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Thermal Expansion of Multifilamentary Nb_3Sn and V_3Ga Superconductive Cables and Fiberglass-Epoxy and Cotton-Phenolic Composite Materials*

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The thermal contraction of multifilamentary Nb_3Sn and V_3Ga superconductive cables and the composite materials, fiberglass-epoxy and cotton-phenolic, was measured from room temperature to 4 K. Both the thermal contraction and the thermal expansion coefficient were tabulated as a function of temperature. The thermal contraction to 4 K of V_3Ga was slightly greater than that of Nb_3Sn. For the composites, thermal contraction to 4 K was 2.8 times higher transverse to the fibers than parallel to them.

§1. Introduction

For the design of superconducting magnet systems, the thermal and mechanical data of the superconducting wire and the structural materials of the magnet are required. One of the most important thermal properties is the thermal expansion. Composite materials like cotton-phenolic and fiberglass-epoxy are often used as the cryogenic construction material, especially fiberglass-epoxy, which has advantages of high mechanical strength at low temperature and light weight. Such composite materials usually have a large thermal expansion coefficient.

A15 superconducting materials have been used to obtain high magnetic fields, and Nb_3Sn and V_3Ga are the most common materials at present. Critical current measurements on these materials have shown a wide variability, due in part to the differential thermal contraction between the sample and the sample holder material.[1] For these reasons, the thermal expansion of multifilamentary Nb_3Sn and V_3Ga, cotton-phenolic, and fiberglass-epoxy (NEMA G-10CR) were measured and the thermal expansion coefficient was calculated from room temperature to 4 K. This was done as part of a program[2–9] at NBS to develop superconductor standards.

§2. Experiment

The thermal expansion measurements of multifilamentary Nb_3Sn, V_3Ga, cotton-phenolic, and fiberglass-epoxy were made in a quartz tube dilatometer.[10] The differential contraction is transmitted by concentric quartz tubes to a room temperature mechanical dial gauge whose sensitivity is 0.5 μm.

The nonmentallics measured were a grade of NEMA Type C cotton cloth reinforced phenolic laminate and a special cryogenic grade of NEMA G-10 fiberglass-epoxy laminate (G-10CR). These laminates are commercial products meeting current NEMA C and G-10 specifications. G-10CR is specially chosen for its low temperature properties and is a heat-activated, amine-catalyzed bisphenol A solid type epoxy resin laminate reinforced with continuous-filament E-glass fabric, silane finished. The G-10CR composite has a yarn count in the glass fabric of 17 ± 1 cm^{-1} (43 ± 3 in^{-1}) for warp, and 13 ± 1 cm^{-1} (32 ± 2 in^{-1}) for fill. The expansion measurements were taken in the normal and warp directions. The cotton-phenolic was measured in the normal and parallel (warp or fill undetermined) directions.

The specimens for measurements parallel to the fiber axis were directly machined (Fig. 1(a)) to dimensions of $6\times6\times199.37$ mm (cotton-phenolic) and $4.2\times4.2\times203.2$ mm (G-10CR). For measurements perpendicular to fiber axes the specimens were prepared using 8 pieces of sample, bonded using a thin epoxy

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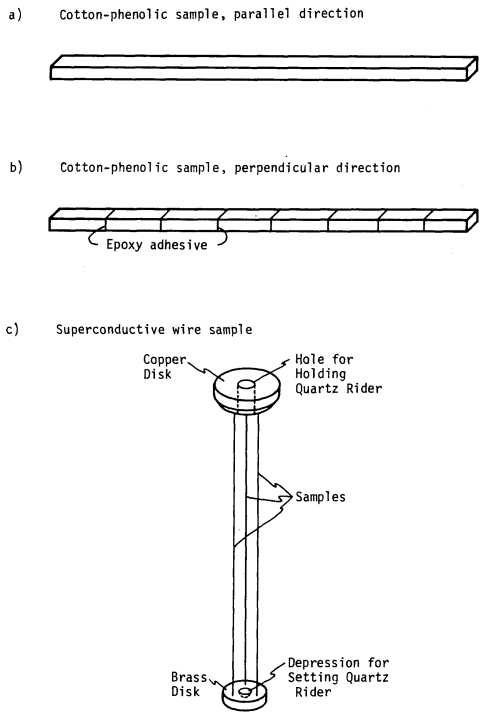

Fig. 1. Sample configuration for thermal expansion experiment.

adhesive (Fig. 1(b)) with the resulting dimensions of $6\times6\times196.62$ mm (cotton-phenolic) and $6.5\times6.5\times199.2$ mm (G-10CR).

