Effects of Cu Stabilizer Configuration on Thermal Stability of Nb_3Sn Composite Superconductors Under Cryocooling Condition

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***Abstract*—It is known that current sharing effects of the stabilizer are limited in cryocooling conditions being different from poolboiling. Therefore we have studied stability under it, focusing on minimum quench energy (MQE) of Nb_3Sn superconductors under various conditions of the applied magnetic field, temperature, and the transport current, for various volume fractions and configurations of Cu stabilizer. From the experimental results, the larger the external Cu volume fraction, the higher the MQE was obtained. All MQE data were summarized by only one line in characteristics of normalized MQE and normalized B (B/B_{c2}). The obtained MQE behavior was to be characterized by only one empirical equation. It is thought that the obtained formula is useful for a standard of designing the Nb_3Sn superconductor and its coil under cryocooled condition.**

***Index Terms*—Cryocooling, MQE, Nb_3Sn wire, thermal stability.**

I. Introduction

RECENTLY a cryocooled superconducting magnet has progressed by development of the 4.2 K GM-cryocooler. A 20-T class cryocooled magnet has been designed [1] for demands of higher magnetic fields. A lot of studies concerning with stability under pool-boiling cooling condition were achieved, however fewer have addressed stability under cryocooling condition.

Previously, there were some reports on thermal stability for CuNb-reinforced Nb_3Sn wires [2], [3], and Nb-Ti-Cu-reinforced ones [4], under cryocooling condition. The higher the applied magnetic field strength, the lower the minimum quench energy (MQE) that indicates thermal stability measured under cryocooling condition, unlike pool-boiling cooling condition. Furthermore, the higher the loading condition (transport current normalized by critical current) and the lower the temperature margin, the lower the obtained MQE. Based on these results, it is suggested from numerical analysis about MQE that the thermal conductivity that contributes to thermal stability is more important than the electrical conductivity under cryocooling condition [4].

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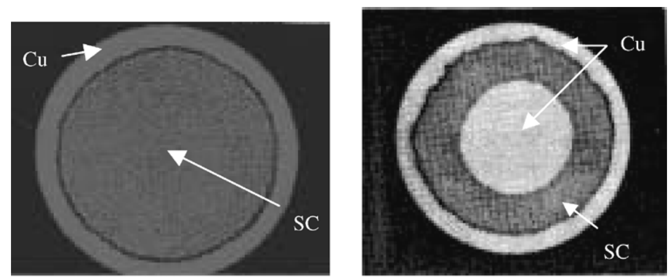

(a) (b)

Fig. 1. Cross-sectional views of Nb_3Sn wire (ϕ 1 mm). (a) Cu stabilizer is placed in the outermost shell (Wire-B); (b) Cu stabilizer is placed in outermost shell and the center of the wire (Wire-D).

In this paper, we study and discuss about the effects of volume fractions and configurations of Cu stabilizer on thermal stability using newly-developed Ta-reinforced Nb_3Sn wires and internally-stabilized wires from the view point of experimental results and empirical formula. There are two types of disturbances resulting in instability: a continuous and internal-oriented phenomenon such as AC losses, and pulsed and external-oriented one. This study has been designed to investigate the latter one caused by wire-movement and cracks in epoxy in the coil.

II. MQE Measurement

A. Experimental Procedure

We measured MQE of two types of Nb_3Sn wires, externally-stabilized wires and internally-stabilized wires. The former has Cu stabilizer only around the exterior of the superconductivity part, and the latter has Cu stabilizer in the central part of the wire. Three kinds of externally-stabilized wires, Wire-A, Wire-B and Wire-C, having different Cu volume fraction and two kinds of internally-stabilized wires, Wire-D having internal and external stabilizers and Wire-E having only internal one, were prepared and measured. Cross-sectional views of the typical Nb_3Sn wires used as samples are shown in Fig. 1 and Table I.

