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Cryocooled Large Bore Superconducting Magnet for a Hybrid Magnet System Employing Highly Strengthened $(Nb,Ti)_3Sn$ Wires with CuNb Stabilizer

K. Watanabe, S. Awaji, and M. Motokawa
Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan
CREST, Japan Science and Technology Corporation

S. Iwasaki, K. Goto, N. Sadakata, and T. Saito
Fujikura Ltd., Tokyo 135-8512, Japan

K. Watazawa, K. Jikihara, and J. Sakuraba
Sumitomo Heavy Industries Ltd., Hiratsuka 254-0806, Japan

Abstract — **Employing newly developed high strength and good conductive $(Nb,Ti)_3Sn$ wires with CuNb composite stabilizer, it is possible to reduce a coil weight of a large bore superconducting magnet by 50-70 %. A cryocooled large bore $(Nb,Ti)_3Sn$ superconducting magnet for a hybrid magnet is made compactly 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 a vacuum epoxy-impregnation equipment for a large-scale superconducting magnet. A 10 T-360 mm room temperature bore cryocooled superconducting magnet is being developed for a hybrid magnet system.**

I. Introduction

It is quite useful to use a high magnetic field for resolving some issues in physical phenomena. A static high magnetic field provides a characteristic experimental method in solid state physics, because a very precise high magnetic field can be maintained for a long time in a large experimental space. Since the very low temperatures down to 20 mK are realized in combination with a dilution refrigerator in static high fields up to 27 T, the temperature dependent properties are explored at a constant high field. It is noteworthy that experimental researches of quantum Hall effect have been made remarkable progress using an advanced environment of both very low temperature and high magnetic fields [1]. One more example for requiring a static high field is the study on high temperature superconductors. The behavior of the upper critical field B_{c2} in high temperature superconductors exhibits the diverging temperature dependence in a low temperature region, and is very different from the saturating behavior in traditional low temperature superconductors [2]. It is considered that $Bi_2Sr_2CaCu_2O_8$ superconductors have extremely large B_{c2} exceeding 50 T even in B//c-axis at 4.2 K, for instance.

Up to now, static high fields up to 35 T 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 large 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, Nb_3Sn superconductors reinforced with a hard Cu housing have been utilized for a high field superconducting magnet with a large bore. This has the disadvantage of producing a large-scale superconducting magnet with heavy cryogenic mass. A problem requiring a lot of liquid helium in a large superconducting magnet is encountered. The Tohoku hybrid magnet needs supplying liquid helium of about 500 ℓ for precooling from 20 K to 4 K and about 70,000 ℓ for magnet operation a year [3]. In addition, a lot of time has to be spent for pouring liquid helium into a cryostat from a transfer vessel.

On the other hand, recent progress achieved the realization of a practical cryocooled superconducting magnet without liquid helium for operation. This is a splendid magnet technology changing a concept in a superconducting magnet operation. Using high temperature Bi-system superconducting current leads enables us to make a compact superconducting magnet combined with a small GM-cryocooler. Since we succeeded in demonstrating a world-first practical 4 T cryocooled superconducting magnet in 1992 [4], a 15 T cryocooled superconducting magnet has recently been developed in 1998 [5]. Figure 1 represents the present status in the development of cryocooled superconducting magnets (CSM). It is found that the rapid growth of CSM has been achieved year after year. From the aspect of generating a high magnetic field, a cryocooled superconducting magnet and a traditional superconducting magnet immersed in liquid helium have become comparable in ability. Now we concentrate on the magnet technology for constructing a large bore and high field superconducting magnet operated without liquid helium. A key issue is how compact and light large bore and high field superconducting magnet can be made.

In order to carry out the desired magnet design, highly strengthened superconducting wires with a small wire diameter are needed. Fortunately, we have succeeded in developing advanced $(Nb,Ti)_3Sn$ superconducting wires with Cu-20wt.%Nb composite reinforcing stabilizer, $CuNb/(Nb,Ti)_3Sn$, in which a part of Cu stabilizer was replaced by Cu-20wt.%Nb composite.

