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Stability of Nb_3Sn Wires with CuNb Reinforcing Stabilizer on Cryocooled Superconducting Magnet

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***Abstract*— The stability of advanced Nb_3Sn wires with CuNb reinforcing stabilizer cooled by refrigerator is studied in order to obtain data base for the future compact design of cryocooled superconducting magnets. The experiments on the critical currents, the minimum quench energy and the normal zone propagation velocity for a cryocooled sample-coil of the CuNb/Nb_3Sn wires are carried out under the condition of the magnetic field up to 15 T at temperatures ranging from 4 K to 10 K. Added to this, we make a comparison between the stability of CuNb/Nb_3Sn and Cu/Nb_3Sn wires in the cryocooling case. It is concluded from this experimental result there are the slight differences between two kinds of wires, which have to be considered for cryocooled magnet design.**

I. Introduction

The CuNb composite, which is a high strength and a high conductivity materials, is considered to be a good reinforcing stabilizer for a superconducting wire in the compact design of high field and large scale magnets. We have developed a bronze-processed multifilamentary Nb_3Sn superconducting wire with CuNb reinforcing stabilizer (CuNb/Nb_3Sn), and mechanical and superconducting properties of the wire immersed in liquid helium have been studied [1]. Recently, on the other hand, cryocooled superconducting magnet was realized using high-temperature superconducting current leads [2]. Since the cryocooled superconducting magnet operates in a vacuum without liquid helium, the design concept of this magnet is supposed to be different from that of the conventional magnet cooled by liquid helium bath. From this point of view, thermal stability of Nb_3Sn superconducting wires need to be reconsidered for cryocooled magnet design.

In this paper, measurements are performed on the temperature and magnetic field dependence of critical current densities and the thermal stability characteristics of Nb_3Sn wires in the cryocooling state. In addition, the difference of the thermal stability between Cu/Nb_3Sn and CuNb/Nb_3Sn wires is discussed.

TABLE I
SPECIFICATIONS OF BRONZE-PROCESSED MULTIFILAMENTARY Nb_3Sn SUPERCONDUCTING WIRES.

	Cu/Nb_3Sn	CuNb/Nb_3Sn
Stabilizer	pure Cu	Cu–20 wt.% Nb
Wire diameter	1.06 mm	1.02 mm
Filament diameter	3.7 μm	3.5 μm
Number of filaments	7849	7849
Bronze/core ratio	3.9	3.9
Cu/CuNb/non Cu ratio	1.21/0/1	0.37/0.86/1
Sn concentration in Cu	Cu–13 wt.% Sn	Cu–13 wt.% Sn
Ti concentration in Nb	Nb–1.2 wt.% Ti	Nb–1.2 wt.% Ti
Barrier materials	Ta	Ta
Twist pitches	21mm	20mm

II. Experimental Apparatus

The experiment is performed with bronze-processed multifilamentary Nb_3Sn superconducting wire which is wound onto an aluminum nitride (AlN) bobbin as a sample coil. Here, two kinds of Cu/Nb_3Sn and CuNb/Nb_3Sn sample coils are prepared for comparison. Table I lists the specifications of the both multifilamentary superconducting wires. A cryocooled sample holder [3], which mainly

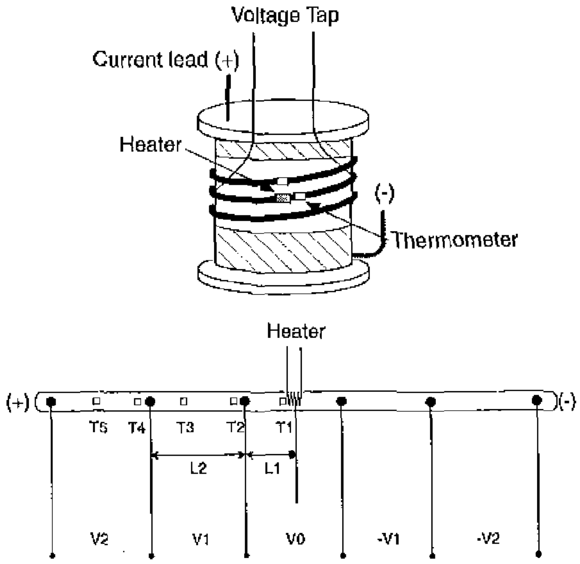

Fig. 1. Schematic of a sample coil and locations of voltage taps and thermometers.

