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Tensile Strain/Transverse Compressive Stress Effects in Bronze Processed Nb-Matrix Nb_3Sn Wires

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Abstract---Mechanical properties and the strain/stress dependence of the critical current I_c of Nb-matrix Nb_3Sn multifilamentary wires fabricated through bronze route were evaluated up to a magnetic field of 14T at 4.2K. The wire showed a 0.2% proof stress of 550MPa, which is 3.4 times higher than that in the conventional bronze processed Nb_3Sn wires. The strain sensitivity of I_c and the reversible strain limit, 0.8%, were almost the same, but the axial tensile strain for the peak I_c, 0.1%, was small as compared with those in the conventional wires. On the other hand, the transverse compressive stress sensitivity of I_c was remarkably low. The irreversible stress where I_c on unloading no longer recovers to the initial value was larger than 300MPa, which is several times higher than those in conventional wires. Thus, these results show that the wire is highly tolerant to the external stress/strain.

I. INTRODUCTION

The superconducting wire for high field large magnets experiences a large electromagnetic force in high fields. Such a force causes an axial tensile stress in the wire, and also a transverse compressive stress, if the radial displacement of the winding is suppressed by some constraints. It has been already reported that in Nb_3Sn superconductor the transverse compressive stress effect is more significant as compared to the axial tensile stress effect[1], [2]. In the case of Nb_3Al superconductor, however, it has been reported that Nb-tube processed Nb_3Al wire where hard niobium is used as a matrix material show much smaller transverse compressive effect than jelly-roll processed Nb_3Al wires where the matrix material is soft copper, and the transverse compressive and axial tensile stress effect may be essentially the same in magnitude[3]. It is generally accepted that a conventional Nb_3Sn wire with Cu stabilizer cannot withstand a huge electromagnetic force without reinforcements. There are many attempts to reinforce the wire without reducing effective current density and stability[4], [5].

In this context, a new bronze processed Nb_3Sn wire has been fabricated in which bronze cores are embedded in the Nb matrix, reverse in construction to the conventional bronze processed Nb_3Sn, although the stabilizing performance of Nb is not enough. The principal aim of this wire fabrication is to examine the effect of the mechanical property of matrix material on both axial and transverse stress/strain dependence of critical current I_c. In this paper, we describe the mechanical properties and axial and transverse stress/strain dependence of the I_c in the Nb matrix Nb_3Sn superconducting wires.

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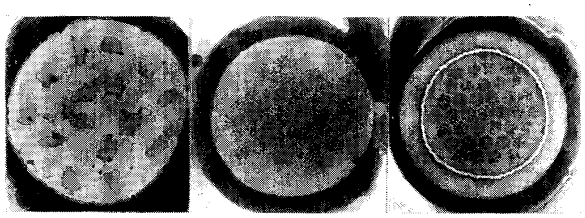
II. EXPERIMENTAL PROCEDURE

Two Nb matrix bronze processed Nb_3Sn superconducting wires [Nb_mNb_3Sn] were fabricated using a bronze process. The number of bronze cores imbedded in the Nb matrix are 15 and 675. For comparison, a conventional bronze processed multifilamentary Nb_3Sn wire [Bz_mNb_3Sn] was also prepared. The specification and the cross sectional view of the wires are given in Table 1 and Fig. 1, respectively. Measurements of the axial tensile strain dependence of I_c as well as the

TABLE I
SPECIFICATIONS OF SURPERCONDUCTING WIRES *

	15 core Nb_mNb_3Sn	675 core Nb_mNb_3Sn	Bz_mNb_3Sn
Wire diameter (mm)	0.75	1.0	0.8
Matrix	Nb	Nb	13wt%Sn-Cu
Number of filaments	15(7at%Sn-Cu)	675(7at%Sn-Cu)	5587(Nb)
Filament dia. (μm)	~70	~ 4.5	3.4
Bronze/Nb ratio	0.16	0.025	4.1
Cu/non Cu ratio	0.18	0.13	0.78
Barrier	-	-	Ta
Heat treatment	700℃ × 72h	700℃ × 72h	750℃ × 192h

* no twist



15 core 675 core
Nb_mNb_3Sn Bz_mNb_3Sn

Fig. 1. Cross-sectional view of samples.