In the experiment, the sample wire was wound around the bobbin made by G-10 with 36 mm diameter. The sample bobbin was installed on the second stage of a GM (Gifford McMahon) cryocooler. A 1.5-mm square thin strain gauge having 120 W resistance was used for generating the heat disturbance, which was stacked on the sample. Voltage taps, V1–V5, and temperature sensors (Cernox), T1–T4, were set on the sample as shown in Fig. 2.

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TABLE I
SPECIFICATIONS OF Nb_3Sn SAMPLE WIRES

	Wire-A	Wire-B	Wire-C	Wire-D	Wire-E
Wire diameter (mm)	1.0	1.0	1.0	1.0	1.0
Filament diameter (μ m)	3.7	8.1	3.5	3.5	5.0
Number of filament	7849	-	7638	11229	8486
Material					
Diffusion barrier	Ta	Ta	Nb	Nb	Nb
Reinforcement	-	Ta	Nb-Ti-Cu	-	-
Volume fraction (%)					
Cu/reinforcement/non Cu	54.75/0/45.26	33.0/15.0/52.0	22.4/24.4/53.2	54.75/0/45.25	20.0/0/80.0
External Cu	54.75	33.00	22.40	21.00	0.00

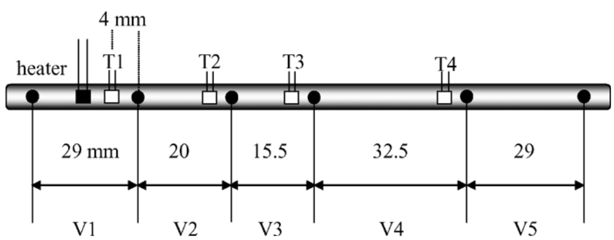

Fig. 2. Location of voltage taps, temperature sensors and heater for disturbance. As the sample is wound like a coil, V5 is located just above V1.

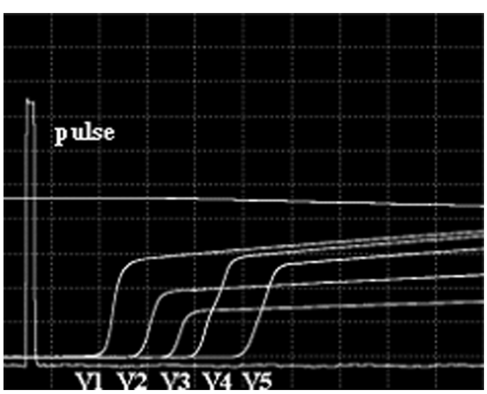

Fig. 3. Oscillograms showing voltage response traces (at V1, V2, V3, V4, V5 and pulse) at quench of the sample wire at 4.2 K and 14.0 T.

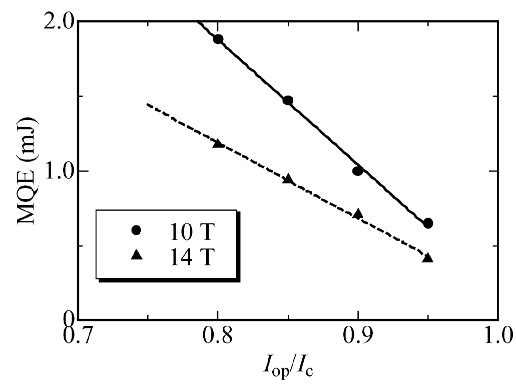

Fig. 4. I_{op}/I_c dependencies of the MQE as a parameter of applied field at 4.2 K (Wire-A).

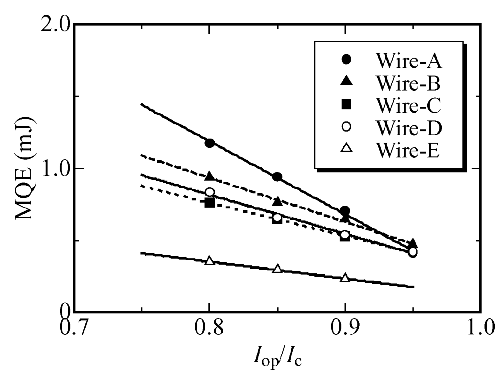

Fig. 5. I_{op}/I_c dependencies of the minimum quench energy for Wires A, B, C, D and E at 4.2 K and 14.0 T.