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consists of a GM-cryocooler, a 50-cm-long copper conduction bar, and high temperature superconducting current leads, is utilized to investigate the thermal stability characteristics in the cryocooling state. The sample coil is set at the bottom side of the copper bar whose top side is connected with the 2nd stage of the GM-cryocooler, the temperature of which is controlled from 4 K to 10 K by a heater equipped into the 2nd stage. The cryocooled sample holder is installed into a room-temperature bore of a water-cooled resistive magnet, and the external magnetic fields up to 15 T are applied perpendicularly to the superconducting wires.

A minimum quench energy MQE and a normal zone propagation velocity v_p are investigated by applying a thermal disturbance, which is supplied by a strain gauge heater with time duration of 0.5 $\sim$ 2 ms at a center position of the sample coil. The positions of voltage taps and thermometers, which are used to measure the stability characteristics, are schematically shown in Fig. 1.

III. Experimental Results and Discussion

A critical current I_c of the sample coil is determined by a 100 μV/m criterion. Fig. 2 shows a critical current density J_c, which is calculated from I_c divided by a cross-sectional area excluding the Cu or CuNb stabilizer, as a function of temperature T at field strength B ranging from 10 T to 14 T. J_c for the CuNb/Nb$_3$Sn wire is slightly lower than that for the Cu/Nb$_3$Sn wire. This degradation of J_c comes from that the residual strain for the CuNb/Nb$_3$Sn wire is larger than that of the Cu/Nb$_3$Sn wire [4]. From Fig. 2, a critical temperature T_c at which J_c goes to zero is obtained to be 9.3 K for the CuNb/Nb$_3$Sn wire and 9.7 K for the Cu/Nb$_3$Sn wire at 14 T. This difference in T_c is also caused by the difference in the residual strain effect as described above.

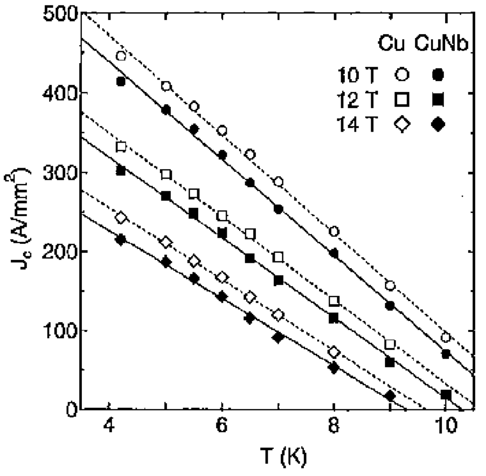

Fig. 2. Critical current densities J_c as a function of temperature T at field strength ranging from 10 T to 14 T. Open and closed marks denote the values for Cu/Nb$_3$Sn and CuNb/Nb$_3$Sn, respectively.

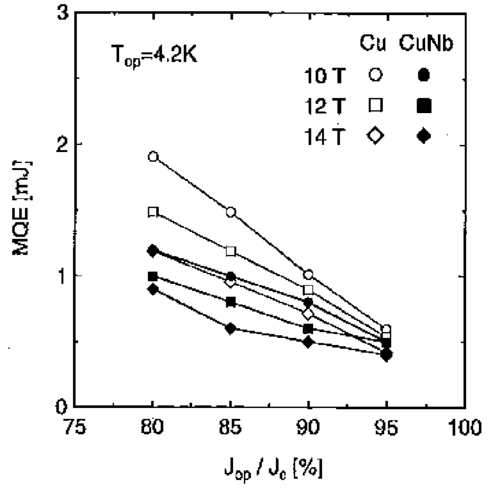

Fig. 3. Minimum quench energies MQE as a function of operating current ratio J_{op}/J_c at 4.2 K for Cu/Nb$_3$Sn (open marks) and CuNb/Nb$_3$Sn (closed marks) wires.

