CURRENT-CARRYING CAPACITY OF COMPOSITE SUPERCONDUCTORS

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Abstract

The maximum transport current I_m of the composite superconductors is investigated both theoretically and experimentally. It is shown that the high values of the transport current observed in these materials is due to the non-linear part of the current-voltage characteristic in the range of low electric fields ($E \leqslant 10^{-6}$ Vcm^{-1}). The conductors of rather different structure with Nb-Ti superconducting filaments were tested in a wide range of the external parameters. It is shown that in the external magnetic fields $B_a \geqslant 1$ T the ratio I_m/I_c (where I_c is the critical current) is the universal function of the single dimensionless parameter which depends on the sample properties and the external conditions. The theory and experiment are in a good agreement.

Introduction

The maximum transport current I_m which can flow in the multifilamentary composite superconductor in a superconducting state may considerably differ from the critical value $I_c = Sx_s j_c$, where S is the cross-sectional area of the conductor, x_s is the concentration of the superconductor in the composite, and j_c is the critical current density. While the current I_c is the inherent property of the superconducting material, the value I_m depends not only on the conductor properties but also on the external conditions.

If the local perturbations in a superconducting system are high enough giving rise to the normal transition, then I_m is obviously restricted by the value of the normal phase minimum propagation current I_p, which may be approximated as:[1]

$$I_p = I_c \cdot (\sqrt{1+8\alpha} - 1)/2\alpha \tag{1}$$

where α is Steckly parameter:

$$\alpha = \frac{S \cdot x_s^2 \, j_c^2}{P \cdot W_o \cdot (T_c - T_o)} \rho \tag{2}$$

P is the cross-sectional perimeter, W_o is the heat transfer coeficient, T_o and T_c are the bath and critical temperatures, and ρ is the specific resistance of the composite in the normal state ($\rho \sim \rho_n$ - the specific resistance of the normal matrix).

In the absence of the strong disturbances the current I_m is defined by the superconducting state stability with respect to the small perturbations. The respective stability criterion has been proposed by Hart:[2]

$$I < I_m = I_c/\alpha \tag{3}$$

The comparison of the Eqs.(1) and (3) leads to the inequality $I_m \leqslant I_p$. More accurate calculations predict that $I_m \leqslant I_p$.[3] The estimate of α at the real values of the parameters ($x_s j_c \sim 10^5$ Acm^{-2}, $\rho \sim x_n \rho_n \sim 10^{-7}-10^{-8}\,\Omega$cm, $S/P \sim 10^{-1}$cm, $T_c - T_o \sim 5$K, $W_o \sim 10^{-1}-10^{-2}$Wcm^{-2}K^{-1}) yields $\alpha \sim 10-10^3$, then $I_m \ll I_p \ll I_c$.

However in many cases the measured value of I_m exceeds the theoretical limit (3) by the factor of $10-10^3$ and $I_p \ll I_m \sim I_c$.[4,5] This fact seems very obscure as small perturbations can not be avoided in any experimental situation. It has been shown in the papers[4-6] that the criterion (3) must be modified to take into account the real I-V characteristic of the superconducting composite. The small perturbations induce the low electric fields in the conductor. In the region of low electric fields the differential resistance of the superconducting composite is much less than the normal matrix one and moreover, it depends on the value of the electric field E and consequently on the magnitude of the perturbations.[4,5,7,8]

Equation for I_m

Assume that a fluctuation causes the conductor temperature to rise by the value of ΔT. This leads to the decrease of the supercurrent contribution to the local current density $j = j(T,B,E)$ where B is the magnetic induction. Then, the resistive component of the current increases giving rise to the increase of the electric field by the value ΔE. As

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it is known the fast heating of the conductor occurs under conditions of frozen-in magnetic flux.[3] This means that $\partial j/\partial t = 0$, $\partial B/\partial t = 0$ or:

$$\frac{\partial j}{\partial T}\Delta\dot{T} + \frac{\partial j}{\partial E}\Delta\dot{E} = 0 \qquad (4)$$

As $j \simeq x_s j_c(T,B)$ and the differential resistance is defined as $\rho(E)=(\partial j/\partial E)^{-1}$, we have from the Eq.(4):

$$\Delta E = -\rho(E)\frac{\partial j_c}{\partial T}\cdot\Delta T$$

The additional power released per unit length of the conductor is:

$$\Delta\dot{Q} = \int_S dS\cdot j\cdot\Delta E \simeq \int_{S'} dS\cdot x_s^2 j_c\left|\frac{\partial j_c}{\partial T}\right|\rho(E)\cdot\Delta T \quad (5)$$

where the integrals are taken over the cross-sectional area of the sample S and S' is the part of the cross-section S which is in the critical state: $x_s j_c S'=I$.

