INTRODUCTION

One of the factors which affects the stability and the transient process character of superconducting magnets (SM) during the energy removal are energy losses generating in the SM winding at a rapid decrease of the magnetic field. Due to a small time constant of such a process, the losses in a high current density SM (dense windings with no cooling channels) are generated under conditions very close to adiabatic ones. Owing to such conditions the SM, as is shown, for example, in /1/, can quench. Due to losses the normal zone velocity in such a winding can be considerably higher than that owing to thermal diffusivity [2].

In this regard it becomes interesting to investigate the losses of composite multifilamentary superconductors (CMS) at a pulse of the transverse magnetic field under adiabatic conditions. First results of such studies were published in paper [3], the experimental method was described. In this paper the results of recent experimental investigations are presented; the method of calculation is described in detail.basic dependences of the losses on various CMS parameters are shown and the explanation of these dependences is given.

EXPERIMENTAL RESULTS

To measure the energy losses of short samples under adiabatic conditions, the method based on the maximum temperature measurement of the sample at a pulse of the transverse magnetic field was developed. The amout of energy, which is necessary to heat up the sample to this maximum temperature, was determined by a pulse heater. The magnetic field pulses with an exponential character of decreasing $B(t) = B_M e^{-t/\tau}$ (to imitate the conditions of the CMS in the winding during the energy removal from the SM) were generated by switching the SM from the current source to the dump resistor of various values. This experimental method was described in more detail in paper [3].

Samples of the CMS with filaments made of a NT-50 alloy [4] (Nb-50 weight % Ti) in the copper matrix have the shape of round wires from 0.7 to 1.5 mm in diameter and/or of a conduc-

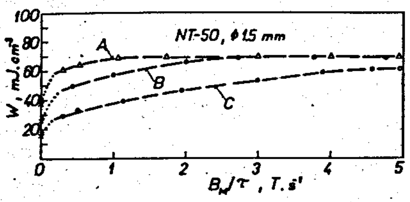


Fig.1. Losses of the conductor 1.5 mm in diameter against the initial value of the magnetic field change rate. $A - B_M = 3$ T, $B - B_M = 1$ T, $C - B_M = 0.5$ T.

tor with a rectangular cross section of 2.0x3.5 mm². First, the dependence of the current density on the magnetic field induction at 4.2 K, critical temperature and specific heat (C) at B = 0 were measured for each sample. For example, for the conductor 1.5 mm in diameter the C temperature dependence at a zero magnetic field can be fitted according to the temperature interval as follows:

$$\left.\begin{array}{ll} 4.2\,K \le T \le 9.0\ K & C(T) = 0.0045\ T^3 \\ 9.0\,K < T < 9.4\ K & C(T) = -2.075\ T + 21.955 \\ 9.4\,K \le T < 20\ K & C(T) = 0.04\ T + 0.0025\ T^3 \end{array}\right\} [J/kgK] \qquad (1)$$

Using the results of measurements presented in paper /5/, the specific heat dependence on the magnetic field induction can be approximated as:

$$C(T,B) = C(T)(1 + 0.05\,B)\ [J/kgK;T]. \qquad (2)$$

The dependences of the energy losses both on the initial value of the magnetic field B_M and on the initial magnetic field decay rate B_M/τ were measured. The value B_M varied from 0.5 up to 5 T; B_M/τ from 0.5 up to 5 T/sec.

As an example, figure 1 presents the losses per unit volume W of the CMS 1.5 mm in diameter (critical temperature $T_c = 9.4$ K, number of filaments N = 61, filament diameter d = = 140 μm, filling factor λ = 0.47 and twist length ℓ_p = 25 mm) against B_M/τ at constant values of B_M. An analogous dependence for the CMS with a rectangular cross section of 2.0 x 3.5 mm² (T_c = 9.36 K, N = 361, d = 80 μm, λ = 0.26 and ℓ_p = 30 mm) for perpendicular and parallel orientation of the magnetic field with respect to a wide (3.5 mm) side of the conductor is presented in fig. 2. The saturation of the $W(B_M/\tau)$ dependence is due to achieving the critical field change rate /6/, which is approximately 1 T/sec. An increase on the $W(B_M/\tau)$ curve for the reetangular cross section conductor, see fig. 2a, (the field is perpendicular to its wide side) starting from a value of ≥ 1 T/sec is caused by the turn normal of the sample due to eddy current losses generated in the copper.