A minimum quench energy MQE is obtained as a minimum value of thermal energy given by the heater, where the sample coil goes to quench. Fig. 3 shows the MQE values at 4.2 K for the Cu/Nb$_3$Sn and CuNb/Nb$_3$Sn wires, varying the operating current density ratio to the critical current density J_{op}/J_c from 80% to 95% and the field strength B from 10 T to 14 T. Both the wires have the same tendency that the MQE values decrease with an increase in J_{op}/J_c and/or B. This dependence of MQE on J_{op}/J_c and/or B admits of two interpretations.

First, the decrease in MQE is considered to be caused by the decrease in a temperature margin, which is defined as a difference between a current sharing temperature T_{cs} and a operating temperature T_{op}. For instance, T_{cs} for CuNb/Nb$_3$Sn wire at 10 T and J_{op}/J_c = 80 % ($J_{op} \simeq$ 330 A/mm^2) is obtained to be about 5.7 K from Fig. 2, and thus the temperature margin is 1.5 K since T_{op} is now 4.2 K. In the same way, the temperature margin is obtained to be about 0.4 K at 10 T and J_{op}/J_c = 95 % and 1.0 K at 14 T and J_{op}/J_c = 80 %, which indicates that the temperature margin decreases with an increase in J_{op}/J_c or B. As a result, the current sharing occurs by the smaller energy of thermal disturbance as increasing J_{op}/J_c or B, which means the decrease in MQE.

Second, the decrease in MQE is considered to be caused by the increase in a joule heating. In general, quench occurs when the total energy of the thermal disturbance given by the heater and the joule heating generated after the current sharing exceeds the cooling capacity of cryogen. If the energy of the joule heating is increasing, the thermal disturbance energy required to cause quench is thought to be decreasing. Indeed, MQE decreases with an increase in the joule heating in the case that J_{op}/J_c increases at a fixed value of B. When B increases at a fixed value of J_{op}/J_c, however, MQE decreases although the joule heating is reduced. Judging from the above, MQE is considered to be affected dominantly by the temperature margin rather than the joule heating. This implies that the current sharing, which depends on the temperature margin, is directly linked to the quench independently of the joule heating in the cryocooled sample coil.

Here, we see the MQE values for Cu/Nb$_3$Sn and CuNb/Nb$_3$Sn wires at 10 T and J_{op}/J_c = 80 % are 1.9 mJ and 1.2 mJ, respectively, which indicates that the MQE for Cu/Nb$_3$Sn wire is 50 % as large as that for CuNb/Nb$_3$Sn. Since a thermal conductivity of Cu is several times larger than that of CuNb, the thermal disturbance applied to the Cu/Nb$_3$Sn wire surface can diffuse faster and the temperature of the Cu/Nb$_3$Sn wire is lower than that of the CuNb/Nb$_3$Sn wire. Thus, it is considered that the large thermal disturbance is necessary to cause quench for Cu/Nb$_3$Sn in comparison with CuNb/Nb$_3$Sn.

Normal zone propagation behaviors through voltage taps V$_0$, V$_1$, V$_2$ [see Fig. 1] are measured at 10 T and 4.2 K for $J_{op}/J_c = 80$ %, as shown in Fig. 4. The time of transition to normal state is defined as when the voltage exceeds 6 μV, since the criterion is 100 μV/m and the length between voltage taps is about 60 mm. The velocity of normal zone propagation v_p is determined from the following equation:

$$v_{pi} = \frac{L_i}{\Delta t_i} \quad (i = 1, 2) \tag{1}$$

where Δt_i is the time for the normal front propagation through the length L_i shown in Fig. 1.

