Current carrying capacity of superconductors for 50 Hz applications

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The I–V characteristic and current carrying capacity of two multifilamentary superconducting composites for 50 Hz applications have been investigated. Several combinations of d.c. and a.c. transport current and d.c. and a.c. external magnetic field were used. The experimental results are compared with the theoretical calculations. It is shown that the theory enables the current carrying capacity at 50 Hz to be established with satisfactory accuracy.

Keywords: superconductors; electrical properties; magnetic fields

At the present, superconducting composites manufactured for 50 Hz applications are being studied intensively[1]. The main attempts to improve these materials are focussed on the following two problems: the current carrying capacity of the superconductor, i.e. the maximum superconducting transport current, I_m, must be as high as possible; and the a.c. loss must be as small as possible. An effective way to reduce a.c. loss in composites is to use a matrix with high transverse resistivity, $\rho_\perp$. However, the increase of $\rho_\perp$ may result in the decrease of the maximum superconducting transport current[2]. Moreover, the electrical insulation reduces the heat flux from the superconductor to the coolant which leads to the same effect on I_m. Thus, the optimal superconducting composite construction ought to be a compromise between two contradicting factors – reducing a.c. loss and obtaining high maximum transport currents.

In the present Paper the current carrying capacity of low loss multifilamentary superconductors is investigated experimentally and theoretically. The experiments have been carried out using composites manufactured by Showa Electric Wire & Cable (SEWC), Japan, and Alsthom Atlantique (AA), France, (see *Table 1*). All measurements were made in liquid He at the temperature $T_0 = 4.2$ K in a transverse magnetic field, B.

The values of I_m were obtained by the following three types of experiments:

1. the sample was inductive and the external d.c. magnetic field was constant. The amplitude of the a.c. transport current was slowly increased up to I_m. It should be noted that the a.c. current produces a small a.c. component superimposed on the d.c. field;
2. the sample was bifilar and at a constant amplitude of the a.c. external magnetic field the d.c. transport current, I, was slowly increased to instability, $I = I_m$; and
3. the sample was bifilar and at a constant value of d.c. transport current, I, the amplitude of the a.c. external magnetic field was slowly increased to instability, i.e. the chosen fixed value of I was equal to I_m.

The frequency, f, of the a.c. current and a.c. external magnetic field was 50 Hz in all experiments. Static I–V characteristics of both SEWC and AA composites were also studied.

Single-layer coils were used for all measurements. The composites were wound onto the cylindrical fibre epoxy formers with spacers (see insert in *Figure 1*). This construction of the samples assures that at least 75% of the wire surface was in direct contact with the liquid helium. The sample parameters are given in *Table 2*.

The static I–V characteristics were measured by the usual four-point method. The magnetic field was generated by a superconducting solenoid with a field uniformity of not less than 2.5% over the sample volume. The measured static I–V characteristics of samples 2 and 3 are shown in *Figures 1* and *2* for different values of B. Under isothermal conditions the I–V characteristics have the form

$$I = I_s(T, B) + I_1(T, B) \ln \frac{E}{E_0} \tag{1}$$

where: $I_s = I(E_0)$; E_0 is a certain fixed value of E; and I_1 is the parameter characterizing the rate of increase of $I(E)$, that is

$$dI/dE = I_1/E$$

The deviation of the measured $I(E)$ curves from the logarithmical law, as seen in *Figures 1* and *2*, is due to

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Table 1 Physical parameters of the two composites used in the experiment

Conductor	Wire diameter, D (mm)	Isolation thickness, d_i (mm)	Composition Nb-Ti : Cu : Cu-Ni	Number of filaments	Filament diameter, d (μm)	Twist pitch, L_p(mm)	Resistance at $T=10$ K, $\rho(\Omega m)$	$\frac{\rho(300\ K)}{\rho(10\ K)}$
SEWC	0.1	0.015	1:0.8:3.7	9720	0.44	1.13	0.75×10^{-7}	1.5
AA	0.12	0.013	1:0.83:1.16	14496	0.60	0.8	3.15×10^{-9}	22

Table 2 Physical parameters of samples 1–3

Sample number	Conductor	Wire length, L_c(m)	Coil diameter, D_c(mm)	Coil length, H_c(mm)	Turn number, N_c	Bifilar or inductive
1	SEWC	2.4	16.1	11.4	48	Inductive
2	SEWC	2.7	16.8	7.5	52	Bifilar
3	AA	2.7	16.4	8.2	52	Bifilar

sample heating[4]. This effect will be discussed further below.