In the stationary state the heat power $\dot{Q}$ is removed by the external cooling. Let us denote the heat flux through the sample surface by $q=q(T)$, then $\dot{Q}=q\cdot P$ in the stationary state and the superconducting state is stable if:

$$\Delta\dot{Q} < \Delta q\cdot P = \frac{\partial q}{\partial T}\cdot\Delta T_W\cdot P \qquad (6)$$

where ΔT_W is the value of ΔT at the surface of the superconductor and from the definition $\partial q/\partial T=W_o$. The heat conductivity of the composite k is high and $W_oS/kP \ll 1$. In this case one can assume that ΔT is uniform over cross-section in the first approximation in $W_oS/kP \ll 1$. Thus from the Eqs.(5) and (6) we find the stability criterion in the form:

$$\int_{S'} dS\cdot x_s^2 j_c\cdot\left|\frac{\partial j_c}{\partial T}\right|\cdot\rho(E) < W_o\cdot P \qquad (7)$$

Suppose that $j_c=j_o\cdot(1-T/T_c)$ and the values j_c and x_s are uniform over the cross-section of the sample. Then we find from the Eq.(7) (cf. the dynamic stability criterion (3)):

$$I < I_m = I_c\,\frac{P\cdot W_o(T_c-T_o)}{S\cdot x_s^2 j_c^2\langle\rho(E)\rangle} \qquad (8)$$

where $I_m/I_c=S'/S$ and

$$\langle\rho(E)\rangle = \frac{1}{S'}\cdot\int_{S'} dS\cdot\rho(E)$$

In a wide range of parameters the I-V characteristics of the composite superconductor may be presented in the form:[4,5,7,8]

$$j = j_o(T,B) + j_1(B)\ln(E/E_o) \qquad (9)$$

where $j_1 \ll j_o \simeq j_c$ and $\partial j_1/\partial T \simeq 0$. Then $\rho(E)=E/j_1$ and $\langle\rho(E)\rangle = \langle E\rangle/j_1$. The value $\langle E\rangle$ is the averaged electric field induced by the perturbation, for example, by the varying transport current I, external magnetic field B_a, external heating.

Thus to find I_m one has to calculate the averaged value of the electric field. For example, in the case of the cylindrical wire when the field E is caused by the transport current increasing with the rate $\dot{I}$ the value $\langle E\rangle$ may be easily found:[6]

$$\langle E\rangle = \frac{\mu_o}{4\pi}\cdot\dot{I}\cdot\left(1 + \frac{I_c}{I}\ln(1 - I/I_c)\right) \qquad (10)$$

In many cases of practical interest the conductor with growing current I is placed in the growing transverse magnetic field B_a. It is impossible to find the exact expression for $\langle E\rangle$ in this situation. To obtain the approximate result one may assume that the electric field is induced in the sample by the transport current I increasing with some effective rate $\dot{I}_{ef}=\dot{I}+d\dot{B}_a/\mu_o$, where d is the conductor diameter. This approach seems to be reasonable as we are interested in the electric field averaged over the cross-section. Then, by means of the Eqs.(8)-(10) we have:

$$-I_m/I_c - \ln(1 - I_m/I_c) = \alpha_{ef}^{-1} \qquad (11)$$

$$\alpha_{ef}=\frac{d\cdot x_s^2 j_c^2\langle\tilde{E}\rangle}{2W_o(T_c-T_o)j_1}, \quad \langle\tilde{E}\rangle = \frac{\mu_o}{8\pi}\left(\dot{I}+\frac{\pi d\dot{B}_a}{\mu_o}\right)$$

It is important that in the case under consideration the ratio I_m/I_c is the function of a single dimensionless parameter α_{ef}, which is the effective Steckly parameter. The value I_m/I_c as the function of α_{ef}^{-1} is shown in Fig.1. At $\alpha_{ef}^{-1} \gtrsim 2$-$3$ the value I_m is practically equal to $I_c(T,B)$. Assuming that $d=0.1$ cm, $x_s j_c=10^5$ A/cm^2, $W_o=10^{-2}$ W/cm^{2}K, $T_c-T_o=5$K, $j_1=10^3$ A/cm^2, we find $\langle\tilde{E}\rangle\sim 10^{-7}$ V/cm and $\alpha_{ef}^{-1} \simeq 5$ at $\dot{I}=10$ A/s and $\dot{B}_a=10^{-2}$ T/s.

The criterion (7) has been found under rather general assumptions. On the other hand, the Eq.(8) and in particular the Eq.(11) are

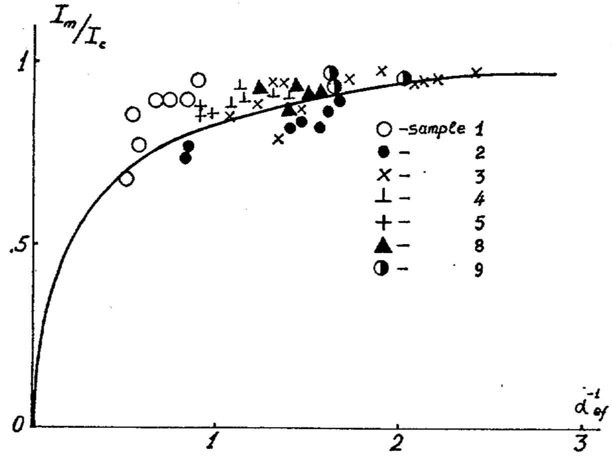

Fig. 1. The value I_m/I_c as a function of α_{ef}^{-1}. Theory - solid line, experiment for 7 different conductors - symbols.