Fig. 5 presents the normal zone propagation velocities v_{p1} for both the wires as a function of the operating current density J_{op} at 4.2 K. The propagation velocities v_{p1} increase with the increase in J_{op}, but are discontinuous where the field strength B is different. For example, the propagation velocity v_{p1} for $J_{op} \simeq 240$ A/mm^2 is larger than that for $J_{op} \simeq 270$ A/mm^2, where the operating current ratios J_{op}/J_c are 95 % and 80 % in the cases of $J_{op} = 240$ A/mm^2 and 270 A/mm^2, respectively. This means the propagation velocities v_{p1} become larger when J_{op}/J_c is larger even if J_{op} is smaller. For the purpose of confirming this, Fig. 5 is redrawn as a function of J_{op}/J_c instead of J_{op}, as shown in Fig. 6. The propagation velocities v_{p1} are linearly enhanced with an increase in J_{op}/J_c. This dependence of v_{p1} on J_{op}/J_c is considered to be related to the temperature margin, which is discussed later. As concerns the dependence on the materials of stabilizer, on the other hand, the values of v_{p1} for CuNb/Nb$_3$Sn wire are slightly smaller than those for Cu/Nb$_3$Sn wire.

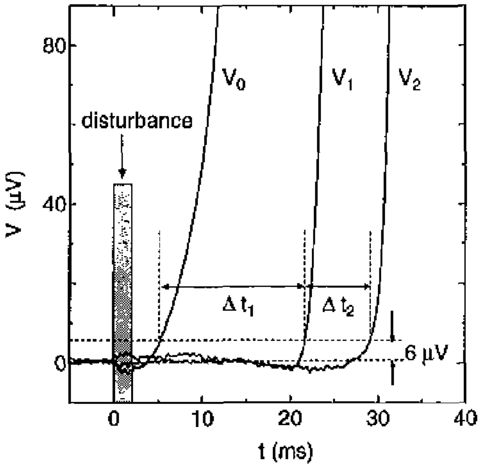

Fig. 4. Typical example of normal zone propagation behaviors observed through voltage taps at 10 T and 4.2 K for $J_{op}/J_c = 80$ %.

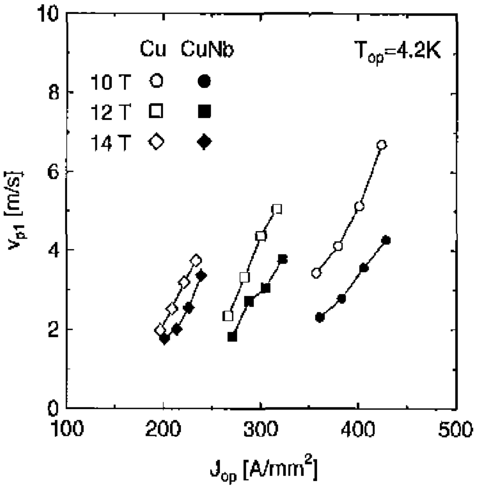

Fig. 5. Normal zone propagation velocities v_{p1} as a function of operating current density J_{op} at 4.2 K for Cu/Nb$_3$Sn (open marks) and CuNb/Nb$_3$Sn (closed marks) wires.

In order to discuss the dependence of the propagation velocities v_{p1} on the operating current density J_{op} and the materials of stabilizer in more detail, experimental results on the propagation velocities v_{p1} are compared with

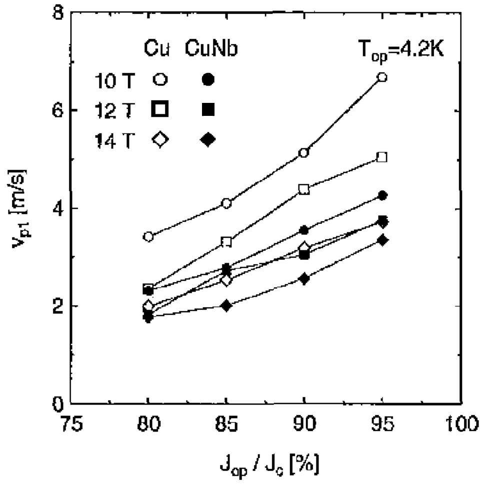

Fig. 6. Normal zone propagation velocities v_{p1} as a function of operating current ratio J_{op}/J_c at 4.2 K for Cu/Nb$_3$Sn (open marks) and CuNb/Nb$_3$Sn (closed marks) wires.