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transverse compressive stress dependence of I_c, were conducted at 4.2K and the magnetic fields up to 14T, using two apparatus inserted in the 15-T superconducting magnet in the Materials Research Institute, Tohoku University. Two samples were used for each measurement condition. The details of the axial tensile testing apparatus and that of the transverse compression apparatus, have been already reported elsewhere [6], [7]. For the transverse compressive test, the width of the pressure block used was 1.5 mm. A copper layer with a thickness of 30 μm was plated electrolytically so as to enable soldering on to copper terminals. The critical current I_c was determined by a 4 probe method using a nominal electrical field criterion of 1μV/cm based on the actual tap separation of 5mm. The compressive stress was estimated by dividing the applied load by the projected compressive area (wire diameter x block width).

III. RESULTS AND DISCUSSION

A. Axial Tensile Strain Effect of Critical Current

The stress-strain curves of Nb_m- and Bz_m-Nb_3Sn wires are shown in Fig. 2. The 0.2% proof stress of 15 core Nb_mNb_3Sn wire is 550 MPa and about 3 times higher than that of Bz_mNb_3Sn wire (160 MPa). The flow stress is also high. This is mainly due to large volume fraction of the matrix Nb with high proof stress (1000 MPa at 4.2K)[3].

The strain dependence of I_c normalized to its peak value I_{cm} in a 15 core Nb_mNb_3Sn wire measured at the magnetic fields of 6, 10 and 14T are shown in Fig. 3, respectively. The result obtained in the Bz_mNb_3Sn wire is also shown in the figure for comparison. The strain sensitivity in Nb_mNb_3Sn wire increases with the increase of magnetic field. The strain for the peak of I_c, e_m, is 0.11% in the Nb_mNb_3Sn wire. It is known that ε_m correspond to the residual strain in the Nb_3Sn filaments. Because the volume fraction of Nb with low coefficient of thermal contraction is large in the Nb_mNb_3Sn wire, ε_m is smaller than of Bz_mNb_3Sn wire (0.33 %). Fig. 4

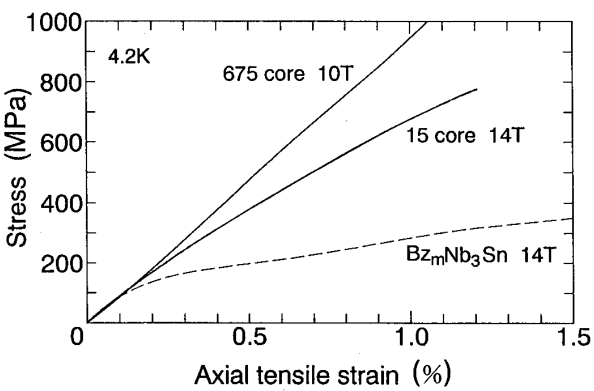

Fig. 2. Stress vs. strain curves.

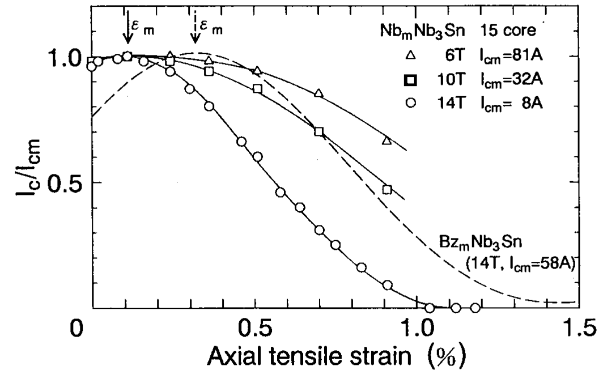

Fig. 3. Strain dependence of I_c normalized to I_{cm}.

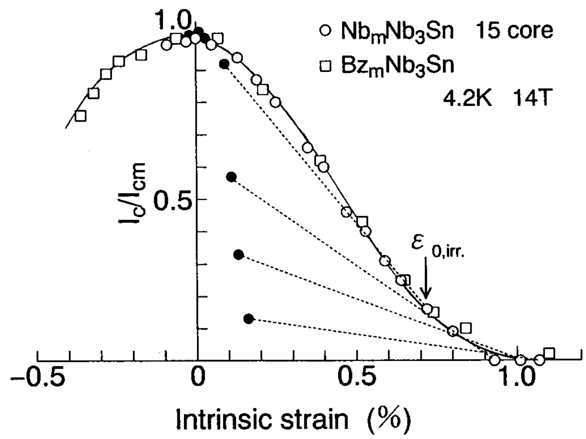

Fig. 4. Strain sensitivity of I_c.

shows the strain dependence of I_c for both Nb_m- and Bz_m-Nb_3Sn wires, where the intrinsic strain is a net strain in the Nb_3Sn filaments which is obtained by subtraction of ε_m from the applied strain. No appreciable difference between the two curves can be seen. This appears to indicate that the Nb_3Sn layers formed in Nb_mNb_3Sn wires are almost the same as those in Bz_mNb_3Sn wires, including the changes in the strain state within applied strain.

