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Authors: 金子 俊郎

Journal or publication title: IEEE transactions on applied superconductivity

Volume: 10

Number: 1

Page range: 1235-1238

Year: 2000

URL: http://hdl.handle.net/10097/34862
Stability of Nb\textsubscript{3}Sn Wires with CuNb Reinforcing Stabilizer on Cryocooled Superconducting Magnet

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Abstract—The stability of advanced Nb\textsubscript{3}Sn 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\textsubscript{3}Sn 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\textsubscript{3}Sn and Cu/Nb\textsubscript{3}Sn 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\textsubscript{3}Sn superconducting wire with CuNb reinforcing stabilizer (CuNb/Nb\textsubscript{3}Sn), 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\textsubscript{3}Sn 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\textsubscript{3}Sn wires in the cryocooling state. In addition, the difference of the thermal stability between Cu/Nb\textsubscript{3}Sn and CuNb/Nb\textsubscript{3}Sn wires is discussed.

Table I

<table>
<thead>
<tr>
<th>Specifications of Bronze-Processed Multifilamentary Nb\textsubscript{3}Sn Superconducting Wires.</th>
<th>Cu/Nb\textsubscript{3}Sn</th>
<th>CuNb/Nb\textsubscript{3}Sn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilizer</td>
<td>pure Cu</td>
<td>Cu-20 wt.% Nb</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>1.06 mm</td>
<td>1.02 mm</td>
</tr>
<tr>
<td>Filament diameter</td>
<td>3.7 μm</td>
<td>3.5 μm</td>
</tr>
<tr>
<td>Number of filaments</td>
<td>78/9</td>
<td>78/9</td>
</tr>
<tr>
<td>Cross-core ratio</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>Cu/CuNb/Ti ratio</td>
<td>Cu-13/10/0.1</td>
<td>Cu-13/0.37/0.86/1</td>
</tr>
<tr>
<td>Sn concentration in Cu</td>
<td>Cu-13 wt.% Sn</td>
<td>Cu-13 wt.% Sn</td>
</tr>
<tr>
<td>Ti concentration in Nb</td>
<td>Nb-1.2 wt.% Ti</td>
<td>Nb-1.2 wt.% Ti</td>
</tr>
<tr>
<td>Barrier materials</td>
<td>Ta</td>
<td>Ta</td>
</tr>
<tr>
<td>Twist pitch</td>
<td>21 mm</td>
<td>30 mm</td>
</tr>
</tbody>
</table>

II. EXPERIMENTAL APPARATUS

The experiment is performed with bronze-processed multifilamentary Nb\textsubscript{3}Sn superconducting wire which is wound onto an aluminum nitride (AlN) bobbin as a sample coil. Here, two kinds of Cu/Nb\textsubscript{3}Sn and CuNb/Nb\textsubscript{3}Sn sample coils are prepared for comparison. Table I lists the specifications of the both multifilamentary superconducting wires. A cryocooled sample holder [3], which mainly...
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 ~ 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 \( \mu \)V/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/NbSn wire is slightly lower than that for the Cu/NbSn wire. This degradation of \( J_c \) comes from that the residual strain for the CuNb/NbSn wire is larger than that of the Cu/NbSn 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/NbSn wire and 9.7 K for the Cu/NbSn wire at 14 T. This difference in \( T_c \) is also caused by the difference in the residual strain effect as described above.

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/NbSn and CuNb/NbSn 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 an operating temperature \( T_{op} \). For instance, \( T_{cs} \) for CuNb/NbSn wire at 10 T and \( J_{op}/J_c = 80 \% \) (\( J_{op} \approx 330 \text{ A/mm}^2 \)) is obtained to be about 5.7 K from Fig. 2, and thus the temperature margin is 1.5 K since \( T_{cs} \) 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 $v_{pl}$ is determined from the following equation:

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

where $\Delta t_i$ 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 $v_{pl}$ for both the wires as a function of the operating current density $J_{op}$ at 4.2 K. The propagation velocities $v_{pl}$ increase with the increase in $J_{op}$, but are discontinuous where the field strength $B$ is different. For example, the propagation velocity $v_{pl}$ for $J_{op} \approx 240$ A/mm$^2$ is larger than that for $J_{op} \approx 270$ 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 $v_{pl}$ 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 $v_{pl}$ are linearly enhanced with an increase in $J_{op}/J_c$.

This dependence of $v_{pl}$ 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 $v_{pl}$ for CuNb/Nb$_3$Sn wire are slightly smaller than those for Cu/Nb$_3$Sn wire.

In order to discuss the dependence of the propagation velocities $v_{pl}$ on the operating current density $J_{op}$ and the materials of stabilizer in more detail, experimental results on the propagation velocities $v_{pl}$ are compared with
Fig. 7. Theoretical normal zone propagation velocities \( v_{\text{col}} \) as a function of operating current density \( J_{\text{op}} \) at 4.2 K for Cu/NbSn wire (open marks) and CuNb/NbSn wire (closed marks) wires.

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

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

where \( C, \rho, \) and \( \chi \) 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

\[
y = \frac{P h (T_{\text{cs}} - T_{\text{op}})}{A \rho J_{\text{op}}^2}, \quad z = \frac{P Q_T}{A C (T_{\text{cs}} - T_{\text{op}})}
\]

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 AIN 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 \( h = 1000 \text{ W/m}^2\text{K} \) and \( Q_T = 15 \text{ J/m}^3 \). 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 \( J_{\text{op}} \) but also \( J_{\text{op}}/J_c \). In addition, it is obtained that the dependence of \( v_{\text{col}} \) on \( J_{\text{op}}/J_c \) gradually appears when \( Q_T \) is decreasing, which means the temperature margin relevant to \( J_{\text{op}}/J_c \) dominantly affects the propagation velocities rather than the Joule heating relevant to \( J_{\text{op}} \) 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/NbSn wire is smaller and larger than that for Cu/NbSn 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 AIN bobbin in the experiment. It is confirmed that the theoretical results \( v_{\text{col}} \) approach to the experimental ones \( v_{\text{pl}} \) by adjusting the value of \( Q_T \) in the term of the transient heat conduction \( z \) in (3).

IV. CONCLUSIONS

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

ACKNOWLEDGMENT

The authors are indebted to H. Izawa and J. Ohno for their collaborations in the preliminary measurements. The experimental work was carried out at High Field Laboratory for Superconducting Materials, IMR, Tohoku University.

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