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LOSSES IN TWISTED COMPOSITE SUPERCONDUCTORS IN A HIGH PULSED MAGNETIC FIELD

V. B. ZENKEVICH* R. G. MINTS* V. V. ANDRIANOV* V. P. BAEV* A. L. RAKHMANOV*

ABSTRACT

An experimental and theoretical study was made of losses in twisted composite superconductors in a strong pulsed magnetic field. The field amplitude reached 4.5T, and the magnetic field variation rate 2,000 T/sec. It is shown that the dependence of the specific heat release on the maximum rate of variation of the magnetic field is essentially nonmonotonic in nature. In the transition to the normal state, the specific losses are considerably lower than in an analogous sample at constant temperature. A comparison between theory and experiment is presented.

This paper contains an experimental and theoretical study of the dissipation of energy in twisted composite multifilament superconductors in a rapidly varying high magnetic field according to $H = H_0 \exp\{-\lambda t\}$. Preliminary information on the technique and some experimental results have been published.[1,2]

The experiments were performed in an apparatus shown in Fig. 1. The value of losses was found by measuring the amount of helium evaporated by the sample, 1, in a double-walled glass calorimeter, 2, placed in the working zone of a pulsed superconducting solenoid, 3. The winding of the pulsed solenoid is made up of four sections connected in parallel and arranged on a common axis. The dimensions of the sections and gaps between them define the ratios between the values of the self-induction and coupling coefficients such as to insure a uniform distribution of the magnetic field.

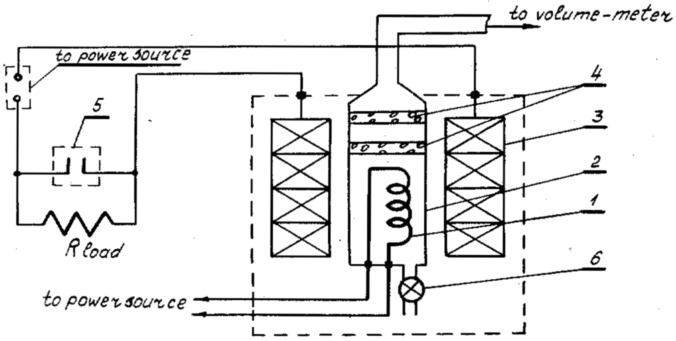

Fig. 1--Diagrammatic view of the experimental apparatus.

In the general case, at a certain value of the total current in the system, one can obtain a preset value of the system inductance, as well as any desired current distribution over the sections, that is the field distribution in the working volume, by selecting the appropriate number of sections, their geometry and gaps between them. Such a winding arrangement utilizes conductors of a relatively low cross section in large systems with a high total current, thereby increasing the system stability. On the other hand, a higher reliability is insured for the case of transition to normal state, since the stored energy is released more uniformly owing to its inductive redistribution.

The outer diameter of the solenoid is 275mm and its inner diameter 150mm; the overall height of the winding is 240mm, with the height of the top and bottom sections being 110mm each and of the central sections 95mm; the gaps between the sections are 10mm. The solenoid inductance is 0.12 H, and the magnetic constant is 3.3×10^{-3} T/A.

The solenoid is wound on a textolite frame with a twisted composite multifilament superconductor cable consisting of a single central copper wire and 18 composite wires with a twist pitch ℓ of 0.5 cm. The composite wires each contain six superconducting Nb-60%Ti filaments with a diameter of about 70 μ. The diameter of all wires is 0.03 cm. The cable is impregnated with an indium-based alloy having an electrical resistivity $\rho = 2 \times 10^{-6}$ ohm-cm at T = 4.2 K. The cable is insulated with a double-wound Lavsan (nylon-type fiber) filament. The maximum stored energy of the solenoid is 140 kJ.

The solenoid discharge into an active load (R_{load}) is effected by means of vacuum switch, 5, with the arc quenched by a reversed polarity current pulse from a bank of capacitors. Switchoffs were effected up to the maximum current value of 1,500 A. The limiting value of the magnetic field decay rate was 2,000 T/sec, with a voltage of over 60 kV occurring at the solenoid ends.

