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Development of a CuNb Reinforced and Stabilized Nb_3Sn Coil for a Cryocooled Superconducting Magnet System

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***Abstract*—The cryocooled large bore CuNb/(Nb,Ti)$_3$Sn superconducting magnet for the hybrid magnet was developed compactly by a React and Wind and tension-winding method. This (Nb,Ti)$_3$Sn coil formation technique results in no need of a large heat-treatment furnace and vacuum epoxy-impregnation equipment for a large-scale superconducting magnet. The magnet was energized successfully to generate 7.4T in a 220mm ϕ room temperature bore. Further, it became clear that there is a problem with connecting technique between winding and terminal. A 10T-360mm room temperature bore cryocooled superconducting magnet is being developed for a hybrid magnet system.**

***Index Terms*—Cryocooled (Nb,Ti)$_3$Sn Magnet, Large bore, React and Wind method, Tension winding technique,**

I. INTRODUCTION

Recently, static high fields up to 35T are available in a hybrid magnet consisting of an outer superconducting magnet and an inner water-cooled resistive magnet. A superconducting magnet in a hybrid magnet inevitably needs a room temperature bore for a resistive insert magnet. As a result, a huge electromagnetic stress is applied to the coil winding in a large bore superconducting magnet. In order to overcome such a huge stress, we have concentrated on CuNb composites which have both high strength and high electrical conductivity, and succeeded in developing advanced (Nb,Ti)$_3$Sn superconducting wires with Cu-20 wt%Nb composite reinforcing stabilizer.[1]-[3]

At the same time, recent progress is achieved by the realization of a practical cryocooled superconducting magnet (CSM) without liquid helium for operation. And the rapid growth of CSM has been achieved year after year.[4]-[6] Now we concentrate on the magnet technology for constructing a large bore and high field superconducting magnet operated without liquid helium. In this paper, we report on properties of a prototype cryocooled magnet system. With this magnet, we aim at the construction of a 10 T cryocooled large bore superconducting magnet wound with highly strengthened (Nb,Ti)$_3$Sn wires.[7]

II. EXPERIMENTAL

A. *CuNb/(Nb,Ti)$_3$Sn wire*

Figure 1 shows the cross sectional view of the developed bronze processed multifilamentary (Nb,Ti)$_3$Sn wire with a CuNb composite, CuNb/(Nb,Ti)$_3$Sn. Table I shows the specification of the CuNb/(Nb,Ti)$_3$Sn wire. This wire has a structure such that a part of the Cu stabilizer of the ordinary Cu/(Nb,Ti)$_3$Sn was replaced by Cu-20wt%Nb composite. Ta was used as a diffusion barrier. Nb cores were fully converted to Nb_3Sn after the heat treatment.

Figure 2 shows critical currents measured at 4.2K and the currents predicted at temperatures from 5K to 6K for CuNb/(Nb,Ti)$_3$Sn by using the scaling law of the global pinning force and magnetic field dependence of the critical current.[7]

TABLE I
SPECIFICATION OF CuNb/(Nb,Ti)$_3$Sn WIRES

	A (inner coil)	B (outer coil)
wire diameter	1.0	
bronze	Cu-13wt%Sn	
core	Nb-1.2wt%Ti	
filament diameter	3.0 μm	2.7 μm
number of filament	8066	9398
bronze ratio	3.25	2.7
Cu/CuNb/non Cu ratio	0.54/0.73/1.00	0.43/0.61/1.00
barrier	Ta	
heat treatment	948K 240hours	

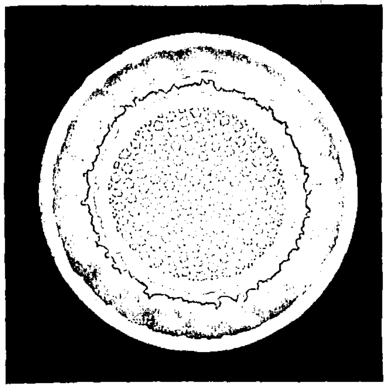

Fig. 1. Cross sectional view of the CuNb/(Nb,Ti)$_3$Sn wire.

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Figure 3 shows the critical current at 10T as a function of applied bending strain, which was applied at room temperature and maintained during cool-down. It appears that the wire could withstand a bending strain of 0.5%. Therefore, we designed the coiling equipment to control the maximum bending strain below 0.4%.

