Nb_3Sn} + V_{Ta}) is $V_f=14.9\%$ in both wires.

It is estimated that the bronze matrix of Cu-13 wt % Sn before reaction changes into the bronze of Cu-4.3 wt % Sn

TABLE III. Elastic modulus for various Nb_3Sn.

	Elastic modulus E (GPa)	Ref.
Nb_3Sn single crystal	165	19, 20
Bronze-route Nb_3Sn wire	51	21
Bronze-route $(Nb,Ti)_3Sn$ wire	109	21

after reaction assuming Nb entirely converted to Nb_3Sn in the wires with the bronze ratio of 4.1. According to the useful relationship[19] in the form of

$$\sigma_{BZ}=18.37\times(\text{wt \% Sn in bronze})+82.7\ \text{MPa}, \qquad (4)$$

the yield stress of the bronze matrix in both Nb_3Sn and $(Nb,Ti)_3Sn$ wires is calculated to be $\sigma_{BZ}=159$ MPa. Further, assuming the typical value of $\sigma_{Cu}=20.7$ MPa in the plastic behavior, $\sigma_f=501$ MPa is obtained by use of Eq. (1).

Here we focus on the value of the elastic modulus for Nb_3Sn compound. Various values of E_{Nb_3Sn} have been reported in single crystals[19,20] and bronze route wires.[21] The important point is that the modulus E in bronze-processed Nb_3Sn wires, which was reported by Bussiere *et al.*,[21] is extremely low due to the martensitic transformation. It is noteworthy that there exists a large difference of E between Nb_3Sn and $(Nb,Ti)_3Sn$ wires. Comparisons of the values of E are made among the Nb_3Sn single crystal, Nb_3Sn wire, and $(Nb,Ti)_3Sn$ wire as indicated in Table III. Using the value of $E_{Ta}=186$ GPa,[21] $E_f=172$, 94.6, and 134 GPa are obtained for E_{Nb_3Sn} = 165, 51, and 109 GPa from Eq. (2). Then the prediction of the residual strain in bronze-processed multifilamentary Nb_3Sn wires is exhibited using Hooke's law of Eq. (3). As a result, $\epsilon_r=0.29\%$, 0.53%, and 0.37% are estimated for E_{Nb_3Sn} = 165, 51, and 109 GPa.

Utilizing analytically derived residual strains, one can compare these values with experimentally measured residual strains for bronze-processed multifilamentary Nb_3Sn and $(Nb,Ti)_3Sn$ wires. It is found that the value of $\epsilon_r=0.35\%$ measured for the Ti-added $(Nb,Ti)_3Sn$ wire is in good agreement with the prediction of $\epsilon_r=0.37\%$ in the case of the elastic modulus with no martensitic transformation. On the other hand, the experimental result of $\epsilon_r=0.44\%$ for the pure Nb_3Sn wire is clearly different from $\epsilon_r=0.29\%$ for Nb_3Sn with $E=165$ GPa, and is reasonably close to the calculated residual strain of $\epsilon_r=0.53\%$ for the Nb_3Sn wire with the low E value due to the martensitic transformation. Therefore, in the compressive residual strain state the bronze-processed Nb_3Sn wire surely exhibits the martensitic transformation. It is found that the martensitic tetragonal phase transformation is effectively suppressed in the bronze-processed Ti-added $(Nb,Ti)_3Sn$ wire.[12] The point is that the martensitic transformation is detectable by the comparison between the analytical result and the direct measurement of the strain effect on J_c for the bronze-processed Nb_3Sn wires with the strain-sensitive character.

IV. CONCLUSION

The clearly different residual strains were obtained from the strain effect on the critical current density J_c for bronze-processed multifilamentary pure Nb_3Sn and 2.3 at. % Ti-added $(Nb,Ti)_3Sn$ wires, which were prepared under the condition of the same wire parameters such as the filament size, filament number, and bronze ratio. It was found that the martensitic transformation for the Nb_3Sn compound largely contributes to the residual strain through the variation of the elastic modulus in bronze processed multifilamentary Nb_3Sn wires. The martensitic transformation is detectable by the strain effect on J_c for the strain-sensitive bronze-route Nb_3Sn composites.

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