The experiment was carried out with the calorimeter valve, 6, closed, thus precluding the possibility of the "expulsion" of helium through the calorimeter bottom due to the inevitable pressure surges. From the calorimeter, the helium gas passes to a flowmeter gas holder with a water seal. The entrainment of liquid droplets by the gas is precluded by means of separators, 4. When calculating the released energy from the measured volume of evaporated helium, a correction was made for the decrease of the liquid helium level in the calorimeter and the replacement of the vacant space with the helium gas at a temperature close to the boiling point. This correction is calculated to an adequate accuracy from the ratio of the densities of the helium liquid and gaseous phases at the saturation line.

The experimental apparatus was checked over a wide range of heat pulse energies and power values with the aid of calibrated pulsed heaters. The scatter of the measured energy values relative to the actual values did not exceed 3%. The estimated total experimental error does not exceed 10%.

The experimental samples of twisted composite multifilamentary superconductors were wound as layered bifilar coils onto a textolite frame. The layers were spaced from each other with the aid of 0.5-mm textolite spacers to provide an access of liquid helium to the inside of the sample for improved cooling.

Shown in Fig. 2 are the results of measuring specific heat release, ϵ, in a NIOMAX TC2035/1.3 × 1.8 twisted composite multifilament superconductor manufactured by IMI (Britain). The sample is a flat bus with a cross section

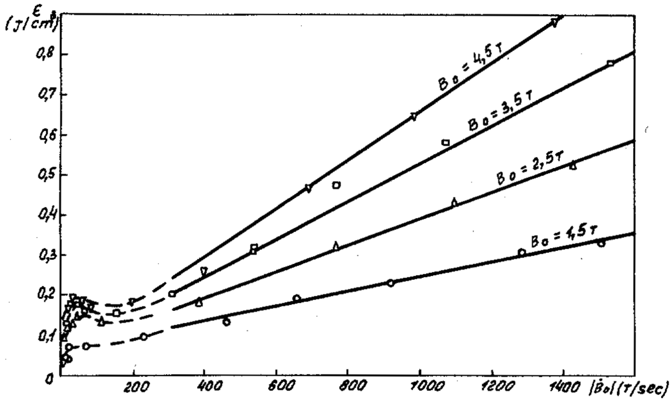

Fig. 2--Dependence of specific losses in a TC2035/1.3 × 1.8 sample on the maximum rate of the magnetic field variation.

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*Inst. High Temp., U.S.S.R. Acad. Sci., I-412, Morovinskoye Shaussee, Moscow, U.S.S.R.

of 1.3×1.8 mm^2 containing 2,035 Nb-60%Ti filaments 23μ in diameter. Each filament is enclosed with a 1 μm thick copper-nickel alloy sheathing. The axial twist pitch is 25 mm. The superconductor concentration $x_s = 0.36$, the copper concentration $x_n = 0.57$.

Presented in Fig. 3 are the results of measuring ϵ in a 49-filament cable sample comprising 42 composite wires and 7 copper wires 0.3 mm in diameter. The twisting is effected according to the 7×7 pattern, the composite wire being similar to the one from which the pulsed solenoid winding was manufactured. The cable is impregnated with a high-resistance indium-based alloy. The superconductor concentration is $x_s = 0.19$, the copper concentration $x_n = 0.50$. Curve 1 ($B_0 = 3.5$T) and the points + on the curve $B_0 = 1.5$T correspond to the experiments in which the sample was connected in series with the pulsed solenoid. In this configuration the sample carries at the moment of discharge a transport current $I_0 = 1{,}050$ A ($B_0 = 3.5$T) and $I_0 = 450$ A ($B_0 = 1.5$T) which also varies synchronously with the external field.