Figure 4 shows the stress-strain curve as a mechanical property of the wire at room temperature. The 0.2% proof stress and Young's modulus for the wire were 220MPa and 100GPa, respectively. Figure 5 shows the result of creep effect for the CuNb/(Nb,Ti)$_3$Sn wire at room temperature. It was found that the wire tension saturated from 125MPa to 110MPa after 70 hours. In this development, we tried winding the Nb$_3$Sn coil by React and Wind technique with a winding tension 125MPa.

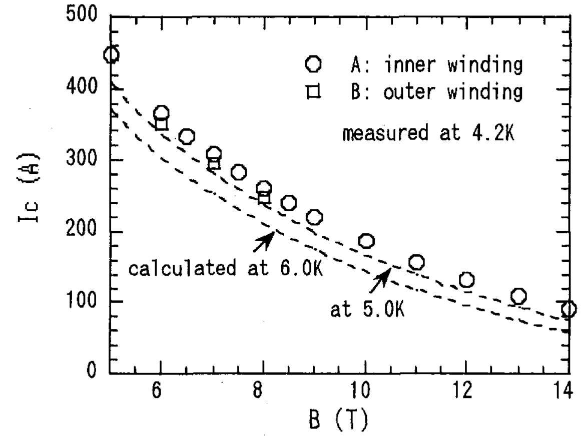

Fig.2. Magnetic field dependence of the critical current for the CuNb//(Nb,Ti)$_3$Sn wire. Predicted properties at 5-6K are indicated by dotted line.

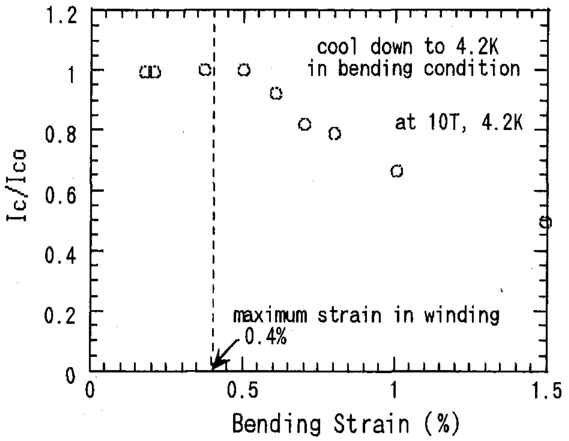

Fig.3. The critical current as a function of applied bending strain.

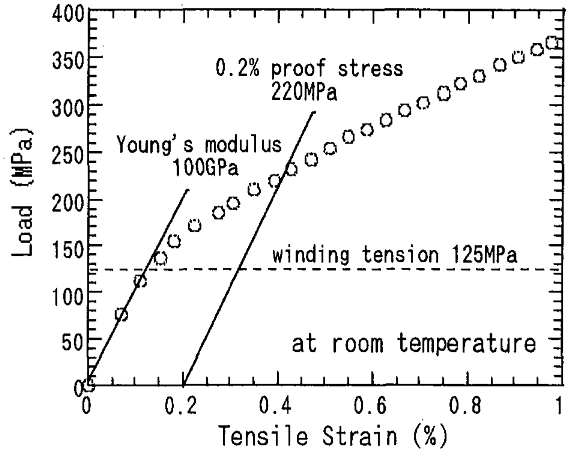

Fig.4. The stress-strain curve as a mechanical property of CuNb/(Nb,Ti)$_3$Sn wire at room temperature

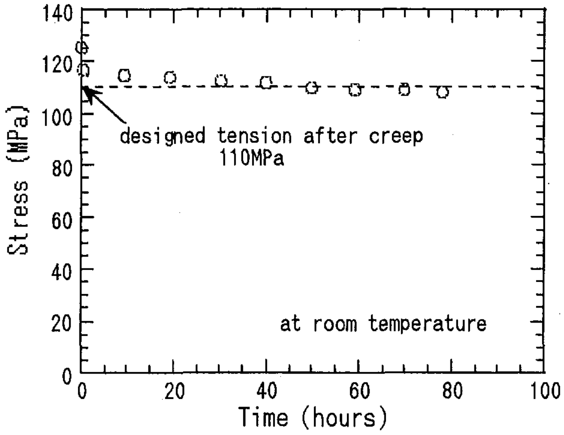

Fig.5. The creep of a CuNb/(Nb,Ti)$_3$Sn wire at room temperature after a tension winding.

