HISTORY EFFECT OF CRITICAL CURRENT DENSITY IN SUPERCONDUCTING MULTIFILAMENTARY Nb-Ti WIRE

E. S. Otabe, T. Matsushita, K. Yamafuji*, K. Matsumoto** and Y. Tanaka**
Department of Computer Science and Electronics, Kyushu Institute of Technology,
680–4 Kawazu, Iizuka 820, Japan
*Department of Electronics, Kyushu University,
6–10–1 Hakozaki, Higashi-ku, Fukuoka 812, Japan
**Yokohama R & D Laboratories, The Furukawa Electric Co., Ltd.,
2–4–3 Okano, Nishi-ku, Yokohama 220, Japan

Abstract — Recently it was reported that the critical current densities measured by four probe method in multifilamentary Nb-Ti and Nb_3Sn wires depended on the history of increasing and decreasing external magnetic field. In this report, dc magnetization and four probe resistive measurements were carried out for Nb-Ti multifilamentary wires, and critical current densities in the filament and matrix were separated. The Campbell method was also used for measuring the history effect of critical current density in the matrix. The history dependence was found only for the current density induced in matrix due to the proximity effect. This close correlation between the proximity effect and history effect shows a similarity to the phenomenon in high-T_c superconductors. The possible reason for the history effect in critical current density is discussed.

I. INTRODUCTION

It has been empirically known that the critical current density in bulk superconductors is a unique function of the external magnetic field and temperature. However, it has been reported that the critical current density has different values depending on the history of the magnetic field and temperature in high-T_c superconducting materials with weak links[1, 2] and some kind of multifilamentary metallic superconducting wires[3]. That is, the value of critical current density in increasing magnetic field process is smaller than that in the case of decreasing process. For high-T_c superconductor, the history effect of critical current density is qualitatively explained to be caused by different magnetic flux distributions inside grains depending on the history of external magnetic field[1].

In the multifilamentary wires with small sizes of filament diameter and filament spacing, superconducting filaments are weakly coupled through matrix due to the proximity effect. This similarity of weak link with high-T_c superconductor may suggest that the history effects in the multifilamentary wire and high-T_c superconductor originate from a similar mechanism.

In this report, history effect of critical current density in superconducting Nb-Ti multifilamentary wire was investigated in detail. The magnetization hysteresis from the filament, matrix and inhomogeneity were separated from the twist pitch dependence of the wire magnetization and the result of four probe measurements. The Campbell method was also used to confirm the history dependent critical current density in the matrix. The reason for the history dependent critical current density is is discussed.

II. EXPERIMENTS

Specimens investigated are Nb-47 wt%Ti multifilamentary wires with Cu matrix. The initial volume ratio of copper to Nb-Ti is about unity. After a repetition of combination of cold drawing and heat treatment at 400 °C for 80 hours for three times, specimens were twisted with the pitch, l_p, of 1.46, 2.96 and 6.02 mm. The common specifications of the specimens are listed in Tab. 1.

The dc magnetization of the sample was measured from signals detected by two pick up coils with sweeping external magnetic field. The sample of $L \sim 4$ m in length was wound on a Bakelite hollow cylinder of 33 mm in outer diameter with a constant interval of 2 mm. The external magnetic field was applied along the coil center up to 1 T with various sweep rates.

The critical current density of the filament, J_{cf}, was measured by four probe resistive method. The sample of 0.3 m in length was wound spirally on a cylindrical holder and the interval of the voltage-tap was 0.2 m. The electric field criterion for determination of the critical current was 5.0×10^{-8} V/m. The external magnetic field was applied perpendicular to the transport current.

The history effect of the critical current density was investigated by comparing following two critical current densities. After the external magnetic field was increased up to B_0, the critical current density was measured by four probe method (J_{c0}). Then the external magnetic field was slightly changed by the amount of B_m and returned to the

Table 1. Common specifications of samples

wire diameter	D_W(mm)	0.144
filament diameter	d_f(μm)	1.26
filament spacing	d_N(μm)	0.31
the number of filaments	N_f	4152

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initial value B_0. The critical current density after this field excursion was measured (J_c). If the critical current density depends on the history and is smaller in the increasing field process as is usually observed, J_c/J_{c0} is expected to be larger than unity for positive B_m values, while it will be equal to unity for negative B_m values.

The history effect of the matrix critical current density was measured by the Campbell method. The external dc and superposed ac magnetic fields were applied similarly to the magnetization measurement. The frequency of the ac magnetic field was 35 Hz. All the measurements were carried out at 4.2 K.