Signals obtained from them were recorded by a personal computer and a digital oscilloscope. Disturbance energy increasing by 0.06-mJ step was inputted to the sample under the transport current of 80% to 95% of critical current. In increasing of stepped input energy, the minimum energy that causes quench of the sample wire was defined as the MQE. The MQE was measured at 4.2 K and applied magnetic fields of up to 14.5 T by the cryocooled superconducting magnet, 15 T-CSM, of Institute for Materials Research, Tohoku University.

B. Experimental Results and Discussion

Fig. 3 shows that voltage-time characteristics of normal state propagation for Nb_3Sn wire observed in the digital oscilloscope did not show a recovery from the normal state to the superconducting state even with a Cu stabilizer for any of these experimental conditions. This result indicates that the occurrence of only a small part of the normal state leads to immediate quenching. It was realized that controlling of the transfer to quenching after the current sharing was not expected because the suppression of joule-heat generation by the stabilization material was insufficient under these cryocooled conditions. This means that the stabilizer has no function as a current bypass under cryocooled conditions.

Fig. 4 shows the transport current (I_{op}) normalized by critical current (I_c) dependencies of the MQE as parameters of the applied fields at 4.2 K in Wire-A. The MQE decreases as I_{op}/I_c increases, showing linear dependence with the MQE against the normalized current region (80% to 95% of I_c).

Fig. 5 shows the normalized transport current vs. the MQE for various wires at 4.2 K and 14 T.

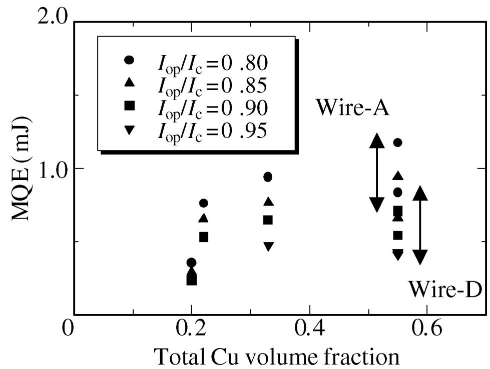

Fig. 6. MQE vs. total Cu volume fraction as a parameter I_{op}/I_c at 4.2 K and 14.0 T.

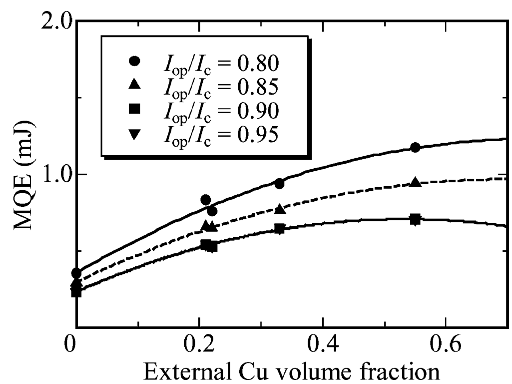

Fig. 7. MQE vs. external Cu volume fraction as a parameter of $I_{\rm op}/I_{\rm c}$ at 4.2 K and 14.0 T.

It shows that all wires have the same trend for $I_{\rm op}/I_{\rm c}$ that MQE decreases with increase of $I_{\rm op}/I_{\rm c}$ but each wire has different MQE values.

Fig. 6 shows Cu volume fraction dependencies of the MQE. The MQE vs. Cu volume fraction is positively correlated at externally-stabilized wires (Wires A, B and C). However, there is no correlation at other wires (Wires D and E) including internal Cu. It is considered that internal stabilizer does not contribute to thermal stability for external disturbances. Therefore, characteristics of the MQE vs. external Cu volume fraction were shown in Fig. 7. It shows clearly positive correlation. We understand that the internal stabilizer does not demonstrate any function as a thermal stabilizer against the external disturbance, because it has no function of a current shunt and a heat drain under cryocooled condition.

