conf-760929--

STRESS-INDUCED HEATING IN COMMERCIAL CONDUCTORS AND ITS POSSIBLE INFLUENCE ON MAGNET PERFORMANCE*

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ABSTRACT

Calorimetric measurements show that significant amounts of heat are generated when a multifilamentary composite conductor is stressed in tension to levels expected to occur in large, high-field magnet systems. When the stress on the conductor is repetitively cycled between zero and some maximum value, the amount of heat produced per cycle is constant after the first few cycles. Comparison is made between calorimetric determinations of heat injections and the work done on the specimen as indicated by stress-strain curves. Stress-strain curves for a number of commercial conductors indicate that the most important determinant of the magnitude of this effect is the choice of matrix material.

INTRODUCTION

Stress-induced heating in composite multifilamentary conductors has been discussed recently[1-4] as a possibly significant source of heating during field cycling in large, high field magnet systems. A measure of the amount of heat generated in a conductor when it is cycled from zero stress ($\sigma = 0$) to some maximum value (σ_{max}) and back to zero may be obtained from a stress-strain curve for the conductor. When copper without filaments is plastically deformed under tensile stress, part of the work done on the specimen appears as heat and part becomes stored energy. Work-hardening also occurs, so that subsequent cycling to stress levels equal to or less than the previous value results in almost reversible stress-strain curves which indicate little net work done on the specimen and therefore little heating.

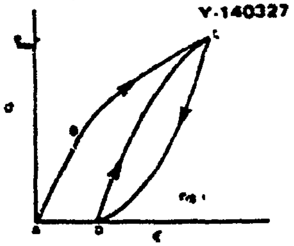

Figure 1 shows, schematically, stress-strain behavior for a composite material, e.g., NbTi filaments in a copper matrix. In the initial linear portion A-B [where B ~ 70 MPa (10 ksi)] of the curve, both filaments and matrix undergo elastic strain. In the region B-C the matrix is plastically deformed and work-hardened, but the filaments are still elastically strained. Sufficiently large stresses would of course plastically deform the filaments as well, but this requires stress-levels much higher than expected to be of practical interest. When the stress is reduced from σ_{max}, the curve is only approximately linear, and the non-linearity increases as the stress is reduced. At D the matrix is in compression due to the elastic stress of the filaments, and the non-linearity of C-D implies that the matrix has again been plastically deformed. The length A-D represents a permanent elongation of the conductor and indicates that the filaments are elastically strained. When stress is again applied the path D-C is followed. This curve is non-linear from the beginning, indicating that even very low stresses are, after an initial loading to above B, dissipative. When the stress is decreased, the path C-D is again followed, and subsequent cycles retrace the loop D-C-D. This description is somewhat idealized, and several cycles may actually be required to "stabilize" the loop.

The area enclosed by A-B-C-D is proportional to the net work done on the specimen when the stress was initially cycled from zero to σ_{max} and back to zero. A portion of this work is stored in the conductor as "stored energy of cold-work" (i.e., in dislocations, point defects, etc.), as elastic strain energy (primarily in the filaments), and the remainder appears as heat. The area of the loop D-C-D is proportional to the work done in non-initial or cyclic stressing to σ_{max}. Again, this work must either be stored in the conductor or appear as heat. Since after a few cycles the area of the loop is approximately constant, and since one would not expect to increase indefinitely the stored energy in the conductor, all of the work done on the conductor after the initial cycling should appear as heat.

We have measured calorimetrically the amount of heat generated in both initial and repetitive stressing of Nb-Ti composite conductors with both copper and aluminum alloy matrices, and compared the results to the corresponding areas of stress-strain curves. We have also measured cyclic stress-strain behavior in a number of commercial conductors to find which properties of the conductor are important in determining the amount of heat produced.

EXPERIMENTAL

The experimental calorimetric apparatus is shown in Fig. 2. The temperature rises ΔT associated with stress-cycling were measured using a silicon diode thermometer on the specimen. With this thermometer it was possible to measure ΔT's as small as a few mK. The stainless steel ballast at the ends of the specimen had a heat capacity ~ 50 times that of the specimen and thus served to limit the changes in temperature to ~ 1.5K or less for the highest stress levels. To determine from ΔT the amount of heat injected one must know the heat capacity of the sample assembly and the thermal resistance between the sample assembly and the bath. Also, the time required for the temperature of the sample assembly to equilibrate after an injection of heat must be sufficiently short that a negligible amount of heat is transferred to the bath. A timed heat pulse using a resistance heater wound on the ballast at one end was used to inject a known amount of heat Q. From the measured temperature rise an effective heat capacity ($C = Q/\Delta T$) of the system was obtained. The coefficient, λ, for heat transfer to the bath was determined from a measurement of T as a function of time as the assembly cooled after an injection of heat. The rate $\dot{T}$ at which the temperature of the system changes is given by $C\dot{T} = \dot{Q} - \lambda\ (T - T_b)$ where $\dot{Q}$ is the rate at which heat enters and T_b is the bath temperature. If $\dot{Q} = 0$, and if $T - T_b$ is sufficiently small that temperature variations of C and λ may be ignored ($T - T_b$ is limited by the heat capacity of the stainless steel ballast), then $\lambda/C = 1/t\ \ln T_o - T_b/T - T_b$, where $T_o = T(t = 0)$. The

Manuscript received August 17, 1976.