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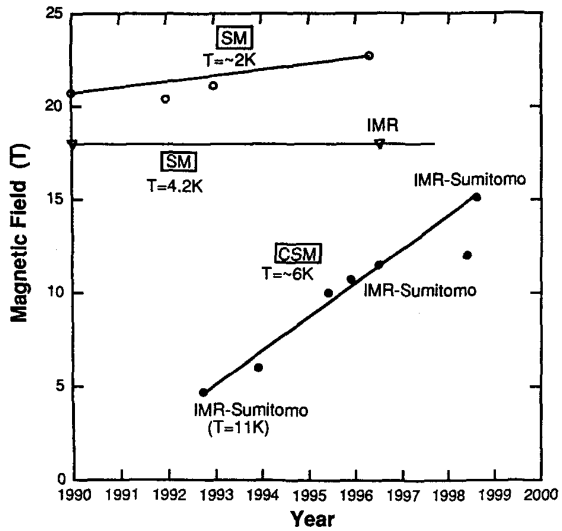

Fig. 1. Progress of $(Nb,Ti)_3Sn$ multifilamentary superconducting magnets. SM represents a superconducting magnet immersed in liquid helium, and CSM a cryocooled superconducting magnet without liquid helium. Operation temperatures adopted for magnets are liquid helium pool boiling temperature of 4.2 K and superfluid helium temperature below 2 K for SM, and solid state conduction cooling temperature of about 6 K for CSM.

Since a $CuNb/(Nb,Ti)_3Sn$ superconducting wire exhibits about twice larger mechanical properties than an ordinary $(Nb,Ti)_3Sn$ one, a very compact superconducting magnet with a large bore is expected to realize employing it.

In this paper, we report on a subject of constructing a 10 T cryocooled large bore superconducting magnet wound with highly strengthened $(Nb,Ti)_3Sn$ wires.

II. 3 km LONG $CuNb/(Nb,Ti)_3Sn$ MULTIFILAMENTARY SUPERCONDUCTING WIRE

$CuNb/(Nb,Ti)_3Sn$ multifilamentary superconducting wires with specifications such as an outer wire diameter of 1.0 mm, filament diameter of about 4 µm, number of filaments of 7849, and Cu and CuNb / non-stabilizer ratio of about 1.0 have successfully been fabricated for practical-scale production of 3 km in length. The remarkable improvement of the mechanical properties with 0.2 % proof stress of 240 MPa for a short specimen in $CuNb/(Nb,Ti)_3Sn$ wires has already been reported [6].

Since a $CuNb/(Nb,Ti)_3Sn$ wire fabricated by a typical bronze process reveals a prestrain value of 0.35 % due to thermal contraction of bronze, the temperature dependence of the upper critical field B_{c2} is obtained as shown in Fig. 2. Comparing with an ordinary bronze-route $(Nb,Ti)_3Sn$ wire with only Cu stabilizer, $Cu/(Nb,Ti)_3Sn$, the B_{c2} value at 4.2 K for $CuNb/(Nb,Ti)_3Sn$ is 24 T and is lowered by about 1 T due to the relatively large prestrain. Using these B_{c2} values at various temperatures, the critical current properties are evaluated. Figure 3 shows critical currents measured at 4.2 K and the currents estimated at temperatures from 4.5 K to 6.0 K for $CuNb/(Nb,Ti)_3Sn$. Based on the scaling law of the global pinning

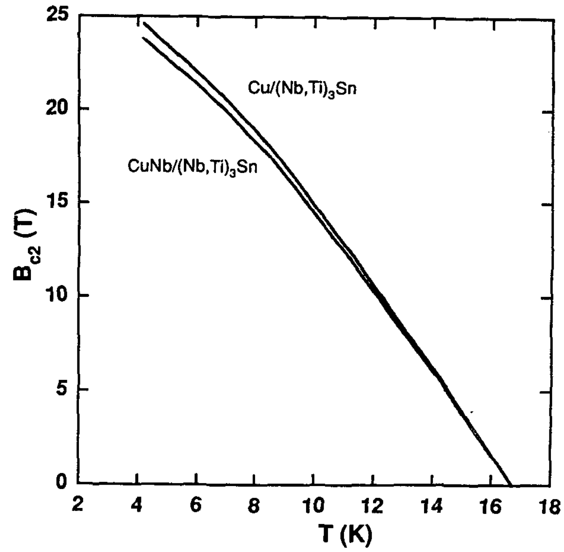

Fig. 2. Upper critical field as a function of temperature for $CuNb/(Nb,Ti)_3Sn$ and $Cu/(Nb,Ti)_3Sn$ wires.

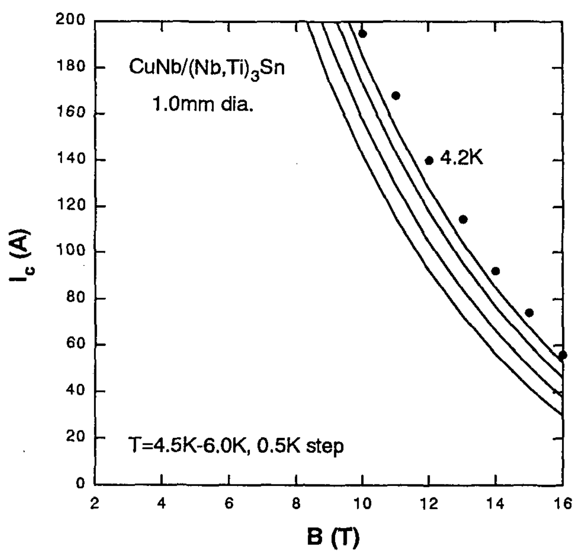

Fig. 3. Critical current as a function of magnetic field for a $CuNb/(Nb,Ti)_3Sn$ multifilamentary wire.