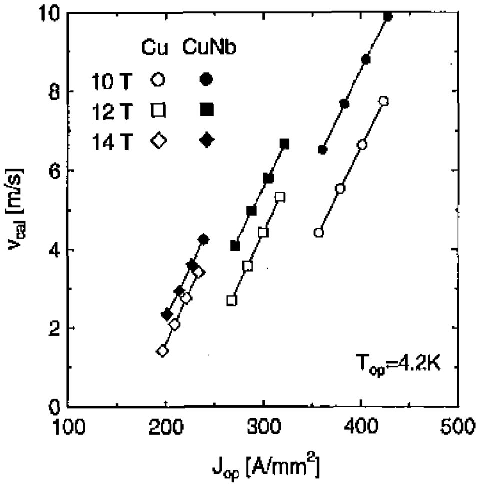

Fig. 7. Theoretical normal zone propagation velocities v_{cal} as a function of operating current density J_{op} at 4.2 K for Cu/Nb_3Sn (open marks) and CuNb/Nb_3Sn (closed marks) wires.

the results of numerical analysis. The theoretical normal zone propagation velocities v_{cal} are calculated using the following equation [5]:

$$v_{cal} = \frac{J_{op}}{C}\left[\frac{\rho\chi}{T_{cs} - T_{op}}\right]^{\frac{1}{2}} \frac{1 - 2y}{(yz^2 + z + 1 - y)^{1/2}} \qquad (2)$$

where C, ρ, and χ are the specific heat, the residual electrical resistivity, and the thermal conductivity, respectively. The terms y and z in (2) denote steady-state and transient heat transfers, respectively, and are defined by

$$y = \frac{Ph(T_{cs} - T_{op})}{A\rho J_{op}^2}, \quad z = \frac{PQ_T}{AC(T_{cs} - T_{op})} \qquad (3)$$

where A is the cross-sectional area and P is the cooling perimeter. Q_T and h denote the latent heat of cryogen and the heat transfer coefficient, respectively. Although these two parameters Q_T and h should be equal to zero in the adiabatic condition (cryocooling condition), we treat them as the finite values of heat conduction because the AlN bobbin on which the superconducting wire is wound has the heat capacity and is considered to work as cryogen.

The numerical results are presented in Fig. 7, where $h = 1000$ W/m^{2}K and $Q_T = 15$ J/m^3. The values of other parameters are taken from previous works [6]. The comparison between the experimental and theoretical results shows a similar tendency that the propagation velocities depend on not only J_{op} but also J_{op}/J_c. In addition, it is obtained that the dependence of v_{cal} on J_{op}/J_c gradually appears when Q_T is decreasing, which means the temperature margin relevant to J_{op}/J_c dominantly affects the propagation velocities rather than the joule heating relevant to J_{op} by the decline in cooling capacity. From the viewpoint of dependence on the materials of stabilizer, on the other hand, we obtain the opposite characteristics that the propagation velocities for CuNb/Nb_3Sn wire is smaller and larger than that for Cu/Nb_3Sn wire in the experimental and theoretical results, respectively. This discrepancy may come from the difference in the transient heat conduction between the superconducting wire and the AlN bobbin in the experiment. It is confirmed that the theoretical results v_{cal} approach to the experimental ones v_{p1} by adjusting the value of Q_T in the term of the transient heat conduction z in (3).

IV. CONCLUSIONS

The stability of advanced Nb_3Sn wires with CuNb reinforcing stabilizer in the cryocooling state is investigated. The minimum quench energy MQE and the normal zone propagation velocities v_{p1} are observed to be depend on not only the operating current density J_{op} but also the operating current ratio J_{op}/J_c, which is found to be closely related to the temperature margin of the superconducting wire. The comparison of stabilities between Cu/Nb_3Sn and CuNb/Nb_3Sn wires reveals that MQE and v_{p1} have the slight differences between two kinds of wires, and thus the differences have to be considered for cryocooled magnet design.

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