III. Empirical Formula

In order to discuss a thermal stability under cryocooled condition at high-field region, an empirical formula about MQE was established, based on these measurement results. The formula is derived by various normalized parameters: the minimum quench energy, the transport current, and applied magnetic filed. Fig. 8 shows applied magnetic field dependencies of the MQE at $I_{\rm op}/I_{\rm c} = 0.8$ for Wires A, B and C. In Fig. 8, B is applied magnetic field and $B_{\rm c2}$, upper critical field, is computed from

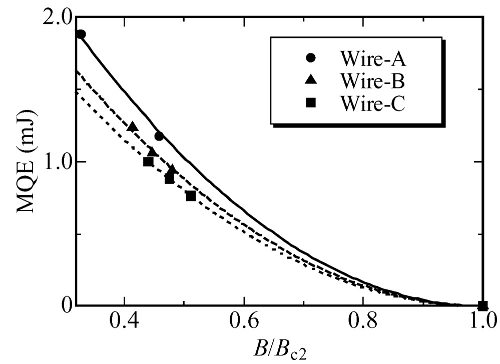

Fig. 8. $B/B_{\rm c2}$ dependencies of the minimum quench energy, as parameters of external Cu volume fraction at 4.2 K and $I_{\rm op}/I_{\rm c} = 0.80$.

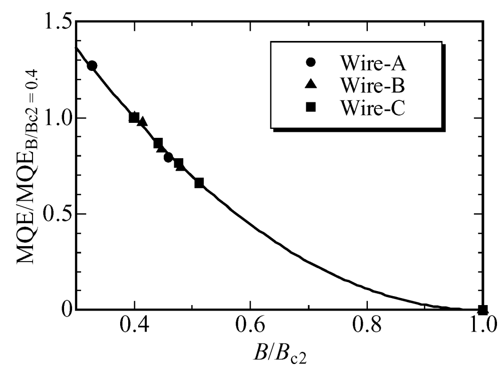

Fig. 9. $B/B_{\rm c2}$ dependencies of the normalized minimum quench energy by MQE at $B/B_{\rm c2} = 0.4$, as parameters of external Cu volume fraction at 4.2 K and $I_{\rm op}/I_{\rm c} = 0.80$.

Kramer's plot [5]. From Fig. 8, the higher $B/B_{\rm c2}$, the lower the MQE was measured, and the higher external Cu volume fraction, the higher the MQE. Fig. 9 shows $B/B_{\rm c2}$ dependencies of the normalized MQE normalized by the one at $B/B_{\rm c2} = 0.4$. In this case, we obtained all plots on one line regardless of external Cu volume fraction.

Based on results of Fig. 9, (1) was derived as a fraction of $B/B_{\rm c2}$; α is a fitting parameter.

$$\frac{MQE}{MQE_{\frac{B}{Bc2}=0.4}} = \alpha\left(\frac{B}{B_{c2}} - 1\right)^2 \tag{1}$$

Fig. 8 and Fig. 9 lead to MQE as a function of x (x: external Cu volume fraction) as given in the following equation,

$$MQE = \alpha\left(\frac{B}{B_{c2}} - 1\right)^2 MQE_{\frac{B}{Bc2}=0.4}(x) \tag{2}$$

Normalized MQE values for $I_{\rm op}/I_{\rm c}$ of 0.85 and 0.9 and Wire-D data adding to Fig. 9 give Fig. 10. It shows that $B/B_{\rm c2}$ dependencies of the normalized MQE showed only one line for all conditions and samples. Equation (3) is derived from (2) and Fig. 10.

$$MQE = \alpha\left(\frac{B}{B_{c2}} - 1\right)^2 MQE_{\frac{B}{B_{c2}}=0.4}\left(x, \frac{I_{op}}{I_c}\right) \tag{3}$$