Both Nb_3Sn and V_3Ga samples were commercially fabricated by cabling and soldering six superconductor strands around a 0.12 mm central tungsten core with a strand pitch of 6.5 mm. Each strand was 0.12 mm in diameter and the Cu/Ga matrix contained 55 V_3Ga/V filaments of 0.010 mm diameter with a twist pitch of 20 mm. The Nb_3Sn and V_3Ga wire samples were arranged as shown in Fig. 1(c) and the sample lengths were 180.84 mm for Nb_3Sn and 180.82 mm for V_3Ga. Three wires were soldered to a copper flange using In–Ag (2 percent) and spaced at 120° intervals around a 4 mm radius. The quartz rider passed through the copper flange and rested on a lower support flange made of brass. The specimens were thus subject to about a 130 gm load. This sample assembly was then suspended inside a high purity copper shield tube which maintained an isothermal condition in a helium gas environment.

The samples were cooled at a rate of 2.5 K min^{-1} from 300 to 4 K. The temperature was determined by a chromel-constantan thermocouple which was either attached directly to the sample (for cotton-phenolic and G-10CR) or positioned inside the copper shield tube (for the case of Nb_3Sn and V_3Ga wire). In the latter case the local helium gas temperature was measured, and the temperature of the sample was assumed to be the same as that of the helium gas.

§3. Calibration of Apparatus

The apparatus was calibrated by measuring the thermal contraction of a polycrystalline OFHC copper bar as shown in Fig. 2(a). The difference between the average measured data and the standard reference material (SRM) data for OFHC copper[11] was used as a correction factor. On the other hand, in measurements of the wire samples as shown in Fig. 2(b), the apparatus was calibrated by measurements of the thermal contraction of OFHC copper wire. The estimated accuracy of these calibration measurements was ±0.005 percent in a total contraction of about 0.2 percent ($\Delta L/L_{293}$).

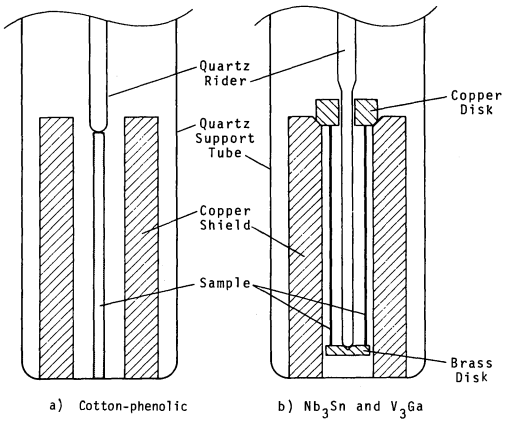

Fig. 2. Sample setting for thermal expansion apparatus.

§4. Results

Thermal expansion referred to room temperature, $(L_{293}\text{-}L_T)/L_{293}=\Delta L/L_{293}$, of multifilamentary Nb_3Sn and V_3Ga, cotton-phenolic, and G-10CR were measured from room temperature to 4 K and the expansion coefficient, $\alpha=(1/L_{293})(dL/dT)$, was obtained. Each specimen was measured three times, and the copper standard was measured before and

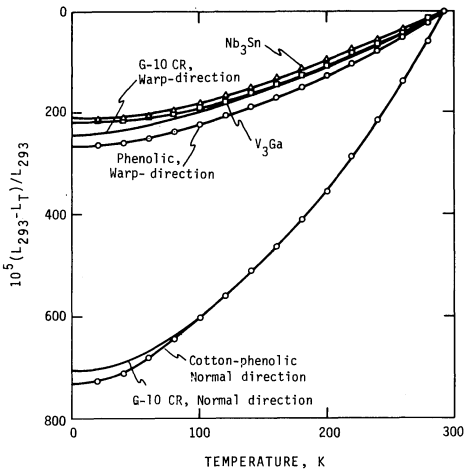

Fig. 3. Comparison of thermal contraction of Nb_3Sn, V_3Ga, cotton-phenolic, and fiberglass-epoxy G-10CR.

after each set of measurements to calibrate the apparatus. The measured thermal expansions ($\Delta L/L_{293}$) of multifilamentary Nb_3Sn, V_3Ga, cotton-phenolic and G-10CR are shown in Fig. 3. For cotton-phenolic and G-10CR, the thermal expansion of each direction is shown because the anisotropy was large. Thermal contraction at 4 K ($\Delta L/L_{293}$) of phenolic perpendicular to the fiber axis was 2.8 times that of the parallel direction at 4 K. For G-10CR it was 2.9 times. The experimental data were fitted with a computer program developed from one by Clark.[10] The form for $\Delta L/L_{293}$ was derived from

$$\Delta L/L_{293}=\frac{L_{293}-L_T}{L_{293}}=a+\frac{T^4}{b+cT^2+dT^3}, \quad (1)$$

which has the appropriate behavior at high and low temperatures. The form used for fitting was

$$T^4=AT^3+BT^2+C\left(\frac{\Delta L}{L}\right)T^3+D\left(\frac{\Delta L}{L}\right)T^2 +E+F\left(\frac{\Delta L}{L}\right), \quad (2)$$

where the coefficients A through F are the fitted constants.