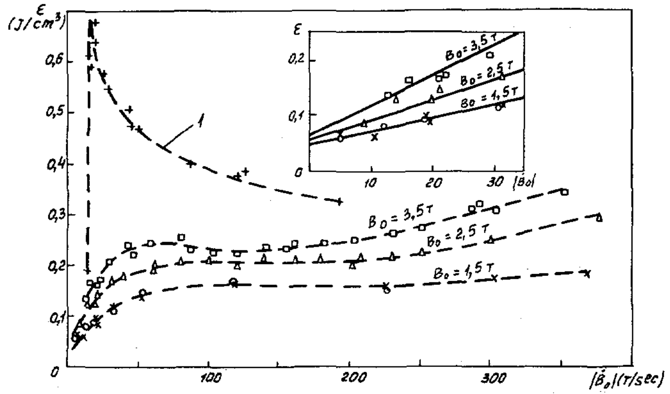

Fig. 3--Dependence of specific losses in a 49-strand cable sample on the maximum rate of the magnetic field variation.

For the theoretical analysis of losses in twisted composite multifilament superconductors we make use of the continuum model.[3,4] It has been shown in Ref. 3 that in the external region of a twisted composite multifilamentary superconductor (saturated zone) the current in superconducting filaments is equal to the critical one. In the internal region the current flows transversely to the filaments over the normal metal matrix. With the assumption that the sample heating is insignificant and the saturated zone thickness is considerably less than the radius of the twisted composite multifilament superconductor, the following expression has been obtained:[3]

$$\epsilon = M_0 H_0 \frac{\lambda\tau_0}{1 + \lambda\tau_0} + \epsilon_H \tag{1}$$

where τ_0 is the characteristic intrinsic time of the twisted composite multifilament superconductor, and ϵ_H are hysteresis losses the expressions for which have also been given in Ref. 3. Note that most important here is the heat released in the internal region. At $\lambda\tau_0 \gtrsim 1$, hysteresis losses are much less than the first term; however as $\lambda\tau_0 \to 0$

$$\epsilon_H \to \epsilon_H(\lambda\tau_0 = 0)$$

In high magnetic fields, which corresponds to the experimental conditions, the saturated zone is small if $\lambda\tau_0 \ll 1$. Shown in solid line in Fig. 3 in the insert are the calculated results according to Eq. (1). The τ_0 parameter was found by the method of least squares from the results of measurements in the field of $B_0 = 1.5$T and equals 0.002 sec. The calculation for $B_0 = 2.5$T and $B_0 = 3.5$T was performed with this particular value of $\tau_0 = 0.002$ sec. As evident, the theory describes the experiment adequately up to $\dot{B}_0 = \lambda B_0 = 30$-40 T/sec, which corresponds to $\lambda\tau_0 = 0.05$ to $0.02 \ll 1$ in the field interval of $B_0 = 1.5$ to 3.5T.

We have considered the parameter region of $\lambda\tau_0 \gg 1$ and shown that, under the conditions of the present experiment, the saturated zone takes up the entire volume of the twisted composite multifilament superconductor. Under these conditions, the value of ϵ is described by the expression:

$$\epsilon = \alpha M_0 H_0^2 \lambda\tau_0 \left(\frac{2\pi R_0}{L}\right)^2 \tag{2}$$

where $\alpha \sim x_n$ is of the order of unity and does not depend on the details of the structure of the twisted composite multifilament superconductor. Note that Eq. (2) describes the losses in a composite conductor in the normal state, while hysteresis losses in this region are known to be small.

In the transition from $\lambda\tau_0 \ll 1$ to $\lambda\tau_0 \gg 1$, the size of the saturated zone increases, while the losses occur mainly in the internal region (compare Eqs. (1) and (2) at $\lambda\tau_0 \sim 1$). Therefore, depending upon the ratio of parameters, a reduction in size of the internal region brings about the appearance of a maximum (and minimum), or a plateau on the curve of the B_0 dependence of ϵ. Based on the qualitative considerations presented in this paper, results obtained by authors of Ref. 3 and the asymptotic expression (2), we have obtained an approximation formula for ϵ, valid at all values of B_0 and $\lambda\tau$. Fig. 4 shows the $\lambda\tau_0$ dependence of ϵ for different values of B_0 and R/L ratio. As seen from Fig. 4, $\lambda\tau_0 \sim 1$ corresponds to the maximum. The value of ϵ here can be found from Eq. (1) and is equal to $\epsilon = 0.4$ to 4 J/cm^3 in the field range $B_0 = 1.5$ to 4.5T of interest to the present authors. However, as seen from the comparison between theory and experiment, the character of the $\dot{B}_0$ dependence of ϵ already varies at $\lambda\tau_0 \ll 1$; in this case, the losses are 4 to 20 times less than the estimated ones.