Table I Coil parameters of a 10 T-360 mm warm bore cryocooled superconducting magnet.

	section 1	section 2	section 3	section 4
superconductor	$CuNb/(Nb,Ti)_3Sn$	$CuNb/(Nb,Ti)_3Sn$	NbTi	NbTi
wire diameter [mm]	1.2	1.0	1.2	1.2
coil inner diameter [mm]	400	480	607	674
coil outer diameter [mm]	460	584	664	754
coil height [mm]	350	390	450	450
operating current [A]	120	120	120	180
overall current density [A/mm^2]	63.7	91.7	86.3	129
generated central field [T]	10.3 (1.5)	8.8 (3.5)	5.3 (1.8)	3.5
maximum field [T]	12.0	10.3	5.5	4.7
wire length [km]	7.6	25.7	18.6	28.8
wire mass [kg]	76.7	180	188	290
wire volume [cm^3]	8600	20200	21000	32500
hoop stress [MPa]	153	227	143	207

force, the temperature and magnetic field dependence of the critical current are estimated by fitting to the actual data measured at 4.2 K.

III. Cryocooled Large bore $CuNb/(Nb,Ti)_3Sn$ Superconducting Magnet

We have established the reliable technique to use a relatively large current capacity of 400 A for a cryocooled superconducting magnet.[4] It is always important to reduce two heat sources through current leads to the second stage of a GM-cryocooler, i.e. conduction heat leaks down the current lead from room temperature and heat generations within the current lead and at the lead connections by ohmic loss. The former conduction heat is surprisingly lowered less than 0.08 W using a pair of high temperature $Bi_2Sr_2Ca_2Cu_3O_{10}$ current leads with a size of 24 mm in outer diameter, 20 mm in inner diameter, and 140 mm in length, which have a lower thermal conductivity than stainless steel and its integral value of 0.42 W/cm from 50 K to 4.2 K. The latter heat generation within the current lead is not appeared in principle, because the critical currents are 1000 A at 77 K in the absence of a magnetic field and 500 A at 50 K in fields up to 4 T for B//c-axis. Heat generation at lead connections are estimated to be 0.32 W for 4 joints using a contact resistance of 0.5 $\mu\Omega$ at 400 A. Therefore, in the case of operating currents of 100-200 A, one notices that current leads are no longer large heat inputs. In order to precool a large bore superconducting magnet in a week from room temperature and lower the coil temperature down to 5.0 K, four GM-cryocoolers will be equipped with a cryostat. A refrigeration capacity is 1 W at 4.0 K for one GM-cryocooler. A temperature rise during a magnetic field sweep in a cryocooled superconducting magnet is associated with an a.c. loss, whose main is due to a hysteresis loss. A hysteresis loss is expressed in the form of

$$Q_h = \frac{8}{3\pi} V \ J_c \frac{d}{4} (\frac{dB}{dt})^2,$$

where Q_h is a hysteresis loss in J, V a volume of superconducting filament cores in m^3, J_c a core critical current density in A/m^2, d a core diameter in m, and (dB/dt) a sweep rate of a magnetic field in T/s. To achieve the coil temperature below 5.0 K by reducing a hysteresis loss during energizing to the maximum field, the superconducting wires with fine filaments of around 5 μm have to be employed. Moreover, we intend to divide the winding with each operating at a different current. The design idea to divide the coil winding into a number of grading sections is essentially based on improving the efficiency of superconductor utilization. In addition, the way of dividing the coil also leads us to reduce a hysteresis loss. This is because an inner coil with a small coil volume is energized with a small operating current. Two operating currents consisting of 180 A for an outermost coil and 120 A for the others are adopted using dual current suppliers. Table I lists coil specifications designed for a 10 T cryocooled superconducting magnet with a 360 mm warm bore. An outer NbTi coil is subdivided into two sections to reduce a coil inductance and an electromagnetic stress. Employing multifilamentary NbTi wires with a wire diameter of 1.2 mm and a Cu and NbTi ratio of 2.0, an outermost section 4 coil is operated at 180 A and followed by an operating current at 120 A for a section 3 coil. A NbTi coil will generate 5.3 T at a center of a 600 mm clear bore. A highly strengthened inner $CuNb/(Nb,Ti)_3Sn$ coil is inserted in a backup NbTi outer coil. Figure 4 shows the critical current at 5.0 K in $CuNb/(Nb,Ti)_3Sn$ wires with load lines for maximum fields at the winding. Although a section 2 coil is wound employing $CuNb/(Nb,Ti)_3Sn$ wires with a 1.0 mm diameter, an innermost section 1 coil is made employing $CuNb/(Nb,Ti)_3Sn$