These equations are represented by the solid lines in Fig. 3. The maximum deviation of the calculated data from the experimental data was less than 8.0 percent, in all temperature ranges. The calculated data in Table I have an estimated uncertainty of $\pm 50\times 10^{-6}$ (or 50 units in the table).

The expansion coefficient, α, was obtained by taking the derivative of the fitted equation. It is more difficult to estimate the accuracy of the coefficient, but at any specific point the maximum error was estimated to be $0.5\times 10^{-6}\ K^{-1}$ (or 0.5 units in the table); however, it is usually much less. The best fitted data are compiled in a standard tabular form also shown in Table I.

§5. Discussion

This experiment showed that these composite materials contract rapidly when cooled. The thermal contraction was very dependent on type of composite lay-up as well as orientation of the composite. Other factors affecting thermal contraction were the specific resin used and the fiber density. As shown in Fig. 3, the thermal contraction of both cotton-phenolic and G-10CR in a direction perpendicular to the fiber was about 2.8 times larger than that in a parallel direction. This is consistent with the large thermal contraction of other composite materials[12] due to the much higher thermal contraction of the epoxy resin as compared to that of the fiber.

There are no data on the thermal expansion of multifilamentary Nb_3Sn and V_3Ga. The only data available are for a multifilamentary NbTi sample, whose thermal contraction was 2650×10^{-6} between 295 and 20 K.[13] The thermal contraction of both multifilamentary Nb_3Sn and V_3Ga wire was thus about 20 percent smaller than that of multifilamentary NbTi wire. This is due in part to the tungsten core whose contraction to 4 K is less than one third that of copper.

As expected, the differences between the thermal contraction of the superconducting wire and the cotton-phenolic and G-10CR were large for the normal direction, and thus the choice of the combination of materials for magnet construction is critical and can lead to significant effects. Superconducting magnets have frequently been impregnated with epoxy to prevent wire movement and enhance stability. Therefore, for the practical use of thermal expansion data, measurements of superconductive wire composites impregnated with epoxy will be needed.[14,15] Also, care must be exercised when mounting specimens

Table I. Low temperature thermal contraction of some superconductors and composites.

T (K)	Nb_3Sn superconductive wire		V_3Ga superconductive wire		G-10CR (warp)		G-10CR (normal)		Cotton-phenolic (warp)		Cotton-phenolic (normal)	
	10^6 $\Delta L/L$	10^6 α (K^{-1})	10^6 $\Delta L/L$	10^6 α (K^{-1})	10^6 $\Delta L/L$	10^6 α (K^{-1})	10^6 $\Delta L/L$	10^6 α (K^{-1})	10^6 $\Delta L/L$	10^6 α (K^{-1})	10^6 $\Delta L/L$	10^6 α (K^{-1})
4	2100[a]	0.0[a]	2180[a]	0.0[a]	2410[a]	0.0[a]	7060[a]	0.0[a]	2640[a]	0.0[a]	7300[a]	0.0[a]
20	2100	0.3	2180	0.4	2410	2.7	7060	6.0	2640	1.4	7300	7.6
40	2090	1.8	2160	1.8	2340	4.5	6900	9.8	2580	3.3	7080	12.8
60	2030	4.4	2110	3.5	2230	5.7	6670	13.1	2500	4.8	6780	16.4
80	1930	6.1	2030	4.8	2110	6.6	6380	16.0	2390	6.1	6430	19.0
100	1790	7.2	1920	6.1	1970	7.3	6030	18.8	2250	7.3	6030	20.9
120	1640	8.0	1790	7.2	1820	7.9	5630	21.6	2100	8.4	5590	22.5
140	1480	8.6	1630	8.2	1650	8.5	5170	24.5	1920	9.4	5130	24.0
160	1300	9.0	1460	9.0	1480	9.2	4650	27.2	1720	10.3	4630	25.8
180	1120	9.3	1270	9.7	1290	9.9	4080	29.8	1510	11.2	4090	28.2
200	930	9.6	1070	10.4	1080	10.5	3460	32.3	1280	12.0	3410	31.0
220	730	9.8	860	10.9	860	11.1	2790	34.5	1030	12.8	2850	34.2
240	540	9.9	630	11.4	640	11.6	2080	36.6	770	13.5	2130	37.3
260	340	10.1	400	11.8	400	11.9	1330	38.6	490	14.2	1360	39.7
273	210	10.2	250	12.1	250	12.1	820	39.7	300	14.5	830	40.8
280	130	10.2	160	12.2	160	12.2	540	40.3	200	14.8	550	41.4
293	0	10.3	0	12.4	0	12.3	0	41.4	0	15.2	0	42.0

[a] = Extrapolated

$\Delta L/L = (L_{293} - L_T)/L_{293}$

$\alpha = (1/L_{293})\, dL/dT$

for critical current measurements so that unmatched thermal contractions don't introduce extra deformation in the wire and cause spurious results.[1] The results compared in Fig. 3 show that the wire specimens should be mounted parallel to the fiber directions for minimum residual stress.

Acknowledgments

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