Figures 3 and 4 show the losses dependences on the magnetic field amplitude B_M at a constant value of B_M/τ for the conductor 1.5 mm in diameter and for the 2.0 x 3.5 mm² conductor, respectively. The losses for all the samples become nearly in-

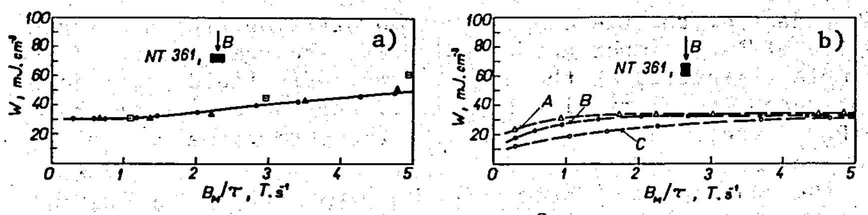
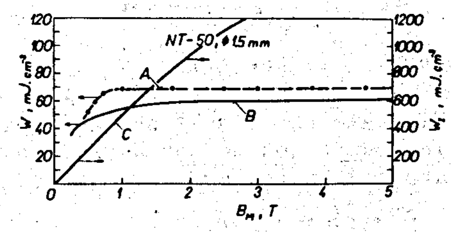


Fig.2. Losses of the 2.0 x 3.5 mm² rectangular cross section conductor against the initial value of the magnetic field change rate. a) field perpendicular to the wide (3.5 mm) side of the conductor. □ - B_M = 5 T, Δ - B_M = 3 T, • - B_M = 1 T. b) field parallel to the wide (3.5 mm) side of the conductor. A - B_M = 3 T, B - B_M = 1 T, C - B_M = 0.5 T.

Fig.3. Losses of the conductor 1.5 mm in diameter against the initial value of the magnetic field. B_M/τ = = 3 T/sec. A - experimental values, B - theoretical result, C - theoretical result under isothermic conditions (T = 4.2 K).



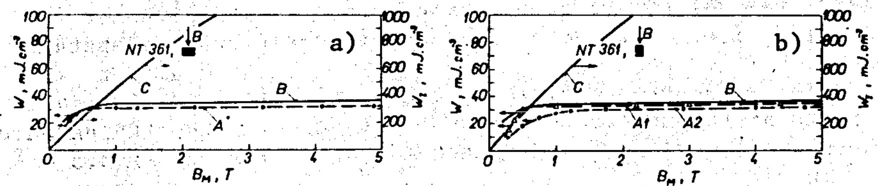


Fig.4. Losses of the 2.0 x 3.5 mm² rectangular cross section conductor against the initial value of the magnetic field.

a) field perpendicular to the wide (3.5 mm) side of the conductor. B_M/τ = 1 T/sec. A - experimental values, B - theoretical result, C - theoretical result under isothermic conditions (T = 4.2 K).

b) field parallel to the wide (3.5 mm) side of the conductor. A1, A2 - experimental values B_M/τ = = 5 T/sec and 1 T/sec, respectively; B - theoretical result, C - theoretical result under isothermic conditions (T = 4.2 K).

dependent of the field amplitude B_M starting from a certain value of B_M. An important fact is that the temperature of the sample registered at the end of a magnetic field pulse does not reach its critical value, i.e., the saturation of the $W(B_M)$ dependence is not caused by the turn normal of the sample.