The value I_1 is relatively high for the investigated composites. At $E_o = 10^{-2}\ \mu V\ cm^{-1}$ the ratio I_1/I_s is ≈ 0.2 for the SEWC conductor and ≈ 0.1 for the AA conductor. For such types of composites it is necessary to characterize their superconducting properties not only by the critical current I_s, but also by the parameter I_1. Note that $I_1/I_s = 0.01$ to 0.05 for bare Nb–Ti or for composites with filament diameters $d > 10\ \mu m$[3–5]. The dependences of I_1 and I_s on B at $E_o = 10^{-2}\ \mu V\ cm^{-1}$ for SEWC and AA are shown in *Figures 3* and *4*, respectively.

The superconducting to normal transition under d.c. conditions occurred at a certain value of $I_q > I_s$ (the quench points are indicated in *Figures 1* and *2* by arrows). The dependences $I_q(B)$ are shown in *Figure 3* for samples 1 and 2 and in *Figure 4* for sample 3. It should be noted that curves $I_q(B)$ and $I_s(B)$ coincide for samples 1 and 2.

The inductive coil 1 was investigated at a constant d.c. external magnetic field (the first type of experiment listed above). An alternating current produces a small a.c. component, $\Delta B(t) = kI$, superimposed on the d.c. external field where coefficient $k = 5.3 \times 10^{-3}\ T\ A^{-1}$ was calculated using the data given in *Table 2*. In the experiment the current amplitude was slowly increased until the instability occurred. The accuracy of I_m determination was not less than ± 0.2 A. Records of the voltage measured on the potential taps and of the current in the sample are shown in *Figure 5*. From this data it can be seen that the instability occurs immediately after the value of the current overruns I_m for the first time. The measured values of $I_m(B)$ for sample 1 are shown in *Figure 3*.

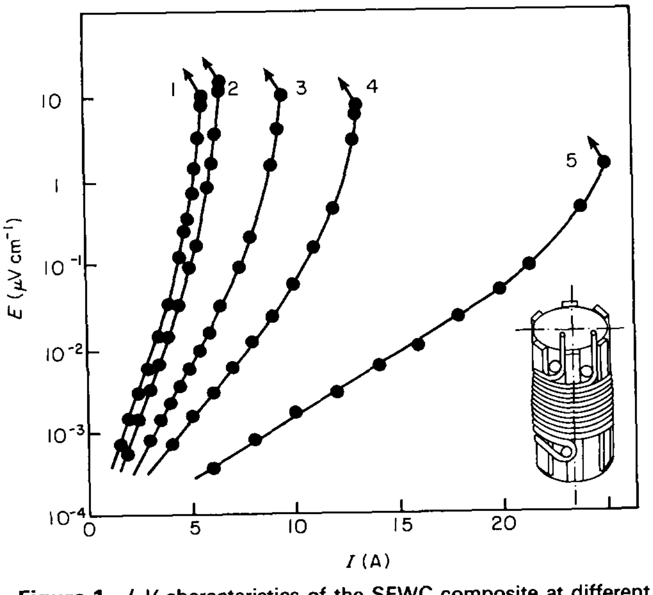

Figure 1 *I–V* characteristics of the SEWC composite at different external magnetic fields. The insert shows the sample construction. 1, 2 T; 2, 1.6. T; 3, 0.8 T; 4, 0.4 T; 5, 0 T