valid only if some additional conditions are fulfilled. The criterion (8) is correct if: 1) $j_c \simeq j_o(1-T_o/T_c)$, 2) $j_c(B) \simeq j_c(B_a)$. In addition to the conditions (1) and (2) for the applicability of the Eq.(11) it is necessary: 3) $\rho(E)=E/j_1$; 4) the electric field E is caused by $\dot{I}$ and $\dot{B}_a$ only, 5) the skin depth corresponding to $\rho = \langle\rho(E)\rangle$ and the current rate of change $\dot{I}_{ef}$ is much greater than the wire radius d/2 or $(\langle E\rangle/\mu_0 j_1 d(\dot{I}/I))^{1/2} \gg 1$. For example, at $\langle E\rangle \sim 10^{-7}$V/cm, $j_1=10^3$A/cm^2, d$\sim$0.1cm and I=10^3A, the value $\dot{I}_{ef}$ could not be higher than 30-50 A/s.

Experiment

The study of the maximum transport current I_m was based on the contactless technique utilizing the principle of flux pumping. The conventional four-terminal arrangement was used to measure the I-V characteristics and j_c. The details of the experiments are described in the papers [5,9]. The samples were 15 composite wires with diameters from 0.03cm to 0.5cm having from 6 to $\simeq$18000 Nb-Ti filaments. They had the normal matrix of rather different composition ($R_{4.2}/R_{300}$ from 10^2 to $2\cdot10^3$) and were coated with the organic insulation (teflon, lavsan, laquer) having the thickness from $3\cdot10^{-3}$ cm to $5\cdot10^{-2}$ cm. The values B_a, $\dot{I}$, $\dot{B}_a$, and I_m varied within the limits: $0<B_a<6$T, 0.1A/s$<\dot{I}<$50A/s, $0<\dot{B}_a<10^{-2}$T/s, 30A$<I_m<10^4$A.

The effective heat-transfer coefficient from the wire to the helium W_o was both measured and calculated using the known values of the thermal conductivities of the insulations. The measured and calculated values are in good (10-20%) agreement.

In our calculations we have used the function $T_c=T_c(B_a)$ presented in the paper [10].

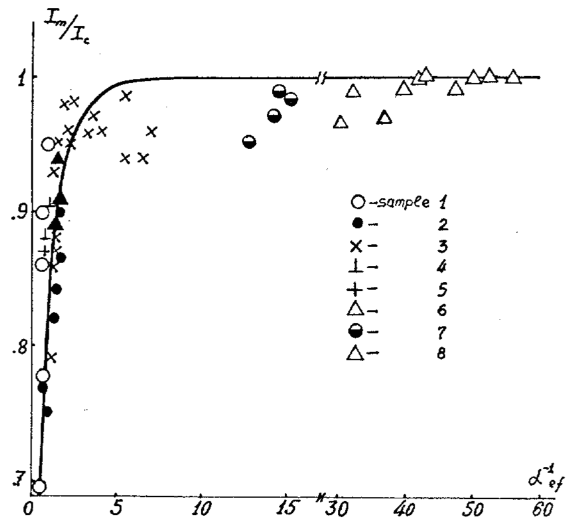

Fig. 2. The value I_m/I_c at large α_{ef}^{-1}: theory and experiment.

Discussion

The measured values I_m/I_c are shown in Figs. 1 and 2 for 9 different conductors. Each point corresponds to I_m measured at fixed B_a, $\dot{I}$, $\dot{B}_a$ and W_o. The theory and the experiment are in a good quantitative agreement. Note, that $I_m \simeq I_c$ at $\alpha_{ef}^{-1} \gg 1$ within $\sim$5-7%. If $\alpha_{ef}^{-1} \gtrsim 15$ the theory and the experiment coinsides within the experimental accuracy (the experimental points at $\alpha_{ef}^{-1} > 60$ are not shown in Fig.2). The comparison of the theory and the experiment was performed without any adjusting parameter.

One can readily see from the Eq.(11) that the value I_m is independent of the normal metal resistance. To verify this prediction the conductor having the aluminium matrix of high conductivity ($R_{4.2}/R_{300}=2\cdot10^3$) were studied. The current I_m was measured for the wires containing $\sim$40%, $\sim$12%, and 0% of Al. In the first two samples the values I_m were identical with accuracy 1.5%. In the third sample the drop of I_m does not exceed $\sim$3-5%.

However, we must note that this result is valid only under definite experimental conditions. The normal matrix is an important component of the composite conductor but we could not discuss this problem here.

Thus, it is shown that the observed high values of transport currents in the composites are due to the low value of differential resistance of the composite superconductors in the region of low electric fields. The simple method to calculate the maximum transport current is proposed in the case when the electric field in the sample is induced by the varying transport current and magnetic field. The ratio I_m/I_c is the function of the single dimensionless parameter under definite experimental conditions.

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