*Research sponsored by the Energy Research and Development Administration under contract with the Union Carbide Corporation in the Metals and Ceramics Division Oak Ridge National Laboratory, Oak Ridge, TN 37830.

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[illegible] C was found to be constant to within [illegible] over times up to 50 sec and initial values of $T - T_b$ up to about .75K, indicating it is justified to ignore the temperature variations of [illegible] and C. At larger values of $T - T_b$ the variation of C must be accounted for. For the initial stress data, the stress was increased from zero to a value σ_{max} and back to zero in a typical time of 5 sec. The temperature was recorded as a function of time during and after the stress cycle, and the maximum value of $\Delta T = T - T_b$ was used to find the heat injected. This was done at successively larger values of σ_{max}. Heat transfer within the sample assembly required 3 to 5 sec after an injection of heat either from the heater or stress cycle for the maximum temperature to be recorded. The rate of heat transfer to the bath was such that during this time no more than 5 to 10% of the heat injected was lost. This same procedure was used for the non-initial or cyclic stress data at the higher stress levels where the amounts of heat injected were large. At low stress levels it was necessary to cycle the stress at a constant frequency and measure the temperature as a function of time. From the rate of heat transfer to the bath and the rate of temperature increase, the rate of heat injection, and thus the amount of heat injected per cycle, was determined. The level to which the specimen had been stressed prior to the repeated loading or cyclic data was not the same for all measurements, and this fact seems to account for some of the scatter in this data.

The calorimetric measurements, normalized to sample volume, have been compared to the areas (measured by a planimeter) enclosed by increasing and decreasing portions of experimentally determined stress-strain curves obtained on similar specimens at 4.2K. In addition, hysteretic loop areas for repeated cyclic stress-strain curves were measured for a number of commercial conductors with varying properties.

RESULTS AND DISCUSSION

Figures 3 and 4 show results for both initial loading and repeated or cyclic loading for two NbTi conductors, one with a copper matrix (18 filaments untwisted), and the other with an Al alloy (5056) matrix (54 filaments, twisted). These conductors are entries 4 and 7 in Table 1. For cyclic loading, the loop areas and calorimetric measurements agree well in the stress range where the data overlap. This region is relatively short because the accuracy of measurement of loop areas is poor for the small loop areas obtained at low stresses. Due to limitations on resolution of strain measurements, ΔT provided a more sensitive measurement of small heat injections than loop areas; however, within accuracies of measurement the two methods are equivalent. The initial loading data for the copper matrix material show a large difference between the two types of measurements. The initial loop areas (A-B-C-D, Fig. 1) which are a measure of the total work done on the specimen, are as much as a factor of 3.5 larger than the heat injected as determined from ΔT. This difference indicates a large amount of stored energy, either as stored energy of cold-work in the copper matrix, or as elastic strain energy in the NbTi filaments. Estimates indicate that the elastic tension in the filaments that remains after the matrix has been plastically deformed accounts for a major portion of the stored energy. For the Al alloy matrix material shown in Fig. 4 much smaller amounts of energy are stored. The strain for a given stress is smaller for this conductor, so that the maximum possible strain energy in the NbTi filaments after the stress is released is smaller.

Figure 5 shows the amount of heat injected per cycle per unit volume of sample when the stress is cycled from zero to σ_{max} to zero for a variety of commercial conductors, as determined from the areas of stress-strain loops. This is the non-initial, cyclic loading case. Table 1 lists properties of the specimens. The obvious conclusion to be drawn from this data is that, of the various conductor properties, i.e. twist pitch, the ratio of normal material to superconducting material, the aspect ratio (thickness to width) of rectangular conductors, the superconducting material, the number and size of the superconducting filaments, and the matrix material, only the last had a significant effect upon the amount of stress-induced heating. Data for all of the conductors with copper matrices, including the Nb_3Sn conductors, fall in a rather narrow band. Heating in the Al alloy matrix material was nearly an order of magnitude lower, and limited data on a Cu-Ni/Cu mixed matrix conductor fell between.