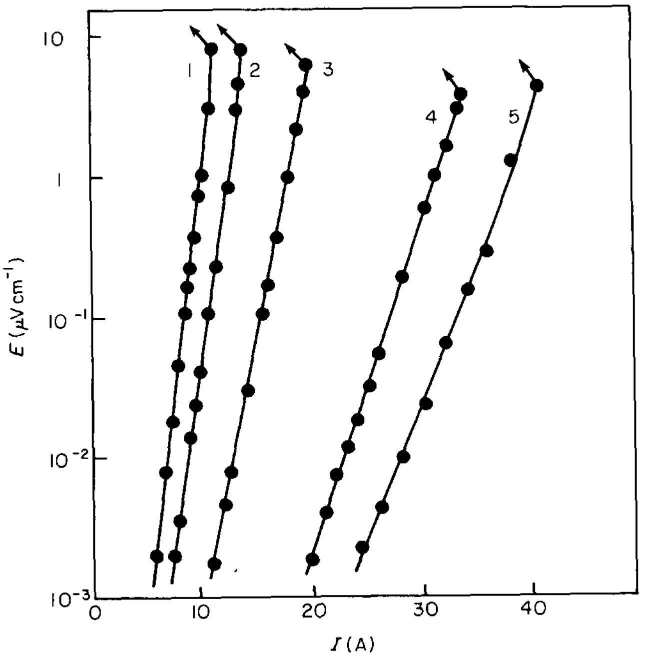

Figure 2 *I–V* characteristics of the AA composite at different external magnetic fields. 1, 2 T; 2, 1.4 T; 3, 0.8 T; 4, 0.3 T; 5, 0.2 T

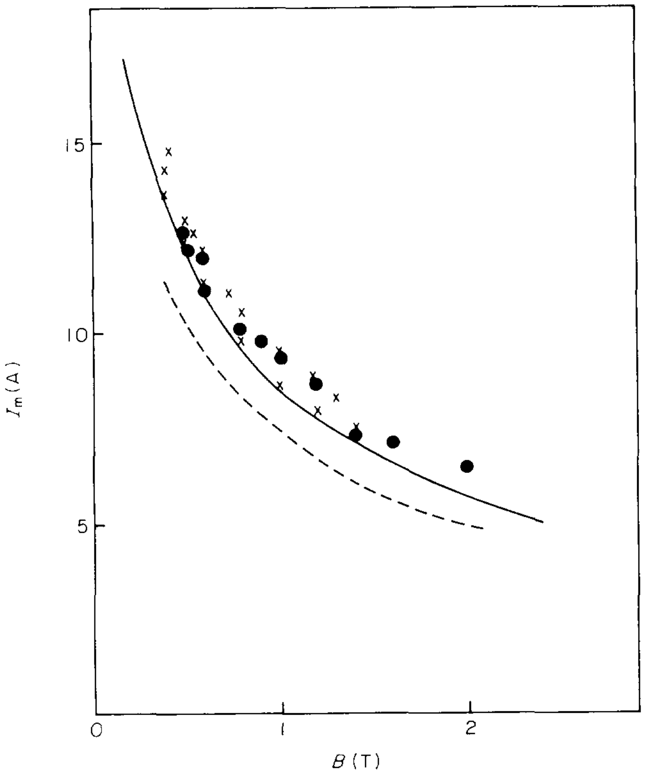

Figure 3 Dependence of current on magnetic field for samples 1 and 2. Sample 1: ——, $I_q(B)$; - - -, $I_s(B)$ for $E_0 = 10^{-2}$ μV cm^{-1}; ●, $I_m(B)$. Sample 2: x, $I_m(B)$

The bifilar samples 2 and 3 were investigated at constant current, I, in an a.c. transverse external magnetic field. The dependence $I_m(B)$ for both samples was obtained using experiments of type 2 and 3 listed above (see *Figures 3* and *4*). It should be noted that both types of measurements give the same value of I_m within the experimental accuracy for each sample. As seen in *Figure 3*, for the SEWC composite the values of I_m are higher than d.c. quench currents, I_q, in the whole range of magnetic fields. Alternatively, for the AA composite, the values of I_m are higher than I_q, up to 0.6 T, then the I_m values decrease rapidly and become considerably lower than I_q.