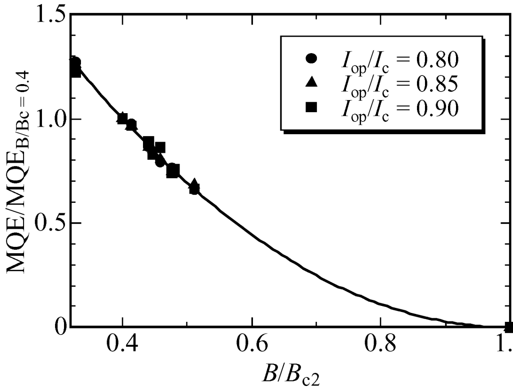

Fig. 10. B/B_{c2} dependencies of the normalized minimum quench energy, as a parameter of I_{op}/I_c at 4.2 K.

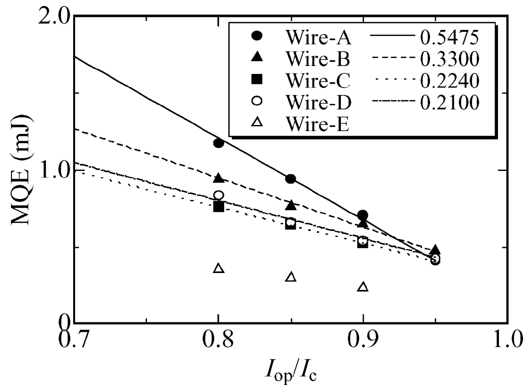

Fig. 11. I_{op}/I_c dependencies of the minimum quench energy, as a parameter of external Cu volume fraction at 4.2 K and 14.0 T.

As the linear dependency between I_{op}/I_c and MQE is shown in Figs. 4 and 5, (4) is derived

$$MQE = \alpha \left(\frac{B}{B_{c2}} - 1\right)^2 \left(\beta(x)\frac{I_{op}}{I_c} + \gamma(x)\right) \qquad (4)$$

Fitting parameters in (4) are calculated from experimental values, as shown in (5).

$$\alpha = 2.7778, \quad \begin{array}{l} \beta(x) = a_1x^2 + b_1x + c_1 \\ \gamma(x) = a_2x^2 + b_2x + c_2 \end{array}$$
$$a_1 = 3.1071, \quad b_1 = 1.9233, \quad c_1 = 8.4754,$$
$$a_2 = -2.8091, \quad b_2 = -0.71681, \quad c_2 = -11.073 \quad (5)$$

Equation (4) has made a possible representation by only one equation of all MQE characteristics.

Calculated lines using (4) are shown in Fig. 11, as compared with experimental results. Both are mostly in agreement. The greatest error is 3.99% (0.033 mJ). In this experiment, disturbance is inputted by 0.06-mJ step. The error between a calculation result and an experiment result has become below the measurement error.

TABLE II
CALCULATED MQE AT 20 T AND $I_{op}/I_c = 0.8$

Wire-A	0.49	(mJ)	40.5% of 14 T
Wire-B	0.40	(mJ)	39.6% of 14 T
Wire-C	0.28	(mJ)	33.8% of 14 T
Wire-D	0.27	(mJ)	33.8% of 14 T

Using (4) MQE value at 20 T and $I_{op}/I_c = 0.8$ were calculated for various wires, as shown in Table II. The lower external Cu volume fraction, the lower the MQE is obtained. Calculated MQE values at 20 T are 30% to 40% of those at 14 T.

IV. CONCLUSION

MQE as functions of temperatures, applied fields, loading conditions (I_{op}/I_c), and external Cu volume fractions for various Nb_3Sn composite wires was measured under cryocooled condition. All MQE data were summarized by only one line in characteristics of normalized MQE and normalized B (B/B_{c2}). The obtained MQE behavior was to be characterized by only one empirical equation. It represents that only external Cu contributes to thermal stability with its thermal conductivity not electrical conductivity. The obtained formula is useful for designing the Nb_3Sn superconductor and its coil under cryocooled condition.

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