The reversible strain limit ε_{irr} beyond which the I_c on unloading starts to deviate from the I_c vs strain curve on loading, means that some permanent defects are introduced in the Nb_3Sn layer. The ε_{irr} for Nb_mNb_3Sn wire is 0.83% and is almost the same as that in conventional Bz_mNb_3Sn wires (typically 0.6-0.8%).

B. Transverse Compressive Stress Effect of Critical Current

The transverse compressive stress dependencies of I_c

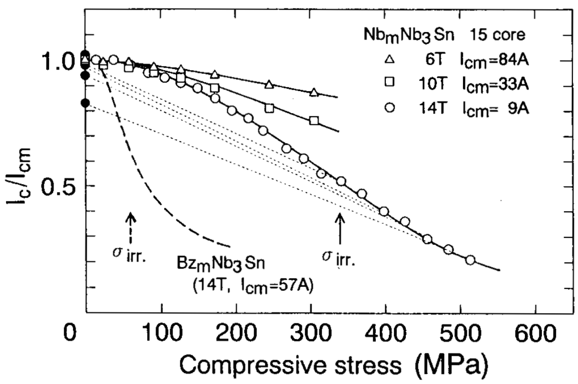

Fig. 5. Transverse stress dependence of I_c normalized to I_{cm}.

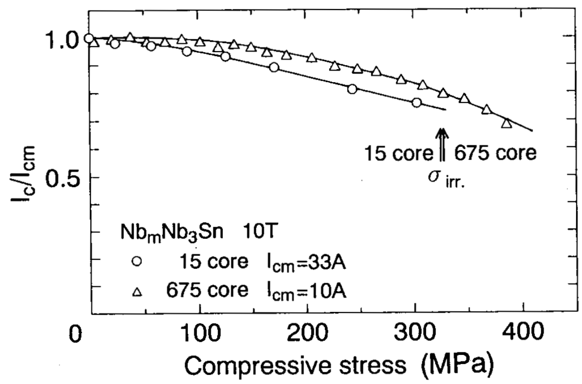

Fig. 6. Transverse stress dependence of I_c in 15 and 675 core wires.

normalized to the I_{cm} at the magnetic fields of 6, 10 and 14T in 15 core Nb_mNb_3Sn wire as well as that in Bz_mNb_3Sn wire at 14T are shown in Fig. 5. I_c degrades monotonically with increase in the stress. The stress dependence is increased with the increase in magnetic field, as in the case of the axial tensile strain effect. The stress which results in the degradation of I_c/I_{cm}=0.9 at 14T is 130 MPa for 15 core Nb_mNb_3Sn wire and is 2.2 times higher than that for Bz_mNb_3Sn.wire

It has been already reported that the I_c degradation due to the transverse compressive stress occurs in two stages as in the case of the axial strain effect[3]. One is the stage I where all the constituents behave elastically and I_c recovers reversibly when the applied stress is removed. In the stage II, I_c does not recover to the initial value after unloading. The I_c degradation in the stage II may be attributed to cracking in the Nb_3Sn filaments due to plastic deformation of the matrix and the local permanent deflection of filaments. For the results obtained on Nb_mNb_3Sn wires, the solid circles in Fig. 5 shows the data of I_c on unloading. The boundary stress between the stage I and II, σ_{irr}, is 330 MPa in Nb_mNb_3Sn wire and is higher about 6 times as compared to 60 MPa in the Bz_mNb_3Sn wire. The matrix Nb with higher proof stress appears to sustain higher stress without plastically deforming than the matrix Cu in Bz_mNb_3Sn. Thus, Nb matrix increases the toleranct stress of σ_{irr}. Furthermore, it was confirmed by the experiment on a 675 core sample that the σ_{irr}, about 320 MPa at 6, 10 and 14T respectively, did not depend on the magnetic field. It indicates that the irreversibility caused by transverse compressive stress is resulted from the mechanical damage to the filaments as in the case of ε_{irr} for the axial tensile strain effects.