Stress-induced heating is likely to be an important factor in the operation of large, high field magnet systems, where large magnetic stresses are encountered. For large coils which are pulsed or cycled on a repetitive basis, stress-induced heating may represent a significant heat load even for coils with low average stress in the windings. Since the same amount of energy is generated per cycle in the windings whether the magnet is charged rapidly or slowly, the rate at which it is produced is proportional to the charging rate. The heat transfer condition between conductor and bath determines the magnitudes of the temperature rise associated with a given rate of energy release, and therefore with a given charging rate. Thus, stress-induced heating may place an upper limit upon charging rate. The large amounts of energy released upon initial stressing may lead to instabilities during the first charging of a magnet, especially if local regions of high stress occur during the "settling in" process. Most of the heating would occur during the increasing stress portion of the cycle, i.e., during charging.

The amount of heat released in the windings when a magnet is charged can be estimated from our data if the distribution of stress within the windings at H_{max} is known. In general this is difficult to determine, but in the case of a long solenoid with a small winding thickness compared to the coil diameter, the maximum stress (at the inside of the winding) will not be too different from the minimum stress (at the outside of the winding). In this case the heat injected per m^3 of conductor in charging from zero to H_{max} and back to zero can be read from our graphs of loss/m^3-cycle, using for σ_{max} the average hoop stress in the magnet at H_{max}. Stress calculations[7] for the reference design of the poloidal field coil of the Oak Ridge Tokamak Experimental Power Reactor Study[8] indicate that this is a reasonable approximation for that coil, even though the winding thickness is not small compared to the coil diameter (3.0 m ID and 3.8 m OD). The heat generated per m^3 of conductor is a rapidly increasing function of stress. Using the data of Fig. 5 for cyclic loading, a coil in which the average stress in the winding at H_{max} is 70 M Pa (~ 10 ksi) would release about 1000 Joules/m^3 of conductor to the He bath in being cycled from zero to H_{max} and back to zero, while this figure rises to 7000 Joules/m^3 for an average stress at H_{max} of 100 M Pa (14.5 ksi), and to about 20,000 Joules/m^3 at 150 M Pa (~ 22 ksi). By way of comparison, we note that according to the most recent calculations the total electromagnetic losses for the poloidal field coil of the Oak Ridge Tokamak EPR Study in cycling the field from 7 Tesla to − 7 Tesla in 2 sec, would be about 1650 Joules/m^3 of winding.

The amount of heat generated in the stress cycle depends strongly upon the initial state of residual stress of the conductor. This in turn depends upon such matters as varying manufacturing processes, conductor tension during winding, and differences in thermal contraction upon cooling of the various components. Therefore, the amount of stress-induced heating reported here can be considered only as indications of the possible magnitudes of thermomechanical heat injections which may be encountered in an actual coil. Also, it is possible that thermomechanical heating may be significant in structural and potting materials of the coil as well as the conductor.

SUMMARY

It has been demonstrated by calorimetric measurements that a large stress-induced heat generated in the windings can be expected upon charging large volume high field magnet systems using filamentary conductors in copper matrices. The amount of heat produced is a rapidly increasing function of stress. These heat inputs appear to be at least comparable to and probably larger than other sources of heat such as eddy current losses in the conductor, even at modest conductor stress levels which may be unavoidable in such large systems. The only conductor characteristic which was found to affect significantly the amount of heat generated for a given stress level is the matrix material, i.e., a multifilamentary conductor with an Al alloy matrix generated amounts of heat per unit volume of conductor which were approximately a factor of 10 less than for conductors with copper matrices. This indicates that efforts to minimize stress-induced heating through conductor design probably should be concentrated upon the properties of the matrix.

ACKNOWLEDGEMENT

Partial funding provided by the Superconducting Magnet Development Program of the Thermonuclear Division of Oak Ridge National Laboratory.

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Table 1. Characteristics of Conductors Tested

Symbol in Fig. 5	Aspect Ratio	Twist Pitch	Number of Filaments	% SC Ratio	Superconductor	Matrix
1 ●	2	40/m	25,000	[illegible]	Nb_3Sn	Copper
2 ◆	3	40/m	1,530	1.6	NbTi	Copper
3 ▲	2	80/m	1,530	1.6	NbTi	Copper
4 ■	2	none	18	2.8	NbTi	Copper
5 ●	3	40/m	18	2.8	NbTi	Copper
6 ▼	2	?	1,591	1.5	NbTi	Cu-Ni/Cu
7 ·	round	80/m	54	1.63	NbTi	Al alloy 5056

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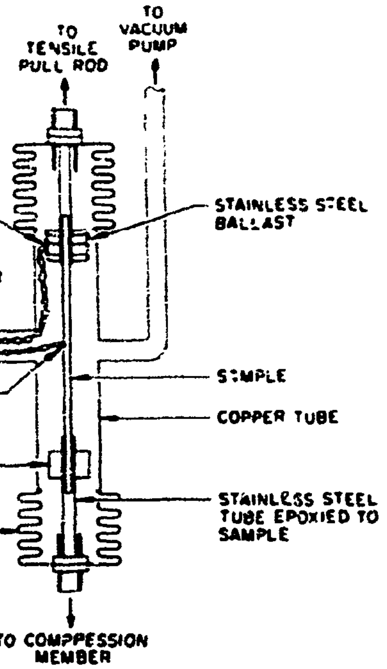

Fig. 2. Schematic diagram of apparatus used to measure stress-induced heat.