B. Cryocooled Magnet System

Figure 6 shows the Nb$_3$Sn coil. Its specification is listed in Table II. Specifications of the NbTi coils are listed in Table III. The insulation of CuNb/(Nb,Ti)$_3$Sn wire was polyimide tape. After a heat treatment at 983K for 240hours, the wire was wound on a SUS bobbin with a tensile tension of 125MPa. Simultaneously, epoxy resin was applied to impregnate the coil. The Nb$_3$Sn coil was divided into two sections, and the number of terminals was 3. The terminals were connected to a cryocooler, so that the windings were refrigerated through terminals in the same as the NbTi coils. The sizes of inner diameter, outer diameter and height for Nb$_3$Sn coil were 262mm, 299mm and 321mm, respectively. The Nb$_3$Sn coil was assembled with outer NbTi coils. The assembled coil would generate a central field of 7.5T in a 220mm room temperature bore.

C. Load Test for the Complete Magnet System

At first, the NbTi coils generated the back up field from 4.2T to 7.4T. Then the current in the Nb_3Sn coil was swept to 166A at the rate of 0.1A/sec. Simultaneously, temperatures of the NbTi coils, Nb_3Sn coil and several cooling stages were measured. The axial strain of the wire on outer and inner diameter of the coils was measured by a strain gage mounted on the wire surface.

TABLE II
SPECIFICATION OF Nb_3Sn COIL

	INNER WINDING	OUTER WINDING
inner diameter	262mm	283mm
outer diameter	283mm	299mm
height	321mm	321mm
number of turns	2661	2128
packing factor	0.620	
coil constant	0.0142T/A	
driving current	166A*	
generating field	2.35T (center)*	
individual inductance	3.73H	
insulation	polyimide	
maximum bending strain	0.4%	
winding tension	125MPa	
fabricated method	react and wind	
impregnation	epoxy resin	

* These values were target values at design.

TABLE III
SPECIFICATION OF NbTi COILS

	INNER COIL	OUTER COIL*
inner diameter	317mm	335mm
outer diameter	335mm	380mm
height	377mm	376mm
number of turns	2396	8460
packing factor	0.820	0.785
coil constant	0.0266T/A	
driving current	220A	
generating field	5.85T (center)	
individual inductance	1.12H	15.8H

* The outer coil is composed of four windings.

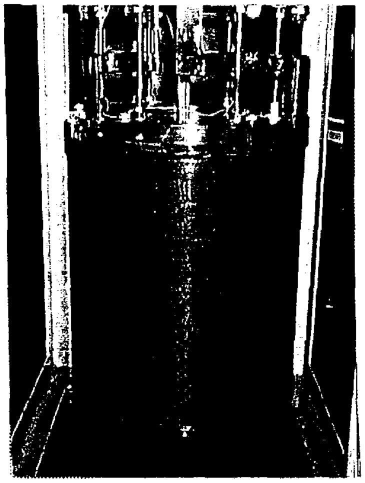

Fig.6. The view of separate Nb_3Sn coil

III. RESULT AND DISCUSSION

Figure 7 shows load lines of the Nb_3Sn coil at the back up field of 2.0T, 3.0T, 4.0T, 5.3T and 5.9T, respectively. The results of the electromagnetic forces calculated at each quench point appear in Table IV. The value for the actually loaded electromagnetic force at the inner wire of winding was about 88MPa at the back up field of 5.9T when the magnetic field generated up to 7.4T.

However, these results indicate that the quench points of Nb_3Sn coil were lower than the estimated value determined from the critical current properties. It became clear that all quenches occurred at the inner winding of the coil. It was confirmed that the NbTi coils and Nb_3Sn coil were refrigerated below 3.8K until the coil quenched.

Figure 8 shows results of the measured axial strain of the wires on outer coil winding when the magnet was operated 2 times at the back up field of 5.3T. The results indicate that the maximum value of strain is 0.12%. Comparison of measured and calculated values of the Young's modulus for structure materials appear in Table V. We see from Table V that the measured value is about 30% lower in comparison with the calculated one. Table VI shows the comparison of thermal contractions from room temperature to 4.2K for SUS and the wire.

TABLE IV
RESULTS OF THE ELECTROMAGNETIC FORCES CALCULATED AT EACH QUENCH POINT

background field (T)	2.0	3.0	4.0	5.3	5.9
force for inner winding (MPa)	74	80	79	85	88
force for outer winding (MPa)	77	72	59	49	33

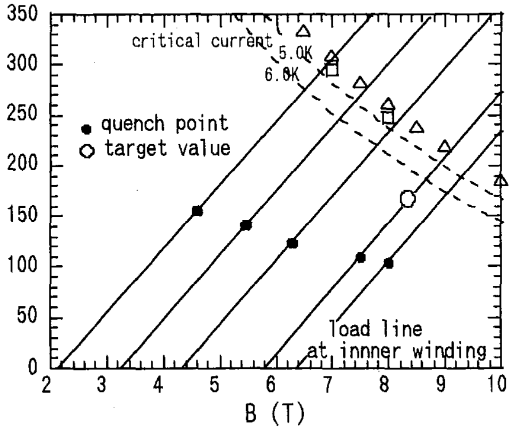

Fig.7. Load lines at the back up fields of 2.0T, 3.0T, 4.0T, 5.3T and 5.9T,respectively.