The transverse stress dependence of normalized I_c at 10T in the 15 and 675 core Nb_mNb_3Sn wires are shown in Fig. 6, respectively. The stress sensitivity as well as the σ_{irr} of two wires are almost the same. However, it has been already shown in the conventional Nb_3Sn wire that σ_{irr} of single core wire is higher than that of the multifilamentary wire[3]. Therefore , Fig. 6 represents that the effect of filament number on the stress dependence of I_c in the bronze processed Nb_3Sn wires depends not only on the filament distribution, one centrally located filament versus numerous distributed filaments, but also upon the matrix material. The σ_{irr} in the Nb_mNb_3Sn wire is smaller by a factor of about 2 as compared with that (700MPa) in a multifilamentary Nb_3Al wire fabricated by Nb-tube method. This may be partly explained by the difference in the strength of the core (coarse Nb_3Sn and ultrafine Nb_3Al), although further study is needed.

C. Comparison Between Axial Tensile Strain Effect and Transverse Compressive Stress Effect

As described above, the magnitude of the transverse compressive stress effect on I_c strongly depends on the mechanical properties of the matrix material of the composite wires. Thus, the large difference in the magnitude of I_c degradation between Nb_m- and Bz_m-Nb_3Sn wires is mainly resulted from large difference in σ_{irr}. Furthermore, it has been confirmed that I_c vs. transverse compressive stress characteristics can be divided into two categories, the reversible stress region (stage I) and the irreversible stress region (stage II) and presumably the mechanism of I_c-degradation may not be the same in each region, as in the case of the axial strain effects. Consequently, in making a comparison of the intrinsic magnitude of I_c-degradation between transverse compressive stress and the axial tensile strain, first, it should be made for I_c-degradation in the same category. Secondly, the stress distribution in the wire cross section should be taken into account. The stress analysis revealed that mean stress is 1.8 times higher and the highest stress is about 5 times as compared with the nominal one for Nb-tube processed Nb_3Al wires. The critical current density changes locally depending on the stress distribution.

Figure 7 shows the comparison of the axial and transverse stress dependencies of I_c in the reversible stress region in the wire. This comparison of stress dependencies of I_c in the same category of I_c was realized in the Nb_mNb_3Sn wires which show much larger σ_{irr} than conventional Bz_mNb_3Sn wires. The axial stress is derived from the axial strain in Fig.3 by

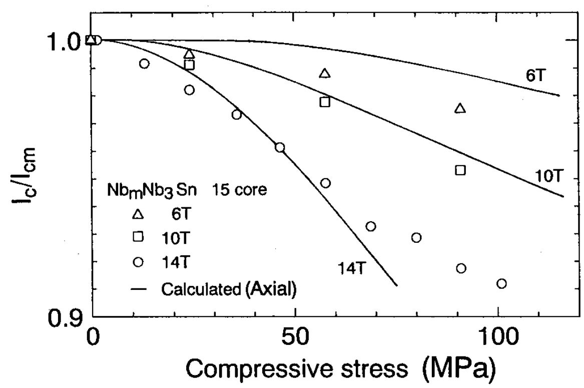

Fig. 7. Comparison of I_c degradation in Nb_mNb_3Sn wire for transverse and axial compressive stress.

multiplying Young's modulus of 80 GPa[9], and then overall I_c is calculated by summation of the local critical current corresponding to the stress distribution in the cross section of the wire. Here, it is assumed that the stress distribution is approximately the same as that derived from a solution for in plane compression of elastic circular plate which has been used in the Nb_3Al wire already reported in [8]. The coincidence between the transverse stress effect of I_c measured and that derived from calculation based on the axial tensile strain effect of I_c indicates that stress dependence of I_c is essentially identical for both axial and transverse direction in the Nb_3Sn wire. Similar results have been reported in the case of Nb_3Sn tape[10] and Nb_3Al wire[8].