III. RESULTS AND DISCUSSION

Magnetic field dependence of the magnetization hysteresis for various twist pitches is shown in Fig. 1. The measured magnetization hysteresis is divided into four contributions:

$$\Delta M = \Delta M_f + \Delta M_p + \Delta M_i + \Delta M_\omega. \quad (1)$$

In the above ΔM_f is the magnetization of the filaments given by

$$\Delta M_f = \frac{4}{3\pi}\mu_0 \lambda J_{cf} d_f, \quad (2)$$

where λ is a volume fraction of the superconducting filaments in the wire. ΔM_p is the magnetization of the matrix due to the proximity effect and ΔM_i is the magnetization due to the inhomogeneities inside the wire such as, sausaging, bridging between filaments, breakage of filaments, superconducting matrix islands and so on. The last term in Eq. (1), ΔM_ω is the magnetization due to the eddy current in the matrix and is proportional to the sweep rate of the external field, $|dB_e/dt|$. ΔM_ω can be neglected for sufficiently low sweep rates. In the present case, magnetization was independent of the sweep rate in the range of $|\dot{B}_e| = 3 \sim 51$ mT/s.

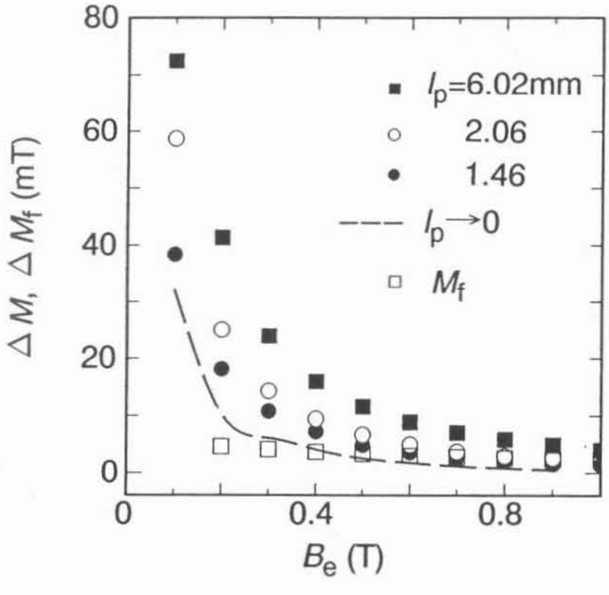

Fig. 1 Observed ΔM for various twist pitches, l_p, and ΔM_f estimated from Eq.(2). Broken line represents ΔM in the limit of $l_p \to 0$ and the difference between broken line and ΔM gives ΔM_i.

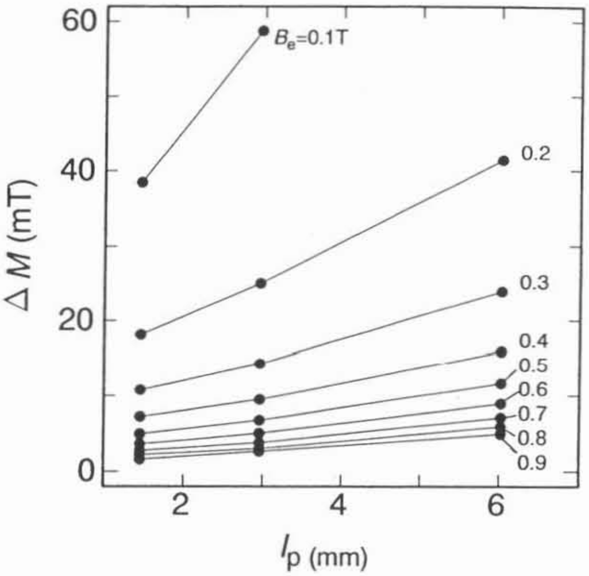

Fig. 2 Dependence of ΔM on l_p for various values of B_e.

