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Development of High Strength Nb_3Sn Conductors for High Magnetic Field Applications

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***Abstract*----- Multifilamentary $(Nb,Ti)_3Sn$ superconducting wires with reinforcing stabilizer of CuNb composite, $CuNb/(Nb,Ti)_3Sn$, were developed. Previously, we researched on the effect of reinforcement of CuNb composite as a CuNb/(Nb, $Ti)_3$ wire and its stability by investigating the MQE(minimum quench energy). A test coil was fabricated using this reinforced wire without extra reinforcing material. The coil was produced by the "react and wind method", then electromagnetic force for the wire was applied by charging electric current in the coil up to 11T. The coil was energized successfully and the generated electromagnetic force for the wire reached 224MPa at 136A and 9T without any degradation of test coil. These results proved that the bronze processed multifilamentary $CuNb/(Nb,Ti)_3Sn$ have an excellent mechanical property, and a possibility to realize compact design of future superconducting magnet was confirmed.**

I. Introduction

Recently, high field superconducting magnets over 20T have been developed. Those magnets tend to be larger because the mechanical property of the superconductor at present requires extra reinforcing substance for electromagnetic force. The superconducting winding in the magnets experiences a huge electromagnetic force in high fields, and such force causes a large tensile stress in the wire. Therefore strong mechanical properties are required for the conductors. For reinforcing and stabilizing the conductors, we concentrated on CuNb composites which have both high yield strength and high electrical conductivity, and developed the CuNb/(Nb,Ti) $_3$Sn wires by a bronze processed multifilamentary $(Nb,Ti)_3Sn$ conductor with CuNb reinforcing stabilizer[1]-[5]. So far, we reported that $CuNb/(Nb,Ti)_3Sn$ wires had 0.2% proof stress which was 1.8 times larger than value for the conventional $Cu/(Nb,Ti)_3Sn$ wires stabilized by Cu, and stability of the developed wire was investigated by measuring its minimum quench energy (MQE)[6]. In this paper, we report development of $CuNb/(Nb,Ti)_3Sn$ wire consist of Cu-20wt%Nb reinforcing stabilizer, Cu-13wt%Sn and Nb-1.2wt%Ti superconducting filaments. A solenoidal wound test coil using this developed wire was fabricated, and its mechanical and superconducting properties were investigated. The results of applying an actual electromagnetic force to the reinforced conductor in magnetic field are reported.

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II. Experimental

A. *CuNb/(Nb,Ti)₃Sn wire*

Figure 1 shows the cross sectional view of the developed bronze processed multifilamentary $(Nb,Ti)_3Sn$ wire with a CuNb reinforcing, $CuNb/(Nb,Ti)_3Sn$. Table I shows the specification of the $CuNb/(Nb,Ti)_3Sn$ wire. This wire has a structure such that a part of the Cu stabilizer of the ordinary $Cu/(Nb,Ti)_3Sn$ was replaced by Cu-20wt%Nb composite. Ta was used as a diffusion barrier. Nb cores were fully converted to Nb_3Sn compounds after the heat treatment.

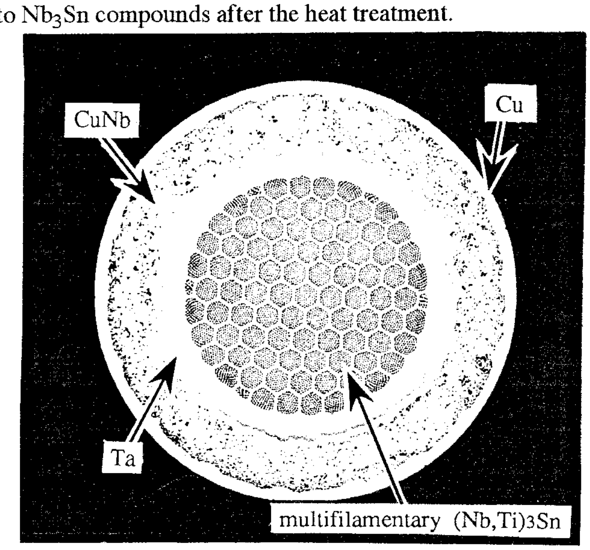

Fig.1. Cross sectional view of the $CuNb/(Nb,Ti)_3Sn$ wire.