The "σ_{irr}" for axial tensile stress effects in Nb_mNb_3Sn is derived to be 576 MPa from ε_{irr} multiplying Young's modulus 80 GPa. This value is close to 594 MPa the "effective"

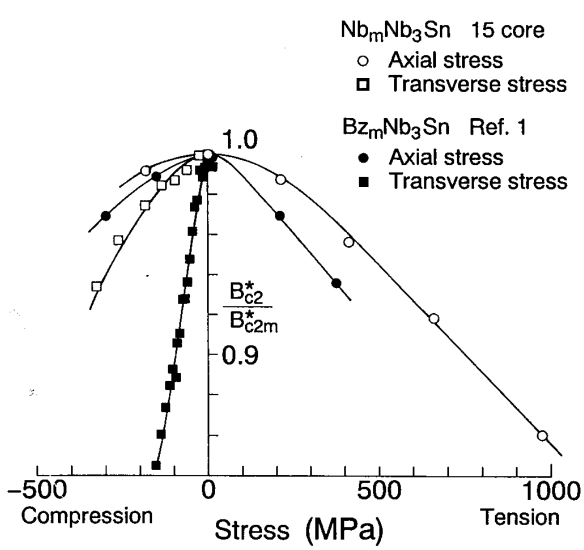

Fig. 8. Intrinsic effect of transverse and axial stress on B^*_{c2}.

irreversible transverse compressive stress, obtained by multiplying 1.8, the ratio mentioned above, to 320MPa. This coincidence, however, is fortuitous because 1) σ_{irr} in the transverse compression is to be controlled mainly by the maximum stress in the cross section of wire and the ratio of the maximum stress to the nominal s_{irr} should be 5, if the configuration of the filaments for Nb_mNb_3Sn and Nb-tube maximum stress in the cross section of wire and the ratio of processed Nb_3Al wires is the same, 2) the magnitude of the tensile stress component which results in the filament fracture in the axial tensile stress effects is different from that in the transverse compressive stress effects.

D. Stress/Strain Dependence of Upper Critical Field

Kramer plots for I_c vs B data in every 1T between 10 to 14T obtained in the experiment shown in Fig. 3 and Fig. 5 exhibited good linear relations. Utilizing them, upper critical fields on loading could be derived. The nominal transverse compressive stress dependence and the axial tensile stress dependence of in Nb_mNb_3Sn wires are shown in Fig. 8. The Young's modulus of 165 GPa is used here so as to compare the present data with the results on the conventional bronze processed Nb_3Sn wires in [1]. The large difference in the transverse compressive stress dependence of B^*_{c2} between Nb_mNb_3Sn and bronze matrix Nb_3Sn in [1] may be attributed to that the latter is derived from I_c vs. stress data including the irreversible stress region. The difference between the stress dependence of B^*_{c2} in the compression side for axial stress and transverse stress effects can be partly explained in the way in the discussion mentioned in the case of I_c, and also, by the difference in Young's modulus, 80 vs. 165 GPa. The reason for the difference in the tensile stress dependence for both wires is not clear. Differences in the stoichiometry or of B^*_{c2m} of Nb_3Sn in both wires and those in the method to derive B^*_{c2m} (Kramer plot in 10-14T vs. strain scaling law in 8-19T) are speculated.

IV. CONCLUSIONS

Axial tensile and transverse compressive tests of two bronze processed Nb matrix Nb_3Sn[Nb_mNb_3Sn] wires and a conventional bronze matrix wire were conducted in a magnetic fields up to 14T at 4.2K. Changes in the critical current in the wires were evaluated. Following results were obtained.

1. The 0.2% proof stress of 15 core Nb_mNb_3Sn wire is 550 MPa and is 3.4 times larger as compared with that (160 MPa) in the conventional wire.

2. The strain for the peak value of I_c in the axial strain dependence of I_c in Nb_mNb_3Sn wire 0.11% is smaller than that (0.33%) in the conventional wire. No difference in the strain sensitivity between them can be seen.

3. The transverse stress dependence of I_c in Nb_mNb_3Sn wire is low as compared with that in the conventional wire. The irreversible transverse compressive stress for I_c, σ_{irr}, does

not depend on a magnetic field. The σ_{irr} in the Nb_mNb_3Sn wire is 330 MPa and is about 6 times higher than that (60 MPa) in the conventional wire.

4. The transverse compressive stress dependence and axial tensile stress dependence of I_c in the reversible stress region in the Nb_mNb_3Sn wires are almost the same in magnitude, if the transverse stress distribution within the cross section of the wire is taken into account.

5. The stress dependence of B^*_{c2} in the Nb_mNb_3Sn wire is smaller than that in the conventional bronze processed wires.

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