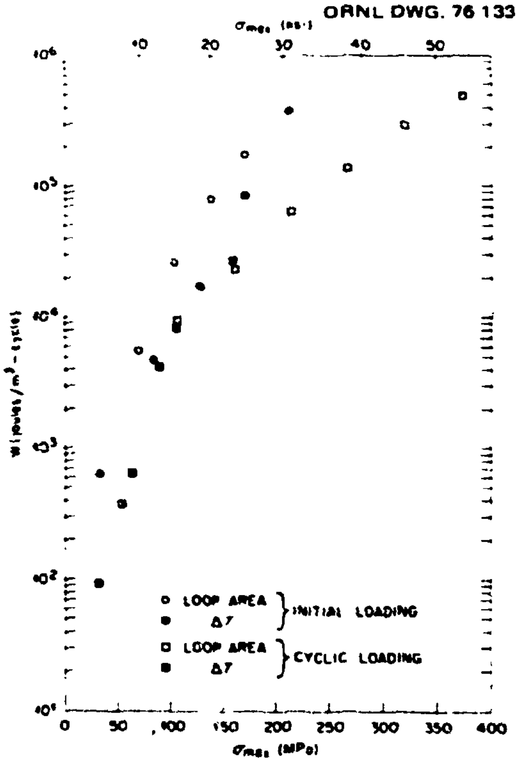

Fig. 3. Comparison of heat generated by stress as obtained from temperature rises to the work done on the specimen found from stress-strain curves for a NbTi conductor with copper matrix (No. 4, Table 1).

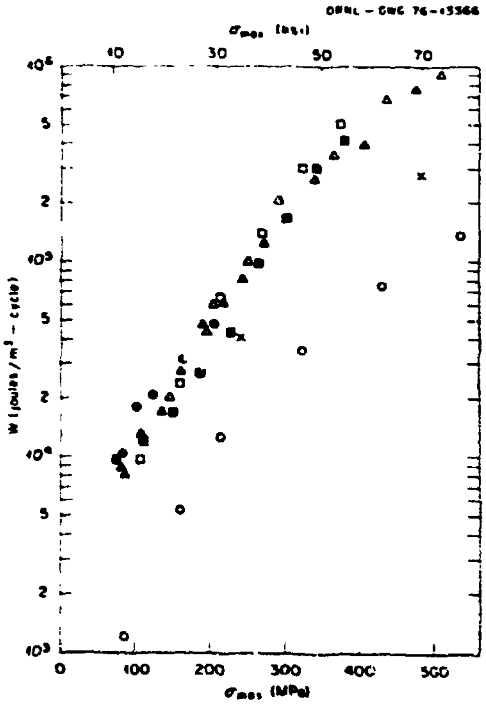

Fig. 5. Stress-induced heating under cyclic stress as a function of maximum stress in the cycle for a number of commercial conductors. The characteristics of the conductors are listed in Table 1.

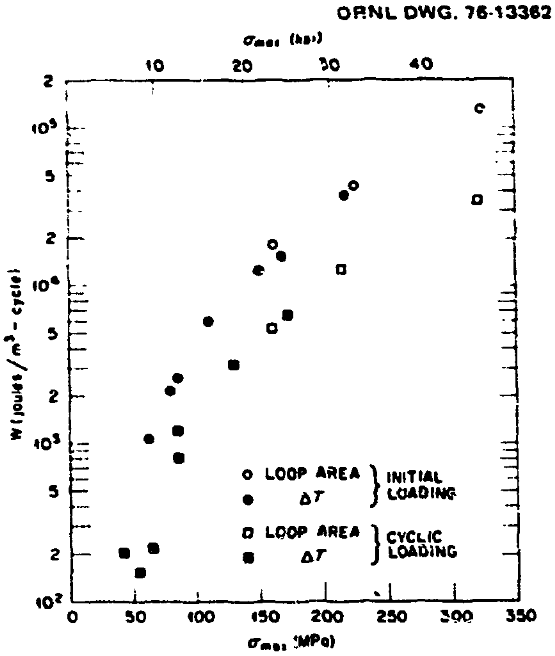

Fig. 4. Comparison of heat generated by stress as obtained from temperature rises to the work done on the specimen as found from stress-strain curves for a NbTi conductor with an Al alloy matrix (No. 7, Table 1).