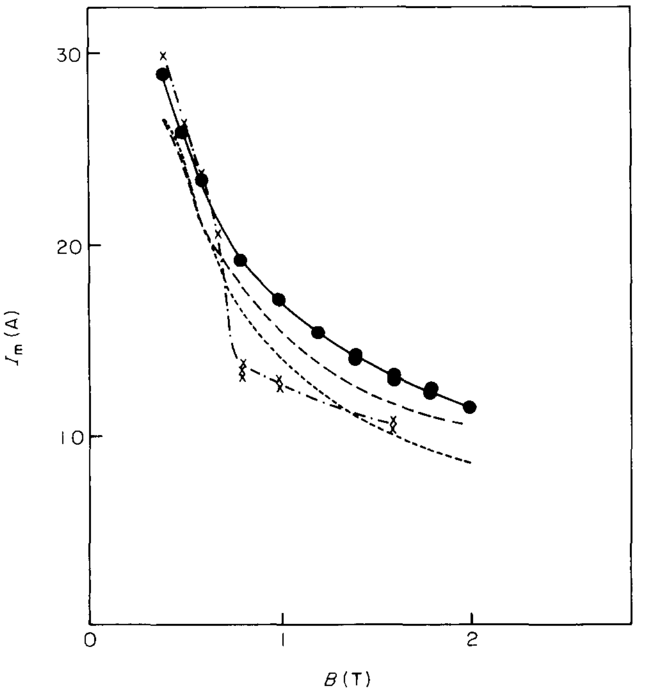

Figure 4 Dependence of current on magnetic field for sample 3. ——, $I_q(B)$; – – –, $I_s(B)$ for $E_0 = 10^{-2}$ μV cm^{-1}; - · - · -, $I_m(B)$, measured; - - - -, $I_m(B)$, calculated

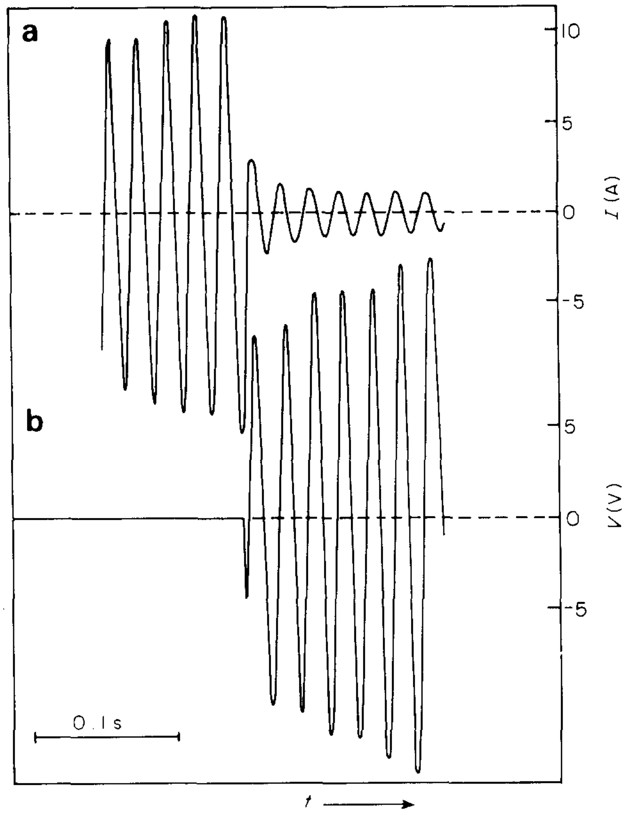

Figure 5 Time dependence of (a) the sample current and (b) the voltage measured on the potential taps for sample 1 with a d.c. external magnetic field of 0.5 T (the first type of experiment listed in the text)

Now let us consider the static I–V characteristics. Equation (1) contains the conductor temperature, T, dependent on E, and this must be taken into account. To obtain the dependence $I(E)$ in the explicit form we suppose that: $(T(E) - T_o) \ll (T_c - T_o)$, where T_c is the critical temperature; I_s is a linear function of T, that is $dI_s/dT = -I_s(T_c - T_o)$; and that I_1 in independent of temperature[6].

Thus, taking into account the current flowing in the matrix, we obtain[4]

$$I = [I_o + I_1 \ln(E/E_o) + EI_1/\alpha E_c]/(1 + I_1 E/I_o E_c) \qquad (2)$$

where $I_o = I_s(T_o, B)$ and

$$E_c = \pi D h (T_c - T_o) I_1 / I_o^2 \qquad (3)$$

$$\alpha = 4\rho_n I_o^2 / \pi^2 D^3 h (T_c - T_o)$$

where: ρ_n is the longitudinal resistivity of the matrix; D is the wire diameter; and h is the heat transfer coefficient.