The characters of $W(B_M/\tau)$ (at B_M= const) and $W(B_M)$ (B_M/τ = =const) for samples having another diameter are analogous to those presented in figs. 1 and 3, respectivily.

LOSSES CALCULATION

When the magnetic field change rate $\dot{B}$ is greater than the critical one $\dot{B}_c^*$ /6/, the CMS can be considered as a D-diameter monofilamentary superconductor with the critical current density $J_c\lambda$, where λ is its filling factor

$$\dot{B}_c^* = 2\rho_e J_c(B,T) D\lambda^{3/2} \ell_p^2 , \qquad (3)$$

where ρ_e is the effective transverse resistivity of the CMS, $J_c(B,T)$ is the critical current density in the filaments. In this case the losses per unit volume of the CMS under adiabatic conditions do not depend on the magnetic field change rate and their increase, according to dB, is determined by:

$$dW = \frac{2}{3\pi} d\lambda \cdot J_c(B,T)dB. \qquad (4)$$

In the d.c. SM, as usual, CMS are used in which during the energy removal and/or quench processes the condition $\dot{B} > \dot{B}_c^*$ is valid, i.e., the energy increase is described by the expression (4).

Under adiabatic conditions at magnetic field change dB a temperature increase of the CMS (dT) results from the heat balance between the energy generated and the CMS enthalpy /1/:

$$\frac{dT}{dB} = \frac{2}{3\pi} D\lambda \cdot J_c(B,T) \frac{1}{\gamma \cdot c(T,B)}, \qquad (5)$$

where γ is the specific mass of the CMS and c(T,B) is its specific heat. The critical current density as a function of the temperature is expressed by the formula given in ref. /7/.

The losses calculation procedure is as follows. At an initial moment (t =0) the sample having a temperature of T =4.2 K is situated in the magnetic field induction B_M as the field decreases by dB, the sample temperature increases by dT determined by the differential equation (5). The c(T,B) and $J_c(B,T)$ values are used to solve this equation in the computer program. The energy increase dW is calculated according to (4). The full losses are given by the sum of energy increases

in the field interval from B_M to zero and over the temperature range from 4.2 K to T_{max}, respectively. The results of the calculations are presented in figs. 3 and 4 (curves B). In the same figures the results of the losses calculations under isothermic conditions are presented, i.e., when the critical current density determined by the magnetic field only (T= const) (curves C). The hysteresis losses (at $B_M/\tau \to 0$) in the CMS are calculated in a similar manner. For these calculations in eq. (4) the filament diameter d is used instead of the effective conductor diameter $D\lambda$. The result is presented in fig. 1 as points $B_M/\tau \to 0$. The experimental results are extrapolated to these points.

The losses of the rectangular cross section conductor are calculated in the same manner as for the round conductors. To do this, the effective diameter of such a conductor is equal to the filamentary zone dimension perpendicular to the magnetic field. The effective filling factor is determined from constancy of the amount of the superconductor in the rectangular cross section conductor and of the round conductor with the effective diameter. The losses calculated are then related to the unit volume of the real CMS.

The reason of some difference in the character between the experimental and theoretical curves $W(B_M)$ (see figs. 3 and 4) in the region of small B_M values is the fact that eq. (4) is valid in the case of full magnetic field penetration into the CMS only. For $B_M \lesssim 1$ T this condition is not fulfilled.

DISCUSSION

The reason of the saturation of the $W(B_M)$ dependence is the presence of back coupling between the energy generated and the increase of the superconductor temperature. The dynamics of the losses generation process and the temperature increase of the sample 1.2 mm in diameter (T_c =9.4 K, N =61, d =110 μm, λ =0.5 and ℓ_p =25 mm) for the field amplitudes B_M=5 T and 1 T obtained from the calculation is presented in fig. 5. For B_T =5 T (solid curves) the power of the losses generated at the beginning of the process is lower than that for B_M =2 T because of lower critical current density. As the temperature increases, $J_c(B,T)$ decreases and the power of the losses decreases as well. The conductor is heated up more intensive at the beginning of the process for B_M=2 T, and the power of the losses decreases faster than for B_M =5 T. Starting from a certain moment, the power of the losses generated for B_M =2 T becomes lower than the one for B_M =5 T. As is seen from figs. 5, the resulting energy is nearly the same for the two field amplitudes B_M =5 T and 2 T, respectively.