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Table I. Specification of the CuNb/(Nb,Ti)$_3$Sn wire

Wire diameter	1.0mm
Bronze	Cu-13wt%Sn
Core	Nb-1.2wt%Ti
Filament diameter	3.9 μm
Number of filaments	7849
Bronze ratio	3.9
Cu / CuNb / nonCu ratio	0.27 / 0.75 / 1
Barrier	Ta

Figure 2 shows the magnetic field dependence of the critical current of the CuNb/(Nb,Ti)$_3$Sn wire of coil samples at 4.2K in magnetic fields. The heat treatment was carried out at 675C° for 240h. The critical current, Ic, was determined by the criterion of electric field of 1μV/cm. The measured Ic values were 63.6A and 189A at 15T and 9T, respectively

Figure 3 shows the stress-strain curve as the mechanical properties of the CuNb reinforced wire at 4.2K, 14T. The yield stress was determined as 0.2% proof stress. The obtained results of the stress at 4.2K in CuNb/(Nb,Ti)$_3$Sn wire were 240MPa which exceeded the value of the conventional Cu/(Nb,Ti)$_3$Sn wire.

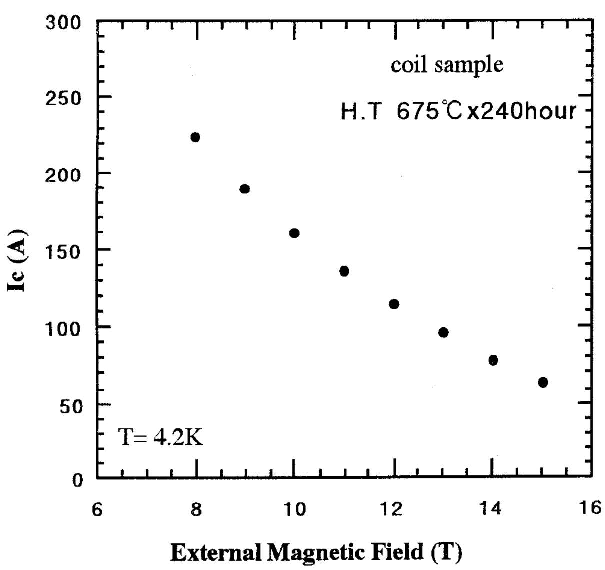

Fig.2. Magnetic field dependence of the critical of the CuNb/(Nb,Ti)$_3$Sn wire.

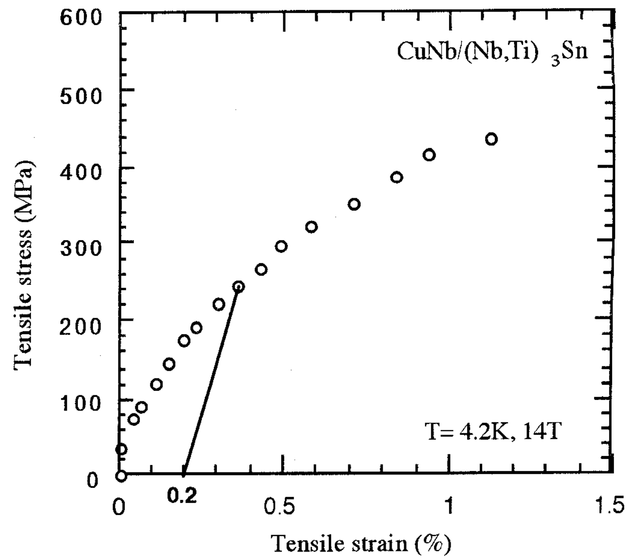

Fig.3. Stress-strain curve of the CuNb/(Nb,Ti)$_3$Sn wire at 4.2K, 14T.