wires with a 1.2 mm diameter to obtain a critical current margin in high fields. When an inner $CuNb/(Nb,Ti)_3Sn$ coil is combined with an outer NbTi coil, the coil assembled will generate a central field of 10.3 T in a 360 mm room temperature bore.

In a cryocooled superconducting magnet system, a stored energy is absorbed by the coil mass in the case of a coil quench. A cryocooled large bore superconducting magnet designed with two operating currents of 180 A and 120 A has a stored energy of about 4 MJ. Considering only superconductor mass of about 730 kg, the average energy divided by coil mass is 5.48 J/g and corresponds to the temperature rise of less than 80 K. Since the actual coil mass amounts to 1.5 times larger cryogenic mass including coil bobbins and flanges, the heat capacity of the whole coil assemble can fully absorb a magnetic stored energy. An important point is that the occurrence of local energy concentration has to be eliminated. Protection diodes are usually equipped inside a cryostat, in order to realize electrically divided coils. Further, a traditional active technique using a dump resistor equipped outside a cryostat is also utilized to extract most of the stored energy.

Here, the advantages of a 10 T- 360 mm bore superconducting magnet employing high strength $CuNb/(Nb,Ti)_3Sn$ wires are evaluated, comparing with employing ordinary $(Nb,Ti)_3Sn$ wires stabilized with Cu, $Cu/(Nb,Ti)_3Sn$. Superconducting magnets constructed so far for a hybrid magnet which generated 8-10 T in a large bore of around 360 mm have heavy coil mass such as 1900 kg [3]. One of great advantages is that the coil weight of a $CuNb/(Nb,Ti)_3Sn$ superconducting magnet made compactly for a cryocooled magnet is extremely reduced by 50-70 %. Since the highly strengthened $CuNb/(Nb,Ti)_3Sn$ wires with a small wire diameter of 1.0-1.2 mm exhibit twice larger stress tolerance of 240 MPa, almost twice larger strain tolerance of 0.35 %, and more than twice larger bending strain tolerance of 0.4-0.5 %, a new magnet technology is available for making a coil. A react and wind method and a tension-winding technique using multifilamentary $CuNb/(Nb,Ti)_3Sn$ wires enable us to realize a coil formation without a large-scale heat treatment furnace and a vacuum epoxy-impregnation equipment.

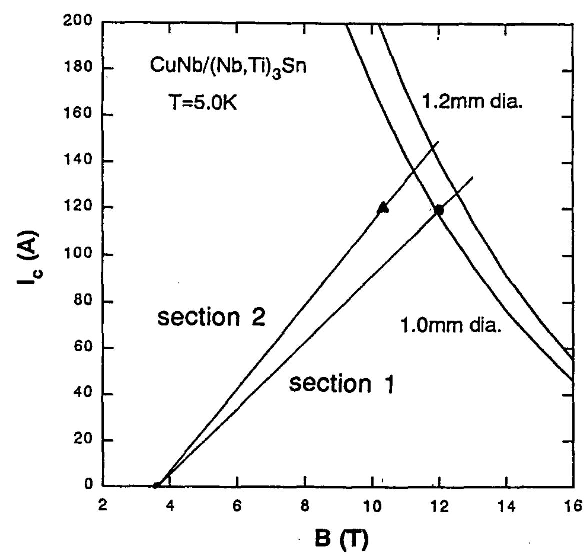

Fig. 4. I_c-vs-B at 5.0 K and load lines for $CuNb/(Nb,Ti)_3Sn$ multifilamentary wires with 1.0 mm and 1.2 mm in outer diameter.

IV. Conclusions

A 10 T cryocooled superconducting magnet with a large room temperature bore of 360 mm for a hybrid magnet can be made very compactly, employing high strength and good conductive $(Nb,Ti)_3Sn$ wires with CuNb composite stabilizer, $CuNb/(Nb,Ti)_3Sn$.

A $CuNb/(Nb,Ti)_3Sn$ superconducting magnet is fabricated by a react and wind and a tension-winding method which enable a new coil formation technique with no need of a large-scale heat treatment furnace and no need of a vacuum epoxy-impregnation equipment.

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