TABLE V
COMPARISON OF YOUNG'S MODUIUS FOR Nb_3Sn COIL

	MEASURED	CALCULATED*
Young's modulus for Nb_3Sn coil	75GPA	110GPA

*Calculated from on volume fraction of the wire and epoxy resin.
Wire: 170GPa, Resin:12.5Gpa, Packing factor::0.62

TABLE VI
COMPARISON OF THERMAL CONTRACTION

	$(Nb,Ti)_3Sn$ wire	SUS 304LN
thermal contraction	0.14%	0.26%

*Indicated contractions from 300K to 4.2K

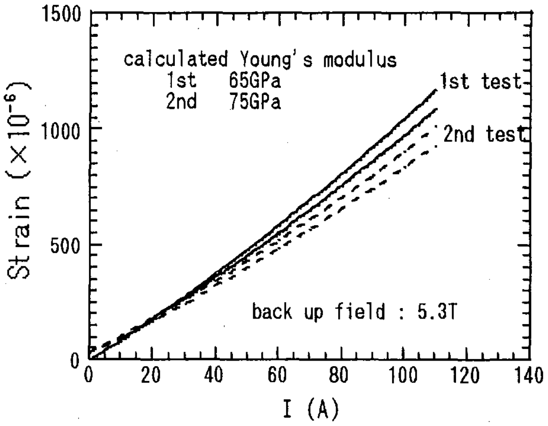

Fig.8. Results of measured axial strain of the wires on outer coil winding when the magnet was operated 2 times.

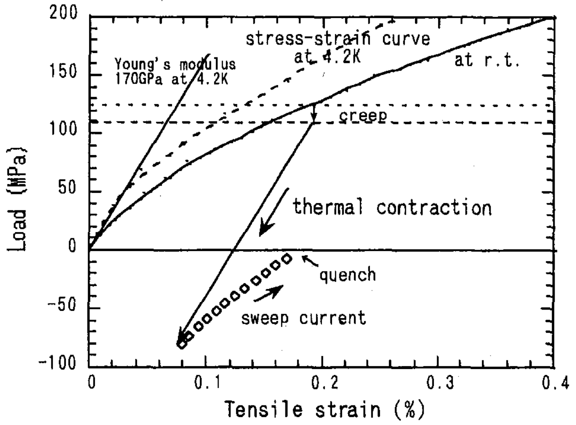

Fig.9. Stress level of $CuNb/(Nb,Ti)_3Sn$ wire in winding of the Nb_3Sn coil

If we look at table VI we see that the contraction of SUS used for the winding bobbin is 0.12 % less than the wire. As a result, it may be presumed that the winding region of Nb_3Sn coil is released from the SUS bobbin at 4.2K. Accordingly, it might be considered that the apparent Young's modulus was lower than the real one since the winding region was fixed moderately with epoxy resin.

Figure 9 shows the stress level of $CuNb/(Nb,Ti)_3Sn$ wire in the winding of the Nb_3Sn. At first step, 125MPa was applied to the wire as winding tension at room temperature. The stress level in the wire was reduced to 110MPa at room temperature due to creep. During was cool down from 300K to about 4K, 0.12%of the strain was released. At this point, it is considered that the winding region of the Nb_3Sn coil is released from SUS bobbin and the distortion between the winding region and SUS bobbin is accumulated in the terminal region of the coil. Finally, the electromagnetic force was loaded to the windings in sweeping the current. In this process, it is considered that the distortion increases at terminal region and the coil reaches a quench.

IV. CONCLUSIONS

The cryocooled large bore $CuNb/(Nb,Ti)_3Sn$ superconducting magnet for the hybrid magnet was developed by a React and Wind and tension-winding method. This $(Nb,Ti)_3Sn$ coil formation technique results in no need of a large heat-treatment furnace and vacuum epoxy -impregnation equipment for a large-scale superconducting magnet. The magnet was energized successfully to generate 7.4T in a 220mm ϕ room temperature bore. Further, it became clear that there is a problem with the connecting technique between winding and terminal. A 10T-360mm room temperature bore cryocooled superconducting magnet is being developed for a hybrid magnet system.

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