B. Test coil

The test coil was fabricated using the CuNb/(Nb,Ti)$_3$Sn wire. Figure 4 shows the view of test coil, and the specification of one is listed in table II. The inner diameter, outer diameter and height of the coil were 247mm, 288mm and 80mm, respectively. The insulation of the wires was a glass tape. This test coil was heat treated at 675C° for 240h in vacuum, then the test coil was impregnated by epoxy resin.

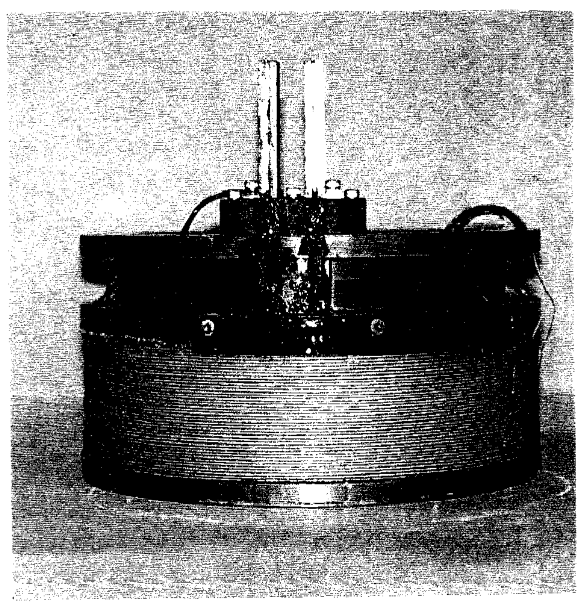

Fig.4. The view of the test coil.

Table II. Specification of the test coil.

Inner diameter of the winding	247mm
Outer diameter of the winding	288mm
Height of the winding	80mm
Number of total turns	629 turns
Fabricated method	Wind and React
Impregnant	epoxy resin

C. Electromagnetic force load test

The test coil was set in the superconducting hybrid magnet, HM-1, at Institute for Material Research, Tohoku University. For this experiment, the water cooled magnet in the HM-2 was removed to obtain 360mmϕ bore at room temperature. Then a liquid helium dewer was set to place the test coil. The external superconducting magnet generated 11T for the test. The center of the external magnet and the test coil was adjusted by measuring the center of magnetic field of both coils by Hall device individually. An actual electromagnetic force load test was carried out by flowing the current in the test coil under static external magnetic field from 7T to 11T. The sweep rate of the current was 20A/min.

III. Results and discussion

Figure 5 shows the transport current properties of the test coil at each external magnetic field, 4.2K. The result showed that the values for the maximum transport current were 95.5A, 114A, 136A and 169A at 11T, 10T, 9T and 7T, respectively. It was found that the measured current values were lower than the values estimated by load line of the coil due to the coil quench. The reason for the quench characteristic is not clear at this moment.

Figure 6 shows results of the electromagnetic force calculated from the test data. The electromagnetic force is obtained from equation (1)

$$F=B\cdot J\cdot R \qquad (1)$$

In this equation, F is the electromagnetic force, B is the magnetic field, J is the current density and R is the radius. The electromagnetic force varies in the coil winding due to the magnetic field distribution, therefore, it is calculated using the outer diameter of the winding at the half height of the coil as the maximum value. Corrected value for B was used because magnetic field generated by the test coil at the circumference directed opposite to the external field. Table III shows the factor used for the calculation. The values for actually loaded electromagnetic force were 195MPa, 210MPa, 224MPa and 211MPa at 11T, 10T, 9T and 7T, respectively. According to the actual load test result, it was confirmed that the CuNb reinforced Nb_3Sn superconductor performed under the huge electromagnetic force above 200MPa at each external magnetic field, as large as 224MPa at 9T, which was the maximum value in our experiment.