The observed magnetization hysteresis becomes small

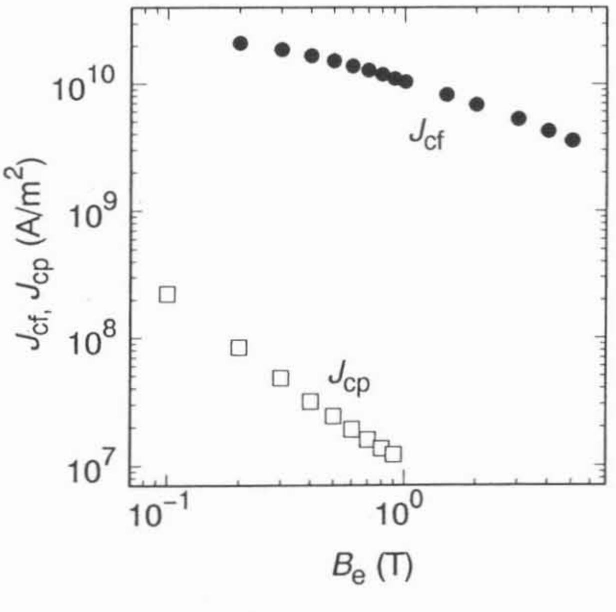

Fig. 3 B_e dependence of J_{cp} and J_{cf}

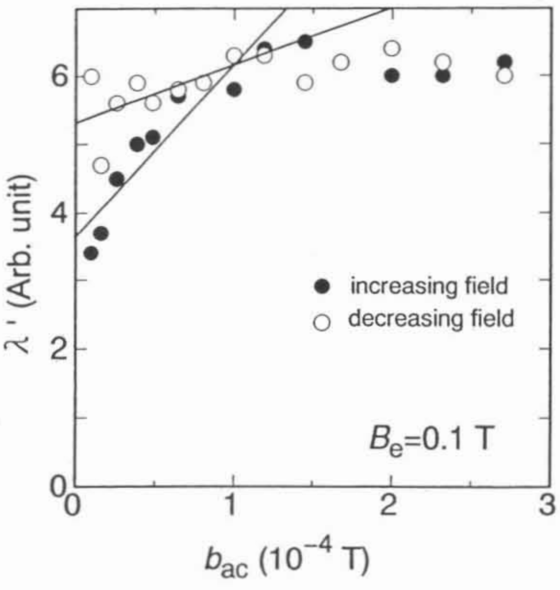

Fig. 4 ac penetration depth as a function of ac magnetic field amplitude in increasing and decreasing dc magnetic field at $B_e = 0.1$ T.

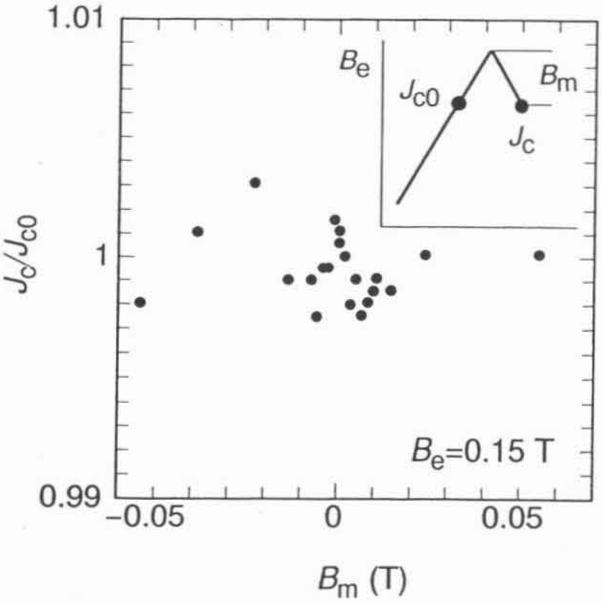

Fig. 5 Normalized critical current density J_c/J_{c0} after field excursion by B_m from $B_e = 0.15$ T. J_{c0} is the critical current density at initial increasing magnetic field process.

according as the twist pitch is decreased. ΔM_f and ΔM_i do not depend on the twist pitch, l_p, in Eq. (1), while ΔM_p is approximately proportional to l_p as[4]

$$\Delta M_p = \frac{2}{\pi^2}\mu_0 \lambda_m \lambda_p J_{cp} l_p \left[1 + \left(\frac{\pi D_W}{2l_p}\right)^2\right], \qquad (3)$$

where J_{cp} is the critical current density in the matrix due to the proximity effect. In Eq.(3), λ_p represents a volume fraction of the matrix in multifilamentary region and is given by

$$\lambda_p = 1 - \frac{\pi}{2\sqrt{3}}\left(\frac{d_f}{d_f + d_N}\right)^2, \qquad (4)$$

and λ_m is a volume fraction of the multifilamentary region in the wire,

$$\lambda_m = \frac{\lambda}{1 - \lambda_p}. \qquad (5)$$

Figure 2 which is a replot of Fig. 1 shows the twist pitch dependence of magnetization for various external magnetic fields, B_e. Since $(\pi D_W/2l_p)^2$ is of the order of 10^{-2} and is negligibly small under the present experimental conditions, ΔM_p is approximately proportional to l_p. Hence, J_{cp} can be estimated from Eq. (3). Figure 3 shows B_e dependence of J_{cp}. The values of J_{cf} observed by four probe method under increasing magnetic field process are also plotted in the same figure. Strictly speaking, the present J_{cf} is slightly different from the critical current density in the filament, since it contains the matrix current. However, J_{cp} is sufficiently smaller than J_{cf} and the error in estimation of J_{cf} is negligible.