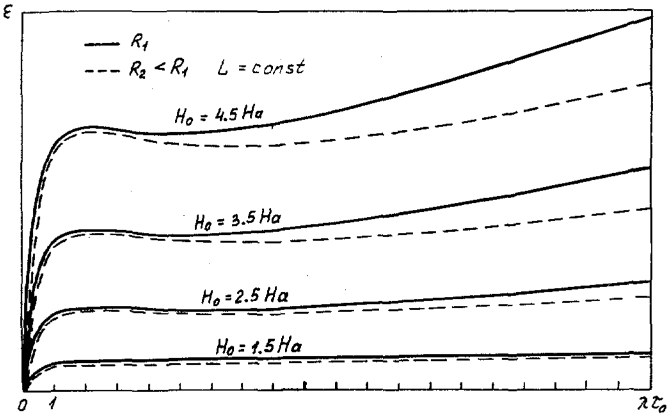

Fig. 4--Theoretical $\lambda\tau_0$ dependence of ϵ on different values of the radius R of the twisted composite multifilament superconductor (with the twist pitch constant).

Note that the value of heat released, ϵ, at which the transition of Nb-60%Ti to normal state takes place, is equal to $Q_0 \sim 0.2 x_s$J/cm^3. Therefore, in order to interpret the experimental results, one should take into account the heating up of the sample.

At $\lambda\tau_0 \ll 1$, it is insignificant and, as already seen, does not affect the $\dot{B}_0$ dependence of ϵ.

At $\lambda\tau_0 \gg 1$, in the course of heat release a transition to the normal state takes place if the magnetic field is sufficiently high. This is observed experimentally as a sharp difference in losses for samples with and without transport current (see Fig. 3), inasmuch as there takes place an additional heat release due to ohmic losses after the transition of the sample with transport current to normal state. As is evident, the transition to the normal state is clearly identified in the magnetic field $B_0 = 3.5$T and is not identified in the field $B_0 = 1.5$T.

In the region of $\lambda\tau_0 >> 1$ and high B_0, the twisted composite multifilament superconductor definitely changes to normal state as early as at the beginning of the heat release. In this case, ϵ comprises two terms: Q_0, the heat released prior to the transition to the normal state (the value Q_0 is practically independent of B_0), and the term of the type of Eq. (2) describing the dissipation in the normal state. Thus, ϵ has the form:

$$\epsilon = Q_0 + \alpha M_0 H_0^2 \lambda\tau_0 \left(\frac{2\pi R_0}{L}\right)^2 \qquad (3)$$

As seen from Fig. 2, the agreement between theory and experiment in the case of such description is quite adequate. The value Q_0, found by the method of least squares from the experimental data, is independent of B_0 and coincides with the calculated value corresponding to the sample heating up to T_c.

In the transition from $\lambda\tau_0 \ll 1$ to $\lambda\tau_0 >> 1$, the character of the processes upon heat release and consequently the appearance of the curve showing the B_0 dependence of ϵ is qualitatively the same as in the absence of heating. It appears difficult to describe quantitatively the losses in this region of parameters.

Therefore, with rapid variations of a strong magnetic field, the twisted composite multifilament superconductor changes to the normal state as early as in the beginning of the discharge, which results in a considerable reduction of the heat evolved as compared to heat released in the same superconductor at constant temperature. The essentially nonmonotonic $\dot{B}_0$ dependence of ϵ in strong magnetic fields is also due to the character of the process flow, as mentioned above. A detailed discussion of the experimental and theoretical results will be published later.

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