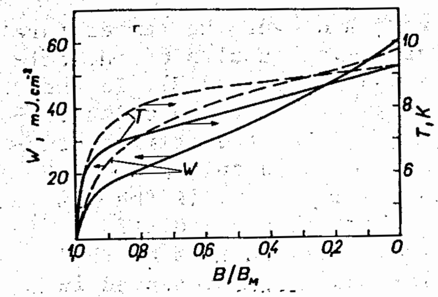


Fig.5. Losses generation process and temperature increase of the conductor 1.2 mm in diameter. Solid lines - B_M =5T, dotted lines - B_M =2 T.

It is important to point out that the temperature of the sample does not reach its critical value but just approaches it to some value. As the temperature approaches T_c, $J_c(B,T)$ decreases to zero and the power of the losses dW/dt also decreases to zero.

To specify the influence of the CMS parameters on the value of the losses, further calculations were done. For these calculations the parameters of the conductor 1.2 mm in diameter were used as relative ones.

The $W(T_c)$ and $W(\lambda)$ dependences are presented in figs. 6 and 7, respectively. These two factors (T_c, λ) affect considerably the losses value. The change of the specific heat and specific mass with changing λ of the CMS was taken into account. The dependence of the losses on K is illustrated in fig. 8, where $K = J_c(B)/J_{co}(B)$ and $J_{co}(B)$ is the measured critical current density of the conductor 1.2 mm in diameter at 4.2 K. The losses are most intensively affected by K at small values of the K region. Further the dependence of the losses on the conductor diameter D was calculated. Figure 9 presents the result together with the three experimental points. Some difference in character of the arrangement of the experimental points from the theoretical one is due to differences in some conductor parameters (T_c, λ, $J_c(B,T)$); for example, T_c = =9.6 K for the conductor 0.7 mm in diameter. The saturation of the losses dependence W(D) can be explained by the presence of back coupling between the increase of the losses and the sample temperature. The dynamics of the losses power for conductors 5, 1.2 and 0.3 in diameter is illustrated in fig. 10 (B_M=5 T, B_M/τ =3 T/sec). According to eq. (4) the losses power of the conductors of large diameter D is high at the very beginning of the process. Subsequently, as the conductor is heated up, the losses power falls down very intensively with dropping $J_c(B,T)$. At a certain moment the power of conductor with a large diameter becomes lower than that of the conductor with a smaller diameter. As the diameter of the CMS increases the temperature back coupling influence on the losses becomes more intensive. In accordance with this, the resulting losses, starting from some conductor diameter, are nearly independent of it.

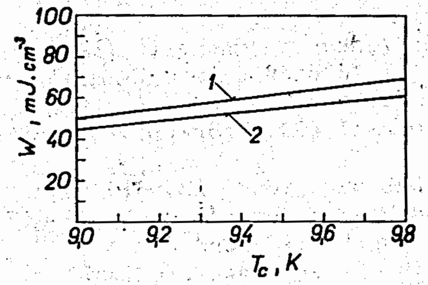


Fig.6. Losses against the critical temperature. Theoretical values. 1-B_M=5 T, 2-B_M=1 T.