It can be seen from Equation (2) that at fixed E there are two possibilities depending on the value of α. First, if $\alpha < 1$ the current, I, increases in comparison with the isothermal I–V characteristic. Second, if $\alpha > 1$ the current, I, decreases with respect to the isothermal I–V characteristic. Using the data given in *Table 1* it can be found that, at any real value of h, parameter $\alpha \gg 1$ for both composites. Thus, the currents corresponding to a specific value of E are lower than those expected from the isothermal I–V characteristics, as seen in *Figures 1* and *2*.

Now let us discuss the results obtained from a theoretical point of view[2,3]. The value of I_m is determined from[3]

$$I_m = \begin{cases} i_m I_s, & i_m < 1 \\ I_s, & i_m \geqslant 1 \end{cases} \tag{4}$$

where i_m is the root of the following equation

$$-\frac{\mu_0}{4\pi}\dot{I}\{i_m + \ln(1 - i_m)\} + \frac{D}{3\pi}\dot{B}\frac{1.5i_m - 1 + (1 - i_m)^{3/2}}{1 - 0.5i_m} = E_c \tag{5}$$

where $\dot{I}$ and $\dot{B}$ are the maximum values of $\partial I/\partial t$ and $\partial B/\partial t$, respectively.

Equations (4) and (5) were found in the first approximation with respect to $I_1/I_s \ll 1$. Thus, for the investigated composites, the accuracy of I_m calculated using Equations (4) and (5) is not higher than $I_1/I_s \approx 10$—20%. Equations (4) and (5) have been successfully used to calculate I_m in the situation when $I(t)$ and $B(t)$ were monotonic functions[2]. The results obtained were in good agreement with the corresponding experiments.

It follows from Equations (3), (4) and (5) that $I_m \geqslant I_s$ at $\partial I/\partial t = 0$ if the a.c. external magnetic field amplitude is less than B_m, where B_m is given by

$$B_m = \frac{3\pi h}{2f}\frac{I_1(T_c - T_o)}{I_s^2} \tag{6}$$

All parameters necessary to calculate I_m were measured in the present experiments except h. To estimate the value of h one has to take into account the heat conductivities of the Cu–Ni matrix and the electrical insulation, and the heat transfer coefficient into the helium[2]. For the given diameters and insulation thickness the estimation gives $h = 400$ up to $600\ \mathrm{W\ m^{-2}\ K^{-1}}$. In our calculations the value of $h = 500\ \mathrm{W\ m^{-2}\ K^{-1}}$ was used.

To find i_m from Equation (5) the values of $D\dot{B}/E_c$ and $\mu_0\dot{I}/E_c$ must be found. For the SEWC composite, the ratio $D\dot{B}/3\pi E_c = 0.4$ to 0.5 and $\pi D\dot{B}/\mu_0\dot{I} = 1.3$ (the first type of experiment listed above) and $\dot{I} = 0$ (the second and third type of experiment listed above). From Equations (4) and (5) it follows that $I_m \geqslant I_s$ for both samples 1 and 2 in the magnetic field region $0 < B < 2$ T. This is in good agreement with the experimental results.

As shown in *Figure 4* for the AA composite, the curve $I_m(B)$ intersects with the curve $I_s(B)$ at $B = B_m$. The value of B_m may be found using Equation (6). Using the parameters mentioned above, the measured values of $I_1(B)$ and $I_s(B)$, and a typical $T_c(B)$ dependence, we obtain $B_m = 0.6$ T. This agrees well with the experimental results. At $B > B_m$ the current $I_m < I_s$. The dependence $I_m(B)$ calculated using Equations (3) and (4) is shown in *Figure 4*. The difference between the theoretical and experimental results does not exceed 25%. Thus, it can be said, in conclusion, that the present theory enables the current carrying capacity of fine filamentary superconducting composites under a.c. conditions to be found with a reasonable accuracy.

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