If the B_e dependence of J_{cp} at low magnetic fields is approximately expressed as

$$J_{cp} \propto B^{-\gamma}, \qquad (6)$$

$\gamma = 1.3$ is obtained. On the other hand, the γ value of J_{cf} is $\gamma = 0.44$. Therefore, J_{cp} decreases rapidly according to an increase of magnetic field, since induced superconductivity in the matrix is easily broken by magnetic field. A typical value of J_{cp} at $B_e = 0.1$ T is 2.1×10^8 A/m^2 which is 150 times smaller than the value of $J_{cf} = 3.1 \times 10^{10}$ A/m^2.

Figure 4 represents the observed ac penetration depth as a function of external ac magnetic field amplitude in increasing and decreasing of processes dc magnetic field process measured by the Campbell method at $B_e = 0.1$ T. The slope of solid lines is proportional to $1/J_{cp}$. It is observed that J_{cp} in decreasing magnetic field process is approximately 4 times larger than that in increasing magnetic field process. This measurement gives J_{cp} of the same order of magnitude with the results obtained from Eq.(3).

The result of normalized critical current density after the excursion of external magnetic field is shown in Fig. 5. However, any remarkable difference is not observed within an experimental error. This means that the history effect occurs only for J_{cp}. If so, the history dependence of the mean critical current density is estimated to be very small. That is, J_c/J_{c0} in Fig. 5 is expected to exceed unity only by 0.003 which is too small to detect exactly.

Therefore, the history effect of the critical current density in the wire is expected to become measurable if

J_{cp} has sufficiently large value. In fact, the history effect was observed for a wire with the filament diameter and filament spacing $3 \sim 4$ times smaller[3] than in the case of the present work. It is needed to investigate, therefore, the case of noticeable proximity effect.

The above results clearly show that the history effect appears in induced superconducting current in matrix due to the proximity effect but not in J_{cf} in superconducting filaments. This suggests a close correlation between the proximity effect and history effect. This close correlation can also be found in existing experimental results: A remarkable history effect of the critical current density has not been observed in conventional bulk superconductor or multifilamentary wire which do not show appreciable proximity effect. In addition, the history effect is likely to become remarkable according as the filament diameter decreases. The similarity that both the proximity and history effects tend to diminish at higher magnetic field is also compatible with the above hypothesis.

The close correlation between the proximity effect and history effect in multifilamentary wires suggests a similarity to the history effect due to weak links in high-T_c superconductors. The critical current density in weakly superconducting regions is history dependent in the both cases. The similarity to high-T_c superconductors may suggest that closed loops of large current in inhomogeneous regions, such as swelled parts in sausaged filaments or bridges between filaments, affect the weakly superconducting region through their dipole magnetic fields. However, this dipole field is estimated to be too small to give rise to appreciable effects.

Therefore, the mechanism which brings about the history effect in multifilamentary wire is open. What cannot be understood in the observed quantities in the present measurement is ΔM_i. ΔM_i can be estimated from the difference between ΔM in the limit of $l_p \rightarrow 0$ which is shown by the broken line in Fig. 1 and ΔM_f. As aforementioned, ΔM_i is considered to originate from inhomogeneities inside the wire. However, if the sausaging, bridging and breakage of filaments are the candidate for responsible inhomogeneities, ΔM_i is proportional to the abovementioned dipole field and remains finite even under high magnetic fields. However, observed ΔM_i decreases with increasing field and disappears at the field above 0.5 T. Therefore, ΔM_i is not the contribution from simple inhomogeneities but is considered to be strongly connected to the proximity effect. It is necessary, therefore, to clarify the mechanism which brings about ΔM_i, which is expected to be closely connected to the mechanism of history effect in multifilamentary wires.

IV. CONCLUSION

The history effect of the critical current density in superconducting Nb-Ti multifilamentary wires was investigated by using several methods. The magnetization of the sample was divided to the contributions from the filaments, matrix due to the proximity effect and inhomogeneities of the wire. The critical current density in the matrix measured by the Campbell method was found to be history dependent. However, the history effect was not observed for the critical current density in the filament. This result shows a close correlation between the proximity effect and history effect and suggests a similarity to the correlation between the weak link and history effect in high-T_c superconductors. However, the mechanism of history effect is not clear at this stage.

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