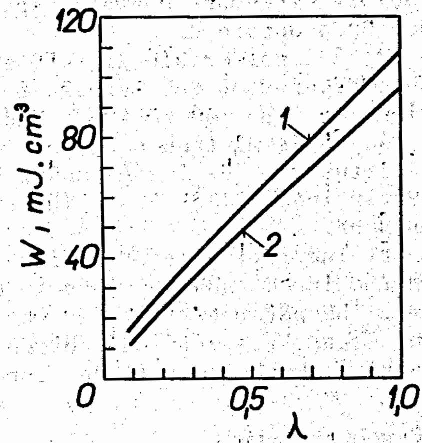


Fig.7. Losses against the filling factor of the CMS. Theoretical values. 1-B_M=5 T, 2-B_M= =1 T.

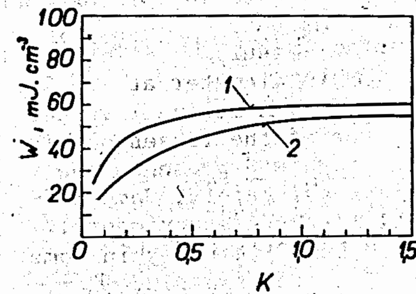


Fig.8. Losses against the ratio $J_c(B)/J_{co}(B)$, where $J_{co}(B)$ is the critical current density measured at T=4.2 K. Theoretical values. 1-B_M =5 T, 2-B_M=1 T.

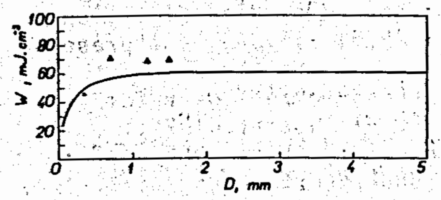


Fig.9. Losses against the conductor diameter. Theoretical value. B_M =5 T. Δ - experimental values.

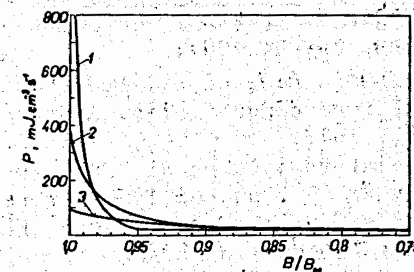


Fig.10. The power of the losses generation process. 1-D = =5 mm, 2-D =1.2 mm, 3-D =0.3 mm.

CONCLUSION

1. The energy losses of the CMS 0.7, 1.2 and 1.5 mm in diameter as well as of the 2.0x3.5 mm² rectangular cross section conductor were measured under adiabatic conditions against the

amplitude and orientation of the transverse magnetic field $B_M \leq 5$ T and the initial magnetic field change rate $B_M/\tau \leq 5$T/sec.

2. The calculation of the losses has been done. A satisfactory agreement between experimental and theoretical results has been obtained.

3. A considerable difference has been found in value and in character of the losses dependences under adiabatic conditions as compared to those under isothermic conditions.

4. Starting from a certain value of the magnetic field amplitude B_M the losses under adiabatic conditions become nearly independent of B_M. The explanation of such a behaviour is done.

5. The influence of various factors and CMS properties on the losses under adiabatic conditions has been investigated. The parameters, which mostly affect the values of the losses are the critical current density, critical temperature, specific heat and filling factor.

ACKNOWLEDGEMENTS

We are grateful to P. Vasilev for measuring the specific heat temperature dependence of the samples.

REFERENCES

1. Luppov V.G. et al. Cryogenics, 1980, 20, p. 571.
2. Kabat D. et al. Cryogenics, 1979, 19, p. 382.
3. Kabat D. et al. To be published in the MT'7 Proc.Karlsruhe, FRG, March, 1981.
4. Nikulin A.D. et al. Proc.Conf. on Technical Application of Superconductivity, Alushta, 1975, vol. 4, 5, Atomizdat, M., 1977.
5. Lejarovski E. et al. Proc. of the Summaries of the 18th USSR Conf. on Low Temperature Physics, Kiev, 1974.
6. Ries G., Brechna H. Report KFK - 1372, Karlsruhe, 1972.
7. Superconducting Magnet Group, RHEL Preprint RPP/A 73, 207, November, 1969.

Received by Publishing Department on May 22 1981.