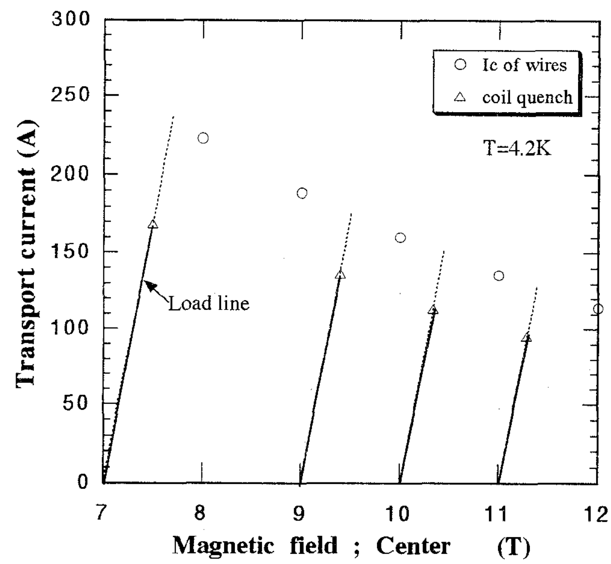

Fig.5. The transport current properties in the test coil at each external magnetic field.

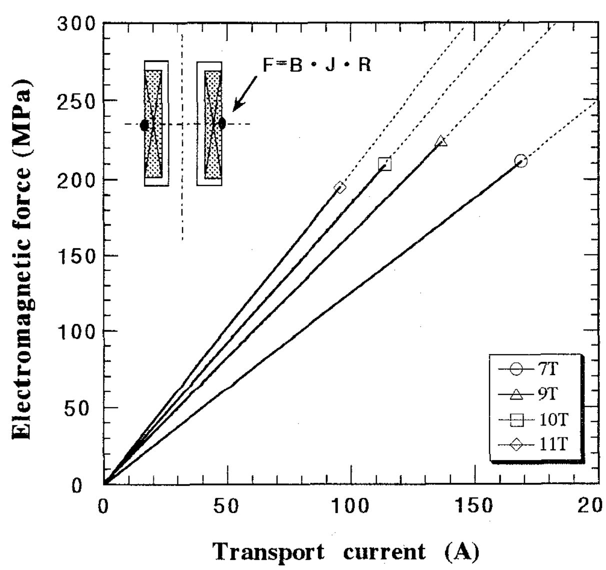

Fig.6. Relationship between the transport current and the electromagnetic force.

Table III. The factor in equation (1).

External magnetic field (T)	7.217	9.297	10.310	11.343
Generated magnetic field of a test coil (T)	0.372	0.300	0.250	0.210
Transport current (A)	169.0	136.3	113.7	95.5
Maximum outer radius (mm)	144	144	144	144
Electromagnetic force (MPa)	212	224	210	195

The tested coil was warmed up to check its degradation by the applied huge force during the load test, we did not find any damage in the windings and impregnated epoxy resin. It is quit difficult to realize such a tough performance for the conventional Nb_3Sn wire of 170MPa yield stress without extra reinforcing materials, and, current density in the coil windings decreases which leads to the size and weight of the winding increases.

We proved the effect of reinforcement of Nb_3Sn wire by replacing the Cu stabilizer for CuNb composite, and its electromagnetic force load test as large as 224MPa by the actual coil operation. This results strongly suggest that an advanced design of future high field magnet by our CuNb reinforced wire.

IV. CONCLUSION

We developed highly strengthened $(Nb,Ti)_3Sn$ wire, and actual electromagnetic force load test was carried out by the test coil. The test coil was fabricated using the bronze processed multifilamentary $(Nb,Ti)_3Sn$ superconducting wires with reinforcing stabilizer of Cu-20wt%Nb composite, CuNb/$(Nb,Ti)_3Sn$ wire. The results showed that it was possible to operate the coil under the electromagnetic force above 200MPa at the external magnetic field of 7T, 9T, 10T and 11T, especially, the maximum electromagnetic force reached 224MPa at 9T.

From the results of the actual load test of the coil, we confirmed an excellent mechanical properties of the developed CuNb reinforced $(Nb,Ti)_3Sn$ wire. This successful performance encourages us that a new concept with advanced design of future high field magnets will be possible.

ACKNOWLEDGMENT

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